Visible to near-infrared integrated photonics light projection systems

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Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy under the Executive Committee of the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2022
Abstract

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Silicon photonics is leading the advent of very-large-scale photonic integrated circuits (PICs) in which lasers, modulators, photodetectors, and multiplexers are integrated on a single chip and synchronized to enable faster data transfer both between and within highly integrated chips. Silicon photonics now extends beyond communication applications, paving new paths for many emerging applications and holding great potential in creating a compact beam projector.

Compact beam steering in the visible and near-infrared spectral range is required for emerging applications such as augmented reality (AR) and virtual reality (VR) displays, optical traps for quantum information processing, biosensing, light detection and ranging (LiDAR), and free-space optical communications (FSO). Here we discuss two novel integrated beam steering platforms in the visible and near-infrared wavelengths, optical phased array (OPA) and focal plane switch array (FPSA), that can shape and steer a light beam.

Previous OPA demonstrations have been mainly limited to the near-infrared spectral range due to the fabrication and material challenges imposed by the smaller wavelengths. Here we present the first active blue light phased array at the wavelength of 488 nm [1, 2], leveraging a high confinement silicon nitride (Si$_3$N$_4$) platform. We randomly and sparsely place the emitters to remove grating lobes, alleviate fabrication constraints at this short wavelength and achieve a wide-angle 1D beam steering over a 50° field of view (FoV) with a full width at half maximum (FWHM) beam size of 0.17°. This demonstration is a crucial first step in realizing a non-mechanical fully-integrated beam steering device for many emerging applications.

Unlike 1D steering OPA, designing 2D OPA impose a different challenge. Numerous issues arise, including complicated waveguide routing and optical crosstalk between channels. Also, creating a highly directional beam without ghost images is required to deploy visible OPAs in emerging applications. However, current demonstrations of visible OPAs, including our first demonstra-
tion, suffer from the issue of low directionality due to the presence of grating lobes, high background noise and a low percentage of power in the main beam. We demonstrate an integrated OPA that generates a highly directional beam at blue wavelengths (488 nm) by leveraging a disordered hyperuniform distribution of emitters. This exotic distribution is found in birds’ cone photoreceptor arrangements, the most uniform sampling given intrinsic packing constraints. Such unique distribution allows us to mitigate fabrication and waveguide routing constraints and achieve a beam with low background noise, high percentage of power and no grating lobes. Large-scale integration of the platform enables fully reconfigurable high-efficiency light projection across the entire visible spectrum. The novel platform offers a viable platform for next-generation applications in visible-spectrum addressing, imaging, and scanning displays.

Although OPA is an invaluable device for creating a highly directional beam on a chip-scale, OPA has an inherent power consumption issue. Its architecture requires simultaneous control of all the phase shifters in the system for operation. We propose a novel silicon photonics FPSA system for beam steering with orders of magnitude lower electrical power consumption than other state-of-the-art platforms. The demonstrated system operates in the near-infrared wavelength regime; however, this can be extended into different wavelengths. Our demonstration enables low-size, weight, and power (SWaP) LiDAR for precision and autonomous robotics and optical scanners for mobile devices.
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Acronyms

AF  array factor.
AMCW amplitude-modulated continuous wave.
AR  augmented reality.
CGH  computer-generated holography.
CMOS complementary metal-oxide-semiconductor.
CMP  chemical mechanical planarization.
DAC  digital-to-analog converter.
DMD  digital micromirror device.
DOE  diffractive optical element.
DUV  deep ultraviolet.
EF  element factor.
FDTD  finite-difference time-domain.
FFT  fast fourier transform.
FMCW  frequency-modulated continuous wave.
FoV  field of view.
FPGA  field-programmable gate array.
FPSA  focal plane switch array.
FSO  free-space optical communications.
FSR  free spectral range.
FWHM  full width at half maximum.
GA  genetic algorithm.
GVD  group velocity dispersion.

HOE  holographic optical element.

HPBW  half power beam width.

IC  integrated circuit.

ICP  inductively coupled plasma.

LCD  liquid crystal display.

LCoS  liquid crystal on silicon.

LiDAR  light detection and ranging.

LPCVD  low pressure chemical vapor deposition.

MEMs  micro-electromechanical systems.

MMI  multi-mode interferometer.

MOE  metasurface optical element.

MTF  modular transfer function.

MZI  Mach-Zehnder Interferometer.

OPA  optical phased array.

OTF  optical transfer function.

PCB  printed circuit board.

PDK  process design kit.

PECVD  plasma-enhanced chemical vapor deposition.

PIC  photonic integrated circuit.

PSLL  peak sidelobe level.

PSLR  peak to sidelobe ratio.

PSNR  peak signal-to-noise ratio.

RGB  red-green-blue.

RIE  reactive-ion etching.
SEM  scanning electron microscope.
SLD  superluminescent diode.
SLM  spatial light modulator.
SNR  signal to noise ratio.
SPAD single-photon avalanche diode.
SWaP size, weight, and power.
ToF  time-of-flight.
VCSEL vertical-cavity surface-emitting laser.
VR  virtual reality.
WDM wavelength division multiplexing.
Acknowledgments

This dissertation resulted from excellent teamwork, great mentorship, and great friendship. I want to thank everyone who helped me grow during my Ph.D. journey.

First and foremost, I would like to thank my great advisor Professor Michal Lipson. I initially started my Ph.D. in a different field. I could safely transition and become one of the photonics people only because she was my advisor. I would knock on her office door again and ask her if I could join her group if I went back six years from now. I am deeply indebted to her unconditional support and guidance throughout my Ph.D. journey. I admire her passion for research. It has deeply resonated with me and given me such a huge inspiration. I am very proud to be one of the Lipsonians. I will continue to pursue ‘garra’ as she said is my biggest virtue.

I am very honored to have world-class leaders in photonics as my committee members. I would like to thank my committee members, Professor Alexander Gaeta, Professor Keren Bergman, and Professor Nanfang Yu. I learned a lot about optics, from nonlinear to systems, from their courses. I would like to thank them for being my committee member and for their guidance and support on my dissertation. I would like to thank Professor Gaeta especially for accepting to serve on the committee on such short notice. I would like to thank Professor Yu for his guidance and feedback on numerous projects I worked on with him. His help and advice helped me grow my critical analytical skills in achieving this milestone. I would like to thank Dr. Zhimin Shi for being a committee member on my dissertation defense and for his helpful comments on complementing my dissertation manuscript. I look forward to working with him at Meta Reality Labs on many breakthrough projects.

I want to thank the funding sources and organizations that supported my research. I was supported by Meta Research Ph.D. Fellowship. This research was also funded by the Defense Advanced Research Projects Agency (DARPA) Extreme Optics and Imaging (EXTREME) (HR0011 10720034) and Modular Optical Aperture Building Blocks (MOABB) (HR0011-16-C-0107). I used the Cornell Nanofabrication Facility, the Columbia Nano Initiative, and the CUNY Advanced Science Research Center to fabricate my devices.
I want to thank all the past members of the group. I gained invaluable skillsets and learned a growth mindset from them, and I would not have survived without their help. I want to thank Professor Aseema Mohanty and Professor You-Chia Chang for being almost second academic advisors for my Ph.D. research. I am deeply indebted for all the things they taught me. I also want to thank Dr. Brian Lee and Dr. Euijae Shim for their constant encouragement so I could get up from many falls. I was genuinely grateful that I met them, became friends, and went through the Ph.D. journey together. I want to thank Dr. Steven Miller, Dr. Christopher Phare, and Dr. Utsav Dave, who taught me a great deal about testing, designing, and fabricating integrated photonics. I could become a better designer from their technical advice and insights. I also would like to thank Dr. Mohammad Amin Tadayon, Dr. Samantha Roberts, and Dr. Oscar Jimenez for their life advice when I was lost in direction and struggling. I want to thank Dr. Moshe Zadka for all the fabrication tricks he taught me. I want to thank Professor Avik Dutt, Professor Xingchen Ji, Dr. Brian Stern, Dr. Yair Antman, Dr. Ohad Westreich, Dr. Jakob Hinney, Dr. Kaiyuan Yao, Dr. Goran Kovacevic, and Dr. Alexandre Freitas. They have taught me a lot about photonics research. They have been great coworkers, collaborators, and also friends.

I want to thank all the current members of the group and their tremendous help. I want to thank Dr. Gaurang Bhatt and Dr. Ipshita Datta for always being there for support and for all the research and life advice they gave me. I will never forget the South Indian dinner we had on my last night in NYC. I want to thank Dr. Andres Gil-Molina, Mateus Corato-Zanarella, and Dr. Janderson Rodrigues for their continuous help on numerous projects I worked with. I learned so much from them as well as their passion and persistence. I want to thank Shriddha Chaitanya for all the little pranks so that research life wasn’t so dull. I want to thank Graydon Flatt and Karl McNulty for their help on my last projects. I want to thank Oliver Wang, Vivian Zhou, Jacob Solomon, and Aryeh Krischer. It was great to get to know the younger generations of the group. I have no doubt that they will continue to produce great works and continue the Lipson group’s legacy.

I also want to thank all my collaborators who helped me survive this journey. I want to thank Dr. Bok Young Kim for all his support and help inside and outside the lab so I could overcome the
hard times. I want to thank him for buying me drinks whenever I hit a wall. I want to thank Heqing Huang for his persistence in our collaborative projects and for teaching me analytical skills. I want to thank Dr. Anthony Rizzo for teaching me all the skills for taping out photonic chips. I want to thank Dr. Janet Kayfetz for being such an excellent writing teacher. I want to thank Tamar Sotnikov for all her support and dedication to our group so we could do research and worry about nothing else.

I would like to thank industry collaborators and mentors who enriched my life beyond academic research. I want to thank Kyle Watson at Trex Enterprises and Barry Silverstein, Dr. Giuseppe Calafiore, Dr. Risheng Cheng, Dr. Zhujun Shi, Dr. Steve Hickman, Dr. Rahul Agarwal, Peter Topalian from Meta Reality Labs. I am very much looking forward to returning to such an incredible team and am very excited to work with them again. I also want to thank my friends, Dr. Xi Wu and Dr. Alec Hammond, whom I met during my internship, for all the inspiration they gave me.

I want to thank KyoHyong Lee, Indian fam (Yeonchan Park, Sunmyoung Yoon, Kwang Sam Park, Junhong Choi, Thomas Woo), Cornellians (Sungjine Ihn, Alex Jintaek Hong, Minjung Suh, Sangwoo Kim, Ethan Sungmin Seo, Taesung Jung, Chris Minyoung Sohn, Pilgyu Francis Lee, Daniel Woo, Jungsoo Kim, Kyoungho Moon, Rebecca Sejung Park, Charles Jeon, Hansung Ko), 102 replacement depot troop members (Isaac Jaesung Lee, Sangjin Park, Chanhee Lee), Tritons (Jongha Jon Ryu, Jinho Young Lee, Moojin Chae, Woojin Choi, Joonseop Sim) and Columbians (Donggwon Kim, Yejun Kim, Jang Won Ko, Andy Chen Wang, Angela Soomin Ryu, Dongkwun Kim, Sunghae Yeo) for being there for me whenever I needed them.

Finally, I would like to thank my father and mother, Hyunjong Shin and Sunyoung Park, for their unconditional love and support, for always believing in me, and for everything they have done for me. I also want to thank my sister, Yuna Shin, and brother-in-law, Sean Kim, for their unconditional support. I would like to thank my grandmother, Hyun Kim, for all the wisdom and love she gave me.

I want to thank everyone I met and interacted with and who influenced me so I could be who I am today.
To my parents, Hyunjong Shin and Sunyoung Park, my sister, Yuna Shin, and my grandmother, Hyun Kim for their unconditional love and support.

Semper Eadem
Chapter 1: Introduction

Rapid growth in smart mobile devices and precision and autonomous robotics demand new sets of devices that can project, receive and measure light with great accuracy and precision. An ability to steer and reconfigure a beam of light that spans from the visible to near-infrared wavelength regime has paved a new path for a new range of applications such as next-generation displays, free-space optical communications, biosensing, coherent imaging, and quantum optics. However, the current systems that offer this functionality either require extremely high-speed electronic integrated circuit (IC) or table-top optics with mechanical moving parts that are large in size and power-hungry. An efficient alternative to these power-hungry and bulky table-top technologies is silicon photonics or photonic integrated circuit (PIC).

Silicon photonics or PIC is delivering a significant advancement in high bandwidth data transfer, being compatible with the existing complementary metal-oxide-semiconductor (CMOS) technology. Much early research in silicon photonics focused on developing and consolidating the critical building blocks such as modulators [3, 4, 5, 6], splitters [7], couplers [8, 9, 10], lasers [11, 12], and multiplexers [13], having the potential to reconfigure a large number of optical signals. With the advent and maturity of the technology and increasing demand to dramatically scale this platform for higher speed and capacity, these devices have extended to large-scale systems and at the same time, opened up new possibilities for more than optical interconnects. Silicon photonics or PIC shows great potential in reconfiguring, manipulating, and projecting light in a chip-scale low-power device. By utilizing this technology, a fully reconfigurable large-scale compact beam steering device is no longer a ludicrous idea and can potentially revolutionize especially the fields of augmented reality (AR)/virtual reality (VR) displays, light detection and ranging (LiDAR) and
free-space optical communications (FSO).

