Integrated Optical Phased Array Based Large Angle Beam Steering System Fabricated on Silicon-on-Insulator

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ABSTRACT

In this paper, we present a highly compact silicon nano-membrane based optical phased array fabricated using conventional CMOS processing on silicon-on-insulator that provides for over 10 degrees of beam steering in a silicon slab at λ=1.55μm using transverse-electrical polarized light. A low loss 1-to-12 multi-mode interference (MMI) optical beam splitter with high uniformity is used to provide inputs to the optical phased array. Using an unequally spaced waveguide array permits us to relax the half-wavelength spacing requirement for large angle beam steering, thereby avoiding the optical coupling between adjacent waveguides and reducing the side-lobe-level of the array radiation pattern. S-bend waveguides convert the equally spaced MMI output to the unequally spaced wave guide array, while passively equalizing the phases of each array element to compensate for the MMI output phase profile. Independently controllable thin film metal heaters are used to achieve phase shifting using the strong thermo-optic response of silicon. Heat-insulating air grooves minimize thermal crosstalk, while also achieving and low power consumption.

Keywords: Beam steering, optical phased array, silicon-on-insulator, thermo-optic

1. INTRODUCTION

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. Mechanical beam steering systems can provide high steering efficiency and large steering angle, but high precision rotating states are required, which makes packaging challenging as well as increase device complexity. In addition, these mechanically steered beams are not potentially fast enough for high-speed applications. 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.

2. DESIGN METHODOLOGY

In order to avoid optical coupling between adjacent waveguides at small inter-element spacing (λ/2, λ=1.55μm) 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

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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).

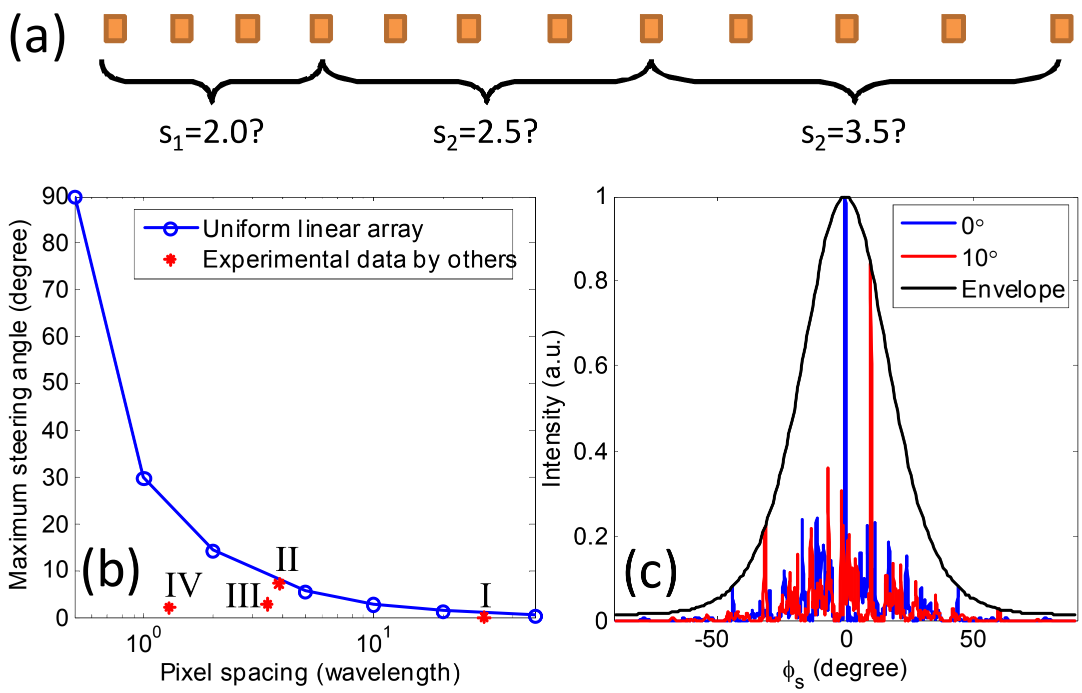

Fig. 1. (a) 12-element non-uniform array design with 3 sub-arrays. (b) The maximum allowable steering angle using a linearly phased uniform array as a function of the inter-element spacing. The maximum allowable angle here is defined as the steering angle at which the side-lobe-level=0dB for the first time as the beam is steering from the broadside angle (φ_{slab}=0°). 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 (φ_{slab}=0°, solid blue line) and a steered (φ_{slab} =10°, 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.

