

Integrated Optical Phased Arrays for Beam Forming and Steering

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Abstract: Integrated optical phased arrays can be used for beam shaping and steering with a small footprint, lightweight, high mechanical stability, low price, and high-yield, benefiting from the mature CMOS-compatible fabrication. This paper reviews the development of integrated optical phased arrays in recent years. The principles, building blocks, and configurations of integrated optical phased arrays for beam forming and steering are presented. Various material platforms can be used to build integrated optical phased arrays, e.g., silicon photonics platforms, III/V platforms, and III-V/silicon hybrid platforms. Integrated optical phased arrays can be implemented in the visible, near-infrared, and mid-infrared spectral ranges. The main performance parameters, such as field of view, beamwidth, sidelobe suppression, modulation speed, power consumption, scalability, and so on, are discussed in detail. Some of the typical applications of integrated optical phased arrays, such as free-space communication, light detection and ranging, imaging, and biological sensing, are shown, with future perspectives provided at the end.

Keywords: integrated; optical phased arrays; beam shaping; beam steering



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1. Introduction

In recent years, optical phased arrays (OPAs) have attracted a great deal of attention. At optical wavelengths, small diffraction angles for a given aperture size can be achieved, compared with microwave radar systems. Featured by precise and agile free-space beam forming and steering [1–12], OPA techniques are highly desirable. However, current commercially available OPA components are mainly based on mechanical control, such as motor-driven rotating collimation stages/mirrors. Mechanical beam steering provides high efficiency and a relatively large scanning angle, through mechanically moving parts such as a gimbal, which can be susceptible to mechanical wear and tear, less stable, and limited in speed [13,14] due to the masses involved. The bulky mechanical steering approach is less preferred as it typically degrades in performance due to acceleration, temperature, vibration, and inertial forces. Additionally, mechanical steering often consumes significant energy. Furthermore, they require a complex assembly and calibration process, causing a greatly high unit cost. More importantly, these mechanical approaches are only capable of steering a single light beam. Arbitrary pointing and rapid steering as needed for advanced communication and sensing applications then become difficult or even incapable [14–19].

Optical beam forming and steering have been demonstrated with minimum mechanical movements or completely solid-state OPAs, and the seminal concept was demonstrated by a 46-channel lithium tantalate phase modulator for one-dimensional (1D) optical beam steering [20]. Existing techniques mainly include liquid crystal (LC) OPAs [21–27], micro-electromechanical system (MEMS) OPAs [28–31], optical fiber phased arrays [32], III–V laser arrays [33], and photonic crystal waveguides with diffraction gratings [34].

LC OPAs are the main OPA technology and take advantage of high birefringence. In these systems, the orientations of liquid crystals induce a change in the refractive index. They thus act as a programmable lens that can steer the light at will. Although the OPA based on cascaded liquid crystal has a large field of view (FOV) and low driving voltage [19], it has a limited operation speed due to the time needed for molecular reorientation [6,14,19,35,36] (typically a few milliseconds response time [6,9,18]). MEMS technology typically suffers from the same drawback [13,36] with tuning speeds typically in milliseconds [18,37]. Additionally, the limited FOV [29,30,37] is another drawback due to the multi-wavelength sizes of elements, which gives rise to grating lobes in the far-field patterns [37].

Additionally, tunable dielectric metasurfaces modulated by liquid crystals provide opportunities to develop the next generation light detection and ranging (LiDAR) and display technologies. A metasurface-based transmissive spatial light modulator generates active beam steering with >35% efficiency and a large beam deflection angle of 11° [38]. A CMOS-compatible all-dielectric silicon (Si)-based metasurface enabled beam steering with high transmission for wavelengths ranging from 2.96 to 3.215 μm . Different steering angles can be achieved by changing the periodicity of the structure [39].

As one of the promising solutions for the next-generation dynamic beam steering, integrated OPAs simultaneously possess the advantages of being stable, rapid, and precise without relying on any mechanical motion, making them robust and insensitive to external constraints such as accelerations. Some of the integrated OPAs are presented in Figure 1. A wire-bonded device on a chip carrier plugged into a breadboard is presented in Figure 1a. Figure 1b shows a one-dimensional 64-channel chip-scale blue light phased array. A kind of III-V/Si phase-shifter-based OPA is shown in Figure 1c. Figure 1d is the photo of a fabricated OPA chip on a penny. Using an integrated approach, the OPAs can be made very small.

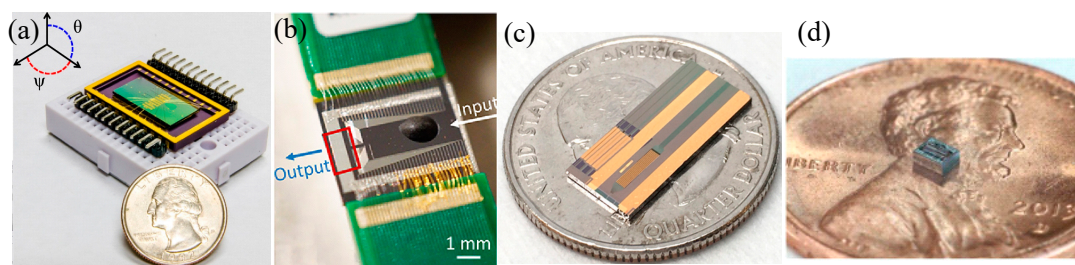


Figure 1. Integrated OPAs. (a) The wire-bonded device on the chip carrier plugged into the breadboard. Reprinted with permission from [40] © The Optical Society. (b) Blue light OPA. Reprinted with permission from [41] © The Optical Society. (c) A set of three 32-channel and one 240-channel OPAs on a coin. Reprinted with permission from the author of [42] published on Arxiv, 2018. (d) A photo of an OPA on a penny. Reprinted with permission from [43] © The Optical Society.

Integrated OPAs generate narrow beams and have a wide steering angle with tuning speeds in the MHz to GHz range [18,44]. Particularly, Si photonics offers a low-cost OPA technology thanks to its compatibility with mature complementary metal-oxide-semiconductor (CMOS) process infrastructure. Moreover, Si photonics promises large-scale implementation with CMOS electronics, efficient optical phase shifters, and laser integration [17,19,45]. The non-mechanical beam steering based on an integrated OPA offers better reliability and reconfigurability. Compared with similar technologies such as MEMS, they are more tolerant to mechanical stresses from vibrations that cause a misalignment in assembled devices [46]. Many pioneering works of integrated OPAs were demonstrated with applications, ranging from free-space communications [47–51], LiDAR [11,17], imaging [52–54], to biological sensing [55,56]. Integrated OPAs are a promising candidate to become the next marketable solid-state dynamic beam steering solution.

In this review, integrated OPAs for beam forming and steering are discussed. The paper is organized as follows. Section 2 gives an overview of the principles of integrated OPAs. The building blocks of integrated OPAs will be given in Section 3. The discussion of configuration is given in Section 4. We then focus our attention on the material platforms of integrated OPAs (Section 5). Various wavelength ranges used in integrated OPAs are discussed in Section 6. The performance of integrated OPAs is given in Section 7. Applications and potential alternatives are discussed in Section 8. We offer a brief outlook for future research potential in Section 9. The conclusions are then summarized in Section 10.

2. Principles

This section dedicates to the physical principles of integrated OPAs, which can be fully explained by the Fraunhofer diffraction. OPAs can be described using a diffraction model or multi-slit diffraction model, which is the simplified version of the former.

There are two kinds of OPAs, namely the waveguide grating antenna (WGA) OPAs with nearly vertical radiation and the end-fire (EF) OPAs with power radiated from the facets of waveguides. Typically, the EF OPAs enable 1D beam forming and steering. Two-dimensional (2D) beam steering can be achieved by the WGA-based OPAs.

2.1. Fraunhofer Diffraction Model

The Fraunhofer diffraction theory [57] can be used to describe the far-field interference of OPAs, in which scalar field e in the x_0y_0 -plane diffracts to the x_1y_1 -plane at a large distance z_0 [13], following the rule below:

$$e(x_1, y_1) = \frac{je^{-jkz_0}}{\lambda z_0} e^{-\frac{jk}{2z_0}(x_1^2 + y_1^2)} \iint e(x_0, y_0) e^{j\frac{2\pi}{\lambda z_0}(x_1x_0 + y_1y_0)} dx_0 dy_0 \quad (1)$$

where k is the free-space wave vector. For the $N \times M$ OPA presented in Figure 2a, the far field at a certain point r is the far-field pattern of one element, i.e., $F(\theta_x, \theta_y)$, multiplied by the sum of all the phase factors [13]:

$$e(r) = F(\theta_x, \theta_y) \frac{e^{-jk_0R}}{R} \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} A_{xy} e^{j\beta_{xy}} e^{-jk \cdot S_{xy}} \quad (2)$$

where $R = |r|$, A_{xy} is the field amplitude, β_{xy} is the relative phase at each element, k_0 is the free-space wave vector, and S_{xy} is the position of the radiating element. θ_x and θ_y indicate the angle of x - and y -direction, respectively. For uniform arrays [13], the far field is:

$$e(r) = F(\theta_x, \theta_y) \frac{e^{-jk_0R}}{R} A e^{j\gamma} \frac{\sin[\frac{N}{2}(k_0\Lambda_x \sin \theta_x - \Delta\varphi_x)]}{\sin[\frac{1}{2}(k_0\Lambda_x \sin \theta_x - \Delta\varphi_x)]} \frac{\sin[\frac{M}{2}(k_0\Lambda_y \sin \theta_y - \Delta\varphi_y)]}{\sin[\frac{1}{2}(k_0\Lambda_y \sin \theta_y - \Delta\varphi_y)]} \quad (3)$$

where γ is a phase factor determined by

$$\gamma = \frac{N-1}{2}(k_0\Lambda_x \sin \theta_x - \Delta\varphi_x) + \frac{M-1}{2}(k_0\Lambda_y \sin \theta_y - \Delta\varphi_y) \quad (4)$$

where Λ_x and Λ_y are the element spacing along the x - and y -axis, respectively. $\Delta\varphi_x$ and $\Delta\varphi_y$ are the phase differences.

In principle, the far-field radiation pattern of OPAs is calculated by the far field of individual antenna multiplied by the array factor [10,58,59]. The far-field pattern can be desirably modulated based on this theory.

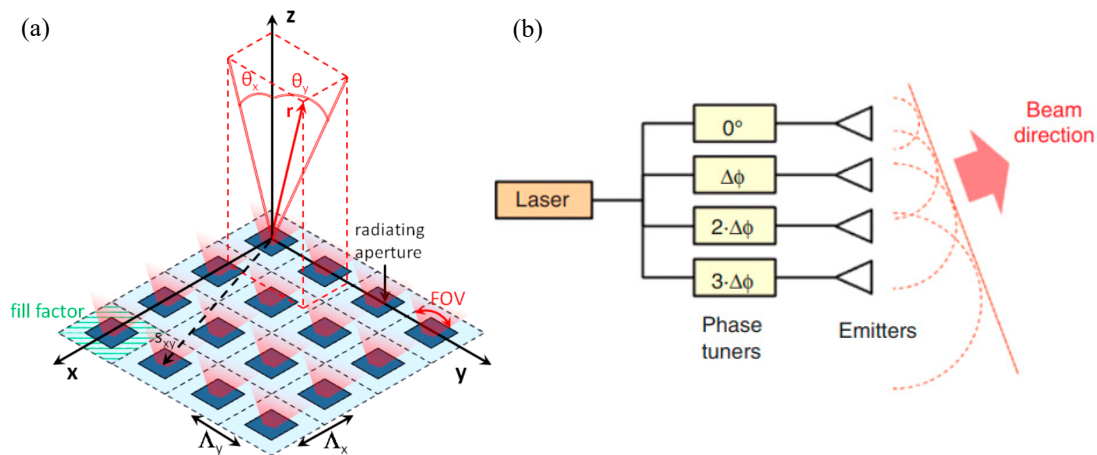


Figure 2. (a) Schematic of an OPA based on WGAs. Reprinted with permission from [13], © Gent University. (b) An OPA based on EF structures. Reproduced from [18] published by De Gruyter, 2016.

2.2. Multi-Slit Diffraction Model

As illustrated in Figure 2b, uniform 1D EF OPAs can be described by the multi-slit diffraction model. The EF OPA is regarded as a rectangular aperture array in the diffraction model. Then the far-field angular intensity distribution [13,59,60] is in the form of:

$$I = I_0 \left[\frac{\sin\left[\frac{1}{2}(k_0\delta_x \sin \theta_x)\right]}{\frac{1}{2}(k_0\delta_x \sin \theta_x)} \frac{\sin\left[\frac{N}{2}(k_0\Lambda_x \sin \theta_x - \Delta\varphi_x)\right]}{\sin\left[\frac{1}{2}(k_0\Lambda_x \sin \theta_x - \Delta\varphi_x)\right]} \right]^2 \quad (5)$$

where δ_x is the element size of the N -element OPA, I_0 stands for the unitary peak intensity in the far field of a single element, and θ_x indicates the angle of x -direction. The identical phase difference of $\Delta\varphi_x$ is applied between adjacent channels placed at a pitch of Λ_x . The EF OPAs are commonly used to achieve 1D beam forming and steering by phase-shifting between waveguides. As shown in Figure 3a, the first fabricated OPA with a half-wavelength element spacing is used to demonstrate beam steering over a range of 64° by integrated thermo-optic (TO) heaters. The measured intensity of the horizontal cross sections and stitched-together captured images are presented at the top and the bottom [61].

2.3. Beam Steering Based on WGAs

Nearly all the proposed 2D OPAs till now depend on WGAs. Not all the 2D OPAs' far-field patterns are completely formed by phase differences. There are some other steering approaches.

2.3.1. 2D Steering Based on Phase Differences

As demonstrated by the Fraunhofer diffraction model and some implementations [10,58], 2D beam forming and steering generate arbitrary and dynamic far-field patterns by manipulating phase differences of 2D WGA-based OPAs. However, in general, an OPA with $N \times M$ elements using phase control [10,58] requires a circuit of $N \times M$ phase shifters, and it becomes a complex system. A similar 2D dynamic forming was demonstrated by 1D long WGA arrays [12], which had much fewer elements.

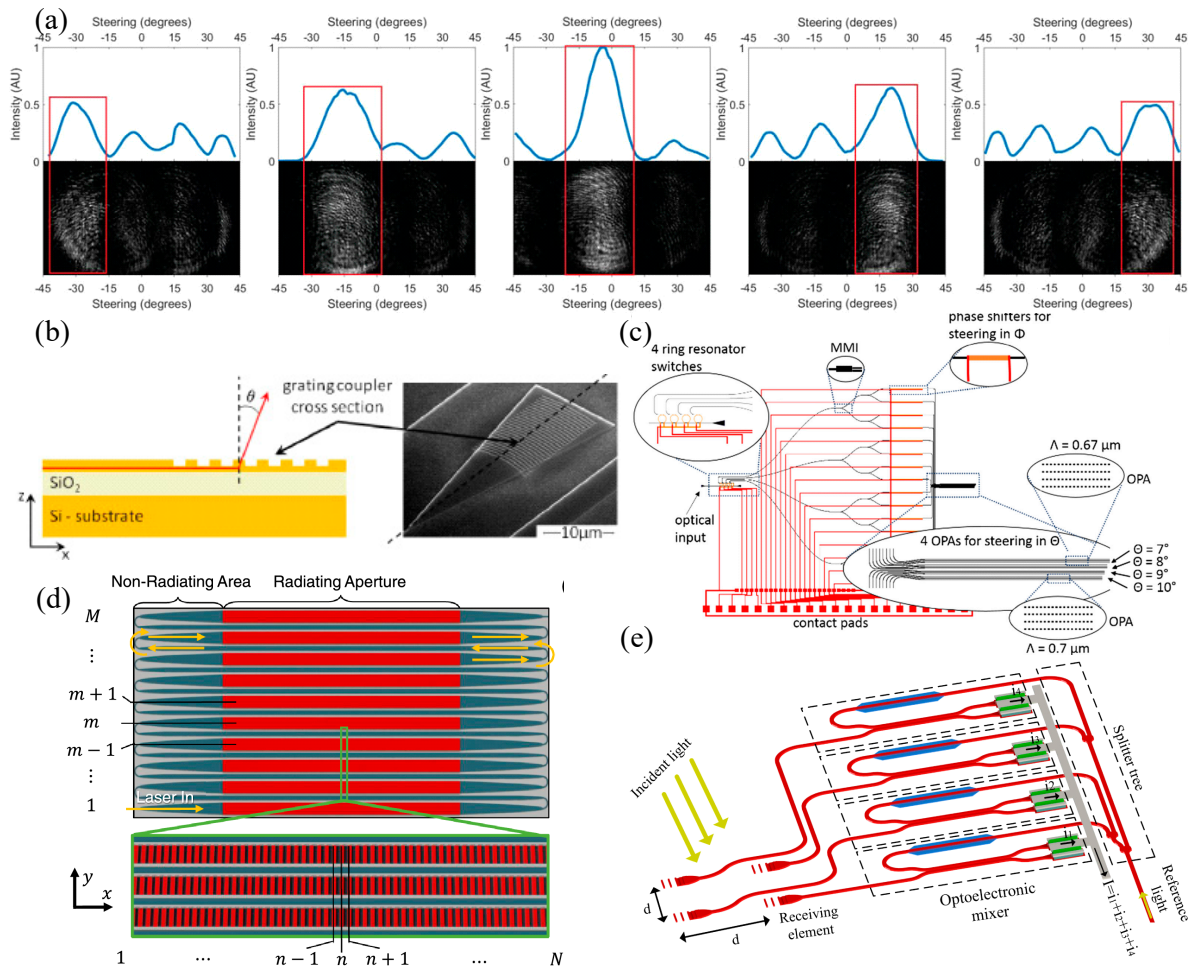


Figure 3. (a) Half-wavelength element spacing OPA with integrated TO heaters for beam steering from left to right. Reproduced from [61] with the permission of AIP Publishing. (b) Schematic view of the cross section of a WGA. Reprinted with permission from [8] © The Optical Society. (c) Schematic image of the proposed 2D beam steering device at a fixed wavelength. Reprinted with permission from [62] © The Optical Society. (d) Schematic of a serpentine OPA. Reprinted with permission from [63] © The Optical Society. (e) A 2×2 OPA receiver. Reprinted with permission from [43] © The Optical Society.

