Large Angle Beam Steering on Silicon Nanomembrane

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Abstract— **We present a phased waveguide array implementation on silicon-on-insulator based on non-uniform array design. Using individually controlled thermo-optic phase shifters, we demonstrate 31.9° beam steering in free space.**

Optical phased arrays (OPAs) represent an enabling technology that makes possible simple, faster, and lightweight laser beam steering with precise stabilization, random access pointing and programmable multiple simultaneous beams. Liquid crystal (LC) based OPAs [1] [2] [3] provide rapid beam steering without expensive and complex mechanical systems. However, LC OPAs suffer from low steering speed (~10ms) and limited steering angle (<10°) [3]. Also, in addition to the degradation of the side-lobe-level, the angular resolution becomes prohibitively coarse with increased steering angle [4].

OPAs can also be implemented using waveguide arrays. A GHz optical beam steering system employing a phased waveguide array on GaAs was demonstrated with a maximum steering angle of about 6° [5]. A thermo-optically controlled OPA fabricated on Silicon-on-Insulator (SOI) enabled demonstration of steering over an angle of 2.3° at a wavelength of 1550 nm [6]. For uniform OPAs capable of large angle beam steering, an inter-element spacing of about one-half the operating wavelength is required. Despite the promises of phased waveguide arrays, strong coupling between adjacent waveguides imposes a great limitation for employing such devices for practical applications if a uniform array configuration is used.

In order to avoid optical coupling between adjacent waveguides at small inter-element spacing ($\lambda/2$, $\lambda=1.55\mu m$) required for large angle beam steering in uniform arrays, we choose a non-uniform array design described in [4]. The prototype design is based on a non-uniform 12-element array, which consists of 3 four-element uniform sub-arrays, as shown in Fig. 1(a). The spacing of each sub-array is chosen such that there is no overlapping of its far-field grating lobes with those of the other two sub-arrays. Fig. 1(b) shows the maximum allowable steering angle using linearly phased uniform arrays as a function of the inter-element spacing and also recent OPA based beam steering results.

Optical components have been designed for SOI implementation. The buried oxide (BOX) layer and the silicon layer are 3μm and 230nm thick, respectively. The waveguide arrays are terminated at a 1cm long and 2cm wide slab waveguide for testing purposes as discussed later. In the far field zone, beam steering angle inside the silicon is achieved by applying phase shifts, which are proportional to the distance of each waveguide from one side of the array. The theoretical far field patterns for steered and non-steered beams are shown in Fig. 1(c).

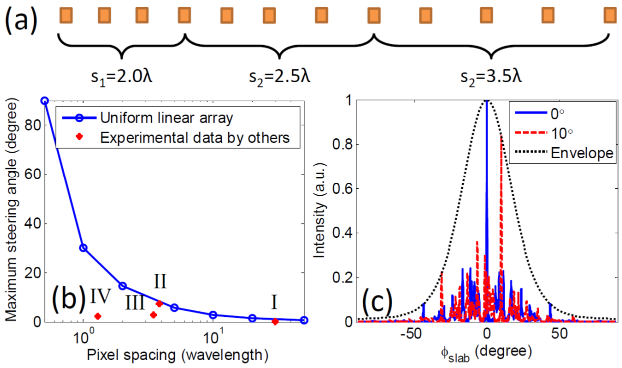

Fig. 1. (a) 12-element non-uniform array design with 3 sub-arrays. (b) The maximum allowable steering angle using a linearly phased uniform array as a function of the inter-element spacing. The maximum allowable angle here is defined as the steering angle at which the side-lobe-level=0dB for the first time as the beam is steering from the broadside angle ($\varphi_{slab}=0^\circ$). The experimental data points, I, II, III, and IV, are bi-directional beam steering angles demonstrated in [2], [7], [5], and [6], respectively. (c) Theoretical far-field pattern for a non-steered ($\varphi_{slab}=0^\circ$, solid blue line) and a steered ($\varphi_{slab}=10^\circ$, dashed red line) beam inside the slab waveguide. The envelope (dotted back line) is the far field pattern of a single 500nm wide and 230nm thick silicon waveguide embedded in silicon dioxide.

A schematic of the OPA device is shown in Fig. 2. The input power from is uniformly divided into 12 waveguides using a 1x12 Multimode Interference (MMI) beam splitter. This 1x12 MMI's width and length are 60μm and 553.4μm, respectively. The input and output access waveguides' widths are 2.6μm, which is the optimum value for high MMI performance [8]. The access waveguides' widths need to be tapered down to 0.5μm for single mode operation under the thermo-optic phase shifters.

There are 12 independently addressed thermo-optic phase modulators to provide continuous phase tuning needed for beam steering. This provides us the advantage of being able to reset after each 2π phase shift. In addition to reducing the power consumption for phase shifting, this can enable larger angle beam steering. The micro heaters are 800nm wide and 500μm long. A 1μm thick silicon dioxide layer deposited on top of the silicon waveguides serves as top cladding.

