Aliasing-free optical phased array beam-steering with a plateau envelope

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Abstract: We investigate the feasibility of generating a plateau envelope for beam-steering with optical phased arrays (OPAs). The design guidelines are summarized from numerical simulations and verified with a fabricated chip, which incorporates both a coupling-suppressed curved waveguide array with a pitch of 0.8 μm for light emission and a 1-μm-long silica cavity for envelope tailoring. This silicon-on-insulator (SOI) based device demonstrates aliasing-free beam-steering over the entire field-of-view available (−32°~32°) with a far-field addressability of 6.71°. The steered beam exhibits a plateau envelope, with a peak intensity fluctuation of less than 0.45 dB, from −30° to 30°. These results represent a significant step towards realizing integrated OPA for optical beam-forming with a large aliasing-free steering range and a uniform beam intensity.

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1. Introduction

Pioneered almost one century ago, the phased array technology implements an array of antennas to focus the electromagnetic wave through constructive interference and subsequently steer them in the free space without mechanical components. Nowadays, with the rapid development of photonic integrated circuits (PICs), chip-scale optical phased arrays (OPAs) hold promise for arbitrary beam-forming flexibility [1], ultra-fast inertia-free beam-steering [2], as well as CMOS-compatible manufacture at a massive scale [3]. These merits render the scheme a phenomenal candidate for applications including projection [4], imaging [5], light detection & ranging (LiDAR) [6,7], and free-space optical communication systems [8].

Nonetheless, since light is relatively weak-confined in the dielectric waveguides compared to the electromagnetic wave in the metallic lines, the half-wavelength pitch desirable for 180° aliasing-free beam-steering is hindered by the evanescent coupling within the dense array, resulting in a typical guideline for emitter spacing to be larger than 2 μm. Therefore, to achieve aliasing-free operation for C-band or shorter wavelengths, the mainstream approach relies on the optimization of a sparse array with non-uniform emitter spacing [6,9] that keeps the side lobes suppressed during the beam-steering process. However, such schemes sacrifice the energy concentration in the main lobe (≤40% typically [10,11]) for the large operation range, which would be disadvantageous regarding power-critical applications such as light detection and ranging (LiDAR), since it induces the degradation of signal-to-noise ratio (SNR).

Besides the sparse arrays, three separate efforts adhere to the uniform array while alleviating the crosstalk via dispersion engineering, either with a small-scale end-fire array composed of 5 emitting elements [12], with photonic crystal structures for antenna segregation [13], or with an array of dispersion-engineered straight waveguides of different widths [14]. Rather than separating emitters spatially, these efforts undermine the coupling condition with structure innovations involving the short coupling distance, the synthesis of a photonic bandgap, and the introduction of phase mismatch between adjacent modes. The
main advantages of such dispersion-engineered OPAs reside in the high energy concentration (72% in [14]) provided by the uniform array.

That being said, the beam-steering envelope demonstrated in [14] is consistent with the far-field diffraction pattern of the single emitting element, resulting in significant declines in the peak intensity of the main lobe at large steering angles. Moreover, almost all prior-art OPAs exhibit similar steering behavior due to the universal modulation effect originated from the diffraction pattern of the element. To broaden this envelope and subsequently to achieve efficient wide range operation, Fourier optics demands the reduction of the emitter size, i.e., a smaller emitting structure with enhanced mode confinement. Though previous efforts have numerically demonstrated its feasibility [15], no practical implementation has been reported in the field of optical phased arrays due to the refined and complicated fabrication process required.

Here, we address the above issues by combining a coupling-suppressed curved waveguide array of a uniform 0.8 μm pitch, together with a silica cavity responsible for the generation of the plateau envelope. The former introduces the phase mismatch between adjacent channels through the implementation of curved waveguides of different radii, while the latter exploits both the reflection in the silica cavity, as well as the moderate coupling remained in the emitting structure, to prune the diffraction pattern of the emitting element. The design is verified numerically and demonstrated with a fabricated chip.

