Novel Broadband OWC Receiver with Large Aperture and Wide Field-of-View

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Abstract *We propose and analyse a low-complexity broadband optical wireless receiver based on a novel 2-dimensional matrix of photodiodes yielding a large aperture and wide FoV in an IR beam-steered system. Experimentally more than 1Gbit/s OOK transmission is shown with 10cm IR beams at a FoV=10°.*

Introduction

Optical wireless communication (OWC) is a very powerful alternative for radio wireless communication. We introduced wavelength-tuned IR beam steering at eye-safe wavelengths beyond 1.5µm, providing not only high capacity per beam at high user density, but also enhanced privacy and energy efficiency, as the beams are only delivered there where and when needed [1]. We also introduced user device localization techniques by which the system can autonomously steer each beam without user intervention [2].

A next key challenge is to create a broadband optical receiver with a large aperture and wide field-of-view (FoV) for capturing the optical beam, in order to obtain a sufficiently large link budget for a high data rate, and also to prevent that the user needs to accurately align the receiver to the beam transmitter. Increasing the aperture without decreasing the FoV is not feasible according to the basic optics law of etendue. Increasing the active area of a surface-illuminated photodiode typically decreases its electrical bandwidth. Hence for a large bandwidth an OWC receiver typically needs to have a small-area photodiode and a large lens aperture which collects as much light as possible and focusses it on the small photodiode, but also implies a small FoV.

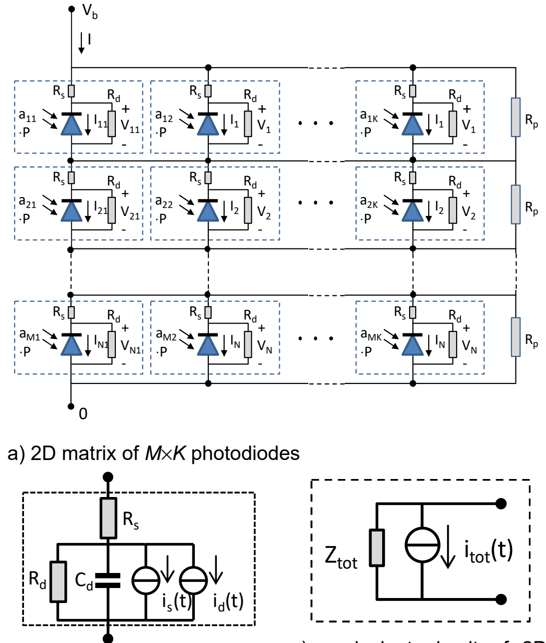
Several approaches have been reported to improve the OWC receiver's performance. Surface grating couplers (SGCs) feeding a waveguide-coupled UTC photodiode can separate the light collection function from the light detection one [3], but the SGC light collection aperture is still limited. Non-imaging optics, i.c. compound parabolic concentrators (CPCs) can offer an increased aperture, but the FoV stays small [4]. Angle-diversity receivers (ADRs) deploying multiple photodiodes can yield a larger aperture and wider FoV [5][6]. Each photodiode needs an individual pre-amplifier, which increases complexity and adds noise. The law of etendue may be broken by wavelength conversion in a phosphorent-doped slab waveguide edge-coupled to a photodiode [7]; the heavily multimoded slab waveguide and the PD area may limit its bandwidth.

In this paper, we propose a large-aperture OWC receiver using a novel arrangement of multiple photodiodes which still achieves the high bandwidth of a single photodiode. It captures more optical power and has an increased FoV, while it only requires a single low-noise pre-amplifier.

Two-dimensional matrix of photodiodes

Putting photodiodes in parallel increases the collectively generated photocurrent but inevitably also adds their capacitances and thus reduces the joint bandwidth. Putting photodiodes in series implies putting their capacitances in series and thus increases the joint bandwidth, but without generating more photocurrent. This option is typically rejected as an ideal photodiode acts as a current source and common wisdom is that current sources cannot be put in series. Recognizing that a typical photodiode is not a perfect current source and has a limited parallel resistance, we reconsidered this option in combination with putting photodiodes in parallel, and thus we propose a 2D matrix of $M \times K$ interconnected photodiodes as shown in Fig. 1, preferably integrated on a single chip.

The well-known equivalent electrical circuit of a single photodiode is shown in Fig. 1.a, where R_s represents the (typically small) series resistance including the connections (wire bondings) to the photodiode, R_d the (large) parallel resistance including the leakage current, C_d the capacitance of the reverse-biased photodiode junction, $i_d(t)$ the (small) dark current generated by thermal effects, and $i_s(t)$ the generated photocurrent where $i_s(t)=R_{PD}\cdot\alpha\cdot P(t)$ with R_{PD} the photodiode responsivity and α the fraction of the instantaneous optical beam power $P(t)$ which impinges on the active area of the photodiode.



