Silicon Photonics for All-Optical Processing and
High-Bandwidth-Density Interconnects

Noam Ophir

Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
in the Graduate School of Arts and Science

COLUMBIA UNIVERSITY

2013
ABSTRACT

Silicon Photonics for All-Optical Processing and High-Bandwidth-Density Interconnects

Noam Ophir

Silicon photonics has emerged in recent years as one of the leading technologies poised to enable penetration of optical communications deeper and more intimately into computing systems than ever before. The integration potential of power efficient WDM links at the first level package or even deeper has been a strong driver for the rapid development this field has seen in recent years. The integration of photonic communication modules with very high bandwidth densities and virtually no bandwidth-distance limitations at the short reach regime of high performance computers and data centers has the potential to alleviate many of the bandwidth bottlenecks currently faced by board, rack, and facility levels. While networks on chip for chip multiprocessors (CMP) were initially deemed the target application of silicon photonic
components, it has become evident in recent years that the initial lower hanging fruit is the CMP’s I/O links to memory as well as other CMPs.

The first chapter of the thesis provides more detailed motivation for the integration of silicon photonic modules into compute systems and surveys some of the recent developments in the field. The second chapter then proceeds to detail a technical case study of silicon photonic microring-based WDM links’ scalability and power efficiency for these chip I/O applications which could be developed in the intermediate future. The analysis, initiated originally for a workshop on optical and electrical board and rack level interconnects, looks into a detailed model of the optical power budget for such a link capturing both single-channel aspects as well as WDM-operation-related considerations which are unique for a microring physical characteristics. The holistic analysis for the full link captures the wavelength-channel-spacing dependent characteristics, provides some methodologies for device design in the WDM-operation context, and provides performance predictions based on current best-of-class silicon photonic devices. The key results of the analysis are the determination of upper bounds on the aggregate achievable communication bandwidth per link, identifying design trade-offs for bandwidth versus power efficiency, and highlighting the need for continued technological improvements in both laser as well as photodetector technologies to allow
acceptable power efficiency operation of such systems.

The third chapter, while continuing on the theme silicon photonic high bandwidth density links, proceeds to detail the first experimental demonstration and characterization of an on-chip spatial division multiplexing (SDM) scheme based on microrings for the multiplexing and demultiplexing functionalities. In the context of more forward looking optical network-on-chip environments, SDM-enabled WDM photonic interconnects can potentially achieve superior bandwidth densities per waveguide compared to WDM-only photonic interconnects. The microring-based implementation allows dynamic tuning of the multiplexing and demultiplexing characteristic of the system which allows operation on WDM grid as well device tuning to combat intra-channel crosstalk. The characterization focuses on the first reported power penalty measurements for on-chip silicon photonic SDM link showing minimal penalties achievable with 3 spatial modes concurrently operating on a single waveguide with 10-Gb/s data carried by each mode. The chapter also details the first demonstration of WDM combined with SDM operation with six separate wavelength-and-spatial 10-Gb/s channels with error free operation and low power penalties.

The fourth, fifth, and sixth chapters shift in topic from the application of silicon photonics to communication links to the evolving use of silicon waveguides for nonlinear
all-optical processing. The unique tight mode confinement in sub-micron cross-sections combined with the high $\chi^{(3)}$ response of silicon have motivated the development of four-wave mixing (FWM)-based processing silicon devices. The key feature of the silicon platform for these nonlinear processing platforms is the ability to finely and uniformly control the dispersive properties of the optical structures in a way that enables completely offsetting the material dispersion and achieve dispersion profiles required for effective parametric interaction of waves in the optical structures. Chapter four primarily introduces and motivates nonlinear processing in communication applications and focuses on recent achievements in non-silicon and silicon FWM platforms.

Chapter five describes some of the author’s contributions on parametric processing of high speed data in silicon nonlinear devices, with first of a kind demonstrations of wavelength conversion of 160-Gb/s optically time division multiplexed (OTDM) data as well as the wavelength-multicasting of a 320-Gb/s OTDM stream. The chapter then details a methodical characterization and demonstration of several record wavelength conversion experiments of data in silicon with 40-Gb/s data wavelength-converted across more than 100 nm with only 1.4-dB of power penalties as well as the wavelength and format conversion of 10-Gb/s data across up to 168 nm with sensitivity gains stemming from the format conversion of about 2 dB and a residual conversion
penalty of only 0.1 dB, achieved by implementing an improved experimental setup. Both experiments highlight the performance uniformity of the conversion process for a wide range of probe-idler detuning settings, showcasing the silicon platform’s unique broadband phase matching properties.

The sixth chapter presents a slight shift in motivation for parametric processing from traditional telecom-wavelength applications to functionalities developed targeting mid-IR operation. Parametric-processing in the silicon platform at long wavelengths holds large potential for performance improvements due to the elimination of two-photon absorption in silicon at long wavelengths as well as silicon’s dispersion engineering capabilities which uniquely position the silicon platform for effective phase matching of significantly wavelength detuned waves. Four-wave mixing signal generation and reception at mid-IR wavelengths are attractive candidates for tunable flexible operation with modulation and detection speeds which are currently only available at telecom wavelengths. With this vision in mind, several contributions detailing extension of FWM functionalities in silicon to operate at wavelengths close to 2 µm with performance equivalent to much smaller detuning setting measurements. The contributions detail the experimental demonstration of the first silicon optical processing functionalities achieved at such long wavelengths including the wavelength conversion
and unicast of 10-Gb/s signals with up to 700 nm of probe-idler detuning, the combined
two-stage 10-Gb/s FWM-link in which both data generation and detection at 1900 nm
is facilitated by parametric processing in silicon with only 2.1-dB overall penalty, the
first ever 40-Gb/s receiver at 1900 nm based on a FWM stage for simultaneous tem-
poral demultiplexing and wavelength conversion, and lastly, the demonstration of a
40-Gb/s FWM-link operation with only 3.6 dB of penalty. The chapter concludes with
a short discussion on possible extensions to enable silicon parametric processing at even
longer wavelengths targeting the mid-IR spectral transmission window of 3-5 μm.
Contents

List of Figures viii

List of Tables xxvii

Glossary xxix

1 Silicon Photonics for High Bandwidth Density Interconnects 1

1.1 Motivation for On-Chip Optics . . . . . . . . . . . . . . . . . . . . . . 1

1.2 Technological Solutions for Chip I/O . . . . . . . . . . . . . . . . . . . 3

1.2.1 Electronic Technological Solutions . . . . . . . . . . . . . . . . . . 3

1.2.2 Optical Technological Solutions . . . . . . . . . . . . . . . . . . . 5

1.3 Silicon Photonic Components for Chip I/O . . . . . . . . . . . . . . . . 8

1.3.1 Waveguides and Couplers . . . . . . . . . . . . . . . . . . . . . . . 8

1.3.2 Resonant Structures . . . . . . . . . . . . . . . . . . . . . . . . . 10
CONTENTS

2.4 Link Power Efficiency ............................................ 43

2.5 Open Issues and Potential Technological Developments ............ 47

  2.5.1 Fiber-Chip Coupling ......................................... 48

  2.5.2 Polarization-Dependence of Silicon Components .......... 50

  2.5.3 Power Efficient Utilization of Optical Links .............. 52

  2.5.4 Joint Electrical and Optical Channel Design ............. 53

2.6 Conclusions ...................................................... 54

3 On-Chip Microring-Based Spatial Division Multiplexing ............ 57

  3.1 Spatial Division Multiplexing for Increasing Waveguide Bandwidth Density ............................................. 59

  3.2 Microring-Based SDM Multiplexer and Demultiplexer .......... 62

  3.3 Single Channel SDM Performance Evaluation .................. 66

  3.4 3-Way WDM With 2-Fold SDM Demonstration ................... 71

  3.5 Conclusions ...................................................... 73

4 Nonlinear All-Optical Processing of Data in Silicon ............. 75

  4.1 Motivation for All-Optical Processing in Communication Systems .......................................................... 75

iii
4.1.1 Potential Candidates for Nonlinear All Optical Processing . . . 76
  4.1.1.1 Contention Avoidance in Optically Switched Networks 76
  4.1.1.2 High Symbol Rate OTDM Processing . . . . . . . . . 78
  4.1.1.3 Expanding Optical Capabilities Beyond Telecom Wave-
           length Domains . . . . . . . . . . . . . . . . . . . . . 80
4.2 Four-Wave Mixing . . . . . . . . . . . . . . . . . . . . . . . . . . . 81
  4.2.1 Physical Phenomena . . . . . . . . . . . . . . . . . . . . . . . 81
  4.2.2 Leading Four-Wave Mixing Platforms . . . . . . . . . . . . . . . 85
4.3 The Silicon Waveguide Nonlinear Platform . . . . . . . . . . . . . . 87
  4.3.1 Dispersion Engineering in Silicon . . . . . . . . . . . . . . . . 88
  4.3.2 Fundamental Challenges of Parametric Processing in Silicon . . 91
  4.3.3 Recent Notable Data Parametric Processing Results in the Silicon 93
5 Broadband Wavelength Conversion in Silicon Waveguides 96
  5.1 Wavelength Conversion of 80- and 160-Gb/s RZ Time Division Multi-
           plexed Data . . . . . . . . . . . . . . . . . . . . . . . . 98
    5.1.1 Experimental Setup . . . . . . . . . . . . . . . . . . . . . . . 99
    5.1.2 Experiments and Results . . . . . . . . . . . . . . . . . . . 101
5.2 High-Repetition Rate Pulsed Pumps vs. CW Pumps for Nonlinear Processing ..................................................... 104

5.3 3-Way Multicast of 320-Gb/s RZ Data ................................................................. 106

5.4 Wavelength Conversion of 40-Gb/s NRZ Data Across the S-, C-, and L-Bands ................................................. 109
  5.4.1 Experimental Setup ............................................................................. 110
  5.4.2 Experiments and Results ..................................................................... 112

5.5 Wavelength Conversion of 10-Gb/s Phase-Modulated Data ................................................................. 115

5.6 168-nm Spanning Wavelength Conversion with Format Conversion of 10-Gb/s Data ............................... 117
  5.6.1 Dispersion-Engineered Silicon Waveguide ......................................... 118
  5.6.2 Wavelength Conversion Experimental Setup ...................................... 119
  5.6.3 Receiver Characterization for Broad Wavelength-Conversion Experiments ........................................ 120
  5.6.4 Wavelength Conversion Experiments .................................................. 122

5.7 Summary and Conclusions ............................................................................. 125
## 6 Mid-Infrared Wavelength-Conversion Devices

6.1 Motivation Shift to Longer Wavelength Applications .......................... [130]

6.2 Accessing MWIR Through Nonlinear Processing in Silicon ............... [133]

6.3 Conversion and Unicast of 10-Gb/s Data from 1900 nm across 700 nm . [136]

6.4 First Demonstration of 10-Gb/s Four-Wave Mixing Links at 1884 nm . [141]
   6.4.1 First Four-Wave Mixing Stage - Wavelength Unicast ............... [143]
   6.4.2 Second Four-Wave Mixing Stage - Wavelength Conversion ....... [145]

6.5 FWM-Based 40-Gb/s Detection at 1860 nm .................................... [147]

6.6 40-Gb/s Four-Wave Mixing Link Operation at 1882 nm .................... [151]

6.7 Extension to MWIR Wavelengths ................................................. [156]
   6.7.1 Materials for Low Loss Guiding ........................................... [156]
   6.7.2 Higher Order Dispersion Phase Matching ......................... [157]
   6.7.3 Quasi Phase Matching in Silicon Waveguides .................... [158]

6.8 Summary and Conclusions ......................................................... [160]

## 7 Summary and Conclusions

7.1 Summary of Contributions ....................................................... [162]

7.2 Conclusions .............................................................................. [167]
CONTENTS

7.3 Future Work Recommendations .................................... 168
7.4 Final Remarks .................................................. 171

References ......................................................... 173
List of Figures

1.1 Illustration of top of the package connectors using a Flex cable versus PCB transmission lines. Figure taken from (1). . . . . . . . . . . . . . 4

1.2 SEM images of three types of resonators: (a) 2D photonic crystal cavity (b) 1D cavity (c) microring resonator cavity. Figure adapted from (2). . II
2.1 Microring-based point-to-point silicon photonic link concept linking two processor/memory nodes. (a) Depiction of a multi-die packaging solution based on direct bonding of both chips on a shared substrate or silicon carrier. The optical die would contain the driver and receiver electronics to the extent needed in close proximity to the optical devices. In-package electrical wires transfer data to/from the optical die. (b) Microring-based point-to-point silicon photonic link. Two optical dies communicate over fiber. Each die includes a transmit module based on a microring modulator array and a receive module based on a microring demultiplexing array. Germanium photodetectors serve for both feedback for thermal stabilization as well as high-speed signal detection. Laser sources are assumed to be off-chip separate units.

2.2 Schematic diagram of multiple microring resonances coupled to a shared waveguide. Each line depicts the response of a single microring. The distance between two repeating resonances of one ring is the free spectral range (FSR). The distance between adjacent channels (and their respective microring modulators/filters) is the channel spacing $\Delta f_{ch}$. 
2.3 Tx module insertion loss and power penalty breakdown for 12.5 Gb/s modulation for different channel spacing values. .......................... 34

2.4 Rx module insertion loss and power penalty breakdown for 12.5 Gb/s modulation for different channel spacing values. The loss and penalty values are shown for the worst case Rx array element (optimized) for each channel spacing. ......................................................... 37

2.5 The required laser optical power per channel for both 12.5-Gb/s and 25-Gb/s cases. The optical power is determined from the optical power budget. The nonlinear power limitation range of aggregate power greater than 20 dBm in the waveguide is overlaid on the graph. The maximal achievable aggregate bandwidth is the intersection of the power-per-channel lines with the border of that area. ................................. 41
2.6 Maximal achievable link bandwidth for both 12.5-Gb/s and 25-Gb/s modulation rates as function of additional loss or penalty beyond the ones included in the power budget detailed in the previous sections. The aggregate achievable bandwidth is highly sensitive to the losses. In the vicinity of the computed power budget the function is approximately linear with a slope of -150 Gb/s per dB or -200 Gb/s per dB (for 12.5 Gb/s and 25 Gb/s respectively)...

2.7 Power efficiency for 12.5-Gb/s modulation as function of the aggregate communication bandwidth realized. The laser power can be reduced by increasing the channel spacing (reducing aggregate bandwidth) till the thermal trimming and tuning power becomes the dominant power consumption element (as it linearly depends on the channel spacing). The optimal operating point is at 437.5 Gb/s aggregate bandwidth which corresponds to 35 wavelength channels at 174-GHz channel spacing..

2.8 Schematic diagram of polarization diversity design using polarization beam splitters and polarization rotators along with double the microring arrays for modulation and demultiplexing on the Tx side and Rx side.
3.1 Schematic diagram of a SDM-based on-chip link which utilized microring WDM modulator arrays for imprinting data on multi-wavelength CW light. The SDM Mux (composed of larger rings with the FSR matching the channel spacing) couples all the wavelength channels from a single array to a specific spatial mode which then propagates in the multi-mode waveguide section. The spatial modes are demultiplexed by a SDM demux and then are further demultiplexed in wavelength in microring-filter arrays leading to detectors.

3.2 Optical performance of the fabricated device. a. Microscope image of the fabricated device. Inset: SEM showing the heater to tune each individual ring resonator. b-d. Optical transmission and crosstalk at the three output ports for signal injection on each of the three input ports measured with tapered lensed fiber input and output.
3.3 Experimental setup for 3-port single-WDM-channel SDM performance evaluation including Pulsed Pattern Generator (PPG), Tunable Laser (TL), Amplitude Modulator (AM), Phase Modulator (PM), Erbium-Doped Fiber Amplifier (EDFA), Isolator (→), Standard Single Mode Fiber (SSMF), Tunable Filter (λ), Digital Communications Analyzer (DCA), Variable Optical Attenuator (VOA), Avalanche-Photodiode (APD-TIA), Limiting Amplifier (LA), and Bit-Error-Rate Tester (BERT). 68

3.4 Eye diagrams for 3-port single-WDM-channel SDM operation at 1563 nm with all microresonators aligned spectrally to maximize transmission on all ports as well as the back-to-back measurements (B2B). Port 1 and 2 which experience lower crosstalk levels (see Table 3.1) have open eye diagrams but port 3 suffers from significant degradation due to the crosstalk leaking primarily from the TE$_1$ mode of port 2. 69

3.5 Optimized SDM performance for 3-port single-wavelength-channel experiment. a. BER measurements for back-to-back (B2B) test case, one-port-at-a-time transmission, and full SDM operation for all 3 ports, showing less than 1.9-dB worst case penalty. b. Corresponding eye-diagrams for the inspected signals. 71
3.6 2-port 3-wavelength channel demonstration. a. Experimental setup for demonstrating combined SDM and WDM operation. b. BER measurements for back-to-back (B2B) test cases and full SDM-WDM operation for both ports showing worst case penalties of 1.4 dB. c. Corresponding eye-diagrams for the inspected signals.

4.1 Dispersion engineering of silicon channel waveguides. (a) Simulated GVD for three different cross-section dimensions for TE and TM polarizations (b) Corresponding acquired phase mismatch in a 1-cm long silicon waveguide. The area in which the phase mismatch is smaller than \( \pi \) is indicated in gray. (c) Simulated resulting conversion efficiency assuming 100-mW CW pump at 1550 nm (with the exception of the black curve for which the pump is set at 1585 nm). Figure adapted from [3].
5.1 Experimental setup of wavelength conversion of 160-Gb/s OTDM RZ data. Dashed lines represent electrical cable, and solid lines represent optical fiber. Highlighted areas signify signal generation, wavelength conversion, and temporal optical demultiplexing and reception functional blocks. Polarization controllers (not marked on the diagram) are used throughout the setup. The silicon waveguide used in this experiment had a linear insertion loss of 6.4 dB with TPA and FCA adding roughly 3 dB of nonlinear loss when high-power optical signals are introduced.
5.2 (a) Output spectrum of conversion after the CW pump is suppressed (to overcome dynamic range limitation of the OSA), with 1541-nm input signal and 1559-nm converted signal. Non-degenerate FWM appears around the 1550-nm pump wavelength. (b) Autocorrelation traces taken on the 80-Gb/s signals before and after wavelength-conversion, overlaid with the autocorrelation trace of 10-Gb/s demultiplexed tributary. (c) Eye diagrams of 10-Gb/s input and 10-Gb/s tributary-demultiplexed signals. (d) Optimized demultipled 10-Gb/s tributary eye-diagram. The uneven shape is a result of the inverted method of demultiplexing where the all-optical gate was set to notch the adjacent tributary rather than isolate a single 10-Gb/s tributary. (e) BER measurements for the optimized demultiplexing settings showing an overall 11.1-dB power penalty - including multiple amplification stages beyond the wavelength conversion process.
5.3 (a) Output spectrum of conversion after the CW pump is suppressed, with 1541-nm input signal and 1559-nm converted signal. Non-degenerate FWM appears around the 1550-nm pump wavelength. (b) Autocorrelation traces taken on the 160-Gb/s signals before and after wavelength-conversion overlaid with the autocorrelation trace of 10-Gb/s demultiplexed tributary. (c) Eye diagrams of 10-Gb/s input and 10-Gb/s tributary-demultiplexed signals.  

5.4 3-way wavelength multicasting of the 160- or 320-Gb/s RZ-OOK OTDM data stream. The setup can reconfigurably perform an OTDM multicast/unicast by turning on and off the CW probes. An OSO is used to inspect the launched signal. Image taken from [4].  

5.5 Wavelength multicasting of a 320-Gb/s RZ-OOK OTDM data stream. Spectra recorded at the chip’s output for configurations ranging from no probes present all the way up to 3-probes (and corresponding RZ idlers) present. An OSO is used to inspect the launched signal as well as the multicasted copy of the signal at 1532 nm from the 3-way multicast configuration. Image taken from [4].
5.6 Wavelength conversion of 40-Gb/s NRZ data: (a) Experimental setup. (b) Overlaid spectra measured at the output of the chip, corresponding to wavelength conversions of 47.7 nm up to 100.2 nm. Beyond the generated idler, additional FWM products are visible at shorter wavelengths (1506.0 nm and 1496.5 nm) corresponding to a FWM process in which two probe photons interact with a single pump photon.

5.7 Wavelength conversion of 40-Gb/s NRZ data with varying probe-idler separations: (a) Eye diagrams for the back-to-back cases (probes) and wavelength-converted signals (idlers) for the listed conversion experiments. (b) BER curves measured for all the 40-Gb/s back-to-back cases (probes) and wavelength-converted signals (idlers) showing average power penalty of 1.47 dB.
5.8 Wavelength conversion of 5- to 40-Gb/s data with 100-nm probe-idler separation: (a) Eye diagrams for the back-to-back cases (probes) and wavelength-converted signals (idlers) for bit rates of 5-, 10-, 20-, and 40-Gb/s for 100.2-nm wavelength conversion. (b) BER curves for back-to-back cases (probes) and wavelength-converted signals (idlers) showing a power penalty of less than 1 dB for bit rates up to 20 Gb/s, and a 1.43-dB penalty for 40-Gb/s signals.

5.9 Data-validation experimental setups for wavelength and format-conversion up to 168 nm with an inset of optical microscope image of four silicon nanowaveguides in a spiral layout.

5.10 Experimental measurement of the APD-TIA-based receiver sensitivity (at BER of $10^{-9}$) using either BER measurements or deriving it from the responsivity based on a fit to a reference sensitivity and producing the relative sensitivity curve based on a shot-noise-limited model.
5.11 Overlaid spectra of wavelength conversion experiments recorded at the chip output, depicting conversion of 60 nm up to 168 nm. Beyond generated idlers, additional FWM products are visible at shorter wavelengths (1497 nm, 1478 nm, 1459 nm) corresponding to FWM in which two probe photons interact with a single pump photon. Some residual TDFA noise is also visible (1522 nm, 1466 nm). . . . . . . . . . . . . . 123

5.12 (a) Recorded BER curves for all probe and idler signals indicating an average 1.9 dB sensitivity gain. (b) Probes and the idlers eye diagrams recorded from the inverted-data differential output port of the APD-TIA. (c) Directly modulated RZ and NRZ back-to-back BER measurements showing a 2-dB APD sensitivity difference between formats. . . . 124

6.1 (a) Atmospheric transmission windows. (source - Wikipedia) (b) Commonly used spectroscopy absorption bands. (source - Wikipedia) . . . . 131
6.2 Overlaid ISA traces at the output of a dispersion-engineered silicon waveguide with a 1546.5-nm ZGVD, pumped with a 10-GHz 1.5-ps FWHM MLL. The probe wavelength generated is varied between 1800 and 1980 nm, producing corresponding idlers between 1356 and 1269 nm and probe-idler separations between 444 and 711 nm. The conversion efficiency for all the conversions is nearly constant at -32 dB. The conversion is slightly less efficient compared to conversions closer to the ZGVS wavelength due to higher insertion loss of the inverse tapers when operating far from the designed wavelength of 1550 nm. Spectral features between 1380 to 1530 nm are ASE emission from the laser used to generate the probe.

6.3 Experimental setups for (a) 10-Gb/s wavelength conversion from 1866 nm to 1321 nm spanning 545 nm combined with a NRZ-to-RZ format conversion (b) Unicast of 10-Gb/s RZ data from C-band to O-band using a probe-idler separation of 700 nm.
6.4 (a) OSA trace recorded at the chips output showing wavelength conversion of a 1866-nm probe to a 1321-nm idler. TDFA noise artifacts are visible at 1450 nm, 1640 nm (not fully suppressed TDFA pump), and at the broad gain region around 1850 nm. (b) Probe BER curve recorded using an Extended-InGaAs photodetector (inset of eye diagram recorded on CSA). (c) Idler BER curve recorded on APD receiver (inset of eye diagram) and an average idlers BER curve based on curves recorded at 1585-nm to 1643-nm. The BER curve has 0.4 dB power penalty compared to the average idlers curve.

6.5 (a) OSA trace recorded at the chips output showing data unicast with a CW 1973-nm probe and a RZ 1271-nm idler. TDFA noise artifacts are now visible at 1640 nm (not fully suppressed TDFA pump), and at the broad gain region around 1850 nm. (b) BER curves recorded for the 10-Gb/s modulated pump before injection into the silicon chip, and the 10-Gb/s generated idler. Eye diagrams for all signals are included as insets.
6.6 (a) FWM-link concept illustration. Data is unicasted from the C-band to a longer wavelength band to generate long-wavelength high speed data in a wavelength-tunable way followed by a wavelength-conversion operation to transfer the data to a lower wavelength for detection. The second FWM stage can also incorporate optical sampling or regeneration. (b) Experimental setup of the double-stage FWM experiment. The first FWM chip performs a unicast from 1546.8 nm to 1884 nm. The second chip performs a wavelength conversion from 1884 nm to 1312 nm.

6.7 Signal progression along the experiments stages: (a) Spectrum at output of the first FWM chip with the 1312-nm CW probe, 1546.8-nm 10-Gb/s RZ pump, and generated 1884-nm 10-Gb/s RZ idler. (b) Spectrum recorded at the 1900-nm isolators output. Beyond the amplified 1884-nm RZ signal, noise features include not fully depleted L-band TDFA pumps, TDFA asynchronous spontaneous emission (ASE) background, and not fully suppressed CW signal at 1312 nm. (c) Spectrum at the output of the second FWM chip with the 1884-nm 10-Gb/s RZ signal as the probe, the 1546.8-nm 10-GHz pulsed pump, and the generated 1312-nm 10-Gb/s RZ signal.
6.8  (a) BER curves and eye-diagrams recorded using the extended-InGaAs PIN-TIA receiver for the 1546.8-nm pump and 1884-nm idler generated by the first FWM stage. (b) BER curves recorded using the InGaAs APD-TIA receiver for the 1546.8-nm pump and 1312-nm idler generated by the second FWM stage. The eye-diagrams were recorded from the inverted-data differential output port of the APD-TIA. . . . . . . . . . 146

6.9  (a) Experimental setup including a generation of a pulsed 10-GHz 1546.5 nm pump and a 40-Gb/s 1866-nm probe which are launched into a silicon waveguide to produce a 1321-nm 10-Gb/s idler (b) OSA trace recorded at the chips output showing the FWM result. . . . . . . . . . . . . . . . . 148

6.10 (a) BER measurements of the 10-Gb/s tributaries. (b) Idler eye diagrams recorded at the inverted-data differential output port of the APD. (c) 40-Gb/s Electrical eye diagram recorded directly from the PPG. (d) 40-Gb/s eye diagram reconstructed from the optical sampling process by sweeping the pump pulse timing (recorded at the APDs output). . . 150
6.11 Experimental setup for FWM-link operation with two FWM stages enabling both generation and detection of 40-Gb/s RZ data at 1882 nm. Insets show DCA traces recorded at 20-ps/div resolution for the 40-Gb/s pulsed pump and 40-GHz pulse-carved probe injected into the first FWM chip. .............................. 152

6.12 Signal progression along the experiment’s stages: (a) Spectrum at output of the first chip with FWM-generated 1882-nm 40-Gb/s RZ idler. (b) Spectrum recorded at the long-wavelength isolators output. Beyond the amplified 1882-nm RZ signal, spectral features include TDFA ASE and traces of the L-band CW pump used to pump the TDFA. (c) Spectrum at the output of the second chip which generates the 1313-nm 10-Gb/s RZ signal tributaries. ........................................ 153

6.13 (a) BER curve measurements recorded for a back-to-back (B2B) case on the 10-Gb/s RZ signal before the temporal multiplexing and amplification and the twice-converted and temporally-demultiplexed 10-Gb/s 1313-nm tributaries. (b) Eye-diagrams recorded out of the 10.7-GHz APD-TIA inverted-output data port for the back-to-back case as well as demultiplexed tributaries. ................................. 154
6.14 SEM images of the different sections of width-modulated silicon waveguide (a)-(d) corresponding to the illustrated structure (e). Figure taken from (5).