The paper is organized as follows. In section 2, the general operating principles of optical phased arrays, especially the half-wavelength criterion for 180° aliasing-free beam-steering, will be reviewed. Basic concepts concerning coupling suppression will also be introduced. We will then elaborate on the investigation as well as the design guidelines of the plateau envelope via simulation in section 3. Finally, the fabricated chip and the experimental results will be presented in section 4. The design and the implications will be summarized in the concluding section.

2. Operating principle and phased array synthesis

Phased array is an array of coherent sources, realized either with an array of phase-locked active emitters or with passive emitters excited with phase-shifted channels split from a common input. Generally, OPAs refer to the devices that divide the input laser beam into multiple coherent channels and subsequently permit the introduction of different phase shifts individually. Figure 1 depicts the schematic of its typical one-dimensional implementation. When the beams processed by such a device recombine in the free space, a stable interference pattern will emerge, enabling flexible imaging and detection applications. Under Fraunhofer approximation, the far-field intensity pattern consists of grating lobes modulated by the element diffraction pattern. The generation of those grating lobes is called beam-forming, while the continuous spatial shifting of the lobes under the diffraction envelope is called beam-steering.

![Figure 1](image_url)

*Fig. 1. Schematic of a typical implementation of one-dimensional OPA, consisting of a common laser input, a block of beam splitters, as well as an array of phase shifters followed by their corresponding antennas for light emission.*
2.1 Phased array beam-forming and beam-steering

Due to the Gaussian-shaped diffraction envelope determined by the element factor, peak intensities of the grating lobes vary accordingly, allowing the differentiation of the main lobe with the highest peak intensity from other grating lobes with lower intensities. Intuitively, beam-steering simultaneously shifts the grating lobes that would be modulated by a fixed envelope. Under the circumstance where one smaller lobe substitutes the main lobe during the steering, aliasing occurs, which hinders the performance of large-range beam-steering. Figure 2 illustrates such an aliased beam-steering process, where the green grating lobe gradually overtakes the red main lobe due to the steering envelope indicated in the orange dashed curve.

![Fig. 2. Six incidences recorded in a simulated beam-steering process of a uniform array with an emitter size of 0.5 μm and a pitch of 1.8 μm. In each incidence, the steering envelope is indicated by the orange dashed curve, and the intensity distribution is depicted by the blue curve. The main lobe highlighted with the red dashed line is steered from 0° to 60°, overtaken by the side lobe highlighted with the green dashed line from (d), causing aliasing and limiting the steering range.](image)

While demonstrations may differ in platforms, architectures, and components, the key metrics for performance evaluation, namely the beam-forming finesse and the aliasing-free steering range, are solely dependent on the geometry properties of the emission array. For uniform one-dimensional arrays, the relationship could be examined with the analytical model, i.e., the multi-slit diffraction model provided by Fourier Optics,
\[
I(\theta) = I_o \left( \frac{\sin \alpha}{\alpha} \right)^2 \left[ \frac{\sin N(d-\varphi)}{\sin\frac{\alpha}{2}(d-\varphi)} \right]^2
\]

\[
\alpha = \frac{1}{2}ka \sin \theta \quad \delta = kd \sin \theta
\]

where \( I(\theta) \) represents the far-field angular intensity distribution of a phase-aligned (an identical phase difference of \( \varphi \) is applied between adjacent channels) array with \( N \) antennas of size \( a \) placed at a pitch of \( d \), \( I_o \) stands for the unitary peak intensity in the far-field if only one channel is excited, the second term \( \sin(\alpha/2)^2 \) is a squared sinc function, representing the far-field diffraction pattern of a uniformly-lit square slit, the last term, a function of \( (\delta-\varphi) \), namely, \( G((\delta-\varphi)) \), corresponds to the multi-slit interference pattern, and \( k \) represents the free space wavenumber of current light frequency. For unmodulated grating lobes, each lobe possesses a peak intensity of \( N^2 I_o \). Equation (1) indicates that the far-field intensity distribution of a uniform array is comprised of a multi-slit interference pattern modulated by the far-field diffraction pattern of the elementary emitter.

