Efficient Light Collection and Direction-of-Arrival Estimation Using a Photonic Integrated Circuit

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***Abstract*— Efficient collection of light into a photonic integrated circuit is becoming increasingly important. To couple light from free-space into an integrated circuit, one needs to efficiently guide it into a photonic wire. By using multiple light capturing elements and tuning their respective phases, it is possible to efficiently guide light into a single-mode waveguide, even when the phase front is distorted. Using a similar approach, a direction-of-arrival estimation is also performed. This is useful in free-space optical links or wavefront analysis. A 16 element integrated structure that performs these functions is presented here. Increasing the number of elements and downscaling the size will further improve the performance.**

***Index Terms*— Coherent beam combining, direction-of-arrival, scattering, optical phased arrays, phase distortion, silicon-on-insulator.**

I. Introduction

PHOTONIC integrated circuits (PIC) have evolved strongly in the past decade. Silicon photonics is one of these PIC platforms that has great potential due to its advanced fabrication technology, relying on the well established CMOS (Complementary Metal Oxide Semiconductor) processes. One of the key functionalities of these PICs is to interface with the outside world. While nanometer scale structures can be fabricated, these need to be excited efficiently. Typically, connecting to the outside world happens through an optical fiber using inverted tapers or grating couplers that have been designed to optimize coupling [1]. For certain applications, however, there is an increasing need to couple directly from free-space to chip. One can think of free-space optical interconnects [2], scanning or sensing devices and short-range optical links.

In this letter, we have investigated an integrated structure that allows efficient coupling from free-space into a single mode integrated waveguide. It consists of an array of apertures. Each aperture couples part of the light into the PIC. Using phase tuners, the phases of all these contributions can be tuned to efficiently combine them into a single mode waveguide. This results in efficient collection of light from e.g. scattering media [3] which is useful in atmospheric propagation error correction [4], Raman spectroscopy [5] or biological applications. Another integrated approach for efficient light collection from biological media has been studied in [6], where a confocal arrangement of two AWGs allows focusing on and collection of backscattered light from a sample.

The technique proposed here, also gives us the possibility to perform Direction-Of-Arrival (DOA) estimation using a straightforward sweeping algorithm. The component is a one-dimensional Optical Phased Array (OPA) fabricated on Silicon-On-Insulator (SOI) of which the far-field characteristics have been studied in detail in [7]. This component allows us to investigate the incoming wavefront and efficiently couple this into an integrated photonic wire.

Firstly, we will discuss the design and fabrication of the component. Secondly, the experimental setup and results are given. A conclusion is finally formulated in Section IV.

II. Design and Fabrication

The component, shown in Fig. 1, was fabricated at IMEC, using standard CMOS processes [8] on a SOI wafer with a 2 μm buried oxide layer and a 220 nm silicon top layer. Strip waveguides are defined with a full 220 nm etch while grating couplers and tapering sections are defined with a 70 nm etch [9]. Light is incident on the integrated probe which consists of 16 grating couplers (Fig. 2) that couple light into the structure based on the principle of diffraction. The (second-order) gratings have a width of 4 μm with a $\Lambda_y = 5$ μm spacing. In the x-direction, the incoupling angle is given by the grating equation:

$$\sin\theta_x = \frac{\Lambda_x n_{eff,gr} - \lambda}{n_{bg}\Lambda_x}, \quad (1)$$

with Λ_x the period of the grating ($\Lambda_x = 630$ nm), λ the free-space wavelength, $n_{eff,gr}$ the effective index of the guided mode in the grating area and n_{bg} the refractive index of the background. The gratings were optimized to couple the TE (Transverse Electric)-like mode at a $\theta_x = 10°$ angle. In the y-direction, the incoming wavefront is sampled into 16 elements. The gratings then taper down to a single mode 450 nm wire. Afterward, the width was increased to 800 nm as a wider waveguide is more tolerant to fabrication deviations, apart from the bends which are 450 nm wide

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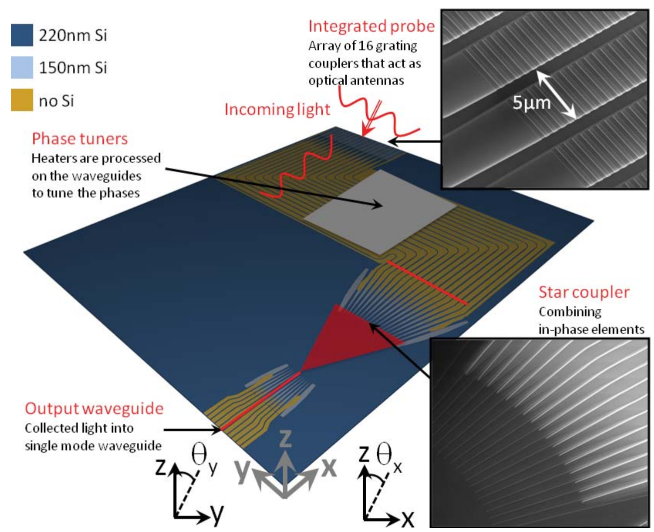
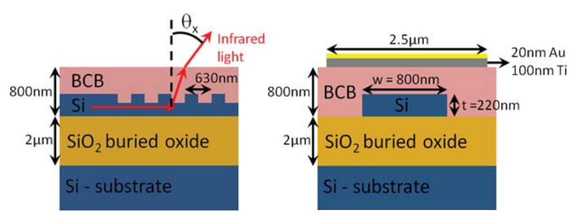


Fig. 1. Schematic of the fabricated component.