2.3.2. Steering Based on Phase Differences & Wavelengths

For this kind of OPAs, each channel contains a diffractive WGA with inherent wavelength-angle dispersion characteristics. Along the axis of the WGA, the outcoupling angle θ shown in Figure 3b is governed by the grating equation [7,8], which is given by

$$\sin \theta = \frac{\Lambda n_{eff} - \lambda_0}{n_{ct} \Lambda}, \quad (6)$$

where Λ is the grating period, n_{eff} is the effective index, n_{ct} is the refractive index of the cladding, λ_0 denotes the wavelength. The beam steering of θ angle can be achieved by wavelength tuning. In addition, the outcoupling angle θ can also be changed by effective index changing [7,51,64] based on thermal or electric optical modulations.

Ultra-large numerical apertures and nearly diffraction-limited far-field beamwidths were achieved by millimeter-scale WGA-based OPAs [65,66]. The azimuthal and polar beam steering can be formed by phase modulators and tunable lasers, respectively [11,12]. For a $N \times M$ array, only N phase controls and one wavelength control are required [12]. The simplified control circuits greatly boost the development and application of OPAs.

2.3.3. 2D Steering Based on Optical Switches at a Fixed Wavelength

2D beam steering at a fixed wavelength can be achieved by optical switches and phase controllers. As illustrated in Figure 3c, the beam steering in polar direction is accessed by actively switching among various WGAs with different diffraction angles, while the beam is azimuthally steered via phase differences. 2D beam steering over an FOV of $3^\circ \times 17.6^\circ$ was demonstrated using a silicon nitride (Si_3N_4) integrated OPA at a fixed wavelength of 905 nm [62]. In this case, optical switches were used to enable beam manipulation and dynamic control. However, the performance and application of the implemented OPA are limited by the FOV, especially for the polar direction. This approach also results in a relatively large chip size.

OPAs consisting of electro-optic (EO) p-i-n phase shifters and TO tunable n-i-n WGAs can be used to demonstrate 2D beam steering at a fixed wavelength. As mentioned above, the effective refractive index n_{eff} in Equation (6) can be changed by the currents in heaters. The lateral radiation can be steered by phase differences based on the electro-optical effect. A 16-element Si OPA enables 2D beam steering of $45.4^\circ \times 10.0^\circ$ with a beamwidth of $3.2^\circ \times 5.8^\circ$ at 1.55 μm . The tuning efficiency is $0.016^\circ/\text{mW}$ in the polar beam steering [64]. The 64-element OPA containing EO p-i-n phase shifters, and TO tunable n-i-n grating radiators covers the FOV of $46.0^\circ \times 10.2^\circ$ with a beamwidth of $0.7^\circ \times 0.9^\circ$ at 1.532 μm [51]. This provides a solution to remove the need for a tunable source or WGAs with different periods as in [62]. Nevertheless, the polar beam steering efficiency is low. The efficiency of OPA is limited by power-hungry TO shifters. The thermal crosstalk raises another problem, especially in the case of large-scale integration.

2.3.4. 2D Steering Completely Based on Wavelengths

Based on the waveguide delay lines and dispersion of WGAs, 2D beam steering can be achieved solely through wavelength tuning. 2D beam steering with beamwidth around $4^\circ \times 4^\circ$ in a range of $50^\circ \times 15^\circ$ was achieved by a wavelength shift of 100 nm [67]. As shown in Figure 3d, 2D beam steering can be achieved by the serpentine OPA structure used for delay-accumulating. The serpentine waveguide structure normally requires no active phase shifters [63]. For a fixed delay length, the wavelength-based 2D OPAs cannot be used to achieve flexible patterns.

Besides, a wavelength-based 2D OPA combining wavelength division filters and a WGA array was proposed to realize 2D optical scanning. The filter module, which consists of a Mach-Zehnder interferometer (MZI) and microring array, divides the input light into different microrings and the corresponding emitters. The 64-channel OPA structure with an FOV of $6^\circ \times 4^\circ$ was realized by changing the input wavelength from 1.55 to 1.56 μm . Voltage adjustment is required in the scanning process to change the refractive index of the upper MZI arm [68]. This 2D OPA with large WGA spacing enables only a limited FOV.

2.4. Transmitters and Receivers

OPA transmitters are capable of beam forming and steering. OPA transmitters consisting of more than a thousand radiating elements [10,16], and showing narrow beamwidths and high resolution [12,65] have been demonstrated. Moreover, blue [41] and red light [65] OPA transmitters in the visible range have also found potential applications in biological sensing [55,56].

Based on the same physical principle and the reciprocity of electromagnetic wave propagation, a transmitter can be theoretically used as its counterpart, i.e., a receiver. Using control circuits, the reconfigurable receiver arbitrarily collects light in the FOV. The straightforward realization of an OPA receiver is yet obstructed due to the low signal-to-noise ratio. It is ineffective to directly use a transmitter as a receiver. An optoelectronic mixer can be used to down-convert optical signals to radio frequencies, with phase and amplitude information maintained. The weak received signals can be detected by highly sensitive detectors [43,69]. Based on the dispersion of gratings, the output diffraction angle

of a transmitter can be changed by wavelength. However, this mechanism does not work for receiving optical signals [48].

The first presented integrated Si OPA receiver with an aperture size of $96 \times 50 \mu\text{m}^2$ contains 32 receiving elements [69]. This 1D OPA with heterodyne detection can selectively collect light from the desired angle and rejects others. The OPA receiver provides a fully programmable angular selectivity with an FOV of 30° and a beamwidth of 0.74° [69]. An optoelectronic mixer is used to enhance the detection sensitivity and robustness against noises and interference. A simplified 2×2 receiver architecture is presented in Figure 3e. The first 2D OPA receiver, which consists of 8×8 receiving elements, can selectively receive light from 64 different angles in an FOV of $8^\circ \times 8^\circ$ [43].

3. Building Blocks

Integrated photonics paves the way for low-cost large-scale OPA chips. As presented in Figure 4, typically, there are four necessary parts in an OPA: laser source, beam splitters, phase shifters, and emitters [12], for efficient light generation, manipulation, and chip-to-free-space transmission. We will discuss each part in detail in this section. Then a brief overview about overlayers and buried oxide (BOX) layers is given. The optimized thicknesses of the overlayers and BOX layers enhance the upward radiation of WGAs.

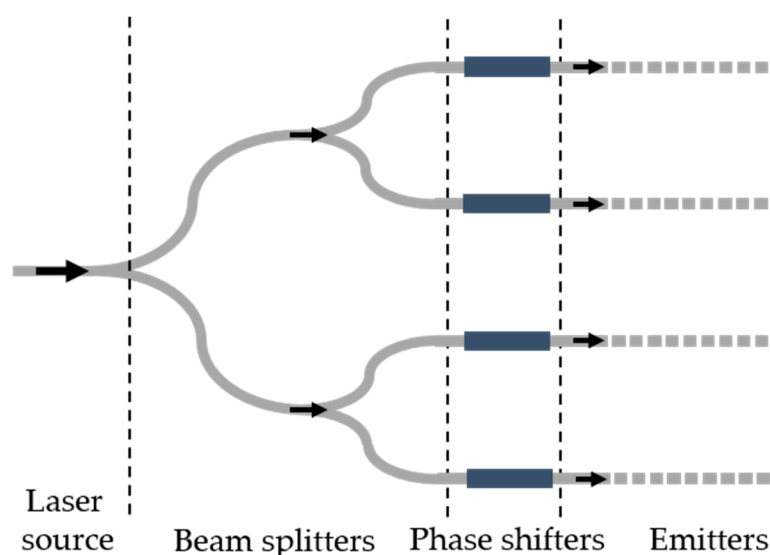


Figure 4. A typical integrated OPA structure.

3.1. Laser Sources

Chip-scale beam forming and steering require high-performance and low-cost integrated OPAs, which can be readily realized with Si photonics technology [11,12]. For the wavelength dependent OPA, it is necessary to have a tunable laser source [64]. The tuning precision needs to be high enough to avoid degradation in the spectral purity and multibeam projection capability of the OPA [45]. On the other hand, a wavelength-fixed laser is required for the phase modulation-based 2D OPAs. Figure-of-merits of lasers, such as output power, linewidth, and tunability, are important to the OPAs.

Due to the absence of a direct-bandgap material, off-chip lasers are widely used in the Si photonic OPAs [7,9–11,14,41,59,65,70,71]. Off-chip lasers provide wide tuning capabilities [72]. Light can be coupled to the photonic components through either a grating coupler [40,45,59,62,70,73,74] or an edge coupler [7,14,65,71,75]. The latter approach allows for the usage of a lensed fiber for highly efficient light coupling [7,72]. The grating coupler can be placed anywhere on the chip but is sensitive to the polarization and wavelength of incoming light. Realizing an efficient grating coupler is quite challenging, which requires complicated design and optimization. Different from grating couplers, edge couplers

have high coupling efficiencies, negligible polarization dependences, and broad working bandwidths. The edge coupler can only be used after the chip is diced. To realize high coupling efficiencies (typically >80%), fabrication of optical-quality facets on the chip sides, which only works well at small volumes, are of great significance [76]. Additionally, relatively complex fabrications and packaging processes are required.

Expensive benchtop tunable lasers with a large form factor restrict the practical use of the OPAs [77,78]. It is thus highly desirable to have the laser sources integrated on-chip, which have been implemented on the Si photonics platform [77,78], the indium phosphide (InP) platform [79,80], and the hybrid III-V/Si platform [81,82].

A monolithically integrated OPA with an on-chip erbium-doped laser was demonstrated for its advantage of CMOS compatibility and fabrication simplicity [78]. The first rare-earth-doped laser monolithically integrated OPA system consists of a Si layer with eight doping masks, two Si₃N₄ layers, three metal and via layers, a dicing trench for smooth edge-coupled facets, and a gain-film trench. The off-chip 980-nm-wavelength pump is coupled into the on-chip laser with a single lasing peak at 1.599 μm and a side-mode suppression ratio (SMSR) of 30 dB. Cascaded phase shifters controlled by electrical signals are demonstrated to reduce complexity while enabling tuning for phase variations [77,78]. Based on 500- μm -long WGAs and 2- μm pitch, the 49-channel OPA with an aperture size of $0.5 \times 0.1 \text{ mm}^2$ showed 15° beam steering and a beamwidth of $0.80^\circ \times 0.16^\circ$ [77]. The OPA with grouped cascaded phase shifters enabled 1D beam steering with a beamwidth of $0.85^\circ \times 0.20^\circ$ and a SMSR of 30 dB [78]. We note that here the OPAs with monolithically integrated erbium-doped lasers can only be tuned by the phase shifters.

Based on the InP platform, a monolithically integrated OPA with 2D optical beam steering with an FOV of $10^\circ \times 6.5^\circ$ and a beamwidth of $2^\circ \times 0.2^\circ$ was achieved. Polar beam steering efficiency of $0.14^\circ/\text{nm}$ was demonstrated by a tunable laser. In addition, very fast beam steering ($>10^7/\text{s}$) in both dimensions has been achieved [79]. As illustrated in Figure 5, a hybrid III-V/Si platform can also be used to achieve OPAs with on-chip laser sources. Using the hybrid platform, a 1D beam steering OPA with an FOV of 12° , a beamwidth of $1.8^\circ \times 0.6^\circ$, and a background noise suppression of 7 dB was achieved [81]. The first fully integrated 2D beam scanner using the hybrid Si platform contained 164 optical components and exhibited an FOV of $23^\circ \times 3.6^\circ$ with a beamwidth of $1^\circ \times 0.6^\circ$ [82].

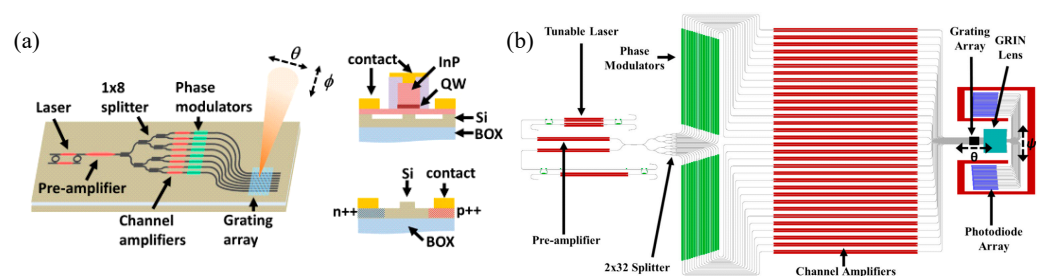


Figure 5. OPAs with on-chip laser sources based on the hybrid III-V/Si platform. (a) Schematics of an OPA with an on-chip laser on the hybrid III-V/Si platform. Reprinted with permission from [81] © The Optical Society. (b) The layout of a fully integrated OPA. Reprinted with permission from [82] © The Optical Society.

Compared with hybrid III-V/Si laser integration approaches, monolithically integrated rare-earth-based lasers offer various highly demanded performance characteristics to the on-chip sources, such as high output power, good thermal stability, and a narrow linewidth [77,78].

In general, on-chip integration of tunable laser sources results in complicated device structures [64], and their performances are limited in output power, linewidth, and tunable range [75]. The tunable lasers on the Si platform typically show tens of mW output power, kHz-level Lorentzian linewidths, and over 40 nm wavelength tuning in the C+L bands [83]. Note that a WGA can only provide a limited FOV over such a tuning range [84], and thus

arbitrary beam forming and steering cannot be achieved by this structure. Additionally, for the laser sources integrated with OPAs, the influence of temperature drift on the emission wavelengths should be considered [73].

The ability to actively switch among lasers [82] or emitters as in Figure 3c [37,62] expands the wavelength-tuning-enabled FOV of WGA-based OPAs. For the fully integrated hybrid Si OPAs, two tunable Vernier ring lasers with different tuning ranges were used to create a much wider wavelength-tuning range [82]. The limitation in FOV with the wavelength-tuning approach can also be expanded through the polarization-division and spatial-division multiplexed nanoantenna arrays, based on which over 40° tuning within a 100-nm wavelength range was achieved [37].

3.2. Beam Splitters

There are three kinds of beam splitters, i.e., the multimode interference (MMI) beam splitters, star couplers, and directional couplers. The MMI splitters equally distribute input power into each output channels [40,59,65,70,71,75]. The star coupler has a smaller footprint [12,35,42,85], which is especially useful for many output channels. Phase alignments are necessary to compensate for the phase error accumulations due to the path-length mismatch in a star coupler [42]. Compared with MMI splitters, star couplers usually have a larger insertion loss [81].

The directional couplers evanescently transfer power from the bus waveguide to the row waveguides and from each row waveguide to the output emitter array. By varying the coupling length, the same amount of power can be set at all the emitters [10,16,17,86,87]. Optical directional couplers can be used to achieve compact large-scale OPAs [16]. To take advantage of the low loss and high-power handling properties of Si₃N₄ and the excellent modulation performance of Si, hybrid OPA chips with Si₃N₄ and Si waveguide layers were realized, which are vertically coupled to each other with adiabatic linear tapers working as directional couplers [88,89]. The directional coupler structures can also be exploited for testing the optical crosstalk between the adjacent [90], the second nearest, and even the third-nearest waveguides. As another example, the wavelength-dependent directional coupler was also used for separating the 1.599 μ m signal wavelength from the 980 nm pump wavelength [77].

3.3. Phase Shifters

As one of the most important performance parameters of the phase-modulation-based OPAs, steering speed is determined by phase tuning agility [46]. The phase shift typically results from a refractive index change, which can be introduced by temperature tuning or carrier injection, corresponding to TO and EO phase shifters [91]. An ideal high-performance optical phase shifter features a low power consumption, a low insertion loss, and a small crosstalk [45]. MZI structures can be used to test and analyze the characteristics of phase shifters [40,70].

TO phase adjustments can be easily achieved without additional optical losses [72]. Up to now, the majority of the reconfigurable optical phase shifters used on the Si platform are based on the TO effects [92]. TO phase shifters consisting of various materials for integrated OPAs were demonstrated. Most of the TO heaters are metal film or metal film stacks, such as Ti [7], TiN [59,68,93], Pt [41,94], and Cu [95]. Commonly used metal stacks include Cr/Au [9], Ti/Au [35,72], and Ni-Cr-Au [96] for better adhesion, among which the Ti/Au metal stack is often chosen in mature fabrication. The Ti/Au metal stack can easily be replaced by the CMOS-compatible metals, such as TiN or W [72]. Apart from metals, alternative materials such as doped Si [12,45,86], polymer [97,98], graphene [75] can also be used as heaters. The doped Si was used for the convenience of the CMOS processes [86]. Polymers feature high TO coefficients and low thermal conductivity, facilitating low-power driving of the phase shifters and a low thermal crosstalk [98]. Thanks to the high thermal conductivity of graphene, a high operation speed on the order of 0.2 MHz was realized [75].