6.15 (a) Experimentally measured conversion efficiency (defined here as ratio of output idler to output probe) for the width modulated waveguide (red dots) compared to a straight waveguide (triangles). A 22.4-dBm CW pump set at 1543 nm was used for these launched on the device for these measurements. (b) Conversion efficiency enhancement of 12 dB at 1668 nm measured from the difference in the curves in (a). Figure taken from (5).
List of Tables

2.1 Loss and power penalties break down by component in the Tx module.

Range of values given for channel spacings varied from 200 GHz to 25 GHz (for 12.5 Gb/s modulation) and from 400 GHz to 50 GHz (for 25 Gb/s modulation). Values for insertion loss and extinction ratio based on results reported in (6, 7).

2.2 Loss and power penalties break down by component in the Rx module.

Range of values for the worst case channel with channel spacings varied from 200 GHz to 25 GHz (for 12.5 Gb/s modulation) and from 400 GHz to 50 GHz (for 25 Gb/s modulation). For the 25-Gb/s case the worst case element at the optimal design point is always the first ring in the Rx array.
2.3 Link power efficiency with component/functionality breakdown at 1.55-Tb/s aggregate bandwidth. ........................................ 45

3.1 CW crosstalk measurements for the 3 modes at the resonances available for operation in the C-band of the DUT when all resonances are co-aligned. These measurements were taken on the polarization maintaining lensed tapered fiber setup. .......................... 66

5.1 Wavelength listing of pump, probe, and idler settings for the first wavelength conversion experiment. ................................. 122
## Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulator</td>
</tr>
<tr>
<td>APD</td>
<td>Avalanche Photo Diode</td>
</tr>
<tr>
<td>ASE</td>
<td>Asynchronous Spontaneous Emission</td>
</tr>
<tr>
<td>AWG</td>
<td>Arrayed Waveguide Grating</td>
</tr>
<tr>
<td>B2B</td>
<td>Back to back</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BERT</td>
<td>Bit Error Rate Tester</td>
</tr>
<tr>
<td>BGA</td>
<td>Ball Grid Array</td>
</tr>
<tr>
<td>CDR</td>
<td>Clock Data Recovery</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>CMP</td>
<td>Chip Multicore Processor</td>
</tr>
<tr>
<td>CROW</td>
<td>Coupled Resonator Optical Waveguide</td>
</tr>
<tr>
<td>CSA</td>
<td>Communication Signal Analyzer</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DCA</td>
<td>Digital Communications Analyzer</td>
</tr>
<tr>
<td>DFB Laser</td>
<td>Distributed Feedback Laser</td>
</tr>
<tr>
<td>DLI</td>
<td>Delay Line Interferometer</td>
</tr>
<tr>
<td>DPSK</td>
<td>Differential Phase Shift Keying</td>
</tr>
<tr>
<td>DUT</td>
<td>Device Under Test</td>
</tr>
<tr>
<td>E-O</td>
<td>Electrical-to-Optical</td>
</tr>
<tr>
<td>EAM</td>
<td>Electro-Absorption Modulator</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>ER</td>
<td>Extinction Ratio</td>
</tr>
<tr>
<td>FCA</td>
<td>Free Carrier Absorption</td>
</tr>
<tr>
<td>FK</td>
<td>Franz-Keldysh</td>
</tr>
<tr>
<td>FMF</td>
<td>Few-Mode Fiber</td>
</tr>
<tr>
<td>FOM</td>
<td>Figure Of Merit</td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectral Range</td>
</tr>
<tr>
<td>Acronym</td>
<td>Term</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>FWM</td>
<td>Four-Wave Mixing</td>
</tr>
<tr>
<td>GVD</td>
<td>Group Velocity Dispersion</td>
</tr>
<tr>
<td>HNLF</td>
<td>Highly Non-Linear Fiber</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>IL</td>
<td>Insertion Loss</td>
</tr>
<tr>
<td>LA</td>
<td>Limiting Amplifier</td>
</tr>
<tr>
<td>MCM</td>
<td>Multi-Chip Module</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
<tr>
<td>MLL</td>
<td>Mode Locked Laser</td>
</tr>
<tr>
<td>MM</td>
<td>Multi Mode</td>
</tr>
<tr>
<td>MMI</td>
<td>Multi Mode Interference</td>
</tr>
<tr>
<td>MWIR</td>
<td>Mid Wave Infra Red</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>MZM</td>
<td>Mach-Zehnder Modulator</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infra Red</td>
</tr>
<tr>
<td>NOLM</td>
<td>Nonlinear Optical Loop Mirror</td>
</tr>
<tr>
<td>NRZ</td>
<td>Non Return to Zero</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>Q</td>
<td>Quality Factor</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QCSE</td>
<td>Quantum Confined Stark Effect</td>
</tr>
<tr>
<td>QPM</td>
<td>Quasi Phase Matching</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RIN</td>
<td>Relative Intensity Noise</td>
</tr>
<tr>
<td>ROADM</td>
<td>Reconfigurable Optical Add Drop Multiplexer</td>
</tr>
<tr>
<td>Rx</td>
<td>Receive</td>
</tr>
<tr>
<td>RZ</td>
<td>Return to Zero</td>
</tr>
<tr>
<td>SA</td>
<td>Sens Amplifier</td>
</tr>
<tr>
<td>SDM</td>
<td>Spatial Division Multiplexing</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>SSMF</td>
<td>Standard Single Mode Fiber</td>
</tr>
<tr>
<td>SWIR</td>
<td>Short Wave Infra Red</td>
</tr>
</tbody>
</table>
Acknowledgments

I would like to acknowledge first and foremost my PhD advisor, Professor Keren Bergman, for her guidance which has greatly contributed to my development as a researcher and for providing the means, academic freedom, and trust to pursue new research ideas.

I also acknowledge Professors Richard Osgood and Tony Heinz who have taught me many of the fundamental aspects of the field of optics as well as contributed to my research through collaborations and guidance. I also wish to thank Professors Chee-Wei Wong, Jeffrey Kash, and Luca Carloni for many discussions on silicon photonics.

To the senior lab members, Alexandr Biberman and Benjamin Lee, I owe thanks for mentoring me in the lab and teaching me how to conduct photonic experimental work. Their contribution to the development of my skill set is immeasurable.

I am thankful to have been able to work with my fellow researchers at the Lightwave Research Lab: Kishore Padmaraju, Qi Li, Lin Xu, Johnnie Chan, Robert Hendry, Sebastien Rumley, Lee Zhu, and Christine Chen. It was a pleasure working with such
gifted people for the past few years.

I owe many thanks to Professors Michal Lipson and Alex Gaeta from Cornell University. Through the collaborations with their research groups much of my research on silicon photonics has been enabled. Their guidance has been crucial to many of our research projects and their vision has guided my research to unexpected directions. Moreover, I am grateful for interacting with their superb (past and present) students and researchers: Amy Turner Foster, Kyle Preston, Sasikanth Manipatruni, Michael Menard, Jaime Cardenas, Lian-Wee Luo, Mark Foster, Yoshi Okawachi, and Ryan Lau. Their design and fabrication work has enabled many of the recent advances in silicon photonics. Working with such outstanding individuals has been a pleasure.

I would also like to take this opportunity to thank Dr. Reza Salem of Picoluz LLC for many discussions and experimental ideas as well as technical support and collaborations in the field of nonlinear photonics. His contributions to many of my nonlinear experimental efforts were of great value and his advice has always been on target. I also want to extend gratitude to Jeffrey Driscoll of the Osgood group for many discussions on optics as well as collaborative work on nonlinear processing devices.

Finally, I would like to thank my friends and lab mates for many technical discussions and for providing moral support when needed. In particular I would like to
mention Daniel Brunina, Caroline Lai, Howard Wang, and Ajay Garg for their contributions and support.
To my parents, Tirza and Zohar, who taught me education and knowledge were worth more than money.
1

Silicon Photonics for High Bandwidth Density Interconnects

1.1 Motivation for On-Chip Optics

While computing system in the last decades of the 20th century kept scaling computing power with a Moore’s law rate to meet demand through transistor size reduction along with clock frequency speed ups, this trend has been halted and even somewhat reversed in terms of the clock speeds for computing chips. Instead, the notion of parallel computation took over to a level where clock speeds have virtually come to a halt at a few GHz but core counts are continuing to grow with quad-core processors becoming
1.1. MOTIVATION FOR ON-CHIP OPTICS

standard even in consumer electronics. The trend of chip multicore processors (CMPs) has been explored much more drastically in server and high-end compute chips (8). Power dissipation has been the main limiting factor in further increasing clock speeds as thermal dissipation faces limitations of how much heat can be sunked away from ever hotter chips as well as a new awareness for the need for power-efficient computing for both devices detached from a power grid (such as the cellular phones) as well as for large scale power-hungry data centers and high-power computers. With modern large CMP chips, the power dissipation of the on-chip interconnect alone has been estimated to reach up to 50% of the chip’s power budget. As CMPs continue to scale to larger sizes, innovative technologies will be required to enable low power high bandwidth communications across the chip.

However, while on-chip interconnects have been able to scale to date to multiple of Tb/s bisection bandwidths (9, 10) thanks to innovations on the CMOS metal interconnect level such as the transition to copper and introduction of low-κ dielectrics (11), the success at the on-chip interconnect level has not been as well translated to increased off-chip interconnect bandwidth. The difficulty in getting bandwidth off the chip is a result of two main problems. The first is the minimal pitch at which electrical connectors can be placed at the chip-to-package interface without inducing crosstalk. This
1.2. TECHNOLOGICAL SOLUTIONS FOR CHIP I/O

limits the overall number of pins available to the chip to use for power, ground as well as I/O. The second is the limitations associated with traversing through bandwidth-limited electrical channels at the package core, socket, and board-level transmission lines (1). As a result, a gap has been formed between on-chip computation capabilities and the off-chip bandwidth, already limiting the effective utilization of compute power as data from memory cannot be fetched and stored fast enough (12).

1.2 Technological Solutions for Chip I/O

1.2.1 Electronic Technological Solutions

Given pin count limitations electronic interconnects have found routes to improve the bandwidth density from the chip by increasing channel rates. These solutions have in part come from aggressive development of power efficient integrated circuits (ICs) in modern CMOS technology to include strong equalization and clock-data recovery (CDR) which allow exceeding the communication bandwidth beyond a given channel electrical bandwidth (13, 14, 15, 16). The power efficiency of such electrical links is inversely proportional to the signaling rate (1). The other complementary approach has to also replace legacy PCB FR4 transmission lines with better conditioned RF channels
1.2. TECHNOLOGICAL SOLUTIONS FOR CHIP I/O

Figure 1.1: Illustration of top of the package connectors using a Flex cable versus PCB transmission lines. Figure taken from [1].

with increased electrical bandwidth. For instance, top-of-the-package-connector-based designs (see Fig. 1.1) utilize high quality RF transmission lines for out-of-package interconnects [13]. These approaches enable few-cm to relatively long (> 50 cm) cable lengths with high data rates (10’s of Gb/s) but typically require connector pitches on the order of several hundred µm to avoid RF crosstalk. These solutions also complicate chip packaging and heat sinking from the chip since the connectors come out from the top. However, even if the transceivers and the improved transmission channels can enable operation within the chips’ power envelope at these data rates, the separate cost of serializing and deserializing these high data rate signaling lanes may have inhibitive power costs and needs to be considered.

Alternatively, a separate approach, not disjoint from the development of efficient transceiver ICs, has been to attempt to break the pin-count limitation by packaging multiple chips and memory in multi-chip modules (MCM) on a shared silicon carrier
equipped with a back-end-of line metal interconnect (17). Using a silicon carrier with a back-end-of-line copper interconnect allows finer BGA pitch as the thermal expansion coefficient of chip and carrier is matched reducing mechanical strains. With potentially less than 50 µm pin pitch (17) and dense wiring between the mounted chips, such solutions improve the local I/O bandwidth and power efficiency between the co-packaged modules.

Finally, a forward looking approach is 3D integration - stacking multiple chips and memory vertically and interconnecting them with through-silicon vias (TSVs) (17). This method avoids off-chip transmission lines altogether though it is faced with significant challenges in terms of the heat sinking as well as the provision of sufficient power, ground, and signal I/O connectors. However, neither the silicon carrier nor the 3D integration solutions do not address by themselves board-level and rack-level interconnect bandwidth.

1.2.2 Optical Technological Solutions

Vertical cavity surface emitting lasers (VCSELs) have been present and been commercialized for short reach optical interconnects (18). The high wall-plug efficiency of these lasers (compared to telecom sources) as well as the ability to directly modulate
the lasers have led to their relative success. As they produce multi-mode light, propagation in multi-mode fiber introduces bandwidth-distance limitations (19). However, co-design with signal processing ICs have enabled the bandwidth-distance product to be overcome to an extent enabling modulation rates beyond 40 Gb/s of a single VCSEL link (20). Reduction of parasitics and recent improvements in transceiver designs have enabled VCSELs to achieve record power efficiencies approaching 1 pJ/bit (21).

Introducing VCSEL technology into the package level with dense integration schemes needs to address energy, footprint, and packaging challenges in particular since each fiber can traditionally carry only a single data channel (18). Some alternatives have included the use of multi-core multi-mode fiber (22) as well as the adaptation of VCSELs to allow coarse WDM operation (23) to increase the transmitted bandwidth per fiber.

Planar waveguide photonic integrated circuits (PICs) present an alternative which resembles the technologies developed for telecom operation, enabling dense WDM and single mode optics in an integrated platform. With single mode operation bandwidth limitations of the fiber are nearly inexistent at relevant short reach distances and losses in fiber can be made as low as 0.2 dB/km. Existing III-V platforms have been developed and optimized for telecom components with excellent performance (24). Com-
plex structures including coherent formats modulators and demodulators have been demonstrated (primarily in InP) for high end telecom links. However, cost, device footprint (stemming from intermediate level of index contrast), and integration potential concerns have limited the adoption of this material platform for large scale cheap compute-system interconnects. Silicon photonics, which uses CMOS materials and the silicon on insulator (SOI) platform to create PICs presents an attractive alternative to many of the functionalities achieved by III-V PICs. As CMOS processes and materials are used to create these PICs, low cost volume production of these devices is possible with potentially very close integration with CMOS electronics - providing performance advantages in reducing parasitics and shortening the electronic transmission lines to the photonic components (25, 26). While germanium and silicon-germanium provide solutions for detection with CMOS-compatible materials, lasing cannot easily be achieved in silicon as it is an indirect bandgap semiconductor material. Hybrid integration of III-V materials on silicon has been suggested as a way to introduce integrated laser sources on the silicon photonic platform (27). The hybrid approach leverages bonded III-V layers on SOI to provide gain (for lasers or on-chip amplifiers) or to realize electro-absorption modulators (27) with all other photonic elements such as waveguiding, switching, and filtering implemented with underlying silicon structures.
1.3. Silicon Photonic Components for Chip I/O

1.3.1 Waveguides and Couplers

The fundamental capacity from which all other devices stem is the ability to confine and guide light with low loss in any material platform. Using primarily silicon as the core material with a high index of refraction of 3.5, high confinement waveguides can be formed either air or silicon-dioxide ($n = 1.5$) clad. Silicon-on-insulator (SOI) wafers with a thick (several micron) bottom oxide have been the silicon photonic workhorse for the most part. The high index of refraction of the core, along with the large index contrast between core and cladding, allow the creation of high-confinement sub-micron cross-section waveguides with low loss bending radii of several microns \(2\). For these type of waveguide side wall roughness resulting from the etching process has been surmised to be the main loss mechanism \(28\). Current SOI waveguides of typical
1.3. SILICON PHOTONIC COMPONENTS FOR CHIP I/O

cross-sections of 500 nm width by 250 nm height have reported losses $\sim 1 - 2$ dB/cm \(^{(29)}\) \(^{(30)}\). Lower loss (0.3 dB/cm) smooth-sidewall waveguides are possible by using oxidation rather than etching to define the structures but resulting with very thin waveguides which have a very delocalized mode \(^{(31)}\).

Alternative core materials which are typically used in the CMOS foundries include silicon nitride as well as poly-silicon which are deposited rather than grown. While silicon nitride provides potential for lower loss waveguiding with a lower nonlinear response, formation of thick enough films of it requires careful attention to stress damage typically required thermal annealing steps in the fabrication process. Poly-silicon which is a partially crystallized version of deposited amorphous silicon also requires thermal annealing steps \(^{(32)}\). The processing temperatures for both materials present some challenges with regard to integration with other processes, especially for back-end integration over pre-existing metal layers but is possible to achieve with low enough temperatures \(^{(32)}\) or pulsed annealing \(^{(33)}\).

However, as the optical mode size of such sub-micron waveguides are much smaller than that of standard silica fibers ($\sim 10\mu m$), and the effective index of silicon and silica is very different, both poor mode overlap and fresnel losses would be high if edge coupling is attempted without a unique taper. An inverse taper with decreasing width
of the confining waveguide (34) is one method to effectively edge-couple fibers and silicon waveguides providing optimized coupling losses of between 0.5 and 1 dB over hundreds of nanometers bandwidth. An alternative approach has been to form Bragg grating structures which couples the optical waveguide-confined mode propagating in the horizontal direction with a vertically directed mode which can be coupled into a silica fiber, with low losses have been shown but with a limited bandwidth and typically a few dBs of loss (25, 35). While the grating-based coupling is less misalignment sensitive, the losses as well as limited bandwidth are not as good as those of edge couplers. However, the advantage of the possibility of wafer-level testing with grating couplers may trump other considerations if good-enough performance can be achieved with them.

1.3.2 Resonant Structures

Optical cavities in which waves travel repeatedly with low loss form resonating structures in which light adds coherently in phase to build up (resonating) or out of phase in which case the signal does not build up. Resonating cavities can be formed based in silicon using photonic crystals (36), microrings (37) (Fig. 1.2), or microdisks (38). In all these structures the resonant effect is based on in phase build up of power at a spe-
1.3. SILICON PHOTONIC COMPONENTS FOR CHIP I/O

Figure 1.2: SEM images of three types of resonators: (a) 2D photonic crystal cavity (b) 1D cavity (c) microring resonator cavity. Figure adapted from (2).

Specific set of wavelengths satisfying the condition that the round trip phase accumulated equals $m \cdot 2\pi$ where $m$ is an integer.

Resonating structures are practical usefulness for WDM communication links as they can be used to address subsets of channels which correspond to their resonant wavelengths while not affecting off-resonance signals. In combination with evanescently-coupled adjacent waveguides resonators can be used to realize different functionalities such as filters, wavelength multiplexers, and wavelength demultiplexers (39). Since the resonant condition wavelength is highly sensitive to phase accumulated in the cavity, the resonance location is highly dependent on the effective index, carrier concentrations, and temperature (in particular in silicon which has a strong thermo-optic response). These effects can be put to use or alternatively be deleterious for system operation - depending on the context used.
1.3.3 Modulators

A modulator is a device which allows an electric signal to control either the phase or amplitude of an optical signal. While the thermo-optic effect is strong in silicon, the time constants associated with thermal diffusion limit thermo-optic based modulators to MHz speeds \cite{2,40}. Therefore, thermal control of light has been adopted mostly for slow tuning of device properties rather than GHz speed modulation. However, the plasma dispersion effect which relates a shift in the index of refraction ($\Delta n$) and absorption coefficient ($\Delta \alpha$) with changes in the electron ($\Delta N$) and hole ($\Delta P$) concentrations in silicon through the following empiric relation \cite{2,41}

$$\Delta n = -[8.8 \times 10^{-22} \cdot \Delta N + 8.5 \times 10^{-18} \cdot (\Delta P)^{0.8}]$$ \hspace{1cm} (1.1)$$

$$\Delta \alpha = 8.5 \times 10^{-18} \cdot \Delta N + 6.0 \times 10^{-18} \cdot \Delta P.$$ \hspace{1cm} (1.2)

Dynamically introducing electrons and holes in silicon can be achieved through the creation of P-I-N or P-N junctions across waveguides in silicon through doping \cite{38} or all-optically \cite{42}. Applying voltage across the diode formed through electrical contacts facilitates control of the amount of carriers in the P-I-N or P-N junctions.

Mach-Zehnder interferometers (MZIs) have been widely used to form modulators
with junctions across the arms used to create a $\pi$ phase shift resulting in creating constructive and destructive interference for on-off-keyed (OOK) modulation of light. While previous generations of silicon MZI modulators (MZM) required large voltage swings of multiple volts $V_{pp}$ (43), depletion mode devices with traveling electrode designs and impedance-matched transmission lines have been shown very recently to enable CMOS compatible voltage swings with differential driving signals (44) capable of operating at speeds of up to 40 Gb/s. These designs though have come at the expense of making the devices longer, with 5-mm long arms in the MZI structure. Though this type of device has an estimated power consumption of 200 fJ/bit, the MZI device footprint may be inhibitive for large scale integration.

Resonant structures, in contrast, can be made extremely compact with microring and microdisk diameters demonstrated with radii less than 5$\mu$m (38, 45). As the resonant wavelength is a function of the phase accumulated in the ring, a very small amount of effective index shift is required to perturb the resonant wavelength. Given a fixed CW laser traveling in the waveguide at a near-resonant wavelength, this perturbation results in amplitude modulation or combined amplitude and phase modulation (46). As a result of the large sensitivity of the resonant transmission properties to the effective index of refraction power efficient modulators with less than 10 fJ/bit have
been shown for both microdisks \(^{(38)}\) as well as microrings \(^{(6, 7)}\). However, as the microresonators are extremely temperature sensitive (\(\sim 10 GHz/°C\) resonance shift), thermal stabilization has to be incorporated as well. As shown later, the cost of thermal stabilization typically overshadows the modulation power dissipation.

An different recent approach to silicon photonic modulators has been based on the Franz-Keldysh (FK) effect in bulk semiconductors or the quantum-confined Stark effect (QCSE) \(^{(47)}\) in a semiconductor quantum-well structure. In both cases the absorption of the material is modified by applied voltage. With integrated silicon photonic waveguides, electro-absorption modulators (EAMs) have been demonstrated to enable modulation bandwidths greater than 40 GHz in III-V hybrid-integrated QCSE devices \(^{(48)}\), germanium/germanium-silicon QCSE devices \(^{(49)}\), germanium-silicon FK devices \(^{(50)}\), or germanium FK devices \(^{(51)}\). These device present also the option of broadband operation with no need for thermal stabilization, but device fabrication is more complex and typically such devices have high insertion loss.

### 1.3.4 Wavelength Multiplexers and Demultiplexers

A basic required building block for WDM communications is the wavelength multiplexer and demultiplexer. The device allows combining multiple wavelength channels
into one waveguide with low loss as while a demultiplexer separates out the different wavelength channels into separate waveguides for detection. Such devices are required to provide high port counts with uniform performance, sufficiently low distortion within the passbands, as well as strong suppression of out of band signals.

Silicon-based arrayed waveguide gratings (AWGs) have very recently been demonstrated with 12 channels at 400 GHz spacing and crosstalk levels of -17 dB (52). Silicon nitride, which is less sensitive to phase errors than silicon, has been shown to be an attractive alternative for AWG construction and has been demonstrated with 40 channels at 200-GHz spacing and 3.5 dB loss (53) or alternatively with very thin (50 nm height) buried channel silicon nitride waveguides which has been shown with 0.5-dB insertion loss for 16 channels at 200-GHz spacing (54). An alternative multiplexer/demultiplexer solution which has gained popularity is the Echelle grating structure which is based on a 2D diffraction grating. With this type of grating structure a 40-channel 100-GHz spacing and 50-GHz 1-dB passbands device has been demonstrated (55).

However, resonator-based tunable wavelength multiplexers and demultiplexers are also possible based on successive microrings coupled to a shared bus waveguide (39). In such a configuration overall device footprint can be much reduced compared to grating based devices and both center wavelength and channel spacing can be fully tunable.
1.3. SILICON PHOTONIC COMPONENTS FOR CHIP I/O

through integrated heaters. However, such a silicon based device requires constant thermal control and tuning mechanisms.

1.3.5 Photodetectors

Germanium-based silicon photonic receivers had been recently demonstrated with bandwidths greater than 40 GHz, as well as with sensitivities in the vicinity of -18.9 dBm at 5 Gb/s at 1300 nm \cite{56} and also shown with greater than 0.8 A/W responsivity at 1550 nm \cite{57} with optimized designs. Germanium avalanche photodiodes (APDs) have recently been accomplished with promising results for high sensitivity detectors with the multiplication region implemented either in silicon in surface vertical APDs \cite{58} achieving sensitivities of -28 dBm for 10-Gb/s data at 1300 nm (but with voltages greater than 20 V), or with waveguide-integrated germanium APD operating with a bandwidth of 40 GHz and a measured sensitivity of -14 dBm at 1550 nm (with only 0.14 A/W responsivity of this device at this wavelength) \cite{59}.

Closer integration with electronics has potential for eliminating parasitic capacitance and resistance between the photodetectors and the trans-impedance amplifiers (TIAs) providing potential for much improved performance as well as potentially ”receiverless” receivers in which the receiver is powered by the optical power delivered by
the signals’ photons \((60)\).

Another potential alternative platform for CMOS-compatible detection is through absorption in poly-silicon photodiodes \((61)\) or ion-implanted silicon \((62)\). Though these detection platforms have much lower responsivity than germanium photodetectors, they are easier to fabricate in silicon and can be useful for detectors where high power may be available, for instance in optical feedback mechanisms for temperatures stabilization \((63)\).