For example, in AR/VR displays, to project computer graphics to fit flawlessly in users’ environments and provide a fully immersive experience, it is critical to realize a near-eye display with adaptivity enabled by gaze-tracking. The realization of such a display requires a compact form of a display with dynamic pixel control and focus tunability and image sensors that can scan the surroundings and pupil of the user. Previous beam steering demonstrations for projector and optical sensor purposes used table-top devices such as liquid crystal displays (LCDs), liquid crystal on silicon (LCoS) spatial light modulators (SLMs), and digital micromirror devices (DMDs), which are bulky and have a limited field of view (FoV). Compact beam steering utilizing PIC is a disruptive technology that offers these functionalities on a chip-scale. In this dissertation, we present novel beam steering PIC devices that achieve reconfigurable chip-scale light projection across the entire visible and near-infrared spectral range.

This dissertation begins with a brief introduction (chapter 2) to beam steering using PIC and two beam steering integrated photonics platforms: optical phased array (OPA) and focal plane switch array (FPSA). The basics of the system architectures, operating principles, and figures of merit of the high-performance beam steering PIC systems are discussed.

In chapter 3, we present the first active blue light optical phased array (OPA) at the wavelength of 488 nm [1, 2], leveraging the Si$_3$N$_4$ platform. Chapter 4 extends the 1D blue light phased array demonstrated in chapter 3 to a two-dimensional (2D) design. We illustrate a practical design solution for achieving a highly directional beam with low background noise without grating lobes. Finally, in chapter 5, we propose a novel integrated focal plane switch array (FPSA) system for beam steering with orders of magnitude lower electrical power consumption than other state-of-the-art platforms [14, 15]. The demonstrated system operates in the near-IR wavelength regime; however, this can be extended into different wavelengths.

We include the discussion and future work for each system within its respective chapters. We conclude with a summary discussing more specific future system designs for the existing platform for higher performance. The works discussed in this dissertation have resulted in several publica-
tions, and some passages in this dissertation have been quoted verbatim from [1, 2].
Chapter 2: Technical background on integrated optical scanning platforms

Optical scanning must provide dynamical scanning of a single narrow and low-divergence beam over a wide angle. Such beam scanning/steering devices should meet low size, weight, and power (SWaP) to integrate seamlessly into applicable systems. The PIC platform offers this low-SWaP feature and can generate, shape, and reconfigure light. PIC technology is well suited for integrating many photonic components, which is a requirement for high-performance integrated optical scanners. The two most promising beam steering PIC technologies that can deliver this goal, as introduced in chapter 1, are OPA and FPSA. In chapter 2, we will introduce these optical technologies on how they work and their most important figures of merit.

2.1 Optical phased arrays (OPAs)

OPAs comprise many coherent emitters and phase shifters fed by a coherent laser source. Light emits from an array of coherent emitters and the emitted light constructively or destructively interferes in the near-field and Fresnel region by controlling the phase and amplitude of emitters. OPAs form a directional light beam in the radiating far-field (Fraunhofer region) following wavefront formation from the Huygens-Fresnel principle. Modifying the phase across the emitters tilts and focuses the beam arbitrarily like a reconfigurable lens. Arbitrary light patterns can be formed by controlling the phase of each emitter.
2.1.1 Radiation pattern of an element to an array

If we assume a coherent emitter is an isotropic radiator [Figure 2.1], we can define the radiating wave as

\[
E(r) \propto \iiint_V d\mathbf{r}' A(\mathbf{r}') e^{-jk|\mathbf{r} - \mathbf{r}'|} \frac{1}{4\pi |\mathbf{r} - \mathbf{r}'|}
\]  

(2.1)
We can approximate $|\mathbf{r} - \mathbf{r}'| \approx |\mathbf{r}| - \mathbf{r} \cdot \hat{\mathbf{r}}$ if we use the parallax method approximating for the far-field ($|\mathbf{r}| \gg |\mathbf{r}'|$). Then, Equation 2.1 becomes

$$E(\mathbf{r}) \propto \frac{1}{4\pi} \iiint_V d\mathbf{r}' A(\mathbf{r}') e^{-jkr} \approx \frac{1}{4\pi r} \iiint_V d\mathbf{r}' A(\mathbf{r}') e^{-jkr'} \hat{\mathbf{r}}$$

(2.2)

This far-field approximation is valid when $r \gg \pi \lambda r^2$. We can rewrite this condition as $r' < r_{max} \equiv W$ in terms of the antenna aperture with a radius $W$. This leads to

$$r \gg \frac{\pi}{\lambda} W^2 = r_R$$

(2.3)

where $r_R$ is the Rayleigh distance and $\lambda$ is the wavelength. In the near-field near the antenna aperture, we can approximate a beam from the antenna as a plane wave with wavefronts parallel to the aperture. Once we are far from the antenna aperture or in the radiating far-field zone (Fraunhofer zone), the wave behaves like a spherical wave and starts to diverge. The wave in the far-field zone radiates to infinity and the amplitude of the wave in the far-field zone decays by $1/r$. In between the near-field and Fraunhofer zone, there is the Fresnel zone where this transition takes place. The Rayleigh distance is the boundary where the Fraunhofer zone starts and the Fresnel zone ends. This Rayleigh distance increases for smaller $\lambda$ and beams at smaller wavelengths collimate for a longer distance before they begin to diverge, given the same aperture size. If we consider an acceptable phase error of around $\pi/8$ [16, 17], the Rayleigh distance can be rewritten as

$$r_R = \frac{2D^2}{\lambda}$$

(2.4)

where $D = 2W$ is the diameter of the antenna aperture. Larger the aperture, the longer the Rayleigh distance and the farther the Fraunhofer zone is.

If we have a linear array of the isotropic radiators defined in Equation 2.1, the radiation field in
the far-field becomes

\[
E(r) \propto \frac{e^{-jkr}}{4\pi r} \iiiint dr'[E_o \delta(y') + E_1 \delta(y' - d_1) + E_2 \delta(y' - d_2) + ... \\
+ E_{N-1} \delta(y' - d_{N-1})]\delta(y')\delta(z')e^{jk'r \cdot \hat{r}}
\]

Because the radiators are aligned on the y axis (r' = \hat{y}'), r' \cdot \hat{r} = y' \sin \phi. This leads to

\[
E(r) \propto \frac{e^{-jkr}}{4\pi r} \iiiint dr'[E_o \delta(y') + E_1 \delta(y' - d_1) + E_2 \delta(y' - d_2) + ... \\
+ E_{N-1} \delta(y' - d_{N-1})]\delta(y')\delta(z')e^{jk'y' \sin \phi}
\]

This equation is the well-known far-field radiation pattern of a phased array.

We can also formulate the far-field radiation pattern of a phased array by drawing the phase relation of each emitter in an array. In Figure 2.2, the phase of the m + 1\textsuperscript{th} antenna leads the m\textsuperscript{th} antenna by \(kdsin\theta\) because the optical path length is longer by \(dsin\theta\).

The formulation is the same as in Equation 2.5. We compute the radiation pattern of the antennae as a group by adding the radiation pattern of each antenna element. If we set one of the antenna elements as a reference, equate its phase to 0 (\(e^{j0} = 1\)), and assume a constant amplitude across the elements, the far-field radiation pattern becomes

\[
AF = 1 + e^{jkd_1 \sin \phi} + e^{jkd_2 \sin \phi} + ... e^{jkd_{N-1} \sin \phi}
= \sum_{m=0}^{N-1} e^{jkmd \sin \phi}
\]

where \(k = \frac{2\pi}{\lambda}\), \(m\) is the corresponding order of elements, \(N\) is the number of elements, \(\phi\) is the angle of the plane wave from the normal plane of the array, \(d_1, d_2, ..., d_{N-1}\) are the distances of emitters from the reference emitter and \(d\) is the constant pitch between emitters if an array is uniform. We
call Equation 2.7 an array factor (AF), representing the response of an array of isotropic elements.

\[ y = \sum_{n=1}^{N-1} d_n \sin \phi_n \]

**Figure 2.2.** Formulation of an array factor from an array of radiating elements. (a) The optical path length of the leftmost point source is \( kd_{N-1} \sin \phi_o \) longer than the rightmost point source when the steering angle is \( +\phi_o \). (b) A phased array steers at \( +\phi_o \) when there is an increasing phase slope of \( +\Delta \psi \) from left to right, assuming an equidistant uniform phased array with \( d \) pitch.
This formulation resembles a Fourier series with a set of sinusoids at a fundamental frequency of \( kdsin\phi \). The associated near-field pattern can thus be calculated by taking the inverse Fourier transform of the far-field pattern. Due to this Fourier relationship, the aperture size needs to be scaled up to achieve a narrow beam in the far-field and vice versa. This series of point emitters simplifies into the well-known sinc pattern observed in uniform phased arrays if the emitter pitch is kept constant inside the array. If each antenna is not an isotropic radiator, the total radiation pattern becomes an array factor multiplied by the field pattern produced by a single element, the element factor (EF). A constant phase profile is required to converge a beam while a slope of phase profile is needed to steer a beam. The steering angle due to the applied phases (multiples of \( \Delta\psi \)) on the emitters is governed by

\[
\phi_o = sin^{-1}\left(\frac{\lambda\Delta\psi}{2\pi d}\right)
\]  

(2.8)

To compute the phase required on each emitter to form a beam at a specific angle, we need to compute for \( \Delta\psi \) with given \( \phi_o \). If an array is not a uniform array, \( d \) and \( \Delta\psi \) are the distance and the phase difference from the reference emitter, respectively.

### 2.1.2 Field of view and resolution of OPAs

Figure 2.3 shows a radiation pattern of a phased array. The FoV of a uniform array [Figure 2.3] is given by

\[
\Delta\phi_{\text{FoV}} = \pm sin^{-1}\left(\frac{\lambda}{2d} \frac{N-1}{N}\right)
\]  

(2.9)

A \( \pm 90^\circ \) beam steering range is achieved with a half-wavelength (\( \lambda/2 \)) pitch and infinite number of elements (\( N \sim \infty \)).

The beam width [Figure 2.3] determines the angular resolution of phased arrays. The beam width of the main lobe at its half-power level is called half power beam width (HPBW) or 3dB beam width in RF/microwave community and full width at half maximum (FWHM) in the optics.
Figure 2.3. Numerical simulation of a uniform phased array radiation pattern. (a) An array of isotropic point sources with \(2\lambda\) pitch. (b) The simulated radiation pattern of the uniform phased array. Grating lobes are present due to the pitch that is larger than \(\lambda/2\). (c) The simulated radiation pattern when the main lobe is steered at \(+\Phi_{FoV}\) [Equation 2.9]. (d) The simulated radiation pattern when the main lobe is steered at \(-\Phi_{FoV}\).
An aperture size can replace \( N_d \) [Equation 2.10] if an array is nonuniform. The FWHM increases as the steering angle increases, and the resolution worsens as phased arrays steer.

We can extend the same analysis with 2D phased arrays.

**Figure 2.4.** Diagram of a 2D phased array. An \( M \times N \) 2D phased array with \( d_x \) and \( d_y \) pitch [Equation 2.11].

In a uniformly spaced 2D planar array [Figure 2.4], Equation 2.7 extends to,

\[
AF = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} e^{jk(nd_x \sin \theta \cos \phi + nd_y \sin \theta \sin \phi)}
\]  

(2.11)

with its FWHMs,

\[
\Delta \phi_{FWHM} = \sqrt{\frac{1}{\cos^2 \theta_o (\Delta \phi_{FWHM_x} \cos^2 \phi_o + \Delta \phi_{FWHM_y} \sin^2 \phi_o)}}
\]

\[
\Delta \psi_{FWHM} = \sqrt{\frac{1}{\Delta \phi_{FWHM_x} \sin^2 \phi_o + \Delta \phi_{FWHM_y} \cos^2 \phi_o}}
\]

(2.12)
where $\theta_o$ and $\phi_o$ are the polar and azimuthal steering angles on the spherical coordinate system, respectively. $\Delta \phi_{FWHM_x}$ and $\Delta \phi_{FWHM_y}$ are the FWHMs defined in Equation 2.10 for the lengths in x and y-dimensions when $\phi_o = 0$.

2.1.3  Phase coherence length

![Figure 2.5. A balanced Mach-Zehnder Interferometer (MZI). Input light is split into the top and bottom waveguide. Random phase errors, $\Delta \phi_1(L)$ and $\Delta \phi_2(L)$ [Equation 2.13] accumulate while light propagates on the top and bottom waveguide, respectively.](image)

For integrated OPAs, the optical phase coherence length is an important parameter that affects the beam quality. Random phase errors add to optical waveguides as effective indices are inconsistent due to thickness variations, waveguide width variations, and other fabrication imperfections.

\[
\Delta \phi_{phase}(L) = \frac{2\pi}{\lambda} \int_0^L \Delta n_{eff}(l) dl
\]  

(2.13)

We can quantify the random phase error in a waveguide with length $L$ [Equation 2.13]. Then, the variance of the random phase error becomes

\[
< \Delta \phi_{phase}(L)^2 > \equiv \frac{2L}{L_{coh}}
\]

(2.14)

\[
< e^{i\Delta \phi_{phase}(L)} > = e^{-<\Delta \phi_{phase}(L)^2>/2} = e^{-L/L_{coh}}
\]

The variance of the random phase accumulation [Equation 2.14] is characterized with the constant $L_{coh}$, the phase coherence length [18, 19, 20, 21]. This definition indicates that $L_{coh}$ is the length
of a balanced Mach-Zehnder Interferometer (MZI) [Figure 2.5] when the average output intensity is lower than the input intensity by a factor of \((1 + e^{-1})/2 \approx 0.6839\). The root mean square of the random phase error is \(\sqrt{2L/L_{coh}}\). When the length is \(L = L_{coh}/2\), the root mean square of the random phase error is approximately 60° [21]. The typical \(L_{coh}\) is 4-5 mm and 1-2 mm for single-mode strip waveguides and rib waveguides, respectively, on SOI wafers at \(\lambda = 1550\) nm [22]. We have experimentally deduced \(L_{coh}\) for \(\text{Si}_3\text{N}_4\) single-mode strip waveguides at \(\lambda = 488\) nm is \(\sim 500\) µm from our samples. We need more statistical samples and analysis to consolidate this result.