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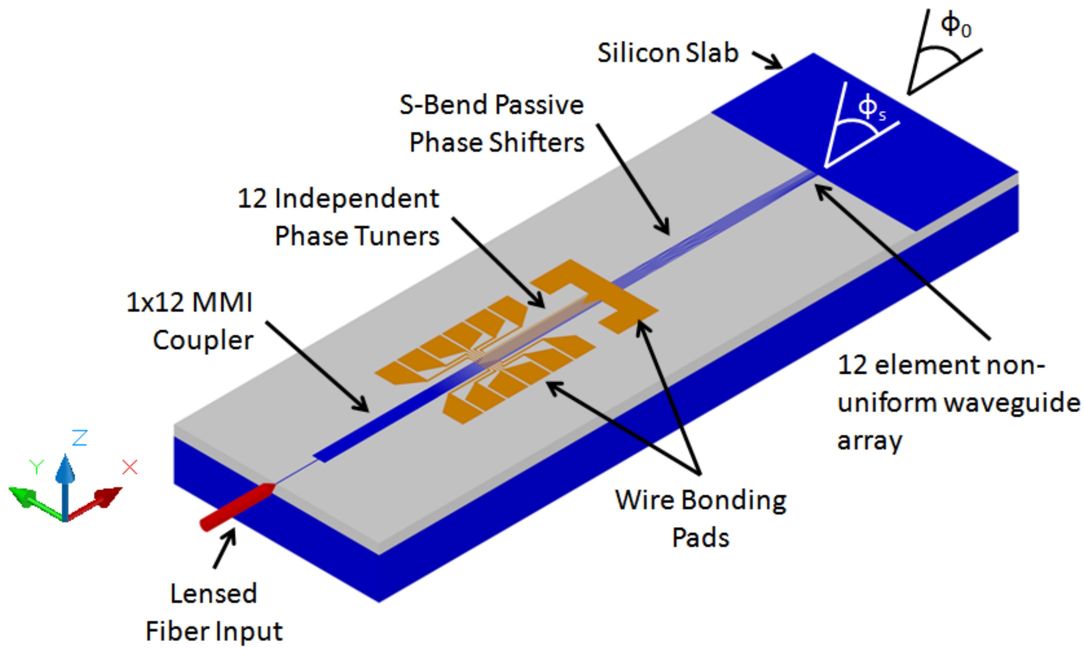

Fig. 2. A schematic of the silicon waveguide based optical phased array.

3. EXPERIMENTAL RESULTS AND ANALYSIS

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. Thermal evaporation and liftoff of 150nm of Cr/Au completes the process. An SEM cross section of the completed microheater over its respective waveguide is shown in Figure 3(a). Note that the voids are caused by “bread loafing” of the PECVD oxide film over the waveguides under specific deposition conditions. While they are undesirable for electronics fabrication such as in inter-metal dielectrics (IMD) or inter-layer dielectrics (ILD), they are advantageous in this application by reducing lateral heat transfer for more efficient waveguide heating by channeling the heat to the waveguide. This is shown in Figure 3(b), which is the simulated thermal profile of a structure which matches our fabricated device.

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 the switching power 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, as shown in Figure 3(c).