Additionally, from the Fourier Optics perspective, the source field could be expressed as an \( a \)-size square slit being spatially convolved to a \( d \)-pitch comb, while in the far-field, convolution is transformed into multiplication, applying the modulation effect to the multi-slit interference pattern. Therefore, it could be concluded that, for uniform arrays, the overall envelope is solely dependent on the emission properties of the elementary emitter. Besides, the number of interference grating lobes are exclusively dependent on the comb pitch. This insight permits the universal application of the following conclusions as long as the array is uniform, allowing both their extension into two-dimensional arrays as well as the tailoring of the envelope by designing the elementary emitter.

The first conclusion is derived through locating the grating lobes, i.e., the maximums of the last term:

\[
\text{max}\{G((\delta-\varphi))\} = \lim_{(\delta-\varphi) \to 2m\pi} G((\delta-\varphi)) = N^2
\]

Therefore, plane waves propagating in the same direction of \( \theta_c \) will interfere constructively if the condition \( kd \sin \theta_c = 2m\pi + \varphi \quad m \in Z \) is satisfied, indicating that grating lobes are periodic w.r.t. \( \sin \theta \), in order words, \( \sin \theta^{(m)} - \sin \theta_c = 2\pi/kd \). For the antenna pitch to be shrunk to half a wavelength, i.e., \( kd = 2\pi d/\lambda \leq \pi \), \( \sin \theta^{(m)} - \sin \theta_c \geq 2 \), it is ensured that only one grating lobe exists during the entire steering process \((-90^\circ \sim 90^\circ)\). When the antenna pitch increases, the available steering range declines with a sinusoidal trend. In our case, we choose a pitch of 0.8 \( \mu \text{m} \), which is slightly larger than half a wavelength (0.775 \( \mu \text{m} \)), due to fabrication limitations.

Another conclusion concerns the far-field addressability, which could be measured by the zero-crossing of the main lobe

\[
\sin \left[ \frac{N}{2}(\delta-\varphi) \right] = 0 \quad \& \quad \delta-\varphi \neq 2m\pi
\]

The neighboring zero-crossings, i.e., the destructive interference points, are at \( \pm 0.5 \lambda/Nd \cos \theta_c \), while the full width at half maximum of the main lobe could be expressed
as $\Delta \theta_{\text{FWHM}} = 0.886 \lambda / Nd \cos \theta_c$, implying that the far-field addressability is largely dependent on the total array span $Nd$.

### 2.2 Dispersion engineering and coupling suppression

The major obstacle to implement a uniform array with a small pitch originates from the intrinsic drawback of dielectric waveguides, where a significant portion of the guided mode resides outside of the geometry boundaries of the high-index core [15,16]. Under the circumstances that such wave-guiding structures are narrowly spaced for a long propagation length [12], which is common in phased arrays with grating structures as passive phased antennas responsible for steering the beam via wavelength tuning [1,7,9], strong coupling will emerge and subsequently compromise the far-field pattern as demonstrated in [13].

To alleviate the undesirable coupling, dispersion engineering relies on the introduction of phase mismatch between the modes inside abreast waveguides, so adjacent channels guide light-wave modes of different propagation constants. This technique has been demonstrated both in the field of mode-division multiplexing (MDM) [16–18] as well as in the efforts to achieve a higher waveguide density from a platform perspective [19,20]. As mentioned in section 1, superlattice comprising waveguides of different widths [20] have been adopted for coupling suppression of an OPA with a half-wavelength pitch in [14], demonstrating the feasibility of the aforementioned principle.

Based on the same scheme, we propose to introduce the phase mismatch by implementing an array of curved waveguides with different radii, imposing a unique propagation constant to each phased channel [21]. A similar structure has been simulated and demonstrated as an MDM MUX/DEMUX in [22], exhibiting an averaged crosstalk suppression of 20 dB. Therefore, the related design details are omitted here. The main advantages for adopting a curved waveguide array for coupling suppression include a simplified yet robust design where the coupling is not only suppressed in adjacent channels but throughout the array, an improved luminous uniformity across the array, as well as comparable scalability if the prior transition stages are carefully designed.

