Two-dimensional Dispersive Beam Steerer Fabricated on Silicon-On-Insulator.

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***Abstract*—A two-dimensional beam steerer on silicon-on-insulator is presented. Steering ranges of 5.5° in one direction and 50° in the other direction have been shown for a wavelength shift of 40nm. The largest measured sensitivity was 10.7° per nanometer wavelength shift.**

I. INTRODUCTION

One of the key elements in free-space optical applications is beam steering [1]. Beam steering can be achieved with several methods such as MEMS (Micro ElectroMechanical Systems), movable mirrors or optical phased arrays (OPAs). The latter have the advantage that they are robust and insensitive to acceleration. When using an OPA, there is a need to tune the phase of each pixel. A popular way of performing this is, for example, using liquid crystals. In [2], an integrated OPA on silicon-on-insulator (SOI) has been demonstrated using thermo-optic phase tuning. Beam steering can, however, also be performed by wavelength tuning. When using diffractive elements, the direction of emission can be controlled by wavelength tuning. A two-dimensional space can then be scanned by using two dispersive elements. This principle has been shown in [3].

In this paper, we present a fully integrated approach to perform two-dimensional wavelength scanning. Therefore we make use of the silicon photonics platform using SOI. The component presented here scans a two-dimensional space using wavelength tuning. The principle is that the beam direction is scanned quickly in one direction while it changes slowly in the other direction when changing the wavelength. The component is quite similar to an Arrayed Waveguide Grating (AWG) in which the last star coupler section has been replaced by gratings for outcoupling. The grating and the AWG delay lines are the two dispersive elements to perform beam steering. Such dispersive components could find applications in, for example, spectroscopy applications or in optical wireless sensor networks. In the latter, the component would act as a cheap node, while the base station would perform wavelength steering and tuning to address the right node. This would result in a complex base station design but cheap optical nodes that can be addressed. Another application could be free space WDM (Wavelength Division Multiplexing) networks, where a room is divided into different sections that are addressed by a different wavelength.

Next, we discuss the design and fabrication of the component. In Section 3 the measurement results are given. Section 4 gives the conclusion.

II. DESIGN AND FABRICATION

The structure (shown schematically in Fig. 1) was fabricated on SOI at *imec*, Leuven using standard CMOS (Complementary Metal Oxide Semiconductor) processes [4], [5]. The buried oxide layer layer is 2µm and the silicon top layer is 220nm high. A deep etch of 220nm was used to etch the waveguides and the star coupler and a shallow etch of 70nm to etch the grating couplers and tapering sections of the star coupler. Light is guided from an optical fiber into the structure using a grating coupler for near vertical coupling of the TE-like mode [6]. The waveguide is then adiabatically tapered to a 450nm wide photonic wire which is the input waveguide shown in Fig. 1. Light is then split through a star coupler into 16 waveguides. There is a fixed delay length ΔL between each waveguide. At the end of each waveguide, the photonic wire tapers to a 800nm wide wire on which a grating is etched.

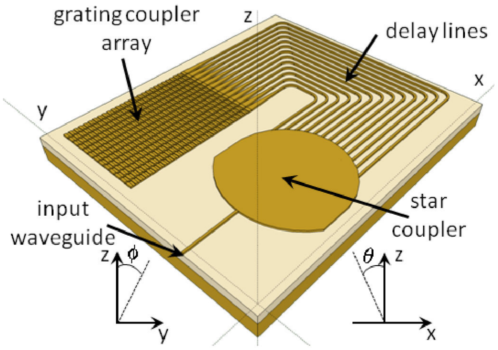


Fig. 1. Two-dimensional beam steerer fabricated on SOI.

The grating is the first dispersive element that will determine the steering in the θ-direction (Fig. 1), given by the grating equation:

$$\sin\theta = \frac{\Lambda_{gr} n_{eff,gr} - \lambda_0}{n_{ct}\Lambda_{gr}} \quad (1)$$

with Λ_{gr} the period of the grating, 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. The steering speed is given by

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} \approx \frac{\mathrm{d}\sin\theta}{\mathrm{d}\lambda} = \frac{\mathrm{d}n_{eff,gr}}{\mathrm{d}\lambda} - \frac{1}{\Lambda_{gr}} \quad (2)$$

where the approximation is valid when the angle θ is relatively small. Note the dispersion factor $\mathrm{d}n_{eff,gr}/\mathrm{d}\lambda$, which cannot be neglected. The dispersion is about -8.9$\times 10^{-4}$/nm for a 70nm deep etched grating in a 800nm wide waveguide.

