Optical wireless communication using silicon-on-insulator technology

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The feasibility of fabricating wireless optical components on Silicon-on-Insulator (SOI) is investigated. Using arrays of grating couplers, a so-called phased array is constructed allowing beam steering and sending light to and receiving light from free space. Using a phased array at the receiver side also allows for more complex modulation formats since light is now captured coherently before being detected in an integrated receiver. Link budget calculations of such phased arrays are performed and show the feasibility of on-chip phased arrays for distances up to a few meter and steering ranges of several degrees.

Introduction

As the data rates are increasing, there is an increasing mismatch between wired and wireless communications. While optical fiber communication easily allows Gigabit-per-second (Gbps) communication, the present mainstream wireless communication, based on a radio-frequency (RF) carrier at 2.45GHz does only offer several tens up to hundreds Mbps due to the limited bandwidth available and interference of other users. At RF side, one is therefore looking at the 60GHz band for short range (~10m) Gbps communication since there is an unlicensed band of 5-7GHz around 60GHz available worldwide [1]. Another option for high-speed wireless communication is wireless optical communication. Optical links are free of FCC regulations resulting in a virtually unlimited bandwidth compared to their RF counterpart. One can then make all-optical networks where only an electro-optic (EO) conversion is necessary at the receiver side [2].
In this paper, the feasibility of on-chip optical wireless components using the Silicon-on-Insulator (SOI) platform is investigated. The SOI platform is CMOS compatible and this allows low-cost, mass-producible optical components to be fabricated. This could be useful in e.g. sensor networks [3]. Link budget calculations demonstrating in which cases an optical on-chip link is useful are presented.
Since directive beams are needed, beam steering is desirable. This beam steering is enabled by an optical phased array (OPA). An OPA consists of an array of radiating apertures of which the phase can be controlled. By applying a linear phase ramp on the array, the beam can be steered. An proof-of-principle OPA on SOI has been demonstrated as well.

Feasibility study of optical links

When following an integrated approach, the radiating apertures – which are for example grating couplers on SOI – are rather small (order of several tens μm). Therefore, link budget calculations are performed to study the feasibility of these links. The link budget of a free-space optical link can be written analog to the well-known Friis formula as:

$$P_r = P_t \eta_t G_t (\frac{\lambda}{4\pi d})^2 Q_{rt} \eta_r G_r \quad (1)$$

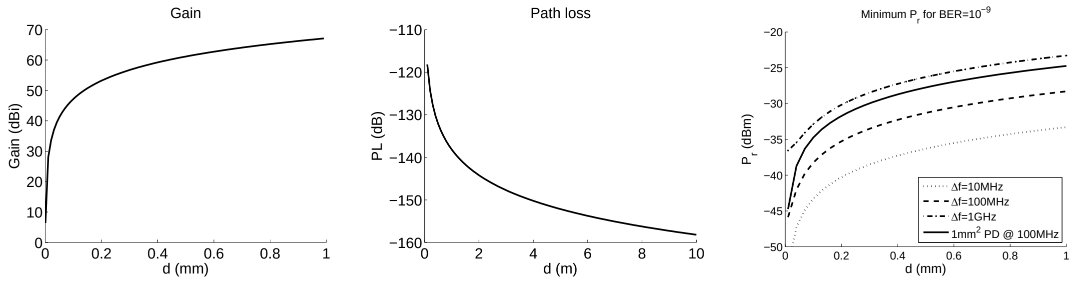
with G_t and G_r the gain of the transmitter and receiver defined as the power-per-unit solid angle radiated in a certain direction (θ, ϕ) compared to the power-per-unit solid angle radiated by an isotropic radiator, η_t and η_r efficiency factors, d the separation between the antennas and Q_{rt} the polarization mismatch factor, which will not be taken into account further. Since the beamwidth of optical beams is not necessarily much larger than the receiving aperture and if we consider that power is radiated only in the upward direction, the gain definition can be generalized as:

$$G(\theta, \phi) = 4\pi \frac{\iint_{\Omega_r} I(\theta, \phi) \sin\theta d\theta d\phi / \Omega_r}{\iint_{\Omega_{z>0}} I(\theta, \phi) \sin\theta d\theta d\phi} \quad (2)$$

with Ω_r equal to the solid angle that sees the receiver. The gain can be shown to be independent of element spacing, but only depends on the total radiating aperture. When the element spacing increases, new sidelobes appear but the lobes get smaller at the same time. The consequence of putting the radiating elements further apart is that we now have a multispot diffuse LAN [4]: i.e. there are several beams emitted by the OPA.
For a two-dimensional array of radiating apertures, the intensity in polar coordinates can be easily found to be the product of the far field of one aperture times the so-called array factor [5]:

$$I(\theta, \phi) = \left| \mathrm{sinc}(\tfrac{A_x \sin\theta \cos\phi}{\lambda}) \frac{\sin(N_x \pi (\Lambda_x/\lambda) \sin\theta \cos\phi)}{\sin(\pi(\Lambda_x/\lambda) \sin\theta \cos\phi)} \mathrm{sinc}(\tfrac{A_y \sin\theta \sin\phi}{\lambda}) \frac{\sin(N_y \pi (\Lambda_y/\lambda) \sin\theta \sin\phi)}{\sin(\pi(\Lambda_y/\lambda) \sin\theta \sin\phi)} \right|^2 \quad (3)$$