### 3. Generation of the plateau envelope

To the best of our knowledge, this is the first time that a plateau envelope has been investigated and characterized in the field of OPAs. As previously discussed, the beam-steering envelope is the far-field diffraction pattern of the emitting element. More precisely, the envelope is the averaged diffraction pattern of all emitting elements should they differ from each other. Before providing the related evidence, we first claim that the silica cavity renders different tailoring to the diffraction pattern of the emitter w.r.t. its relative position inside the array. Nonetheless, the varying diffraction patterns converge sharply from the flank to the center, allowing the characterization of the overall tailoring effect via the characterization of the far-field diffraction pattern of the central emitter. Additionally, it should be noted that the silica cavity exists between the emission facet of the uniform array and the free space. Therefore, it is relatively insensitive to the optical circuit design of the array. That is why in this section, most simulations will be based on uniform arrays comprising straight waveguides with coupling strengths tuned by coupling length. By default, the simulation wavelength is 1.55 $\mu$m, the array pitch is 0.8 $\mu$m, the coupling length is 7 $\mu$m, which introduces a limited coupling close to that of the curved waveguide array. Besides, the cross-section of the standard waveguide is 220 nm high, 500 nm wide, surrounded by thick silica layers as cladding and perfectly matched layers (PMLs) to eliminate reflection on all sides. The central waveguide indicates the 8th waveguide in an array of 16 channels.

#### 3.1 Observation and characterization

The initial observation of this effect emerged from the device design stage, the goal of which is to establish a finite-difference time-domain (FDTD) model to simulate the beam-steering
process of a given OPA. By attaching an extra 1-μm-long silica layer after the emission facet of the silicon waveguide array, a silica cavity is formed interfacing silicon waveguides and air, where multi-reflections occur. In such a structure, it is observed that the far-field pattern of the central waveguide exhibits a plateau shape in the in-plane angular axis parallel to the array, i.e., the phased array scanning direction. Meanwhile, the Gaussian shape is maintained in the out-of-plane angular axis perpendicular to the array, namely the vertical tilt direction. Figure 3 shows the OPA structures with and without the silica cavity and their corresponding far-field diffraction patterns calculated on a hemisphere with a radius of 1 m. It is evident that the silica cavity significantly tailors the diffraction pattern of the element.

![Diagram](image)

Fig. 3. (a, b) Schematics of the SOI-based 16-channel OPA, the underlying silicon substrates are omitted to highlight the silica cavity. (c, d) Normalized optical angular intensity distributions of the far-field diffraction pattern of the central emitter, captured on a hemisphere with a radius of 1 m. (e, f) Corresponding parallel (orange curve) and perpendicular (blue curve) axial optical intensity distributions, together with their corresponding angular plateau size indicated by the red/blue dashed lines. Left column: OPA with 1-μm-long silica cavity; right column: OPA without silica cavity. (g) Comparison of the parallel-axis intensity distributions of the OPA with (red curve) and without (black curve) the silica cavity, together with their corresponding angular plateau size indicated by the red/black dashed lines.

The pattern tailored by the silica cavity exhibits a pillow shape in Fig. 3(c). Additionally, it can be measured in Fig. 3(e) that a plateau region with degradation of less than 0.45 dB (90%) extends from −30.4° to 30.4°, while the overall distribution is raised from that of the perpendicular axis.
Regardless of the configurations, the intensity distributions generally rise from $-90^\circ$ to the peak/plateau and decline from the peak/plateau to $90^\circ$. The strength of the tailoring is characterized by calculating the angular range between the points where its optical intensity drops to 90% of the peak value, namely the angular plateau size. It has been confirmed in all parametric sweeps that the in-band intensity variation is correlated with the angular plateau size, implying that the larger the plateau is, the smaller the in-band variation is. Therefore, only the angular plateau size illustrated in Figs. 3(e) and 3(f) are adopted for the characterization of the tailoring strength. A comparison between the parallel-axis intensity distribution with or without the silica cavity is provided in Fig. 3(g) to highlight the tailoring.

