are hence able to excite pulses in each other, mimicking neuron functionality as optical spiking neurons.

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Off-chip beam steering using optical phased arrays on silicon-on-insulator

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Optical beam steering can find applications in several domains such as laser scanning, LiDAR (Light Detection And Ranging), optical switches and interconnects. Present beam steering techniques such as liquid crystals or MEMS-technology are limited in speed and/or performance. Therefore we have studied the possibilities of the silicon photonics platform in beam steering applications. In this paper, we have investigated a 16 element one-dimensional optical phased array on silicon-on-insulator with a field-of-view of 23°. Using thermo-optic phase tuners, we have shown beam steering and shaping over the complete field-of-view. This clearly shows the potential of silicon photonics in beam steering applications.

Introduction

Free-space beam steering can on the one hand be used in laser scanning applications such as LiDAR (Light Detection And Ranging), optical wireless links, remote node interrogation ... but can also find applications in the very short range such as in optical switches and optical interconnects. Optical Phased Arrays (OPAs) provide a way to efficiently steer an optical beam without any mechanical motion, making them insensitive to acceleration [1]. In this paper, we have investigated the use of the silicon photonics platform in beam steering applications. Beam steering on this platform has already been investigated in [2] and [3] where a one- and two-dimensional OPA on silicon-on-insulator (SOI) has been demonstrated, respectively. In the former, the beam could be steered to a small angle as there was only one heater electrode. In the latter, sidelobe levels were high due to the very small fill factor of the OPA. As has been shown in [4], a beam can also be steered in the two-dimensional space using wavelength tuning only. Here we present a design that combines both full thermo-optic and wavelength beam steering. Due to full control over the phases, the beam can be steered in one dimension over its complete field of view while a grating is used to steer the beam in the other dimension using wavelength tuning.

Design and Fabrication

The beam steering component shown in Fig. 1(a) was fabricated in *imec*, Leuven through ePIXfab which uses standard CMOS (Complementary Metal Oxide Semiconductor) - compatible processes. An SOI wafer with a 2μm thick buried oxide layer and a 220nm top silicon layer was used. Two deep-UV (UltraViolet) lithography etch steps are then used: one of 220nm to pattern the waveguides and the star coupler and one of 70nm to pattern the out-coupling gratings and the tapering sections of the star coupler. After the S-shape, the waveguides taper to a 4μm width on which a 70nm deep grating is etched

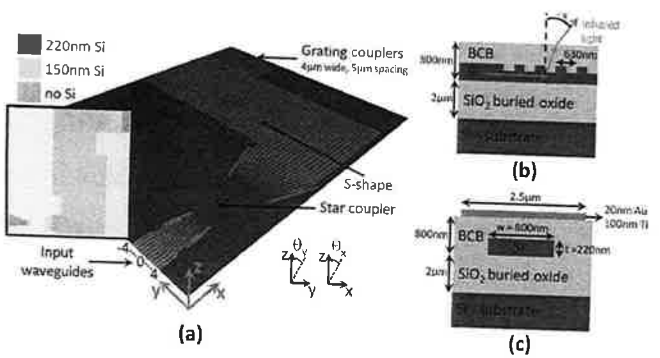


Figure 1: (a) Virtual fabrication of a one-dimensional OPA on SOI. Light enters through the input waveguide of the star coupler and couples off-chip using grating couplers, on the S-shape heaters are processed (not shown in the Figure) to tune the respective phases of the different grating couplers. The inset shows a microscope image of the fabricated component before heater processing. (b) Cross-sectional view of the grating coupler. (c) Cross-sectional view of the thermo-optic phase tuners.

with a period of 630nm and a duty cycle of 0.5. The gratings are separated 5μm. A cross-sectional view of the grating is shown in Fig. 1(b). Afterward a BCB (benzocyclobutene) layer of about 800nm is spun on top of the component on which 2.5μm wide, 450μm long heaters are processed using contact mask lithography consisting of a 100nm Ti layer and a 20nm Au layer to avoid oxidation of the heater as shown in Fig. 1(c). The input waveguides shown in Fig. 1(a) are connected with a grating coupler which is optimized for near vertical coupling of infrared light from a fiber to the fundamental TE-like mode of an integrated circuit [5]. These are used to excite our structure. For the remainder of this paper, we assume to work only with TE-like light.

