Optical Wireless GbE Receiver with Large Field-of-View

Ton Koonen[(1)], Ketemaw Mekonnen[(1)], Frans Huijskens[(1)], Ngoc Quan Pham[(1)],
Zizheng Cao[(1)], Eduward Tangdiongga[(1)]

[(1)] Institute for Photonic Integration, Eindhoven Univ. of Technology,
Groene Loper 19, 5612AP Eindhoven, The Netherlands, a.m.j.koonen@tue.nl

Abstract We expanded our concept of *N*×*N* matrix of photodiodes, scalable to large aperture and wide field-of-view while retaining high bandwidth. A simple GbE OWC receiver with 4×4 matrix and single TIA was realised and showed a FoV>10 deg. We demonstrated GbE real-time high-definition video streaming.

Introduction

Optical wireless communication (OWC) by means of narrow infrared beams can achieve a high spatial density of many beams each providing very high wireless capacity to users individually, as such a beam does not need to be shared among multiple users as is done in WiFi and LiFi [1]. This OWC concept offers several advantages with respect to radio-based wireless communication. It is not disturbed by EMI, which is of particular interest in e.g. harsh industry 4.0 environments. Because a beam is not shared with others, a user has a guaranteed link capacity without time-consuming and contention-risky MAC protocol, and has high privacy and security. By timely and accurately steering the beam, no beam energy is wasted, thus improving the system's energy-efficiency.

Next to system modules which steer the beams and localize the users for this, a crucial part of the system is the OWC receiver. It must be broadband, while able to capture the beam with a large field-of-view (FoV; entry aperture as well as angular aperture). Such large FoV significantly eases the alignment of the receiver to the beam, and maximizes the optical power captured in order to maximize the link budget and thus enable a high data rate. At the same time, the receiver should also have a large bandwidth to handle such high data rates without needing complex signal processing for spectrum compression which would increase latency. Typically, the bandwidth of a photodiode decreases when its aperture (its active area) increases, and thus its junction capacitance grows. A larger beam can be condensed onto a small photodiode by a lens system with larger aperture, but then the physical law of etendue commands that the angular FoV decreases.

Several efforts to increase the OWC receiver's aperture while preserving a high bandwidth have been reported, such as angle-diversity receivers (ADRs) which use multiple small photodiodes whose outputs are individually amplified by TIAs and summed [2], PIC concepts where a (large) surface grating coupler (SGC) collects the light and feeds it via a waveguide to a separate bandwidth-optimized photodiode [3], non-imaging optics such as compound parabolic concentrators [4], and wavelength conversion in a phosphorent slab waveguide or fiber [5]. All these methods increase FoV but at expense of receiver complexity and large required input power.

In order to enlarge the OWC receiver's FoV while also having a large bandwidth, we previously proposed [6] an integrated 2D matrix of photodiodes followed by only a single low-noise electronic preamplifier, yielding a relatively simple yet wideband OWC receiver with wide FoV. Here, we report an improved 2D PD matrix which is scalable to arbitrary aperture while retaining the high bandwidth. First results are reported with high-density gigabit ethernet (GbE) optical wireless streaming of high-def video.

Matrix of photodiodes

Fig. 1.a shows the concept of arranging photodiodes in a 2-dimensional matrix, which we introduced at ECOC2020 [6]. It can be applied in an OWC receiver and requires only a single TIA (not a TIA per photodiode as in an ADR). The photodiodes are grouped in *K* columns and *M* rows. By applying Thevenin's and Norton's theorem, this photodiode matrix is represented by the equivalent circuit shown in Fig. 1.b composed of a current source $i_{tot}(t)$ and impedance Z_{tot} as [6]

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

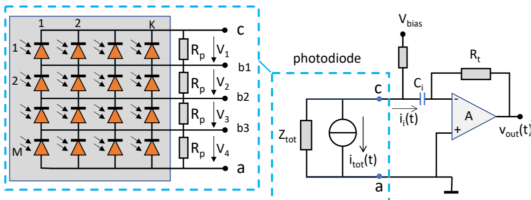
$$Z_{tot} = \frac{M\, R_p\, [R_d + R_s\,(1 + j\omega\, R_d\, C_d)]}{R_d + (R_s + K \cdot R_p)\,(1 + j\omega\, R_d\, C_d)}$$

where i_d is the dark current of a single PD, C_d the capacitance of its reverse-biased junction, R_d the resistance representing its dark current, R_s the resistance of the PD bond wires, $P(t)$ instantaneous power of the incident optical beam, and $\overline{a_{mk}}$ is the average fraction of this power incident on the $(m,k)^{th}$ photodiode. Z_{tot} can be decomposed in a resistive part and a capacitive part $(K/M)\cdot C_d$. The resistors R_p are

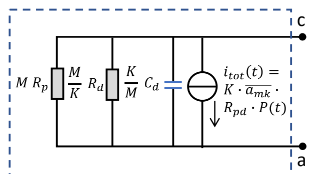
978-1-6654-3868-1/21/$31.00 ©2021 IEEE

added to reduce unbalance in the reverse voltages of the photodiodes when these are not evenly illuminated.