3.2 Analyses and design guidelines

Though 3D-FDTD simulation provides accurate modeling for general purposes, it would be computationally intense to perform parameter sweeps with the desired accuracy. Besides, albeit our conclusions could be extended to two-dimensional arrays regardless of their architecture, our current design is a one-dimensional array involving no variation in the axis perpendicular to the circuit (namely the Z axis). Therefore, two-dimensional FDTD simulation incorporating circuit level propagation feature, i.e., the variational FDTD solver, is employed for the following simulations. In such a scenario, it should be noted that the simulated far-fields are the Fourier transform from one-dimensional source fields with no information concerning the expansion of the mode in the Z axis. In other words, the far-field is projected with the assumption that the mode field is uniform in the Z axis, implying that the cavity effect is more explicitly revealed for a well-defined one-dimensional source field, rather than being averaged over the Z axis with Gaussian distribution characteristics.

Based on the characteristic metric, i.e., the angular plateau size, we provide the guidelines as well as the analyses on how to obtain a plateau envelope. To begin with, the cavity effect on a single waveguide is verified by varying the cavity length, exhibiting no tailoring effect as commonly reported in other applications. By calculating the output-transmitted intensity as a function of cavity length, the typical Fabry–Pérot (F-P) resonant effect emerges, implying that the cavity could potentially facilitate the out-coupling of the beam from the waveguide to the free-space. Therefore, we introduce another metric, namely transmittance, which calculates the average output intensity in the far-field over the largest angular plateau range ever documented in the parameter sweep, for the characterization of the out-coupling. Note that the transmittance here is a redefined relative metric which is proportional to its commonly-known physical definition. The simulated field pattern, as well as the extracted performances, are presented in Fig. 4, revealing the aforementioned phenomenon.

Since the cavity has no tailoring effect on one single waveguide, we then vary the total number of waveguides inside the array from 1 to 55, while the cavity length is fixed to 1 $\mu$m, to verify the contribution from the size of the array. The results are shown in Fig. 5. It is confirmed that with this arrangement, the corresponding far-field diffraction patterns converge to the plateau envelope rapidly both in terms of their shape as well as the shaping factor, i.e., the angular plateau size. Meanwhile, the out-coupling transmittance is generally stabilized.

Additionally, the default configuration is revisited to investigate the contribution of the cavity length. Light is launched from the 8th channel in a fixed array comprising 16 waveguides. The cavity length varies from 0 to 2 $\mu$m with a step-size of 0.05 $\mu$m. As shown in Fig. 6, the length of silica cavity largely modifies the far-field pattern, which is quantized by the fluctuation of the angular plateau size. The out-coupling measured by the mean value of transmittance follows the pseudo-periodic trend as previously presented in Fig. 4(b) with a similar period. It is revealed that a 1-$\mu$m-long silica cavity provides a significant tailoring effect, together with a moderate improvement in transmittance compared to no cavity.
Fig. 4. (a) Two-dimensional electric-field diffraction pattern of the configuration where a cavity with a variable length is attached to a single silicon waveguide, revealing the effect of the silica cavity at the waveguide end. (b) Angular plateau size and transmittance as a function of silica cavity size. The far-field pattern adheres to the Gaussian shape, resulting in a little variation in the angular plateau size. Meanwhile, the transmittance exhibits an F-P resonance fringe characteristic.

Fig. 5. (a) Two-dimensional electric-field diffraction pattern of the configuration where a fixed-length cavity is attached to an array of variable size, revealing the contribution of the array. (b) Angular plateau size and transmittance as a function of waveguide number. The out-coupling transmittance is generally stabilized at 0.86. The far-field diffraction pattern converges to the plateau shape after the waveguide number in the array exceeds 19.

Fig. 6. (a) Two-dimensional electric-field diffraction pattern of the configuration where a length-varying cavity is attached to a fixed array, revealing the contribution of the cavity. (b) Angular plateau size and transmittance as a function of silica cavity length. The out-coupling transmittance still exhibits an F-P modulation effect. The far-field diffraction pattern varies considerably in terms of the light intensity angular distribution.