By using thermo-optic phase tuners, the beam can be shaped and steered in the θ_y-direction. A simple heater design was proven to be sufficient to demonstrate the steering capabilities. The power needed for a π phase shift at 1550nm was measured to be around $P_\pi = 15 - 20$mW. In the θ_x-direction, the beam characteristics are determined by the out-coupling grating with an angle given by the grating equation:

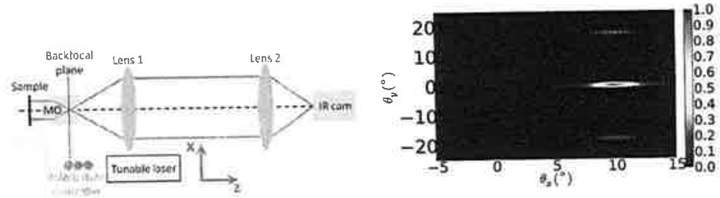
$$\sin\theta_x = \frac{\Lambda_{gr} n_{eff,gr} - \lambda}{n_{ct}\Lambda_{gr}}, \tag{1}$$

with Λ_{gr} the period of the grating (Λ_{gr}=630nm), λ the free-space wavelength, $n_{eff,gr}$ the effective index of the guided mode in the grating area and n_{ct} the refractive index of the background which is air ($n_{ct} = 1$) in this case.

Measurement setup

The far-field characteristics of the beam steering component are investigated using a Fourier imaging setup. The far-field is imaged on the back-focal plane of a high numerical aperture (NA=0.5) microscope objective (MO). This image is brought back to

an infrared camera using two lenses [6]. Every point in the to a specific direction of emission and thus represents the far-field of the beam steering component. Light from a tunable laser is sent through a polarization controller and is then coupled into the beam steering component using a grating coupler for near-vertical coupling. The radiated light is then imaged using the Fourier imaging setup as shown in Fig. 2(a). A probe card is placed in front of the sample to drive the different heaters.

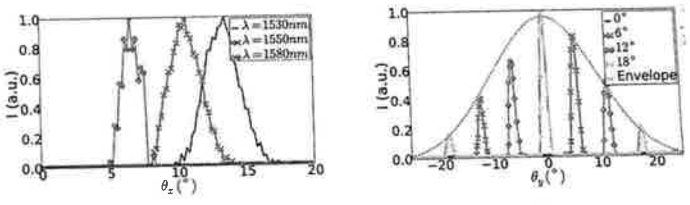


(a) (b)

Figure 2: (a) A Fourier imaging setup is used to study the far-field characteristics of the beam steering component. (b) Measured far-field pattern of the beam steering component at a wavelength of 1550nm.

Measurement results and discussion

In Fig. 2(b), the measured far-field of the beam steering component is shown at a wavelength of 1550nm. A broad beam in the θ_x-direction can be seen, which is determined by the out-coupling grating and centered around $\theta_x = 10°$ being the out-coupling angle of the grating given by Eq. (1). In the θ_y-direction, a typical OPA far-field pattern can be seen. The beam is narrow and the different output orders are visible with a spacing of 18°. This spacing can be increased by decreasing the waveguide spacing. Next, we will investigate cross-sectional views of the far-field of the beam steering component to study the wavelength and thermo-optic steering behavior.



(a) (b)

Figure 3: Measured far-field in the (a) θ_x-direction using wavelength steering and (b) θ_y-direction using thermo-optic steering at 1550nm. The beam is steered to the angles 0°, 6°, 12° and 18° with a beam width of 1.27°. The dashed line shows the envelope of the far-field pattern.

