Chip-to-chip Optical Wireless Link Feasibility Using Optical Phased Arrays on Silicon-On-Insulator.

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***Abstract*—One- and two-dimensional integrated optical phased arrays (OPAs) on silicon-on-insulator have been fabricated and measured having directivities of more than 40dBi and steering ranges up to 10°. These OPAs would allow data rates of 100Mbps at distances up to 0.5m.**

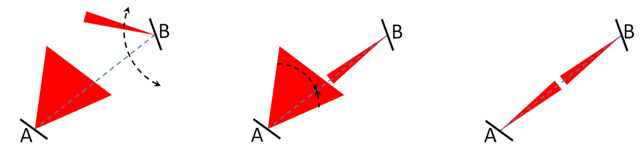
I. Introduction

As the radio frequency (RF) spectrum is getting more and more congested and since there is only a limited bandwidth available in the RF spectrum, optical wireless links are gaining importance for high speed wireless data transfer. Optical links however have some inherent disadvantages: line-of-sight is needed for high speed operation, ambient light interference, eye and skin safety regulations and relatively high optical powers need to be received. On the other hand, optical links have a high security and frequency reuse, do not suffer from electromagnetic interference and have a virtually unlimited bandwidth free from regulations. [1]

To get directive links and allow mobile connectivity, beam steering is needed. Optical phased arrays (OPAs) have been recognized to allow rapid, versatile beam steering without mechanical motion, making them robust and insensitive to acceleration. [2].

The present wireless optical systems mainly use bulk components. In this paper, the feasibility of using integrated components for short-range, high-speed wireless links is investigated. We therefore make use of the silicon photonics platform using silicon-on-insulator (SOI). Silicon has proven to be an ideal material for passive optics while integration with III-V materials can deliver active functions such as light generation. This paper will focus on the optical antennas which consist of arrays of grating couplers and the possible links we can achieve with these components. One- and two-dimensional OPAs will be investigated.

Beam steering and shaping capability can be added by adding phase tuners. An easy, low-cost phase tuning mechanism in silicon is thermo-optic phase tuning. Such an one-dimensional OPA on SOI has been demonstrated in [3]. Another way of steering could be performed by wavelength tuning. Combining both can decrease the need of active phase tuners. Having beam shaping and steering capability, a wireless link can be established as shown in Fig. 1. When only beam steering is availaible, a broad beam could be mimicked by quickly scanning the entire space.



(a) A sends a broad beam towards B. B then steers the beam towards A.

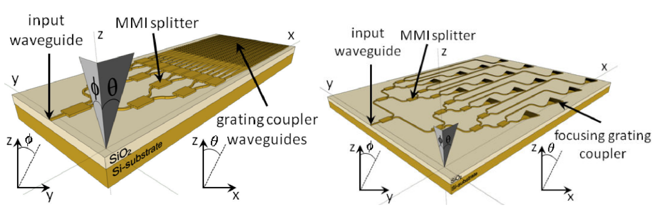
(b) B sends a beam to A. A reshapes its beam to improve reception.

(c) The reciprocal wireless link has been established.

Fig. 1. Possible way of establishing an optical link using OPAs on SOI.

In the following section we discuss the design and fabrication of the components. Section 3 describes the measurement results. Next, the feasibility of these components for short range chip-to-chip communication is discussed. In Section 5 the conclusion is given.

II. Design and Fabrication



(a) 1D OPA

(b) 2D OPA

Fig. 2. Optical phased arrays fabricated on silicon-on-insulator.

The components were fabricated on SOI using standard CMOS (Complementary Metal Oxide Semiconductor) processes at *imec*, Leuven [4], [5]. The SOI box layer is 2μm with a silicon top layer of 220nm. Two etch steps are used, one deep etch of 220nm to etch the waveguides and MultiMode Interference (MMI) splitters, and one of 70nm to etch the grating couplers. The latter have shown to be an efficient way to guide light from fiber to chip. These grating couplers can now also act as optical antennas sending light to free space. The efficiency of a grating coupler from fiber to chip with one etch is about -5.2dB. This can be increased up to -1.6dB by using a silicon overlay [6]. Light from an optical fiber is coupled into the structure using a grating coupler for near vertical coupling of the TE-like mode in a 10μm waveguide which then tapers down to a 450nm wide photonic wire which is the input waveguide in Fig. 2.