### 2.1.4 Recent demonstrations of OPAs

Phased array technology has been widely used in the RF/microwave community and is the core technology leading 5G innovation and beyond. This technology started to be utilized by the optics community as early as the 1970s [23]. Meyer demonstrated a 1D OPA using phase shifters based on bulk lithium tantalate in 1971 [24]. In 1973, Ninomiya presented a 1D OPA made of lithium niobate electro-optic prism deflectors [25]. Many other early works of OPAs were published in the 1990s, primarily leveraging liquid crystal technology [26, 27, 28, 29, 30]. Vasey et al. used an integrated aluminum gallium arsenide (AlGaAs) platform for demonstrating a 1D OPA [31] in 1993. In 1994, Tanone et al. showed beam steering of visible light using a liquid crystal television panel with polarizers removed as an OPA platform [27]. However, a several hundred \(\lambda\) pitch and the limited phase modulation restricted the steering angle to less than 0.1°.

Recently, OPAs have been demonstrated on integrated photonics platforms achieving significantly higher FoV and lower SWaP [21, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48]. A lot of these integrated OPAs have been demonstrated both in 1D [46] and 2D with tunable laser sources leveraging a dispersive nature of grating emitters [49] [Figure 2.6]. The polar (θ) steering angle on a grating emitter depends on the input laser wavelength, providing an additional degree of freedom for steering. However, many of these demonstrations have remained in the near-infrared regime due to the fabrication and material challenges imposed by the smaller wavelengths. Figure 2.6 shows examples of recently demonstrated OPAs on silicon photonics platforms.
Figure 2.6. Previous demonstrations of an OPA. (a) A 512-element active OPA using low-power phase shifters. Reprinted with permission from [49]. ©2020 Optica Publishing Group. (b) A λ/2-pitch OPA demonstrating close to 180° FoV. Reprinted with permission from [46].

2.2 Focal plane switch arrays (FPSAs)

Another promising PIC technology that can deliver this compact non-mechanical beam steering is an FPSA. FPSAs work in a much simpler method with smaller nodes to tune than OPAs. In
contrast to OPAs, in which many emitters emit simultaneously to form a beam, only a single emitter emits at a time in FPSAs. An integrated FPSA optical scanner consists of an imaging lens and an array of emitters on a PIC platform [Figure 2.7]. The optical switches on the chip direct light from the input laser to one of the emitters. The emitted light then goes through the imaging lens, which decides the emission angle depending on the emitter’s position with respect to the optic axis of the lens.

The PIC with an array of integrated optical antennae should be placed at the back focal plane of the imaging lens. FPSAs function similarly to cameras in which light at a certain angle within the FoV of an imaging lens maps to a specific pixel of an image sensor at the back focal plane of the lens. In contrast to cameras, we can achieve a coherent detection using FPSAs because FPSAs are laser-based. As only one pixel is illuminated at a time, the power consumption of FPSAs is far lower than OPAs.

2.2.1 Field of view and resolution of FPSAs

The optical paths from grating emitters are shown in Figure 2.7. The angular resolution of an FPSA system is determined by

$$\phi_{res} = \tan^{-1}\left(\frac{d}{f}\right)$$

(2.15)

where $f$ is the focal length of the lens and $d$ is the pitch between the emitters. The beam waist is given by $2f \cdot \tan(\phi_{div}/2)$ where $\phi_{div}$ is the divergence angle of the grating emitters. There is a gap in the beam scanning unless the beam spot diameter from the grating emitters and the pitch are the same as the grating size (fill factor~ 100%). An object to be scanned has to be placed away more than by

$$l = 2f \cdot \frac{\tan(\phi_{div}/2)}{\tan(\phi_{res})}$$

(2.16)

from the front focal plane of the imaging lens. This is the distance ($l$) in which the beam waists between the adjacent beams stop overlapping one another. The FoV of an FPSA system is determined
by

\[ \phi_{FoV} = \tan^{-1}\left(\frac{Nd}{f}\right) \]  

(2.17)

where \( N \) is the number of elements. The FoV is the difference in the angle of emission from the two outermost gratings. The imaging lens has to be sufficiently large such that it covers the divergent angle from the two outermost gratings to prevent vignetting.

### 2.2.2 Recent demonstrations of FPSAs

FPSAs are more nascent technology than OPAs. They have been recently demonstrated on integrated photonics platforms [14, 15, 50, 51, 52, 53]. One of the recent demonstrations used a metasurface lens for the imaging lens to decrease the overall system size [53, 54] [Figure 2.8].

**Figure 2.7.** Schematic of a 1D FPSA. (a) The angle between the light from the neighboring emitters decides \( \phi_{res} \) [Equation 2.15]. (b) The angle between the light from the outermost emitters determines \( \phi_{FoV} \) [Equation 2.17].
Similar to OPAs, many of these demonstrations have remained in the near-infrared regime due to the fabrication and material challenges imposed by the smaller wavelengths. Figure 2.8 shows an example of recently demonstrated FPSAs on silicon photonics platforms.

**Figure 2.8.** Previous demonstrations of an FPSA. A 4×4 FPSA with a metasurface lens on top. Reprinted with permission from [53]. ©2021 Optica Publishing Group.

### 2.3 OPA and FPSA comparison

Both platforms offer a high number of resolvable angles in their FoV to create a high-resolution point cloud. As illustrated in [53], the number of resolvable angles in OPAs is given by

\[
\frac{\Delta \phi_{FoV}}{\Delta \phi_{FWHM}} = \frac{2 \sin^{-1} \left( \frac{\lambda}{2d} \frac{N-1}{N} \right)}{\pi \frac{\lambda}{\sqrt{2} \sin \phi_o} \frac{d}{Nd}} \approx 1.13N \tag{2.18}
\]
to the first-order Taylor’s expansion, assuming $\Delta \phi_{FWHM}$ is constant along the FoV. The number of resolvable angles in FPSAs is the same as the number of emitters in the system. OPAs and FPSAs are both highly scalable on PIC technology; however, FPSAs have a similar number of resolvable angles to OPAs, with much smaller active photonic components to control.

One of the main applications for these platforms is LiDAR [55]. The laser beam scans the environment and measures the reflected light, creating a point cloud. One governing equation in radar or LiDAR applications is the Friiss transmission formula [56] [Equation 2.19],

$$P_r = P_t \frac{A_r A_t}{d^2 \lambda^2}$$  \hspace{1cm} (2.19)

where $P_r$ and $P_t$ are the received and transmitted power, $A_r$ and $A_t$ are the effective aperture area of the receiving and transmitting antenna, $d$ and $\lambda$ are the distance, and wavelength, respectively. The equation is reasonably accurate when negligible atmospheric absorption and unwanted reflections are observed [Figure 2.9]. One important thing to note in this equation is that we need a sizeable effective aperture for effective communication for LiDAR or FSO.

Although FPSAs have a much less number of active photonic structures than OPAs to tune at once, FPSAs systems can only handle significantly less transmitted and received power than OPAs. The large external lens compensates for the effective aperture in the Friis transmission formula [Equation 2.19]. However, the transmitted power is small because all the optical power is

![Figure 2.9. A simplified RF/FSO communication system. A transmitter and a receiver are separated by distance $d$. $P_t$ is the transmitted power and $P_r$ is the received power.](image-url)
guided in only one of the waveguides and emerges from a single grating emitter. If the material platform is silicon, the optical power in the waveguide has to be kept below \(\sim 100 \text{ mW}\) to keep the nonlinear loss and the free carrier absorption due to two-photon absorption below 3 dB/cm [57, 53]. In contrast, the optical power is split in \(N\) number of waveguides in OPAs. Hence, the long-haul FSO or LiDAR can be challenging to achieve using FPSAs. FPSAs are best suited for optical scanners or FSO devices in the next-generation mobile devices such as AR/VR displays or smartphones in which low-SWaP is a must and mid-range ranging or communication is sufficient.

In the subsequent chapters, we demonstrate the novel OPA platforms in the visible wavelength range that have not been demonstrated before and the novel FPSA platform that shows unprecedented SWaP.
Chapter 3: An integrated blue light phased array

Compact beam steering in the visible spectral range is required for a wide range of emerging applications, such as AR and VR displays, optical traps for quantum information processing, biological sensing, and stimulation. OPAs can shape and steer light to enable these applications with no moving parts on a compact chip. However, OPA demonstrations have been mainly limited to the near-infrared spectral range due to the fabrication and material challenges imposed by the shorter wavelengths. Here, we demonstrate the first chip-scale phased array operating at blue wavelengths (488 nm) using a high confinement Si$_3$N$_4$ platform. We use a sparse aperiodic emitter layout to mitigate fabrication constraints at this short wavelength and achieve wide-angle beam steering over a 50° FoV with a FWHM beam size of 0.17°. Large-scale integration of this platform paves the way for fully reconfigurable chip-scale 3D volumetric light projection across the entire visible range. The results described in this chapter have been published in [1, 2].

3.1 Introduction

There is a need to rapidly and precisely reconfigure visible light for many emerging applications, spanning holographic displays [58, 59, 60, 61, 62, 63, 64, 65, 66, 67], quantum information processing [68], and biological sensing and stimulation [69, 70, 71]. AR and VR displays and volumetric displays require 3D reconfigurable optical patterns of red, blue, and green light [58, 59, 60, 61, 62, 63, 64]. Quantum and biological applications also rely on resonances of molecules, atoms, and ions within the visible spectral range from 400 to 700 nm for micron-scale optical stimulation. These visible light applications are limited by bulky table-top devices. LCDs, LCoS SLMs, DMDs and acousto-optic deflectors are adopted for visible applications, but they are bulky and have a lim-
ited FoV due to their large pixel width [58, 59, 60, 61, 62, 63, 64]. An efficient alternative to these bulky table-top devices is the use of OPAs that enable arbitrary reconfiguration of 3D volumetric light patterns at a compact chip scale with no moving parts, functioning as reconfigurable lenses.

While recently demonstrated chip-scale OPAs enable high-resolution, wide-angle steering applications, chip-scale OPAs have relied on silicon (Si), limiting their operation to the near-infrared spectrum [21, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48]. OPA systems for visible wavelength range applications require photonic structures with a smaller pitch than the wavelengths, as well as control over a large number of active elements. Silicon photonics/PIC has met this demand of massive [32] and dense integration [46]; however, the bandgap of Si (~1 eV) still limits the operation of the system to greater than 1 µm wavelengths. Material platforms including Si$_3$N$_4$, titanium dioxide (TiO$_2$), aluminum nitride (AlN), and lithium niobate (LiNbO$_3$) are being actively explored to create photonic systems in the visible wavelength range [68, 69, 70, 71, 72, 73, 74, 75, 76]. Despite the recent progress, it remains a challenge to demonstrate large-scale PIC at shorter wavelengths [65, 66, 67].

### 3.2 New design for visible phased arrays

Here we demonstrate a chip-scale phased array operating at blue wavelengths ($\lambda = 488$ nm) by leveraging a high confinement Si$_3$N$_4$ waveguide platform [Figure 3.1]. Si$_3$N$_4$ has a wide transparency window starting at 400 nm, resulting in waveguide propagation losses down to 0.25 dB/cm at 650 nm [72] and 3 dB/cm at 473 nm [71]. A few Si$_3$N$_4$ phased arrays have been demonstrated but they have either been passive devices [65, 67], limited to small-scale systems [66], or outside the visible wavelength range [48]. We leverage our recent demonstration of a high confinement Si$_3$N$_4$ platform in the blue wavelength range to create a large-scale photonic system [71]. Microheaters fabricated above the silicon dioxide (SiO$_2$) cladding of the waveguides control the phases of the individual channels, serving as thermo-optic phase shifters. Because of the shorter wavelength and high confinement of the waveguides, the microheaters can be in close proximity to the waveguides without inducing loss from the metals. Our scheme achieves a time response of 20 µs
and a $P_\pi$ of $\sim 30$ mW [71], which are on the order of Si thermo-optic phase shifters in the near-IR despite the lower thermo-optic coefficient $\left(\frac{dn}{dT}\right)$ of Si$_3$N$_4$ ($\frac{dn_{Si}_3N_4}{dT} \sim 2.4 \times 10^{-5}$ RIU/K, $\frac{dn_{Si}}{dT} \sim 1.8 \times 10^{-4}$ RIU/K).

Figure 3.1. One-dimensional 64-channel blue phased array. (a) Schematic of a one-dimensional 64-channel blue phased array with sparse aperiodic emitter arrangement. Inset: 1-to-2 multimode interferometer (MMI) splitter tree. (b) Optical microscope image of a fabricated device with a splitter tree, thermo-optic phase shifters, and aluminum wires. Inset: blue light propagation through the splitter tree. (c) Optical image of the one-dimensional 64-channel blue phased array wire-bonded to a printed circuit board (PCB). The output edge emitters overhang the heatsink to ensure unobstructed convergence of the output beam. The red box indicates area shown in (b). (Reprinted with permission from [2]. ©2021 Optica Publishing Group.)
3.3 Design and fabrication of a blue light phased array

Using this platform, we design and fabricate a one-dimensional (1D) 64-channel blue phased array based on 200 nm thick Si₃N₄ [Figure 3.1(b)(c)]. To reduce propagation loss and phase error, the waveguides are widened to 1 µm in straight sections to minimize sidewall scattering. The width of the waveguides is reduced to 300 nm, equivalent to the width of single-mode waveguides, for the bends to prevent conversion to higher-order modes. We use a cascaded 1×2 MMI splitter tree to split the input light into each channel. The output of the MMI tree is sent to thermo-optic phase shifters that control the phases of each channel. The platinum microheaters of the phase shifters are 300 µm long, 600 nm wide and 100 nm thick with 1 kΩ resistance. They are deposited on top of the 660 nm plasma-enhanced chemical vapor deposition (PECVD) SiO₂ cladding [71]. We design the phase shifters to be 30 µm apart in the lateral direction to ensure minimal thermal crosstalk. The outputs of the phase shifters are routed to a sparse array of aperiodically spaced waveguides spanning 970 µm. The waveguide array terminates at the facet and emits light from the edge of the chip, in this way functioning as an array of edge emitters. This aperiodic 1D edge emitter array forms a converged beam along the azimuthal angle φ (phase-controlled direction) and a diverged beam along the polar angle θ [Figure 3.1b]. We mount the chip to a heat sink and wire bond it to a PCB connected to the digital to analog converters [Figure 3.1c].