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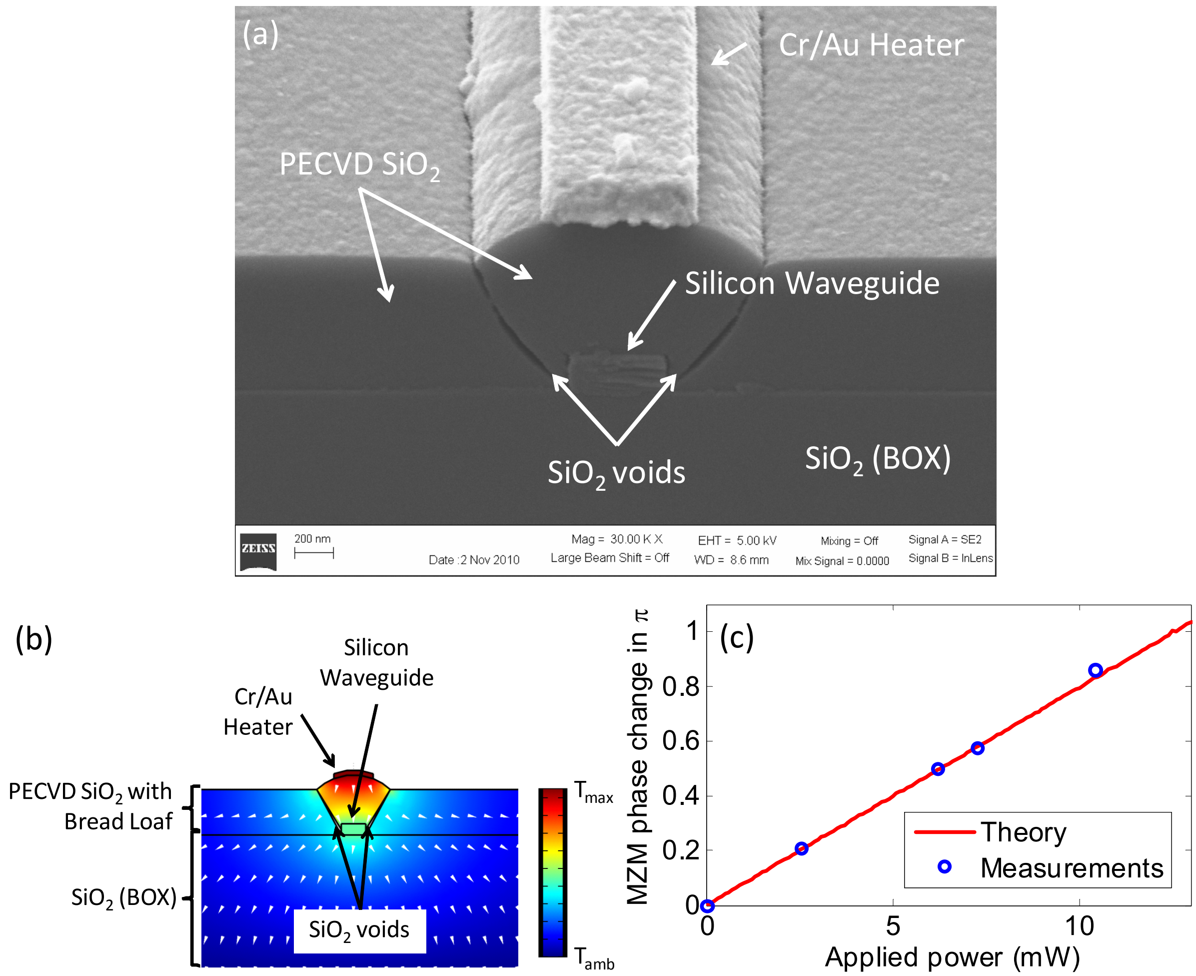

Fig. 3 (a) SEM cross section of a heater over its waveguide with oxide voids caused by PECVD bread-loafing. (b) Simulated thermal profile using PECVD SiO2 with bread loafing that shows reduction in lateral heat transfer and more efficient heating of silicon waveguide. (c) Electrical power vs phase change in MZM showing P_π value of 12.4mW.

Figure 4(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 4(a) and (b), respectively. Figure 4(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 4(c) and 4(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.