As presented in Figure 6a, metal heaters are widely used and placed far enough from the waveguides to reduce optical loss due to metal absorption [7,35,41,72,96]. The separation layer hinders heat transfer, which prolongs heating and cooling time [75]. Usually, a TO phase shifter possesses inherent drawbacks of a large power consumption and a low speed [70], and thus a large thermal time constant limits the maximum steering speed [52] and generally requires a power of >10 mW for a 2π phase shift [11].

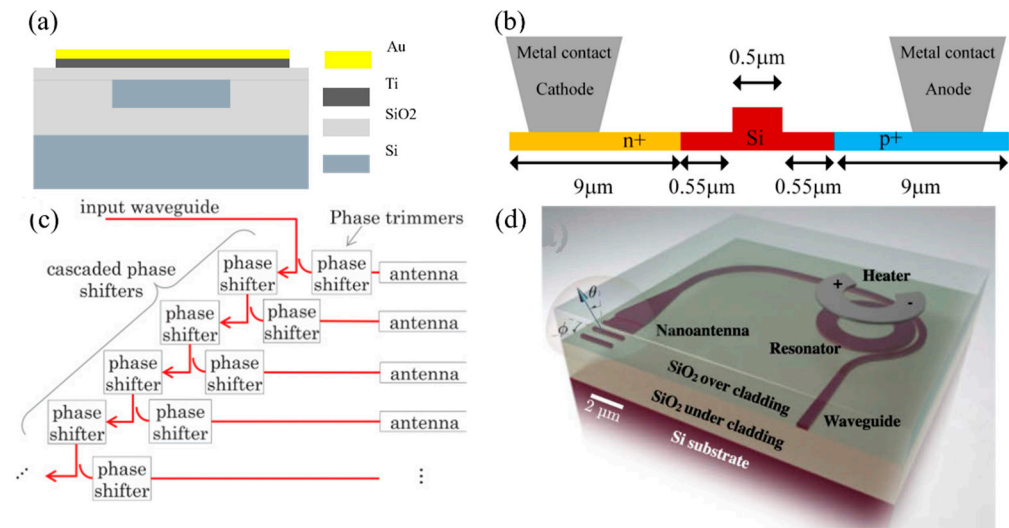


Figure 6. (a) Cross section of a TO phase shifter. (b) A p-i-n junction-based EO phase shifter for OPAs. Reprinted with permission from [43] © The Optical Society. (c) Simplified schematic of a cascaded-shifters-based OPA. Reprinted with permission from [99] © The Optical Society. (d) A compact spiral phase shifter. Reprinted with permission from [100] © The Optical Society.

Some novel structures [45,64] and materials [75,97,98] can be used to increase efficiency and speed. An efficient spiral TO phase shifter with a compact form factor was used to achieve a negligible crosstalk [45], while another highly efficient phase shifter was also proposed with a very small power consumption [101]. Impurity-doped contact heaters feature higher heating efficiencies and faster responses compared with non-contact metal heaters [64]. Graphene contact heaters directly on waveguides can be used to enhance heating efficiency [75]. Polymers have high TO effects and low thermal conductivities, which can be used as efficient phase modulators with low drive power [97,98]. A 16-channel polymer EF OPA with TO modulators and a small P_π of 2.5 mW was implemented [98]. However, polymer-based OPAs occupy a large chip size due to low refractive indices. A substrate functions as a heat sink. Deep etched trenches help to improve thermal isolation, confine heat, and increase phase-shifting efficiencies [45,72,75,81,93,102].

EO phase shifters have low crosstalk and high electrical bandwidths [11] and consume lower power than TO phase shifters [11,103]. A schematic of a p-i-n-junction-based EO phase shifter for OPAs is shown in Figure 6b [43]. The measured power consumption of the EO phase shifter was only $2 \mu\text{W}$ for a 2π phase shift [11], which is more than 3 orders of magnitude less than TO shifters. A 512-element OPA only required 1.8 W of power [104]. The dense III-V/Si phase-shifter-based OPA consumed less than 3 nW power for a 2π phase shift [42]. Additionally, the switching time of an EO phase shifter based on a p-n or p-i-n [44,52,70,81,82] junction can be as high as tens nanosecond level [64], which is much faster than a TO phase shifter. It is worth mentioning that EO phase shifters relying on the Pockels effect require a lower driving power. As an example, monolithically integrated lithium niobate (LiNbO_3) EO phase shifters with CMOS-compatible voltages enable excellent EO modulations [105], which can be readily used for power-efficient large-scale OPAs.

A fine-tuning system with simplified control can be achieved with a cascaded optical phase shifter architecture, which also enables compact packaging with a small

footprint [17,77,78,99,106], as shown in Figure 6c [99]. However, the grouped phase shifters hinder flexible steering. In general, without individual control, cascaded phase shifter structures may be more susceptible to thermal crosstalk as pointed out in [82]. Apart from the ability to achieve full 2D steering, an OPA with independent phase control enables phase calibration to mitigate fabrication errors, crosstalk, thermal and electrical drifts [45]. Significant flexibilities of OPAs with individually controlled phase shifter are achieved at the cost of increased chip complexities and sizes [45]. To alleviate demands, a folded row-column architecture was used to significantly reduce required phase shifter drivers and control circuits [45]. As presented in Figure 6d, ultra-compact ring resonator structures with a radius of a few microns can be used as compact phase shifters by varying the round trips experienced by light [100].

3.4. Emitters

As a part of integrated OPAs, antennas are used to transmit or receive light. There are two kinds of emitters, i.e., the EF structures with power radiated from the facets of waveguides and the WGAs with nearly vertical emission. Typically, the EF OPAs and the WGA-based OPAs enable 1D and 2D beam forming and steering, respectively. In EF OPAs, 1D beam forming and steering are demonstrated only by adjusting the phase difference between adjacent elements [41,59,61,94,107]. Using long WGAs as emitters instead, a 1D OPA allows for 2D dynamic beam forming and steering through wavelength-tuning in the polar direction, where the azimuthal dynamical control is still based on the refractive-index tuning [12,42]. Fully reconfigurable 2D patterns can only be generated with 2D WGA-based OPAs by varying phase differences [10,58,86]. By changing the phase differences with control circuits, flexible manipulation and dynamic control can be achieved. The beamwidth in the far-field pattern can be compressed by large apertures [108].

On-chip guided optical modes are scattered into free space at every periodically perturbed section of a WGA, where a local refractive index contrast is introduced commonly through etching, and the strength of light scattering in a WGA is determined by etching depths. Millimeter-scale WGAs enable uniform emission by varying duty cycles [14,109]. This essentially builds a large aperture [108]. A millimeter-long Si/Si₃N₄ WGA was used to achieve a diffraction-limited beamwidth of 0.089° and maximum FOV simultaneously [109]. The 500-μm-long WGA enabled a large emitting aperture and a small beamwidth of 0.15° [14].

Without breaking the up/down symmetry in WGAs, about half of light radiates to substrates [99]. Any downward radiation causes decreased efficiency. Additionally, the downward radiation experiences multiple reflections and leads to beam interference and fluctuation in the far-field pattern [71,99]. Considering the power losses of sidelobes, the estimated efficiency can be even as low as ~25% [99]. To significantly improve the efficiency, distributed Bragg reflectors [90] or metal layers [76] underneath the WGAs were fabricated to reflect the undesirable downward emission, which increased manufacturing costs.

A dual-layer millimeter-scale Si₃N₄ WGA with upward radiation efficiency of 93% at 1.55 μm was proposed [108]. The perturbation strength was aperiodically modified along the millimeter-scale antenna such that uniform and efficient emission was achieved for the first time. This allows for the elimination of blind spots [108]. A new type of high-contrast WGAs with a flat interference zone greatly improved the emission efficiency and were used to achieve beam steering without crosstalk [110].

Usually, a deposited overlayer is used to protect OPAs. The overlayer interface together with a BOX-substrate interface unavoidably forms a Fabry-Perot cavity. In this case, light emitted into free-space experiences a transmission response varying with angles [108]. Directionality of WGAs depends on the thicknesses of both the upper and lower claddings, which should be optimized to enhance transmission toward free space [71,76,90]. To match the optimal thickness, commercial-available customized Si-on-insulator (SOI) wafers [76] and fabrication processes with designed overlayer thickness should be applied. Optical lengths of the cavity (including BOX layer and waveguide) should be odd-integer multiples

of a quarter wavelength to maximize upward emission. Such a cavity suppresses reflection at the air interface [71].

4. Configurations

In terms of emitter types, OPAs can be sorted into EF OPAs, WGA-based OPAs, and OPAs based on other emitter structures. The configurations of OPAs based on emitters will be discussed here.

4.1. EF OPAs

Typically, EF OPAs can only be tuned by the phase difference between adjacent elements. As presented in Figure 7a, the first experimentally demonstrated aperiodic OPA was implemented on SOI [9]. The 12-channel unequal spaced OPA with a silica (SiO_2) overlay and individual TO phase shifters enabled an FOV of 31.9° at $1.55 \mu\text{m}$ [9].

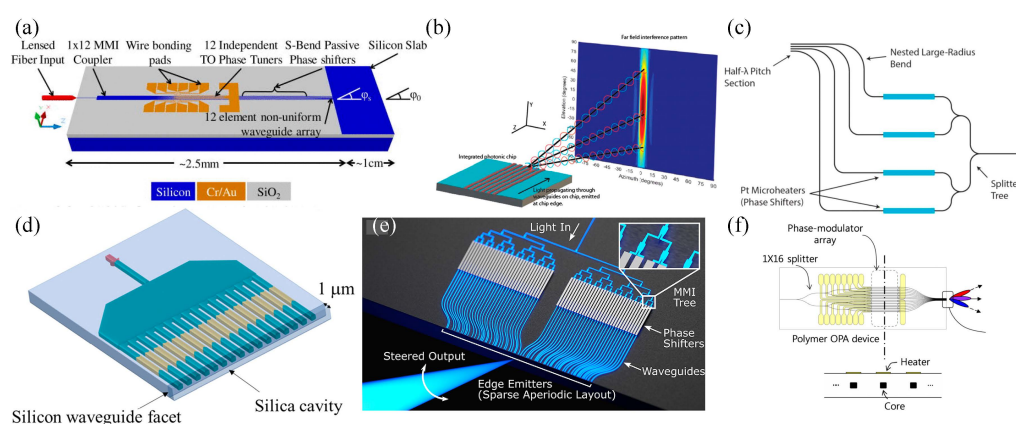


Figure 7. EF OPA structures. (a) A SOI-based EF OPA. Reproduced from [9] with the permission of AIP Publishing. (b) The first demonstrated half-wavelength spacing OPA. Reproduced from [61] with the permission of AIP Publishing. (c) A dispersion-engineered half-wavelength EF OPA with low crosstalk. Reprinted with permission from the author of [94] published on Arxiv, 2018. (d) A SOI-based EF OPA with a SiO_2 cavity for envelope tailoring. Reprinted with permission from [59] © The Optical Society. (e) A 1D 64-channel blue OPA with sparse aperiodic spacing. Reprinted with permission from [41] © The Optical Society. (f) Schematic of a 16-channel polymer EF OPA. Reprinted with permission from [98] © The Optical Society.

The highly desirable OPAs with wide FOVs are usually limited by grating lobes. An OPA with half-wavelength spacing eliminates the grating lobes and maximizes main lobe power. The first demonstrated OPA with half-wavelength spacing was presented by EF structures [61], as illustrated in Figure 7b. The OPA formed an FOV of 64° with a beamwidth of 17° at $1.55 \mu\text{m}$ [61]. FOVs are limited by the strong crosstalk of waveguides that are placed in close proximity, compared with their mode sizes. Crosstalk should be suppressed to achieve high-performance OPAs. A dispersion-engineered half-wavelength EF OPA with low crosstalk is shown in Figure 7c [94]. Even for several millimeter lengths, light propagates still in the input waveguide. The coupling among the nearest, second nearest, and third-nearest neighbors of the OPA was below 17 dB. An FOV of 180° and $>72\%$ efficiency was obtained by this EF OPA [94]. The dispersion-engineered OPAs enable wide FOVs and high efficiencies with low crosstalk. However, it is important to note that the optical intensity at large angles are weak under a Gaussian envelope in the far-field pattern. It is difficult to obtain precise imaging with this OPA.

A plateau envelope is meaningful for the precise imaging of OPAs, especially for the OPAs with a large steering angle. A $1\text{-}\mu\text{m}$ -long SiO_2 cavity was used to tailor the envelope of the EF OPA presented in Figure 7d. The steered beam exhibited a peak intensity fluctuation of less than 0.45 dB from -30° to 30° . The OPA incorporates a

coupling-suppressed curved waveguide array with a near-half-wavelength pitch and enables aliasing-free beam steering with an FOV of 64° and a beamwidth of 6.71° [59]. Due to fabrication limitations, the pitch of $0.8\ \mu\text{m}$ is slightly larger than half wavelength. Sparse OPAs can partially release the fabrication difficulties in forming a small pitch. A schematic of a 1D 64-channel sparse blue light OPA is presented in Figure 7e. The Si_3N_4 EF aperiodic OPA enabled an FOV of 50° and a full width at half-maximum (FWHM) beamwidth of 0.17° in the visible spectral range (488 nm) [41].

Typically, most implemented EF OPAs are based on Si photonics. EF OPAs can also be fabricated based on polymers [97,98]. Polymers have high TO effects and low thermal conductivities, which can be used as efficient phase modulators with a low drive power. As shown in Figure 7f, a 16-channel polymer EF OPA with TO modulators implemented a lower P_π of 2.5 mW [98].

As mentioned above, EF OPAs typically enable 1D beam forming and steering. Complicated EF OPA structures enable 2D patterns. A mirror mounted on a rotating stage was used to achieve a 2D dynamical pattern [41]. Additional off-chip cylindrical lenses were needed to collimate the diverging light of EF OPAs [41,98]. To achieve upward emission, a 45° mirror was set to direct the beam [98]. Furthermore, a kind of hybrid three-dimensional (3D) waveguide structures offered 2D patterns [111,112]. Main evaluation parameters of some EF OPAs in recent years are given in Table 1.

Table 1. Main evaluation parameters of some EF OPAs.

λ , μm	FOV	Spot	Pitch, μm	Array	Size, mm^2	Material	Shifter	Power, mW/π	Speed, μs	SLL, dB	Ref.
0.488	$>50^\circ$	0.17°	>1.95	64	0.97	Si_3N_4	TO	30	20	6.05	[41]
1.55	32°	N/A	>3.1	12	N/A	Si	TO	12.4	10	3	[9]
1.55	64°	6.71°	0.775	16	N/A	Si	TO	N/A	N/A	9.4	[59]
1.55	180°	1.6°	0.775	64	N/A	Si	TO	N/A	N/A	11.4	[94]
1.55	64°	17°	0.775	5	N/A	Si	TO	N/A	1000	N/A	[61]
1.55	164°	0.062°	>4.14	128	N/A	N/A	N/A	N/A	N/A	14.3	[107]
1.55	7°	N/A	12	16	N/A	N/A	TO	2.5	N/A	4.8	[98]
1.55	19.1°	3.9°	4.5	8	N/A	polymer	EO	N/A	0.5	N/A	[97]

4.2. WGA-Based OPAs

The first OPA introduced in Si photonics was implemented based on WGA structures, as presented in Figure 8a. The 1D 16-element WGA-based OPA was fabricated on the SOI platform. An FOV of $2.3^\circ \times 14.1^\circ$ was demonstrated with both TO phase modulation and wavelength tuning [7]. A 4×4 WGA-based OPA with an FOV of 1.5° was subsequently realized by the same group (Figure 8b). Wavelength tuning based on grating dispersion was exploited to decrease the number of phase controls [8]. The achieved FOV of 1.5° is relatively narrow due to the small fill factor of the OPA, which can be further improved by redesigning OPA with a proper fill factor. An 8×8 WGA-based OPA with Si heaters presented in Figure 8c enabled an FOV of $6^\circ \times 6^\circ$ and a beamwidth of $1.6^\circ \times 1.6^\circ$. Lightly doped Si waveguides, which provided considerable resistances and low optical losses, and heavily doped Si leads were used as heaters to drop most of the heating power on waveguides. Zigzagged Si lead structures were used to increase the heating length and to provide thermal isolations between waveguides and metal contacts. The measured TO efficiency was about 8.5 mW per π phase shift [58].

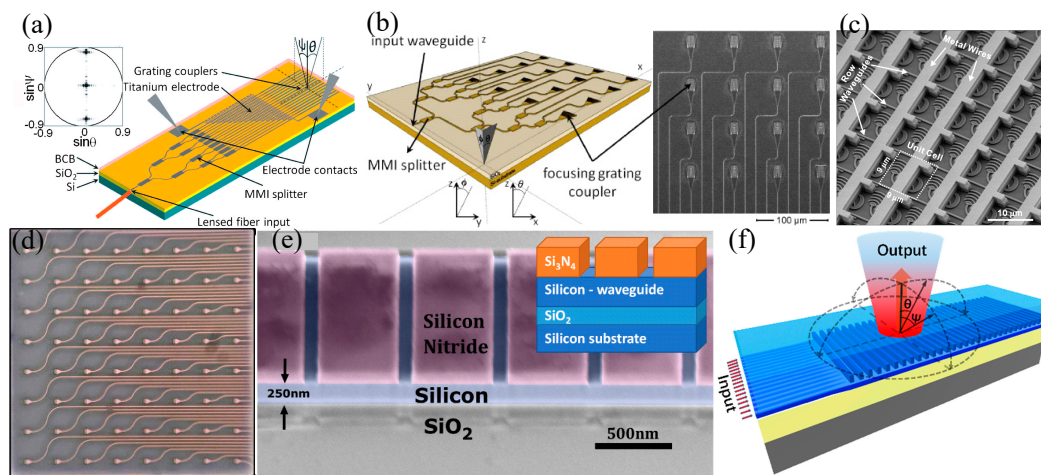


Figure 8. WGA-based OPAs. (a) The first OPA introduced in Si photonics. Reprinted with permission from [7] © The Optical Society. (b) A 4×4 WGA-based OPA. Reprinted with permission from [8] © The Optical Society. (c) SEM of a fabricated OPA after dry etching away the dielectric SiO_2 . Reprinted with permission from [87] © The Optical Society. (d) An 8×8 OPA receiver. Reprinted with permission from [43] © The Optical Society. (e) False-colored tilted SEM of an aperiodic $\text{Si}/\text{Si}_3\text{N}_4$ grating. Reprinted with permission from [109] © The Optical Society. (f) A high contrast WGA-based OPA with high efficiency and low crosstalk. Reprinted with permission from [110] © The Optical Society.