Dense integration in the visible spectral range is challenging due to limitations imposed by fabrication constraints and optical crosstalk. The traditional phased array design is a periodic arrangement of emitters at a pitch (d) of a half-wavelength to eliminate the grating lobes that limit the FoV to \( \pm \sin^{-1}\left(\frac{d}{2L} \frac{N-1}{N}\right) \) [Equation 2.9]. However, this traditional design has three challenges in the optical domain. First, there is strong crosstalk by evanescent coupling between waveguides in close proximity [46]. Second, fabricating the small gaps between the emitters when the pitch is smaller than the wavelength is challenging at short wavelengths in the visible spectral range and especially at a large scale. At blue wavelengths, the half-wavelength pitch (= 244nm) is the width of a single-mode waveguide. Third, achieving a small beam divergence requires a large number of
phase shifters and emitters, dramatically increasing system complexity and power consumption.

To address these three challenges, we use a sparse spatial arrangement of emitters aperiodically positioned in multiples of $\lambda$ ($\lambda$-grid) to construct a low-divergence beam with grating lobes far away from the main beam. We iterate on the emitter arrangement until a uniform modular transfer function (MTF) is achieved, where the MTF is the amplitude of the optical transfer function (OTF),

![Figure 3.2.](attachment:fig32.png)

(a) Numerical simulation of radiation patterns for a sparse aperiodic phased array with an average spacing of 31.5$\lambda$ ($\sim$ 15.4 µm). No grating lobes are present within the FoV of 60°. The beam is steered at 0° (blue), 5° (orange), 10° (yellow), 15° (purple), 20° (green), 25° (cyan) within the FoV. (b) Numerical simulation of radiation patterns for a uniform phased array with 31.5$\lambda$ ($\sim$ 15.4 µm) pitch. Many closely spaced grating lobes are present (grey box). The white box indicates the FoV of 1.8°. The beam is steered at 0° (blue), 0.45° (orange), and 0.9° (yellow) within the FoV. Inset: radiation patterns for the uniform phased array across the range of (a). (Reprinted with permission from [2]. ©2021 Optica Publishing Group.)
fast fourier transform (FFT) of the system’s point spread function. This design ensures that our arrangement represents all spatial frequencies uniformly. The FoV and angles of grating lobes in our case are determined by the lowest common divisor of the emitter arrangement, grid spacing ($\lambda$) in this case. The designed aperiodic arrangement of 64 emitters in 970 $\mu$m size aperture has an average spacing of 31.5$\lambda$ and minimum spacing of 4$\lambda$, addressing the problem of crosstalk and resolving the gaps. Our emitter arrangement has a theoretical peak to sidelobe ratio (PSLR) of 9 dB, which corresponds to 2% power in the main beam [Figure 3.2a]. Using the sparse and aperiodic nature of emitters covering a large aperture, we only need 64 elements to achieve an FoV of 60° and a FWHM beam size of 0.026°. In contrast, using the traditional periodic $\lambda$-pitch design, we need 1920 elements to achieve the same FoV and FWHM beam size, 30 times more elements than in our phased array. A uniformly spaced OPA with our average spacing as a pitch would result in a radiation pattern with many closely spaced grating lobes leading to a small FoV of 1.8° [Figure 3.2b]. For a given number of elements in a sparse aperiodic array, there is a trade-off between the power in the main beam and FWHM with varying average pitch. The power in the main beam and FWHM both increase by decreasing the average pitch of the aperiodic phased array. With the 5$\lambda$ average pitch of 64 emitters, the performance can be improved to a PSLR of 12.5 dB with a FWHM of 0.16° and 11.5% power in the main beam. By utilizing sparsity and aperiodicity, we achieve a low-divergence beam over a wide FoV relaxing fabrication constraints and optical crosstalk at shorter wavelengths [33, 43, 44, 40].

3.4 Measurement and analysis of the blue light phased array

3.4.1 Beam steering

We achieve beam steering over a 50° FoV with a FWHM beam size of less than 0.17° [Figure 3.3b,c]. Images of converged beams reflecting off a piece of paper are shown in Figure 3.5a. The average PSLR of the beams at eight different angles is 6.05 dB. The measured PSLR is slightly less than the theoretical value of 9 dB due to the strong background light from the input fiber. The
output power of the beam is about 5 µW, approximately 30 cm away from the chip with an input power of 10 mW, which is a result of chip losses and fraction of power in the main beam.

**Figure 3.3.** Measurement setup and measured radiation patterns. (a) Measurement setup with a single-element photodiode on a rotation stage. The output beam is focused and far-field-like patterns attained in the Fresnel region at the aperture of the photodiode. (b) Measured optical power versus angle for converged beams at different angles in the phase-controlled direction, showing a 50° (±25°) FoV. (c) Magnified view of the converged beam at 0° with an FWHM beam size of 0.17°. (Reprinted with permission from [2]. ©2021 Optica Publishing Group.)
As opposed to long-range LiDAR, where power in the main beam is of critical importance due to losses incurred in the roundtrip received signal, many applications in the visible wavelength range such as AR headsets and optogenetics do not require high powers (< 300 nW [77, 78]) but require high-resolution light projection over a large FoV. The on-chip loss is a combination of about 5.5 dB loss for 1 cm of propagation length, 2.5 dB loss for cascaded MMI splitters (0.3 dB per MMI splitter), and 8 dB for insertion coupling loss. On average, the OPA consumes about 2 W of total electrical power to converge a beam with the current phase shifters. To measure the radiation patterns, we place a single-element photodiode on a mechanically rotating arm in the radiative near-field (Fresnel) region approximately 30 cm away from the chip [Figure 3.3a]. We attain far-field (Fraunhofer)-like patterns at the aperture of the photodiode by focusing the output beam [79, 80]. Our measurement setup avoids optical aberrations otherwise present in the wide FoV measurement with high numerical aperture Fourier lenses. We measure the radiation patterns of the phased array across an FoV along the azimuthal angle from -35° to 35° along the azimuthal angle[Figure 3.3a]. We use a genetic algorithm to converge beams at different angles by searching for the associated voltages at each phase shifter that maximize the output beam power [46]. The FWHM beam size is larger than the diffraction-limited beam size (0.027°) due to experimental limitations imposed by the larger aperture size of the photodiode and the angular resolution of the azimuthal rotation stage.

### 3.4.2 Image projection

To show the potential of this type of platform for image projection, we generate 2D images of letters [Figure 3.5b]. For steering along the azimuthal angle ($\phi$), we use four converged beams between -16° and -14°. For steering in the polar angle ($\theta$), we collimate the diverging light in the polar angle ($\theta$) with a cylindrical lens and use a mirror mounted on a rotation stage. We create the 2D images by summing frames from a video of the raster-scanned beams.
3.5 Conclusion

Our chip-scale phased array for blue light can be scaled up to a 2D architecture with compact grating emitters. By using the sparse aperiodic layout, we relax fabrication constraints and routing issues. The wide transparency window of Si$_3$N$_4$ makes it possible for this platform to be extended to other wavelengths, such as red and green, to create fully reconfigurable 3D volumetric light patterns covering all red-green-blue (RGB) colors. The propagation loss of the system can be improved by multipass and chemical mechanical planarization (CMP) techniques [81, 82]. Additionally, the PSLR of the phased array can be increased to 16-19 dB by running an optimization algorithm on the arrangement of emitters [44]. For AR head-mounted displays, PSLR of 17 dB and FoV 40-45° with FWHM beam size of 0.02° [83, 84] are desirable. With the recent demonstration of robust and ultra-low-power phase shifters in the visible [76, 81], this Si$_3$N$_4$ platform can be extended to large-scale systems with high directivity and high-efficiency beam formation.
Figure 3.5. Images of converged beams at several different angles. (a) Top view images of a sheet of light formed at different angles reflecting off of the reflective surface. The strong background is due to the scattered light from the input fiber. (b) Images produced by summing frames from raster-scanned videos of letters (“C O L U M B I A”) demonstrating the potential of the platform for image projection. Steering along the azimuthal angle ($\phi$) is achieved using phase shifters. The polar angle ($\theta$) is steered using a rotation stage. (Reprinted with permission from [2]. ©2021 Optica Publishing Group.)

3.6 Discussion

3.6.1 Percentage of power in the main beam

In this work, we optimized our array for a small FWHM over an FoV to maximize the number of addressable points for light projection. Smaller FWHM is preferred when high-resolution is required. As described in the main manuscript, visible applications such as AR headsets and optogenetics typically need less than 300 nW of optical power per point [77, 78].
Figure 3.6. Theoretical power in the main beam (%) and its FWHM (degree) with respect to the average array pitch in a 64-channel aperiodic phased array. Power in the main beam and FWHM both increase as the average pitch of a 64-channel aperiodic phased array decreases.

We have generated radiation patterns of 64-channel aperiodic OPA with a varying average pitch to demonstrate the trade-off between power in the main beam and its FWHM. The power in the main beam and FWHM both increase by decreasing the average pitch of the aperiodic phased array [Figure 3.6]. A uniform phased array with a pitch same as the average pitch of an aperiodic phased array has similar power in the main beam but a smaller field of view due to the grating lobes. This design trade-off should be considered for high performance depending on the specific application.

3.6.2 Optimized array design: optimization algorithm-based arrays and non-redundant arrays

Optimization algorithm-based array

As shown in Figure 3.6, the power in the main beam, thus background noise, improves as the average pitch becomes smaller. The demonstrated OPA in chapter 3 has a large aperture with only 64 elements and, as a result, has high background noise. If the small FWHM of the beam is not a strict requirement in designing an optical scanning system, we can implement an algorithm to develop optimized arrays with smaller average interelement spacing that achieve very low back-
ground noise without grating lobes. Here we show four simple methods to generate such OPAs. We first use a random method to generate a phased array design while enforcing a constraint on the minimum spacing. The antenna elements are placed randomly on a 1D space, and we iterate the design until the average background noise reaches below a threshold we set, which is 19 dB in this case. Figure 3.7d shows the radiation pattern from the resulting array.

We also apply the Constrained Optimization By Linear Approximation optimizer (COBYLA) in the SciPy library in Python, a genetic algorithm (GA), and Powell’s method to generate optimized arrays. We enforce the constraints of the minimum interelement spacing and the same aper-

![Figure 3.7](image_url)

**Figure 3.7.** Far-field radiation patterns of different optimization-based arrays. (a) The far-field radiation pattern of a 128-channel COBYLA-based array. (b) The far-field radiation pattern of a 128-channel GA-based array. (c) The far-field radiation pattern of a 128-channel Powell optimization-based array. (d) The far-field radiation pattern of a random array.
ture size to compare each algorithm’s performance accurately. Figure 3.7 shows the optimization algorithms’ resulting far-field patterns. The loss functions for the optimization algorithms were set to minimize the average background noise. All four methods generate similar results, around 19 dB of PSLR for the element count [Figure 3.7]. The computation speed to generate arrays using each method is not further studied here. When generating arrays with thousands of elements, one can choose the method that yields the lowest computation overhead since all the methods generate similar PSLR for a large number of elements.

Non-redundant array

We also study a non-optimization-based method and apply a ‘Golomb ruler’ concept from the mathematics field. A Golomb ruler is a set of integer positions on a ruler such that the distances between any two pairs are unique [85, 86, 87] [Figure 3.8]. A Golomb ruler is a 1D placement of positions, and a Costas array [88, 89] is an equal representation in the 2D space of a Golomb ruler. Only Golomb ruler-based arrays are studied here for an OPA design.

To form a sharp beam profile, the MTF of an array (the autocorrelation of the near-field pattern of an array) must be flat. Grating lobes disappear if one can design a sparse array with a uniform MTF. Also, to achieve the maximal spatial frequency component of the MTF, we need the MTF to be as broad as possible. To achieve a broad MTF, a near-field pattern of an array needs to be mutually different, have different spatial frequencies, and be distributed as uniformly as possible. A Golomb ruler achieves this feature and only fills each spatial frequency in the MTF domain with a single pair of antenna elements, thus spreading the MTF power uniformly, providing an excellent solution to form a sharp beam profile. However, even if the MTF is uniform at all non-zero spatial frequencies, there will always be a significant MTF component at zero spatial frequency, leading to a large uniform haze in a formed image [Figure 3.8].