The passive s-bend phase shifters follow next, which compensate for the quadratic MMI beam splitter output phase profile [9] and change the separation of the uniform waveguide array to that of the non-uniform array at the output.

We have used SOI from SOITEC with 3µm BOX and 250nm top silicon layer, which is oxidized to create an oxide etch mask, leaving a final silicon thickness of 230nm. Patterning of this silicon layer was achieved by using the JEOL JBX600 electron beam lithography system and RIE etching. A 1µm film of plasma-enhanced chemical vapor deposition (PECVD) silicon dioxide was deposited using the Plasmatherm 790 system for top cladding. The MMI coupler was shown to have an insertion loss of 1.13dB, and uniformity of 0.72dB using TE polarized [10].

After PECVD SiO_2 deposition, thermo-optic metal heaters 500µm in length and 800nm wide are patterned over the waveguides by e-beam lithography and alignment. In order to apply the correct phase shift to each of the 12 waveguides using the thermo-optic phase shifters in the OPA during active beam steering, we fabricated Mach-Zehnder (MZ) modulators to determine P_π, with dimensions identical to the OPA with regard to waveguide size, separation, and heater length and width. For our heater, we determined that P_π=12.4mW.

Figure 3(c) demonstrates the measured beam steering angle at the edge of the silicon slab when linear phase shift values are applied to the array element. The theoretical steering angles as a function of the input power to the outermost array element, which needs the largest phase shift, are calculated using the phase shift data from the Mach Zehnder test. Despite the highly efficient thermo-optic phase shifters, the power required for beam steering becomes prohibitively large. The maximum power our multi-channel programmable voltage source does not allow steering angles larger than about 2.5° inside the silicon slab. Top-down IR images of the non-steered and steered beam at 2.5° are shown in Fig 3(a) and (b), respectively. Figure 3(d) shows beam steering angles achieved by applying modulo 2π phase shifts to the independently controlled electrodes. Using phase resets with the independently controlled phase shifters, as shown in [11], would reduce the maximum power consumption by the heater. We were able to steer the beam at 10.5° inside the silicon slab with side-lobe-level (SLL) better than 3dB, while limiting the maximum power per channel to less than $P_{2\pi}$=24.8mW.

Note that the steering angle in air is changed, as the beam couples out of the silicon slab. Also shown in Figure 3(c) and 3(d) is the steering angle for air, which can be determined by the use of Snell's law, where n_{eff}=2.9. We determine that a steering angle in free space of over 30º has been achieved, which to our knowledge, is the largest reported to date.

In summary, we have demonstrated large angle optical beam steering in free space of over 30º using a silicon nanomembrane based unequally spaced optical phased array that relaxes the strict waveguide spacing requirement for large angle beam steering. Our optical beam steering system is fabricated on SOI using CMOS compatible processes. Phase modulation is achieved thermo-optically via the use of thin-film metal heaters that are independently controlled.

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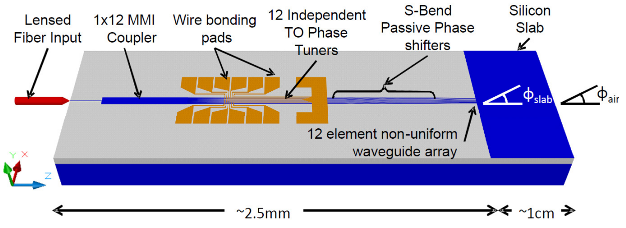

Fig. 2. A schematic of the silicon waveguide based optical phased array.

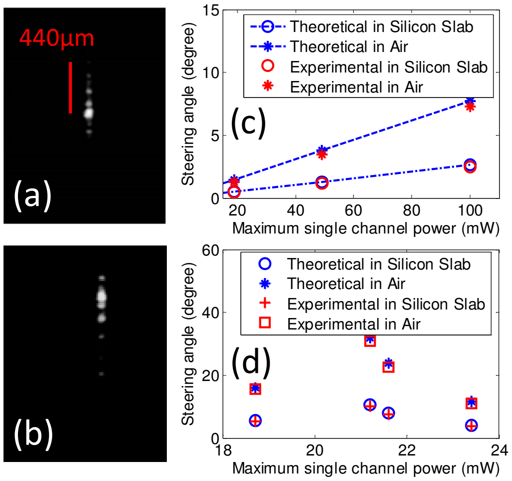

Fig. 3. Top down IR images of the far field viewed at the end of the silicon nanomembrane slab (a) non-steered beam, (b) beam steered at 2.5° in silicon. Steering angle vs maximum power applied in a single channel for both the silicon slab and in air (c) without reset and (d) with reset.