### 1.3.6 Laser Sources for Silicon Photonic Interconnects

Commercial wavelength-stabilized sources used in WDM telecom systems typically operate at \(\sim 1\%\) wall-plug efficiency because of the significant portion of power spent on cooling and temperature stabilization of each laser cavity as well as the IL associated with multiplexing multiple signals into a single fiber. Higher efficiency relaxed-wavelength-stabilization concepts allow for finite amount of wavelength drift are not suitable for dense WDM grids. Therefore, developing telecom-grade laser sources with high wall-plug efficiency is key for creating low power optical WDM interconnects. Multi-wavelength lasers, utilizing a single cavity to generate multiple laser channels simultaneously \((64, 65)\), are highly attractive because only a single cavity needs to be
stabilized. Such systems are starting to be commercially available and are a subject of ongoing research at both 1.3 and 1.55 \( \mu \)m. Such quantum-dot fabry-perot lasers show potential for low relative-intensity noise (RIN) operation but further scaling of the number of lasing lines and output power is required as well as improved channel power uniformity. A different possible solution could be based on parametric oscillators to generate multiple wavelengths. In these solutions only the seed laser and the parametric cavity need to be thermally stabilized. However, such parametric solutions still require significant improvements to provide suitable stable sources.

### 1.4 Chapter Summary

In this chapter motivation and technological challenges for silicon photonic targeted for compute systems interconnects have been presented and some of the recent progress on significant components for enabling these type of photonic links was reviewed.

Chapter 2 covers a case study of how these elements could be combined for a dense WDM microring based link. This analysis attempts to capture accurately the loss and penalty budget dependence on the physical nature of the microring resonances as well as deduce the aggregate bandwidth limitations and power efficiency of such links.
Chapter 3 introduces the concept of on-chip spatial division multiplexing (SDM) and the first demonstration and characterization of a microring-based SDM multiplexer and demultiplexer system.
Chapter summary and key contributions - This chapter details the end-to-end analysis of an unamplified silicon photonic microring-based off-chip link for chip to memory or chip to chip communications. The microring link is designed for dense WDM operation to leverage the unique wavelength-localized operation of the microrings and maximize the bandwidth achieved per fiber. In order to investigate the performance and scaling limitations
of such a link an optical power budget analysis is performed based on best of class existing devices as well as analytic and simulated results. One unique feature of this analysis is that the spectral channel-spacing is taken into consideration for computing penalties and losses arising from the operation of these devices in a WDM context (rather than stand alone operation). This yields a strong dependence of the optical power budget on the channel spacing parameter. The optical power budget yields as a result the required optical power per channel from which the aggregate bandwidth limitations can be deduced based on the nonlinear optical upper threshold for the silicon devices. Optimal designs for the devices as well as sensitivity to additional losses are obtained. The analysis provides quantitative measures for the achievable energy efficiency and bandwidth density that could be reasonably realized within several years. The results also highlight key device attributes that require significant advancement and point out the need for improvements in laser wall-plug efficiencies to realize sub-pJ/bit scale optical links.

Although the single microring-modulator link can be of interest for niche applications, the real advantage of using microring-based components is in WDM link
construction where their wavelength-selectiveness becomes an advantage as a single microring can be used to address (modulate or filter) a single wavelength channel propagating on a bus waveguide. Furthermore, the small footprint of each microring (compared to other silicon photonic devices) allows dense integration of hundreds of devices per $mm^2$ which enables achieving Tb/s aggregate rates per link (with multiple links per die) potentially achievable. Multiple architecture design papers have explored high bandwidth microring-based links and interconnects \cite{67,68,69,70,71} but full-link optical power budget analyses and the resulting aggregate bandwidth limitations have only been partially addressed, typically not taking into consideration the power penalties induced by the non-ideal devices used to implement interconnect as well as cross-channel effects such as intermodulation and crosstalk (and the wavelength-channel-spacing dependence of such effects).

In this chapter an optical power budget of a single unamplified microring-based WDM link assuming current best of class reported devices is analyzed. A combination of empiric measurements and analytic models are used to model the behavior of the different elements in the link. The analysis provides quantitative measures for the maximal achievable bandwidth per link that could be reasonably realized within several years. The full optical power budget to determine the achievable bandwidth as well
2.1. MICRORING LINK DESIGN

as to enable a power consumption analysis including transmit and receive circuitry, photonic-device power dissipation, and laser power. The analysis excludes data serialization/deserialization costs which will also impact actual design choices for such links. The results highlight key device attributes that require significant advancement and point out the need for improvements in laser wall-plug efficiencies to provide sub-pJ/bit scale optical links.

2.1 Microring Link Design

2.1.1 Intermediate Future Integration Options

Full monolithic integration of silicon photonics within a computing chip offers a significant potential performance boost thanks to close integration with the electronics (71, 72), but integration of photonics on the same silicon as the processors is likely to become commercially feasible in the long term (greater than 10 years) because it will require significant modifications and the addition of fabrication steps to existing chip-fabrication facilities. In the near term, board-level optical modules offer significant flexibility but do not provide a solution for getting the data in and out of the chip package. Therefore, the discussion of feasible intermediate-future systems is narrowed
down to integration of silicon photonic technology as separate optical dies within a package (Fig. 2.1). These dies are connected to the processor either through a shared substrate, a silicon carrier, or die stacked (17). Such optical dies would include a limited amount of electronics as much as required to drive the optical link.

For this case study best current research devices are assumed to be possible candidates for production with certain improvements and assumptions detailed within the link buildup. The analysis is aimed to be agnostic as much as possible of the underlying compute system in order to keep the results as general as possible and applicable to multiple integration options, while capturing the key features and trade-offs of such a microring link.

### 2.1.2 Key Design Assumptions and Objectives

The first design objective of the link is to maximize the aggregate WDM bandwidth per link where a link is defined as a single pair of transmit and receive structures connected by a single data transmitting optical fiber. A secondary objective / constraint however is to keep power efficiency at reasonable values (target is as close as possible to 1 pJ/b). The design includes a dense WDM implementation with multiple ring modulators coupled to a shared bus waveguide on the transmit (Tx) side and similarly rings used
2.1. MICRORING LINK DESIGN

Figure 2.1: Microring-based point-to-point silicon photonic link concept linking two processor/memory nodes. (a) Depiction of a multi-die packaging solution based on direct bonding of both chips on a shared substrate or silicon carrier. The optical die would contain the driver and receiver electronics to the extent needed in close proximity to the optical devices. In-package electrical wires transfer data to/from the optical die. (b) Microring-based point-to-point silicon photonic link. Two optical dies communicate over fiber. Each die includes a transmit module based on a microring modulator array and a receive module based on a microring demultiplexing array. Germanium photodetectors serve for both feedback for thermal stabilization as well as high-speed signal detection. Laser sources are assumed to be off-chip separate units.

for filtering from a shared bus waveguide for the wavelength demultiplexer (demux) on the receive (Rx) side as shown in Fig. 2.1

Since each ring modulator or filter should address only a single channel, the working spectrum is limited by the smallest FSR in the system (corresponding to the largest ring). Therefore the rings should be as small as possible to provide the largest possible
2.1. MICRORING LINK DESIGN

available FSR. For a silicon ring with sufficiently high quality factor \(Q\) 10,000 this radius has been calculated to be around 1.7 \(\mu\)m \((37, 73)\). Increasingly larger rings can be added to the array until the largest ring resonances start overlapping the smallest rings resonance. This limitation dictates approximately 50 nm of operational spectrum with an optimized choice of ring radii ranging from \(\sim 1.8 \mu\)m to 1.9 \(\mu\)m, assuming operation at wavelengths around the telecom band of 1.55 \(\mu\)m \((73)\). The analysis assumes operation around 1550 nm telecom band since most reported results are currently for this wavelength range. However, this is more an artifact of test-equipment availability and 1300 nm is a likely candidate operating wavelength for short-reach systems do not need to include EDFA amplification due to the relatively higher responsivity of germanium at 1300 nm \((59)\).

Given the non-monolithic integration options assumed, the analysis focuses on two modulation rates per channel which seem likely candidate representative rates of 12.5 Gb/s and 25 Gb/s. Though lower data rates have been shown in a similar study to have the potential for power efficiency optimality \((71)\), the data rate will likely heavily depend on the chip clock frequency (with power-efficient SerDes typically implemented for a data rate which is twice the clock frequency \((56)\), packaging considerations, and the number of within-package pins allocated for communications to the optical module.
These data rates seem to be emerging for electrical chip I/O circuitry regardless of optical technologies \cite{13, 14} and are therefore good candidates to be compatible with the electronic transceivers which will exist on the chip for electronic transmission lines.

### 2.1.3 Link Construction

The WDM link presented here (Fig. 2.1) is composed of an off-chip multiwavelength laser source which feeds into a Tx module through polarization maintaining (PM) fiber. The Tx module is composed of a series of microring depletion-mode modulators coupled to a shared waveguide. Each modulator has a drop port with an integrated photodetector (PD) for thermal feedback for stabilization purposes \cite{63}. An additional feedback mechanism based on an integrated thermistor has also been demonstrated \cite{74}. The output of the Tx module is connected through PM fiber to the Rx module which has a microring-based spectral-demux. The demux is assumed to be composed of one or several cascaded microring stages per wavelength channel to provide sufficient inter-channel-crosstalk suppression. The microrings functioning as filters in this module are also equipped with thermal stabilization mechanisms. The filtered channels are fed into Germanium avalanche photodiodes (APDs)-based receivers for data detection \cite{59}.

The assumption that APDs are required to achieve the optimal sensitivities implies
2.1. MICRORING LINK DESIGN

Shot-noise limited power penalty models \((75)\) rather than the thermal-noise-limited models (which apply to PIN PDs which have also been developed in the silicon photonic platform \((57)\)). Shot-noise-limited power-penalty models are somewhat larger than thermal-noise-limited-derived models and therefore are an appropriate upper bound on the penalties expected in such a system. However, actual system design and optimization will depend on the choice of detector type.

While the modulator drivers can be perhaps located relatively far away from the modulators without significant performance penalties, the receiver front end circuitry must be included in close proximity to the PDs to avoid extra parasitic capacitance. This implies that at least some electronics must be located within the optical module (by limited monolithic integration of dedicated electronics, chip bonding, or other 3D integration methods). The electronic transceivers (or partial circuitry) for electronic transmissions between the optical die and the processor chip will have to be present in the optical die.

It is also important to note that microdisks \((38)\) can be used instead of microring structures as the principle of operation is identical. Microdisks however potentially have superior potential performance as the vertical PN junction better overlaps the optical \((38)\). On the other side, choice of microdisks for system design reduces flexibility as
2.1. MICRORING LINK DESIGN

disks are more susceptible to excitation of unwanted higher order radial modes (in particular at larger radii).

Figure 2.2: Schematic diagram of multiple microring resonances coupled to a shared waveguide. Each line depicts the response of a single microring. The distance between two repeating resonances of one ring is the free spectral range (FSR). The distance between adjacent channels (and their respective microring modulators/filters) is the channel spacing $\Delta f_{ch}$.

2.1.4 Thermal Stabilization

The rings span the full operational wavelength band with frequency-equidistant ring resonances (as illustrated in Fig. 2.2). Assuming the Tx (or Rx respectively) rings laid out tightly on a single die, fabrication variations result in an nearly even shift of the all ring resonances (with up to 50 GHz random variation in either direction from the designed frequency comb spacing) \cite{76,77}. Based on the repeating nature of the ring
resonances, this fixed fabrication-stage shift from the designed set of resonances results primarily in a cyclical transformation of the channel assignments to each microring in the Tx and Rx rather than thermally tune each ring to a predetermined fixed wavelength channel. This can be assumed to be done once at link setup with a static barrel shifter switch rather than a dynamic barrel shifter concept (77) and therefore requires thermal tuning of each ring only to ”snap” it to the nearest longer-wavelength wavelength channel. The amount of thermal power required to achieve that is therefore proportional to the wavelength spacing of the channels rather than the microrings’ FSR.

However, the thermal heaters are also required to stabilize the microrings’ operation through thermal fluctuations as to be expected in the chip’s package. Dynamic thermal fluctuations’ swing within the chip’s package are assumed to be around 40 °C rather than the a 100 °C specification. With a 10 GHz/°C resonance shift sensitivity (77), this results in 400 GHz of dynamic resonance shift per microring to be thermally stabilized.

The overall average power to be spent on fabrication-related thermal tuning as well as dynamic stabilization is related to both factors through the following linear relation

\[
E[heater\ power] = \rho \cdot (a \cdot \Delta T_{max} + b \cdot \Delta f_{ch})
\]  

(2.1)
where $a$ and $b$ are constants, $\rho$ is the thermal tuning efficiency, $\Delta T_{max} = 400$GHz is the maximal thermal swing, and $\Delta f_{ch}$ is the channel spacing. $b \sim 1$ based on monte-carlo simulations reported in (77). As the system can only heat the microrings but not cool them actively, the system has to run "hot" - i.e, when the ambient temperature is low the heaters are driven with high current to heat the rings while when the ambient temperature is high the heaters are driven with low current to introduce less local heating. Therefore, $a$ is related to the ambient temperature $T$ through $a = 1 - E[T]/\Delta T_{max}$. For a uniform temperature distribution $a = 0.5$. $\rho$ can be assumed to equal 4.4 $\mu$W/GHz based on reported power-efficient integrated heaters (78). Thermal crosstalk between the devices can be avoided by formation of trenches between devices (39).

2.2 Optical Power Budget Analysis

As both insertion loss (IL) and power penalties increase as the channel spacing is reduced (due to the finite roll-off of the microrings’ resonance-response tails), the overall loss and penalties are examined for a range of channel spacings at both modulation rates. The loss and penalties determine how much laser power is required per channel
as well as the aggregate laser power present in the bus waveguide.

Two primary nonlinear effects - two photon absorption (TPA) and TPA-induced free carrier absorption (FCA) will cause a sharp increase in propagation loss in the bus waveguide at high powers. Therefore the aggregate optical power in the waveguide is limited to be \( \sim 20 \text{ dBm} \) (21 dBm launched from fiber). Other potential limits on optical power lie in the stability bound within the microring modulators which limits the per-channel power reaching the microring modulator to \( \sim 6 \text{ dBm} \) \( \text{(79).} \)

In the rest of this section the loss and power penalties are analyzed for each module with a component-level breakdown and a module-level loss and penalties as function of channel spacing. The power penalties are computed assuming a shot-noise limited model as APDs are assumed at the receiver side.

### 2.2.1 Tx Module

Since the link would ideally operate in a CMOS environment, high-speed RF signals are limited to operate at CMOS-compatible voltage levels, i.e. around 1 Vpp. Extremely low-power (10 fJ/bit) microring modulators have been demonstrated to date with these driving conditions \( \text{(6,7,38).} \) Given a driving voltage limitation of 1 Vpp (and therefore, a given amount of resonance shifting), one now needs determine the optimal relative
2.2. OPTICAL POWER BUDGET ANALYSIS

wavelength positioning of the channel with respect to the resonance. A fundamental trade-off exists here: a small wavelength detuning from the resonance results in high extinction ratio (ER) but along with a high insertion loss (IL) (6). Modulator quality factor (Q) values are set to be $\sim 12,000$ (cavity loss limited at small radii) for 12.5-Gb/s modulation rate whereas $Q \sim 8,000$ (photon-lifetime limited) is used for 25-Gb/s modulation rate. Modulation ER power penalties are computed relative to a 20-dB ER commercial grade modulator. The OOK-modulation average power loss is also computed according to the ER of the devices.

<table>
<thead>
<tr>
<th>Table 2.1: Loss and power penalties break down by component in the Tx module. Range of values given for channel spacings varied from 200 GHz to 25 GHz (for 12.5 Gb/s modulation) and from 400 GHz to 50 GHz (for 25 Gb/s modulation). Values for insertion loss and extinction ratio based on results reported in (6, 7).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Component</strong></td>
</tr>
<tr>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Edge Coupler Loss (x2)</td>
</tr>
<tr>
<td>Bus Waveguide Loss</td>
</tr>
<tr>
<td>Modulator Loss</td>
</tr>
<tr>
<td>Modulation Penalty</td>
</tr>
<tr>
<td>OOK-Modulation Loss</td>
</tr>
<tr>
<td>Array-Induced Loss</td>
</tr>
<tr>
<td>Intermodulation Penalty</td>
</tr>
</tbody>
</table>

Beyond IL and power penalty arising from single ring operation, additional average loss (73) and intermodulation crosstalk penalties (80) are accrued from the operation of these within an array of devices on a shared bus waveguide since the spectral features
2.2. OPTICAL POWER BUDGET ANALYSIS

Figure 2.3: Tx module insertion loss and power penalty breakdown for 12.5 Gb/s modulation for different channel spacing values.

of the rings extend to adjacent wavelength channels. The IL (Table 2.1) is computed similarly to the method reported in (73) while assuming a 42-pm (5.3-GHz) dynamic shift of each modulator (6).

Edge-coupler loss is assumed to be 1 dB/facet (with 0.5 dB/facet perhaps possible (34, 81) and bus-waveguide propagation loss is assumed 1.7 dB/cm (30). The length of the waveguide is scaled proportionally to the number of modulators while assuming an approximate 60-µm by 60-µm footprint per modulator (to include contacts and thermal
2.2. OPTICAL POWER BUDGET ANALYSIS

isolation trenches besides the actual microring) and staggered layout of modulators on both sides of the waveguide. Table 2.1 details the parameters assumed and Fig. 2.3 details the overall loss and penalties accrued in the Tx module at a set of representative values for 12.5 Gb/s modulation.

2.2.2 Rx Module

As with the modulator array, operation of a WDM demux requires consideration of the channel spacing. In particular, design of the filtering stages as well as Q factors of each ring requires balancing of loss and sideband truncation penalties with inter-channel crosstalk penalties. Both filtering and crosstalk penalties are computed from analysis and simulation of the ring filtering response. The simulation for computing the power penalty from side-band truncation by a ring filter was based on the methods developed for (82) though adjusted for a shot-noise limited penalty model (83) and corrected filtering signal processing of the optical signals. For simplicity of analysis, only 1st-order ring filters are considered rather than higher-order filters (84). 0.5-dB IL for a signal dropping through a ring on resonance (85) is assumed as well as 0.5-dB IL for an optical power tap and PD - if required for providing thermal stabilization feedback (in case multiple filtering stages are used per channel).
2.2. OPTICAL POWER BUDGET ANALYSIS

The choice of Q for the microring filters trades-off inter-channel crosstalk suppression with signal degradation due to sideband attenuation as well as array-induced loss (similar to the Tx module). Unlike the Tx module, for which the losses and power penalties for all the channels are roughly equivalent, in the Rx module the channels differ in loss and penalties experienced. Assuming equal Q factors for all the rings, the channel corresponding to the first filter element in the Rx module experiences the highest crosstalk but the lowest propagation loss and no array-induced loss at all. However, channels which correspond to filters located further away down the Rx bus waveguide experience less crosstalk (as channels are gradually filtered off from the bus waveguide) along with higher propagation loss corresponding to the physical distance traveled as well as array loss from power lost to other channel’s filters.

Table 2.2: Loss and power penalties break down by component in the Rx module. Range of values for the worst case channel with channel spacings varied from 200 GHz to 25 GHz (for 12.5 Gb/s modulation) and from 400 GHz to 50 GHz (for 25 Gb/s modulation). For the 25-Gb/s case the worst case element at the optimal design point is always the first ring in the Rx array.

<table>
<thead>
<tr>
<th></th>
<th>12.5-Gb/s Modulation</th>
<th>25-Gb/s Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge Coupler Loss (x1)</td>
<td>1 dB</td>
<td>1 dB</td>
</tr>
<tr>
<td>Bus Waveguide Loss</td>
<td>0.08 - 1.36 dB</td>
<td>0.08 dB</td>
</tr>
<tr>
<td>Ring Drop Loss</td>
<td>0.5 dB</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Array Induced Loss</td>
<td>0 - 0.64 dB</td>
<td>0 dB</td>
</tr>
<tr>
<td>Truncation Penalty</td>
<td>0.12 - 0.89 dB</td>
<td>0.12 - 1.08 dB</td>
</tr>
<tr>
<td>Crosstalk Penalty</td>
<td>0.36 - 1.23 dB</td>
<td>0.44 - 2.41 dB</td>
</tr>
</tbody>
</table>
2.2. OPTICAL POWER BUDGET ANALYSIS

Figure 2.4: Rx module insertion loss and power penalty breakdown for 12.5 Gb/s modulation for different channel spacing values. The loss and penalty values are shown for the worst case Rx array element (optimized) for each channel spacing.

For ease of analysis the losses and penalties are computed for only two representative elements in the array - the first element and the one before last (which still has significant crosstalk contribution from the last channel to be filtered but also has almost all the accumulated propagation and array loss). The design is optimized so as to minimize the losses and penalties for worst case considering both channels, guaranteeing acceptable loss and penalties for the worst case path.

The results of this computation show that for minimizing the loss and penalties of
2.2. OPTICAL POWER BUDGET ANALYSIS

the worst case channel, single-ring per channel filtering is optimal. Waveguide propagation insertion loss is computed similarly to that of the Rx module. Table 2.2 details the loss and penalty parameters used and Fig. 2.4 depicts the overall loss and penalties accrued in the Rx module filtering stages up to the APDs at a representative set of points for the 12.5-Gb/s modulation rate case.

2.2.3 Fiber and Connector Loss

Optical propagation losses (0.2 dB/km in standard single mode fiber) and dispersion penalties up to distances of 1 km are likely negligible in the examined system. However, single mode fiber connectors (0.1 - 0.5 dB/connector loss) might be a much bigger obstacle to realizing such systems because of the high cost, cleanliness required, and connection accuracy required to achieve low losses. If multiple of these connectors are required, losses can increase rapidly if the connectors are not optimally connected. However, in order to ascertain upper limits on bandwidth the fiber and connector loss are assumed to be minimal 0.5 dB overall.
2.2.4 Germanium Receiver Sensitivity

Recent results in waveguide integrated germanium detectors have shown promising results which could potentially approach performance of III-V-based detectors \(^{(46, 87)}\). It is possible from these to extrapolate -16-dBm sensitivity at 12.5 Gb/s and -12-dBm at 25 Gb/s rate when operating at a wavelength of 1300 nm. For the analysis it is assumed that sufficient advancements can be made to enable these sensitivities to apply to 1550 nm, or alternatively, design and operate the link at the 1300-nm wavelength band (if integration with EDFAs or existing long-haul telecom infrastructure is not required). Closer integration with electronics (with lower parasitic capacitance) and improved APD designs provide potential for sensitivity improvements \(^{(59)}\). Therefore, a uniform 4-dB improvement is assumed to be possible at all bit rates within a few years, which implies a sensitivity of -20 dBm at 12.5 Gb/s and -16 dBm at 25 Gb/s.

High sensitivity silicon photonic receivers are one of the critical components that require further technological advancements. Theoretical bounds of closer integration of CMOS electronics with germanium structures give potential for much improved sensitivities by achieving extremely low parasitic capacitances \(^{(26)}\). The integration of the trans-impedance amplifier (TIA) and limiting amplifier (LA) or sense amplifier
(SA) in very close proximity to the germanium within the optical die is important to avoid excessive parasitic capacitance.

As jitter is not directly addressed in the model, an additional estimated power penalty of 2 dB for 12.5 Gb/s and 3 dB for 25 Gb/s is added to the optical power budget for the link.

### 2.3 Aggregate Achievable Link Bandwidth

With the assumed receiver sensitivities and computed loss and penalty budget, the required laser power per channel can be ascertained per channel spacing (Fig. 2.5). Given an aggregate optical power limit in the silicon waveguides this implies maximal aggregate achievable bandwidth of such a link design. Under the assumptions in this analysis, these limits come out to be \( \sim 1.8 \) Tb/s for 12.5-Gb/s modulation rate (145 wavelength channels) and \( \sim 1.7 \) Tb/s for 25 Gb/s (67 wavelength channels). The inferior scalability of the 25-Gb/s rate is mostly because of the fundamentally lower detector sensitivity at the higher data rate. In both cases the aggregate average power in the waveguide dictates the per-channel optical power limit rather than the microring-modulator instability threshold \( [79] \).
2.3. AGGREGATE ACHIEVABLE LINK BANDWIDTH

Figure 2.5: The required laser optical power per channel for both 12.5-Gb/s and 25-Gb/s cases. The optical power is determined from the optical power budget. The nonlinear power limitation range of aggregate power greater than 20 dBm in the waveguide is overlaid on the graph. The maximal achievable aggregate bandwidth is the intersection of the power-per-channel lines with the border of that area.

The first obvious conclusion from these results is that for microring links or interconnects the optical power budget and allowable channel count cannot be decoupled and computed separately. This is especially true at the high-bandwidth densities cases such as examined here. These results also highlight the need for further experimental characterization efforts of behavior of such many-channel links as the scaling of channel
2.3. AGGREGATE ACHIEVABLE LINK BANDWIDTH

count at the link level is not trivially derived from single device operation.

Figure 2.6: Maximal achievable link bandwidth for both 12.5-Gb/s and 25-Gb/s modulation rates as function of additional loss or penalty beyond the ones included in the power budget detailed in the previous sections. The aggregate achievable bandwidth is highly sensitive to the losses. In the vicinity of the computed power budget the function is approximately linear with a slope of -150 Gb/s per dB or -200 Gb/s per dB (for 12.5 Gb/s and 25 Gb/s respectively).

It is also worth investigating how the aggregate achievable bandwidth would vary as function of added fixed losses, such as those which could be introduced in a realistic scenario due to chip-coupling misalignment or some fabrication variation in the de-
2.4. LINK POWER EFFICIENCY

vicces. Alternatively, device improvements may enable lowering the required power per channel. By examining the maximal achievable link bandwidth versus loss or penalty variation (Fig. 2.6) it can be seen that the aggregate achievable bandwidth depends strongly on the losses. In the vicinity of the working point of computed losses (i.e, 0 dB added loss point), the slope is fairly constant at -150 Gbps/dB for 12.5-Gb/s modulation and -200 Gbos/dB for 25-Gb/s modulation, making the 12.5 Gb/s modulation rate slightly less sensitive to added losses. The figure also indicates the cutoff points at which the required optical power exceeds either the aggregate optical power limit or the per component power limit.

