Aliasing-free Beam-steering Over the Entire Field of View Utilizing a Bent Waveguide Array with a Uniform Half-wavelength Spacing

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Abstract *We demonstrate a 16-channel optical phased array capable of aliasing-free beam-steering. The array is composed of uniform elements with half-wavelength spacing. To suppress crosstalk between adjacent channels, the waveguide phase mismatch is introduced utilizing bent waveguides of different radii.*

Introduction

Ever since 2009[1], solid-state beamforming and beam-steering schemes enabled by the optical phased array (OPA) technology have been under growing investigations for their merits such as lack of inertia as well as chip-scale compactness.

While many efforts have been made, either to scale up the array with less DAC units responsible for beam-steering[2], to implement the array on platforms that are transparent to a larger range of wavelength[3], or to provide on-chip calibration methods for practical implmentation[4], few address the inherent weakness of OPAs that resides in the relatively low confinement of the optical dielectric waveguides and the resulted evanescent coupling within the dense array. The guideline emitter spacing (~2 μm) to avoid crosstalk for a uniform array is well beyond the desirable half-wavelength metric which in turn hinders aliasing-free operation over the entire field of view.

The de facto approach to achieve aliasing-free operation nowadays involves optimization of a sparse array with non-uniform emitter spacing[5] that keeps the side lobes suppressed during the beam-steering process. Yet, the large operation range is achieved at the cost of low energy concentration in the main lobe (≤ 40% typically[6]), which further implies degradation of signal to noise ratio in power critical applications such as light detection and ranging (LiDAR).

Early this year, C. T. Phare et al.[7] demonstrated a 64-channel uniform array of half-wavelength spacing, minimizing the coupling of modes between adjacent channels by placing waveguides of two different widths (300 nm/400 nm) alternately. The aliasing-free operation is achieved together with a main-lobe energy concentration of 72%. Still, the array is composed of non-uniform elements to provide the necessary phase mismatch.

Here, we demonstrate a uniform array of 16 identical channels where the waveguide phase mismatch is introduced by different bent radii of the densely packed bent waveguide array (DPBWA). The array is capable of aliasing-free operation over the entire field of view currently available ($-40° \sim +40°$). Note that this range is limited only by the numerical aperture of our imaging system. The full-width at half-maximum (FWHM) of the main beam is 6.709° which is in agreement with the theoretical prediction (6.28°). In addition, the energy concentration within the FWHM and the entire main lobe are 46% and 63% respectively.

Operating Principle & Device Design

A phased array is an array of coherent sources. It can generate arbitrary stable patterns throughout the entire free space due to constructive and destructive interference.

Given a one-dimensional uniform array of N antennas each with an identical width of a, while the pitch, i.e. the center to center spacing between adjacent antennas is d, and φ is used to represent the phase difference between adjacent channels. Then the intensity distribution in the far-field can be described according to the Fraunhofer diffraction approximation with respect to the diffraction angle θ_d.

$$\mathrm{I}(\theta_d) = I_0\left(\frac{sin\alpha}{\alpha}\right)^2\left(\frac{sin\frac{N}{2}(\delta-\varphi)}{sin\frac{1}{2}(\delta-\varphi)}\right)^2 \quad (1)$$

$$\alpha = \frac{1}{2}kasin\theta_d\,;\ \delta = kdsin\theta_d$$

Eq. (1) comprises an intensity constant I_0, an envelope term dependent solely on the diffraction properties of a single antenna, and a grating term dependent on the periodic arrangement of the antennas. The grating term will reach its maximum whenever $\delta - \varphi = 2m\pi$, where the phase difference from the source is canceled by the phase difference from different optical path and thus interferes constructively. The final intensity pattern is the periodic grating term modulated by the envelope term.

To achieve aliasing-free operation so that only one grating lobe resides within the envelop during the entire beam-steering process, a direct approach is to increase the grating free spectral range (FSR) to cover the entire envelop. When the antenna pitch is below half-wavelength, i.e. $kd < \pi$, even if the main lobe is already at $\theta_d^0 = 90°$ ($kdsin\theta_d^0 - \varphi^0 = 2m\pi$), there is still no other diffraction angles θ_d' that can satisfy the constructive interference condition ($kdsin\theta_d' - \varphi^0 = 2m\pi$) within the entire field of view (FOV: $-90° \sim +90°$). That's the why it's desirable to shrink the antenna spacing down to the level comparable to half a wavelength.