a) 2D matrix of $M \times K$ photodiodes

b) equivalent circuit of single photodiode

c) equivalent circuit of 2D matrix of photodiodes

Fig. 1: Modelling of matrix of photodiodes

The resistors R_p are included to reduce the unbalance in reverse bias voltage across the photodiodes in case all photodiodes are not equally illuminated. By applying repetitively Thévenin's and Norton's theorem, the whole $M \times K$ photodiodes matrix can be represented by the equivalent photodiode circuit shown in Fig. 1.c, of which the output current and internal impedance Z_{tot} are

$$i_{tot}(t) = \frac{K \cdot [i_d + R_{PD} \cdot \overline{a_{mk}} \cdot P(t)]}{1 + \frac{R_s}{R_d}\,(1 + j\omega\, R_d\, C_d)}$$

$$Z_{tot} = \frac{M\, R_p\, [R_d + R_s\,(1 + j\omega\, R_d\, C_d)]}{R_d + (R_s + K \cdot R_p)\,(1 + j\omega\, R_d\, C_d)}$$

where $\overline{a_{mk}}$ is the average fraction of the optical beam power which arrives onto the $(m,k)^{th}$ photodiode.

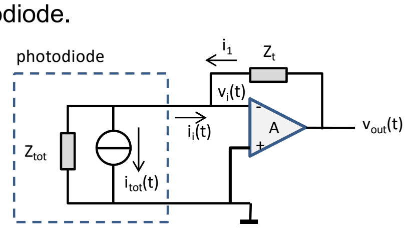


Fig. 2: Transimpedance amplifier

When applying the photodiode matrix in an optical receiver using a transimpedance pre-amplifier (TIA) circuit as in Fig. 2, its transimpedance $Z_T = v_{out}(t)/i_{tot}(t)$ near $\omega=0$ (DC) and its -3dB bandwidth ω_{-3dB} (with $R_s \ll R_d$) are

$$Z_T(\omega = 0) = \frac{A \cdot Z_t}{1 + A + \frac{Z_t}{M\, R_p} + \frac{K}{M} \cdot \frac{Z_t}{R_d + R_s}}$$

$$\omega_{-3dB} \approx \frac{M}{K} \cdot \frac{1}{C_d} \left[\frac{1 + A}{Z_t} + \frac{1}{R_p} \right] + \frac{1}{R_d C_d}$$

When using a single photodiode, we have

$$Z_T(\omega = 0) = \frac{A}{1 + A} Z_t$$

$$\omega_{-3dB} = \frac{1 + A}{C_d \cdot Z_t}$$

Hence in good approximation (given that $R_d \gg R_s$ and $R_p \gg Z_t/(1+A)$) the -3dB bandwidth of the receiver using the $M \times K$ photodiode matrix is (M/K) times the bandwidth using a single photodiode. With the $M \times K$ photodiode matrix and neglecting dark current, the generated current is $i_{out}(t) \approx K \cdot R_{PD} \cdot \bar{a} \cdot P(t)$, so about K times as large as for a single photodiode (see Fig. 3). In particular: with a square $M \times M$ matrix of photodiodes in a TIA the same bandwidth is achieved as with a single photodiode, whereas the active area is M^2 times larger, and the output signal is M times larger.

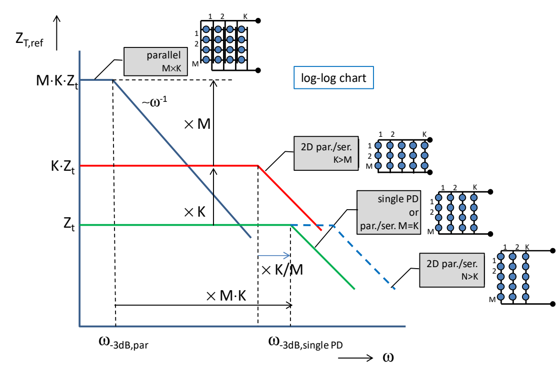


Fig. 3: Frequency characteristics of PD matrix-based optical receiver

Optical system design

A lens system with wide aperture is needed to collect as much light as possible from the incoming beam and to project it onto the photodiode matrix; see Fig. 4. In order to distribute the light as evenly as possible among the photodiodes, the beam spot diameter D_c should be at least equal to the PD matrix diameter D_2 and the matrix be put at a distance $x = p \cdot f$ before the lens' focal plane. The half-angle field of view (FoV) α (reached when spot displacement Δ becomes $\Delta > ½\,(D_c - D_2)$ such that the spot no longer fully covers the PD matrix) is

$$\tan(\alpha) = \frac{p \cdot D_1 - D_2}{2f\,(1 - p)}$$

and the beam-to-PD matrix coupling factor at incidence angle α is

$$T(\alpha) = T_{beam-lens} \cdot T_{lens-PD} \cdot \cos\alpha \cdot \eta \cdot \frac{1}{p^2} \cdot \left(\frac{D_2}{D_0}\right)^2$$

where η is the fill factor of the PD matrix. So for a large FoV the lens' focal length f should be as short as possible. Moreover, increasing the defocusing parameter p increases the FoV, but reduces the power received by the PD matrix, hence needs to be optimized with respect to these constraints. Fig. 5 shows the attainable FoV α and coupling factor T versus the defocusing p for the design values used in our system, i.e. for a 4×4 PD matrix (diameter D_2=1.32mm and fill factor η=42.4%) and a single PD with area diameter D_2=0.25mm. It can be observed that for a given acceptable coupling factor T the attainable FoV with the PD matrix is significantly larger than for the single PD.