2.4 Link Power Efficiency

As the required laser power is dependent on the channel spacing, the aggregate is fixed at 1.55 Tb/s for both modulation rate scenarios in order to compare them. This corresponds to 124 wavelength channels at 50-GHz spacing for 12.5-Gb/s modulation and 62 wavelength channels at 100-GHz spacing for 25-Gb/s modulation. Power consumption of different components is based primarily on reported values from literature where available. The power consumption consists of power dissipated in the Tx module, the
2.4. LINK POWER EFFICIENCY

Rx module, the off-chip laser sources, and the electronic transmission lines connecting the optical die with the processor chip.

The Rx component dissipates power on amplifying/conditioning the signal for driving the modulator, the dissipation in the modulator itself, and the thermal stabilization of the modulator. Extremely low-power (10 fJ/bit) microring modulators have been demonstrated to date with 1-Vpp driving conditions for the microring modulators assumed. Low power modulator driver circuits for modulators with higher voltage swings ($2V_{pp}$) have been demonstrated with 0.14 pJ/bit efficiency at 10 Gb/s (56). Here it is assumed that the same numbers can be reasonably applied to 12.5 Gb/s operation, and that 0.3 pJ/bit is achievable for 25 Gb/s (quadruple amount of power dissipated but also double the bit rate). Thermal stabilization of microring modulators has been demonstrated using analog (63) or digital electronic feedback circuits (88) using sensing of the optically-modulated signal. From (63), the circuitry for thermal feedback can be projected to consume 0.24 mW per ring. The thermal trimming and tuning of the rings requires an average power dissipation of 1.1 mW for 50-GHz spacing or 1.32 mW for 100-GHz spacing. In terms of power per bit, this corresponds to 0.11 pJ/bit for the 12.5-Gb/s modulation case, and 0.06 pJ/bit for the 25-Gb/s modulation case. The Rx module requires equal amount of thermal trimming and stabilization power
2.4. LINK POWER EFFICIENCY

as the Tx but also requires additional power for the receivers. Based on a sense-amp design, 0.4-pJ/bit receivers have been demonstrated at 10 Gb/s (56). For the sake of the analysis it is assumed that 25-Gb/s receivers could be developed to work at 1 pJ/bit.

Table 2.3: Link power efficiency with component/functionality breakdown at 1.55-Tb/s aggregate bandwidth.

<table>
<thead>
<tr>
<th>Component</th>
<th>12.5-Gb/s Modulation</th>
<th>25-Gb/s Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microring Modulation</td>
<td>0.01 pJ/bit</td>
<td>0.01 pJ/bit</td>
</tr>
<tr>
<td>Modulator Driver</td>
<td>0.1 pJ/bit</td>
<td>0.3 pJ/bit</td>
</tr>
<tr>
<td>Modulator Thermal Stabilization</td>
<td>0.11 pJ/bit</td>
<td>0.06 pJ/bit</td>
</tr>
<tr>
<td>Demux Thermal Stabilization</td>
<td>0.11 pJ/bit</td>
<td>0.06 pJ/bit</td>
</tr>
<tr>
<td>APD and Receiver Circuitry</td>
<td>0.4 pJ/bit</td>
<td>1 pJ/bit</td>
</tr>
<tr>
<td>Laser source</td>
<td>5.56 pJ/bit (1% efficiency, 0.7 mW)</td>
<td>7 pJ/bit (1% efficiency, 1.8 mW)</td>
</tr>
<tr>
<td></td>
<td>0.56 pJ/bit (10% efficiency, 0.7 mW)</td>
<td>0.7 pJ/bit (1% efficiency, 1.8 mW)</td>
</tr>
<tr>
<td>Electronic Transmission</td>
<td>1 pJ/bit</td>
<td>2 pJ/bit</td>
</tr>
</tbody>
</table>

For non-monolithic integration with a computing chip, electronic data communications will be required. Based on recent advances in low-power transceivers and assuming further scaling of power with smaller CMOS nodes, it seems realistic to achieve this with 1-2 pJ/bit power cost (15 16). From the previous section the laser power required at these working points can be determined to be 0.7 mW for 12.5 Gb/s and
2.4. LINK POWER EFFICIENCY

1.8 mW for 25 Gb/s. With current DFB technology of individually packaged lasers a 1% wall-plug laser efficiency would make the laser power overshadow all other link components. 10% wall-plug efficiencies which might be possible with multi-wavelength lasers (64, 65) (by amortizing the temperature control and cooling of a single cavity over many wavelength channels) make approaching a 1 pJ/bit target objective more realistic.

As seen from Table 2.3, only with a projected 10% or better laser wall-plug efficiency, and at 12.5-Gbps modulation rate does the link achieve an overall power efficiency of 2.29 pJ/bit for 1.55 Tb/s aggregate bandwidth. As the required laser power is inversely proportional to the channel spacing, it is possible to lower the aggregate bandwidth in order to achieve superior power efficiency. However, as the thermal trimming power for fabrication variations increases linearly with the channel spacing, the channel spacing cannot be arbitrarily made large. Therefore, an optimal operating point exists for 12.5 Gb/s modulation rate at 174-GHz channel spacing allowing 2.04 pJ/b dissipation by the link. With only 35 wavelength channels used at this channel spacing value, the link provides only 437.5 Gb/s aggregate communication bandwidth. The trade-off between power efficiency and link bandwidth is presented on Fig. 2.7. Closer integration on the chip with flip-chip bonding can potentially eliminate portions of the 1 pJ/bit electronic
2.5. OPEN ISSUES AND POTENTIAL TECHNOLOGICAL DEVELOPMENTS

data transmission costs.

![Figure 2.7](image)

Figure 2.7: Power efficiency for 12.5-Gb/s modulation as function of the aggregate communication bandwidth realized. The laser power can be reduced by increasing the channel spacing (reducing aggregate bandwidth) till the thermal trimming and tuning power becomes the dominant power consumption element (as it linearly depends on the channel spacing). The optimal operating point is at 437.5 Gb/s aggregate bandwidth which corresponds to 35 wavelength channels at 174-GHz channel spacing.

2.5 Open Issues and Potential Technological Developments

While the analysis shows the likely potential ceiling for microring-based silicon photonic off-chip links, there are still multiple open questions and technological challenges
2.5. OPEN ISSUES AND POTENTIAL TECHNOLOGICAL DEVELOPMENTS

that will still need to be addressed. This section identifies several of the key fundamental issues and trade offs which will be needed to be addressed on the path to commercializing these type of links.

2.5.1 Fiber-Chip Coupling

As typical silicon waveguide dimensions are 450-nm width and 250-nm height, it is clear that a large mismatch exists between the mode size in a silicon waveguide and that of a standard single mode fiber (≈ 10 µm mode field diameter). To that end inverse tapers have been introduced (34) for efficient edge coupling between the waveguides and tapered lensed fibers with mode sizes matched to be several microns. While these type of edge couplers provide low-loss coupling over a very broad range of wavelengths, they are extremely sensitive to misalignment - with ≈ 1-dB loss for a 1-µm displacement. Therefore, sub-micron precision is required for the fiber packaging which may be unreasonable for commercial applications.

Grating couplers provide a vertical coupling solution which is advantageous for wafer-level testing (before dicing), is much less sensitive to misalignment, and can be used with regular non-tapered single mode fibers (35). Coupling efficiency however is typically significantly lower than that of an inverse taper and more importantly, has a
large spectral dependence limiting the operational bandwidth significantly. It should be noted that if the 1-dB bandwidth is considered, the operating point for the analysis would have to assume the 1-dB loss per coupler addition for a worst case channel.

Recent efforts have attempted to reduce the inverse taper coupling sensitivity based on a Luneberg-Lens design implemented with gray-scale lithography \(^{(89)}\). This type of solution can be used to increase tolerance to fiber alignment. However, to date this concept has only been implemented in the horizontal axis and not the vertical one. Edge couplers defined by etching rather than polishing \(^{(90)}\) improve repeatability and loss of edge couplers, and combined with v-grooves on chip, may provide a repeatable edge coupling solution though robust packaging of fibers to these facets has yet to be explored. Coupling from a cleaved single mode fiber with a 10.4 \(\mu\)m spot size has been demonstrated with a \(Si_3N_4\) inverse taper nested in a silica cantilevered waveguide \(^{(91)}\) with 0.7-dB/facet loss and with a nested silicon waveguide and taper it achieved 1.5-2 dB/facet. With the larger mode size misalignment sensitivity can be greatly reduced, as well as allow operation with standard cleaved fiber rather than lensed tapered fiber.
2.5. OPEN ISSUES AND POTENTIAL TECHNOLOGICAL DEVELOPMENTS

2.5.2 Polarization-Dependence of Silicon Components

The large majority of silicon photonic components demonstrated to date are polarization sensitive, operating optimally for the quasi-TE polarization. Therefore the light has to be co-polarized for all the wavelength channels on the correct polarization before being coupled to the optical dies. In the analysis it was assumed that polarization maintaining fiber was to be used, providing a solution for this problem. PM fiber however is currently extremely expensive and it is not clear it can be mass produced or at a reasonable cost for implementation at the volume required for data-center level interconnects.

One potential solution is to make polarization insensitive structures but it is not clear whether microrings can be made to be polarization insensitive in a simple fabrication process. An alternative approach is to implement polarization-multiplexing in the design of the link (see Fig. 2.8). This type of design would include low loss on-chip polarization beam splitters (PBS) and polarization rotators (PR) in both the Tx and Rx modules. Furthermore, the multiwavelength laser input must separately be ensured to carry equal amount of power on both the TE and TM polarizations for both branches of the Tx module. Assuming an extra 1-dB per facet loss introduced by
2.5. OPEN ISSUES AND POTENTIAL TECHNOLOGICAL DEVELOPMENTS

the PBS and PR, and equal power distribution between the two polarization mode, an extra 6-dB loss would have to be added to the link budget, resulting at a reduction of $\sim 900 \text{ Gb/s}$ (Fig. 2.6) from the aggregate bandwidth for each polarization mode. Since both polarizations would be used in the link the aggregate link bandwidth can still reach greater than $1.5Tb/s$. However, remaining unsolved issues for this design still remain in the operable bandwidth of the PBS and PR devices which might introduce significant limitations, affect on detector sensitivity, as well as the potentially larger power dissipation of a polarization-diversity WDM receiver to be used.

![Figure 2.8](image.png)

**Figure 2.8:** Schematic diagram of polarization diversity design using polarization beam splitters and polarization rotators along with double the microring arrays for modulation and demultiplexing on the Tx side and Rx side.

As a side note, an alternative is to integrate the PBS into the grating coupler as has been demonstrated in (94) rather than use edge couplers. The drawbacks, as mentioned before, are primarily the bandwidth limitations and increased loss introduced by these
structures. Even with this scheme, a solution to guarantee equal laser power goes to both arms of the Tx module from the laser needs to be provided.

2.5.3 Power Efficient Utilization of Optical Links

The analysis presented in this chapter assumed full link utilization in time, i.e., it is always transmitting data. However, data transmissions between processor and memory are typically bursty in nature. In general, many communication protocols transmit packets rather than continuous data streams. WDM photonic links however are typically not amenable to rapid on-off transitions. In particular, for wavelength-accurate lasers usually need to operate over a period of time to stabilize, and therefore turn-on operation involves a latency for stabilization. Similarly, the wavelength-sensitive microring devices need wavelength stabilization and the period of turn-on till stabilization would fundamentally take several microseconds corresponding to the MHz bandwidth of the heat diffusion process from the ohmic heaters to the photonic components. As many communication types, and in particular processor-memory transactions, are extremely latency sensitive, multiple microseconds of turn-on delay could be unacceptable.

Assuming always-on lasers and constant thermal stabilization of the photonic com-
2.5. OPEN ISSUES AND POTENTIAL TECHNOLOGICAL DEVELOPMENTS

ponents results in a strong inverse relation between the link utilization percentage and
the power efficiency. Since the laser power dissipation is the largest static power dis-
sipation component, it is of importance to address this aspect first. One potential
architectural solution is to switch one multiwavelength laser source between multiple
chips. However, the implications from this type of network resource sharing have to be
explored. Alternative solutions could be the development of rapid turn on/off lasers or
adoption of dedicated protocols and system operation profiles which require constant
transmission constantly.

2.5.4 Joint Electrical and Optical Channel Design

Finally, an open topic which can reduce the power dissipation of the link from a holistic
electronic and photonic perspective is the joint design of the electronic transmission
channels with the photonic components. Similar to an approach developed for improv-
ing VCSEL links reported in [95], an extension of this approach could be applied for
the design of the link as a whole could benefit from a joint optimization of the differ-
ent components. This, however, comes at the expense of reducing design flexibility of
the optical die and electronic transceivers. As the electronic channels performance are
highly distance dependent (due to the strong filtering effects of the wire channels), this
might also place stringent restraints on the optical die location and layout.

2.6 Conclusions

This chapter presented the case study of a WDM microring-based silicon link for chip I/O designs. The goals of the analysis were to determine the aggregate bandwidth upper limit for a realistic link composed of best of class current researched devices as well as determine the power efficiency expected of such a link. A design methodology based on the optimization of the physical device characteristics for WDM operation was introduced to achieve best optical performance. The results indicate that operation within a WDM context must take into account not only channel-specific operation but also the impact on adjacent wavelength channels in terms of losses and power penalties. As a result, the optical power required per channel is highly dependent on the channel spacing and the device characteristics, in particular in the dense-WDM scenarios.

For a best case scenario and assuming nonlinear upper limits to optical transmission in the waveguide, the aggregate link bandwidth was shown to be limited to \(\sim 1.8\) Tb/s for 12.5 Gb/s modulation rate while the 25-Gb/s modulation rate achieves lower aggregate bandwidth due to the lower receiver sensitivity at the higher bit rate. For
2.6. CONCLUSIONS

such a data rate, the link would occupy around $1.5 - mm^2$ (based on the footprint assumptions made earlier) and require only 3 optical connectors to the die or a single multi-port connector.

The analysis shows a high dependence of the overall power efficiency on laser wall-plug efficiency, driving the need for further development of higher-sensitivity receivers as well as more efficient multi-wavelength laser sources. Furthermore, as laser power plays a key role in the overall efficiency, the efficiency is inversely proportional to the channel spacing and hence the link aggregate bandwidth.

At the same time, silicon photonic photodetectors will have to continue improving to realize sensitivities sufficient to meet the power budget constraints of unamplified links. Further improvements will also be required to enable a transition from point-to-point links to higher-complexity and consequently higher-loss interconnects that pass through system networks. Potential for such dramatic performance improvements in germanium photodetectors lies in the close integration with the electronic circuitry.

In addition, these system-scale interconnects will further drive the need for chip-scale energy efficient optical amplification. Component performance improvements must at the same time be accompanied with continued emphasis on dense device integration and testability along with optical packaging. Fiber packaging with $\mu m$-level
precision is one of the key challenges the industry will have to tackle going forward to enable low-loss single-mode die-to-fiber interfaces.
Chapter summary and key contributions - this chapter detail’s the author’s contribution on the first experimental data transmission characterization of a microring-based on-chip spatial division multiplexing (SDM) scheme. The device characterized contained a three-port spatial multiplexer, multimode waveguide, and three-port spatial demultiplexer with multiple single-mode ports to the multiplexer and demultiplexer. In order to characterize its performance a multi-port edge-coupling setup was constructed and used to operate all three supported modes simultaneously with decorrelated
data channels. Device performance was initially investigated with three-mode operation on a single wavelength with 10-Gb/s data per spatial mode (30-Gb/s aggregate multiplexed bandwidth in the multimode waveguide). Penalties arising from filtering, propagation, and mode crosstalk, were investigated and inter-channel crosstalk was shown to be the main cause of signal degradation. By tuning the microrings used for the multiplexing, performance for all three SDM channels was balanced to show a maximal device power penalty of 1.9 dB. In the next stage the microring SDM scheme’s WDM-compatibility was demonstrated by operating the device with three wavelength channels per spatial mode with two of the spatial modes supported by the device and the WDM channels covering the full C-band, achieving 60 Gb/s of aggregate bandwidth transmission in the multimode waveguide. Even with combined WDM and SDM operation power penalties were shown to be less than 1.4 dB for all the channels. This comprises of the first error-free transmission and BER characterization of the microring-based on-chip SDM scheme. The demonstration validates the scheme’s potential for combined WDM and SDM operation which is a prerequisite for SDM providing performance gains for on-chip
3.1 Spatial Division Multiplexing for Increasing Waveguide Bandwidth Density

Although wavelength parallelism can be utilized to attain the high bandwidth-densities in on-chip waveguides or fibers connecting silicon photonic components, in both telecom and datacom applications, there is a growing need to increase the data capacity per fiber. In the past few years growing amount of attention has been focused on implementation of spatial division multiplexing (SDM) as a method to increase the bandwidth density per optical fiber on top of high-spectral efficiency methods such as orthogonal frequency division multiplexing (OFDM). SDM has mostly been implemented using multi-core fibers (MCF) or few-mode fibers (FMF) with the key challenge being mode multiplexing and demultiplexing with low mode crosstalk. Multiple-input-multiple-output (MIMO) techniques from wireless systems have also been adopted for spatial-mode demultiplexing. Similarly to fiber communications, SDM can be also attractive for on-chip optical interconnects as it can potentially make use of lower loss multimode (MM) waveguides, increase the band-
3.1. SPATIAL DIVISION MULTIPLEXING FOR INCREASING WAVEGUIDE BANDWIDTH DENSITY

width density of on-chip interconnects, reduce the number of waveguide crossings for an on-chip interconnect, and add an additional design degree of freedom (see schematic in Fig. 3.1). However, on-chip SDM remains challenging due to the difficulty in controlling the coupling between the different propagating modes in the waveguide as well as correct multiplexing and demultiplexing of the propagating modes.

![Figure 3.1](image)

**Figure 3.1:** Schematic diagram of a SDM-based on-chip link which utilized microring WDM modulator arrays for imprinting data on multi-wavelength CW light. The SDM Mux (composed of larger rings with the FSR matching the channel spacing) couples all the wavelength channels from a single array to a specific spatial mode which then propagates in the multi-mode waveguide section. The spatial modes are demultiplexed by a SDM demux and then are further demultiplexed in wavelength in microring-filter arrays leading to detectors.

While on-chip SDM has been the subject of some theoretical-analysis (103, 104, 105) and experimental demonstrations (106), the typically used Multi-Mode Interference
3.1. SPATIAL DIVISION MULTIPLEXING FOR INCREASING WAVEGUIDE BANDWIDTH DENSITY

(MMI) couplers and Mach-Zehnder interferometers have large footprints, complicated designs and are not easily scalable to handle more higher order modes. Another critical drawback is that these devices are not reconfigurable to optimize the multiplexing performance. In particular, a key on-chip-SDM device challenge is to maintain Wavelength-Division Multiplexing (WDM) compatibility so as to provide actual performance gains over existing network-on-chip designs. A microring based SDM multiplexer and demultiplexer technique \cite{107,108} can provide this type of functionality while supporting WDM as well. In this section, the first experimental data evaluation of this type of device is detailed - implementing both SDM and WDM in a single on-chip SDM link. This first of a kind prototype designed to support 3 spatial modes is shown to be able to operate with less than 1.9-dB penalty for 3x SDM single channel operation and less than 1.4-dB penalty for 2x SDM with 3x WDM operation with WDM wavelength channels spanning the full C-band.
3.2 Microring-Based SDM Multiplexer and Demultiplexer

The silicon photonic platform is in particular attractive for implementing this approach as the propagation constants of the spatial modes can be engineered to differ significantly thanks to the high core-cladding (Si/SiO2) index contrast. By selectively phase matching the propagation constants of specific spatial modes in a MM waveguide and a neighboring single-mode microring, the coupling efficiency can be optimized to implement mode multiplexing or demultiplexing functionalities. Such a microring-based device is inherently compact and can be made reconfigurable by utilizing either the thermo-optic or the plasma-dispersion effect. The design can be made WDM-compatible by designing the free-spectral range (FSR) of the microrings to match the channel wavelength spacing and this approach is also easily scalable by additional of more microrings to handle higher-order modes.

The matching of specific modes in the MM waveguide to an evanescent coupled single mode ring is achieved by adjusting the MM waveguide width at the coupling region. The multiplexer structure is composed of adiabatically connected sections of MM waveguide of increasing width. Each section is evanescently coupled to a single
3.2. MICRORING-BASED SDM MULTIPLEXER AND DEMULTIPLEXER

Figure 3.2: Optical performance of the fabricated device. a. Microscope image of the fabricated device. Inset: SEM showing the heater to tune each individual ring resonator. b-d. Optical transmission and crosstalk at the three output ports for signal injection on each of the three input ports measured with tapered lensed fiber input and output.

A prototype was fabricated at the Cornell Nanofabrication Facility based on this design (additional details available at [108]). By setting the MM waveguide sections in the fabricated DUT’s 3x SDM multiplexer (Fig. 3.2) to be 450-, 930-, and 1410-nm wide, corresponding selective coupling to the TE_0, TE_1, and TE_2 is achieved. The single-mode ring dedicated for coupling to a specific mode. The 250-nm tall by 450-nm wide waveguide composing of all the rings has an effective index of 2.457, which matches the effective index of only one propagation mode (TE_i, i = 0, 1, 2, ...) at each section of the MM waveguide.
demultiplexer was similarly constructed of receding width MM waveguide sections each coupled to a single single-mode ring. The separation gaps of each microring from the waveguide were designed to achieve uniform coupling strength in each section to the relevant mode. All the microrings were designed to have an identical FSR so as to enable WDM operation with the same set of wavelength channels on all the spatial modes. Integrated resistive heaters enable tuning the ring resonances and aligning the resonance combs.

Spectral transmission scans for each combination of input and output ports, with 1-mW input power at quasi-TE polarization, serves to characterize the fundamental optical performance properties of the device, in particular the crosstalk resulting from the spatial multiplexing and demultiplexing. Fig. 3.2.b shows the transmission spectrum at output port 1 from each input. The insertion loss of this port is -13 dB and the optical crosstalk (defined as the ratio of desired signal power to the sum of the interfering channels power) can be as low as -30 dB. Although the light is coupled to the chip for this scan using a polarization maintaining lensed tapered fiber, it is evident from the TM resonances visible on the scan that a non-pure quasi-TE polarization was excited on chip. This is likely a result of polarization rotation in the single mode inverse tapers. The quasi-TM mode is overcoupled resulting in low-Q TM resonances.
which have a slightly different FSR of 5.15 nm. Similarly, the insertion loss of port 2 is -16 dB and the optical crosstalk is -18 dB (Fig. 3.2c) while port 3 has an insertion loss of -26 dB and crosstalk of -13 dB (Fig. 3.2d). Port 3 has a much higher insertion loss than the other two ports as the microring-to-waveguide coupling achieved for this mode was weaker in this prototype due to a design miscalculation. This could be adjusted by narrowing the separation gap for the TE$_2$. The crosstalk in port 3 is also higher due to the suboptimal phase matching for this mode which resulted in higher degree of coupling to non-TE$_2$ modes, as well as the much higher power TE$_0$ and TE$_1$ modes present in the MM waveguide (as they are better coupled in the multiplexer from their respective input ports). It is important to note that intra-channel crosstalk as experienced from this type of device carries a heavy power penalty cost with it given by (3.1)

$$\text{Power Penalty} = -10 \log_{10}(1 - 2\sqrt{\epsilon})$$ (3.1)

where $\epsilon$ is the crosstalk level (ratio of desired signal power to sum of interfering signals powers). The penalty arising from this type of crosstalk is particularly high since the interfering signals are coherent with respect to the desired signal. For instance, even a -20-dBm interchannel crosstalk level results in a 1-dB penalty while a -10-dBm
3.3. SINGLE CHANNEL SDM PERFORMANCE EVALUATION

crosstalk level corresponds to a penalty greater than 4 dB. The combination of sub-optimal implemented phase matching in the device along with the inherent sensitivity to erroneous polarization components give rise to wavelength- and port-dependent crosstalk values. Table 3.1 lists measured crosstalk levels for the ring resonances that lie in the C-band. These values indicate that the main source of signal degradation in the on-chip SDM system will be interchannel crosstalk as the microring resonances are broad enough to accommodate 10-Gb/s data signals without noticeable degradation.

Table 3.1: CW crosstalk measurements for the 3 modes at the resonances available for operation in the C-band of the DUT when all resonances are co-aligned. These measurements were taken on the polarization maintaining lensed tapered fiber setup.

<table>
<thead>
<tr>
<th>Resonance Wavelength (nm)</th>
<th>Port 1 (dB)</th>
<th>Port 2 (dB)</th>
<th>Port 3 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1532</td>
<td>-24.1</td>
<td>-18.3</td>
<td>-9.5</td>
</tr>
<tr>
<td>1540</td>
<td>-29.6</td>
<td>-17.3</td>
<td>-7.8</td>
</tr>
<tr>
<td>1547</td>
<td>-22.9</td>
<td>-17.6</td>
<td>-11</td>
</tr>
<tr>
<td>1555</td>
<td>-25.1</td>
<td>-14.8</td>
<td>-12.9</td>
</tr>
<tr>
<td>1563</td>
<td>-26.3</td>
<td>-17.8</td>
<td>-11.3</td>
</tr>
</tbody>
</table>

3.3 Single Channel SDM Performance Evaluation

The goal of the first experiment was to characterize the device performance with a single WDM channel which was spatially multiplexed into and demultiplexed out of all three SDM modes propagating in the MM waveguide. In order to examine the performance
of the DUT, same-wavelength decorrelated data signals were simultaneously launched into all three inputs of the DUT using a pitch-reducing fiber array (PROFA) and recovered from each of the three outputs one at a time using a lensed tapered fiber. In order to perform a fair assessment of device performance, all three input signals are launched with the same optical power. The PROFA alignment was within 2-dB of the optimal alignment for all three input ports simultaneously.

Intra-channel crosstalk results in interference of same-wavelength signals. Since a single tunable laser was used to generate all the data signals launched into the DUT, the signals must be made phase decoherent. In a test setup not employing any phase decoherence mechanisms, the slowly changing coherent interference would result in a slow change of the output signal power as the phases leading to the DUT change as a result of thermal fluctuations in the test-setup fibers. These power fluctuations (on the temporal order of multiple seconds) prevent accurate BER measurements over short time spans. In order to enable BER measurements over short time spans, two decoherence mechanisms were employed simultaneously to average out the slow phase fluctuations: 1. The arms leading to the multiplexer input ports were decorrelated by 0.5 km SSMF. This is close to the 1-km coherence length of the 200-kHz linewidth laser used in the experiment providing some phase decoherence of the signals. 2. In
order to guarantee full phase orthogonality regardless of the intrinsic laser linewidth, phase modulation of a repeating linearly chirped signal is introduced as well. The chirp, consisted of a frequency sweep from 20-MHz to 10-MHz over a 5-ms period. With a 0.5-km path difference (roughly 2.5 $\mu$s relative delay), the phase difference between adjacent ports oscillates over $2\pi$ at 5-kHz guaranteeing averaging of the phase difference in power and BER measurements which were averaged over more than 100 ms.