A Golomb ruler has a unique feature of an inter-pair integer multiple distances to obtain minimum redundancy of the Fourier component sampling. Suppose we keep the same minimum interelement distance. In that case, this unique feature results in large average interelement spacings.
and aperture sizes of Golomb ruler-based arrays compared to the previous algorithm-based methods [Figure 3.8]. This trend is more evident as the number of elements increases in the arrays. Since Golomb ruler-based arrays have a larger aperture size compared to other types of arrays with the given number of elements, Golomb ruler-based arrays usually have more significant background noise for a large number of elements. Even for a small number of elements, we start seeing the trend. For example, a 26-channel Golomb ruler-based OPA at near-IR wavelengths has 9.93 dB

$$\text{minimum spacing} = \lambda$$

![Random array](image1)

![Golomb ruler-based array](image2)

**Figure 3.8.** Comparison of a Golomb ruler-based array and a random array with the same minimum interelement distance. (a) Comparison of 1D emitter placements of a 26-channel Golomb ruler-based array to a random array. Golomb ruler-based arrays are much larger than random arrays if the same minimum interelement distance is applied. (b) The far-field radiation pattern of the Golomb ruler-based array. The PSLR is 9.93 dB. (c) The far-field radiation pattern of the random array. The PSLR is 10.56 dB.
of PSLR compared to a random array’s 10.56 dB of PSLR [Figure 3.8]. The minimum distance of unit one in the Golomb ruler is set to \(1\lambda\) for low optical crosstalk [Figure 3.8]. Golomb ruler-based and algorithm-based arrays also show similar PSLR when there is a smaller number of elements in the same aperture size. However, Golomb ruler-based arrays perform better in forming an image than algorithm-based arrays. For 8-channel OPAs with the same size aperture, the image created

![Figure 3.9](image)

**Figure 3.9.** Comparison of a small-scale Golomb ruler-based and random array with the same aperture size. (a) 1D emitter placements of an 8-channel Golomb ruler-based and random array with the same aperture size. (b) The far-field radiation patterns of the Golomb ruler-based and random array. The EFs are dipoles. (c) Example scanned image patterns of the Golomb ruler-based and random array. (d) 1D line plots of the scanned examples in (c).
by a Golomb ruler-based array has a higher signal to noise ratio (SNR) than the image formed by a random array [Figure 3.9].

As the number of elements increases, the MTF or the autocorrelation function of random arrays averages out and fills the spatial frequencies in the MTF reasonably well. Thus, the performance of Golomb ruler-based arrays and random arrays for the same aperture size converge as the number of elements increases. Even though Golomb rulers are advantageous in designing OPAs with few elements, OPAs with few elements do not produce high-performance beams and often are not useful in many practical applications. In addition, considering the slow computation speed of designing Golomb ruler-based arrays, designing random or optimization-based arrays is a better choice for many elements. In most applications, many antenna elements are desired for OPAs to achieve a small FWHM with low PSLR.

In chapter 3, we only investigated designing a 1D OPA. Designing an OPA becomes even more challenging when developing an optimized design for a large 2D phased array. Routing waveguides to individual emitters without crossing other waveguides in 2D space is a complex problem [Figure 3.10]. Now, the design must incorporate enough routing spaces with random placements of emitters in 2D space. The challenges associated with the 2D design and the optimal solution to these challenges are addressed in chapter 4.

![Figure 3.10. Waveguide routing issues in nonuniform 1D and 2D OPAs. (a) Waveguide routing in a 1D OPA. (b) Waveguide routing in a 2D OPA. The waveguides start crossing other waveguides and grating emitters.](image-url)
3.7 Appendix

3.7.1 Fabrication of thermo-optic tunable Si$_3$N$_4$ photonic integrated circuit (PIC)

Figure 3.11. The fabrication process of a thermo-optic tunable Si$_3$N$_4$ PIC. (a) Design is patterned on top of 200 nm thick Si$_3$N$_4$ on a 4 µm buried oxide layer by electron-beam lithography (Elionix ELS-G100) with ma-N 2403 photoresist. (b) Waveguide structures are etched by inductively coupled plasma (ICP) using fluorine-based reactive-ion etching (RIE). Then, the patterned resist is removed. (c) The Si$_3$N$_4$ waveguides are cladded with 660 nm thick SiO$_2$ by PECVD. (d) Microheater wires are patterned using electron-beam lithography. 10 nm titanium (Ti) and 100nm platinum (Pt) are sputtered on top of the SiO$_2$ cladding and then lifted off. (e) Electrical routing wires and wire-bond pads are patterned using deep ultraviolet (DUV) lithography and a double-layer of Poly(methyl methacrylate) (PMMA). The oxide formed on top of the microheater wires during the fabrication process is removed by ion milling before the wire and pad metal deposition. 10 nm Ti and 800 nm Al are sputtered and lifted off.
Chapter 4: A disordered hyperuniform OPA

Creating a highly directional beam without ghost images is a requirement for deployment of visible OPAs in many emerging applications such as next-generation displays, optical traps for quantum simulation, and optogenetic neural probes. Current demonstrations of visible OPA suffer from the issue of low directionality\(^1\) because of the presence of grating lobes or high background noise and low percentage of power in the main beam. We resolve this issue with an integrated OPA consisting of a disordered hyperuniform distribution of emitters that generates a highly directional beam at blue wavelengths (488 nm). We place individual emitters in a two-dimensional (2D) layout with a disordered hyperuniform distribution to mitigate fabrication and waveguide routing constraints, and achieve a beam with low background noise and no grating lobes or ghost images. Large-scale integration based on this approach enables high-efficiency beam formation across the entire light spectrum and offers a viable platform for next-generation applications in visible-spectrum addressing, imaging, and scanning display.

4.1 Introduction

Building a 2D beam steering OPA with a highly directional beam is challenging at visible wavelengths. While traditional near-infrared (near-IR) phased arrays are able to steer in one of the two dimensions by utilizing diffraction gratings with a tunable input source [21, 33, 38, 43, 49, 90], visible light phased arrays cannot steer light beams using the same method. This limitation of

\(^1\)Directivity is a parameter of an antenna that measures how much the radiation is concentrated in a single direction. Directivity is defined as

\[
\frac{\int_0^{\pi} \int_0^{2\pi} U(\theta, \phi) \sin \theta \, d\theta \, d\phi}{\int_0^{\pi} \int_0^{2\pi} U(\theta, \phi) \, d\theta \, d\phi}
\]

where \(U(\theta, \phi)\) is the radiation intensity. Directivity remains constant for the phased arrays with the same aperture size and element counts since the value depends on the highest power in the radiation \((U(\theta, \phi))_{\text{max}}\). Here, we define a highly directional beam as the beam with high percentage of power concentrated in the main beam without grating lobes.
visible light phase arrays is due to the lack of wide availability of tunable narrow-band light sources in the visible spectrum. In addition, even a visible-spectrum tunable source is available, the tunable output color would be undesirable for most applications: displays need stable coloration, optical traps have to match with atomic or molecular transition frequencies, and fluorophores have to be excited with light at the peak of their excitation spectrum.

To resolve these challenges, an OPA with compact emitters in a 2D layout [32, 36, 40, 44, 66, 91] instead of an array composed of a long diffraction grating in a 1D layout [21, 33, 38, 43, 49, 90] is required. The new design must also address the problem that periodic integration of compact emitters in a 2D layout creates grating lobes resulting from large pitches between the emitters due to fabrication constraints and optical crosstalk among the channels [2, 66]. Random arrays [33, 40] and aperiodic arrays generated from optimized algorithms [2, 43, 44, 91] resolve these issues; however, they unevenly sample the 2D aperture with large minimum spacings between antenna elements that lead to high background noise in the radiation pattern and low power in the main beam. To form a directive emission with low background noise, we propose a novel approach that simultaneously samples the aperture more evenly and more aperiodically.

### 4.2 New design for highly directional OPAs without grating lobes

Our visible light phased array produces a highly directional beam without any grating lobes by leveraging a disordered hyperuniform distribution [92]. This structural pattern is also observed in nature, specifically in the photoreceptors of a bird’s retina [93, 94], which have been shown to possess a disordered hyperuniform distribution (Figure 4.1), an exotic pattern that suppresses long-range density fluctuations while maintaining local disorder. This irregular photoreceptor pattern observed in the bird retina achieves efficient packing without high-order diffraction peaks [93], a property equally desirable for an OPA. A disordered hyperuniform array recently demonstrated in the microwave regime with 16 antenna elements [95] shows promise; however, it is more suitable for shorter wavelength regimes where crosstalk is more severe and λ/2 pitch between antenna elements is impossible to achieve. For an OPA for visible wavelengths, the distance between
Figure 4.1. OPA leveraging a disordered hyperuniform pattern found in the photoreceptor pattern of a bird’s retina. This exotic type of pattern is known to suppress long-range density fluctuations while maintaining local disorder. This irregular pattern achieves efficient packing without high-order diffraction peaks.

antenna elements needed for waveguide routing with minimal optical crosstalk is much larger relative to wavelength compared to that of near-IR or microwave wavelengths. Therefore, the design for an OPA must consider the space required for waveguide routing. Our design satisfies this requirement by maintaining enough interelement distances, and offers enough disorder locally to remove grating lobes, and enough uniformity globally to achieve low background noise.

The structure of a 2D array layout can be characterized by its radial distribution function, \( g(r) \), and its structure factor, \( S(k) \). The structure factor of a 2D disordered hyperuniform array satisfies vanishing values for all \( k \) points inside a disk region with finite radius (also called “stealthy disordered hyperuniform” [94]) where \( S(k)=0 \) for \( |k|<K \), with no other peaks elsewhere [96]. We compare the structure factor of a 2D disordered hyperuniform array with a uniform array of a square lattice, and a constrained random array, each with \( N=400 \) points (Figure 4.2). We generate the constrained random array (Figure 4.2c) by randomly placing each point in a square region with a size of \( L/2\sqrt{N} \), centered in a square lattice, so that the minimum distance between neighboring
points is constrained to be larger than $L/2\sqrt{N}$. We create constrained random arrays for comparison to hyperuniform arrays instead of completely random arrays. This constrained random design mitigates the problem found in completely random arrays where no constraint on the minimum adjacent distance is applied, causing problems with waveguide routing and resulting in systems

![Figure 4.2. Layout, radial distribution function and structure factor comparisons of hyperuniform, uniform and constrained random patterns. a-d: Real-space layout of (a) a disordered hyperuniform pattern, (b) a uniform pattern, (c) a constrained random. Each pattern contains $N=400$ points. d-f: Radial distribution functions of the point patterns in a-d. g-i: Structure factors of the point patterns in (a-d).]
unsuitable for experimental demonstrations. The constrained random arrays in our comparison also keep the average noise floor lower by mitigating the issue of a small number of elements filling a large aperture, which is associated with completely random arrays if we impose the minimum adjacent distance constraint.

For a uniform array (Figure 4.2b,f), perfect orders in both short-range and long-range give rise to evenly spanned Bragg peaks in its structure factor (Figure 4.2j). For a constrained random array, the perfect real-space orders are broadened (Figure 4.2g), which leads to descending intensity in its high-order diffraction peaks (Figure 4.2k). In comparison, a disordered hyperuniform array (Figure 4.2a) shows no visible order in its radial distribution function other than the peak for the nearest-neighboring distance (Figure 4.2e). Still, it possesses a hidden long-range order such that its structure factor is zero in a finite region around $k=0$ (Figure 4.2i), which is ideally suitable for radiation in only the main lobe, with no high-order diffraction peaks.

We achieve a higher percentage of power in the main beam with a lower PSLL simultaneously from a disordered hyperuniform phased array compared to other types of phased arrays. We compare the power in the main beam ($\%$) and the PSLL (dB) of the hyperuniform arrays to uniform arrays, constrained random arrays, and non-redundant arrays [97]. The PSLL is the second highest

![Figure 4.3](image_url)

**Figure 4.3.** Numerical simulation characterizing radiation properties of several distinct OPAs. (a) Percentage of power in the main beam and (b) Peak sidelobe level (PSLL) of different array types as a function of the number of emitting elements.
power level after the main lobe. We keep the same minimum nearest-neighboring interelement 
distance in the four different arrays at $15\lambda$, a reasonable number for a fabricatable design (Figure 4.3). We create constrained random arrays for comparison to hyperuniform arrays instead of completely random arrays. This constrained random design mitigates the problem found in completely random arrays where no constraint on the minimum adjacent distance is applied, causing problems with waveguide routing and resulting in systems unsuitable for experimental demonstrations. The constrained random arrays in our comparison also keep the average noise floor lower by mitigating the issue of a small number of elements filling a large aperture, which is associated with completely random arrays if we impose the minimum adjacent distance constraint. In contrast, non-redundant arrays [2, 91] have a small number of elements filling a large aperture due to the minimum adjacent distance constraint. Due to its large average adjacent distance and greatest common divisor ($= 15\lambda$) of array placements, the broad and flat array feature of the non-redundant arrays does not achieve side-lobe free beam steering. The aperture size for the uniform arrays, constrained random arrays, non-redundant arrays, and disordered hyperuniform arrays are identical, but the non-redundant arrays are $\sim 22.5$ times larger. The angular radiation distribution of each emitter (element factor) is taken as a dipole for the simplicity of analysis.