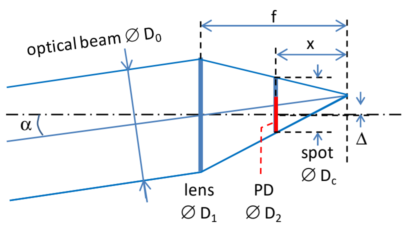


Fig. 4: Projecting the beam onto the PD matrix

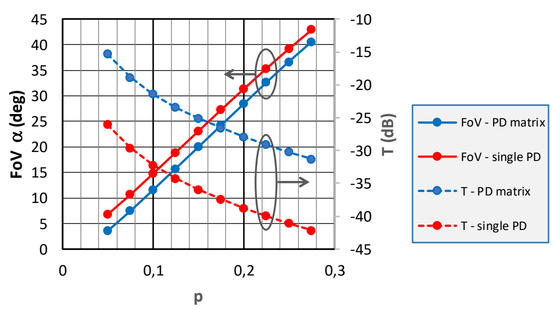


Fig. 5: FoV and beam-to-PD matrix coupling T vs. defocusing p (beam D_0=10cm, lens D_1=50mm, f=10mm, PD matrix D_2=1.32mm, η=42.4%)

Experimental results

We designed a 4×4 PD matrix using 4 quad photodiodes packaged in a TO-5 can from Albis Optoelectronics, where the PD elements in each quad were cascaded and the quads were then put in parallel; see Fig. 6 (left). A single PD element had a diameter of 215µm, a capacitance of 2.3pF, and 1GHz bandwidth. The capacitance of the packaged 4×4 PD matrix was found to be 3.6pF (note: the TO-5 package adds a parasitic capacitance of 1pF). We built the OWC receiver module shown in Fig. 6 (right). We applied a common-base transistor stage in order to minimize the impedance load to the PD matrix and thus maximize bandwidth, and subsequently applied a 700MHz bandwidth TIA. The receiver is equipped with a Fresnel lens with a large D/f ratio (f=10mm, D=50mm) in order to maximize the FoV. The receiver's frequency characteristics are shown in Fig. 7; the measured -3dB bandwidth is 610MHz. We deployed the receiver in our OWC demonstrator described in [1]. Good BER performance was obtained up to at least 1Gbit/s (see Fig. 8), over a sizable area as shown in Fig. 9. This area corresponds to a FoV half-angle of ~ 10 degrees, which is mainly limited by the wall of the TO-5 can which blocks part of the beam. When removing this wall, the FoV is expected to be at least 20 degrees according to Fig. 5.

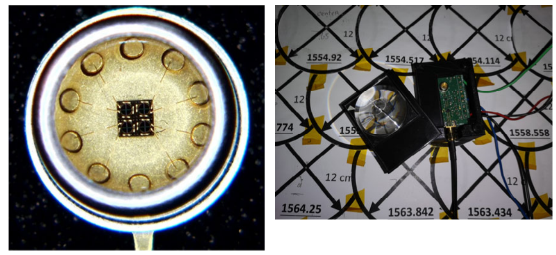


Fig. 6: Packaged 4×4 PD matrix (left); OWC receiver module with Fresnel lens cap (right)

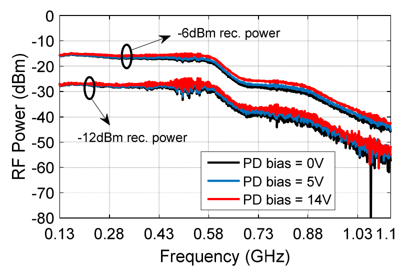


Fig. 7: Frequency characteristics of OWC receiver with 4×4 PD matrix

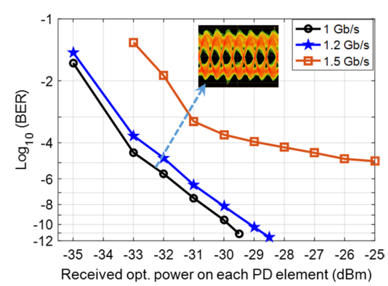


Fig. 8: BER performance for various OOK bitrates

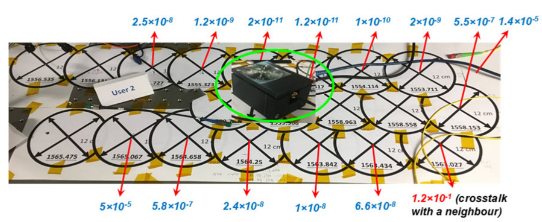


Fig. 9: BER at different OWC cells in the user plane for 1Gbit/s OOK transmission (cell diameter 10cm)

Concluding remarks

The feasibility of using a two-dimensional matrix of photodiodes to create a low-complexity broadband OWC receiver with large FoV and aperture was shown. A first prototype showed more than 1Gbit/s transmission and FoV=10°.

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