**Figure 3.3:** Experimental setup for 3-port single-WDM-channel SDM performance evaluation including Pulsed Pattern Generator (PPG), Tunable Laser (TL), Amplitude Modulator (AM), Phase Modulator (PM), Erbium-Doped Fiber Amplifier (EDFA), Isolator ($\rightarrow$), Standard Single Mode Fiber (SSMF), Tunable Filter ($\lambda$), Digital Communications Analyzer (DCA), Variable Optical Attenuator (VOA), Avalanche-Photodiode (APD-TIA), Limiting Amplifier (LA), and Bit-Error-Rate Tester (BERT).

In the first experiment (Fig. 3.3) a single laser channel at 1563 nm was modulated with PRBS $2^{31} - 1$ on-off-keyed (OOK) data by an amplitude modulator and then further phase-imprinted with a swept-frequency sinusoidal as described above. The
3.3. SINGLE CHANNEL SDM PERFORMANCE EVALUATION

data signal was then amplified, split evenly, delayed through fiber spans, and adjusted in polarization to be and simultaneously launched in quasi-TE polarization to the multiplexer ports with an even 8.6-dBm per port. The fiber spans leading to the device also ensured the data was decorrelated (in terms of the imprinted PRBS data) between the ports. Polarizers and polarization controllers set the launched polarization on chip through non-PM tapered-lensed fiber to be quasi-TE on all input ports (as any quasi-TM polarized light would result in additional crosstalk). The demultiplexed signals are recovered one at a time for inspection on a DCA and for BER evaluation on a BERT. The PPG, BERT, DCA are all triggered off of a shared distributed 10-GHz clock.

![Eye diagrams for 3-port single-WDM-channel SDM operation at 1563 nm with all microresonators aligned spectrally to maximize transmission on all ports as well as the back-to-back measurements (B2B). Port 1 and 2 which experience lower crosstalk levels (see Table 3.1) have open eye diagrams but port 3 suffers from significant degradation due to the crosstalk leaking primarily from the $TE_1$ mode of port 2.](image)

**Figure 3.4:** Eye diagrams for 3-port single-WDM-channel SDM operation at 1563 nm with all microresonators aligned spectrally to maximize transmission on all ports as well as the back-to-back measurements (B2B). Port 1 and 2 which experience lower crosstalk levels (see Table 3.1) have open eye diagrams but port 3 suffers from significant degradation due to the crosstalk leaking primarily from the $TE_1$ mode of port 2.

Given equal power injected on all ports, the projected crosstalk on port 3 (dominated by $TE_1$ contributions) would result in extremely high values (-10 dB) corresponding to greater than 4 dB power penalties. This crosstalk-resulting degradation...
3.3. SINGLE CHANNEL SDM PERFORMANCE EVALUATION

is immediately visible on the eye diagrams (Fig. 3.4) for this setting. However, one advantage of our scheme is that the device performance can be optimized since the microring resonators are tunable. However, by wavelength detuning the TE\textsubscript{1} multiplexer ring, the TE\textsubscript{1} mode power in the MM waveguide can be lowered resulting in lower crosstalk levels on output port 3 at the expense of increased crosstalk and spectral filtering penalties on output port 2. The power penalties measured on ports 2 and 3 (see Fig. 3.5.a) were balanced with this method to equal 1.9-dB penalty on both ports (measured at a BER of 10\textsuperscript{-9}). Reducing the TE\textsubscript{1}-mode power also increases the effective crosstalk level on port 1 but results in a 0.5-dB relatively low penalty. Error free transmission (BER < 10\textsuperscript{-12}) and open eye diagrams (Fig. 3.5.b) were observed for all output ports. In order to investigate the crosstalk contribution to the penalties, the channel performance with only one port injected at a time was measured. By performing this measurement it is possible to observe that transmission penalties resulted only in 0.1-dB penalties on ports 1 and 2 and 0.8-dB on port 3 (with the higher penalty on port 3 resulting from the higher insertion loss on this port which lead to a larger OSNR degradation at the post-chip EDFA). Therefore it was concluded that the crosstalk contributed between 0.4 and 1.8 dB of penalty on the different ports and was the main limiting factor in device operation.
3.4 3-WAY WDM WITH 2-FOLD SDM DEMONSTRATION

In the second experiment the ability to leverage the microring-based spatial multiplexing method for WDM links is demonstrated. For this experiment a slightly modified setup (Fig. 3.6a) was used to both decorrelate the wavelength channels as well as include more polarizers to ensure all the wavelength channels are launched on chip at the quasi-TE polarization with equal power. The wavelength channels were set to span the full C-band (limited by the EDFA gain band, the ring resonances extend well into the L-band) and the ring resonances were tuned on-resonance to maximize power.
3.4. 3-WAY WDM WITH 2-FOLD SDM DEMONSTRATION

Figure 3.6: 2-port 3-wavelength channel demonstration. a. Experimental setup for demonstrating combined SDM and WDM operation. b. BER measurements for back-to-back (B2B) test cases and full SDM-WDM operation for both ports showing worst case penalties of 1.4 dB. c. Corresponding eye-diagrams for the inspected signals.

transmission at 1547 nm. The power penalties for both ports varied between 0.6 and 1.4 dB for all three wavelength channels (Fig. 3.6b) with performance variation attributed to varying levels of crosstalk for the different resonances used (low crosstalk levels for the 1532- and 1547-nm channels while higher crosstalk levels achieved for the 1563-nm channel). A likely cause for the variation is the slight wavelength-dependence
of the polarization rotation in the inverse tapers where the polarization (with one polar-
ization controller used for all the wavelength channels) was optimized to suppress
TM crosstalk at 1532 nm. This issue does not arise when only a single channel is used
as the polarization can be optimally set for it. Error free transmission was observed for
all three channels and open eye diagrams (Fig. 3.6c) verify correct operation for all
three channels at the two output ports. The results show that only a minimal penalty
is added by extending the device operation to support WDM on top of the SDM which
is a key advantage of the microring-based SDM design.

3.5 Conclusions

In this chapter an on-chip silicon photonic SDM scheme was introduced. Such schemes
can improve the bandwidth density per waveguide using few-mode waveguides to trans-
mit data across a chip. The microring based approach supports WDM and is directly
extendable to larger numbers of spatial modes. The first data characterization was
reported for a microring-based SDM device showing proof of feasibility of using this
device in both single channel and WDM settings. Single channel operation with all
three spatial modes was shown to result in up to 1.9-dB penalties in the DUT where
3.5. CONCLUSIONS

this performance was achievable using the inherent tuning capability of the microrings. WDM operation with no channel-specific tuning was demonstrated with three WDM channels and two spatial modes with less than 1.4-dB worst case penalties (partially attributed to inherent crosstalk and partially to non-optimal polarization achievable in the WDM test configuration). While the fabricated device itself had non-ideal properties, simulations indicate that with adjusted design and fabrication crosstalk levels lower than -20 dB are achievable with this scheme for all the wavelength channels. However, polarization sensitivity with this device is inherently high in the implemented design.

As losses and penalties on a silicon photonic chip at the single link level are still prohibitive, this type of device is likely more forward looking and will not be directly applicable to near term photonic interconnects. Furthermore, the design and fabrication of multimode waveguide bends and crossings which would not result in spatial mode coupling has yet to be shown. However, this device shows a proof of feasibility for flexible on-chip SDM based on microring resonators. As silicon photonic further develops and on-chip interconnects become more feasible, on-chip SDM might become a useful tool to augment WDM operation.
4

Nonlinear All-Optical Processing of Data in Silicon

4.1 Motivation for All-Optical Processing in Communication Systems

Nonlinear optical devices have been a subject of extensive research for enabling processing functionalities which are either not possible by traditional optical or electrical-optical systems, or extremely inefficient with traditional solutions. As signaling rates and channel counts continue to increase in optical networks of all types, the rising
power and complexity costs of network components may make all-optical processing subsystems become viable for integration with conventional interfaces to address specific performance bottlenecks in optical communication systems.

4.1.1 Potential Candidates for Nonlinear All Optical Processing

4.1.1.1 Contention Avoidance in Optically Switched Networks

Optical switches in WDM-employing networks require the ability to switch wavelength channels between multiple physical fibers and multiple wavelength slots depending on the wavelength-allocation scheme and available channels in each fiber. Traditionally, these switches include loptical-to-electronic (O-E) and electrical-to-optical (E-O) interfaces to receive and retransmit each switched channel and the switching itself is performed in the electrical domain. However, such switches scale poorly in power and cost as channel rates increase due to the need to deserialize and reserialize the data from the optical channel rates (at tens of Gb/s) to lower electronic-switch-compatible line rates of only several Gb/s. Furthermore, as WDM networks transition towards higher channel symbol rates and more complex coherent communication signal constellations,
the O-E and E-O interfaces would have to scale in complexity and supported data rates to match these trends.

An alternative to such O-E and E-O interfaces’ switches is implementing the switching in the optical domain (109). Existing switches can first improve power efficiency by addressing only channels that need to be switched rather than requiring receiving and retransmitting all the data going through the switch. With existing commercial reconfigurable optical add-drop multiplexer (ROADM) switches only wavelength channels that need to be switched or added pass through the O-E and E-O interfaces while the rest of the channels can remain in the optical domain as they continue to propagate on the same fiber. Such switches may offer improved performance but the O-E and E-O interfaces still have to support the high bit rates of the optical channels and therefore require high complexity high-power transceivers.

Fully optical transparent switching, in the sense that the switched channel can also remain in the optical domain, can provide improved scalability with regards to supporting high data rates at a low switching power cost. However, switching wavelength channels spatially requires the wavelengths on the destination fiber to be available, which may result in suboptimal channel utilization and reduced flexibility in the system wavelength allocation. Wavelength converters can solve this problem by converting
the data channel (in the optical domain) to available wavelength-channel slots. Beyond providing an optical means to solving wavelength contention, all-optical wavelength converters provide the network improved flexibility with regards to wavelength allocation and reorganization. Wavelength converters may rely on nonlinear effects such as cross-gain modulation (110) or cross-phase modulation (111), but as discussed later, four-wave mixing offers a significant advantages for implementing the functionality for spectrally-efficient data formats which rely on phase information as well as amplitude information, and operate agnostic of the channel data rates.

4.1.1.2 High Symbol Rate OTDM Processing

With WDM data capacity in standard fiber-based links becoming a significant limiting factor for long haul interconnects, limited by the achievable filter designs, much emphasis has been put in recent years on developing signaling schemes which achieve superior spectral efficiency (bit/s/Hz) to provide performance closer to the Shannon capacity limits of fiber channels (112). To this end coherent modulation formats coding multiple bits per symbol have been developed (113 114). In parallel, increasing research attention has been given to high-baud-rate Optical Time Division Multiplexing (OTDM) signaling and Orthogonal Frequency Division Multiplexing (OFDM) super
4.1. MOTIVATION FOR ALL-OPTICAL PROCESSING IN COMMUNICATION SYSTEMS

channels (115). In WDM systems the channel aggregate achievable bandwidth is limited by the filtering capability limitations - i.e., achievable flatness and roll-off of the optical filters used to multiplex or demultiplex the wavelength channels. OTDM and OFDM concepts sacrifice some of the flexibility and complexity of the components in favor of increasing the spectral efficiency.

OTDM communication systems use high signaling rates to achieve the high spectral efficiency. In this implementation type, the limiting factor is transformed from wavelength-domain filtering (in WDM) to its analog time-domain counterpart of temporal multiplexing and demultiplexing (116). However, since electrical interfaces can only operate at a few tens of GHz due to the O-E interface physical limitations (photodetector bandwidth, electrical component bandwidth), the O-E interface must include a pre-processing stage in the optical domain to translate the high-bit rate optical stream to spatially-separate lower-bit-rate tributaries which can be directly converted to the electrical domain. Such temporal demultiplexing solutions have been proposed based on a variety of nonlinear optical platforms (116, 117, 118, 119). Temporal serializing of an OTDM stream requires accurate tunable delay elements, which can be implemented also using nonlinear processing (120). Signal grooming, allowing the extraction of a single tributary from an OTDM stream (analogous to filtering a
4.1. MOTIVATION FOR ALL-OPTICAL PROCESSING IN COMMUNICATION SYSTEMS

single channel in a WDM system) is also an extremely important functionality for enabling OTDM ROADMs which has been demonstrated with nonlinear processing using periodically-poled $LiNbO_3$ \cite{121}. Other functionalities such as multicasting (duplicating bit streams) when applied to high speed OTDM streams also benefit from all-optical implementation based on nonlinear processing as it bypasses the need for the O-E / E-O interfaces.

4.1.1.3 Expanding Optical Capabilities Beyond Telecom Wavelength Domains

An alternative approach to increasing the data carry capacity of optical fibers is to expand the operating wavelengths beyond existing communication bands. The advent of erbium doped fiber amplifiers have enabled the development of long haul transmission but only in limited bands defined by the gain spectrum of the erbium. Additional rare earth materials have also been implemented for providing gain at shorter and longer wavelengths \cite{122, 123}. Raman gain has also been demonstrated in silicon to potentially enable amplification at wavelengths longer than the erbium gain region \cite{124}.

Parametric amplification offers an alternative solution for expanding the utilized
spectral bandwidth in telecom systems. Parametric amplifiers based on highly non-linear fiber have been shown to provide significant gain bandwidths greater than 100 nm \(^{125}\) and net gain beyond 20 dB. Recently, parametric gain demonstrated at long-wavelength \((\lambda > 2\mu m)\) pumped silicon waveguide \(^{126}\) and with further work may become applicable for providing gain at the vicinity of the operational telecom wavelengths.

Beyond providing gain at non-conventional wavelengths, parametric wavelength converters offer also a different path to enabling communications through the translation of signals from easily operable wavelength bands to longer wavelengths and also converting such signals back to shorter wavelengths for detection. This approach is further detailed in chapter \(^{4}\) for its application to mid-IR communications.

### 4.2 Four-Wave Mixing

#### 4.2.1 Physical Phenomena

Four-Wave Mixing (FWM) is a parametric process facilitated by bound-electron interaction with an electromagnetic field propagating in a medium. The resulting polarization vector \(\mathbf{P}\) includes not only a linear dependency (1\(^{st}\) order) on the electric field
4.2. FOUR-WAVE MIXING

E but also higher order terms due to the anharmonic reaction of the bound electrons. The general vectorial relationship between $E$ and $P$ \cite{127} is expressed as

$$P = \varepsilon_0 (\chi^{(1)} \cdot E + \chi^{(2)} : EE + \chi^{(3)} : EEE + \ldots)$$  \hspace{1cm} (4.1)$$

where $\varepsilon_0$ is the vacuum permittivity and $\chi^m (m = 1, 2, \ldots)$ are the susceptibility tensors of order $m$. FWM (as well as other effects such as cross phase modulation and self phase modulation) is facilitated through the $3^{rd}$ order susceptibility term $\chi^{(3)}$ which enables an exchange of energy between four co-propagating electric fields. Such energy transfers are only efficient if energy conservation and phase matching conditions are met. For a partially degenerate interaction in which two of the four fields are contributed by a pump field, energy conservation is satisfied by

$$2\omega_p = \omega_i + \omega_s$$ \hspace{1cm} (4.2)$$

where $\omega_p$, $\omega_i$, and $\omega_s$ are the pump, idler, and signal frequencies respectively. In two pump photons get annihilated to create one idler and one signal photon. The linear
4.2. FOUR-WAVE MIXING

Component of the phase mismatch for this configuration is given by

\[ \Delta k_{\text{linear}} = k_i + k_s - 2k_p \]  

(4.3)

where \( k_i \), \( k_s \), and \( k_p \) are the corresponding wavenumbers for these fields. Efficient energy transfer through FWM interaction requires \( \Delta k \cdot L \ll 2\pi \) where \( L \) is the interaction length and \( \Delta k = \Delta k_{\text{linear}} + 2\gamma P_p \) is the overall phase mismatch which also includes the nonlinear phase contribution from the optical pump where \( P_p \) denotes the pump’s power and \( \gamma \) is the nonlinearity coefficient. The linear phase mismatch is affected only by even dispersion terms due to the symmetry of the process, and therefore phase matching is typically achieved by engineering the group velocity dispersion and fourth-order dispersion terms.

The nonlinearity coefficient \( \gamma \) which indicates the strength of the parametric interaction is given by

\[ \gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \]  

(4.4)

where \( n_2 = (3/8n) \cdot \text{Re}\{\chi^{(3)}\} \) is the real nonlinear component of the index of refraction, \( \lambda \) is the center wavelength of the participating waves, and \( A_{\text{eff}} \) is the effective overlap mode area of the waves. The nonlinearity coefficient and phase mismatch determine
the parametric gain $g$ for degenerate FWM through

$$g = [(\gamma P_0)^2 - (\Delta_k / 2)^2]^{1/2} = [\gamma P_p \Delta k_{linear} - (\Delta k_{linear} / 2)^2]^{1/2}. \quad (4.5)$$

The terms "signal" and "idler" waves are sometimes associated with the "Stokes" (lower energy) and "Anti-Stokes" (higher energy) bands. For the purpose of this work the term "Probe" is used to describe the optical signal input introduced into the nonlinear device with the pump and "Idler" is used to describe the optical signal generated through the nonlinear interaction.

For a wavelength-conversion device which is injected with probe and pump signals and generates an idler, the conversion efficiency is defined by the ratio between the output idler power $P_{idler,out}$ and the input probe power $P_{probe,in}$ by $GCE = P_{idler,out} / P_{probe,in}$ by (128)

$$GCE = P_{idler,out} / P_{probe,in} = \left[ \frac{\gamma P_p}{g} \sinh(gL) \right]^2 \quad (4.6)$$

where $L$ is the interaction length when assuming negligible linear and nonlinear losses. In practice, linear and nonlinear make this valid only to an effective length of $L_{eff} = (1 - \exp(\alpha L)) / \alpha$ where $\alpha$ is the loss coefficient (129). Accurate solutions to the conversion efficiency in the presence of loss require numerical evaluation.
4.2. FOUR-WAVE MIXING

The important take aways from this set of equations are the following: a. The strength of the parametric interaction is proportional to the nonlinear response of the material and inversely proportional to the effective mode overlap area. b. The phase mismatch between the propagating waves $\Delta k$ which is determined by the dispersion of the nonlinear medium is key for achieving efficient conversion efficiency or parametric gain. c. Loss mechanisms strongly limit conversion efficiency.

4.2.2 Leading Four-Wave Mixing Platforms

As bulk silica has a natural low nonlinear response, nonlinear effects in standard fiber are typically weak. Highly nonlinear fibers (HNLFs) have been developed in the last few decades based on implantation of elements such as germanium in silica to enhance the nonlinear response $\gamma$. Alternatively, non silica bismuth-glass $\gamma \approx 1360W^{-1}km^{-1}$ and chalcogenide-glass $\gamma \approx 1200W^{-1}km^{-1}$ fibers have been developed for their much higher nonlinear response. With low coupling loss to regular fiber and high effective nonlinear response, HNLF has been used to construct broadband parametric amplifiers, process 1.28-Tbaud OTDM signals, as well as enable wavelength conversion across hundreds of nanometers. Multiple other nonlinear signal processing functionalities have also been demonstrated with
4.2. FOUR-WAVE MIXING

HNLF with applications for coherent modulation formats as well as all-optical logic operations \cite{139, 140, 141}.

However, the fundamental challenge in these systems is attaining accurate uniform dispersion profiles across length of fiber between multiple several to hundreds of meters. As the dispersion of the fiber is strongly dependent on the core dimensions at the nanometer scale, fabrication variations in the drawing process of the fiber result in a nonuniform dispersion profile \cite{136}. Recently, post-fabrication solutions relying on mapping the dispersion along the length of the fiber and applying varying amounts of strain along the length of it to compensate have been demonstrated \cite{142}. However, this mapping and post fabrication compensation is a work intensive process likely not suitable for wide scale commercial application. Alternatively, non-step-index refractive index profiles have been suggested to reduce the sensitivity to dimensional variations and can potentially increase the phase matched bandwidth of HNLF \cite{143, 144}.

Chalcogenide glasses which were used to form HNLF have alternatively also been shown in a PIC configuration with much shorter device length (on the order of up to 10 cm). The fabrication of chalcogenide high-confinement waveguides (based on the high refractive index \cite{145}) has provided a platform with effective nonlinearity as high as $\gamma \approx 13.6 \times 10^5 W^{-1} km^{-1}$ \cite{146} as well as enabled the achievement of much
4.3. THE SILICON WAVEGUIDE NONLINEAR PLATFORM

better dispersion control along with the high nonlinearity of the platform, enabling nonlinear processing of OTDM signals at T\text{baud} speeds (119, 147). With negligible two-photon absorption compared to silicon and low propagation losses, chalcogenide waveguides are also able to achieve very high conversion efficiencies (147). Further order-of-magnitude enhancements of the effective nonlinearity has been shown to be possible with the incorporation of photonic chrystal structures though at the expense of the dispersion engineered bandwidth (148). However, chalcogenide photosensitivity (145) - the change of chemical bonds in response to exposure to light, makes this material platform problematic to work and prone to photo-darkening (149). The complexity of processing due to the chemical sensitivity of the platform also makes the material system expensive and complex to mass produce.

4.3 The Silicon Waveguide Nonlinear Platform

While nonlinear optical effects such as Raman gain (124, 150, 151) and all-optical switching mediated by carrier generation (42, 152) has been demonstrated in silicon, some of the most promising nonlinear processing results in silicon have relied on parametric $\chi^{(3)}$ effects for either XPM (111) or FWM (153). Silicon’s high nonlinear re-
response $n_2$, along with the high mode confinement provide for a uniquely high effective nonlinearity $\gamma \approx 1.5 \times 10^5 W^{-1} km^{-1}$ \cite{154} which is several orders of magnitude higher than that of highly nonlinear silica fiber ($\gamma \approx 21 W^{-1} km^{-1}$ \cite{145}). More importantly though is the ability to tightly and uniformly control the waveguide dispersion that allows achieving FWM phase matching properties unique to this platform.

Relatively high propagation losses in silicon waveguides greater than 1 dB/cm however dictate optimal (FWM interaction efficiency wise) waveguide lengths of up to several centimeters. While the limited interaction length limits the parametric gain and conversion efficiencies attainable in the silicon platform, the shorter interaction length $L$ allows for a larger phase mismatch $\Delta k$ while still attaining effective FWM interaction.

### 4.3.1 Dispersion Engineering in Silicon

Phase matching in silicon waveguides for degenerate FWM (single pump) has been reported based on either optimizing dispersion over a central band extending continuously from the pump wavelength or by optimizing higher order dispersion to enable narrower phase matched bands further separated from the pump wavelength \cite{4} as seen in Fig. 4.1 detailing the simulated dispersion, phase mismatch, and resulting
4.3. THE SILICON WAVEGUIDE NONLINEAR PLATFORM

conversion efficiency. Both approaches rely on the ability to tailor the dispersive properties of the waveguide by controlling its structure and dimensions. Slot waveguides were also investigated for dispersion engineered properties (155). Ridge waveguides with a very thin (30 nm thick) slab surrounding the core of the waveguide have shown the broadest continuous phase matching bandwidth to date (156, 157) with conversion efficiency 3-dB bandwidths of up to 936 nm. The slab affects the dispersive properties of the waveguide as well as provides a means to implement a P-I-N structure to extract carriers through doping of slab regions on both sides of the waveguide (158).

A slightly different approach recently demonstrated used quasi-phase matching (QPM) to create phase matched sidebands detuned from the pump wavelength (5). This approach relies on a periodic corrugation of the waveguide width phase match a set of wavelengths detuned from the pump. The advantage of this approach is that the spectral separation between the phase-matched signals can be controlled by the period of the phase-matching feature rather than the exact waveguide dimensions. Furthermore, for each pump wavelength, there is guaranteed to exist a set of bands of quasi-phase matched bands determined by the QPM grating period - hence the pump can be more flexibly located regardless of a ZGVD wavelength.
4.3. THE SILICON WAVEGUIDE NONLINEAR PLATFORM

![Dispersion engineering of silicon channel waveguides](image)

**Figure 4.1:** Dispersion engineering of silicon channel waveguides. (a) Simulated GVD for three different cross-section dimensions for TE and TM polarizations (b) Corresponding acquired phase mismatch in a 1-cm long silicon waveguide. The area in which the phase mismatch is smaller than $\pi$ is indicated in gray. (c) Simulated resulting conversion efficiency assuming 100-mW CW pump at 1550 nm (with the exception of the black curve for which the pump is set at 1585 nm). Figure adapted from (3).
4.3. THE SILICON WAVEGUIDE NONLINEAR PLATFORM

4.3.2 Fundamental Challenges of Parametric Processing in Silicon

One of the main limitations of using silicon waveguides for parametric processing are TPA and the resulting free carriers resulting in FCA. As the free carriers can absorb single photons without limitations, the FCA results in a significant increase in loss. Untreated carrier lifetimes in the silicon structure can be hundreds of picoseconds to nanoseconds with the main recombination mechanism being surface recombination \(^{159}\). Therefore, while very smooth side-walled waveguides, such as those of etchless waveguides, may have very low propagation losses, they also typically exhibit very long carrier lifetimes \(^{159}\) which are deleterious to achieving effective FWM. One solution is to implement a P-I-N diode across the waveguide by doping the slab and negatively biasing the diode to sweep out carriers. This method has been shown to reduce carrier lifetimes \(^{158}\) and improve the conversion efficiency of a FWM in silicon waveguides \(^{160}\).

A separate challenge has to do with the extreme sensitivity of the dispersion properties to waveguide geometry. While this strong dependence of the dispersion on the waveguide dimensions allows the creation of tailored properties, this also makes these
structures extremely intolerant to fabrication variations if the full phase-matched bandwidth is to be achieved (alternatively, for sub 150-nm separations the accurate location requirement of the pump wavelength relative to the ZGVD can be relaxed significantly \(161\)). A waveguide dimension variation of 10 nm results in approximately 12 nm shift of the ZGVD wavelength \(156\). While this can be addressed by fabricating multiple samples of varying design widths (given a fixed shift of the fabricated width with respect to design) to attain one sample of the desired ZGVD, this is not a scalable method to producing waveguides of desired specifications. Another frequently fabrication intolerance is to the slab height, with over-etching significantly affecting the dispersive properties of the device required to attain conversion bandwidth of hundreds of nanometers.