To further investigate how the array size and the cavity length contribute to the generation of the plateau envelope, both parameters are set as variables while the corresponding transmittance together with the plateau size is measured and charted in a contour map. The
number of waveguides inside the array is varied from 5 to 25 waveguides with a step-size of 1, while the cavity length is varied from 0 to 2 μm with a step-size of 0.05 μm. It can be observed in Fig. 7(a) that the F-P resonance-induced periodic variation of the transmittance holds regardless of the array size. Moreover, the significant values of angular plateau size form an h-shape branch with local maximums appeared around 0.5 μm and 1 μm in Fig. 7(b).

![Fig. 7. (a) Contour map of the transmittance with brighter colors for larger values. The out-coupling always exhibits pseudo-periodic intensity variation w.r.t the cavity length. (b) Contour map of the angular plateau size. The local maxima are indicated with the gray dashed lines.](image)

Based on the analyses above, we attribute the generation of the plateau envelope to both the multi-reflection inside the silica cavity and the silicon grating formed by the facets of the waveguide array. By comparing the electric field patterns in Figs. 4, 5, and 6, it can be inferred that when light reflected by the silica-air surface reaches the end-facets of silicon waveguides, beam components of specific spatial frequencies experience larger reflections from the facet grating, resulting in energy transfer from the Gaussian core of base spatial frequency to the interfering grating lobes of larger spatial frequencies. Therefore, the near field experiences significant redistribution and is subsequently transformed into a plateau shape in the far-field. Due to the sophisticated nature of the multi-reflection process between the silica-air interface and the silica-silicon interface, a reliable analytical solution would involve multiple integrals over every sub source on both interfaces of the cavity, resulting in a complicated description comparable to a numerical solution. At the current stage, we limit our discussion on the tailoring effect to a parametric study, and we will look into certain qualitative description based on the scattering matrix method in the future.

Going back to the default array given in the beginning of this section, we have claimed that the silica cavity induces different tailoring w.r.t the relative position of the element within the array, and that the diffraction pattern of the central element is nonetheless a suitable sample for us to characterize the tailoring due to the fact that varying diffraction patterns converge sharply from the flank to the center. Here, the evidence is provided by individually launching light into waveguides at different relative positions in the array and characterizing the corresponding far-field diffraction patterns. Figure 8 shows the simulated structure, the field distribution and the characterized results, which supports the previous claims.
Finally, to verify that the averaged element factor determines the beam-steering envelope, as well as to predict the theoretical performance of our design, all waveguide channels are excited with light sources of a linear phase difference to form an optical beam emitting from the array. By tuning the phase difference, the main lobe is steered within the envelope, exhibiting a plateau feature as shown in Fig. 9. Aliasing is also observed at around 70°, which is close to the theoretical calculation (75°) with the ideal phase-matching condition explained in Section 2. The noise crosstalk level is around −12 dB, while the main lobe intensity fluctuates within 0.4 dB from 30° to 30° coinciding with the previous 3D-FDTD simulations.

4. Experimental results

Figure 10(a) illustrate the mask layout of the OPA device, comprising an input grating coupler, 15 cascaded multimode interference (MMI) couplers, 16 thermo-optical (TO) phase shifters based on thin-film TiN heaters, an array of 16 curved waveguides with a 1-μm-long silica cavity at the end facet. The TiN heaters are connected via aluminum wires to electrical
pads positioned along the chip edges. The OPA chip was fabricated in a silicon-on-insulator (SOI) wafer comprising a 220-nm-thick top silicon layer and a buried oxide layer with a thickness of 2 μm. All fabrication processes are CMOS-compatible. Initially, a 10-nm thick film of silicon dioxide was deposited via plasma enhanced chemical vapor deposition (PECVD) to form a hard mask. Then, the pattern was defined on the spin-coated photoresist by deep ultraviolet (DUV) photolithography and transferred to the hard mask. Through reactive-ion etching (RIE), the silicon layer is partially etched by 70 nm to form the grating coupler. Afterward, the photoresist was coated and patterned to form a protective layer over the defined grating, while RIE was applied for the second time to etch the silicon by another 90 nm, leaving a 60-nm-thick silicon slab. Again, the protective photoresist was coated and patterned over the defined structure, while RIE was applied for the third time to etch the silicon down to the box, concluding the definition of passive components. After the removal of the photoresist as well as the hard mask, a 1.5-μm-thick silicon dioxide was deposited using PECVD on top of the waveguides both as the upper-cladding and as a separation layer between the waveguides and the TiN heater. Next, a 120-nm-thick TiN layer was sputtered and patterned for thermo-optical tuning. In addition, another 0.73-μm-thick silicon dioxide layer was deposited, followed by the etching of contact holes, and the definition of aluminum metal connections via sputtering and plasma dry etching. After that, segmented deep trenches between the heaters are etched down to the silicon substrate to improve the power efficiency and to suppress the thermal crosstalk. Eventually, deep silicon etching combining RIE and inductively coupled plasma (ICP) etching was applied 1 μm away from the emission facet, defining the silica cavity. For device verification, all the electrical pads were wire-bonded to a printed circuit board (PCB) so that control voltages can be applied onto the chip, while the light was launched into the grating coupler from a flat-facet fiber held by a 6-axis alignment stage. The detailed design parameters for the output section of the curved waveguide array are labeled in Figs. 10(b) and 10(c). Figure 10(d) shows the microscope image of the fabricated chip.