The delay lines will now determine the steering in the ϕ-direction (Fig. 1). The grating couplers are placed in an N-array configuration with positions $\mathbf{s}_n = n\Lambda_y\mathbf{u}_y$ with Λ_y the spacing of the elements in the y-direction and $n = 0 \ldots N-1$. The far field can be calculated by multiplication of the far field of one grating coupler with the array factor T [7]:

$$T = \sum_{n=0}^{N-1} A_n e^{-j\beta_n} e^{j\mathbf{k}\cdot\mathbf{s}_n} = \sum_{n=0}^{N-1} A_n e^{-j\beta_n} e^{jk_0[n\Lambda_y \sin\phi]} \quad (3)$$

where β_n is the phase delay between the elements, $\mathbf{k}$ is the wave vector (in air) with magnitude k_0 and A_n is the amplitude of each element which is further assumed to be 1. The length difference ΔL results in a phase delay of:

$$\beta_n = n_{eff}\frac{2\pi}{\lambda} n\Delta L \quad (4)$$

with n_{eff} the effective index of the fundamental TE-like mode. The array factor can then be calculated in closed form:

$$T = e^{j\left[(k_0\Lambda_y \sin\phi - k_0 n_{eff}\Delta L)\frac{N-1}{2}\right]} \frac{\sin\left(N\frac{k_0\Lambda_y\sin\phi - k_0 n_{eff}\Delta L}{2}\right)}{\sin\left(\frac{k_0\Lambda_y\sin\phi - k_0 n_{eff}\Delta L}{2}\right)} \quad (5)$$

The array factor is maximum in the ϕ-direction for

$$\sin\phi = q\frac{\lambda}{\Lambda_y} + \frac{n_{eff}\Delta L}{\Lambda_y} \quad (6)$$

with q an integer. Due to the delay lines, the absolute value of q will be large. The beams will shift at a rate of

$$\frac{\mathrm{d}\phi}{\mathrm{d}\lambda} \approx \frac{\mathrm{d}\sin\phi}{\mathrm{d}\lambda} = \frac{q}{\Lambda_y} + \frac{\mathrm{d}n_{eff}}{\mathrm{d}\lambda}\frac{\Delta L}{\Lambda_y} \quad (7)$$

where the angle ϕ is assumed to be relatively small. Note that q will be negative so that the beam will shift in the negative ϕ-direction for increasing wavelength. To reduce the effect of phase noise in the delay lines due to fabrication tolerances, the delay lines are tapered to a 800nm wide waveguides. The effective index at $\lambda = 1550$nm for this wire is $n_{eff} \approx 2.648$. There are two main contributions to the dispersion: material dispersion and waveguide dispersion. Whereas the former is relatively weak for the wavelength range considered here, the latter can have a significant influence due to the extremely high confinement in the small photonic wires. The change of n_{eff} with wavelength is negative as well and is about -8.2×10^{-4}/nm around $\lambda = 1550$ nm for a 800nm wide wire. This influence is reduced by having a wider waveguide. For comparison, this dispersion value is about -0.013/nm in a 450nm wide wire. However, the factor $\Delta L/\Lambda_y$ can become large so that the influence of dispersion cannot be neglected. Different wavelength scanners were fabricated and measured. The gratings were etched in a 800nm wide wire with a period of 670nm and a fill factor of 50%. The effective index of the grating area is then about 2.48. Eq. (1) then gives a mean outcoupling angle $\theta_0 = 9.6°$ at $\lambda = 1550$nm. The steering speed given by Eq. (2) is then $\mathrm{d}\theta/\mathrm{d}\lambda \approx 0.137°$/nm. The spacing of the gratings was $\Lambda_y = 2$µm. The steering speed in the ϕ-direction given by Eq. (7) depends mainly on the length difference ΔL and is summarized in Table I for the fabricated components.

ΔL (µm)	q	$\mathrm{d}\phi/\mathrm{d}\lambda$ (°/nm) (theory)	$\mathrm{d}\phi/\mathrm{d}\lambda$ (°/nm) (meas.)
29.2	-50	-2.12	-2.16
58.5	-100	-4.24	-4.37
87.7	-150	-6.36	-6.47
117.0	-200	-8.47	-8.69
146.2	-250	-10.60	-10.72

TABLE I
THEORETICAL AND MEASURED RESULTS OF THE FABRICATED COMPONENTS.

III. MEASUREMENT RESULTS

A Fourier imaging setup was used to investigate the far field pattern of the components as shown in Fig. 2 [8]. The far field is imaged onto the back-focal plane of a microscope objective (MO). In this plane, one point corresponds to a specific direction of emission. This plane is then brought back to the infrared camera by means of two lenses. The numerical aperture (NA) of the microscope objective determines the maximum direction of emission that is captured by the measurement setup. An MO with a NA of 0.5 was used meaning that the maximum angle with respect to the normal of the surface that can be measured is 30°.