Based on the same physical principle and the reciprocity of electromagnetic wave propagation, a WGA-based transmitter can be theoretically used as its counterpart. Figure 8d shows the fabricated chip of a 64-element WGA-based OPA receiver [43].

Integrated OPAs suffer from a trade-off between the FOV and the beamwidth. A narrow beamwidth in the far field can be obtained by a large aperture aperiodic emitter array. In contrast, an aperiodic OPA with inherent sidelobe suppression enables a wide FOV, and millimeter-scale aperiodic WGAs can achieve almost uniform emission [108]. As shown in Figure 8e, a millimeter-long aperiodic $\text{Si}/\text{Si}_3\text{N}_4$ WGA obtained a wide FOV and a diffraction-limited beamwidth of 0.089° simultaneously [109]. A 2D 125-element OPA based on aperiodic WGAs enabled an FOV of $18.5^\circ \times 16^\circ$ by leveraging wavelength tuning and phase control. A narrow beamwidth of $0.15^\circ \times 0.25^\circ$ was achieved by this OPA with a large aperture size of $0.5 \times 0.5 \text{ mm}^2$ [14]. A sparse aperiodic OPA based on custom WGAs with tapered slabs and multiple dielectric sections enabled a high FOV-to-beamwidth ratio of $16^\circ/0.8^\circ$. More than 400 resolvable spots were achieved by the 128-element OPA [45].

Some novel WGA-based OPAs have been implemented [110,113]. A high-contrast WGA-based OPA with a flat interference zone presented in Figure 8f was used to achieve greatly enhanced emission efficiency [110]. The emission efficiency exceeded 50% in a broad wavelength range from 1.48 to $1.62 \mu\text{m}$, with its peak value of 93.9% at $1.55 \mu\text{m}$. The proposed structure worked as a whole device to achieve beam steering without crosstalk. The 16-channel OPA enabled an FOV of $45.6^\circ \times 20.2^\circ$ and a beamwidth of $2.4^\circ \times 2.5^\circ$ [110]. In another work, a WGA-based multi-beam steering OPA enabled a flat-top envelope near the wavelength of 905 nm, which is achieved by using five non-uniformly placed WGAs in one channel. The 11-channel OPA enabled an FOV of $68.8^\circ \times 77^\circ$ and a beamwidth of 6.5° [113].

Typically, a 1D WGA-based OPA can be used to realize 2D dynamic beam forming and steering by phase modulation and grating dispersion in the azimuthal and polar directions, respectively [7,8,64]. This type of OPAs was widely demonstrated for its simple device configuration. N phase shifters and one tunable laser are needed for an N -channel OPA [12]. 1D long-WGA-based OPAs with narrow beamwidths enable excellent 2D dynamic beam forming and steering [11,12,65,66]. However, 1D WGA-based OPAs are limited by wavelength-dependent performance and the price of a precise laser. In this sense, if more steering flexibility is required, one has to resort to 2D OPAs.

A 2D OPA based on WGAs generates a 2D pattern by phase modulations of WGAs [10,58]. A 2D WGA-based OPA enables highly desirable flexible optical manipulation and dynamic control at a fixed wavelength. The scalability of the OPAs, which is limited by control complexities and power consumption, is the main issue to be solved. Main evaluation parameters of some WGA-based OPAs are given in Table 2.

Table 2. Main evaluation parameters of some WGA-based OPAs.

λ , μm	FOV, $a^\circ \times b^\circ$	Spot, $a^\circ \times b^\circ$	Pitch, μm	Array	Size, mm^2	Material	Shifter	Power, mW/π	Speed, μs	SLL, dB	Ref.
0.635	146	0.06×0.07	2	N/A	0.5×0.5	N/A	N/A	N/A	N/A	8.7	[65]
0.905	3×17.6	4.3×0.7	3	4×4	$- \times 0.09$	Si_3N_4	TO	87.6	N/A	N/A	[99]
1.064	$11 \times -$	1.1	2	16	N/A	Si_3N_4	TO	~95	~125	N/A	[93]
1.30	80×17	0.14×0.14	7.25	128	1	Si	TO	8	N/A	8.9	[12]
1.55	2.3×14.1	2.7×2.4	2	16	N/A	Si	TO	8.2	N/A	N/A	[7]
1.55	20×14	1.6×0.6	3.5	16	4×0.2	Si	TO	~215	N/A	10	[96]
1.55	6×6	N/A	N/A	8×8	N/A	N/A	TO	8.5	N/A	N/A	[10]
1.55	10×6.5	2×0.2	5.5	8	$- \times 0.5$	InP	EO	N/A	0.5	N/A	[79]
1.55	20×15	1.2×0.5	4	16	N/A	N/A	TO	20	N/A	>10	[40]
1.55	23×3.6	1×0.6	4	32	N/A	Si	EO	160	0.02	5.5	[82]
1.55	1.6×1.6	N/A	33	8×8	N/A	N/A	TO	N/A	N/A	11	[86]
1.55	1.5×1.5	0.5×0.5	50	4×4	<1	Si	EO	N/A	0.005	N/A	[52]
1.55	46	0.02×0.02	4	1024	4×4	Si_3N_4	N/A	N/A	N/A	10	[65]
1.55	46×36	0.85×0.18	2	50	N/A	Si	TO	13	N/A	8	[17]
1.55	6.6	N/A	N/A	N/A	$- \times 1$	Si/ Si_3N_4	N/A	N/A	N/A	N/A	[66]
1.55	180	N/A	>2.3	N/A	N/A	N/A	N/A	N/A	N/A	>13.5	[114]
1.55	45	0.03	2	1024	0.004×0.06	Si	TO	48	N/A	9	[16]
1.55	70×14	0.15×0.15	1.3	512	N/A	N/A	TO	2.6	N/A	8	[104]
1.55	$106 \times -$	6.2×3.8	0.9	20	$35 \times -$	Si	N/A	N/A	N/A	7	[60]
1.55	66×3.3	N/A	1.3	24	$5 \times -$	Si/ Si_3N_4	TO	11	N/A	7	[90]
1.55	45.6×20.2	2.4×2.5	N/A	16	$0.08 \times -$	Si	N/A	N/A	N/A	28.4	[110]
1.55	10×45.4	5.8×3.2	2	16	1.75×1.2	Si	EO & TO	N/A, 2.3	N/A, 0.068	N/A	[64]
1.55	56×15	0.04	1.65	512	10	N/A	EO	<1	<30	12	[11]
1.55	$- \times 8.6$	N/A	N/A	N/A	$4 \times -$	Si/ Si_3N_4	N/A	N/A	N/A	N/A	[115]
1.55	51×28	0.78×0.02	2	32	$10 \times -$	hybrid	EO	1.5×10^{-6}	6.1×10^{-4}	16	[42]
1.55	18.5×16	0.15×0.25	4	125	0.5×0.5	N/A	TO	20	N/A	7.4	[14]
1.55	97×17.1	2.3×2.8	N/A	32	N/A	Si/ Si_3N_4	TO	N/A	N/A	N/A	[88]
1.55	$130 \times -$	2.52	0.8	33	0.026×0.09	Si	N/A	N/A	N/A	5.2	[116]
1.50	7×7	N/A	11	8×8	1×0.95	N/A	TO	N/A	N/A	N/A	[74]
1.55	16×16	0.8×0.8	5.6	128	2.08	Si	TO	10.6	N/A	12	[45]
1.55	70×6	0.15×0.08	1.3	512	$2 \times -$	Si	TO	1.7	6.5	7.5	[103]
1.55	8.9×2.2	0.92×0.32	10, 40	8×8	7×3	Si	EO	17	0.05	N/A	[44]
1.55	97×17.1	2.3×2.8	1	32	N/A	Si	TO	N/A	N/A	N/A	[117]
1.55	$- \times 7.4$	0.2×0.6	4	32	N/A	Si_3N_4	N/A	N/A	N/A	N/A	[71]
4.6	12.7×12	3.08×0.18	6	12	$2 \times -$	Ge/ Si_3N_4	TO	~52	N/A	N/A	[72]

4.3. Other OPAs

The above-mentioned EF OPAs and WGA-based OPAs are the most common structures for dynamic beam manipulation. Beam forming and steering can also be realized by other OPAs. A bidirectional wide-angle WGA for OPAs with wide FOVs [118], an optical scanning structure based on wavelength division filters [68], and a polarization-division and spatial-division multiplexed nanoantenna array [37] will be discussed here.

As mentioned above, without breaking the up/down symmetry of a WGA, nearly half of the input power radiates downwards. Downward radiation causes a decreased efficiency and fluctuation in the far field [72,105]. It is difficult to eliminate downward radiation. Meanwhile, it is challenging to realize WGA-based OPAs with high efficiencies and full FOVs. A bidirectional wide-angle WGA for OPAs presented in Figure 9a was used to solve these problems [118]. An FOV of 180° was achieved by taking advantage of the bidirectional radiation characteristic of the WGA. Additionally, power consumption, control units, and the number of elements of OPAs could be decreased to half due to the bidirectional radiation. This WGA solved the problem of weak intensity of large steering angles simultaneously, and approximately uniform intensity was achieved, making it a promising candidate for high-performance OPAs [118].

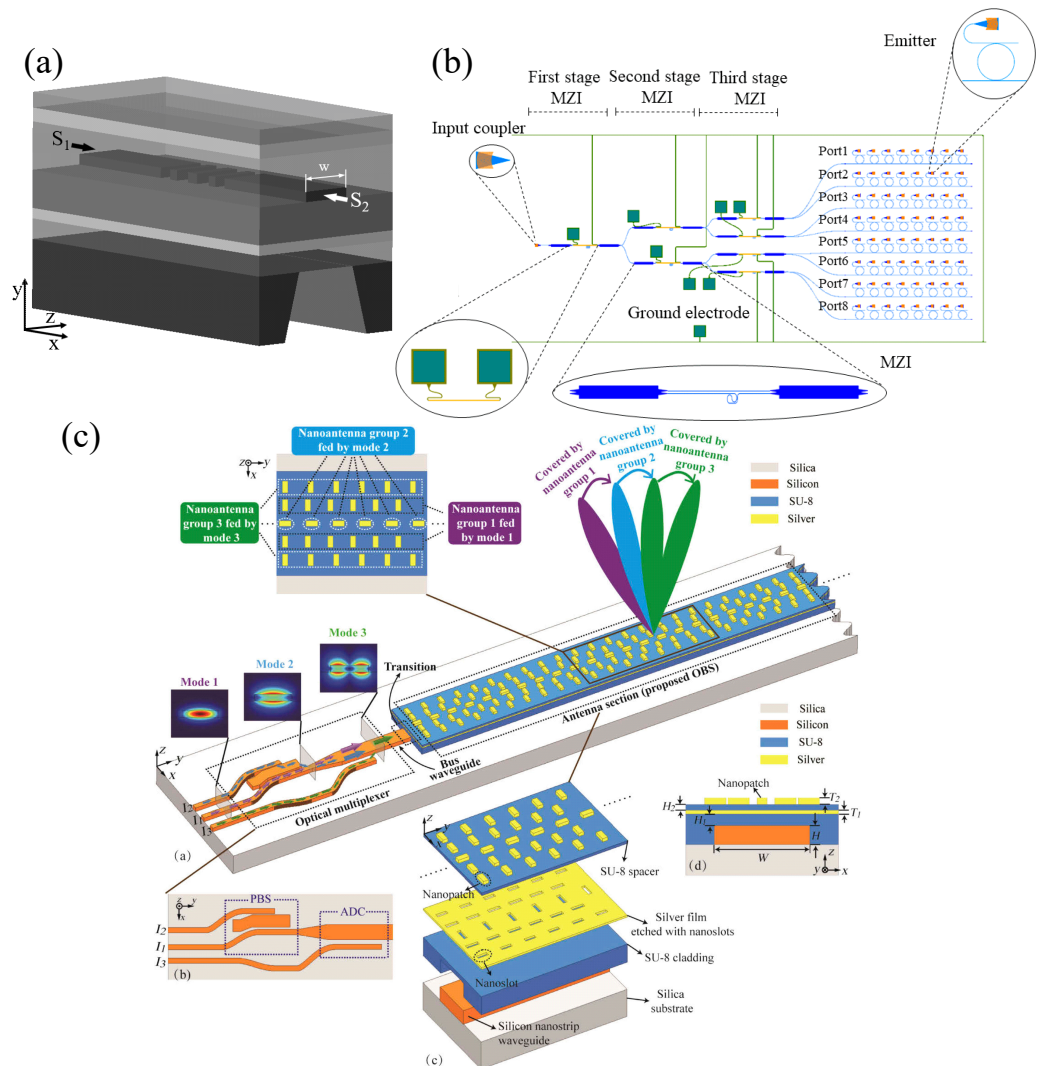


Figure 9. Some structures for beam forming and steering. (a) A bidirectional wide-angle WGA for OPAs [118]. (b) A 2D 8×8 optical scanning structure with wavelength division filters and emission array. Reproduced from [68] published by IEEE, 2019. (c) A polarization-division and spatial-division multiplexed nanoantenna array. Reprinted with permission from [37] © The Optical Society.

An OPA combining microring-based emitters and wavelength division filters presented in Figure 9b realized 2D optical scanning completely through wavelength tuning [68]. The MZIs and microring array separated different wavelengths from the input light and sent them to the corresponding emitters. For this 64-channel structure, an FOV of $6^\circ \times 4^\circ$ was realized by wavelength tuning from 1.55 to 1.56 μm [68]. This 2D OPA

with a large WGA spacing resulted in a limited FOV and a wide beamwidth. The FOV should be widened for practical applications. Additional collimation lenses are needed for high-performance beam forming and steering with narrow beamwidths.

The long-WGA-based OPA has a narrow FOV because of the limited wavelength tunability. The narrow FOV can be expanded by the polarization-division and spatial-division multiplexed nanoantenna array presented in Figure 9c [37]. Three independently controlled nanoantenna groups were densely packed and fed by a common Si nanostrip. The OPA enabled an FOV of 40° in a wavelength tuning range of 100 nm [37]. Some drawbacks of this device are: a custom mode converter is needed in the OPA; more nanoantenna groups are needed to resemble OPAs with narrow beamwidths; complex control circuits are needed for large-scale structures; the loss is significant for the application of silver antennas.

5. Material Platforms

Integrated OPAs demonstrated on photonics platforms enable low-cost chip-scale applications. In addition to conventional Si platforms, OPAs have been implemented on other photonic integrated platforms. The major platforms of integrated OPAs, which include Si photonics platforms, III/V platforms, and III–V/Si hybrid platforms, will be discussed in this section.

5.1. Si Photonics Platforms

There are four major Si photonics platforms, which can be used for integrated OPAs. As two main platforms, most integrated OPAs are implemented based on the Si platform or the Si_3N_4 platform. Based on mature Si/ Si_3N_4 platform, large-scale WGAs of mm-size can be accurately and reliably fabricated. The high-power handling problem of large-scale OPAs can also be solved by the Si/ Si_3N_4 platform. The germanium (Ge)/ Si_3N_4 platform is mainly used for the mid-infrared (MIR) applications, thanks to the very low optical absorption of Ge in this wavelength range.

5.1.1. OPAs Based on the Si Platform

Si photonic devices consist of many important components of photonic integrated circuits (PICs) because of the availabilities of the large-area Si wafers, the mature CMOS-compatible fabrication technology, the sophisticated assembly processes, and the monolithically integrated Ge photodetectors and modulators [119]. The high refractive-index contrast between Si and SiO_2 offers strong light confinement, thus enabling high-density PICs. As an example, Si photonic devices have been exploited as fast optical interconnectors for CMOS electronics [120,121]. In addition, Si is an excellent material for its low-loss window extending from 1.1 to $7\ \mu\text{m}$ [121]. For OPA applications, each closely placed antenna of an OPA should provide a 2π phase tunability to allow flexible reshaping of the far-field radiation. Versatile phase-tuning mechanisms such as efficient TO effect and fast free-carrier dispersion make Si PICs a promising candidate to address the stringent design and fabrications of OPAs [58].

For typical SOI wafers, the BOX thickness is $1\text{--}3\ \mu\text{m}$ for efficient optical mode confinement in the devices [122]. To enable single-mode optical waveguides at telecommunication wavelengths, the top Si thickness is usually at least 200 nm [122]. Typically, there are two types of SOI wafers. The ones with a top Si layer of 220 nm are typically used for passive devices at $1.55\ \mu\text{m}$, and the ones with a thicker top Si layer of 500 nm are used for heterogeneously integrated Si photonic devices at the same wavelength [114]. SOI wafers with different geometrical specifications are commercially available [76]. As a fundamental platform for photonic integrated devices, SOI platforms have been exploited for the realization of various EF OPAs [9,59,61] and WGA-based OPAs [7,8,14–17,35,67,87,96,117].