With the highest percentage of power at the main beam and the lowest PSLL, the scaling behaviors of the radiation properties show a clear advantage for the disordered hyperuniform array over the other three types as the number of elements increases. Specifically, for the number of elements increasing up to 484, the power in the main beam of the disordered hyperuniform array continuously increases to $\sim 50\%$, and rapid decays in its PSLL stabilize at -13 dB (Figure 4.3). For the constrained random array, the power in the main beam rises to the same percentage but the PSLL stabilizes at -3 dB. For the uniform array, the power in the main beam is also the same but the main beam power is similar to the power in its side lobes, resulting in a 0 dB PSLL. For the non-redundant array, the power in the main beam is only $\sim 5.6\%$ and the PSLL results in 0 dB due to its large adjacent distance. We also compare the radiation patterns of 256-channel OPA of the two array types that has the same aperture size, the uniform array and the constrained random array
Figure 4.4. Numerical simulation of different 256-channel phased array radiation patterns. a-c: Near-field/real space layout with an average spacing of 15\(\lambda\) (\(\lambda=488\) nm) of (a) a disordered hyperuniform array, (b) a uniform array, (c) a constrained random array. d-f: Far-field radiation patterns over the polar angle (\(\theta\)) of (d) the disordered hyperuniform array, (e) the uniform array, and (f) the constrained random array. g-i: The same radiation patterns are plotted in dB-scale for (g) the disordered hyperuniform array, (h) the uniform array, and (i) the constrained random array. Far-field radiation patterns are limited to an angular range of 0 to 10 degrees for clearer visualization of the beams. No grating lobes are present for the disordered hyperuniform array. Many closely spaced grating lobes are present for the uniform and constrained random array. j-l: Far-field radiation patterns over the full 180° of (j) the disordered hyperuniform array, (k) the uniform array, and (l) the constrained random array. m-o: The same radiation patterns are plotted in dB-scale for (m) the disordered hyperuniform array, (n) the uniform array, and (o) the constrained random array.
We observe that the radiation patterns from a hyperuniform array show a clear single converged beam without grating lobes, unlike those from a uniform array and constrained random array. This finding is consistent with its structure factor $S(k)$, which characterizes the diffraction property and shows no other peaks elsewhere.

4.3 Design of a disordered hyperuniform OPA

4.3.1 A disordered hyperuniform layout

Here, we describe our design of a 2D 32-channel hyperuniform blue phased array ($\lambda$=488 nm) with the compact emitters positioned in a disordered hyperuniform layout, ensuring phase matching at each emitter of the 2D array (Figure 4.5). We scaled down the size to 32-channels to keep the entire device within the phase coherence length [18, 19, 20, 21] of the Si$_3$N$_4$ waveguide at $\lambda$=488 nm. The average spacing between the emitters is kept at $\sim 15\lambda$ for ease of routing. The emission of individual emitters of the hyperuniform array is centered at 10 degrees along the polar angle, $\theta$ (emitting at a non-normal angle for maximum efficiency without back-reflection). The emitters are 3.197 $\mu$m in length and 1.235 $\mu$m in width, comprising eight grating periods. Since the path lengths to individual emitters on the hyperuniform array are different, the path matching section readjusts the phase at each individual channel based on its phase profile. The path-matching section comprises multi-clothoid bends [98] and a section with straight waveguides (Figure 4.5). The latter adds extra lengths to accurately adjust the phase and phase delay at each of the channels. We use a multi-clothoid bend to keep the device footprint compact, so that the whole device falls within the phase coherence length of the platform without adding serious phase error. We design the multi-clothoid bends to be low loss. The whole size of the single-multi-clothoid bend is kept around 72 $\mu$m$^2$, and the insertion loss is only 0.03 dB at $\lambda$=488 nm (Figure 4.5). The far-field radiation pattern of a phased array is the radiation pattern of the antenna element multiplied by that of an array factor. Since the emission of individual antenna elements is centered at 10 degrees from the surface normal our array factor is designed to form a converged beam at the same angle.
Figure 4.5. Phase profile and path-matching section of a 32-channel disordered hyperuniform blue phased array. (a) Simulated near-field pattern of the 32-channel hyperuniform blue phased array. (b) Phase profile required at each emitter to emit the beam at 10° on the polar angle. (c) Diagram of the path matching + phase delay section to path match and match the phase profile at each emitter. The section comprises a straight section that accounts for path matching and phase delay with two multi-clothoid bends [98]. The multi-clothoid bends are used to minimize the footprint of the section. (d) Finite-difference time-domain (FDTD) simulation of the multi-clothoid bend at $\lambda = 488$ nm. (e) Insertion loss of the single multi-clothoid bend near $\lambda = 488$ nm.
Specifically, the section with straight waveguides in the path-matching section introduces phase delays, allowing the array factor to form a coherent converged beam at the angle.

We simulate the near-field and far-field patterns of a 32-channel hyperuniform blue phased array at $\lambda=488$ nm (Figure 4.6). The simulations cover the $\pm 20^\circ$ span (Figure 4.6bc), and the whole $180^\circ$ span (Figure 4.6de). The ticks in the axes in Figure 4.6bc and de indicate $5^\circ$ and $20^\circ$, respectively. The radiation pattern of each emitter (element factor) is taken as a dipole for the simplicity of analysis. The average interelement spacing is around $15\lambda$ at $\lambda=488$ nm. The beam converges at $10^\circ$ on $\theta$. The background is lower near the main lobe and higher on the outer ends.

**Figure 4.6.** Numerical simulation of a 32-channel hyperuniform blue phased array. (a) Simulated near-field pattern of the 32-channel hyperuniform OPA at $\lambda=488$ nm. The average spacing is kept $15\lambda$ ($\lambda=488$ nm). (b,c) Simulated far-field radiation patterns of the phased array steered at $10^\circ$ on the polar angle ($\theta$) in linear-scale and dB-scale, respectively. The radiation patterns are plotted up to $\pm 20^\circ$ on $\theta$. (d,e) The same far-field radiation patterns plotted over the whole $180^\circ$ span.
4.3.2 Compact emitters

![Diagram of the Emitter](image)

**Figure 4.7.** Numerical simulation of a compact emitter in a 32-channel hyperuniform blue phased array. (a) Diagram of the compact emitter. The pitch is kept at 335 nm to emit at 10° on the polar angle (θ) at λ=488 nm. The duty cycle of the design is 0.55. The size of the compact emitter is kept long so that the remaining light that did not emit will be small and not cause interference patterns. (b) Far-field radiation pattern of the compact emitter. The upward efficiency is 37.6%. The emitter emits at 10° on θ.

We design a compact emitter as an antenna element of the 32-channel hyperuniform blue phased array. The emitter emits at 10° on θ to maximize the emission efficiency with low backward reflection (Figure 4.7). The upward emission efficiency is calculated to be 37.6%. The pitch is kept at 335 nm for 10° θ emission with a duty-cycle of 0.55. We design the emitter to be longer than typical compact emitters to minimize the remaining light from emission to prevent interfering with the upward emissions from different emitters. We can deposit thin overlays of other higher-index materials to enhance the wider radiation angle. A higher refractive index material is preferred for the gratings of the compact emitter for wider angle emission with shorter emitter length.

4.3.3 Input grating coupler

We design an input grating coupler for low insertion loss in the visible wavelengths. Inverse taper couplers are challenging to fabricate in visible wavelengths since the width of the tapered tip reaches ~50 nm for maximum coupling. Such narrow tips are hard to resolve and are low-yield.
In addition, a slight fabrication variation at this scale induces a significant difference in coupling efficiency. We design a fully-etched input grating coupler to mitigate these issues. Partially etched grating couplers can also be designed for higher upward emission and higher coupling efficiency. The thickness of the buried oxide layer is one of the critical parameters in determining the coupling efficiency Figure 4.8. We optimize the buried oxide thickness to be 1 µm for maximum efficiency.

**Figure 4.8.** Numerical simulation of an input grating coupler at $\lambda = 488$ nm. FDTD simulation is shown on the left with insertion loss of 3.84 dB. Pitch and duty-cycle (DC) are 380 nm and 0.4, respectively. The optimal BOX thickness is 1 µm.

### 4.4 Fabrication of the disordered hyperuniform OPA

We fabricate the 2D hyperuniform blue phased array using a high-confinement silicon nitride platform in the blue wavelength range (Figure 4.9). 175 nm of low pressure chemical vapor deposition (LPCVD) Si$_3$N$_4$ is deposited on 1 µm of thermal silicon dioxide. We pattern the waveguides using electron beam lithography and a fluorine-based etch. We use wide waveguides (800 nm wide) in straight sections to reduce phase error and propagation loss of individual channels. We reduce the width of the waveguides to 350 nm for the bends to prevent conversion of the fundamental waveguide mode to higher-order modes. 660 nm of LPCVD SiO$_2$ cladding is deposited on top of the waveguides. Our design comprises four sections: 1) input coupler, 2) 1×2 MMI splitter tree, 3) path matching and phase delay section, and 4) hyperuniform array. After the input coupler, the 1×2 MMI tree splits the input light into each channel (Figure 4.9). The outputs of the MMI splitter tree are connected to the path-matching section and routed to the emitters of the hyperuniform array.
Figure 4.9. Two-dimensional 32-channel hyperuniform blue phased array. (a) Schematic of the two-dimensional 32-channel hyperuniform blue phased array with a path matching + phase delay section. Inset: Path matching + phase delay section. It comprises a section with straight waveguides and multi-clothoid bends [98]. (b) Optical microscope image of a fabricated device with (c) a hyperuniform array, (d) a splitter tree, and (e) a path matching + phase delay section.

4.5 Measurement and analysis of the disordered hyperuniform OPA

4.5.1 Beam convergence

Our 2D hyperuniform blue phased array produces a highly directional output beam of an FWHM of $0.854^\circ \times 0.689^\circ$ with 16.5% power in the main beam. The measured beam divergence
angles are very close to our simulation of the ideal highly directional beam. The measured power ratio is slightly lower but comparable to the simulated power of 21.6% in the main beam. The percentage of power is calculated using the output power in the main beam, the total chip loss, and the input power (The percentage of power = Output power in the main beam / (Input power * Total chip loss)*100 [%]). A high percentage of power is concentrated in the main beam with

![Simulated and Measured Radiation Patterns](image)

**Figure 4.10.** Simulated and measured radiation patterns of a 32-channel disordered hyperuniform blue light phased array. (a,b) Simulated near-field and far-field patterns of a 32-channel hyperuniform phased array. The beam is projected at 10 degrees on θ. (b,d) Measured near-field and far-field patterns of the fabricated device. (e) Images created by raster-scanning the highly directional beam formed by the device using a 2D galvo mirror (logos of Lipson Nanophotonics Group (Lng) and of Columbia Engineering). Right: Schematic of the measurement setup with a camera, a 2D galvo mirror, and an iris blocking light from the input fiber.

50
a low PSLL as a result of the hyperuniformity layout. To measure the far-field radiation patterns of the device, we placed a visible camera with a lens in the far-field regime of the OPA. We used a microscope objective to measure the near-field radiation patterns. The simulated and measured near-field patterns are shown in Figure 4.10a and b and a comparison of the simulated and measured far-field converged beams (Figure 4.10b,d) shows that the measured FWHM, $0.854^\circ \times 0.689^\circ$ are slightly higher than the simulated FWHM of $0.662^\circ \times 0.629^\circ$ (Figure 4.10b,d), indicating that the measured beam preserves the high directional characteristics. The difference in simulated and measured FWHMs is likely due to unbalanced MMIs and non-uniform emission intensity of the compact emitters due to fabrication variations.

We have three experiment setups to measure the near-field, far-field radiation patterns, and the percentage of power in the main beam (Figure 4.11). An objective lens and a lens are added to a visible camera to measure the near-field patterns of the 32-channel hyperuniform blue phased array.

![Experiment setup to measure the near-field, far-field radiation patterns, and power in the main beam of a 32-channel hyperuniform blue phased array. (a) Near-field measurement setup. An objective lens with a lens is used to focus onto the near-field of the device. (b) Far-field measurement setup. A single visible camera is used to measure the far-field radiation pattern of the device. (c) Percentage of power in the main beam is measured with an iris, a lens, and a power meter. An iris is added before the lens to filter out the main beam to calculate the percentage of power in the main beam.](image-url)

Figure 4.11.
To calculate the percentage of power in the main beam, we filter out only the main beam using the iris before the lens to measure the power in the main beam. Then, we measure the input power and calculate the percentage of power with the total chip loss (The percentage of power = Output power in the main beam / (Input power * Total chip loss)*100 [%]).

4.5.2 Image projection

Our compact hyperuniform phased array system is ideal for numerous emerging next-generation applications. In an example demonstration of its potential utility for image projection, we used the output beam produced by the hyperuniform phased array to generate 2D images. A 2-axis galvo mirror system was used to steer the output beam in two dimensions to display an image (Figure 4.10e). We placed an iris to block the input fiber light and shrank the beam size to make the displayed image fit the camera's aperture. The footprint of the whole scanning system can be miniaturized to fit on a chip via co-integration of a micro-electromechanical systems (MEMs) mirror on top of the hyperuniform OPA (Figure 4.12). The narrow-linewidth input laser sources to these photonic chips make it possible for the systems to have a very wide color gamut. The compact system is also ideal for laser beam scanning displays, micron-scale optical stimulation for quantum and biological applications since the SNR is high without any grating lobes. Our chip-scale hyperuniform OPA can replace bulky lens-based collimators for table-top scanning devices.

4.6 Conclusion and discussion

Our 2D hyperuniform blue phased array platform accurately projects a highly directional beam using a chip-scale device with a single-wavelength laser source. This hyperuniform platform forms the core of an approach for a 2D scanning visible light phased array for compact, large field-of-view, ghost-less, beam projection system. More specifically, our platform can enable an active scanner by integrating compact low-power phase shifters [54, 81] and integrated narrow-linewidth visible lasers [99], and can also be implemented using other electro-optic material platforms such
as aluminum nitride [74] and lithium niobate [75] for high-speed beam projection, enabling ghostless high frame rate video display. This hyperuniform platform can also be extended into near-IR [21, 32, 33, 36, 38, 40, 43, 44, 49, 90, 91] or UV [74, 100] wavelengths with the transparent electro-optic material platforms.

Going forward, we see that the hyperuniform array design can be extended into a “multihyperuniform” array, a hyperuniform array composed of multiple subsets of elements, each forming a hyperuniform layout itself [93]. This expanded multicolor phased array platform can enable ultra-compact tri-color laser beam scanning displays and multi-color optogenetic control of different neural populations [101, 102], addressing a single neuron at once with single-cell resolution across the many regions.