That being said, since the light is relatively weak confined within the dielectric waveguide, strong coupling and resulted crosstalk could turn the dense waveguide array into a super antenna or at least an array with less effective operating elements. Though coupling is actually a process that evolves with the propagation, the typical guideline to avoid undesirable crosstalk is about 2 μm, which is well beyond the half-wavelength threshold.

The practical way to suppress the coupling is to introduce a mode mismatch so that adjacent waveguides have different effective index and subsequently could not couple to each other effectively. This could be done either by dispersion engineering the width of the waveguide, or by designing an array of bent waveguides with different bent radii, i.e. the densely packed bent waveguide array (DPBWA).

Since the variation in the waveguide width can be limited by the narrow spacing between abreast channels and the requirement that the luminance should be uniform across the array, the latter approach is far more desirable with both a uniform waveguide width as well as different propagation constants in every waveguide so that the coupling is not only suppressed between adjacent waveguides but throughout the entire array.

Based on the working principle discussed above, we designed a 16-channel optical phased array with a grating coupler input, traditional broad-band cascaded power splitters and thermo-optical phase shifters, and a DPBWA optimized for a 0.8 μm spacing. For typical design flow of DPBWAs, we refer to the work by H. Xu et al.[8] The design mask layout and the fabricated chip as well as a group of zoom-in pictures of the DPBWA are shown in Fig. 1. The detailed design parameters for the output section of our DPBWA are labelled in Fig. 1 (c), (d).

Experimental Results

To verify the coupling suppression between adjacent channels in our design, a reference device was designed by connecting two identical DPBWAs with centrosymmetry. The measured crosstalk (CR) at 1550 nm wavelength between adjacent ports varies from -12.6 dB (the worst case) to -27.5 dB (the best case), while the channel insertion loss (IL) fluctuates around -2 dB.

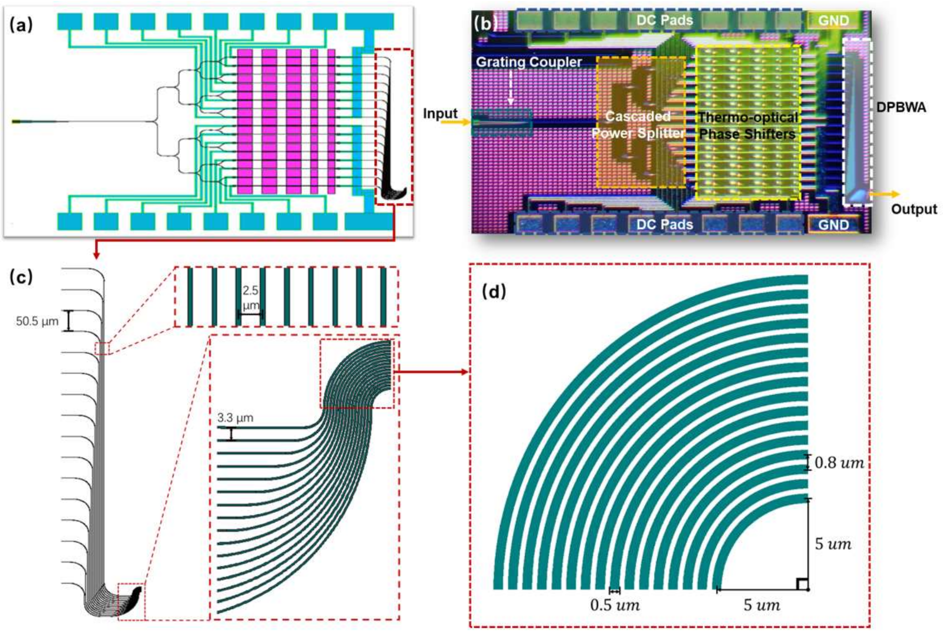

Fig. 1: (a) Mask layout of the entire chip. (b) Microscope image of the fabricated chip. (c) Zoom-in of the DPBWA together with its transition waveguide sections that reduce the spacing from 50.5 μm to 0.8 μm. (d) Concentric bent waveguides in the DPBWA with its key design parameters labeled.