The first experimentally demonstrated aperiodic EF OPA was implemented on the SOI platform [9], where an FOV of 31.9° was achieved with individually controllable TO shifters at a wavelength of $1.55\ \mu\text{m}$ [9]. The first demonstrated OPA with half-wavelength spacing

was achieved by EF structures [61]. The SOI-based OPA shown in Figure 10a incorporated a near-half-wavelength curved waveguide array for crosstalk suppression [59]. The OPA with a $0.8\ \mu\text{m}$ pitch enabled aliasing-free beam steering of 64° with a beamwidth of 6.71° . A $1\text{-}\mu\text{m}$ -long SiO_2 cavity was exploited for plateau envelope tailoring. The steered beam exhibited a peak intensity fluctuation of less than $0.45\ \text{dB}$ in the emission direction of -30° to 30° [59].

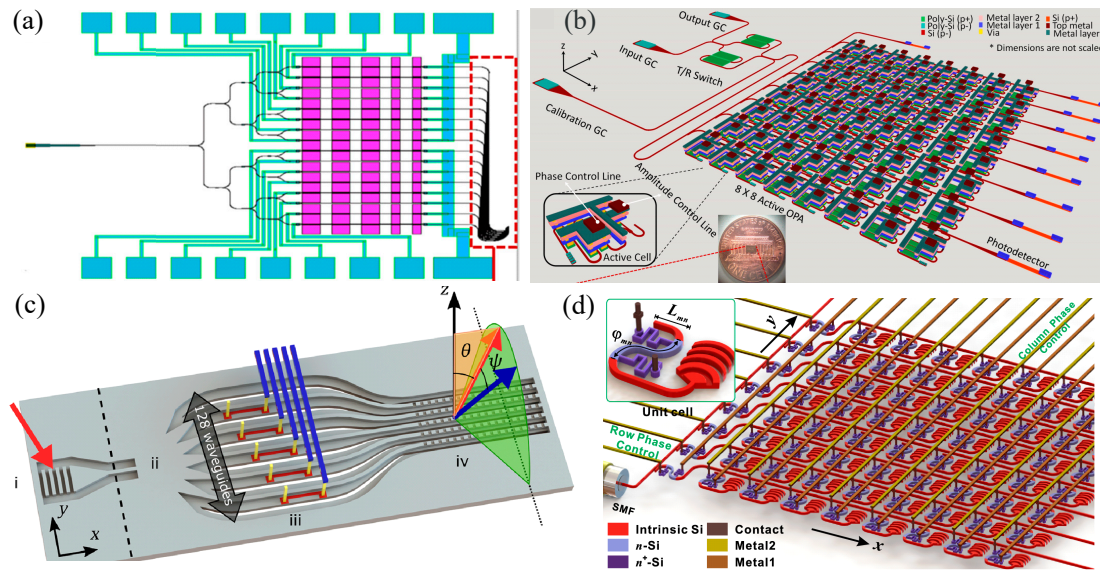


Figure 10. Typical OPA structures based on the Si platform. (a) The structure of an OPA chip with a plateau envelope. Reprinted with permission from [59] © The Optical Society. (b) An 8×8 monolithic OPA. Reprinted with permission from [86] © The Optical Society. (c) A 1D aperiodic high-resolution aliasing-free OPA. Reprinted with permission from [12] © The Optical Society. (d) A 2D aperiodic Si-based OPA with independently tunable phase shifters. Reprinted with permission from [87] © The Optical Society.

The first OPA introduced in Si photonics was implemented by a 1D 16-element WGA. An FOV of $2.3^\circ \times 14.1^\circ$ was achieved by the OPA with $0.8\text{-}\mu\text{m}$ -wide waveguides, spaced $2\ \mu\text{m}$ apart [7]. An FOV of 23° and a beamwidth of 1.27° were shown by an OPA of similar configuration, whose waveguides have a wider width of $4\ \mu\text{m}$ and a separation of $5\ \mu\text{m}$ [35]. In contrast, 2D OPAs can also be fabricated on the same platform. A 2D WGA-based OPA presented a small FOV of 1.5° [8]. An individually controlled 125-channel 2D Si OPA enabled a large FOV of $18.5^\circ \times 16^\circ$ by leveraging both wavelength tuning and phase control. A phase tuning efficiency of $20\ \text{mW}/\pi$ and a narrow beamwidth of $0.15^\circ \times 0.25^\circ$ were shown by this OPA with a large aperture size of $0.5 \times 0.5\ \text{mm}^2$ [14]. The first demonstration of coherent solid-state LiDAR was implemented by a Si OPA with cascaded phase shifters, and simultaneous distance and velocity measurements were performed using triangular frequency modulations [17].

As the electronic wirings for controlled phase shifters occupy an increasingly large area with the growing number of elements on OPAs, it is quite challenging to realize large-scale OPAs integrated with electronic controls on a single chip. Monolithically integrated OPAs provide a reliable and low-cost solution with densely distributed circuits and reduced footprints [16,86,122]. The first monolithically integrated OPA transceiver with individual amplitude and phase control is presented in Figure 10b [86]. This 8×8 OPA chip included TO phase shifters and attenuators, WGAs, and control electronics, and there were in total more than 300 optical components and over 74,000 electrical components. The OPA enabled a narrow FOV of $1.6^\circ \times 1.6^\circ$ and a sidelobe suppression ratio of $11\ \text{dB}$ [86]. Another monolithically integrated OPA chip consisted of 1024 uniformly spaced WGAs, 1192 phase shifters, and 168 attenuators. The OPA with an aperture size of $5.7 \times 6.4\ \text{mm}^2$ presented a

directional beam with a narrow beamwidth of 0.03° , which can be steered in a wide FOV of 45° [16].

Typically, well-designed aperiodic OPAs have wide FOVs. The aperiodic large-scale OPA presented in Figure 10c enabled a dramatical 2D beam steering capability of having more than 60,000 resolvable points within an FOV of $80^\circ \times 17^\circ$, enabled by the great beam directionality with a narrow beamwidth of $0.14^\circ \times 0.14^\circ$ [12]. The 2D 8×8 aperiodic Si OPA shown in Figure 10d consisted of individually controlled phase shifters, allowing both amplitude and phase engineering of the emitted optical beam from the OPA. The demonstrated OPA also enabled sidelobe suppression [87]. A 128-element aperiodic Si OPA based on a two-chip solution enabled a greatly high FOV-to-beamwidth ratio of $16^\circ/0.8^\circ$ [45]. For the OPAs based on directional couplers to distribute input power into each output channels, the minimal spacing between adjacent antennas is limited by the size of directional couplers, which might result in a relatively narrow FOV of the OPA. In addition, an OPA using directional couplers generally takes a large overall size. A novel serial WGA-based Si OPA significantly reduced the overall chip size and increased power efficiency while maintaining comparable far-field performance [123].

In addition to the above-mentioned OPA transmitters, integrated OPA receivers can also be demonstrated on the Si platform. The first 1D Si OPA receiver with an aperture size of $96 \times 50 \mu\text{m}^2$ presented an FOV of 30° and a beamwidth of 0.74° [69]. The first 2D OPA receiver on the Si platform was shown with an FOV of $8^\circ \times 8^\circ$ and a beamwidth of $0.75^\circ \times 0.75^\circ$ [43].

A wide variety of novel integrated OPAs have also been implemented on the Si photonics platform. Some examples are shown as follows. A half-wavelength-pitch EF OPA with an FOV of 180° was demonstrated by minimizing the mode overlaps of waveguides in the phase space [94]. A sparse aperiodic OPA based on WGAs provided beam steering in the full visible space while preserving a narrow beamwidth of $\sim 0.1^\circ$ and a high SMSR of 13.5 dB [114]. A 1D 512-element OPA with significantly low power consumption of $<1 \text{ mW}$ enabled a wide FOV of $56^\circ \times 15^\circ$ and $<30 \mu\text{s}$ high-speed 2D beam steering. A coherent 2D solid-state LiDAR based on this OPA could extract the velocity on diffusive targets at a range of near 200 m [11]. Based on p-i-n EO phase modulators, a fast OPA presented 2D beam steering at a frequency of 20 MHz. After calibration of the randomly distributed initial phases by interference, the OPA enabled an FOV of $8.9^\circ \times 2.2^\circ$ and a beamwidth of $0.92^\circ \times 0.32^\circ$ [44].

Si photonics provides a promising platform to realize high-yield the near-infrared (NIR) OPAs, and offers high-performance with competitive low-price for applications such as free-space communications, LiDAR, imaging, and biological sensing. Some issues remain to be further resolved, such as the strong nonlinear absorption of Si at high input powers.

5.1.2. OPAs Based on the Si_3N_4 Platform

The demonstrated OPAs on SOI platform are mainly limited to applications in the NIR spectral range due to the material transparency window. The Si platform offers a high refractive index and active functionalities, such as TO phase shifters and photodiodes. However, owing to the high index contrast, Si devices suffer from significant scattering losses from surface roughness [121]. Additionally, it is challenging to achieve highly desirable large apertures with Si WGA-based OPAs. A variation of just 1 nm in the etch depth of a Si/ SiO_2 grating increases more than 11 percent of the grating strength [109]. The lengths of Si WGAs to emission light are typically shorter than a few hundred micrometers [66]. Furthermore, Si devices suffer from strong nonlinear absorption effects in the telecommunication wavelength ranges, such as two-photon absorption, free carrier absorption, and large lowest-order nonlinear effects [119]. The nonlinearity-induced phase changes and material loss limit the scalability and output power of Si-based OPAs [65].

As a vital alternative to its Si counterpart, Si_3N_4 is transparent from visible to MIR [124]. It is suitable for non-telecommunication applications such as augmented reality and virtual reality displays, quantum information processing, biological sensing, and biological

stimulations. Additionally, the lower index contrast between a Si_3N_4 waveguide and its SiO_2 cladding reduces the waveguide losses due to the sidewall roughness scattering and dispersion, and lowered the sensitivity of device performance to variations in waveguide dimensions [119,125]. Si_3N_4 has a superior passive optical property. It is CMOS-compatible and more phase stable due to its five times smaller TO coefficient compared to Si [119]. Si_3N_4 is spotlighted as a prominent substitute for Si without two-photon absorption and free-carrier absorption in the telecommunication wavelength range [119,125]. The lowest-order nonlinear susceptibility of Si_3N_4 is about 20 times smaller than that of Si [119], which allows for the low-loss propagation of high-power guided modes, making it an ideal material for large-scale PICs [65]. Together with the moderate refractive index, Si_3N_4 -based OPA allows for further scaling up of the aperture size [65].

Owning to the aforementioned merits of Si_3N_4 , various integrated OPAs have been demonstrated on the Si_3N_4 platform [41,62,65,71,93,108]. A passive large-scale Si_3N_4 OPA with a large aperture size of $4 \times 4 \text{ mm}^2$ was demonstrated at the wavelength of $1.55 \mu\text{m}$. A record small beamwidth of $0.021^\circ \times 0.021^\circ$ and a sidelobe suppression ratio of 10 dB were achieved by this OPA [65]. The first OPA in the visible range (635 nm) with a large aperture of $0.5 \times 0.5 \text{ mm}^2$ and a beamwidth of $0.064^\circ \times 0.074^\circ$ was demonstrated [65]. A sparse aperiodic Si_3N_4 OPA was designed to mitigate the fabrication constraints at a short wavelength of 488 nm. An FOV of 50° and a beamwidth of 0.17° were achieved by the blue light OPA [41]. A 16-channel Si_3N_4 OPA exhibited an FOV of $\sim 12^\circ$ and a beamwidth of $\sim 1.1^\circ$ at $1.064 \mu\text{m}$ [93].

A dual-layer millimeter-scale Si_3N_4 WGA-based OPA with unidirectional emission was achieved with extremely high upward radiation efficiency of 93% at $1.55 \mu\text{m}$ [108]. The aperiodic antenna presented uniform emission on a millimeter scale for the first time, allow for a highly effective aperture with the elimination of blind spots [108]. Another Si_3N_4 WGA-based OPA enabled a beamwidth of $0.2^\circ \times 0.6^\circ$ and an FOV of 7.4° were shown by wavelength tuning from 1.53 to $1.63 \mu\text{m}$ [71]. A 2D Si_3N_4 OPA shown in Figure 11a enabled an FOV of $3^\circ \times 17.6^\circ$ at a fixed wavelength of 905 nm, where 2D beam steering was achieved by phase shifters and switching among various WGAs with different periods [62]. For the large-scale Si_3N_4 OPAs, the moderate refractive index of Si_3N_4 might lead to crosstalk among close placed antennas, which should be effectively suppressed.

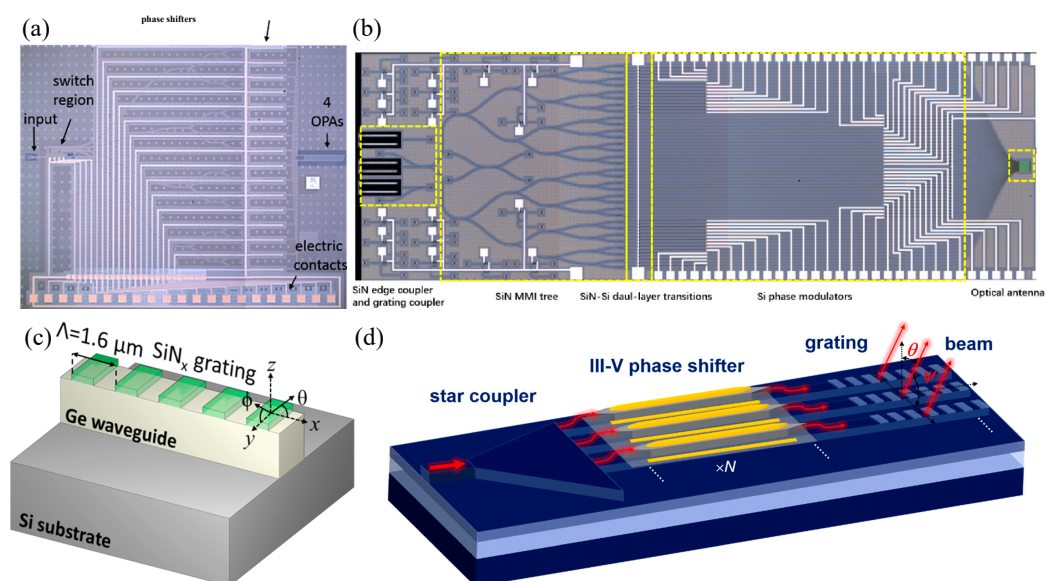


Figure 11. OPAs based on non-Si platforms. (a) Microscope image of a Si_3N_4 OPA for 2D beam steering at a fixed wavelength of 905 nm. Reprinted with permission from [62] © The Optical Society. (b) A Si/ Si_3N_4 dual-layer OPA. Reprinted with permission from [88] © 2020 Chinese Laser Press. (c) A Si_3N_4 /Ge-on-Si WGA for MIR OPAs. Reproduced from [72] published by IEEE, 2019. (d) A III-V/Si OPA. Reprinted with permission from [126] © The Optical Society.

5.1.3. OPAs Based on the Si/Si₃N₄ Platform

Structures based on the Si/Si₃N₄ platform, which is also named Si₃N₄ overlay grating [109], Si₃N₄ assisted grating [90], and Si/Si₃N₄ dual-layer structure [115], combine the advantages of Si and Si₃N₄, and enable millimeter-scale WGAs with weak perturbations and uniform emission for the realization of OPAs with large apertures and narrow beamwidths. The WGA performance sensitivity to the shallow etched depth is mitigated on the Si/Si₃N₄ platform compared to pure Si, thanks to the reduced refractive index of Si₃N₄. It also allows the operation aperture of the OPAs to be extended [65,109]. In addition, a Si/Si₃N₄ WGA with a nano-scale Al₂O₃ layer between the Si₃N₄ and Si, which serves as an etch-stop layer, is robust to fabrication variations [109].

The millimeter-long aperiodic Si/Si₃N₄ WGA presented in Figure 8e simultaneously enabled a diffraction-limited beamwidth of 0.089° and a wide FOV [109]. Light is highly confined in the Si input waveguide and the mode is weakly perturbed by a deposited Si₃N₄ layer. The millimeter-long WGA was robust to fabrication variations [109]. In another work, over 1-mm-long Si/Si₃N₄ aperiodic WGA enabled uniform emission and a narrow divergence [66]. Aperiodic WGA of even 1-cm-length has been realized, with a metal mirror underneath to achieve unidirectional radiation, and a diffraction-limited beamwidth of 0.02° was demonstrated [127]. A fabricated 5 mm-long OPA with 60 nm partially etched Si₃N₄ on the Si waveguide enabled crosstalk below −12 dB. An FOV of 66° × 3.3° was achieved via phase modulations and wavelength tuning [90]. Broadband high efficiency of more than 86% from 1.5 to 1.6 μm has been achieved in another Si/Si₃N₄ dual-layer WGA [115].

As mentioned above, a Si-based OPA chip cannot handle high power due to the strong nonlinear absorption effect [88], which results in relatively low emission power of the OPA. This issue can be partly solved by using the combined Si/Si₃N₄ platform, where extremely low-loss Si₃N₄ waveguides function as the power carrier and splitter and Si WGAs are used as emitters. Near lossless vertical transition between a Si₃N₄ layer and a Si layer was achieved by a pair of adiabatic linear tapers [88,89]. A 32-channel Si/Si₃N₄ dual-layer OPA presented in Figure 11b enabled an FOV of 96° × 14° and a beamwidth of 2.3° × 2.8°. A pair of 100-μm-long adiabatic linear tapers functioned as a vertical coupler on the WGA-based OPA chip [88]. A similar 64-channel OPA enabled a beamwidth of 0.4° × 0.47° [89]. The Si₃N₄/Si double-layer structure can also be used to implement EF OPAs.