An alternative solution to provide efficient parametric processing in a CMOS-compatible platform is to use a silicon-nitride core instead of silicon. Although the lower index of refraction (and hence lower index contrast) require making the waveguides larger and although the nonlinear coefficient is lower than silicon’s, this platform choice is of interest because it does not experience TPA because of the larger bandgap of silicon-nitride. This has enabled experimental demonstrations of supercontinuum generation spanning greater than one octave \(162\) as well as optical-parametric-oscillators
4.3. THE SILICON WAVEGUIDE NONLINEAR PLATFORM

(OPOs) formed from ring structures using this material [163].

4.3.3 Recent Notable Data Parametric Processing Results in the Silicon

Wavelength conversion of data has been demonstrated with 10- and 40-Gb/s with silicon waveguides in the C-band showing greater than 2.9 dB at 40 Gb/s [164] with up to ∼ 50-nm probe-idler separations. The wavelength conversion of multiple channels simultaneously was also demonstrated in silicon [165] showing very small relative power penalties for increasing the number of 10 Gb/s OOK converted channels from one to two, indicating no noticeable crosstalk in the process (but showing generation of additional non-degenerate FWM products as a result of their interaction). Polarization-independent waveguide designs have also been demonstrated with a dual-pump configuration [166] though at the expense of the ultra-broad dispersion engineering and showing greater power penalties overall (greater than 3.7 dB for 10-Gb/s DPSK channels). Wavelength conversion of OTDM data streams, of which the first results were reported in the next chapter, was also later demonstrated by other research groups at 160-Gb/s and 320-Gb/s for both OOK and DPSK data formats [167, 168] using a HNLF-based nonlinear optical loop mirror (NOLM) for temporal demultiplexing.
4.3. THE SILICON WAVEGUIDE NONLINEAR PLATFORM

Wavelength multicasting, which is achieved by modulating pump with OOK data and combining it with multiple CW probes in a nonlinear silicon waveguide has also been demonstrated - initially with up to 16-way multicasting of 40-Gb/s signals (169) with 1.3-dB power penalty and with a 3-way 160-Gb/s OTDM setting. A separate experimental effort later extended to implement double-pump 6-way multicasting of 10-Gb/s DPSK data with up to 3.8-dB power penalty though with non-uniform channel performance (170) (the dual pump configuration required to retain the phase information of the pump). The same dual-pump multicast setting was also adapted for polarization insensitive operation (171) but with a significant increase to power penalties (up to ~ 8 dB penalty for the worst case channel).

Silicon photonic crystal waveguides have also been proposed for enhancing the FWM efficiency based on the slow light enhancement of the nonlinearity (172, 173). Silicon photonic crystals have been used to demonstrate both 160-Gbaud OTDM demultiplexing (174) as well as OSNR monitoring based on 3rd harmonic generation which couples vertically out of the waveguide (175). However, the inclusion of these slow light mechanisms comes at a trade-off to both loss as well as phase-matched bandwidth (because of increased GVD (172)) which reduce the overall device functionality. Also relying on slow-light enhancement coupled-resonator optical waveguide (CROW)
silicon structures have been shown to enhance FWM efficiency \cite{176}.

Signal processing capabilities based on FWM in silicon have also been demonstrated including record speed 1.28 TBaud temporal demultiplexing of OTDM signals reported in \cite{177, 178}, signal regeneration and grooming \cite{153}, and logic operations such as performing a phase-data XOR relying on the phase relationships of the pumps and signals in a non-degenerate FWM process \cite{179}. NRZ to RZ format conversion has also been demonstrated in silicon waveguides using cross-phase modulation \cite{111}, showing a 2.5-dB sensitivity gain from the NRZ-to-RZ format conversion. A time-lens implementation based on silicon waveguides which also provides time-resolved imaging for short-pulses and OTDM has been demonstrated as well using silicon waveguides for the FWM element \cite{180}. 
Chapter summary and key contributions - this chapter details the author’s contributions on the subject of silicon wavelength-conversion devices for flexible operation within the region of telecom operation around 1550 nm. Bit-error rate measurements are used to validate device performance beyond conversion efficiency metrics. These experiments include some of the first demonstrations of high-bit rate OTDM data processing in silicon leveraging the low level of dispersion in the broadband dispersion-engineered silicon waveguides. The experiments include the first demonstration of
data-validated wavelength conversion of 80- and 160-Gb/s OTDM data as well as a 3-way wavelength-multicast of 320-Gb/s OTDM data using FWM in silicon waveguides. The rest of the chapter details the systematic characterization of using silicon waveguides for wavelength conversion of NRZ data across varying probe-idler separations, showing the strength of silicon waveguides in enabling equal performance regardless the conversion distance over the full span of the 1550-nm centered telecom bands. These experiments include the first demonstrations of fixed-performance wavelength conversion with probe-idler detuning ranging above 50 nm validated with data measurements for 5-, 10-, 20-, and 40-Gb/s NRZ data with less than 1.5 dB power penalty, the first demonstration of conversion of 10-Gb/s DPSK data in silicon waveguides, and a wavelength conversion in silicon of 10-Gb/s data combined with NRZ-to-RZ format conversion across 60- to 168-nm probe-idler separations, with 1.9-dB sensitivity gain and only 0.1-dB residual signal degradation relative to the receiver’s 2-dB sensitivity difference between RZ and NRZ data. A recurring theme in these measurements is the emphasis on the ability to leverage a single waveguide to perform in a signal-idler-detuning agnostic fashion - with
equal conversion efficiencies and power penalties for all probe-idler settings.

5.1 Wavelength Conversion of 80- and 160-Gb/s RZ Time Division Multiplexed Data

As detailed in the previous chapter, one of the strengths of all-optical processing is the ability to manipulate extremely high baud-rate signals - both for manipulation without having to traverse an O-E-O interface as well as a required pre-processing step to the O-E interface. Manipulation of OTDM in signals had been initially demonstrated in silicon with a limited validation in the form of spectrum and autocorrelation traces. Data measurements require the ability to demultiplex the OTDM signal into its lower rep-rate tributaries in order to receive. For the sake of this demonstration the author set up an all-optical sampling gate based on XPM in SOAs nested within a MZI structure as well as several cascaded amplitude modulators. The nested SOAs allow optical gating with sub-ps gate durations using a push-pull optical control mechanism (131). The wavelength conversion of a 80- and 160-Gb/s stream was followed by the demultiplexing stage in order to evaluate the data integrity.
5.1. WAVELENGTH CONVERSION OF 80- AND 160-GB/S RZ TIME DIVISION MULTIPLEXED DATA

5.1.1 Experimental Setup

The experimental setup consisted of three major sections, namely signal generation, wavelength conversion, and optical demultiplexing and reception (highlighted in Fig. 5.1). Signal generation consisted of modulating the output of a 10-GHz mode-locked-laser (MLL) at 10-Gb/s with a $2^{31} - 1$ PRBS pattern from a PPG and then using optical time-division multiplexing stages to produce either an 80-Gb/s or 160-Gb/s aggregate stream.

Figure 5.1: Experimental setup of wavelength conversion of 160-Gb/s OTDM RZ data. Dashed lines represent electrical cable, and solid lines represent optical fiber. Highlighted areas signify signal generation, wavelength conversion, and temporal optical demultiplexing and reception functional blocks. Polarization controllers (not marked on the diagram) are used throughout the setup. The silicon waveguide used in this experiment had a linear insertion loss of 6.4 dB with TPA and FCA adding roughly 3 dB of nonlinear loss when high-power optical signals are introduced.
5.1. WAVELENGTH CONVERSION OF 80- AND 160-GB/S RZ TIME DIVISION MULTIPLEXED DATA

To achieve wavelength conversion, the data was amplified using an EDFA, a CW optical pump was produced by an amplified tunable laser, and both signals were combined using a wavelength-division-multiplexer (WDM), set to TE polarization, and coupled into the silicon waveguide. The output of the waveguide was filtered using a tunable grating filter and amplified to recover the converted signal for further processing. The final stage of optical signal processing consisted of temporally demultiplexing the 80-Gb/s or 160-Gb/s streams down to the 10-Gb/s tributaries and inspecting them. The demultiplexer optically gated the data signal using a combination of an integrated SOA-based MZI and two cascaded commercial amplitude modulators. The SOA-MZI device created optical gates using a push-pull configuration where a portion of the original 10-GHz pulse train of the MLL was used to inject electrical carriers into the SOAs in the MZI arms, shifting the phases and toggling the interference state at the output. VODs and VOAs were used to properly configure this push-pull mechanism. The cascaded modulators were driven with 20- and 10-GHz clock sources to complement the gating operation of the optical gate, further suppressing the adjacent tributary bits. The demultiplexer output was received on a photodetector (PIN-TIA) with a limiting amplifier and then examined on a BERT for BER characterization. Power taps were used throughout to examine the signals using an autocorrelator and a digital...
5.1. WAVELENGTH CONVERSION OF 80- AND 160-GB/S RZ TIME DIVISION MULTIPLEXED DATA

communications analyzer (DCA).

5.1.2 Experiments and Results

The first experiment is of a wavelength conversion of an 80-Gb/s aggregate stream in the silicon waveguide. The conversion efficiency was measured to be -27.3 dB, with injected 23.8-dBm CW pump power and 14.5-dBm average signal power (Fig. 5.2a). Autocorrelation traces of both data input and wavelength-converted data are taken, showing no significant pulse broadening (Fig. 5.2b). The converted data after being demultiplexed, as seen on a DCA (Fig. 5.2c), shows no additional broadening when inspected on an autocorrelator.

The demultiplexer was then optimized BER-wise by using the BERT readings. The optimal demultiplexed signal for BER measurements was attained by resetting the all-optical gate to temporally notch out a single tributary while the modulators served to suppress the other unwanted tributaries, resulting in a significantly visually different but fully open eye-diagram (Fig. 5.2d). Error-free operation was observed for the converted 10-Gb/s tributary, and a BER curve was taken to inspect the power penalty for the entire system, where the back-to-back case was defined as the original 10-Gb/s stream before the temporal multiplexing stages. The entire system power
penalty is measured to be 11.1 dB (Fig. 5.2(e)). This significant power penalty is partially attributed to the demultiplexing mechanism and partially to the multiple amplification stages beyond the wavelength conversion process.

**Figure 5.2:** (a) Output spectrum of conversion after the CW pump is suppressed (to overcome dynamic range limitation of the OSA), with 1541-nm input signal and 1559-nm converted signal. Non-degenerate FWM appears around the 1550-nm pump wavelength. (b) Autocorrelation traces taken on the 80-Gb/s signals before and after wavelength-conversion, overlaid with the autocorrelation trace of 10-Gb/s demultiplexed tributary. (c) Eye diagrams of 10-Gb/s input and 10-Gb/s tributary-demultiplexed signals. (d) Optimized demultipled 10-Gb/s tributary eye-diagram. The uneven shape is a result of the inverted method of demultiplexing where the all-optical gate was set to notch the adjacent tributary rather than isolate a single 10-Gb/s tributary. (e) BER measurements for the optimized demultiplexing settings showing an overall 11.1-dB power penalty - including multiple amplification stages beyond the wavelength conversion process.
amplification and filtering stages in the complete experimental setup.

The second step in this experiment included scaling the OTDM data rate to 160-Gb/s by adding an additional 2x temporal multiplexing stage. The conversion efficiency stays similar at -27.1 dB for this case as well. Autocorrelation traces indicate no observable pulse broadening due to the wavelength-conversion process and optical gating. However, a more significant noise floor appears on the autocorrelation trace of the demultiplexed signal - indicating not fully suppressed 10-Gb/s tributaries of the 160-Gb/s signal. For this case the previous arrangement of tributary suppression by the all-optical gate is not applicable as it would require notching additional tributaries.

The extinction ratio of the all optical gate was later measured to be around 8 dB with a predicted performance limit of around 12 dB. In either case, the noise contributed from the unsuppressed signals is a limiting factor for this experiment. As shown by other groups subsequently, FWM-based processing of high speed OTDM signals in silicon is viable at symbol rates as high as 1.28 Tbaud using the silicon waveguide platform \cite{177, 178}.
5.2. HIGH-REPETITION RATE PULSED PUMPS VS. CW PUMPS FOR NONLINEAR PROCESSING

Figure 5.3: (a) Output spectrum of conversion after the CW pump is suppressed, with 1541-nm input signal and 1559-nm converted signal. Non-degenerate FWM appears around the 1550-nm pump wavelength. (b) Autocorrelation traces taken on the 160-Gb/s signals before and after wavelength-conversion overlaid with the autocorrelation trace of 10-Gb/s demultiplexed tributary. (c) Eye diagrams of 10-Gb/s input and 10-Gb/s tributary-demultiplexed signals.

5.2 High-Repetition Rate Pulsed Pumps vs. CW Pumps for Nonlinear Processing

While a CW pump is preferable in many settings since the device setting and operation can be agnostic of the processed signals and the modulation format stays unaltered, the conversion efficiency achievable with this type of optical pump is limited due to the average power limitations in silicon waveguides (both damage as well as TPA and FCA induced nonlinear losses). High average-power fiber-to-chip coupling also induces
5.2. HIGH-REPETITION RATE PULSED PUMPS VS. CW PUMPS FOR NONLINEAR PROCESSING

coupling instabilities due to the flux of photons emitted from the edge of the tapered fiber as well as heating of the silicon chip which causes coupling fluctuations as the chip heats and slightly expands. For the reasons above, to achieve stable operation with silicon all-optical processing devices it is preferable to keep the optical power to relatively low levels (less than 200 mW launched).

While a pulsed pump is required for operations in which the pulsed signal is designated as the pump to achieve a certain functionality (such as the multicast of OTDM signals as detailed in Section 5.3), a pulsed pump also provides additional advantages. One feature it potentially provides is timing signal regeneration - reducing jitter and pulse reshaping as reported in (153). But more crucial to operation with the current generation of silicon FWM devices in existence, concentrating the pump energy into pulses rather than CW operation increases the instantaneous conversion efficiency (in terms of peak powers) as the instantaneous conversion efficiency depends quadratically on the pump peak power rather than the average power. Furthermore, given the carrier recombination exponential-decay rate process in silicon, TPA-induced carrier population (which causes unwanted FCA) has a greater duration to decay between optical pulses compared to CW operation. As the typical carrier lifetime in a silicon waveguide is on the order of several hundred picoseconds, operating with a 10-GHz repetition rate
pulsed pump has a noticeable advantage over a CW pump.

The main drawbacks of this method of operation are the implications on format conversion which might be unwanted in optical networks, as well as the required pump pulse-rate matching with the processed signal bit-rate.

5.3 3-Way Multicast of 320-Gb/s RZ Data

One alternative configuration for FWM-based processing of data is the unicast or multicast operation in which the data to be processed is imprinted on the optical pump rather than the probe. As the idler amplitude is quadratically proportional to the pump amplitude, all amplitude information on the pump is copied over to the idler (with a regenerative property due to the extinction ratio doubling). A unicast is achieved when a single-wavelength probe signal is introduced into the FWM medium resulting in a single generated idler (besides secondary mixing terms). A multicast results from the introduction of several wavelength-separated probes along with a single pump - in which case several wavelength-separated idlers are formed. Each of these idlers carries a copy of the original information carried by the pump signal.
Figure 5.4: 3-way wavelength multicasting of the 160- or 320-Gb/s RZ-OOK OTDM data stream. The setup can reconfigurably perform an OTDM multicast/unicast by turning on and off the CW probes. An OSO is used to inspect the launched signal. Image taken from [4].

For this set of experiments the MLL signal is modulated, compressed in time using a commercial solitonic pulse compressor, and then multiplexed in time to generate the high data rate OTDM streams. The pulse compression shortens the pulse duration from around 1.5 ps down to 0.7 ps, while also significantly broadening the signal spectrum. The resulting OTDM stream is therefore made more sensitive to dispersion, requiring the inclusion of dispersion compensating fiber (DCF) to offset dispersion accrued on the different fiber-based components of the experiment. In order to temporally inspect...
the data signals an optical-sampling oscilloscope (OSO) based on FWM in a HNLF was used to capture the eye diagrams of one of the multicasted signals to validate correct operation.

**Figure 5.5:** Wavelength multicasting of a 320-Gb/s RZ-OOK OTDM data stream. Spectra recorded at the chip’s ouput for configurations ranging from no probes present all the way up to 3-probes (and corresponding RZ idelrs) present. An OSO is used to inspect the launched signal as well as the multicasted copy of the signal at 1532 nm from the 3-way multicast configuration. Image taken from [4].

By selectively turning on the different CW probe seeds a 1-, 2-, and 3-way multicast is achieved with no compromise to performance (Fig. 5.5). The eye diagram for the longest-wavelength idler that falls within the c-band is recorded on the OSO showing
5.4. WAVELENGTH CONVERSION OF 40-GB/S NRZ DATA ACROSS THE S-, C-, AND L-BANDS

a fairly open eye. Although the quadratic amplitude relation between the pump and probe doubles the extinction ratio of the OOK modulation (for a unicast/multicast configuration), it also extenuates any tributary residual amplitude uneveness which is created during a non-ideal OTDM multiplexing process. Though BER evaluation of the signals was not possible at the time of this experiment, the potential for multicasting very high bit rate OTDM signals is demonstrated.

5.4 Wavelength Conversion of 40-Gb/s NRZ Data Across the S-, C-, and L-Bands

While the previous largest reported probe-idler wavelength detuning had been 50 nm (164), this experiment targeted detunings to over 100 nm which fully covers the telecom used bands. The introduction of dispersion engineered waveguides allows FWM probe-idler detunings to potentially be extended from several nm ranges to much larger ranges covering up to hundreds of nanometers (156). This experiment extends from the previously reported 50-nm detuning up to 100 nm as well as validate performance at modulation rates from 5 Gb/s up to 40 Gb/s to test the wavelength-converter modulation-rate agnostic operation.
5.4. WAVELENGTH CONVERSION OF 40-GB/S NRZ DATA ACROSS THE S-, C-, AND L-BANDS

5.4.1 Experimental Setup

A 1.1-cm long silicon waveguide with a 290-nm 720-nm cross section, fabricated at the Cornell Nanofabrication Facility, is used for this experiment. The waveguide is
surrounded by a 30-nm thick slab which serves primarily for dispersion engineering. The waveguide is formed on a silicon-on-insulator (SOI) platform using electron-beam lithography followed by reactive-ion etching. Each end of the waveguide has an inverse-taper mode converter for efficient coupling to tapered fibers resulting in 6.4-dB fiber-to-fiber linear insertion loss (with approximately 3-dB additional nonlinear as a result of TPA and FCA at high optical powers). The zero-group-velocity-dispersion (ZGVD) wavelength for this waveguide was calculated to be approximately 1577 nm (156).

The experimental setup used to evaluate the wavelength conversion (Fig. 5.6) included a continuous-wave (CW) probe produced by a tunable laser (TL) modulated with a $2^{15} - 1$ PRBS pattern which was generated by electrically multiplexing (MUX) a lower data rate PRBS pattern from a PPG. A fixed CW 22-dBm 1552.5-nm pump was created by amplifying the output of another TL using an erbium-doped fiber amplifier (EDFA). The modulated probe in the S-band of the ITU grid was amplified using a thulium-doped fiber amplifier (TDFA), filtered using a Fabry-Perot band-pass filter, and combined with the pump. The probe and pump were both set to the TE polarization using a fiber polarizer, and injected into the silicon device. Following the device, a portion of the power was tapped for examination on an OSA. The wavelength-converted data signal was recovered using additional filtering and amplification stages.
5.4. WAVELENGTH CONVERSION OF 40-GB/S NRZ DATA ACROSS THE S-, C-, AND L-BANDS

It was inspected using a digital communications analyzer and was received for BER evaluation using a photodetector (PIN-TIA) followed by a limiting amplifier. The electrical received signal was demultiplexed (DEMUX) and then fed to the BERT. A VOA was used to vary the optical power incident on the receiver. An electrically-distributed tunable clock source determined the modulated data rates, scaling between 5 Gb/s and 40 Gb/s. The probe-idler detuning ranges span 47.7 nm to 100.2 nm. Back-to-back eye diagrams and BER curves were recorded on the probe just before it was combined with the pump.

5.4.2 Experiments and Results

In the first experiment, the data rate of the probe was set to be 40-Gb/s and the probe wavelength was scanned to vary the conversion distance between 47.7 nm and 100.2 nm with 10.5-nm steps. The conversion efficiency, defined as the ratio of output idler average power to input probe average power, remains nearly constant at -31.9 dB for all probe-idler separations (measured from Fig. 5.6 with the added 9.4-dB waveguide insertion loss), as it was well within the operational bandwidth of the waveguide. Open eye diagrams were recorded for all wavelength-converted signals (Fig. 5.7), showing minimal signal degradation. The signal integrity degradation of the wavelength con-
5.4. WAVELENGTH CONVERSION OF 40-GB/S NRZ DATA ACROSS THE S-, C-, AND L-BANDS

Figure 5.7: Wavelength conversion of 40-Gb/s NRZ data with varying probe-idler separations: (a) Eye diagrams for the back-to-back cases (probes) and wavelength-converted signals (idlers) for the listed conversion experiments. (b) BER curves measured for all the 40-Gb/s back-to-back cases (probes) and wavelength-converted signals (idlers) showing average power penalty of 1.47 dB.
5.4. WAVELENGTH CONVERSION OF 40-GB/S NRZ DATA ACROSS THE S-, C-, AND L-BANDS

The wavelength conversion process was quantified using BER curves measured for the back-to-back and wavelength-converted data signals, showing a consistent 1.47-dB power penalty (Fig. 5.7). This power penalty included signal degradation induced by the post-conversion EDFA and filters. The improved power penalty compared to the previously reported 2.9-dB penalty on a similar device \(164\) was due to improvements made to the experimental setup in the data generation and reception electronics as well as optimization of the optical amplification and filtering stages.

In the second experiment, the probe was set at a fixed wavelength of 1504 nm (corresponding to a 100.2-nm probe-idler detuning), and the modulation rate was varied between 5, 10, 20, and 40 Gb/s by changing the tunable clock source frequency while keeping the rest of the experimental setup fixed. Open eye diagrams were recorded on the wavelength-converted signals (Fig. 5.8), and signal degradation was quantified using BER measurements (Fig. 5.8). This resulted in power penalty measurements of 0.98, 0.91, 0.80, and 1.43 dB, corresponding to the data rates of 5, 10, 20, and 40 Gb/s, respectively. The deviation in power penalties for the 5-Gb/s to 20-Gb/s rates is within experimental variation. The 0.5-dB relative increase in power penalty for the 40-Gb/s data rate is partially attributed to more pronounced sideband attenuation by the post-conversion 1.5-nm-wide filter and to the initially lower extinction ratio of \(114\).
5.5 WAVELENGTH CONVERSION OF 10-GB/S PHASE-MODULATED DATA

the 40-Gb/s modulated probe which incurs a larger power penalty from the OSNR degradation.

5.5 Wavelength Conversion of 10-Gb/s

Phase-Modulated Data

As spectral efficiency is becoming increasingly important in long haul communication links, coherent modulation formats encapsulating data in the signal phase as well as amplitude are entering the new communication standards. FWM is a coherent process and therefore supports wavelength conversion of such formats. A direct extension of the OOK experiment demonstrated the first wavelength conversion of differential-phase-shift keyed (DPSK) signals in silicon at 10-Gb/s. The experimental setup differed in the usage of a phase modulator to generate the differential phase PRBS pattern instead of an amplitude modulator and the use of a delay line interferometer (DLI) to translate the information from phase to amplitude prior to detection on a photodetector. The experimental results showed that for several wavelength separations a consistent 1-dB power penalties can be achieved [152] - similar to the OOK power penalty measured for 10-Gb/s OOK. The platform’s support of processing of both amplitude and phase mod-
Figure 5.8: Wavelength conversion of 5- to 40-Gb/s data with 100-nm probe-idler separation: (a) Eye diagrams for the back-to-back cases (probes) and wavelength-converted signals (idlers) for bit rates of 5-, 10-, 20-, and 40-Gb/s for 100.2-nm wavelength conversion. (b) BER curves for back-to-back cases (probes) and wavelength-converted signals (idlers) showing a power penalty of less than 1 dB for bit rates up to 20 Gb/s, and a 1.43-dB penalty for 40-Gb/s signals.
ulations shows the potential for support of higher complexity mixed phase-amplitude
signaling formats such as quadrature amplitude modulation (QAM).

5.6 168-nm Spanning Wavelength Conversion
with Format Conversion of 10-Gb/s Data

Though record low wavelength-conversion power penalties were demonstrated in section
5.4 these measurements only show an upper bound on the actual penalty achievable
since the measurement also include OSNR degradation as a result of the amplification
after the chip. Furthermore, since an amplifier is required in that experimental setup,
the operation wavelengths are limited to the gain bands of erbium and thulium. There-
fore, an experiment designed without the need for a post-chip amplifier is desirable.
The implementation is achieved through the use of an Avalanche Photodiode (APD)
which provides improved sensitivity. In order to lower the average optical power needed
to be launched on the chip, while maintaining high-speed operation, a high-repetition
rate mode-locked laser (MLL) is also incorporated to act as the optical pump. This
allows injection of less than 20 dBm on the chip while achieving sufficiently high peak
powers to create sufficiently efficient FWM. The lower powers both serve to make the
device more power efficient as well help stabilize the coupling - which is key for low penalty operation. The incorporation of a mode-locked laser also facilitates a NRZ-to-RZ format conversion which further improves detection sensitivity, resulting in overall consistent sensitivity gain (negative power penalty). This section details the characterization of a FWM silicon used for wavelength conversion of 10-Gb/s data across more than 168 nm.

5.6.1 Dispersion-Engineered Silicon Waveguide

The 1.1-cm long silicon nanowaveguide used in this experiment has a 300-nm by 710-nm core cross section with a surrounding 30-nm tall silicon slab. The device dimensions provide a ZGVD wavelength within the C-band. Unlike previous devices used, this nanowaveguide is laid out in a tight spiral (see Fig. 5.9 inset) occupying less than $1mm^2$ which serves to overcome e-beam-stitching errors in the fabrication process. However, the spiral design also limits performance as the heating from the optical power dissipated in the device is much more localized compared to a non-spiraled waveguide and therefore the coupling is much more sensitive to the launched optical powers. Inverse tapers provide for efficient broadband coupling to tapered fibers. The device was measured to have linear losses of 8.4 dB in this device (with TPA and
TPA-induced FCA contributing 2-dB additional nonlinear loss when a 19-dBm optical pump is launched into the nanowaveguide).