The 1D OPA shown in Fig. 2(a) consists of an array of waveguides on which a grating is etched. The 2D OPA shown in Fig. 2(b) consists of an array of focusing grating couplers. This reduces the need of a long taper [7]. Nonetheless, the spacing remains rather large resulting in multiple sidelobes. This has no significant influence on the link budget as shown in [8].

III. Measurement Results

A. Measurement Setup

The far field of the OPAs was measured using a Fourier imaging setup [9]. In such a setup the far field is imaged on the back-focal plane of a microscope objective (MO) with a large numerical aperture (NA). This plane is then imaged onto an infrared camera using two extra lenses.

B. One-dimensional OPA

When designing 1D OPAs, there are several parameters one needs to take into account. The beam direction in the θ-direction can only be steered by changing the wavelength, since the direction of outcoupling is determined by the grating equation:

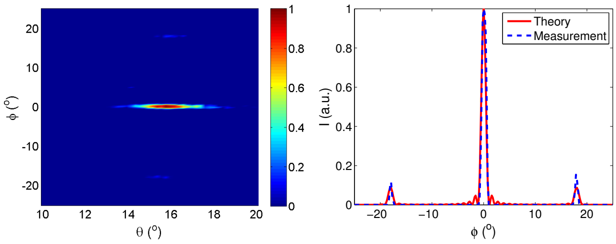
$$\sin\theta = \frac{\Lambda_{gr} n_{eff} - \lambda_0}{n_{ct}\Lambda_{gr}} \qquad (1)$$

with Λ_{gr} the period of the grating, λ_0 the free-space wavelength, n_{eff} the effective index of the guided mode and n_{ct} the refractive index of the background which is air in this case. The width of this beam is determined by the strength of the grating. When having a standard etch of 70nm, the FWHM (full-width-half-maximum) beamwidth $\Delta\theta_0$ is about 2.5° around λ =1550nm. By changing the fill factor of the grating, the grating can be made somewhat weaker. This results in a longer outcoupling length and thus a narrower beam. However, the effect is limited to about 0.1°.

The FWHM beamwidth $\Delta\phi_0$ in the ϕ-direction is determined by the aperture size, which is determined by the number of waveguides and the width of the waveguides. Wider waveguides can provide a narrow beam with fewer elements, but the steering range is decreased. This steering range is determined by the far field pattern of one waveguide. Two different types of 1D OPAs were fabricated and measured:

- waveguide width of 800nm, spaced 2μm, grating period of 630nm and fill factor of 0.5: the mean θ angle of emission is about 2°. These OPAs have a large coverage range in the ϕ-direction of about 120°, but a limited directivity.
- waveguide width of 4μm, spaced 5μm, grating period of 630nm and fill factor of 0.8: the mean θ angle of emissions is about 16°. These OPAs have a higher directivity but the coverage range in the ϕ-direction is now limited to about 15°. The large fill factor did not result in a significant narrowing of the beam. The far field of this OPA is shown in Fig. 3.

The results are summarized in Table I. Note that for the last array, no accurate measurement was performed since the beamwidth became smaller than a few camera pixels. The theoretical expected and measured directivity (defined in section IV) is given as well.



(a) (b)

Fig. 3. (a) Far field of a one-dimensional 16 element OPA spaced 5μm at a wavelength of 1550nm. (b) Cross section of (a) at θ=16°.

N	Λ (μm)	w_{wg} (μm)	ff	$\Delta\theta_0$	$\Delta\phi_0$	D_{th} (dBi)	D_{meas} (dBi)
8	2	0.8	0.5	2.5	6.42	29.9	30.0
16	2	0.8	0.5	2.5	3.35	32.8	32.7
16	5	4	0.8	2.4	0.98	41.2	42.4
32	5	4	0.8	2.4	X	43.8	X

TABLE I

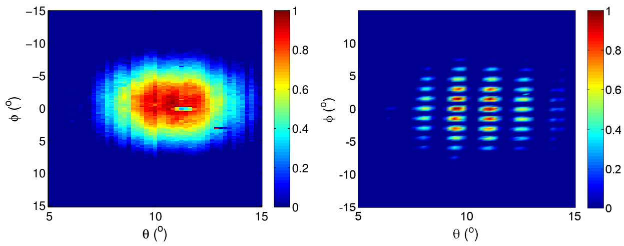
Parameters of the fabricated measured 1D OPAs at λ =1550nm.