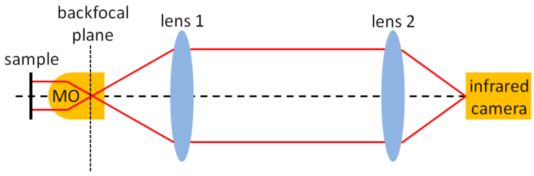
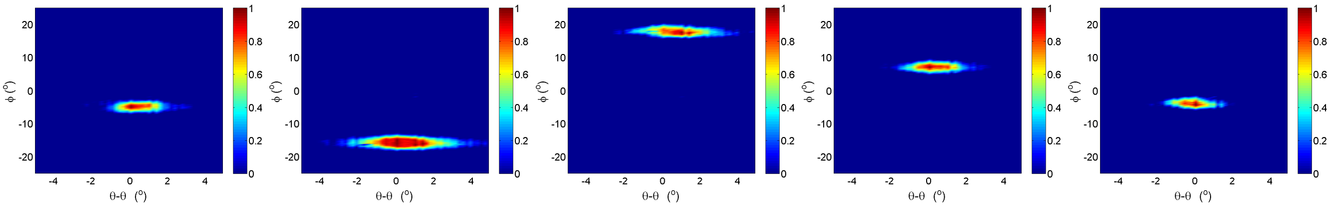


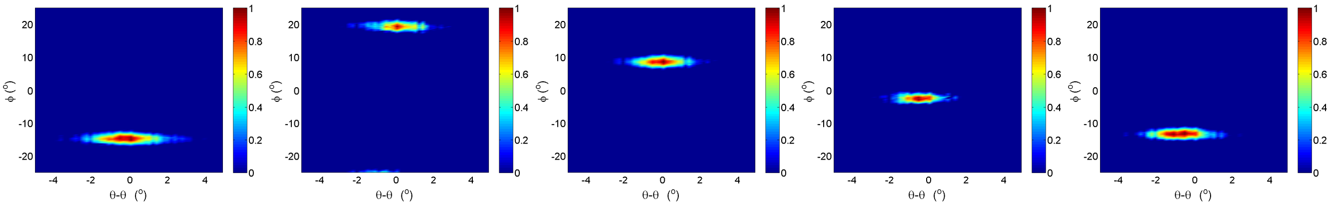
Fig. 2. A Fourier imaging setup was used to measure the far field of the beam steerers.

Fig. 3 shows the far field pattern of one of the beam steerers with $q = -250$ at ten different wavelengths. The FWHM-width (full-width-half-maximum) is about 2.5° in both the θ- and ϕ-direction. Due to the spacing of 2µm, there is more than one lobe emitted by the array, not visible in Fig. 3. These are spaced about $\mathrm{asin}(\lambda/\Lambda_\mathrm{y})$ which is about 50.8° at a wavelength of 1550nm.

In order to scan the complete 2D space, the beam should shift 50° in the ϕ-direction when it has shifted 2.5° in the θ-direction (as the FWHM beam width is 2.5°). The latter happens over a wavelength range of about 18nm. The



(a) λ=1545nm (b) λ=1546nm (c) λ=1547nm (d) λ=1548nm (e) λ=1549nm

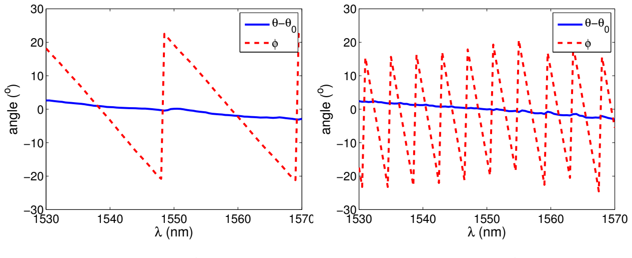


(f) λ=1550nm (g) λ=1551nm (h) λ=1552nm (i) λ=1553nm (j) λ=1554nm

Fig. 3. Far field of the 2D beam steerer of order $q = -250$ at 10 different wavelengths.

minimum steering speed in the ϕ-direction should thus be 2.78°/nm. The results of the steering speed in the ϕ-direction is given in Table I. A good agreement with the theoretical expected values can be seen.

The steering speed in the θ-direction is the same for all components and was measured to be 0.137°/nm which corresponds to the theoretical value. The position of the beam for two of the fabricated components can be found in Fig. 4. The θ angle varies slowly while the ϕ angle changes quickly when changing the wavelength. At each jump, we focus on a different lobe emitted by the grating array. This lobe then shifts out of the measurement range until a new lobe appears.



(a) q=-50 (b) q=-250

Fig. 4. Position of the beam for different orders q of the delay length ΔL.

The beam width can be decreased in the ϕ-direction by having more waveguides. The beam width in the θ-direction depends on the strength of the grating. This strength is strongly dependent on the grating etch. Having an etch of less than 70nm would result in a weaker grating with a longer outcoupling length and thus a narrower beam. This would increase the sensitivity of the component.

IV. CONCLUSION

A two-dimensional beam steerer on SOI has been presented. Steering ranges of about 5.5° in the θ-direction and 50° in the ϕ-direction were measured for a wavelength shift of 40nm. The maximum measured sensitivity of shift in the ϕ-direction was 10.7°/nm. This sensitivity can be further increased by increasing the delay lengths resulting in a faster steering speed or by having more waveguides resulting in a narrower beam.

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