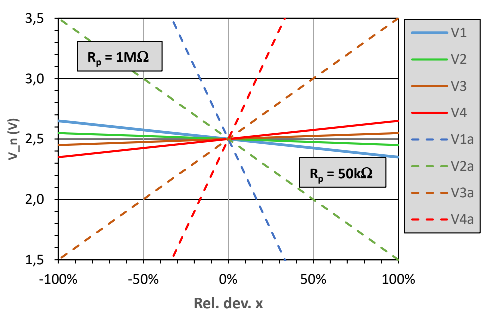
The photodiode matrix can be readily applied in the simple transimpedance amplifier configuration of Fig. 1.a, of which the bandwidth for $R_p >> Z_t/(1+A)$ and $R_d >> (K/M) \cdot R_t/(1+A)$ is given by $\omega_{-3dB} \approx (M/K) \cdot (1+A) / (C_d \cdot |Z_t|)$, i.e. M/K times larger than with a single photodiode. Thus, using a square $M \times M$ photodiode array, the active detection area is M^2 times larger, the bandwidth is the same, and the output signal is M times larger as compared to using a single photodiode.



a) 2D matrix of photodiodes applied in transimpedance amplifier



b) Equivalent circuit of 2D matrix of photodiodes



c) Bias voltage unbalances at uneven illumination (V_{bias}=10V, M=4; *dashed*: R_p=1MΩ, *solid*: R_p=50kΩ)

Fig. 1 OWC receiver employing a two-dimensional matrix of photodiodes

At uneven illumination of the photodiodes in the matrix, the bias voltages among the photodiodes will vary, which may affect their operation. Even if the photodiodes are perfectly identical, when the fraction a_m of the beam's power is uneven the deviation of the bias voltage V_m across the m^{th} row from the average V_{bias}/M is given by $V_m \approx V_{bias}/M + R_p \cdot R_{pd} \cdot P \cdot (\overline{a_m} - a_m)$ for $R_p \gg R_s$. This deviation at uneven illumination is reduced by a not too large parallel resistance R_p, as is illustrated by Fig. 1.c. If R_p stays much larger than $R_t / (A+1)$, the bandwidth of the OWC receiver is not affected.

As the thermal noise of the TIA electronics (with white noise power density N_0 and bandwidth B) typically dominates the shot noise from the photodiodes, the output signal-to-noise ratio is $SNR_{therm} \approx \left(R_{pd} \cdot K \cdot \overline{a_{mk}} \cdot P\right)^2 / (2\,N_0\,B)$. Hence the SNR performance of the OWC receiver using the matrix of photodiodes is found to be K^2 times larger than using a single photodiode.

Capturing the beam by the photodiode matrix

We use a large aperture optical lens in order to collect as much power of the beam as possible onto the photodiode matrix, while also aiming to evenly illuminate the photodiodes and maximize the FoV. As we introduced in [6], and is shown in Fig. 2, this is achieved by a defocussing factor p, where $p=x/f$ with x being the distance from the PD before the focal plane and f the lens' focal length.

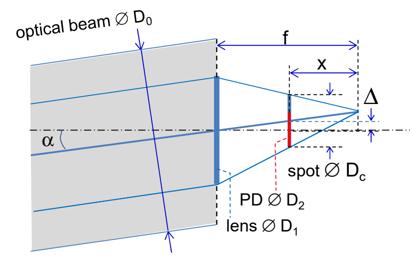


Fig. 2 Capturing the beam by the photodiode

This defocusing diminishes the captured power, but increases the FoV angle. Theoretically, in a first approach we assumed an aberration-free lens and a uniform beam. The coupling fraction T of the beam's power P onto all photodiodes for $p>D_2/D_1$ is $T = \cos\alpha \cdot \eta \cdot \left(\frac{D_2}{p\,D_0}\right)^2$ and $T = \cos\alpha \cdot \eta \cdot \left(\frac{D_1}{D_0}\right)^2$ for $0 < p \leq \frac{D_2}{D_1}$; the FoV angle α_{max} is $\tan\alpha_{max} = \frac{|p \cdot D_1 - D_2|}{2\,f\,(1-p)}$ where D_0 is the beam's diameter, D_1 the lens' diameter, D_2 the diameter of the photodiode matrix and η its fill factor (ratio of its active area and total circumscribed area).