The measured data are shown in Fig. 2. As both the structure and the coupling are symmetric, only the crosstalk between the n^{th}-port to the $(n+1)^{th}$-port was measured.

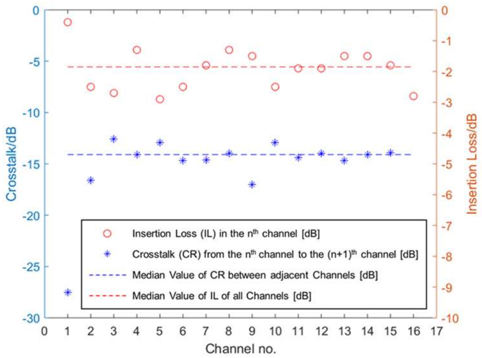

Fig. 2: Measured inter-channel crosstalk (blue stars, blue dash-line) and insertion loss (red circles, red dash-line) for each channel.

Next, we performed phase alignment to trim the phase differences between adjacent channels, in order to form a fine beam with high energy concentration. The phase trimming was done by adjusting the voltages applied to the thermo-optical phase shifters based on the feedback from our imaging system. The far-field pattern of the aligned phased array coincides with the theoretical predictions as shown in Fig. 3.

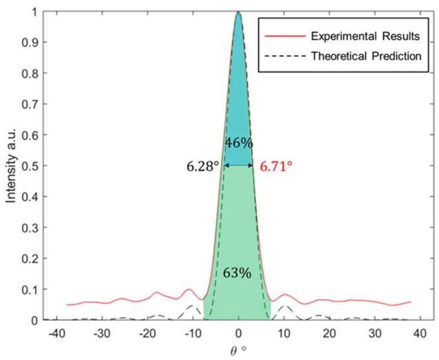

Fig. 3: Far-field intensity pattern of the aligned phased array (red line) together with the theoretical prediction by Eq. (1) (black dashed line). The measured FWHM is $6.71°$ compared to the predicted $6.28°$. The energy concentration within the FWHM and the main lobe are 46% and 63%, respectively.

Finally, since the phase difference φ between adjacent channels are now equal to each other, wavelength tuning will introduce additional phase shift proportional to φ, and hence, steer the beam in the far-field. A total of 21 incidents (the slices in Fig. 4) are recorded by the near-infrared imaging system. It reveals that the OPA achieves aliasing-free operation within the entire field of view available, i.e. $-40° \sim +40°$. Note that the middle left ring-shape pattern which dims gradually in slices No.1, 2, 3, is the leaked light from the fiber at the fiber to chip interface.

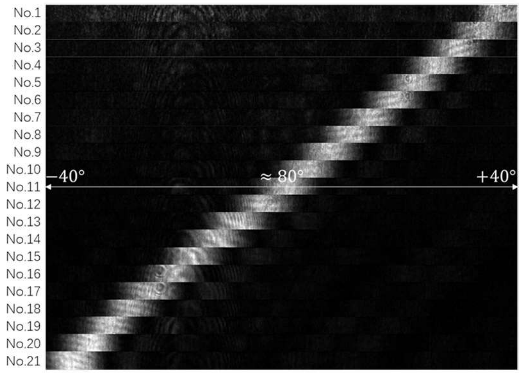

Fig. 4: Far-field pattern made of 21 slices at different beam angles during the beam steering process. The slices are cropped from the same vertical position with the same height.

Conclusions

We designed and fabricated a 16-channel uniform OPA of half-wavelength spacing utilizing a DPBWA structure for inter-channel evanescent coupling suppression. It achieved aliasing-free beam-steering with a main lobe of high energy concentration ($46\%/63\%$) that exceeds the theoretical maximum of non-uniform arrays ($\leq 40\%$). Note that theoretically, our design could form a main lobe with energy concentration of $73\%/90\%$ and steer it within a FOV of $150°$.

Acknowledgements

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