(a) (b)

Fig. 2. Cross section of (a) grating coupler shown as the integrated probe in Fig. 1 and (b) heaters used to tune the phase as shown in Fig. 1.

to allow sharp bends. By heating the waveguide, the phase of the light is tuned due to the temperature dependence of the refractive index of silicon [10], [11]. The heaters are processed by spinning a 800 nm BCB (benzocyclybutene) layer on the SOI chip and patterning 2.5 μm wide, 500 μm long heaters using our in-house contact mask lithography. A cross sectional view of the heaters can be found in Fig. 2. The voltage-phase relationship of these heaters was characterized in previous work [7]. The 16 waveguides then gradually taper to a 2 μm wide shallow etched waveguide spaced 2.2 μm before entering the free propagation region of the star coupler. The free propagation region has a length of 54.5 μm and will focus the in-phase light on a 1.35 μm wide shallow etched waveguide. This waveguide finally tapers to a 450 nm strip waveguide shown as the output waveguide in Fig. 1.

III. Measurement Results and Discussion

A. Collection of Scattered Light

Fig. 3 shows a schematic of the measurement setup used to capture scattered light. Infrared light from a tunable laser goes through a polarization controller and is focused just above the sample with a plano-convex lens. No direct light then hits the structure. A diffuser is placed in the Rayleigh range of the focused light to scatter the light. This scattered light falls on the structure and is, after passing through the PIC, coupled into an optical fiber which is connected to an optical power meter. The heaters are electrically probed using a probe card to individually address the heaters.

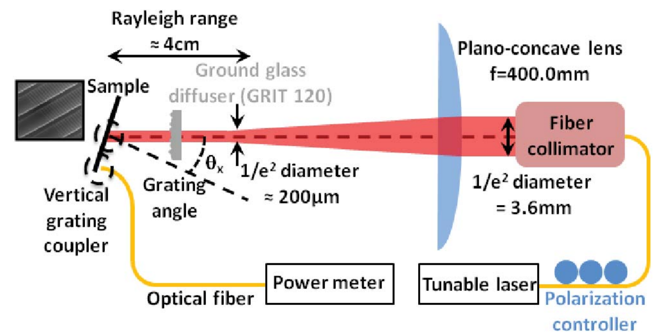


Fig. 3. Collection of scattered light.

The scattered light has a random phase on each element of the structure. These 16 random phases need to be tuned to be combined into a single mode waveguide. The optimization of this problem, with 16 elements, can in theory be done using a gradient based algorithm in around 100 iterations [12]. Such an algorithm is however not robust against small measurement fluctuations. Therefore an annealing algorithm – available in the Python SciPy package [12] – was used, which takes about 10 times longer but is more likely to find the optimum. Fig. 4 shows such a typical optimization run. As the scattering is wavelength dependent, we have performed this optimization for different wavelengths as shown in Fig. 5. The speed of the heaters was measured to be 20 kHz so that 1000 iterations can happen in 50 ms. We believe that this can be increased by an order of magnitude by developing dedicated optimization algorithms and heater design.

The process of phase recombination becomes clear when looking at the example of a $N \times 1$ combiner. On average, each arm holds a power of P/N. When the phase of each contribution is random, there is on average a $1/N$ loss factor, so the total average loss is $N \times 1/N \times P/N = P/N$. Note that this is an average loss. If, for example, the phases are set to interfere destructively, there will be almost no power after combining (explaining the dips in Fig. 5). However, by efficient phase recombination, all the power in the arms can be added coherently such that the $1/N$ loss factor disappears. The improvement is thus a factor N or, for a 16 element array, 12 dB. For the 16 element structure, a general increase of more than 10 dB was measured, while also the large dips have disappeared due to the efficient phase recombination. This agrees well to the theoretically expected value.