C. Two-dimensional OPA

The 2D OPA consists of an $N\times N$ array of grating couplers. The spacing in the x- and y-direction, denoted as Λ, is taken to be identical. The far field of one focusing grating coupler determines the envelope of the pattern and thus the steering range. This is shown in Fig. 4(a). The FWHM width in the θ-direction is 4.8° and in the ϕ-direction 9.6° at a wavelength of 1550nm. The mean angle of emission is about 12° and is determined by the grating equation. By placing these couplers in an array configuration, we obtain a far field as shown in Fig. 4(b). Multiple sidelobes arise due to the large element spacing. Steering in the θ-direction can be done by using wavelength tuning: this will shift the envelope due to the grating equation, however since the elements have a delay length of ΔL between them in the x-direction, the emission lobes will shift as well due to this delay:

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} \approx \frac{q}{\Lambda} + \frac{\mathrm{d}n_{eff}}{\mathrm{d}\lambda}\frac{\Delta L}{\Lambda} \qquad (2)$$

where n_{eff} is the effective index of the delay waveguides and q is the order of the delay (=-$n_{eff}\Delta L/\lambda$). Adding N phase tuners would allow steering and shaping in the ϕ-direction. Adding phase tuners to each element allows full beam steering and shaping. The parameters of the fabricated OPAs can be found in Table II. For the 8×8 array, the directivity could not be measured accurately due to the limited resolution of the measurement setup.



(a) (b)

Fig. 4. (a) Far field of one focusing grating coupler. (b) Far field of a 2×2 optical phased array spaced 60µm fabricated on silicon-on-insulator at a wavelength of 1550nm.

N	Λ (µm)	ΔL (µm)	D_{th} (dBi)	D_{meas} (dBi)
2	60	87.2	34	37.0
4	60	72.2	40	38.4
8	80	90.0	46	X

TABLE II
PARAMETERS OF THE MEASURED 2D OPAS AT λ =1550NM.

IV. CHIP-TO-CHIP LINK

To determine the link possibilities, the optical analog of the Friis formula can be used:

$$P_r = P_t \eta_t D_t (\frac{\lambda}{4\pi d})^2 Q_{rt} \eta_r D_r \quad (3)$$

with P_t and P_r the transmitted and receiver power, D_t and D_r the antenna directivity of the transmitter and receiver OPA, η_t and η_r the efficiency factors, d the separation between the antennas and Q_{rt} the polarization mismatch factor. The directivity is defined as the power-per-unit solid angle radiated in a certain direction (θ, ϕ) compared to the power-per-unit angle radiated by an isotropic radiator:

$$D(\theta, \phi) = 4\pi \frac{I(\theta_0, \phi_0)}{\iint I(\theta, \phi) \sin\theta \mathrm{d}\theta \mathrm{d}\phi} \quad (4)$$

This is only valid when the optical beam size is large compared to the receiver. Since we are dealing with very small radiating apertures, this assumption is valid. Because the light is guided into a photonic wire before detection, coherent detection can be used to boost the sensitivity by 20dB [10]. A typical link budget for a chip-to-chip links using integrated OPAs is given in Table III. The directivity of the OPA is set to 42dB. The polarization loss has been set to two times 3dB at the transmitter and receiver side.

The minimum received power depends on the data rate. A $P_r = -47.3$dBm would allow operation up to about 100Mbps [10]. For high speed links of 10Gbps, receiver sensitivities of the order of -15dBm are needed. This will thus need other receiver design including collective optics for example to improve the link budget. Such an approach using an integrated receiver array with a lens on top is shown in [11]. The OPAs can still act as steerable transmitters.

P_t	(dBm)	10.0
η_t	(dB)	-1.6
D_t	(dBi)	42.0
loss@0.5m	(dB)	-132.1
Q_{rt}	(dB)	-6.0
η_r	(dB)	-1.6
D_r	(dBi)	42.0
P_r	(dBm)	-47.3

TABLE III
TYPICAL CHIP-TO-CHIP LINK BUDGET FOR A WIRELESS OPTICAL LINK.

V. CONCLUSION

One- and two-dimensional OPAs on SOI have been presented allowing wireless communication using a fully integrated approach. These OPAs allow beam steering with directivities of more than 40dB while steering in one or two directions over about 10° is possible by wavelength tuning and/or phase tuning. The feasibility of these OPAs to be used in a reciprocal link has been shown. This shows that we can achieve data rates up to 100Mbps over a distance of 0.5m.

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