To reduce speckle issues in some applications such as AR/VR displays, one can temporally multiplex, add random phase [103, 104], or even couple partially coherent light sources such as superluminescent diodes (SLDs) [105]. A hyperuniform array with partially-coherent light sources might induce larger background noise; however, partially-coherent sources with computer-generated holography (CGH) still achieve a good peak signal-to-noise ratio (PSNR) [105]. Similarly, a hyperuniform OPA would still form a coherent converged beam with acceptable background noise. A fully-integrated hyperuniform visible OPA can be coupled to a waveguide display as a laser beam scanning or holographic display (Figure 4.12) with phase retrieval/CGH algorithms such as the Gerchberg-Saxton algorithm [106] or even the recent neural holography algorithms [107, 108]. Our work paves the way in many disciplines, adding valuable assets to existing technologies.
Figure 4.12. Applications of a disordered hyperuniform phased array. (a) MEMs mirror mounted laser beam scanning device. A MEMs mirror is fabricated on top of a passive disordered hyperuniform phased array to enable beam steering. The disordered hyperuniform phased array is utilized as a collimator for the MEMs mirror. (b) Fully-integrated low-power beam scanning device. An integrated injection-locked laser is integrated with a disordered hyperuniform phased array. (c) Light engine for AR displays. A hyperuniform OPA can be monolithically integrated or bonded to an optical combiner/waveguide display. The hyperuniform OPA can have downward emission or upward emission depending on the coupling schemes to the waveguide display. The outcoupler can be any fabrication compatible optical elements such as, holographic optical elements (HOEs) [109, 110], diffractive optical elements (DOEs) [111] and metasurface optical elements (MOEs) [112].
Chapter 5: A foundry-compatible low-SWaP FPSA for LiDAR and FSO

Compact beam steering with no moving parts is the critical technology for enabling low-cost LiDAR and FSO. Although various platforms have been proposed, each providing a specific advantage, none has achieved low power consumption for many emerging applications, especially mobile applications. The current chip-scale 2D beam steering technologies still require simultaneous control of many active photonic structures, leading to high power consumption. Here we demonstrate a scalable platform of foundry-fabricated low-SWaP FPSA that comprises 1024 pixels of photonic structures, enabling beam steering in 2D space using a single wavelength laser. The proposed platform shows at least an order of magnitude lower power consumption than the state-of-the-art technology. This platform, based on a matrix of switchable thermo-optic add-drop filters, and microring emitters, enables steering using less than 10 mW of total electrical power. Further reductions of each microring’s power consumption can decrease the total power consumption to 2 µW utilizing the state-of-the-art phase shifter [41]. Our proposed architecture opens the door to foundry-fabricatable, low-SWaP beam steering 3D cameras for the next-generation mobile applications in which low-SWaP performance is crucial.

5.1 Introduction

3D sensors are crucial for many emerging technologies, including LiDAR for autonomous robots and AR/VR displays. Flash LiDAR systems are now deployed in mobile platforms such as smartphones using vertical-cavity surface-emitting laser (VCSEL) technology with single-photon
avalanche diode (SPAD) arrays; however, their FoV is limited compared to scanning LiDARs.

Scanning LiDARs have a more extended FoV; however, they consist of bulky non-integrable tabletop optics or power-hungry structures. Much previous research has been aimed at solving these challenges and developing an integrated low-SWaP scanning LiDAR. The two silicon photonics LiDAR platforms that gained the most interest are OPA and FPSA.

OPAs [21, 32, 33, 36, 38, 40, 43, 44, 49, 66, 90, 91] have been extensively studied in the integrated photonics community as they provide fast, precise, and wide FoV scanning with no moving parts. However, high-resolution, wide-angle steering and high directivity OPAs have high power consumption and complex system architectures. Such an OPA requires many actively-controlled waveguides, and the power consumption scales linearly with the number of waveguides (N) in the array. An OPA with a thousand waveguides consumes tens of watts [21, 33] unless the power consumption of individual phase shifters is reduced [41, 47, 49]. In addition, most OPAs require widely tunable lasers to steer in the second dimension via wavelength tuning [21, 33, 38, 43, 49, 90]. The system, comprising thousands of digital-to-analog converters (DACs) to control phase shifters and widely tunable lasers, is complex and expensive. Novel OPA architectures have been introduced to reduce the power consumption by controlling sub-groups of phase shifters [21, 44, 113]; however, they are sensitive to accumulative phase errors [subsection 2.1.3], thus limiting their scalability.

FPSAs are an efficient alternative to OPAs as FPSAs resolve the issue of scalability and power consumption simultaneously [14, 15, 50, 51, 52, 53]. FPSAs function similarly to cameras in that each angular information within the FoV of an imaging lens maps to a pixel or an emitter at the back focal plane of the lens. As only one pixel is illuminated at a time, the number of photonic structures that operate at once is far fewer than OPAs. In FPSAs, light only emits from a single element, and the lens collimates the emission to form a beam. The lens performs a spatial Fourier transform, converting the light emission from different positions to different angles in the far-field. Recent demonstrations have successfully achieved 3D imaging using the FPSAs with an MZI switch tree [14, 50, 51, 52, 53] or MEMs structures [15]. However, the MZI switch
tree requires a large footprint and pitch with considerable power as the total power consumption scales with $log_2 N$, where $N$ is the number of waveguides. In addition, these platforms still require simultaneous control of multiple photonic structures to emit the light from the chip. The MEMs structures used in the FPSAs also require a large footprint and pitch between the emitters, and high operating voltage, which are incompatible with CMOS ICs [15]. We need a new platform with significantly few compact operating structures that can be controlled with low voltage when the system operates.

### 5.2 Low-size, weight, and power (SWaP) beam steering platform

Here we demonstrate a foundry-fabricated 1024-pixel silicon photonics FPSA for LiDAR; the largest demonstrated silicon photonics FPSA with the lowest power consumption and smallest footprint platform to the best of our knowledge. In this work, we present a novel platform of light-emitting microring matrix for 2D beam steering [Figure 5.1]. Our system consists of three building blocks: 1) an array of add-drop microring filters to select the row of the matrix of emitters, 2) a matrix of microring emitters in which a single emitter emits at a time, and 3) an external lens to collimate the emitted light. The platform is based on the add-drop microring filters with high extinction to actively switch light among $N$ different rows of waveguides. We place an external electronic switch [the left row-selection switch in Figure 5.1a] to select each add-drop filter. Each drop port of the microring filters critically couples to multiple identical microring resonators that serve as emitters [53]. We design gratings along the sidewall of each microring resonator for compact and efficient diffraction to free space [Figure 5.3a] [53]. While the add-drop filters direct the light to a specific row of the waveguides, the microheater wires on top of the microring emitters choose which column to emit. We have another external electronic switch [the column-selection switch in Figure 5.1a] on top of the microring emitter matrix to select the matrix column. In contrast to our previous demonstrations, we also connect the microheaters in rows so we can multiplex the ground wires using another electronic switch [the right row-selection switch in Figure 5.1a]. The electronic switches on the top and the right of the emitter matrix choose which microring
Figure 5.1. The proposed low-SWaP FPSA. (a) Diagram of the proposed FPSA. The FPSA consists of two row-selection switches, one column-selection switch, an array of add-drop filters, a microring emitter matrix, and an imaging lens. The left row-selection switch controls the array of resonant add-drop filters. The column-selection switch on top of the microring emitter matrix and the right row-selection switch controls the microring emitter matrix. (b) Diagram of the beam steering method. An emitter emits a diverging beam, and an imaging lens on top collimates the beam. The resolution depends on the pitch between emitters and the lens’s focal length. (c) The FPSA operation. (i) One of the switches in the left row-selection switch closes and controls one of the add-drop filters—the light couples to one of the rows in the microring emitter matrix. (ii) One of the switches in the column-selection switch closes to control a microring emitter in the column of the microring emitter matrix. (iii) One of the switches in the right row-selection switch closes and grounds one of the rows. The microring, which corresponds to the column selected by the column-selection switch and the row selected by the right row-selection switch, falls into its resonance. The light emits from the microring emitter and collimates through the imaging lens.
emitter to bias. The light is emitted as the selected microring emitter falls into its resonance. Only one microring emitter emits at once. An external lens is placed on top of this integrated optical scanner, converting the emitted light into a collimated beam.

### 5.3 New design for a low-SWaP FPSA

#### 5.3.1 Power consumption

![Power consumption comparison](image)

**Figure 5.2.** Size and power consumption comparison of previously demonstrated FPSAs [14, 50, 53]. The dotted lines indicate the increase in power consumption and average pitch with the number of elements. The beginnings of the lines show the power consumption and pitch reported in the published manuscripts [14, 50, 53]. The ends of the lines are the extrapolated values when the emitters are 128×96 arrays. The values of [14, 50, 53] are extrapolated for an apple-to-apple comparison. Our work achieves the lowest power consumption and small pitch between emitters simultaneously.

This novel light-emitting matrix platform achieves the lowest power consumption and smallest footprint compared to the other state-of-the-art platforms, offering the best scalable solution up to date. By using an array of add-drop filters and a microring emitter matrix, our system reduces the power consumption and complexity of the system by orders of magnitude compared to traditional
FPSAs. For large-scale systems, the $\log_2 N$ scaling is more favorable than the $N^2$ scaling in OPAs; however, the power is still considerable when $N$ becomes a large number. Our previously demonstrated $4 \times 4$ FPSA [53] had a total power consumption of $P_\pi/2 \cdot \log_2 4 + 4 \cdot P_{\mu\text{-ring emitter}} = 56.8$ mW. The other platforms that only use an MZI switch tree have a power consumption of around $P_\pi/2 \cdot \log_2 4^2 = 160$ mW for $4 \times 4$ beam steering [14, 50]. However, this MZI-only platform does not scale well because the routing complexity worsens significantly with an increase in element counts if only the MZI tree is used. The pitch between emitters also increases significantly [Figure 5.2], degrading the resolution [Equation 2.15]. Also, the footprint of the MZIs in the FPSAs is significant compared to their emitting region. The MEMs-based FPSA [15] also suffers from a large pitch (55 µm) and high power consumption due to high operating voltage (60 - 80 V). In contrast to these platforms, our FPSAs only consume $2 \cdot P_\pi/2 = P_\pi$ with an average pitch of ~14µm. This platform’s advantage grows much more significant as the number of elements scales [Figure 5.2]. In addition, our platform does not require high operating voltage and can be co-integrated with CMOS ICs with smaller technology nodes. Unlike other platforms where all the photonic structures in the same column are actuated [15, 53], only one emitter actuates at once, avoiding unnecessary ohmic losses. Our platform offers the most scalable solution among the other demonstrated platforms.

5.3.2 Microring emitters

We leverage our previously demonstrated microring emitters to efficiently couple light to free space with a small physical footprint [53]. In FPSAs, the angular resolution is determined by $\theta_{res} = \tan^{-1} \frac{p}{f}$ where $p$ is the pitch of emitters. It is critical to design a compact emitter with a small pitch between emitters to achieve a high resolution. We design emitters with gratings on the outer sidewall of compact microrings [53, 114, 115, 116] to combine both the capability of an optical switch and a grating emitter. To optimize the emission efficiency, we design the strength of the sidewall grating for critical coupling. This grating period ensures phase matching between the waveguide mode and free space emission. The gratings cover the entire microring circumference.
with an angular period of $\pi/12$ except the coupling region to the bus waveguide [Figure 5.3]. The grating phase matches the clock and counter-clock-wise modes, and these two modes appear as a double-dip in the spectrum, resulting in right and left circular polarization. Both modes can be coupled to emit light to free space, providing variability in polarization which is advantageous in

![Figure 5.3](image-url)

**Figure 5.3.** Scanning electron microscope (SEM) images and micrographs of the fabricated FPSA. (a) SEM image of the microring emitter matrix. The pitch between the emitters is kept at 18 µm and 10 µm on the x and y-axis, respectively, to minimize the thermal crosstalk. A close-up SEM image of a microring emitter, indicated by the black rectangle in the SEM of the microring emitter matrix, is shown on the right. The ring diameter is 5 µm and the waveguide width of the ring is 1.5 µm. (b) Micrograph of the packaged 1024-pixel FPSA. The chip size is 4×4mm$^2$. (c) A close-up micrograph of (b).
imaging and FSO over other platforms. The microrings have a diameter of 5 µm and a waveguide width of 1.5 µm. The doped Si microheater wires are fabricated surrounding the microring emitters on the same layer, offset by 2 µm to ensure unobstructed light emission from the gratings. The pitch between the emitters is kept at 18 µm and 10 µm on the x and y-axis, respectively, to minimize the thermal crosstalk.

5.3.3 Architecture

We design our 1024-pixel silicon photonics FPSA for LiDAR, the largest and smallest footprint silicon photonics FPSA that meets the foundry standards [Figure 5.3]. We utilize the add-drop filter process design kit (PDK) the AIM Photonics Foundry provided for the array of add-drop filters. We design the microring emitters (100 nm grating depth) to meet the fabrication standards of the foundry. We use two different layers of metals with vias for the electrical wires to connect the microheaters in the matrix. We connect the external electronic switches on a PCB, controlled by a field-programmable gate array (FPGA), to the emitter matrix and the array of the add-drop filters [Figure 5.1a]. The chip size for the 1024-pixel FPSA is 4×4mm², including the electrical pads [Figure 5.3b]. The proposed platform has a straightforward calibration method. We connect grat-

![Figure 5.4. Photograph of the packaged chip on the beam steering experiment setup.](image-url)
ing couplers at each end of the bus waveguides. It is straightforward to measure the transmission spectrum of the microrings and calibrate to their resonances. The platform is robust to temperature variations as we can leverage this direct feedback. We can replace the grating couplers with photodiodes for fully on-chip monitoring.

