End-Fire Silicon Waveguide Array as a Platform for High Power Beam Shaping and Steering

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Abstract: We demonstrate a scalable array of end-firing silicon waveguides as a platform for high-speed, high-power operation beam-steering applications. We fabricate devices, culminating in 16×1 arrays with a measured central lobe FWHM of 7°±0.6°.

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1. Introduction

Numerous applications benefit from optical beam steering and control, ranging from free space communications to biological imaging and sensing. Traditionally, optical beam steering has involved mechanical solutions utilizing moving mirrors that come with significant cost, weight, and perform with relatively slow operation. These limitations have motivated the search for non-mechanical (i.e. no moving parts) concepts for optical beam steering and there has been a considerable body of work with particular focus on free space optical communications. These applications have unique challenges but tend to focus on lower optical power operation and therefore reasonable losses can be afforded. For applications requiring both high speed and high power operation, in particular high peak power where a low-loss platform would be crucial to maintain system robustness, the corresponding space is ripe for innovation. Here, we focus on investigating potential solutions for high power operation beam steering. As an added benefit, lower power operation applications would also benefit from a low-loss platform.

Here we utilize a highly compact chip-scale device based on integrated silicon photonics. The scalability of silicon devices is particularly attractive to high power applications as the power can be spread across a large number of elements. Additionally, a large array provides better beam control in the form of a small angular divergence. Lastly, this approach has no moving parts with the potential to yield the smallest cost, size, weight, and power for the targeted applications. Recently, integrated photonic beam steering devices utilizing phased arrays of nanoantenna structures [1] or much larger grating couplers [2,3] for emission of light normal to the plane of the chip have been demonstrated providing 2D arrays of emitters and on-chip control. However, these approaches require complex fabrication procedures, and in the case of some nanoantenna approaches, inherently lossy metals, that introduce losses ultimately limiting the device to lower power applications. In-plane devices have also been shown, but previous demonstrations relied on additional structures between waveguide termination and light emission for further beam steering [4], or did not operate in free space [5]. Here we focus on demonstrating an array of waveguides that emit light in-plane from waveguide terminations at the chip's edge with an inherently low-loss design making it an ideal platform for high power, high energy applications.

2. Device Design

In phased array devices, minimization of waveguide pitch provides the maximum achievable beam steering angle, and therefore utilization of a high index contrast platform providing maximum optical confinement becomes critical. Non-uniform spacing of emitting elements can provide better total steering angle with a larger waveguide pitch thereby avoiding crosstalk issues between adjacent waveguides [4], but the uniformity of the beam cannot be maintained through the entire steering range and such an approach would need to be customized for each specific application. Using FDTD simulation software (Photon Design FIMMwave) TE-polarized light is launched into a uniform array of 500 nm wide×220 nm tall silicon waveguides clad in silicon dioxide at a wavelength of 1550 nm. With a waveguide spacing, or array pitch, of 900 nm (including the width of the waveguide), individual modes undergo minimal crosstalk (<23 dB) over a propagation length of 10 μm. Provided a full 180° phase shift can be achieved between adjacent waveguides through phase control, a full steering range of 82° is predicted. Since this pitch is only necessary for the emitting output, the waveguides can be spaced further apart over the remainder of the on-chip device to avoid unwanted crosstalk. The output of a phased array device is an interference pattern of the outputs of each individual emitting element, which forms a series of lobes in the far field. The simulated beam steering for a 16×1 array of such waveguides is shown in Fig. 1a–j, for adjacent waveguide phase shifts of 0, 45, 90, 135, and 180°, respectively. The simulated far field arrays confirm the estimated beam steering range.

3. Device Fabrication

Multiple array devices were fabricated on silicon-on-insulator wafers with a top silicon thickness of 220 nm covered by 100 nm of thermally grown silicon dioxide on a buried oxide layer 3 μm thick. Arrays of 2, 4, 8, and 16 waveguides of dimensions 500 nm×220 nm and output pitch of 900 nm were patterned using electron beam lithography. E-beam resist was used as an etch mask to create a hard mask in the thermal oxide layer using reactive ion etching. This hard mask was then used to pattern the waveguides in the silicon layer with inductively coupled plasma etching. Finally, the waveguides were clad with 1 μm of silicon by plasma enhanced chemical vapor deposition.