Fig. 10. (a) Mask layout of the entire OPA chip. (b) Zoom-in of the curved waveguide array together with its transition sections that reduce the pitch from 50.5 μm to 0.8 μm. (c) Concentrically curved waveguides in the emission section with its critical design parameters.
labeled accordingly. (d) Microscope image of the fabricated chip. The footprint of the chip is 1.4 mm by 1.7 mm.

To measure the coupling between adjacent waveguide channels in the OPA, we also designed a separate reference device comprising two identical curved waveguide arrays connected in centrosymmetry as illustrated in Fig. 11(a). By coupling light into an input channel and monitoring the output light at that channel and the leakage light at the adjacent channel, we can obtain the insertion loss (IL) and crosstalk (CT), respectively. Figure 11(b) shows the IL and CT measured from all 16 waveguides. It is confirmed that the CR at 1550 nm wavelength varies from −12.6 dB (the worst case) to −27.5 dB (the best case). The average channel IL is 1.93 dB. Additionally, it has been measured in other reference devices that the typical insertion losses of the grating coupler, the MMI coupler, and the silicon waveguide, are approximately 6 dB/facet, 0.4 dB/stage, and 3 dB/cm at the operating wavelength. Based on these characterizations, the total insertion loss of the device is around 12.4 dB comprising 6 dB from one grating coupler, 1.6 dB from 4 stages of MMIs, 0.9 dB from a circuit length of coarsely 3 mm, neglectable loss from the TiN heaters, 0.9 dB from the CWA (half of that of the reference device), and an estimated reflection loss of 3 dB from the emitting facet with the silica cavity. This proof-of-concept design is not optimized for loss. Nonetheless, a discussion on the feasibility to mitigate this loss is provided in the last section to reveal its potential.

Fig. 11. (a) Schematic of the reference curved waveguide array with the same design parameters as those in Fig. 10. (b) Measured inter-channel crosstalk (blue stars) and insertion loss (orange circles) for each channel. Median values representing the typical performances are indicated by dashed lines with the same color.

Next, we performed the beam-forming experiment via applying a linear phase difference to the adjacent waveguides in the OPA. By upgrading the Fourier imaging system previously calibrated in [23], we imaged the far-field pattern onto the sensor plane of our near-infrared camera. An optimization algorithm was implemented in the control PC, which interfaces both the multichannel DC source as well as the near-infrared camera, to tune the voltages applied to the TO phase shifters automatically. We measured and examined multiple objective functions, including full-width at half-maximum (FWHM) of the main lobe, shape likelihood factor, and energy concentration in the FWHM. We selected the sequential quadratic programming (SQP) algorithm for multiple phase alignments inside the available field of view (−32°–32°).