Si₃N₄-on-Si WGAs are promising for highly desirable large-scale OPAs and for high-power applications. Compared with Si OPAs, devices based on the Si/Si₃N₄ platform need additional deposition and etch processes. High-efficient vertical couplers between the double layers should be designed for the Si/Si₃N₄ platform-based OPAs.

5.1.4. OPAs Based on the Ge/Si₃N₄ Platform

MIR OPAs employing wafer-scale fabrication are attractive to chemical and biological sensing, spectroscopies, thermal LiDAR, and free-space optical communications overcoming some atmospheric turbulence and scintillation [72,124]. Additionally, MIR OPAs can also benefit from exploiting the transparency window of the atmosphere and high eye-safety optical power levels [72]. However, current Si photonics platforms involving Si and SiO₂ are incompatible with MIR for the strong material absorption [124]. Due to the large transparency window covering 2–14 μm and CMOS compatibility [124], Ge is a promising material for the MIR waveband. Compared with Si photonic structures, Ge-based photonic structures have a larger TO effect coefficient and a higher refractive index [72]. The free-carrier effect is more pronounced [72]. A Ge/Si₃N₄ WGA for OPAs presented in Figure 11c was capable of 2D beam steering at 4.6 μm [72]. The linearly tapered millimeter-long WGA with uniform emission intensity realized an FOV of 12.7° × 12° and a beamwidth of 3.08° × 0.18° [72]. Another chip-scale Ge-Si₃N₄ OPA enabled the same FOV and a beamwidth of 2.86° × 0.47° [102]. Ge has been widely used in Si photonic foundries, making it attractive for MIR OPAs [72,102].

5.2. III-V Platforms

As one of the III–V semiconductor material, InP is an ideal integration platform for components operating in the wavelength range of 1.3–1.6 μm [128]. In addition, various monolithically integrated active and passive components have been implemented on the InP platform [79,128,129]. Potentially all components necessary for beam steering can be integrated on the InP platform [79]. The platform allows for the placement of amplifiers and lasers, ultra-high-performance modulators, and wideband photodetectors in the C and L band in PICs [129], and full PICs can be tested on wafer for the integration of sources and detectors [129]. Based on the integrated semiconductor optical amplifiers on the InP platform, high optical power for large-scale OPA applications can be potentially generated [79]. InP phase shifters with current injections enable up to a gigahertz bandwidth, and the tuning time of the widely tunable laser is reduced to a few nanoseconds [79], enabling very fast beam steering with InP OPAs. Furthermore, InP is a mature platform for large-scale photonic integration. The InP platform with standardization of photonic integration processing, which enables the realization of a broad range of applications with dramatically reduced cost, is a versatile and easily accessible generic integration platform for PICs [129]. This allows a scalable solution for large-scale PICs. An OPA based on the InP platform enabled an FOV of $10^\circ \times 6.5^\circ$ and a beamwidth of $2^\circ \times 0.2^\circ$. The longitudinal beam steering efficiency of the integrated tunable sampled-grating distributed Bragg reflector laser was $0.14^\circ/\text{nm}$. Very fast beam steering ($>10^7/\text{s}$) in both dimensions was achieved [79].

5.3. III-V/Si Hybrid Platforms

The Si platform is commonly used to fabricate integrated OPAs. Up to now, the majority of the variable optical phase shifters used on the Si platform are based on TO effects [92]. TO phase shifter-based Si OPAs suffer from limited bandwidths (typically a few kHz) that decrease beam steering speed. High-power consumption and thermal crosstalk limit the integration densities of the OPAs [42]. EO Si phase shifters based on p-n junctions are capable of dense integrations with high operation speeds (tens of GHz) and low power consumption ($<2\ \mu\text{W}$) [42]. However, the efficiency of the EO Si phase shifters is inherently limited by the free carrier dispersion effect, resulting in high operation voltages or excessive lengths [42]. Modulation effects in III–V/Si phase shifters, such as the quantum-confined Stark effect, band filling, band shrinkage, and the Pockels effect, can be used to increase modulation efficiencies and decrease operating voltages [42,85]. In addition, the III–V/Si phase shifter with higher electron mobility decreases carrier absorption loss and potentially allows for low residual amplitude modulations and high-speed operations [85]. Furthermore, the heterogeneous III–V/Si integration approaches can potentially realize fully integrated OPA systems [42].

An integrated OPA with an on-chip laser, amplifiers, and phase modulators was fabricated on the III–V/Si hybrid platform [81]. The OPA with an FOV of 12° and a beamwidth of $1.8^\circ \times 0.6^\circ$ was achieved by phase modulations [81]. As illustrated in Figure 11d, an OPA consisted of a star coupler, III–V/Si phase shifters, and WGAs [126]. The 4- μm -pitch heterogeneous phase shifters in the OPA enabled very low $V_{2\pi}$ of only 0.35–1.4 V across 200 nm, low residual amplitude modulation of only 0.1–0.15 dB for a 2π phase shift [126]. The first fully integrated 2D OPA on a III–V/Si hybrid platform consisted of 164 integrated components and two steering lasers with different tuning ranges. The OPA with a chip size of $6 \times 11.5\ \text{mm}^2$ enabled an FOV of $23^\circ \times 3.6^\circ$ and a beamwidth of $1^\circ \times 0.6^\circ$ [82]. Another high-performance III–V/Si phase shifter enabled a $V_{2\pi}$ of 0.45 V and residual amplitude modulation of 0.15 dB at 1.55 μm . The OPA based on this III–V/Si phase shifter achieved a power consumption of less than 3 nW for a 2π phase shift and a SMSR of 16 dB [85]. The 32-channel OPA with 4 μm pitch enabled 2D beam steering with an FOV of $22^\circ \times 28^\circ$ and a beamwidth of $0.78^\circ \times 0.02^\circ$ [85]. Another 32-channel OPA with 2- μm pitch demonstrated an FOV of $51^\circ \times 28^\circ$ [42].

6. Wavelengths

In terms of steering wavelengths, OPAs can be sorted into visible-spectral-range OPAs [41,65], NIR OPAs [10,12,62,93], and MIR OPAs [72,102]. As summarized in Tables 1 and 2, the majority of the OPAs work at a center wavelength of 1.55 μm .

OPAs in the visible spectral range (from 400 to 700 nm) are required for a wide range of emerging applications, such as augmented and virtual reality displays, biological sensors, and imaging [55,56]. Si_3N_4 is transparent in the visible spectral range [65,119]. The first large-aperture visible (635 nm) OPA with a sharp beamwidth of $0.064^\circ \times 0.074^\circ$ was demonstrated based on Si_3N_4 WGAs. The aperture size was $0.5 \times 0.5 \text{ mm}^2$ [65]. The first chip-scale blue light (488 nm) OPA using a Si_3N_4 platform achieved an FOV of 50° and a beamwidth of 0.17° [41].

Demonstrated OPAs are mainly working in the NIR communication spectral range [6–12,15–17,35,45,46] due to the transparency windows, high refractive index contrast of materials, convenient availability of sources, and CMOS compatibility. A Si_3N_4 OPA achieved 2D beam steering with an FOV of $3^\circ \times 17.6^\circ$ at a fixed wavelength of 905 nm [62]. Another 16-channel Si_3N_4 OPA showed an FOV of $\sim 12^\circ$ and a beamwidth of $\sim 1.1^\circ$ at 1.064 μm [93].

Additionally, MIR OPAs are attractive to chemical and biological sensing, spectroscopy, thermal LiDAR, and free-space optical communications overcoming some atmospheric turbulence and scintillation [72,124]. OPAs based on Ge/ Si_3N_4 WGAs achieved 2D beam forming and steering at 4.6 μm [72,102]. A fabricated OPA was capable of 2D beam steering with an FOV of $12.7^\circ \times 12^\circ$ and a beamwidth of $3.08^\circ \times 0.18^\circ$ [72]. Another MIR OPA achieved the same FOV and a different beamwidth of $2.86^\circ \times 0.47^\circ$ [102].

7. Performances

Here, we will discuss some main evaluation parameters of OPAs, which are FOVs, beamwidths and sidelobe suppression, modulation speeds, power consumption. It is important to note that one of critical factors determining FOVs, beamwidths and sidelobe suppression is the crosstalk and suppression among arrayed waveguide channels, and the efforts paid to reduce it should be reviewed first. For high-performance applications, large-scale OPAs are necessary. The scalability of OPAs will also be discussed. Finally, the calibration of OPAs to compensate for fabrication errors and mitigate crosstalk will be shown.

7.1. Crosstalk and Suppression

In large-scale OPAs, array performances can be degraded by unwanted coupling (optical or thermal) among tightly spaced components. Crosstalk is typically suppressed by enhanced light confinement and a mode mismatch between adjacent components. Increased thermal resistance can be applied among thermally sensitive components [92].

In theory, an OPA with a half-wavelength pitch enables a highly desirable FOV of 180° [59]. Compared with metal materials in radio-frequency phased arrays, the mode confinement of a dielectric waveguide is weak. A significant portion of the guided mode resides in cladding layers [59]. Crosstalk produced by mode superposition in OPAs with narrow pitches leads to scattered spots [117]. Standard 220 nm-high and 400 nm-wide Si waveguides should be placed at least $\sim 1 \mu\text{m}$ apart to minimize evanescent crosstalk [130].

Some efforts made to suppress optical crosstalk are presented in Figure 12. Demonstrated approaches to suppress optical crosstalk mainly include waveguide pairs with inserted periodic strips [131,132], waveguide superlattices with phase mismatches [133,134], subarray superlattice structures [60,116], half-wavelength-pitch waveguide arrays with minimized overlaps in phase space [94], curved waveguide arrays with different radii [59], sparse aperiodic structures [114], and waveguide arrays with photonic crystal slab insulators [135].

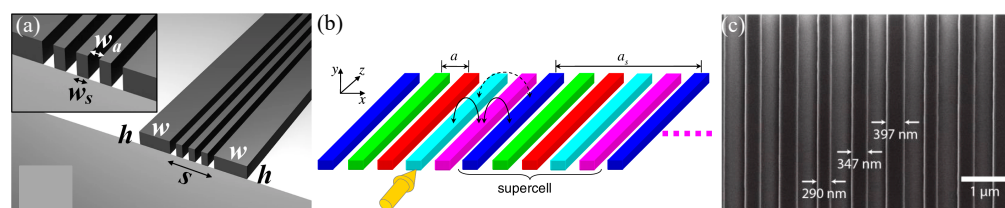


Figure 12. Some optical crosstalk-suppressed structures. (a) The configuration of Si waveguide pair with an inserted periodic Si strip array. Reproduced from [131] published by Springer Nature, 2017. (b) Schematic of waveguide superlattice structures. Reprinted with permission from [134] © 2020 Chinese Laser Press. (c) Top-view SEM of an OPA with varying waveguide widths for minimizing overlaps in phase space. Reprinted with permission from the author of [94] published on Arxiv, 2018.

As shown in Figure 12a, a periodic Si strip array was introduced between Si waveguide pair for efficient crosstalk reduction in PICs [131]. Two asymmetrical Si strips [132] can be used as well. Waveguide superlattice structures in Figure 12b were specially designed waveguide array with submicrometer/subwavelength pitches to achieve a very low crosstalk [134]. The waveguide superlattice with phase mismatches achieved by periodically varying widths of waveguides enabled a half-wavelength-pitch OPA with a low crosstalk [133,134]. SEM of an OPA with varying waveguide widths for minimizing the overlap between adjacent waveguides in phase space is shown in Figure 12c [94]. The half-wavelength-pitch EF OPA without crosstalk achieved an FOV of 180° and a $>72\%$ efficiency simultaneously [94]. Phase mismatches of a curved waveguide array can be introduced by waveguides with different radii. A 16-channel curved waveguide array with $0.8 \mu\text{m}$ pitch achieved crosstalk of -27.5 dB at a wavelength of $1.55 \mu\text{m}$ [59].

For WGA-based OPAs, crosstalk can also be suppressed by other approaches. The photonic bandgap of a 2D photonic crystal was used to optically isolate each element in a 16-channel WGA-based OPA with a small element spacing [135]. By changing the width of each element of a WGA-superlattice, a phase mismatch was introduced between adjacent antennas to prevent crosstalk. A WGA-superlattice-based OPA with a spacing of $0.9 \mu\text{m}$ achieved an FOV of 106° [60]. Another WGA-superlattice-based OPA with a near-half-wavelength spacing ($0.8 \mu\text{m}$) overcame conventional crosstalk problems and achieved an FOV of 130° and a beamwidth of 2.52° [116]. High-contrast WGAs of an OPA with a flat interference zone worked as a whole device to achieve beam steering without crosstalk. The emission efficiency of the OPA was 93.9% at $1.55 \mu\text{m}$ and exceeded 50% in a range of wavelength from 1.48 to $1.62 \mu\text{m}$ [110].

Both optical crosstalk and thermal crosstalk affect the applications of OPAs. As mentioned above, many effective efforts have been proposed to suppress optical crosstalk between adjacent waveguides. The tunability of a phase shifter is affected by heat leakage generated by other ones. Thermal crosstalk and phase mismatches disturb beam forming and steering. OPAs with cascaded phase shifters [77,78,99] are more susceptible to thermal crosstalk [82]. Compact thermally isolated phase shifters are highly desirable for large-scale OPAs.

FOVs of OPAs can be widened by decreasing spacing. In terms of heat leakage, OPAs with large pitches should be implemented to avoid thermal crosstalk among heaters [8,74,86,98]. However, the FOV is narrow. Some typical thermal crosstalk suppression structures for OPAs are presented in Figure 13. The thermal crosstalk problem can be settled by fan-in/fan-out sections [41,64,95,104], S-bends [81,98], deep etched isolation trenches [12,45,59,72,74], and a combination of fan-in/fan-out sections and deep etched isolation trenches [75]. Additionally, dummy phase shifters can also be used to reduce temperature gradient and crosstalk [38].

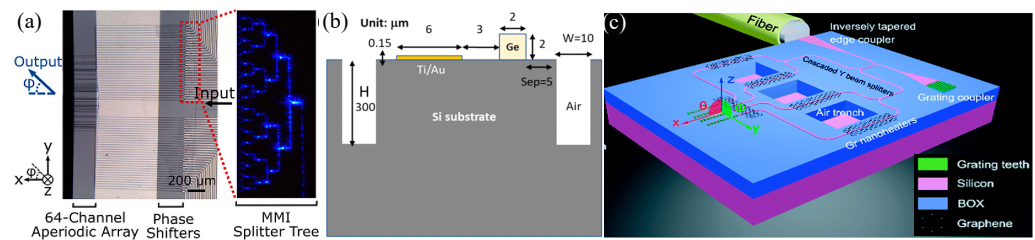


Figure 13. Some typical thermal crosstalk-suppressed structures for OPAs. (a) An OPA with a fan-in/fan-out section for thermal crosstalk suppression. Reprinted with permission from [41] © The Optical Society. (b) Cross-section of a TO phase shifter with deeply etched trenches. Reproduced from [72] published by IEEE, 2019. (c) An OPA with both a fan-in/fan-out section and deeply etched isolation trenches. Reproduced from [75] published by The Royal Society of Chemistry, 2018.

Based on the fan-in/fan-out sections shown in Figure 13a, TO phase shifters of a 64-channel blue light OPA were 30 μm apart in the lateral direction to ensure minimal thermal crosstalk. The outputs of the phase shifters were routed to a sparse aperiodic array of 970 μm spanning [41]. The spacing of the phase shifters of a Si₃N₄ OPA for visible light communications was more than 20 μm. After phase shifters, the distance between the waveguides was narrowed down to 1.52 μm for beam steering [95]. TO phase shifters in a 512-element Si OPA were 20 μm separated to minimize thermal crosstalk. The OPA with a decreased emitter spacing of 1.3 μm shown an FOV of 70° × 14° [104]. To reduce bend losses of waveguides, the bend radii of fan-in/fan-out sections should be large enough. The chip sizes are typically large.

In a III–V/Si hybrid OPA, S-bends after splitters were 150 μm separated to reduce thermal crosstalk. Additional S-bends reduced the spacing to 5.5 μm for output [81]. S-bends after TO phase modulators were used in a 16-channel polymer OPA to decrease the output waveguide pitch to 12 μm [98].

A cross section of the TO phase shifter of a MIR OPA is shown in Figure 13b. Deeply etched trenches reduce thermal crosstalk and decrease the required power for a 2π phase shift by more than an order of magnitude [72]. Based on compact spiral TO phase shifters and deep trenches around, 20 μm apart placed phase shifters in a sparse aperiodic OPA yielded low thermal crosstalk [45]. For aliasing-free OPAs with plateau envelopes, deep trenches among heaters were etched down to Si substrates to suppress thermal crosstalk and improve power efficiencies [59]. Deeply etched thermal isolating trenches on sides of TO phase shifters in an $N \times N$ OPA with $2N$ phase shifters worked as well [74].

A combination of fan-in/fan-out sections and deeply etched isolation trenches shown in Figure 13c was used to suppress thermal crosstalk [75]. To reduce thermal crosstalk, waveguide pitches in conventional structure was on the order of 100 μm, which can be reduced by one order using direct contact graphene heaters. Deeply etched trenches, which taking advantage of the poor thermal conductivity of air, improved heating efficiency by a factor of 2 [75].

A variety of effective implementations have been demonstrated for optical crosstalk suppression. Compared with fan-in/fan-out sections and S-bend structures, which occupy large areas, chip sizes of OPAs with deeply etched trenches are smaller. Well-designed compact spiral TO shifters with deeply etched trenches are attractive. Contact heaters with deeply etched trenches are useful to suppress thermal crosstalk.