### 5.6.2 Wavelength Conversion Experimental Setup

The experimental setup (Fig. 5.9) for this set of measurements includes a CW tunable laser (TL) whose output is on-off-keyed modulated by a commercial $LiNbO_3$ Mach-Zehnder modulator (MZM) with a $2^{31} - 1$ PRBS pattern. The modulated light is amplified by an S-band TDFA before being filtered ($\lambda$) and combined with a pulsed pump using a band combiner. The 1.5-ps, 10-GHz repetition-rate pump (located at 1555 nm) is generated by amplifying the output of a MLL by an EDFA. The combined signals are set to TE polarization and launched into the nanowaveguide. The nanowaveguides output is filtered by a band filter to allow reception of the converted
signal on a 10.7-GHz bandwidth InGaAs avalanche-photo-diode (APD-TIA). A variable optical attenuator is included before the receiver to facilitate measurement of BER curves. The output of the receiver is electrically amplified by a limiting amplifier (LA) before being evaluated on a BERT. A 40-GHz DCA is used to record the eye diagrams from the photodetectors output, and an OSA is used to record the spectrum at the nanowires output.

5.6.3 Receiver Characterization for Broad Wavelength-Conversion Experiments

In order to consistently compare BER performance resulting from the wavelength conversion at significantly wavelength-separated wavelengths, the receiver’s inherent sensitivity wavelength dependence must be characterized and later factored out from the results. This is especially true when operating close the the receiver’s cut-off wavelength (in this case, 1650 nm for an InGaAs APD). The sensitivity was directly measured with back-to-back setups using several lasers and a 10-Gb/s OOK modulator designed for operation at 1550 nm as shown in Fig. 5.10. An alternative method to derive the wavelength dependence of the sensitivity is to use the vendor-provided responsivity vs. wavelength data and assume a shot-noise limited model (incurring a $10 \log_{10}(\sqrt{\eta})$)
dependence of the relative power penalty on the responsivity $\eta$) and calibrate the curve to a reference sensitivity value (Fig. 5.10).

![Graph showing sensitivities](image)

**Figure 5.10:** Experimental measurement of the APD-TIA-based receiver sensitivity (at BER of $10^{-9}$) using either BER measurements or deriving it from the responsivity based on a fit to a reference sensitivity and producing the relative sensitivity curve based on a shot-noise-limited model.

While the direct measurement of the sensitivity using BER curves has inherent measurement inaccuracies (due to the measurement variation itself as well as the wavelength-dependent performance of both lasers and modulators), using the responsivity-derived method requires assuming an idealized simplified model for the photodetector and is based on an indirect measurement. Therefore, the direct sensitivity measurements were adopted as the method for factoring out the wavelength dependence of the receiver out of the following measurements.
5.6.4 Wavelength Conversion Experiments

The device’s broadband performance was validated by varying the probe wavelength over the S-band in discrete steps as detailed in Table 5.1. A relatively low 16.5-dBm average-power pump (launched onto the nanowaveguide) which yielded a conversion efficiency of -32.4 dB which was sufficient in order to recover the converted signals while minimizing chip-heating-induced coupling fluctuations. The pump wavelength in this set of measurements was sufficiently close to the ZGVD wavelength to yield near-constant conversion efficiency (see Fig. 5.11), which showed the relative flexibility of a single nanowaveguide with regard to pump, probe, and idler wavelengths, as afforded by the flat dispersion profile of the device.

**Table 5.1:** Wavelength listing of pump, probe, and idler settings for the first wavelength conversion experiment.

<table>
<thead>
<tr>
<th></th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>1555</td>
</tr>
<tr>
<td>Probe</td>
<td>1525 1515 1505 1495 1485 1475</td>
</tr>
<tr>
<td>Idler</td>
<td>1585 1596 1607 1619 1631 1643</td>
</tr>
<tr>
<td>Separation</td>
<td>60 81 102 124 146 168</td>
</tr>
</tbody>
</table>

Data measurements show open eye diagrams (Fig. 5.12b) on both probe and idler signals. In order to factor out the receivers wavelength-varying sensitivity from the characterization of the FWM process, a set correction factors based on the direct back
5.6. 168-NM SPANNING WAVELENGTH CONVERSION WITH FORMAT CONVERSION OF 10-GB/S DATA

Figure 5.11: Overlaid spectra of wavelength conversion experiments recorded at the chip output, depicting conversion of 60 nm up to 168 nm. Beyond generated idlers, additional FWM products are visible at shorter wavelengths (1497 nm, 1478 nm, 1459 nm) corresponding to FWM in which two probe photons interact with a single pump photon. Some residual TDFA noise is also visible (1522 nm, 1466 nm).

sensitivity back-to-back measurements was used. The difference between the reference sensitivity (set as the C-band value) and the sensitivity at each wavelength was set as a relative correction factor. Subsequently, each BER curve for the probes and idlers (Fig. 5.12.a) is shifted horizontally by an amount equal to the relevant correction factor in order to deduce the power penalty resulting primarily from FWM. The resulting average sensitivity gain of 1.9 dB is in agreement with previously published similar results which utilized XPM in silicon to achieve the format conversion and were limited to the C-band (111). The sensitivity gain stems from the NRZ-to-RZ format conversion. This is verified by comparing the receiver’s sensitivity to 10-Gb/s modulation of
5.6. 168-NM SPANNING WAVELENGTH CONVERSION WITH FORMAT CONVERSION OF 10-GB/S DATA

Figure 5.12: (a) Recorded BER curves for all probe and idler signals indicating an average 1.9 dB sensitivity gain. (b) Probes and the idlers eye diagrams recorded from the inverted-data differential output port of the APD-TIA. (c) Directly modulated RZ and NRZ back-to-back BER measurements showing a 2-dB APD sensitivity difference between formats.

the MLL output (RZ) and a CW TL output (NRZ) showing a 2-dB difference (Fig. 5.12c). The relative 0.1-dB residual penalty suggests the penalties from noise added in the parametric process can be made fairly small. These results suggest the inherent penalties from the FWM process in silicon waveguides are significantly lower than had been previously reported - likely due to penalty contributors such as unfiltered ASE entering the waveguide and OSNR degradation at the post-conversion amplifier. Fundamentally, silicon waveguides can potentially have lower NF than HNLF as Raman noise (183) as the Raman effect in silicon occurs only at a 15.6-THz detuned band...
5.7 Summary and Conclusions

The experiments reported in this chapter covered exploration and characterization of nonlinear all-optical data processing leveraging FWM in low-dispersion silicon waveguides engineered to provide phase matching. The low dispersion and broad phase-matching allowed the first demonstrations of wavelength conversion and multicasting of OTDM data in silicon waveguides with up to 320 Gbaud, verified with data measurements to guarantee correct transmission. The second effort focused on showing how the broad phase matched bandwidth can allow for tunable equal-performance wavelength conversion across wavelength spans covering the telecom bands around 1550 nm. With optimized experimental setups, not only was the conversion range extended to record probe-idler separations of 168 nm, but concurrently power penalties were minimized to 1.4 dB for 40-Gb/s NRZ data and 0.1-dB residual penalty for 10-Gb/s data in a setup leveraging NRZ-to-RZ format conversion in the same nonlinear processing step. Both efforts presented record low penalties for processing using FWM in silicon as well record conversion distances, with a stronger emphasis in the latter experiment on the
need for accurate accounting for the measurement system’s dependence on wavelength.

While the author presented some of the first results on high-speed OTDM processing in silicon, other research groups have been able to push these results to higher symbol rates exceeding 1 Tbaud using well optimized OTDM testbeds (177). The engineered low-dispersion achieved uniformly along the length of the silicon waveguides, combined with the short total required length (order of a single centimeter) give a fundamental advantage for this platform over HNLF-based processing due to the smaller amount of walk-off between the co-propagating short-duration pulses participating in the process. As such, silicon waveguides can provide some unique capabilities for niche devices performing temporal sampling or OTDM processing.

The author’s contributions on demonstrating detuning-agnostic operation of silicon wavelength converters demonstrate the broad-wavelength operability of these devices previously predicted only by conversion-efficiency measurements without data validation. The detuning-agnostic results covering the S-, C-, L-, and U-bands show promise for agile wavelength conversion in silicon with low penalties. However, the low conversion efficiencies still limits the platform’s usability as the power loss requires pre- and post-amplification. Though devices with unique features have been developed, such as PIN structures to extract carriers (158), low-propagation loss waveguides (31), and
improved-damage-threshold inverse tapers \cite{90}, no device to date has been demonstrated with all these elements concurrent with the accurate waveguide dimensions required for dispersion engineering. Furthermore, stable edge coupling of high optical powers to inverse tapers still needs to be tackled through either improved taper design to make the taper less dislocation sensitive or by fiber-chip packaging.
Chapter summary and key contributions - this chapter details the author’s contributions on the subject of long-wavelength SWIR and MIR parametric processing devices based on silicon. The concept of enabling high speed transmission and reception through FWM platforms is presented and motivated. The chapter proceeds to detail several experimental efforts to demonstrate the silicon FWM platform capabilities in enabling these type of operations with most of the results focusing in the wavelength ranges of 1800 to 1900 nm. The first demonstration focused on demonstrating wave-
length conversion and unicast based on mixing of signals from 1550 nm and 1900 nm at 10 Gb/s to produce converted signals at 1300 nm, showing only a relative 0.4-dB increase in power penalty relative to those reported in section 5.6. This result highlights the direct extension performance wise of operations with 700 nm probe-idler separations as those with few-nm separations. Utilizing both unicast and wavelength conversion stages a 10-Gb/s FWM-based link is then assembled. In such a link, high-speed OTDM data is generated at 1884 nm using a FWM stage mixing signals from 1300 nm and 1550 nm, and then converted back to a shorter wavelength for detection using a second FWM stage. These demonstrations comprise of a wavelength-tunable high-speed link at wavelengths approaching 2000 nm, with a total power penalty of 2.1 dB. The operation of FWM-based detection is then extended to 40-Gb/s operation utilizing a 4:1 sampling scheme concurrently with the wavelength conversion. The FWM-based receiver, which operates agnostic of the detected-signal wavelength, is demonstrated with error-free reception of a 1866 nm 40-Gb/s signal - a feat which is not possible with currently available semiconductor photodetectors. The 40-Gb/s detection capability allows the extension of
the FWM-based link operation to higher bit rates, which is then demonstrated at 40-Gb/s with only a 1.5-dB increase in penalty compared to the 10-Gb/s link. The ability to effectively export telecom-grade operating speeds in a continuously wavelength tunable way to the 1700-2000 nm band is a unique novel capability enabled by the excellent phase matching achieved in dispersion engineered silicon waveguides. The chapter is concluded with methods to extend operation to wavelengths beyond 2000 nm and further into the mid-wave IR, covering both efforts on quasi-phase matching as well as higher-order-dispersion-based phase matching.

6.1 Motivation Shift to Longer Wavelength Applications

While most telecom and datacom developed technologies have focused in the Near IR (NIR) and shorter range of the SWIR (up to around 1675 nm) because of technological advantages in operating at these sets of wavelength bands, many applications requiring optical sensing or transmission also exist at longer wavelengths. Absorption spectroscopy and remote sensing techniques, based on transmitted light exciting vibra-
6.1. MOTIVATION SHIFT TO LONGER WAVELENGTH APPLICATIONS

Multimodal modes of polarizable molecules, have to operate at wavelengths corresponding to the vibrational-frequencies within a molecule - which are located primarily at wavelengths longer than 2000 nm (Fig. 6.1.b). For these type of applications, broad spectral sources or widely tunable lasers are required, as well as high sensitivity photodetectors.

Alternatively, for free-space communication applications it is beneficial to transmit within the atmospheric transmission windows (Fig. 6.1.a) of the mid-wave IR (MWIR) at 3000 - 5000 nm or the long-wave IR (LWIR) range at 8000 - 12000 nm. In order to enable such free-space links tunable lasers with high-speed modulators (or

![Figure 6.1:](image-url) (a) Atmospheric transmission windows. (source - Wikipedia) (b) Commonly used spectroscopy absorption bands. (source - Wikipedia)
6.1. MOTIVATION SHIFT TO LONGER WAVELENGTH APPLICATIONS

directly modulated lasers (184)) are required as well as high-bandwidth high-sensitivity photodetectors which can operate at these longer wavelengths.

While external cavity quantum cascade lasers provide potential for tunable sources in MWIR wavelengths (185), integrated optics platforms for the MWIR have yet to be developed to allow high speed modulators because of the required material platforms that have only partially been developed to allow low-loss guiding of light as well as the need for specialty optical fiber. While these obstacles can potentially be overcome with low-loss integrated wave-guiding platforms (such as silicon on sapphire, silicon on nitride, or other structures (186) (187) (188)) and specialty fibers (for instance, using chalcogenides (189)), direct detection receivers are fundamentally performance limited at these wavelengths. Semiconductor photodetectors suffers from significant performance degradation as longer wavelengths are targeted due to the lower photon energies requiring narrow energy bandgaps - leading to relatively large dark currents at room temperature. While this can be partially addressed by cryogenic cooling, these mechanisms complicate integration, increase cost, and limit device bandwidth (190). Recent efforts on strained superlattice InGaAs photodetectors (191) (192) have aimed to provide recent demand to detection at wavelengths longer around 2000 nm but receiver sensitivities of such devices are still significantly lower than those of telecom-
wavelength receivers and their operation cannot be extended to MWIR wavelengths.

6.2 Accessing MWIR Through Nonlinear Processing in Silicon

As silicon itself is transparent continuously form 1200 to 6600 nm \[188\] it should be feasible to use the silicon photonic platform to guide light and manipulate it. Functionnalities such as modulation have recently been shown in silicon using identical designs to those operating in the telecom bands \[193\]. Following the same logic, it is possible to extend nonlinear processing in silicon waveguides to operate at longer wavelengths.

A big advantage to leveraging silicon in the long-SWIR and MWIR is that TPA and the resultant FCA can be fully eliminated using pump signals at wavelengths longer than 2200 nm (in which case three-photon absorption and the resulting FCA would become the limiting factor but at an order of magnitude lower cross-section for the interaction). Therefore, significant FOM improvement can be expected for silicon at these wavelengths. Another significant advantage of using silicon for these operations is the dispersion engineering which had previously been applied to ZGVD around the C-band. The same methodology can be applied to achieve ZGVDs around 1900 nm.
or 2300 nm to enable operation with phase matched bandwidths extending as high as 3000 nm. Several alternative approaches to achieve discrete phase matched bands will be discussed towards the end of the chapter in section 6.7.

By adapting similar silicon waveguide structures, dispersion engineering can be applied to obtain broad continuous phase-matched bandwidths centered around longer ZGVD wavelengths of 1900 nm (157) and even 2300 nm (194) though, to date, achieving lower CW-pump conversion efficiencies compared to lower ZGVD smaller waveguides. Similarly, silicon waveguides have been used to achieve on-chip gain above 2000 nm (126) as well as generate super-continuum and observe onset of other nonlinear effects though these demonstrations have been shown only with low duty cycle pulsed lasers with peak powers of several tens of Watts coupled into the waveguide (190, 195).

Fourth-order dispersion phase matching has been shown to generate narrow phase matched bands which enable conversion between telecom bands and the longer end of the SWIR (190). An OPO based on a fiber based feedback loop with an air-clad silicon FWM waveguide was recently demonstrated with 54-dB parametric gain per path through the waveguide with pumping peak powers of $\sim 24$ W (196).

However, as these capabilities are being developed, and while they are not yet mature to enable system-level operations on data (whether due to low conversion ef-
6.2. ACCESSING MWIR THROUGH NONLINEAR PROCESSING IN SILICON

Figure 6.2: Overlaid ISA traces at the output of a dispersion-engineered silicon waveguide with a 1546.5-nm ZGVD, pumped with a 10-GHz 1.5-ps FWHM MLL. The probe wavelength generated is varied between 1800 and 1980 nm, producing corresponding idlers between 1356 and 1269 nm and probe-idler separations between 444 and 711 nm. The conversion efficiency for all the conversions is nearly constant at -32 dB. The conversion is slightly less efficient compared to conversions closer to the ZGVS wavelength due to higher insertion loss of the inverse tapers when operating far from the designed wavelength of 1550 nm. Spectral features between 1380 to 1530 nm are ASE emission from the laser used to generate the probe.

ficiencies or limited bandwidths), it is worthwhile advancing with existing devices to extend operation to longer wavelengths in the SWIR which are not accessible easily with commercially available devices as a stepping stone to producing these functionalities in the MWIR. As dispersion engineered silicon waveguides with C-band ZGVDs can have phase matched bandwidths extending beyond 2000 nm (156), these can be used
6.3 Conversion and Unicast of 10-Gb/s Data from 1900 nm across 700 nm

The first immediate extension to the results reported in section 5.6 is to attempt to utilize a similar setup to extend the same operation to a longer conversion range (Fig. 6.3a). In order to enable the operation at 1900 nm an extended cavity laser (ECL) is used to generate CW light at 1866 nm and a TDFA optimized for long-wavelength operation provides amplification in this wavelength range. Both a C-band pump and a 1900-nm probe are combined and launched into the FWM silicon waveguide. By gradually tuning the ECL to longer wavelengths and optimizing the FWM operation the ZGVD wavelength for the waveguide (same as used before) can be determined to be 1546.5 nm (as the value that maximizes the conversion bandwidth). Band combiners are used both for combining the pump and probe as well as filtering the idler after the chip. Further suppression of the probe after the FWM process is achieved by coiling an optical fiber tightly (around 2.5 cm diameter), creating bending losses at the longer
6.3. CONVERSION AND UNICAST OF 10-GB/S DATA FROM 1900 NM ACROSS 700 NM

Figure 6.3: Experimental setups for (a) 10-Gb/s wavelength conversion from 1866 nm to 1321 nm spanning 545 nm combined with a NRZ-to-RZ format conversion (b) Unicast of 10-Gb/s RZ data from C-band to O-band using a probe-idler separation of 700 nm.

wavelength. Since the APD is not sensitive above 1650 nm, the 1866-nm probe is received using a 10-GHz strained-lattice InGaAs PIN photodetector, while the idler is received using the APD. A 10-GHz communications-signal-analyzer (CSA) is used to record the eye diagrams from the photodetectors output.

The recorded conversion spectrum (Fig. 6.4a) shows a conversion efficiency of -32 dB in this setup corresponding to an injected pump power of 19 dBm (7-dBm 1866-nm probe launched, -25-dBm 1321-nm idler generated). Open eye diagrams (Fig. 6.4b and 6.4c insets) are observed for both probe and idler and error-free operation is achieved for both. However, a direct power penalty characterization of this mode of operation is not achievable because of the APD upper cutoff wavelength (preventing detection of the probe) and the strained-lattice InGaAs PIN does not provide sufficient sensitivity.
to detect the idler at 1321 nm. Therefore, in order to characterize performance, a reference curve is derived from the averaged idler BER curves from section 5.6. As the conversion setup is fundamentally similar, the idlers for both conversions should roughly overlap. Once the 1321-nm BER measurements are calibrated to account for the APD wavelength-dependent sensitivity (directly measured using a dedicated O-band DFB and 10-Gb/s modulator), the 1320-nm wavelength-converted signal can be compared to this reference case (Fig. 6.4). The relative penalty of 0.4 dB shows this case is nearly equivalent in performance with the difference likely attributed to lack of filtering of the ASE from the TDFA.

Another FWM-based functionality of interest is the unicast in which the data imprinted on the pump signal is transferred to the idler (and to a lesser degree to the probe). In this case, a 700-nm spanning unicast is demonstrated to show the potential of this type of operation which has the benefit of also providing sensitivity gain through signal regeneration by ER doubling (153) as well as the filtering (through the FWM process) of ASE which does not satisfy the phase matching conditions required by the pump signal as much of the C-band ASE is detuned from the ZGVD wavelength. The experimental setup for this configuration (Fig. 6.3 b) includes modulation of the pump with on-off keying data and both pump (in a back-to-back case) and idler are
6.3. CONVERSION AND UNICAST OF 10-GB/S DATA FROM 1900 NM ACROSS 700 NM

Figure 6.4: (a) OSA trace recorded at the chips output showing wavelength conversion of a 1866-nm probe to a 1321-nm idler. T DFA noise artifacts are visible at 1450 nm, 1640 nm (not fully suppressed T DFA pump), and at the broad gain region around 1850 nm. (b) Probe BER curve recorded using an Extended-InGaAs photodetector (inset of eye diagram recorded on CSA). (c) Idler BER curve recorded on APD receiver (inset of eye diagram) and an average idlers BER curve based on curves recorded at 1585-nm to 1643-nm. The BER curve has 0.4 dB power penalty compared to the average idlers curve.

received by the APD-TIA. In this experiment the data originates in RZ format and is maintained as RZ on the idler.
6.3. CONVERSION AND UNICAST OF 10-GB/S DATA FROM 1900 NM ACROSS 700 NM

Figure 6.5: (a) OSA trace recorded at the chips output showing data unicast with a CW 1973-nm probe and a RZ 1271-nm idler. TDFA noise artifacts are now visible at 1640 nm (not fully suppressed TDFA pump), and at the broad gain region around 1850 nm. (b) BER curves recorded for the 10-Gb/s modulated pump before injection into the silicon chip, and the 10-Gb/s generated idler. Eye diagrams for all signals are included as insets.

The recorded conversion spectrum (Fig. 6.5a) at this setting shows similar conversion efficiency (-34.9 dB which includes 3-dB on-off modulation-related loss) compared
6.4. FIRST DEMONSTRATION OF 10-GB/S FOUR-WAVE MIXING LINKS AT 1884 NM

to the second experiment. Open eye diagrams (Fig. 6.5.b insets) as well as error-free operation are observed for both pump and idler RZ-data signals. The pump back-to-back eye diagrams and BER curves (Fig. 6.5.b) are recorded just before it is launched on the chip. After the chip the idlers BER curve is measured and observed to have a sensitivity gain of 1 dB. As before, the APD wavelength-dependent sensitivity is adjusted for using the computed correction factors (using the sensitivity measured at 1312 nm since the direct measurement sensitivity at 1271 nm was not available at the time). The majority of this sensitivity gain is likely due to the C-band ASE not being translated to the O-band efficiently.

6.4 First Demonstration of 10-Gb/s Four-Wave Mixing Links at 1884 nm

Based on the wavelength conversion and unicast functionalities demonstrated for large probe-idler separations in section 6.3, a more complex scheme for both generating and detecting the long wavelength high-speed signals can be attempted. The concept, shown in Fig. 6.6.a consists of a first stage which unicasts data from the C-band to the target wavelength, in this case 1884 nm, and then a second stage which wavelength
6.4. FIRST DEMONSTRATION OF 10-GB/S FOUR-WAVE MIXING LINKS AT 1884 NM

converts the data to a short wavelength for detection. By incorporating two stages for the data generation and detection, link operation at a long wavelength can theoretically be achieved without any wavelength-specialized equipment and any performance compromise. In practice, as the conversion efficiency of current silicon FWM chips is still relatively low, long-wavelength amplification is required to compensate for power losses through the setup.

Figure 6.6: (a) FWM-link concept illustration. Data is unicasted from the C-band to a longer wavelength band to generate long-wavelength high speed data in a wavelength-tunable way followed by a wavelength-conversion operation to transfer the data to a lower wavelength for detection. The second FWM stage can also incorporate optical sampling or regeneration. (b) Experimental setup of the double-stage FWM experiment. The first FWM chip performs a unicast from 1546.8 nm to 1884 nm. The second chip performs a wavelength conversion from 1884 nm to 1312 nm.

As shown earlier in Fig. 6.2, the conversion setup is widely tunable to produce
equal-efficiency conversion for all probe-idler separations spanning greater than 700 nm with the silicon waveguide (with ZGVD at 1546.5 nm), therefore allowing equal-performance tunable FWM link operation based on a single silicon waveguide at any wavelengths between 1700 nm and 2000 nm.

6.4.1 First Four-Wave Mixing Stage - Wavelength Unicast

The experimental setup (Fig. 6.6.b) included two cascaded FWM stages. The first stage was used to unicast a 10-Gb/s RZ signal from the C-band to much longer wavelengths. For this stage, a 15-dBm continuous wave (CW) probe was produced by a 1312-nm DFB laser which was amplified by a high power SOA and combined with a 10-Gb/s RZ pump using a band wavelength division multiplexer. The 17-dBm RZ pump (corresponding to 37.7-dBm peak power) was produced by a 1546.8-nm 10-GHz MLL with a 1.5-ps pulse width which was modulated by a Mach-Zehnder modulator (MZM) with a $2^{31} - 1$ PRBS from a PPG, and amplified by an EDFA. Both pump and probe were launched onto the first FWM chip to generate a 1884-nm idler. The recorded spectrum at the nanowaveguides output (Fig. 6.7.a) shows a -36.7-dB conversion efficiency (13 dBm probe injected at 1312nm, -36.7 dBm idler generated at 1884 nm). This conversion efficiency also encapsulates the 3-dB on-off modulation loss.
6.4. FIRST DEMONSTRATION OF 10-GB/S FOUR-WAVE MIXING LINKS AT 1884 NM

![Graphical representation of signal progression](image)

**Figure 6.7**: Signal progression along the experiments stages: (a) Spectrum at output of the first FWM chip with the 1312-nm CW probe, 1546.8-nm 10-Gb/s RZ pump, and generated 1884-nm 10-Gb/s RZ idler. (b) Spectrum recorded at the 1900-nm isolators output. Beyond the amplified 1884-nm RZ signal, noise features include not fully depleted L-band TDFA pumps, TDFA asynchronous spontaneous emission (ASE) background, and not fully suppressed CW signal at 1312 nm. (c) Spectrum at the output of the second FWM chip with the 1884-nm 10-Gb/s RZ signal as the probe, the 1546.8-nm 10-GHz pulsed pump, and the generated 1312-nm 10-Gb/s RZ signal.

as the idler is imprinted with the pump’s modulation. The generated 1884-nm signal then passed through a TDFA and a 1900-nm isolator providing amplification as well as
filtering away the pump and most of the 1312-nm probe (Fig. 6.7b). The eye diagram and BER curve of the signal at this point were recorded using an extended-InGaAs PIN-TIA photodetector. The same receiver was also used to record the back-to-back case defined as the MZM output in the C-band (prior to entering the EDFA). The photodetector sensitivity vs. wavelength is accounted for in this case based on a the photodetector’s responsivity and assuming a thermal-noise limited PIN receiver model in this case (which results in a worse-case power penalty estimate). Open eye-diagrams on both signals and was observed and a 0.4-dB power penalty was measured as a result of the process (Fig. 6.8a). As before, the FWM in the unicast configuration does not efficiently convert much of the C-band ASE to the long wavelength (while also providing some ER regeneration) therefore resulting in an overall low penalty.

