Feasibility Study of Integrated Optical Phased Arrays for Indoor Gb/s Wireless Optical Links

Karel Van Acoleyen[(1)], Hendrik Rogier[(2)] and Roel Baets[(1)]

[(1)] Photonics Research Group, Department of Information Technology, Ghent University - IMEC, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium,
[(2)] Electromagnetics Group, Department of Information Technology, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium,
✉ karel.vanacoleyen@intec.ugent.be

Abstract *Link budget calculations are performed to study the potential of integrated optical phased arrays for Gb/s wireless links. A link with two integrated OPAs is feasible with a beam steering range of a few degrees.*

Introduction

As data rates are increasing and fiber-to-the-home is finding its way to the customer, there is an increasing bandwidth mismatch between wired and wireless systems. Optical wireless links offer a solution due to their huge unlicensed bandwidth and immunity to electromagnetic interference. Several review papers have been reported on wireless indoor optical links[1]. Directive optical beams are needed for Gb/s links and thus adaptive beam steering is desirable. An optical phased array (OPA) enables this beam steering[2]. In an earlier paper we demonstrated an OPA on a CMOS-compatible silicon-on-insulator platform[3]. In this paper, the power requirements for optical links using integrated OPAs are discussed. These OPAs enable single chip wireless transceivers in e.g. sensor network applications. The case of a reciprocal link in which transmitter and receiver are both optical phased arrays as well as a non-reciprocal link in which the receiver is a large area photodiode is discussed.

Link budget calculations

The link budget of a free-space radiofrequency (RF) link is given by the well-known Friis formula:

$$P_r = P_t M_t G_t \left(\frac{\lambda}{4\pi d}\right)^2 Q_{rt} M_r G_r \qquad (1)$$

with G_t and G_r the antenna gain of the transmitter and receiver, M_t and M_r the mismatch factors, d the separation between the antennas and Q_{rt} the polarization mismatch factor, which will not be taken into account further. For an optical link, the mismatch factors can be replaced by efficiency factors $\eta_{t,r}$. The gain 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. 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:

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

with Ω_r equal to the solid angle that sees the receiver. The path loss exponent in (1) is 2 since we are looking at line-of-sight links.

Gain of an optical phased array

When considering a 2D 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[4]:

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

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. Let us look at a practical example of a 5×5 array consisting of radiating apertures of $10\mu\mathrm{m} \times 10\mu\mathrm{m}$ at a wavelength of $\lambda = 1.55\mu\mathrm{m}$. The gain for $\theta = 0$ of the OPA as a function of the spacing is found in Figure 1. Whenever a new lobe appears, there is a dip in the gain after which the gain increases again due to the narrowing such that the average gain remains constant. The consequence of putting the radiating elements further apart is that we now have a multispot diffuse LAN[1]: i.e. there are several beams emitted by the OPA. In the inset of Figure 1, the far field pattern $(\theta, \phi = 0)$ for a spacing of $10\mu\mathrm{m}$ and $50\mu\mathrm{m}$ is shown as well. The FWHM divergence of the main beam at $\theta = 0$ equals to $1.58°$ and $0.32°$, respectively.

Receiver sensitivity

The detector responsivity is taken to be R=0.6A/W. For optical receivers there are two main noise contributions: 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[5]. The shot noise spectral density is given by $\sigma_s^2 = 2q(I_p + I_d + I_a)\Delta f$ with I_p the signal cur-

978-3-8007-3173-2 © VDE VERLAG GMBH

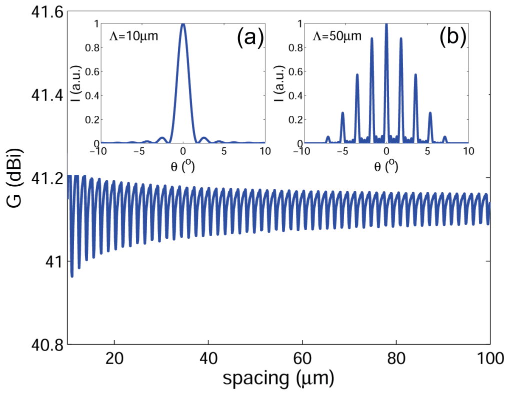

Fig. 1: Gain for $\theta = 0$ as a function of spacing of the array elements for a 5×5 OPA of $10\mu m \times 10\mu m$ apertures. Insets (a) and (b) show the far field pattern in the $(\theta, \phi = 0)$ direction for a spacing of $10\mu m$ and $50\mu m$ respectively.