7.2. FOV, Beamwidth, and Sidelobe Suppression

Integrated OPAs enable beam steering with no moving parts. Aliasing-free [12,59] OPAs with wide FOVs [94,114], narrow beamwidths [12,65], and plateau envelopes [59,113,118] are highly desirable. As a fundamental evaluator of OPAs, FOVs, also named steering angles, steering ranges, steering abilities, and addressability, determine the range of beam forming and steering. The beamwidths, also termed beam divergences, spot sizes, and divergence angles, are the sizes of transmitted or received spots of OPAs. FOVs and beamwidths are

typically described in degrees. The ratio between an FOV and a beamwidth is the number of resolvable points, which determines the maximum theoretically resolvable directions during steering. Resolvable points of an OPA are the multiplication of the number of resolvable points along two steering axes [12]. OPAs suffer from a trade-off between FOVs and beamwidths [109], which can be mitigated by metasurface-based OPAs [136]. These OPAs achieve wide FOVs and narrow beamwidths simultaneously [131]. Efficient radiation with a narrow beamwidth is essential for OPA-based applications over long distances. Considering the diffraction nature of light, a large-scale OPA is required [15].

Based on the phased array principle, the lateral FOV, φ , [7] is given by

$$\sin \varphi = \frac{\lambda \Delta \phi}{2\pi d} \quad (7)$$

where $\Delta \phi$ is the uniform phase difference between the WGAs with a spacing, d . The beamwidth is proportional to the ratio of wavelength to the multiplication of the aperture size of the N -element OPA and the cosine of the steering angle φ [7], as

$$\Delta \phi_{FWHM} \approx \frac{0.886\lambda}{Nd \cos \varphi} \quad (8)$$

FOVs are limited by grating lobes, when the pitch is larger than half wavelength [18,59]. For an OPA with a fixed number of emitters, the FOV can be widened by decreasing the spacing. However, the resolution of the OPA is unchanged for the increased main lobe beamwidth [12,117]. As described above, element pitches cannot be too small to avoid on-chip coupling between adjacent elements [12,60,117]. An off-chip divergence lens can widen FOVs, in which the resolution is unchanged for the expanded beamwidth [12].

Aperiodic arrays solve the issues of strong optical coupling between adjacent waveguides and fabrication difficulties in forming small pitches simultaneously [6]. Wide FOVs and high SMSRs can be simultaneously achieved by well-designed aperiodic OPAs [41,59,60,107,114,137] at the cost of decreased main lobe efficiencies and signal-to-noise ratios [59,107,114,137]. As the aperture is the same, the main lobe width is preserved by the sparse aperiodic arrays with a simplified control circuit [114]. Additionally, sidelobes of WGA superlattices are strongly suppressed by misaligning steering angles of sidelobes in different sub-arrays [60]. Aperiodic large-scale OPAs require complex design, increased fabrication complexity, and cost [60]. A 128-channel aperiodic OPA exhibited an impressively high-performance steerability with over 60,000 resolvable spots, where a wide FOV of $80^\circ \times 17^\circ$ and a narrow beamwidth of $0.14^\circ \times 0.14^\circ$ were achieved simultaneously [12].

Furthermore, multi-beam steering can also widen FOVs. Multiple-beam scanning can be realized in an OPA with a large element spacing by utilizing higher-order grating lobes [113]. The OPA with an 11×11 beam array and a flat-top envelope was proposed at a wavelength of 905 nm [113]. The OPA consists of non-uniformly distributed antennas with specially designed Dammann gratings. A total scanning FOV of $68.8^\circ \times 77^\circ$ was achieved by the OPA with a beamwidth of 6.5° perpendicular to the WGAs [113].

Moreover, a kind of complex circular OPAs can be used to realize wide FOVs and even 360° scanning [138–141]. Complex control circuits [139,140] and downward radiation [138,141] of circular OPAs are the issues to be solved.

An FOV of 180° has been aimed by an EF OPA [94] and a WGA-based OPA [114]. Other relatively wide FOVs of WGA-based OPAs presented in recent years are $97^\circ \times 17.1^\circ$ [117], $80^\circ \times 17^\circ$ [12], $70^\circ \times 14^\circ$ [104], $70^\circ \times 6^\circ$ [103], $56^\circ \times 15^\circ$ [11], $51^\circ \times 28^\circ$ [42], and $46^\circ \times 36^\circ$ [17]. A near diffraction-limited beamwidth of $0.021^\circ \times 0.021^\circ$ has been achieved [65]. Some narrow beamwidths, such as $0.064^\circ \times 0.074^\circ$ [65], $0.15^\circ \times 0.08^\circ$ [103], $0.78^\circ \times 0.02^\circ$ [42], $0.14^\circ \times 0.14^\circ$ [12], $0.15^\circ \times 0.15^\circ$ [104], $0.10^\circ \times 0.75^\circ$ [65], $0.85^\circ \times 0.18^\circ$ [17], have also been successfully demonstrated.

7.3. Modulation Speed

Steering based on wavelength sweeping due to grating dispersion has its speed determined by tunable lasers [96]. Phase-based steering speeds are determined by dynamical modulations of phase shifters [46]. The phase shifters should be compact (ideally with sub-wavelength pitches), low-power, and capable of a full 2π coverage [142].

For OPAs based on TO shifters, contact TO phase shifters were used to enhance heating efficiencies and steering speeds [64]. Graphene has high thermal conductivity and a high steering speed. With the combination of deeply etched trenches and graphene phase shifters, an OPA operated at 0.2 MHz was realized [75].

Compared with TO phase shifters, EO phase shifters based on the carrier induced index effect provide high-speed steering [64,79] with low power consumption [64]. Steering speeds of MHz level [44,79,97] and even GHz level [42,52,64] have been achieved by OPAs with EO phase shifters. An OPA utilizing the EO effect of InP achieved a sweeping speed of 1 MHz [79]. Another OPA with p-i-n EO phase shifters showed a beam steering speed of 20 MHz [44]. An 8-channel EF OPA with EO polymer phase shifters enabled an optical beam scanning of 2 MHz [97]. In most cases, phase modulation speeds are not a major concern of OPAs for microsecond scale scanning abilities of phase shifters [142].

7.4. Power Consumption

Typically, 1D long-WGA-based OPAs and 2D WGA-based OPAs can be used to achieve 2D beam forming and steering. Expensive precisely tunable lasers are necessary for 1D long-WGA-based OPAs. Grating-dispersion-based OPAs with compromised spectral purities, multi-beam projection capabilities [45] have wavelength-dependent components such as input grating couplers and power splitters [64]. 2D WGA-based OPAs are superior to 1D long-WGA-based OPAs without these compromises. However, a challenge for large-scale 2D OPAs is high power consumption [75].

Large-scale OPAs are highly needed for high-performance applications. Large-scale antennas are crucial to increase the aperture sizes of OPAs. Total power consumption of phase shifters and corresponding driver circuits are usually proportional to the number of antennas [45]. High-performance beam steering is hindered by thermal managements and power consumption [15]. Typically, a power-hungry TO phase shifter of a long-range (over 100 m) OPA application (like LiDAR) consumes a power of tens of milliwatts. Overall power consumption of hundreds of watts is needed for an OPA with thousands of power-hungry phase shifters [103]. However, due to the power capacity of demonstrated OPAs, large-scale OPAs are limited by the unaffordable power level [103]. The overwhelming power consumption of OPAs should be decreased.

The simplest way to lower the power consumption of large-scale OPAs is to decrease the number of phase shifters [74,113]. Additionally, the power consumption can be decreased by adoptions of EO phase shifters [11,42] and multi-pass structures [15,103]. Furthermore, a high-swing pulse-width modulation driving circuit can also be used to reduce the power consumption of OPAs [45,143].

For a 2D $N \times N$ OPA, the total power consumption can be significantly reduced by decreasing the number of phase shifters to only $2N$ [74]. As presented in Figure 14a, an 8×8 OPA was implemented using 16 phase shifters placed outside of the array aperture [74]. Compared with a typical OPA with the same angular range and beamwidth, a multi-beam steering OPA contained fewer phase shifters [113]. Low power consumption can be achieved by the multi-beam steering OPAs.

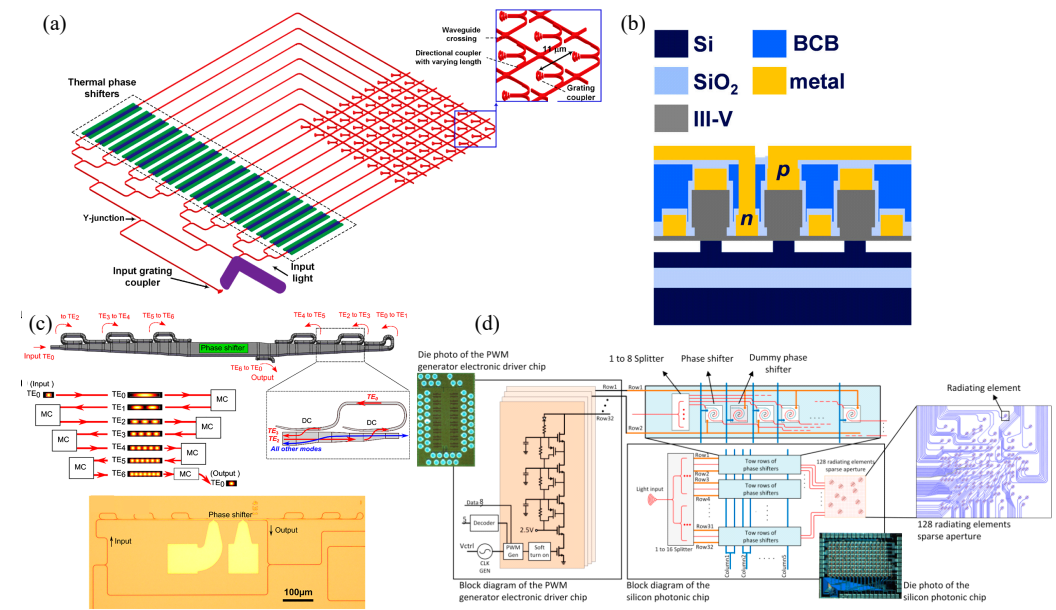


Figure 14. (a) An 8×8 OPA structure with 16 phase shifters placed outside of the array aperture. Reprinted with permission from [74] © The Optical Society. (b) Cross section of a III-V/Si phase shifter. Reprinted with permission from [126] © The Optical Society. (c) A multi-pass photonic structure based on mode multiplexing. Reprinted with permission from [103] © The Optical Society. (d) A two-chip solution OPA and die photos of fabricated chips. Reprinted with permission from the author of [143] © The Author(s).

OPAs require densely integrated high-performance power-efficient phase shifters [126]. The maximum static power consumption of an EO phase shifter of OPAs for long-range LiDAR and free-space communications was only $2 \mu\text{W}$ for a 2π phase shift. It was orders of magnitude less than TO shifters [11]. A III-V/Si heterogeneous phase shifter shown in Figure 14b provided a greatly low static power consumption ($<3 \text{ nW}$) and a high speed ($>1 \text{ GHz}$) [126]. Another heterogeneous phase-shifter-based OPA utilizing III-V multiple-quantum-well structures achieved a low operating voltage of 0.45 V and low power consumption of less than 3 nW for a 2π phase shift [42].

A multi-pass photonic structure shown in Figure 14c relied on spatial mode multiplexing to circulate light multiple times through a phase shifter [103]. A conversion to a different orthogonal spatial mode occurred each time when light was recirculated, eliminating unwanted interference, and maintaining broadband operation. By embedding a TO phase shifter in the multi-pass structure, a 2D 512-element OPA based on this structure achieved an FOV of $70^\circ \times 6^\circ$ and consumed power of 1.9 W . The power consumption of the TO phase shifter was $1.7 \text{ mW}/\pi$ [103].

TO phase shifters of a sparse OPA system shown in Figure 14d were electrically routed in a row-column fashion to reduce the number of electrical drivers. A custom pulse-width-modulated CMOS electronic chip reduced the power consumption of drivers [143]. By leveraging recent advances in the monolithic integration of photonic and electronic circuits, a large-scale coherent detector array with 512 pixels achieved an accuracy of 3.1 mm at 75 m when using only 4 mW of radiated optical power. This power was one-order smaller than existing solid-state systems at such ranges [144].

7.5. Scalability

Large-scale 1D OPAs have been implemented, such as 512-element OPAs [11,103,104] and 1024-element OPAs [16,65]. However, an expensive precisely tunable laser source is necessary for wavelength-tuning-based OPAs [11,104]. On-chip integrated tunable lasers are complex [64] and limited by power, linewidths, and tuning ranges [75,83,84]. Addi-

tionally, the OPA compromises its spectral purity, multi-beam projection capability [45], and wavelength-dependent performance [64]. 2D OPAs are superior to 1D OPAs without these problems.

Scalability is directly related to high-performance OPAs. Scalability of 2D OPAs is limited by huge power consumption [68,100,103], narrow FOVs [45], large sizes of phase shifters [68,100], and complex control circuits [10,16,103,116,144]. Owing to difficulties in providing electrical and photonic connections to every pixel, previous LiDAR systems have been typically restricted to fewer than 20 pixels [144]. Typically, each element needs a phase shifter [100]. Overall power consumption of an OPA linearly increases with the number of elements. The scalability of OPAs is challenged by overwhelming power consumption and high drive voltages of phase shifters [45,103,143]. In addition, the scalability and output power of Si OPAs are limited by nonlinearity losses and phase changes [65]. FOVs are limited by large element spacing for optical feeds, layouts of large-size WGAs, and crosstalk suppression [45]. Large-scale OPAs incur placement/routing congestion [45].

Low power consumption and wide FOVs can be achieved by sparse aperiodic OPAs [114]. Sparse OPAs with enough room for optical feed distribution are attractive for large-scale OPA-based applications [45], in which 128 antennas can be accommodated with crosstalk suppressed by sparse OPAs. Control complexities can also be decreased by adding another chip. Aperiodic OPAs avoid aliasing induced by sidelobes at the cost of increased design complexities [116]. As presented in Figure 14d, a two-chip solution of low-power sparse aperiodic OPA was implemented to solve the problem of scalability. The OPA provided enough room for planar optical feed distribution as well as an adjustable far-field pattern with minimum sidelobes and a narrow beamwidth [143].

The challenge of scalability can also be lightly addressed by serpentine OPAs. A serpentine OPA based on serially interconnected WGAs supported fully passive, wavelength-controlled 2D beam steering. An implemented serpentine OPA produced 16,500 addressable spots only by wavelength tuning [63]. It is challenging to implement very large-scale serpentine OPAs for the high-power handling ability of materials. Additionally, inline architectures with matched phase shifters, antenna pitches, high aperture fill factors, and minimized footprints were inherently scalable to thousands of elements [11]. A Si/Si₃N₄ dual-layer OPA chip was used to solve the issues of material-limited power and high loss propagation. Evanescent coupling between a pair of adiabatic linear tapers was used to achieve near-lossless vertical transitions between Si₃N₄ and Si layers [88,89]. Leveraging recent achievements in the monolithic integration of photonic and electronic circuits, a dense array of heterodyne detectors combined with a readout architecture enabled straightforward scaling to arbitrarily large arrays [144]. A 512-pixel large-scale coherent detector array was demonstrated in a 3D imaging system [144].

In addition, large-scale OPAs are limited by sensitivities to fabrication imperfections, phase mismatches, and temperature gradients [16]. It is hard to eliminate these flaws, which can be greatly decreased by precise fabrications and optimized element distributions. Calibration can also be used to partially solve these problems.

7.6. Calibration

Since OPAs operating at short wavelengths, performance monitoring and calibration are essential due to potentially significant pattern changes produced by slightly unavoidable processing imperfections [86]. Optical crosstalk deteriorates and even destroys patterns of OPAs. In addition, phase modulations, wavelengths of semiconductor lasers, and effective indexes are sensitive to temperature drift [73]. Thermal crosstalk and diffusions lead to performance degradations and errors due to the temperature dependence of steering angles, sidelobe suppression, and beamwidths. The effect of a temperature drift on the performance of OPAs should be considered [16]. Furthermore, electrical drifts are also universal in driving circuits. To correct phase errors and achieve designed far-field patterns, OPAs should be calibrated [40,72,102,107]. Independently controlled OPAs enable phase calibration to mitigate fabrication errors, crosstalk, thermal and elec-

trical drifts [45,92,96,142,145,146]. For some OPAs, cascaded phase shifters are grouped to achieve fine tuning of the beam to compensate for any phase noise due to fabrication errors [106].

In principle, OPA calibration requires measuring relative amplitudes and phases of all elements and compensating for mismatches [142]. Intensity has much less effect than phases on overall beamforming [146]. After measuring far-field patterns and discerning relative phases, an OPA was calibrated by iterative adjusting variable phase shifters [92]. A calibration with directly extracted phase differences from interference fringes was used to align random phases of another OPA [145]. Additionally, a look-up-table was used to calibrate element phase distributions of an OPA to achieve flexible 2D beam pointing within an FOV [11].