6.4.2 Second Four-Wave Mixing Stage - Wavelength Conversion

For the second FWM stage the generated 1884-nm 10-Gb/s RZ signal was combined with a non-modulated 16.5-dBm pulsed pump (34.2-dBm peak power) and both are launched into the second FWM chip to generate a copy of the 10-Gb/s RZ data at 1312 nm. The timing of the pump with respect to the 1884-nm RZ signal was adjusted
6.4. FIRST DEMONSTRATION OF 10-GB/S FOUR-WAVE MIXING LINKS AT 1884 NM

with a variable optical delay (VOD) to yield the best temporal overlap. The second stage resulted in a conversion efficiency of -12.8 dB (-6.2-dBm probe injected at 1884 nm, -24.2-dBm idler generated at 1312 nm) (Fig. 6.7.c). The conversion efficiency is higher in this stage since both pump and probe are pulsed, temporally aligned, and equal in duration in this case. The 1312-nm RZ signal then went through a band

![Figure 6.8](image)

**Figure 6.8:** (a) BER curves and eye-diagrams recorded using the extended-InGaAs PIN-TIA receiver for the 1546.8-nm pump and 1884-nm idler generated by the first FWM stage. (b) BER curves recorded using the InGaAs APD-TIA receiver for the 1546.8-nm pump and 1312-nm idler generated by the second FWM stage. The eye-diagrams were recorded from the inverted-data differential output port of the APD-TIA.
6.5. FWM-BASED 40-GB/S DETECTION AT 1860 NM

splitter and VOA before being received by an avalanche photodiode (APD-TIA) for data validation. The back-to-back case for evaluating the overall performance was measured, as before, at the MZMs output before the first conversion stage (using the APD-TIA). The overall power penalty for both FWM operations was measured to be 2.1 dB (Fig. 6.8b), of which 0.4 dB was accounted for by the first FWM stage with its amplification and filtering, and 1.7 dB penalty from the second FWM stage which is mainly attributed to non-ideal suppression of the 1312-nm background signal and the non-filtered TDFA ASE (as seen in Fig. 6.7b).

6.5 FWM-Based 40-Gb/s Detection at 1860 nm

As the continuous phase matched wavelength band and the fundamental all-optical process should allow operation with signals with hundreds of GHz bandwidth, there is no prevention from extending the concept of FWM-assisted detection to data rates higher than 10 Gb/s. Furthermore, the FWM stage can provide beyond the wavelength-conversion functionality an additional temporal demultiplexing capability (177) to further assist detection of high-speed signals at the long wavelengths of interest. If the wavelength-conversion is implemented using a pulsed pump, this additional capability
6.5. FWM-BASED 40-GB/S DETECTION AT 1860 NM

Figure 6.9: (a) Experimental setup including a generation of a pulsed 10-GHz 1546.5 nm pump and a 40-Gb/s 1866-nm probe which are launched into a silicon waveguide to produce a 1321-nm 10-Gb/s idler (b) OSA trace recorded at the chips output showing the FWM result.

comes at no extra processing or complexity cost as the pulse repetition rate can simply be adjusted to the desired demultiplexed rate to address one tributary at a time (or all tributaries simultaneously with additional hardware and a higher complexity system (197)). In this demonstration, a 40-Gb/s FWM-assisted receiver is demonstrated which outperforms bandwidth wise any currently commercially available (to the best knowledge of the author) for operation at wavelengths above 1700 nm. Using the broad-continuous phase matching in silicon waveguides, this approach should be directly extendable to wavelengths up to 2400 nm (157) with no loss of processing bandwidth.

The experimental setup for this experiment (Fig. 6.9a) differs from the wavelength conversion setup in section 6.3 in that a 40-Gb/s PPG and modulator are used to
generate the modulated 1866-nm probe and that a variable optical delay (VOD) is implemented in the pump generation in order to enable adjusting the pump pulse-train timing relative to the probe modulation (which was previously adjusted electronically). The VOD is constructed on a motorized stage to allow software-controlled sweep of the relative pump-probe timing.

The spectrum at the output of the chip shows a -29.9-dB conversion efficiency (8-dBm launched 1866-nm probe, -21.9-dBm generated 1321-nm idler) (Fig. 6.9b), consistent with previous experiments for a launched 17.3-dBm MLL-produced (10-GHz repetition rate, 1.5-ps pulse width) pump. However, the wavelength conversion operation also encapsulates a 4:1 down-sampling operation, producing 10-Gb/s tributaries (at RZ format) of the original NRZ 40-Gb/s probe. In order to validate correct demultiplexing and conversion of the data, BER measurements (Fig. 6.10a) are taken and eye diagrams recorder (Fig. 6.10b) on the generated idler for all 4 10-Gb/s tributaries (generated one at a time, corresponding to 4 different VOD settings). The BER measurements show uniform performance. The sensitivity at a BER of $10^{-9}$ is measured to be -28.8 dBm (using the same wavelength-dependent sensitivity calibration as the reference) shows a 1.3-dB penalty compared to the 10-Gb/s wavelength conversion reported in section 6.3. This difference in performance is attributed to the
6.5. FWM-BASED 40-GB/S DETECTION AT 1860 NM

Figure 6.10: (a) BER measurements of the 10-Gb/s tributaries. (b) Idler eye diagrams recorded at the inverted-data differential output port of the APD. (c) 40-Gb/s Electrical eye diagram recorded directly from the PPG. (d) 40-Gb/s eye diagram reconstructed from the optical sampling process by sweeping the pump pulse timing (recorded at the APDs output).

lower extinction ratio achieved with the the 40-Gb/s modulator.

Alternatively, by sweeping the pump timing across more than a 100 ps range, recording the output electrical signals from the APD, and post-processing these results in software, it is possible to reconstruct the fully sampled 40-Gb/s eye diagram. The reconstructed eye-diagram (Fig. 6.10(d)) shows an open 40-Gb/s eye comparable to the recorded electrical eye recorded directly from the PPGs output (Fig. 6.10(c)), demonstrating the optical sampling functionality achievable with this setup. While optical sampling oscilloscopes (OSO) based on FWM in HNLF have been limited so far to telecom bands operation, this demonstration shows silicon’s potential to facilitate the
6.6 40-GB/S FOUR-WAVE MIXING LINK OPERATION AT 1882 NM

construction of ultra-high bit rate OTDM OSO in vastly longer wavelengths. With the advent of sub-ps thulium-based MLLs operating at the 2000-nm region \(^{(198)}\), OSOs based on silicon FWM can fill the need for temporal imaging of these signals.

6.6 40-Gb/s Four-Wave Mixing Link Operation at 1882 nm

Once 40-Gb/s FWM-based detection is established, it is possible to proceed to expand the FWM-link concept, established in section \(6.4\) to operate at 40 Gb/s or even at higher symbol rates. For this configuration of a FWM link, it is beneficial to use the second FWM stage to perform the temporal demultiplexing on top of the wavelength conversion to the shorter wavelengths. However, scaling to higher OTDM data rates does come at the expense of the conversion efficiencies for both stages. Given a fixed average power limitation injected into the waveguides, increasing the repetition rate lowers the peak power, resulting in a quadratically-related lower instantaneous conversion efficiency. The lower instantaneous conversion efficiency is somewhat balanced out by a larger temporal portion of the probe participating in the FWM process, resulting in a smaller overall hit to the conversion efficiency (in terms of average power ratios)
which is just linearly proportional to the pulse repetition rate. Furthermore, as the second FWM stage now also has the task of temporal sampling, a portion of conversion efficiency (average power) is lost in the second stage as only one tributary is sampled at a time.

The experimental setup to achieve 40-Gb/s long-wavelength link operation (Fig. 6.11), consisting of a 40-Gb/s unicast stage to 1882 nm and second 4:1 down-sampling and wavelength conversion (to 1312 nm) stage requires some alternations to the ex-

![Figure 6.11](image_url)

**Figure 6.11:** Experimental setup for FWM-link operation with two FWM stages enabling both generation and detection of 40-Gb/s RZ data at 1882 nm. Insets show DCA traces recorded at 20-ps/div resolution for the 40-Gb/s pulsed pump and 40-GHz pulse-carved probe injected into the first FWM chip.
Figure 6.12: Signal progression along the experiment’s stages: (a) Spectrum at output of the first chip with FWM-generated 1882-nm 40-Gb/s RZ idler. (b) Spectrum recorded at the long-wavelength isolators output. Beyond the amplified 1882-nm RZ signal, spectral features include TDFA ASE and traces of the L-band CW pump used to pump the TDFA. (c) Spectrum at the output of the second chip which generates the 1313-nm 10-Gb/s RZ signal tributaries.

For the first FWM stage the 1312-nm probe is now imprinted with a 40-GHz sinusoid to carve pulses. This guarantees a larger portion of
6.6. 40-GB/S FOUR-WAVE MIXING LINK OPERATION AT 1882 NM

Figure 6.13: (a) BER curve measurements recorded for a back-to-back (B2B) case on the 10-Gb/s RZ signal before the temporal multiplexing and amplification and the twice-converted and temporally-demultiplexed 10-Gb/s 1313-nm tributaries. (b) Eye-diagrams recorded out of the 10.7-GHz APD-TIA inverted-output data port for the back-to-back case as well as demultiplexed tributaries.

The probe’s average optical power is concentrated in the time slots corresponding to the 40-GHz repetition-rate pump pulses. The 40-Gb/s OTDM pulsed pump is generated from a MLL which is modulated at 10-Gb/s and then temporally interleaved to generate the 40-Gb/s 2^7 − 1 PRBS pattern. The result of the first FWM stage (Fig. 6.12a) shows a conversion efficiency of -35 dB (which includes the 3-dB loss due to the imprinting of the pump’s on-off modulation on the converted signal). Since there are no 40-GHz detectors available at the generated signal’s wavelength, the only way
to verify link operation is to convert the signal to the O-band for detection. Prior to that stage, two TDFAs are used to amplify 40-Gb/s 1882-nm signal sufficiently. The second stage then includes combining a 10-GHz pulsed C-band pump, derived from the same MLL, with the 1882-nm signal. The signal generated at 1313 nm through the FWM in the second waveguide (with -27.3-dB conversion efficiency) (Fig. 6.12c) is a 4:1 down-sampled version of the 40-Gb/s signal as the pump operated at the 10-Gb/s tributary rate. In order to sample all 4 tributaries of the signal the pump delay is adjusted manually. Open eye diagrams (Fig. 6.13b) and error-free operation are observed with uniform power penalties of 3.6 dB for all four 10-Gb/s tributaries (Fig. 6.13a). The 1.5-dB increase in penalty compared to the 10-Gb/s FWM link is attributed primarily to the addition of the second TDFA - which resulted in additional OSNR degradation. The OSNR degradation from the TDFA can be partially combated by incorporating an ASE-rejection bandpass filter either at 1900 nm or at O-band (which was not available at the time of the experiment).
6.7 Extension to MWIR Wavelengths

Two significant obstacles exist in trying to extend the conversion from MWIR wavelengths beyond 3000 nm to the telecom bands. The first obstacle is the material platform used as silicon di-oxide starts absorbing at wavelengths longer than 2700 nm. The second obstacle is that the continuous FWM bandwidth achievable is limited to \(~ 900 \text{ nm} \) \((157)\). In order to adapt silicon waveguides to bridge MWIR and telecom bands low-loss waveguides are required which can also provide phase-matching across broad wavelength ranges.

6.7.1 Materials for Low Loss Guiding

While crystalline silicon core waveguides based on thick BOX SOI with air or oxide cladding can provide sufficiently low losses to operate at up to perhaps 3000 nm, lower loss substrate and cladding materials are required for extending to longer wavelengths. Crystalline silicon on saphire (SOS) has been shown to be a leading candidate though saphire introduces difficulty in terms of the fabrication process because of the material toughness. An alternative is to use SiN in combination with either amorphous silicon or poly-silicon which can be deposited on top of the SiN. Hydrogenated amorphous silicon
6.7. EXTENSION TO MWIR WAVELENGTHS

in particular has shown some very promising capabilities for FWM (199, 200, 201) though exhibiting some optical degradation properties (200). Coupler design for signals very much separated must also be taken into consideration as even inverse tapers exhibit several dB coupling differences when detuned multiple hundreds of nanometers away from the nominal design wavelength of the taper.

6.7.2 Higher Order Dispersion Phase Matching

In order to achieve phase matching at wavelengths greatly separated from the pump wavelength, it is possible to utilize the phase-matched side lobes generated by the fourth-order dispersion as suggested previously (128) and also experimentally demonstrated (190). Furthermore, the location of these side-lobes can be tuned by adjusting the pump wavelength in a given waveguide. Therefore, for a desired idler wavelength, joint tuning of the pump and probe wavelengths. However, this comes at increased complexity compared to the fixed-wavelength pump enabled by the continuous phase matched waveguides. For a broadband sensor application, this requires prior knowledge of the signal’s wavelength - reducing usefulness.
6.7. EXTENSION TO MWIR WAVELENGTHS

Figure 6.14: SEM images of the different sections of width-modulated silicon waveguide (a)-(d) corresponding to the illustrated structure (e). Figure taken from [5].

6.7.3 Quasi Phase Matching in Silicon Waveguides

An alternated approach to phase match the nonlinear process is to use quasi-phase matching using either material or waveguide features. This approach, which had previously been implemented in periodically-poled lithium niobate (PPLN) devices [202], can provide for phase matching across potentially very large wavelength separations. One way to implement this method is with width-modulation of the silicon waveguide structure [5], which requires only a subtle periodic change of the waveguide width (30-nm sinusoidal-modulation amplitude over periods on the order of 1 mm - as shown in Fig. 6.14).

This approach was experimentally demonstrated to yield conversion efficiency enhancements (compared to a non-corrugated waveguide) in side-lobes extending well
6.7. EXTENSION TO MWIR WAVELENGTHS

**Figure 6.15:** (a) Experimentally measured conversion efficiency (defined here as ratio of output idler to output probe) for the width modulated waveguide (red dots) compared to a straight waveguide (triangles). A 22.4-dBm CW pump set at 1543 nm was used for these launched on the device for these measurements. (b) Conversion efficiency enhancement of 12 dB at 1668 nm measured from the difference in the curves in (a). Figure taken from (5).

Away from the pump wavelength on the order of 10 dB (Fig. 6.15). This approach presents an interesting alternative to the other dispersion-engineering approaches which are highly sensitive to the exact waveguide dimensions and accurate location of the pump at the ZGVD wavelength (or as required to tuned for higher order dispersion matching). Simulation results (5) predict applicability of this approach also to longer wavelengths than those shown experimentally.
6.8 Summary and Conclusions

This chapter presented contributions on developing FWM-based functionalities uniquely enabled on the silicon platform with dispersion engineering of the waveguide structures. The focus point of this effort was to extend previously developed data-processing operations in the telecom bands to operate at much longer wavelength bands approaching 2000 nm. The wavelength conversion and data unicasting functionalities were presented and investigated as separate operations for both 10 and 40 Gb/s data rates with low power penalties. The next stage was to combine both operations to enable a FWM-link concept which relies on both signal generation and detection using FWM stages. This enables establishing wavelength-flexible links at long SWIR and potentially mid-IR wavelengths based on the unique capabilities of the silicon platform for nonlinear processing. The demonstration of these capabilities culminated to a 40-Gb/s link operated at 1882 nm with overall uniform 3.6-dB power penalties for all four 10-Gb/s data tributaries.

Extension of these capabilities to longer wavelengths is possible either direct adaptation of these methods with longer-ZGVD waveguides or the adoption of different phase-matching mechanisms (whether separate fourth-order dispersion generated side
lobes or quasi-phase matched bands). However, performing data operations with such devices still requires improvements to insertion loss and conversion efficiency in order to enable recovering the data. The low conversion efficiencies are exacerbated for operation at wavelengths at which amplification is not available or where higher losses are encountered (for instance, free space propagation). The extension to pump wavelengths beyond 2200 nm however presents a path for improving the FOM achievable in silicon and provides the potential for realistic deployment of such devices for mid-IR operation, in particular on the detection side.
Summary and Conclusions

7.1 Summary of Contributions

This dissertation detailed several key contributions made by the author in the field of silicon photonics. These included characterization and analysis of resonator-based components for optical communications for either on- or off-chip interconnects as well as characterization and demonstration of parametric processing of data in silicon waveguides designed to enhance nonlinear interactions. For both linear and nonlinear applications of silicon photonics, data-quality evaluations were used whenever possible to quantitatively characterize device or process performance. Such characterizations provide figures of merit such as power penalty which can then be used for system-level
7.1. SUMMARY OF CONTRIBUTIONS

design and analysis, such as detailed in chapter 2 of this dissertation and are required for engineering of systems based on such building blocks. The following list reiterates some of the most notable technical achievements described in this dissertation:

- **Analysis of silicon photonic microring WDM links**
  - Integration of empiric and analytic models for single-device and WDM-array-level microring operation for to provide module level loss and penalty quantitative values as function of the wavelength-channel-spacing.
  - Introducing methodology for physical device parameter optimization of the wavelength demultiplexer based on worst-path analysis.
  - Determining upper aggregate bandwidth bounds per link based on power budget and nonlinear power limits of the platform.
  - Sensitivity analysis of achievable bandwidth to additional loss and penalty mechanisms.
  - Power efficiency analysis of the link as well as establishing aggregate bandwidth versus power efficiency trade-off stemming from the physical mechanisms unique to microrings.
7.1. SUMMARY OF CONTRIBUTIONS

- **First demonstration and performance characterization of on-chip microring-based on-chip spatial division multiplexing**
  - Characterization of inter-channel crosstalk in 3-mode SDM multiplexer and demultiplexer system.
  - Performance evaluation of single-wavelength 3-mode SDM system operation at 10-Gb/s per mode with error free transmission and low penalties on all ports, achieving 30 Gb/s aggregate transmission bandwidth on a single multimode waveguide.
  - Demonstration and characterization of WDM operation of microring-based SDM system with 3 concurrent 10-Gb/s wavelength-channels per mode over 2 spatial modes, achieving 60 Gb/s aggregate transmission bandwidth on the multimode waveguide.

- **FWM-based processing of high data rate OTDM signals in silicon waveguides**
  - First data-validated demonstration of wavelength conversion of 80- and 160-Gb/s OTDM streams in silicon waveguides.
7.1. SUMMARY OF CONTRIBUTIONS

– First demonstration of a 3-way wavelength multicast of a 320-Gb/s OTDM stream with qualitative data evaluation.

• Detuning agnostic FWM-based wavelength-conversion of data in silicon waveguide

– First demonstration and characterization of wavelength conversion of 40-Gb/s NRZ data spanning 50- to 100-nm probe-idler separations with uniform record performance.

– First demonstration and characterization of wavelength conversion combined with NRZ-to-RZ format conversion over 50- to 168-nm probe-idler separations with uniform performance

• Long-wavelength SWIR and MWIR optical processing based on silicon waveguides

– First demonstration of data-validated wavelength conversion and unicast operations on 10-Gb/s data with probe-idler separations up to 700 nm, and equivalent performance to telecom-band operation.
7.1. SUMMARY OF CONTRIBUTIONS

- First demonstration of double-FWM-stage link operating at 10-Gb/s at 1884 nm with data generation and detection using telecom-band components.

- First demonstration of a FWM-based 40-Gb/s receiver operating at 1866 nm leveraging a silicon waveguide for wavelength conversion and 4:1 down-sampling.

- First demonstration FWM-based 40-Gb/s link operation at 1882 nm with data generation and detection implemented with telecom-band components.

Additional technical contributions of the author pertaining to silicon photonics which deserve mention but were not detailed explicitly in this document include:

- First demonstration of error-free on-chip integrated microring link (modulator and detector) operating at 3-Gb/s [203].

- First demonstration and characterization of WDM transmission over a chip-scale low-loss silicon-nitride waveguide, with error free transmission of 1.28 Tb/s data [204].

- Initiation and technical assistance in the first microring-modulator intermodulation crosstalk quantitative evaluation [80].
7.2. CONCLUSIONS

- Initiation and technical assistance in the first characterization of the upper limit of the optical power modulated by a microring modulator (79).

7.2 Conclusions

Silicon photonics has made great strides in recent years towards becoming a commercially viable technology for datacom applications with the evolution of low-power low-footprint silicon modulators as well as high sensitivity CMOS-compatible photodetectors. Integrated microring WDM links shows that aggregate data rates greater than a terabit per second which could provide bandwidth densities much higher than those possible with electronic technology. However, key challenges remain packaging of silicon photonics as well as lowering the static power dissipation of the photonic links in order to allow reasonable power efficiency values even at non-constant utilization.

While spatial division multiplexing for on-chip applications, it is not clear whether they provide immediate performance gains for photonic networks on chip though the ability to manipulate spatial modes can be beneficial for future applications. Further research on multimode waveguide crossings as well as the ability to prevent mode coupling through waveguide bends is still required to make the on-chip spatial division
7.3. FUTURE WORK RECOMMENDATIONS

Dispersion engineering in silicon waveguides has shown potential for OTDM at data processing at record 1-Tbaud speeds. The instantaneous response of the parametric process combined with the small walk off over a cm-scale-long waveguide provide potential for even faster operation than can be demonstrated with current testbeds. The unique phase matching achievable with dispersion engineered waveguides, along with the lack of two-photon absorption which limits performance at telecom wavelengths, also make silicon an attractive platform for parametric processing in the MWIR with FWM pumping at \( \lambda_p > 2200\text{nm} \). As demonstrated in the detailed experiments, tunable-wavelength multi-Gb/s FWM-links could be operated in the MWIR for potential free-space communication applications.

7.3 Future Work Recommendations

While some capabilities for microring-based silicon photonic chip I/O and networks on chip have been demonstrated, substantial integration of multiple components has still to be explored. In view of the author’s research experience and the recent developments in the field, the following ideas are suggested for research:
7.3. FUTURE WORK RECOMMENDATIONS

- Rapid WDM link setup with multiple microrings on a single bus waveguide. While the locking of microrings to a given wavelength channel has been shown, the required link setup with multiple rings and wavelength channels still requires investigation.

- Exploration of predicted photonic chip I/O link power efficiency for realistic traffic patterns for chip to memory interconnects and architectural design solutions to the large static power dissipation of such links.

- Exploration of polarization diversity link architectures to enable reducing the amount of polarization maintaining fiber required for such links.

- Development of digital implementations of currently demonstrated analog thermal-feedback circuits for improved power efficiency in a digital CMOS platform.

- Exploration of channel spacing achievable with second-order ring switches and the ability to thermally fine tune and stabilize a higher-order microring switch in order to provide improved performance.

- Multiport photonic switch characterization with added emphasis on crosstalk and the resulting penalties in microring-based switch designs.
7.3. FUTURE WORK RECOMMENDATIONS

- Investigation of crosstalk in network on chip designs as well as better integration of penalty models in photonic network simulation tools such as developed in the Lightwave Research Lab.

On the topic of nonlinear silicon photonic waveguides, given improvements to packaging and low-loss coupling of fiber to silicon components at high power, the following directions could provide potential unique performance of this nonlinear platform:

- Integration of silicon FWM waveguides additional silicon photonic components to build higher-functionality on-chip optical processing modules (similar to that demonstrated in separate chips in (205)). Potential systems include:
  
  - OTDM demultiplexer based on a multicast operation with multiple short-duration probe-signals followed by integrated spectral filtering with an Echelle grating.
  
  - Chip integrated time-lens utilizing dispersive silicon photonic elements with a FWM waveguide to implement the time lens mechanism fully on a single chip (180).

- Extension of previous FWM efforts with 2000-nm ZGVD-wavelength waveguides to implement a $> 10Gb/s$ 2400-nm receiver.
7.4. FINAL REMARKS

• Extending same operation for longer-ZGVD-wavelength structures (157) to enable multi-Gb/s operation at wavelengths approaching 3 µm.

• Investigation of the ability to simultaneously wavelength-convert C-band ASE sources to 2400 nm as a simple alternative to supercontinuum generation at long wavelengths for absorption spectroscopy applications.

7.4 Final Remarks

While silicon photonic nonlinear processing platforms have yet to reach parametric gain competitive with that achievable in other nonlinear platforms, further work on minimizing coupling and propagation losses of dispersion engineered waveguides along with concurrent integration of carrier-extraction mechanisms holds the key for high performance silicon parametric processing platforms. For future all-optical processing systems to become a reality, extremely efficient parametric platforms will have to be developed which will be able to provide the processing capability without the need for multiple-Watts optical pumping. The unique processing capabilities in the silicon photonic platform is also a potential key for bridging performance gaps between the difference parts of the spectrum in the future. However, conversion efficiency im-
provements are still required to deliver mW power levels at the output of the silicon waveguides which could be made useful for MWIR applications.

In the more immediate future, it seems like silicon photonic communication modules are positioned best to provide commercially-viable solutions for off-chip communication bottlenecks. With the adoption of the technology by chip manufacturers such as Intel, hopefully silicon photonic will gain sufficient momentum to overcome problems which academia has yet to address fully such as packaging and system-level scalability. While monolithic integration faces many challenges, it is the elimination of intermediate electrical transmission lines between logic and photonic circuits that provides the greatest potential for performance gains, and seems like is the direction the field is heading towards in the long run.
References


REFERENCES


[43] M.R. Watts, W.A. Zortman, D.C. Troetter, R.W. Young, and A.L. Lentine. Low-Voltage, Compact, Depletion-
REFERENCES


[56] Xuezhe Zheng, Dinesh Patil, Jon Lexau, Frankie Liu, Guoliang Li, Hiren Tracker, Ying Luo, Ivan Shubin, Jieda Li, Jin Yao, Po Dong, Dazeng Feng, Mehdi Asghari, Thierry Pinguet, Attila Mekis, Philip Amberg, Michael Davringer, Jon Gaensley, Hesam Fathi Moghadam, Elad Alon, Kannan Raj, Ron Ho, John E. Cunningham, and Ashok V. Krishnamoorthy. Ultra-efficient 10Gb/s hybrid integrated silicon photonic


[69] D. Vantrease, R. Schneider, M. Monchiero, M. McLaren, N.P. Jouppi, M. Fiorentino, A. Davis, N. Binkert, R.G. Beausoleil,
REFERENCES


REFERENCES


REFERENCES


REFERENCES


REFERENCES


[146] Xin Gal, Duk-Yong Choi, S. Madden, D. Bolla, and B. Luther-Davies. Ge11.5As24Se64.5 chalcogenide glass nanowires with a nonlinear parameter of 136,000 W−1 km−1 at 1550 nm. In Optical Fibre Technology (ACOFT), 2010 35th Australian Conference on, pages 1–3, 2010.


REFERENCES


REFERENCES


REFERENCES