rent, I_d the dark current ($\sim 1\mathrm{nA}$), I_a the ambient light current and Δf the effective noise bandwidth. The ambient light irradiated by the sun in the 1000nm-1700nm range is equal to 285W/m^2[6]. The thermal noise spectral density is given by $(4k_B T/R_L)\Delta f$ with k_B Boltzmann's constant, T the noise temperature and R_L the load resistance. The load resistance R_L together with the capacitance C of the detector put a limit on the bandwidth of the receiver. This bandwidth is given by $\Delta f = 1/[2\pi(\tau_{tr} + \tau_{RC})]$, with τ_{tr} the depletion width ($\sim 5\mu\mathrm{m}$) divided by the drift velocity of the carriers ($\sim 10^5\mathrm{m/s}$) and $\tau_{RC} = RC$. In the following, a bandwidth of $\Delta f = 1$GHz is chosen. For a reciprocal link, the area of the detector can be very small ($A \sim 50\mu\mathrm{m}^2$[7]) since it is the OPA which guides the light into a single mode waveguide for detection. Hence, this method also allow for heterodyne detection. For a non-reciprocal link with a large area photodiode the received power increases, but also 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[8].

Reciprocal link

The case of a reciprocal link of $d = 10\mathrm{m}$ in which both sender and receiver are an optical phased array is considered here. As explained before, the spacing of the elements does not have an effect on our link budget. The BER as a function of the transmitted power for a link using two OPAs with efficiency factors $\eta_{t,r} = 0.5$ is given in Figure 2. Although the gain of a 5×5 OPA of $10\mu m \times 10\mu m$ apertures is around 41dBi, the path loss of 158dB at $\lambda = 1.55\mu m$ is too severe to overcome, even when using heterodyne detection. When using individual elements of $50\mu m \times 50\mu m$, we get a BER of 10^{-9} for $P_t = 4.5\mathrm{mW}$ but the steering range is now reduced from 7.9° to 1.6° due to the larger aperture size of the individual elements. The main trade-off is thus steering range versus power budget.

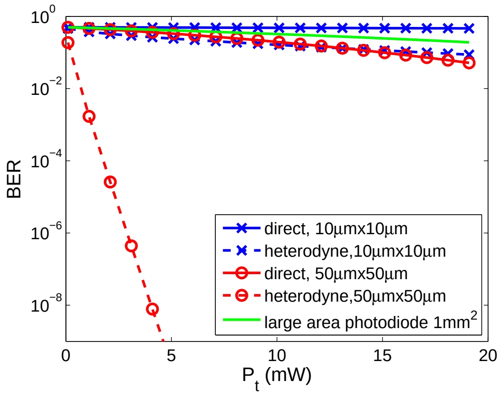

Fig. 2: BER as a function of transmitted power for a reciprocal link of a 5×5 OPA of $10\mu m\times10\mu m$ and $50\mu m\times50\mu m$ for direct and heterodyne detection (with $P_{LO} = 2\mathrm{mW}$) using intensity modulation. The case of a non-reciprocal link with a large area photodiode of 1mm^2 and an 5×5 OPA of $50\mu m \times 50\mu m$ apertures is shown as well.

Non-reciprocal link

When using a large area photodiode as receiver, two limiting factors come into play: ambient light and diode capacitance. The ambient light problem can be greatly reduced by means of an optical filter. To keep the bandwidth constant with increasing diode area, the load resistance should decrease which increases the thermal noise. When using a 5×5 OPA of $50\mu m \times 50\mu m$ apertures and a large area photodiode of 1mm^2, a Gb/s link at $d = 10\mathrm{m}$ cannot be achieved as shown in Figure 2. An option to use this type of OPA transmitter is explained in[9], where a lens is used, which then focuses the light on an array of small photodiodes. The receiver then also becomes angle dependent however.

Conclusion

A link budget analysis was made of a wireless optical link using integrated optical phased arrays. When having a reciprocal link, a Gb/s link can be established at the penalty of a limited steering range. A non-reciprocal link with an OPA transmitter and a large area photodiode receiver suffers especially from diode capacitance problems limiting the bandwidth. The reciprocal link is a very attractive option since heterodyne detection can be used, which greatly increases the receiver sensitivity.

References

1 R.J. Green et al., IET Commun. **2**, 3–10 (2008).
2 P.F. McManamon et al., Proc. of the IEEE. **84**, 268–298 (1996).
3 K. Van Acoleyen et al., Opt. Lett. doc. ID 107101 (posted 8 April 2009, in press).
4 M.I. Skolnik, *Introduction to radar systems*, McGRAW-HILL (1962).
5 K.D. Langer et al., Proc. ICTON'08, WeB4.1(2008).
6 C.A. Gueymard, Solar Energy **76**, 423–453 (2004).
7 J. Brouckaert et al., IEEE Phot. Techn. Lett. **19**, 1484–1486 (2007).
8 G.P. Agrawal, *Fiber-Optic Communication Systems*, John Wiley & Sons (2002).
9 D.C. O'Brien et al., IEEE Comm. Magazine March (2003).