Figure 12 illustrates the images from the near-infrared camera together with the measured data. One may notice in Fig. 12(b) that the intensity distribution is non-uniform on the axis perpendicular to the array. This phenomenon is consistent throughout the beam-steering process and is attributed to the reflections from both the extra 1-μm-long silicon substrate under the silica cavity and the top silica-air interface of the cavity, which subsequently interfere with the beam formed by the OPA chip in a fashion similar to the Lloyd's mirror experiment. Nonetheless, since little pattern variation is observed on the axis parallel to the
array due to this interference, this phenomenon is neglectable to one-dimensional beam-forming and beam-steering, specifying that the horizontal intensity distribution for each incidence is averaged by column in the same region indicated by the orange dashed box in Fig. 12(b). By sampling according to the given specification, the far-field pattern after beamforming is consistent with theoretical predictions. The measured FWHM is 6.71°, the energy concentration in the FWHM, i.e., the integral of intensities within the FWHM divided by the integral over the entire intensity distribution, is 46%. Additionally, the energy concentration in the main lobe, which is defined between the two nearest local minimums around the peak, i.e., between the 1st-order destructive interference points, is 63%. Moreover, the beam-steering process verifies the simulated plateau envelope, with peak intensity fluctuating within 0.45 dB, and a worst-case noise suppression ratio of 9.37 dB.

Fig. 12. (a) Measured far-field intensity pattern of the aligned phased array (red line) together with the theoretical prediction via numerical simulation (black dashed line). The nearest local minimums of the experimental data, i.e. the 1st-order destructive interference points, are marked by blue dots. (b) Corresponding far-field image captured by the near-infrared camera when the beam is formed at the center of the FOV. the characterization region, also the region where incidences are cropped, is indicated by the orange dashed box. (c) The steered beams quantized
by the averaged intensity distribution from the same characterization region with different incidences colored individually. (d) 14 slices cropped from the corresponding far-field patterns recorded by the near-infrared imaging system during the beam-steering process. (e) Normalized peak intensity (orange squares) and noise suppression w.r.t. the largest side lobe (blue triangles) for each incidence. The dashed lines indicate the median values.

To conclude, the demonstrated uniformity among the peak intensities of the main lobes not only extends the effective steering range for LiDAR application operating in a noisy environment, but also, it provides a hardware efficient solution for OPA-based free-space optical communications, where the angular plateau implies a stable quality of service (QoS) throughout the typical indoor scenario. Additionally, the dynamic range of the sensors in the aforementioned applications could now be traded for refined resolution, providing either a more precise distance measurement, or more symbols for signal representation.

5. Conclusions

We have reported an SOI-based OPA with a curved waveguide array for inter-channel coupling suppression. The far-field diffraction pattern presents a plateau envelope, caused by the F-P effect from a silica cavity at the emitting end of the waveguide array. Numerical simulations were conducted to investigate the influence of various geometric parameters on the far-field pattern. It was revealed that a 1-μm-long silica cavity can effectively increase the plateau size in the envelope of the diffraction pattern and the optical transmittance of the OPA. The measurement of the OPA demonstrates aliasing-free beam-steering with a plateau envelop with intensity fluctuation of less than 0.45 dB from −30° to 30°, consistent with the numerical simulations. For the current design, it is estimated that the total insertion loss is around 12.4 dB with a major portion originated from the regular uniform grating coupler with an etched depth of 70 nm. By adopting more complicated designs, e.g. adiabatic grating with an underlying metal layer [24], the coupling loss can be reduced to 0.58 dB/facet. Additionally, by substituting strip waveguides with shallowly-etched rib waveguides [25] for long straight sections, and by fabricating the strip waveguides with ArF immersion lithography [26], the average waveguide propagation loss can be reduced to 0.2 dB/cm. The MMI loss can be controlled within 0.06 dB/stage with an improved design [27]. By striking a compromise between the plateau size and the emitting efficiency, the emitter reflection loss can be suppressed to below 2 dB. Therefore, we estimate that the device insertion loss can be less than 3 dB with an optimized design. Moreover, low loss waveguides and MMIs also increase the scalability of the design. To conclude, it is demonstrated that the silica cavity can tailor the far-field diffraction pattern of the OPA, which opens a new degree of design freedom to achieve the desired beamforming and steering with high energy concentration and uniformity of luminescence.

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