5.4 Conclusion and discussion

The FPSA is currently under test. We can further improve the demonstrated platform by optimizing design methodologies. We can achieve higher resolution by decreasing the pitch between the emitters. We can place the microheaters on top of the microring emitters instead of putting them on the side, similar to our previous demonstration, to decrease the thermal crosstalk [53]. We can also design the microring emitters utilizing the athermal vertical pn modulator [117] to minimize the thermal crosstalk and provide faster speed. The total power consumption can be as low as 2 µW if we utilize the state-of-the-art Si phase shifter [41]. We can further decrease the whole system size using metasurface lenses similar to our previous demonstration [53]. The platform and operating voltage for the photonic structures on this chip are CMOS-compatible; thus, we can monolithically integrate them into a single chip. We can co-integrate our previously demonstrated microring lasers [118, 49] for a fully integrated system. This emitter matrix platform is not constrained to microring emitters. We can also leverage the emitter matrix platform with a MEMs switch [15] or an add-drop filter [119] and a grating. This platform extends beyond the silicon photonics platform and can also be realized with other material platforms and in different wavelengths, visible or mid-infrared. To reduce the insertion loss from the add-drop filters, we can add additional layers of add-drop filters to break down the serial insertion loss into half or more.

The proposed platform is compatible with the traditional time-of-flight (ToF), frequency-modulated continuous wave (FMCW), and amplitude-modulated continuous wave (AMCW) imaging [section 5.5] but also can go beyond traditional scan-based methods. We can utilize our platform for computational imaging such as single-pixel imaging by simultaneously controlling multiple microring emitters and adding-drop filters. A single-pixel camera produces an image by using com-
pressed sensing. It measures the correlated intensity from a series of spatially resolved patterns on a single-pixel detector [120]. One can tune inside the extinction regions in the transfer function of the microring emitters to control the emission intensity and produce the correlated intensity. Our platform can replace SLMs or DMDs in single-pixel imaging and provide a compact form factor without bulky optics. One can adopt compressed sensing techniques for eye-tracking [121] with the proposed FPSA and a single near-infrared photodiode instead of a near-infrared camera to decrease the cost. By incorporating the near-infrared and visible wavelength decoupling technique in an optical combiner [122], we can co-integrate this low-SWaP near-infrared FPSA platform with visible beam steerers from chapter 3 and chapter 4 for an AR display.
5.5 Appendix: imaging modalities

Here we describe different imaging modalities that can be used with the proposed low-SWaP FPSA platform. The advantages and disadvantages of each method are not discussed here as they are not the main scope of this dissertation.

5.5.1 Time-of-flight (ToF) imaging

One of the most adopted imaging modality schemes in 3D imaging is ToF imaging. It is a straightforward scheme involving a pulsed light source, a detector, and an IC that measures the round-trip delay between a transceiver. The generated light pulse illuminates an object. The detector measures the reflected pulse, and depending on the distance, the reflected light experiences a delay by \( t_D = 2 \cdot \frac{D}{c} \) where \( D \) is the distance to a target and \( c \) is the speed of light. \( D \) is calculated as \( D = \frac{1}{2} \cdot c \cdot t_D \). The precision of the ranging is determined by \( \delta D = \frac{1}{2} \cdot c \cdot t_{clk} \), where \( t_{clk} \) is the clock cycle of the IC.

This imaging modality requires the most simple photonic circuitry among other imaging modal-
ities; however, it requires the most complex electronic circuitry. The driver IC controls and synchronizes the IC detectors and PIC with high-speed signals. The range precision of ToF depends on the minimum timing precision of the ICs.

5.5.2 Frequency-modulated continuous wave (FMCW) imaging

![FMCW imaging with the low-SWaP FPSA platform.](image)

FMCW imaging is another popularly adopted imaging modality in both radar and LiDAR. The photonic components in FMCW LiDARs are more complicated than the ones in ToF LiDARs. An FMCW LiDAR comprises a tunable laser with a coherent receiver that consists of an optical mixer (balanced photodiode) and a local oscillator path. The wavelength of the input laser is linearly modulated (up-chirp and down-chirp) with time. The laser light hits a target, reflects back to the receiver, and interferes with the local reference of the laser. The time delay between the return signal and the local part causes a frequency difference. This beat frequency is 

\[ f_{\text{beat}} = 2 \cdot \frac{\Delta B}{c T_s} \cdot D, \]

where \( \Delta B \) is the change in the laser bandwidth/chirp, and \( T_s \) is the time taken for a single ranging measurement (either up-chirp or down-chirp). \( f_{\text{beat}} \) can be different between the up-chirp and...
down-chirp due to the doppler shift. The following equation averages this doppler shift: \[ D = \frac{1}{2} \cdot c \cdot \frac{T_s}{\Delta B} \cdot \frac{f_{\text{beat,up}} + f_{\text{beat,down}}}{2}. \]

5.5.3 Amplitude-modulated continuous wave (AMCW) imaging

![Diagram of AMCW imaging with the low-SWaP FPSA platform.](image)

**Figure 5.7.** AMCW imaging with the low-SWaP FPSA platform.

AMCW imaging is similar to ToF and FMCW imaging, but an intensity pattern is encoded instead of the frequency chirp in the laser source. The amplitude of the input laser source is modulated at RF frequency. Similar to FMCW imaging, where the difference in frequencies between the transmitted and received signal is measured, the difference in the phase shift is measured in AMCW imaging. The phase shift is measured by beating the local branch of the signal with the reflected signal from a target. The distance is calculated as \[ D = \frac{1}{2} \cdot c \cdot \frac{\Delta \phi}{2\pi f_{\text{mod}}}. \]
Summary and future work

In this dissertation, we presented novel integrated beam steering and shaping platforms spanning from visible to near-IR wavelengths, paving new paths for emerging applications. The proposed platforms open up a new door for AR and VR displays, optical trapping for quantum information processing, biological sensing and stimulation, and optogenetics. Here we present outlooks and future applications to our current platforms.

Proposed novel platforms of the OPA

Thermo-optic polymer phase shifter-based phased array

The blue light OPA presented in chapter 3 is power-hungry due to the low thermo-optic coefficient of Si$_3$N$_4$. We can heterogeneously integrate higher thermo-optic or electro-optic coefficient materials onto our existing platform to reduce power consumption. One example of integrable higher thermo-optic coefficient materials is a polymer. Polymer-cladded slot waveguides or photonic crystals at near-infrared wavelengths have been demonstrated for electro-optic and thermo-optic cases [123, 124]; however, the fabrication constraints for visible wavelengths are challenging to achieve. Here we propose a polymer-based (SU-8) waveguide to enhance the phase-shifting effect with relaxed fabrication constraints. We highlight the thermo-optic method here for the simplicity of analysis. Still, we can utilize the same approach for the electro-optic method using other electro-optic polymer materials such as a liquid crystal. Figure 5.8a shows the SU-8 cladded narrow (80 nm wide) Si$_3$N$_4$ waveguide and its power efficiency compared to the typical SiO$_2$-cladded Si$_3$N$_4$ waveguide (300 nm wide). SU-8 can also be utilized to make a waveguide using electron-beam lithography. Figure 5.8bc shows the proposed polymer (SU-8) waveguide schematic with an order of magnitude higher thermo-optic coefficient than the Si$_3$N$_4$ phase shifter in chapter 3.
Figure 5.8. The proposed polymer phase shifter for visible phased arrays. (a) The phase shifter is cladded with SU-8 (it can be other polymer materials). The SU-8 cladding is hard-baked at 300 °C. The temperature only rises by 7 °C in operation. The thermo-optic improvement is \( \times 10 (\sim 2.5 \text{ mW/}\pi) \) compared to SiO\(_2\) cladding (\( \sim 24 \text{ mW/}\pi \)). The device can be further improved by making the waveguide with the polymer. (b) The proposed low-power polymer waveguide phase shifter. When SU-8 is used for the waveguide instead of cladding, the power consumption reduces to \( \sim 2 \text{ mW/}\pi \). An adiabatic coupler transitions from a Si\(_3\)N\(_4\) waveguide to a polymer waveguide (SU-8 in this case but can be a liquid crystal, or other polymer materials can be used). Multi-clothoid bends [98] shrink the overall footprint and utilize the thermal crosstalk to improve the overall power efficiency. The proposed platform consumes \( \sim 0.7 \text{ mW/}\pi \) with low insertion loss in theory. (c) Optical microscope image of the 500 nm thick and 500 nm wide SU-8 waveguides fabricated with electron-beam lithography and hard-baked at 300°C.
The light transitions to the polymer waveguide (500 nm wide and 500 nm thick) with an adiabatic transition from the Si$_3$N$_4$ waveguide (300 nm wide and 180 nm thick). By hard-baking the SU-8 waveguides at 300 °C and cladding with SiO$_2$, other subsequent fabrication steps can be processed on top.

**Strongly over-coupled µ-resonator phase shifter-based phased array**

We demonstrated a novel phase shifter with sub-mW power consumption per $\pi$ phase shift leveraging a microring resonator in the over-coupled regime [76, 81, 125]. When the coupling ratio from a bus waveguide to a cavity is much higher than the radiation loss and scattering loss inside the optical cavity, the cavity operates in the strongly over-coupled regime [76, 81, 125]. The transmission and phase spectrum of the strongly over-coupled optical cavity shows that the insertion loss is close to 0 dB, but the phase shift undergoes close to a full $2\pi$. We leverage this over-coupled resonator-based phase shifter as a critical building block for our visible phased array. Figure 5.9 shows the proposed schematic. We leverage a racetrack resonator instead of a ring resonator to ensure long coupling length. Inside the racetrack resonator, we use a single-mode waveguide only for the coupling region and adiabatically widen it to a multimode waveguide to reduce scattering loss and achieve the strong over-coupling condition. We add an interferometric structure with directional couplers between each channel to characterize the over-coupled resonator [126]. We design hybrid couplers to tap out only 10% of the power in each waveguide. A grating emitter is added at each end of the interferometer so that we can calibrate the transfer characteristic of each over-coupled phase shifter for beam convergence using a near-IR camera from the top. We can replace the grating emitter with a photodiode for a more straightforward on-chip calibration. Figure 5.9d shows the fabricated chip. Instead of the current end emitter arrangement, the over-coupled phased array can be combined with the disordered hyperuniform emitter arrangement Figure 5.9e. The device is currently under test.
**Figure 5.9.** The proposed strongly over-coupled µ-resonator phase shifter platform. (a) PIC layout of the strongly over-coupled µ-resonator phase shifter. We use a single-mode waveguide only for the coupling region and adiabatically widen it to a multimode waveguide to reduce scattering loss and achieve the strong over-coupling condition. (b) Optical microscope image of the phase shifter. (c) PIC layout of the over-coupled resonator phase shifter-based phased array. We add an interferometric structure with directional couplers between each channel to characterize the over-coupled resonators. (d) Optical microscope image of the phased array. (e) The fabricated 1024-channel disordered hyperuniform emitter arrangement. The over-coupled phase shifters can be combined with the disordered hyperuniform emitter arrangement.
Applications of the FPSA

Coherent polarimetric imager

We can replace the microring emitters in the low-SWaP FPSA with add-drop ring resonators coupled with grating emitters [Figure 5.10]. We can design these grating emitters to have different polarizations. The new platform can enable high precision and accuracy laser-based polarization imaging by iterating grating emitter designs with different polarizations [Figure 5.10]. This coherent polarization imager can reveal hidden features and provide rich polarization information not present in traditional intensity-based coherent imagers. This imager can be a valuable toolset for many imaging applications such as polarization-sensitive optical coherence tomography (PS-OCT) [127] and eye-tracking for near-eye displays [128].

**Figure 5.10.** The proposed coherent silicon photonic polarization imager. Each microring emitter is replaced with an add-drop resonator and a polarization-selective grating. We can achieve coherent polarization imaging with high accuracy and precision by having differently polarized gratings.
FSO wavelength division multiplexing (WDM) with the Kerr frequency comb-driven silicon photonic transceiver

The proposed low-SWaP FPSA platform can be used for FSO with WDM by integrating the recently demonstrated Kerr frequency comb-driven photonic transmitter [129]. We can design the microring emitters and add-drop ring resonators to match their free spectral range (FSR) to the multiples of the frequency comb line spacings. Due to the significant size difference among the microring emitters, add-drop resonators, and normal group velocity dispersion (GVD) microresonators, their FSRs do not match. De-interleaving stages are necessary to separate the frequency comb lines to match the FSRs of the microring emitters and the add-drop resonators. Each FPSA can be connected to each bus of the de-interleaved frequency comb lines. The microring emitters can emit all the frequency components simultaneously. Due to the different resonant mode orders of the microring emitters for each frequency comb line, the efficiency and the polarization (radial or azimuthal) of the emitted light can be different. We can synchronize multiple Kerr frequency combs sources [130] to increase the output power in each spectral line. This proposed platform will enable a new class of massively parallel terabit-scale FSO for future wireless optical communication [131].
Figure 5.11. The proposed FSO WDM transceiver. Synchronized, highly efficient frequency combs [130] can produce high-power coherent light sources with massively parallel wavelengths. The Kerr frequency comb-driven silicon photonic transceiver [129] can be combined with the low-SWaP FPSA. This FSO WDM transceiver enables free-space high data transmission at Tbits/s.
References


[131] “Expanding global internet access - x, the moonshot factory (project taara),” X, The Moonshot Factory. eprint: https://x.company/projects/taara/.