B. Direction-of-Arrival Estimation

Fig. 6 shows the measurement setup used for DOA estimation. The sample is mounted in the center of a motorized tilt stage such that the θ_y-angle of incidence can be tuned. Light is incident onto the structure from a certain θ_y-angle and by imposing a linear phase sweep over the waveguides, the DOA can be estimated. When there is a uniform phase difference $\Delta\phi$ between each element, the structure will efficiently couple light from an angle θ_y:

$$\sin\theta_y = \frac{\lambda}{2\pi\Lambda_y}\Delta\phi, \qquad (2)$$

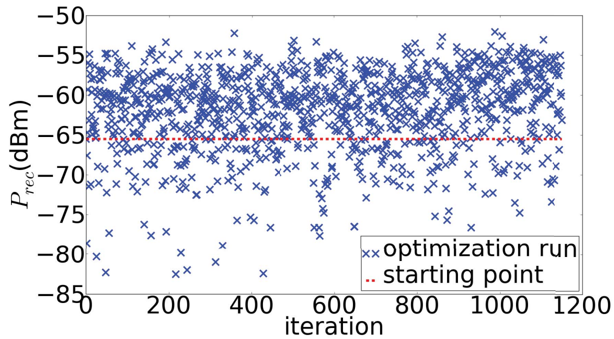


Fig. 4. Optimization of the random phases at $\lambda = 1550$ nm. The red dashed line shows the starting point.

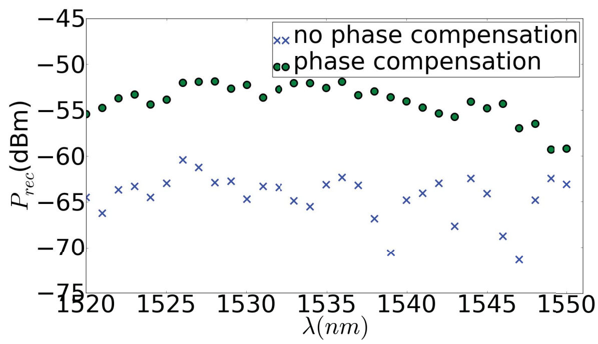


Fig. 5. Optimization of the random phases for different wavelengths. A general increase of 10 dB can be seen.

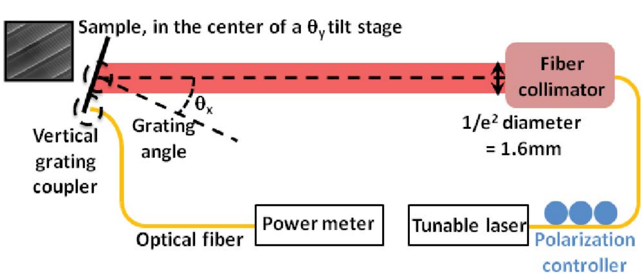


Fig. 6. Direction-of-arrival estimation.

with Λ_y the spacing of the elements. Due to this spacing, there will be ambiguity because of the higher orders of the array. Only within the free-spectral range ($\theta_{FSR} \approx \arcsin\lambda/\Lambda_y$) of the array, the direction can be determined without ambiguity, which is 18° for the structure with 5 μm spacing. This angle range can be increased by decreasing the spacing. The spacing can become as small as 1.5 μm for 450 nm waveguides without significant coupling between the waveguides. However, by decreasing the element spacing, the collection and resolution will decrease as the number of resolvable directions scales with the number of elements $N(=16)$. Thus a trade-off needs to be made between complexity, efficiency and performance of the system.

When the light hits the structure, the phases over the heaters are swept to determine the direction of arrival. Fig. 7 shows the result of this sweep for an angle of incidence of $\theta_y = 5°$. There is a clear peak visible at this angle, but also at the $\theta_y = -13°$ angle due to the FSR of the array. The width

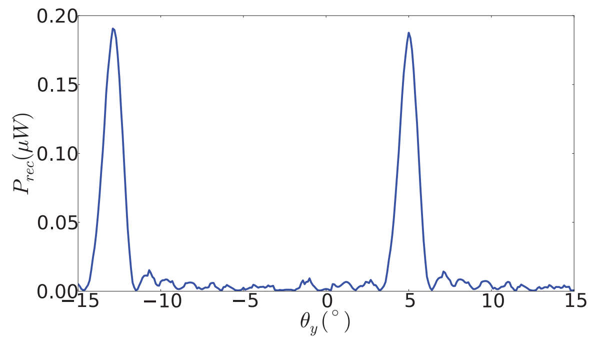


Fig. 7. Direct-of-arrival measurement when light impinges at a 5° angle.

of the peak is determined by the spatial distribution of the incoming field and the number of light capturing elements. As this number is limited to 16, the peak is quite wide with a full-width-half-maximum peak of 1.24°.

IV. Conclusion

We have shown an integrated optical phased array on SOI that is able to efficiently couple light into a photonic integrated circuit. An increase of 10 dB was seen when coupling light, scattered by a diffuser, into a 16 element array. Furthermore, by applying a uniform phase difference between the elements, a direction-of-arrival measurement can be done. The signal direction can be determined unambiguously in a one-dimensional 18° space. This can be improved by downscaling the component and increasing the number of elements.

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