Each waveguide array device has a single optical waveguide input that is then split into 2, 4, 8, or 16 waveguides using multimode interference (MMI) couplers. The resulting waveguides are spaced 5 μm apart across the majority of the propagation length. When approaching the output facet of the device the waveguides are brought to the desired array pitch of 900 nm using a series of s-bends and meanders designed to maintain optical path length equal in all devices within a single array.

4. Experimental Results

Light from a Santec ECL-200 tunable laser set to 1550 nm wavelength is sent through a polarization controller and coupled into the device via lensed fiber. The output of the array device is collected by an objective lens with a numerical aperture of 0.68 and focal length of 3.1 mm followed by a convex lens with a focal length of 150 mm. The lenses are spaced from one another by the sum of their focal lengths. A magnified image of the device output is formed at the focal length on the opposite side of the convex lens with magnification equal to the ratio of the two focal lengths (or 150 mm/3.1 mm = 48.4). A Sensors Unlimited 640HSX-1.7RT short wave infrared camera was positioned 180 mm from this focal plane to image the far field output. Because these devices are one-dimensional horizontal arrays as shown in Fig. 1k, their outputs have no confinement in the vertical direction, and the lobal definition is observed in the horizontal direction. This is shown in Fig. 1l for a 2, 4, 8, and 16 waveguide device. The experimentally measured (points) and simulated (line) full-width-half-maximum (FWHM) of the central lobe in the far field pattern are plotted as a function of the number of waveguides in the array in Fig. 1m for a variety of device designs. For the 16×1 array, the simulated central lobe FWHM of 5.5° matches reasonably well with the measured FWHM of $7.1^\circ \pm 0.6^\circ$. Although the experimentally measured values exhibit some deviation from simulation, as shown in the figure, the measurements of the central lobes for the various devices do follow the trend as predicted by our simulations.

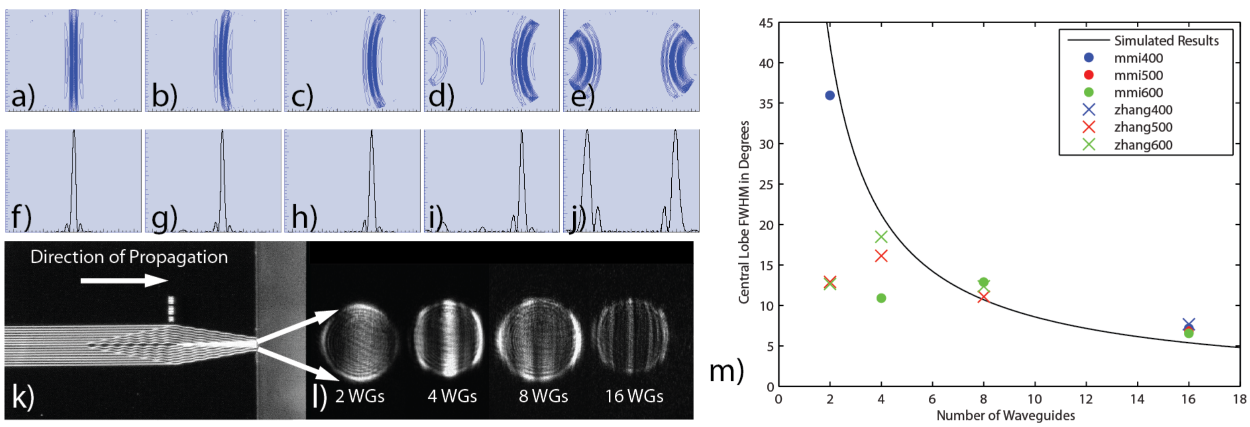

Fig. 1. (a-e) Contour profiles of the far field output of a 16×1 array with 900 nm pitch, with 0, 45, 90, 135, and 180° of phase shift respectively between each waveguide. (f-j) Horizontal cross-sectional profiles of the center of the far field outputs above. (k) Output of a 16×1 device. (l) Far field patterns of a 2, 4, 8, and 16, waveguide device. (m) Comparison of horizontal FHWM for simulations and measured results. MMI or Zhang refer to waveguide splitters used for device fanout, either a 1×2 MMI coupler or the coupler described in [6], and 400, 500, or 600 refers to the E-beam exposure dosage in μC/cm^2.

In conclusion, we have demonstrated a potential path to an innovative platform for higher-power handling and fast beam steering applications. Future implementations will incorporate phase control elements for active beam steering control. Measured beam widths exhibit good agreement with simulation, and the arrays can be scaled to larger numbers for improved beam shaping. The simplified design reduces sources of fundamental loss, allowing for high peak power applications.

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