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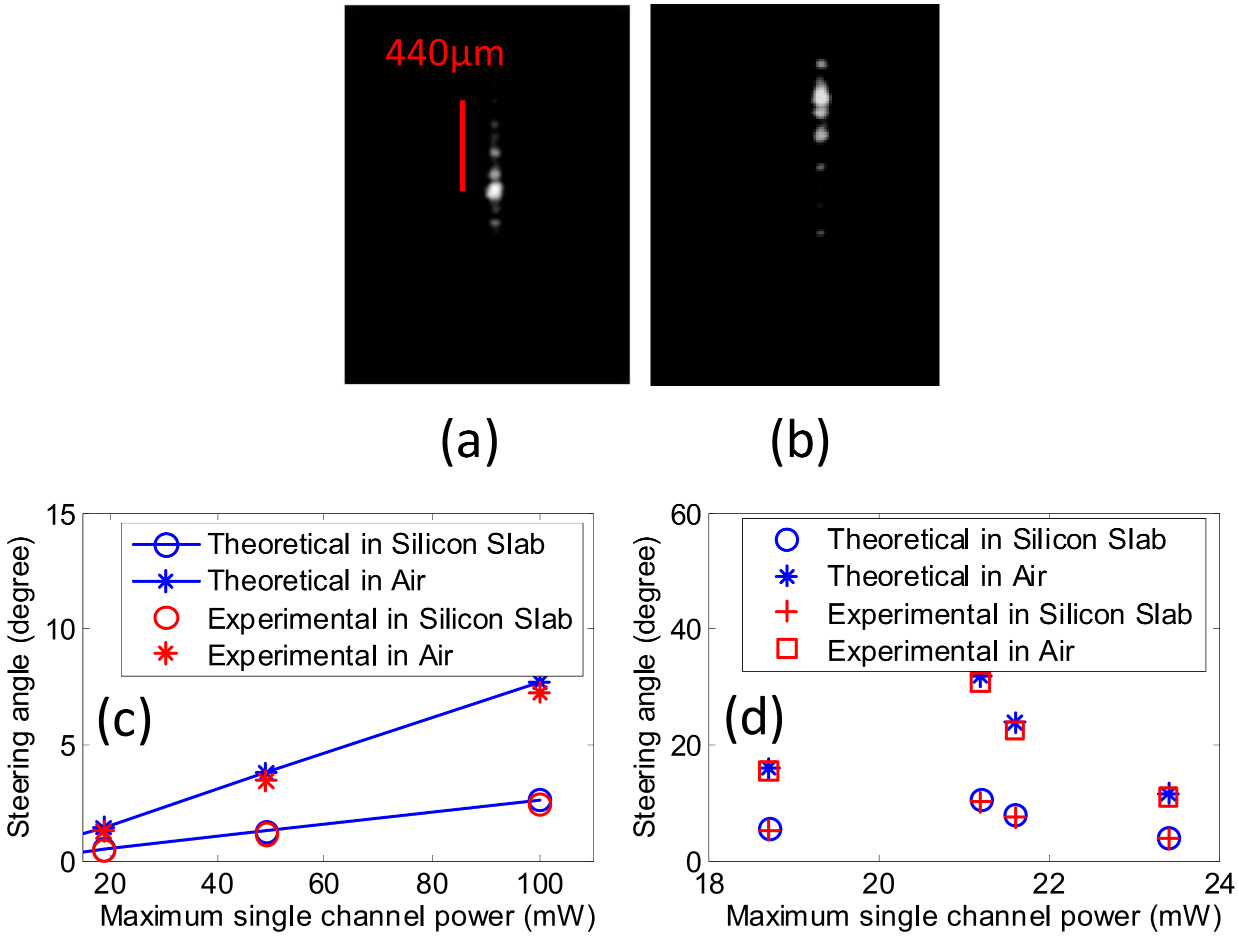

Fig. 4. Top down IR images of the far field viewed at the end of the silicon nanomembrane slab (a) non-steered beam, (b) beam steered at 2.5° in silicon. Steering angle vs maximum power applied in a single channel for both the silicon slab and in air (c) without reset and (d) with reset.

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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