with $A_{x,y}$ the aperture size, $N_{x,y}$ the number of elements and $\Lambda_{x,y}$ the spacing of the elements in the x- and y- direction which will be taken to be the same for simplicity in the following. By substituting (3) into (2) the gain of the OPA is calculated. The steering range of the OPA is defined by the size of a single element since this determines the envelope of the radiated pattern.
The main noise contributions are thermal noise and shot noise. In optical wireless links, ambient light shot noise has been recognized to be one of the limiting noise factors although at high data rates, the thermal noise becomes more important [6]. Additionally, the load resistance together with the capacitance of the detector put a limit on the bandwidth of the receiver which is detrimental when using large area photodiodes. For a reciprocal OPA link on-chip – an OPA as transmitter and receiver – the area of the detector can be very small ($A \sim 50\mu m^2$) since it is the OPA which guides the light into a single mode waveguide for detection [7]. Hence, this method also allows for heterodyne detection which can result in up to 20dB extra sensitivity. For a non-reciprocal link with a large area photodiode the received power increases, but so does the ambient light noise contribution and thermal noise due to the smaller load resistor that is needed to comply to our specified bandwidth. When one knows the noise power, the BER can easily be calculated. The gain as a function of the total radiating aperture size, path loss as a function of distance and needed received power for a BER of 10^{-9} as a function of the total radiating



(a) (b) (c)

Figure 1: (a) Gain as function of aperture diameter, (b) Path loss as a function of distance, (c) Minimum P_r as a function of aperture diameter.

$A(mm^2)$	0.01	0.1	1
$G(dB)$	47.2	57.2	67.2
$P_{r,min}$	-38.2	-28.2	-23.2
$losses\ allowed(dB)$	137.2	152.6	167.7
$d(m)$	< 1	< 5	< 30
$steering(^\circ)$	8	2.5	0.8

Table 1: Examples of possible links using a 10×10 OPA with $P_{transmit} = 10dBm$.

aperture size for reciprocal links is shown in Figure 1. Note the relatively high powers that are needed compared to RF sensitivities. While an RF receiver only needs a power of the order of nW, for optical receivers this is of the order of μW. This is because an optical receiver is a so-called quadratic receiver: optical power is converted into an electrical current and thus the electrical power scales with the optical power squared. Large path losses thus cannot be tolerated [2].
The case in which the receiver is a large area photodiode is shown as well in Figure 1(c), clearly showing that an OPA receiver performs better. Let us look at an example of a 10×10 array consisting of radiating apertures of $10\mu m \times 10\mu m$ at a wavelength of $\lambda = 1.55\mu m$. Some examples of possible links are given in Table 1 where no efficiency losses are assumed. Transmit power at 1550nm is limited to 10mW due to eye-safety regulations. It can be concluded that links are possible for small steering ranges, since matrix addressing issues are limiting the number of addressable elements and it is the size of the individual elements which determines the steering range. Note the very favorable link budget for a total radiating aperture of $1mm^2$. The steering range is however decreased dramatically since the size of the individual elements increases [8].

Optical Phased Array on Silicon-on-Insulator

A one-dimensional OPA was fabricated on SOI with an oxide thickness of 2μm and a silicon thickness of 220nm using standard CMOS processes in IMEC. Two etching steps are used, one of 220nm for etching the waveguides and the multimode interference (MMI) splitters and the second of 70nm to etch the grating couplers. The OPA itself consists of an array of 16 grating couplers with a width of 800nm, a period of 630nm and a duty cycle of 0.5. The waveguides are spaced 2μm apart. A benzocyclobutene (BCB) layer of approximately 1μm is spun on top and a titanium electrode is sputtered with a thickness of approximately 100nm. The specific shape of the electrode puts a linear phase ramp on the waveguides resulting in thermo-optic steering. By changing the wavelength, one can steer in the other direction. Continuous thermo-optic steering of 2.3° and wavelength steering of 14.1° is reported [9].

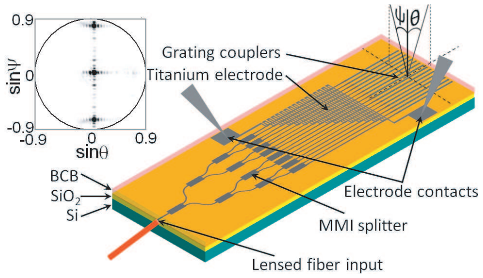


Figure 2: 1D optical phased array on SOI, the inset shows the measured far field pattern.

Conclusions

The SOI platform offers a promising solution for low-cost, small optical wireless components. Link budgets have been performed showing that links are possible for short distances (several meters) and steering ranges of several degrees when the number of addressable elements is limited. A proof-of-principle 1D optical phased array on SOI has been presented.

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