Fig. 3(a) shows the far-field pattern along the θ_x-direction for three different wavelengths. The FWHM beam width is measured to be 3.0°, 2.8° and 1.6° for a wavelength of

1520nm, 1550nm and 1580nm, respectively and the beam is steered over a 6.7° range for a 60nm wavelength shift. As the field that leaves a grating coupler with a fixed grating period is an exponential decaying field, the far-field pattern does not look very nice as can be seen in Fig. 3(a). The smaller beam width for increasing wavelength can be explained due to the fact that the grating couples the light out less efficiently, so that the exponential tail becomes larger and the far-field beam width will decrease.
In Fig. 3(b), a cross-sectional view of the far-field in the θ_y-direction is shown when the beam is steered at different angles using the thermo-optic phase tuners. The beam is steered over the complete FOV in the θ_y-direction. As the phase change ϕ is directly proportional to the dissipated power in the heater, and the latter is proportional to the applied voltage V squared, we use the a simple quadratic model to determine the right voltages where the 2π phase resets can be taken into account.

Conclusion

We have shown a 16 element one-dimensional optical phased array on silicon-on-insulator. The field-of-view was 23° using 4μm wide grating couplers spaced 5μm. The different output orders of the array were spaced 18°. This field-of-view and output order spacing could easily be increased by decreasing the waveguide width and spacing, respectively, but will result in a broader beam as the number of elements stays constant. The beamwidth was 1.27°. Using thermo-optic phase tuners, the beam was steered over its complete field-of-view. Using wavelength tuning over a range of 60nm, the beam was steered over 6.7° in the other dimension.

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Automatic Transmission Parameters Measurement and Radiation Pattern Simulation for an RF Photonic Integrated Beamformer

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We present the implementation and demonstration of a software tool for the performance characterization of integrated N-by-1 photonic beamformers for phased array antennas. The software operates the automatic measurement of the transmission parameters of an equivalent N+1 ports microwave network, corresponding to the complex excitations of the individual antenna elements of the array. The measured excitations are used to simulate the array factor generated by the optical beamformer and to analyze it in terms of maximum directivity, sidelobe levels and wideband behaviour. The software provides a useful tool to test the wideband performance of the network, the effects of excitation inaccuracies, and a straightforward evaluation of the effects of amplitude and phase weighting for beam shaping.

Introduction

Phased array antenna systems have gained much interest in modern wireless systems (e.g. radar, radio communications, satellite reception, radio astronomy) mainly thanks to the specific ability of this type of antenna structures to dynamically reconfigure their radiation characteristics [1]. In fact, the radiation pattern of an antenna array directly depends on the complex excitations, provided by the so-called beamforming network (BFN), to the individual antenna elements constituting the array. The ability to reconfigure those excitations allows to modify important radiation characteristics of the antenna array, as the spatial pointing direction of the main antenna beam, its shape, the levels of the sidelobes, the possibility to place nulls of radiations in desired directions, and more. This gives a large degree of flexibility when compared to individual antennas, making arrays highly desirable in many applications within the field of wireless communications. In very broadband applications, and where continuous tunability of the beam direction is required, it might become advantageous to realize the beamformer employing *optical* technology, thanks to inherent advantages of photonics such as compactness, light weight, low loss, frequency independence, large instantaneous bandwidth and inherent immunity to electromagnetic interferences [2, 3]. In this case we refer to the beamformer as *optical beamforming network* (OBFN).

To characterize the performance of any beamforming network, it is very useful to analyze the characteristics of the *radiation pattern* generated when this feeding network is connected to an actual antenna array. In general, this type of test requires the integration of the OBFN with an antenna system, in an anechoic chamber or another suitable environment, using a complex measurement setup, leading to a characterization process which might be expensive and not trivial to realize.

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