OPAs with fabrication imperfections have undesired steering angles and usually require time-consuming calibration before practical uses. Some calibrations have been applied for different cases [69,96,146–149]. Phase errors and background peaks of an OPA were minimized by feedback from a real-time far-field images infrared camera using a brute-force hill-climber optimization [96]. A phase modulation based on gradient ascent algorithm could also be used to calibrate OPAs [69]. A fast OPA calibration technique based on a stochastic parallel gradient descent algorithm (SPGDA) achieved the same quality images with random phase modulations. The SPGDA was three times faster than calibration used in a raster scanning scheme. Additionally, the SPGDA removed blurring and improved beam quality [147]. A chaotic stochastic parallel gradient descent algorithm combining chaos theory and SPGDA achieved fast adaptive phase correction with improved accuracy [148]. The SPGDA converged slowly and was easily stuck to a local minimum. A deterministic stochastic gradient descent algorithm provided a rapid on-chip calibration, which was scalable to OPAs with flexible channel counts. In this way, chip sizes and complexities of OPAs were significantly reduced [149]. Mature optimizations, such as hill-climbing, stochastic gradient descent algorithm, genetic algorithm, particle swarm optimization, generally provide good calibration. However, such approaches are not well scalable and generally suffer from local extremum uncertainty. They are severe issues for OPAs with element spacing larger than a wavelength. A modified rotating element electric field vector approach was used to calibrate the initial condition of an OPA [146]. The approach follows a sequential individual antenna phase calibration process. A calibration result with more accuracy and predictability was achieved [146].

8. Applications & Potential Alternatives

Large-scale OPAs with fast manipulation and dynamical steering provide a low-cost chip-scale solution for many high-performance applications. Some other structures function as potential alternatives to integrated OPAs. Applications of OPA will be discussed in this section. Some potential alternatives will be discussed.

8.1. Applications

Integrated OPAs possess stable, rapid, and precise beam steering with the removal of mechanical components, making them robust and insensitive to external turbulences. As a low-cost high-performance solution to beam steering, integrated OPAs generate narrow beams. Many applications based on integrated OPAs have been implemented, from free-space communications, LiDAR, imaging, biological sensing, to special beam generation.

8.1.1. OPAs for Free-Space Communications

Integrated OPAs provide non-mechanical beam steering. It is attractive to free-space communications for chip-scale size, light weight, and low power consumption. It is a promising option for free-space satellite communications with constrained size, weight, and power [91]. Compared with transmission over optical fibers, OPA-based free-space transmissions do not degrade the quality of tens of Gb/s signals [51].

A hybrid PIC composed of a SiO₂ planar lightwave circuit together with a 3D waveguide PIC was demonstrated for 15 orbital angular momentum (OAM) states [47]. A 20 Gb/s quadrature phase shift keyed signal for free-space space-division-multiplexing coherent optical transmission link was built. The capability for error-free transmission at an optical signal-to-noise ratio (OSNR) > 14 dB was shown for individual OAM beam multiplexing/demultiplexing. For two OAM states, an OSNR of >18 dB was achieved by the hybrid PIC [47]. An integrated OPA is a compact and low-cost solution to realize indoor optical wireless communication with limited mobility. A Si-based EF OPA was experimentally demonstrated in 12.5 Gb/s data transmission over 1.4 m free space distance [49]. A static 50 m lens-free point-to-point optical communication link at a data rate of 10 Gb/s was shown by two passive OPAs. A similar structure composed of an active OPA transmitter and multiple OPA receivers placed 1 m apart enabled a point-to-multipoint communication link at a 1 Gb/s data rate [11]. Another OPA consisting of 64-element EO p-i-n phase shifters and TO tunable n-i-n grating radiators was used for error-free transmission. The OPA with an FOV of $46.0^\circ \times 10.2^\circ$ and a beamwidth of $0.7^\circ \times 0.9^\circ$ was built for a 32 Gb/s data rate over 3 m [51].

8.1.2. OPAs for LiDAR

LiDAR is an important application of OPAs. In [14], the following requirements were listed as potential goals of developing OPAs for LiDAR applications: a resolution of 0.1° – 0.2° in horizontal and vertical directions, a horizontal FOV of $>90^\circ$, a power budget of 10–30 W or lower, and a system cost of 100–200 dollars or lower.

Integrated OPA-based LiDAR has been implemented [11,17,144]. A coherent solid-state LiDAR was presented by an integrated transmitting and receiving frequency-modulated continuous-wave circuit [17]. A triangular frequency modulation method was performed to measure distances and velocities simultaneously. The OPA using a grouped cascaded phase shifter architecture was demonstrated for an FOV of $46^\circ \times 36^\circ$, a beamwidth of $0.85^\circ \times 0.18^\circ$, and a noise-limited resolution of 20 mm with a 2 m range [17]. A 1D 512-element OPA consuming <1 mW total power exhibited high-speed (<30 μ s) 2D beam steering within an FOV of $56^\circ \times 15^\circ$ [11]. Simultaneous velocity extraction of diffusive targets at a range of ~200 m was shown by a coherent solid-state LiDAR, and OPA-based 3D coherent LiDAR was presented with raster-scanning arrays [11]. Owing to difficulties in providing electrical and photonic connections to every pixel, previous LiDAR systems were typically restricted to fewer than 20 pixels [144]. By leveraging achievement in monolithically integrated photonic and electronic circuits, a large-scale coherent detector array with 512 pixels was demonstrated recently [144]. The LiDAR system contains a dense optical heterodyne detector array combined with an integrated electronic readout architecture. An accuracy of 3.1 mm at 75 m was achieved using only 4 mW of light, which was an order of magnitude more accurate than existing solid-state systems at such ranges. The system enabled straightforward scaling ability and eliminated trade-off between FOVs and ranges [144].

8.1.3. OPAs for Imaging

OPAs hold great potential in desirable high-precision imaging at short wavelengths [150]. Chip-scale autostereoscopic displays [53], ghost imaging [54], 3D hologram in the near field [150], and incoherent beam steering and imaging [151] have been demonstrated by OPAs.

An image projection system using an array of integrated OPAs as chip-scale autostereoscopic displays was presented [53]. Each OPA illuminated a desired virtual object from a different angle, and this recreated a virtual object in space with continuous parallax observability. In total, 16 Si₃N₄ OPAs were used to generate a static image with a viewing angle of 5° at a wavelength of 635 nm. Each OPA was composed of 32×32 WGAs with different passively encoded phases [53].

Unlike conventional OPA beam scanning, the ghost imaging (GI) scheme enabled calibration-free robust imaging [54]. An integrated Si OPA chip presented in Figure 15a was demonstrated for GI applications. A slit pattern with over 90 resolvable points in one dimension was retrieved by driving 128 phase shifters using rapid changing random electrical signals. 2D imaging can be demonstrated by additional wavelength tuning [54].

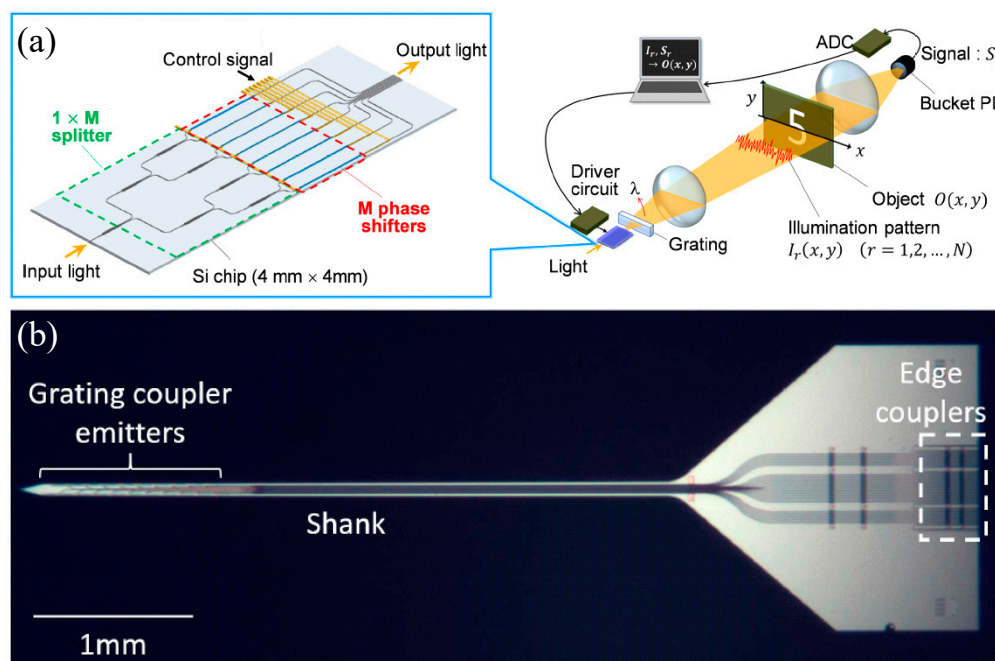


Figure 15. Applications of OPA structures. (a) An integrated OPA chip and the schematic of a ghost imaging system. Reprinted with permission from [54] © The Optical Society. (b) An implantable probe based on WGA-based OPA for optogenetic neuromodulation. Reprinted with permission from [56] © The Optical Society.

Previous imaging-oriented OPAs have been implemented in the far field with a single focal plane for 2D imaging. In contrast, multiple patterns focusing on different projection distances in the near field created a framework for generating a 3D hologram. A 128×128 WGA-based OPA with an aperture of $1.2 \times 1.2 \text{ mm}^2$ generated flexible 3D holograms in the near field [150]. The near-field vertical distance of each desired plane was different. Back propagations of desired image planes superimposed to a common plane. Flexible 3D holograms in the near field could be obtained by required amplitude and phase distributions utilizing Fresnel backpropagation [150].

While recent advances in Si photonics have enabled large-scale OPAs for coherent imaging, some applications require incoherent and/or broadband light [151]. A 64×64 WGA-based OPA using a planar, fractal, path-length-matched “H-tree” structure enabled incoherent beam steering and natural light imaging. A resolution of 5 mm at 18 m apart, which roughly matched a diffraction-limited resolution of $240 \mu\text{rad}$, was achieved by the individually controlled OPA [151].

8.1.4. OPAs for Biological Sensing

Neural stimulation refers to activation of neurons by an external stimulus to induce an action potential, including electrical, thermal, optical, and mechanical approaches [152]. Electrical stimulations have yielded tremendous results and are standardly employed in activating neuronal responses. Electrical stimulations suffer from drawbacks such as electrodes’ invasiveness, interference with environment, signal artifacts, and limited resolution [152]. Alternative optical stimulation methods have achieved comparable performance in activating physiological responses, and greatly improved spatial resolution and cell-type

specificity [152]. Implantable optical devices with precise stimulation ability to deep brain region neurons and high probe matching speeds are highly needed in neuroscience [56]. OPAs offer a wider range of operation, greater specificity in tissue stimulation, and a lesser need for physical repositioning of the device, which can be used in a variety of biological applications [152].

A 1×16 passive Si EF OPA achieved a beamwidth of 7° for temperature-dependent infrared neural stimulation [152]. A temperature change of up to 1.4°C , which was sufficient for triggering biological responses, was observed on a biological phantom [152]. An implantable probe based on OPAs presented in Figure 15b enabled optogenetic neuromodulation [56]. The probe rapidly ($<20\ \mu\text{s}$) switched and routed multiple optical beams by electrically tuning. The Si_3N_4 WGA-based probe stimulated the identified sets of cortical layers' neurons and recorded produced spike patterns by co-fabricated electrical recording sites simultaneously [56]. Coherent beam steering was achieved in vitro mouse brain tissue by a wavelength-tunable implantable neural probe employing Si_3N_4 WGA-based OPAs [153]. An OPA probe immersed in a fluorescein solution generated a continuous FOV of 30° by wavelength tuning from 485 to 491 nm. A FWHM of $<18\ \mu\text{m}$ over a propagation distance of $400\ \mu\text{m}$ was achieved. Potential 2D beam forming and steering could be achieved by an additional MEMS mirror-based input scanning system [153]. Another implantable neurophotonic probe based on Si_3N_4 WGAs realized optogenetic stimulation of rodent brains [55]. The probe's operation wavelength range of 430–645 nm covered the excitation spectra of multiple opsins and fluorophores. A small volume of the brain could be illuminated by a high-resolution optogenetic stimulation based on the probe. The structure could also be used as fluorescence imaging applications [55].

8.1.5. OPAs for Special Beam Generation

Special beam generation is potentially used for applications at the cutting edge of lightwave technologies, such as communications, sensing, optical micromanipulation, scalable laser lithography, optical coherence tomography, and even quantum information. Some special optical beams can be generated by OPAs, such as beams with focusing ability in the near field [154], quasi-Bessel beams [155], and beams carrying OAM states [47,156].

Compared with standard far-field diffracting beam generation, OPA-based beam generation presents a new functional modality of near-field focusing. A 512-antenna splitter-tree-based OPA produced a spot size of $7\ \mu\text{m}$ at a focal length of 5 mm. A spot size of $21\ \mu\text{m}$ at a focal length of 5 mm was achieved by a 1024-antenna pixel-based OPA. A 10,000-antenna pixel-based array enabled the same spot size at a focal length of 10 mm [154]. Integrated OPAs could generate quasi-Bessel beams in the near field. A 1D WGA-based OPA architecture was modified to experimentally demonstrate an on-chip quasi-Bessel-beam with a Bessel length of $\sim 14\ \text{mm}$ and $\sim 30\ \mu\text{m}$ power FWHM [155]. A hybrid PIC composed of a SiO_2 planar lightwave circuit and a 3D EF OPA demonstrated 15 OAM states for free-space space-division-multiplexing coherent optical transmission [47]. A Si WGA-based OPA generated light-carrying optical OAM with states of $l = \pm 1$ and $l = \pm 3$ [156].

8.2. Potential Alternatives

There are some potential alternative structures to integrated OPAs, which can be used to achieve resemble applications of integrated OPAs for optical wireless communications and LiDAR as examples.

An integrated structure based on optical switches and micro-resonator emitters produced 2D steering at a single wavelength, in which a metalens collimated beamwidths of micro-resonator emitters. It was robust to environmental variations [15]. Not all the phase shifters are turned on simultaneously. Optical-switch-based structures possess an important advantage of low power consumption, which is highly desirable for large-scale OPAs. Additional metalenses for beamwidth collimation increase system complexities.

WGA-based OPAs with off-chip lenses for 2D beam steering are shown in Figure 16a [157] and Figure 16b [158]. Similar to the above-mentioned metalens, off-chip lenses improved FOVs and beamwidths. However, the resolution was the same for expanded FOVs and beamwidths. Applications based on these structures are limited by the reconfigurability of large-size off-chip lenses.

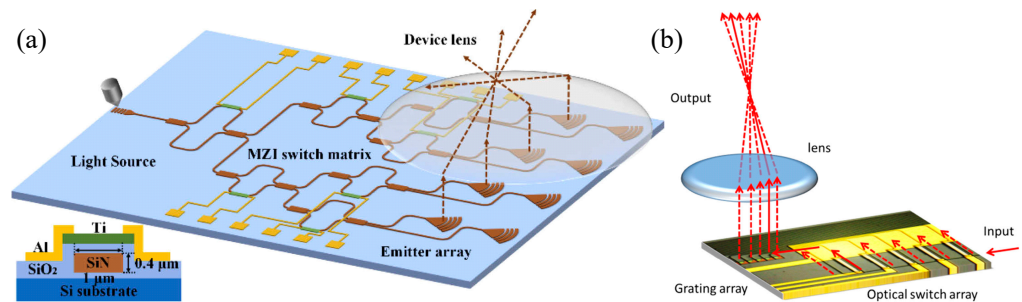


Figure 16. Potential alternatives of integrated OPAs. (a) A lens-based integrated 2D beam-steering device. Reprinted with permission from [157] © The Optical Society. (b) A beam switching optical scanner. Reprinted with permission from [158] © The Optical Society.

Based on metal–insulator–metal plasmonic structures, an integrated OPA with five switchable beams at a spacing of 15° was proposed at a wavelength of $1.55\ \mu\text{m}$ [159]. The OPA was composed of 6 plasmonic nanoantennas with feeding waveguides. A graphene-based power splitter conducted input power into a selected port. A plasmonic Rotman lens was designed to realize a desired phase shift between adjacent antennas. A high directivity of 12.1 dB and a gain of 2 dB were shown by numerical simulation [159]. The silver phase shifter is high-power consumption. The large beamwidth of this complex structure should be decreased for further applications.

9. Outlook

More applications can be achieved based on integrated OPAs. Monolithically integrated OPAs take advantage of full integration and small chip sizes. EF OPAs can be used for 1D beam forming and steering. Wavelength-tuned 1D long-WGA-based OPAs with phase modulations decrease steering complexities in 2D steering. Problems of expensive precisely tunable laser sources [11,45] and limited performance [64,84] could be solved. Simplified high-performance on-chip tunable lasers are highly desirable. Large-scale sparse aperiodic 2D OPAs, which have wide FOVs and narrow beamwidths, are promising candidates for high-performance OPA-based applications. Design complexity of large-scale sparse aperiodic 2D OPAs need to be decreased for further applications. A two-chip integrated OPA with a sparse aperiodic aperture might be a promising solution [45].

For applications based on precise beam forming and steering, WGAs with normal direction radiation [64,113] as well as structures with plateau envelopes [59,113,118] can be highly desirable. Modulation speeds are greatly enhanced by EO phase shifters based on the carrier density changing function. Monolithically integrated LiNbO₃ EO phase shifters [105] and contact graphene heaters with high efficiencies and operation speeds, low power consumption [75] can be used for excellent EO modulations. To decrease optical losses of sharp waveguide bends, 45° angle placed antennas may be used to enable optical routing through two sides of the aperture [45]. Fabrication errors need to be carefully treated [142].

10. Conclusions

In conclusion, we have overviewed beam forming and steering with integrated OPAs. Principles, building blocks, and configurations are discussed. Integrated OPAs have been implemented on various platforms, mainly including Si photonics platforms, III–V platforms, and III–V/Si hybrid platforms. In terms of employed wavelengths, OPAs can be

used for different applications. Some important performance parameters are discussed in detail, such as FOV, beamwidth, sidelobe suppression, modulation speed, power consumption, and scalability. Some typical applications of integrated OPAs have been given, together with potential alternatives.

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