However, typically the beam diameter is (considerably) larger than the lens diameter, hence lens aberrations will affect the imaging of the beam onto the photodiode matrix. Also the beam does not have a uniform profile. Hence we have assessed by means of 3D ray tracing, the beam-to-PD matrix coupling factor T and FoV angle a_{max} for the theoretical case of a uniform beam and thin lens, as well as the realistic case of a Gaussian beam with D_0=100mm and Fresnel large aperture lens with f=10mm and D_1=50mm (which we use in our lab experimental setup). The results are shown in Fig. 3, where 25117 rays were traced, hence the results are accurate up to T=-24dB. It shows that the FoV α_{max} obtainable with a 4x4 matrix of ∅150µm photodiodes (D_2=1.32mm, η=42.4%) is substantially higher than with a single photodiode (D_2=250µm).

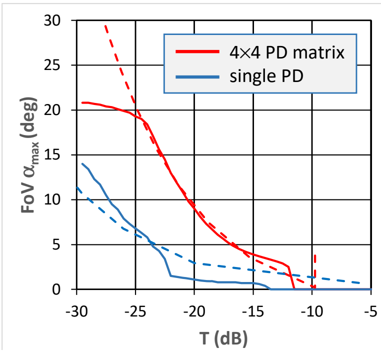


Fig. 3 FoV α_{max} vs. beam-to-PD coupling T (*solid*: Gaussian beam, Fresnel lens, ray traced; *dashed*: uniform beam, thin lens, theory)

Experiments

In our first OWC receiver prototype, we used a 4×4 PD matrix based on 4 quad photodiodes in a TO-5 can [6]. This architecture did not allow inclusion of the balancing resistors R_p, and the generic scalability of the $N \times N$ matrix to larger N. Hence we designed a rectangular matrix of ∅150µm photodiodes: Fig. 4.a shows the wire-bonded 4×4 one we designed, which was made and packaged in a TO-46 can by Albis Optoelectronics. Measured cathode-to-anode capacitance was ~3pF, which equals the capacitance of a single PD of ~2.3pF plus the added TO-46 parasitic capacitance of ~0.7pF, confirming the validity of our PD matrix concept.

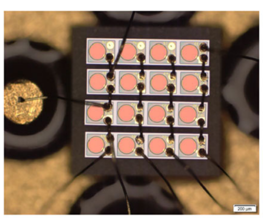
Mounted on a PCB together with a low-input impedance common-base stage, a 700MHz 10kΩ TIA and buffered differential output amplifier (Fig. 4.b), a receiver sensitivity (per PD element) of -30.5 dBm at 1Gbit/s and -29.0 dBm at 1.25Gbit/s (GbE speed) was obtained (Fig. 4.c). A FoV half-angle α_{max} of ~10 degrees was measured in our OWC demo setup (Fig.5.a), which agrees with the simulation results (Fig. 3).

We have combined our OWC receiver with a commercial GbE media converter which we have adapted, and validated this combination in our OWC lab testbed. Equipped with the large aperture Fresnel lens (∅50mm, f=10mm), real-time GbE video transmission has been successfully demonstrated, as shown in Fig. 5.b.

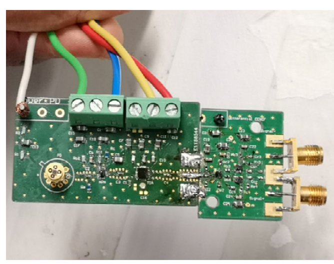
Concluding remarks

We designed and validated our OWC receiver concept deploying a scalable 2D matrix of photodiodes. It needs only a single TIA, and can achieve a bandwidth at least equal to that with a single photodiode, but with a significantly larger Field-of-View. By interconnecting already the photodiodes in a matrix configuration by on-chip metallization tracks, the design can be simplified further. 1GbE operation with a FoV of at least 10 degrees has been shown. We also demonstrated real-time GbE video streaming in our OWC testbed, thus showing the path towards higher TRL of a dense GbE OWC system

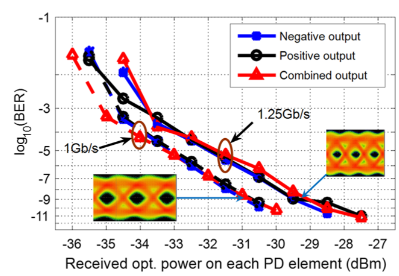
We acknowledge Albis Optoelectronics for realizing the packaged photodiode matrix, and the Dutch Gravitation programme for funding.



a) 4×4 PD matrix

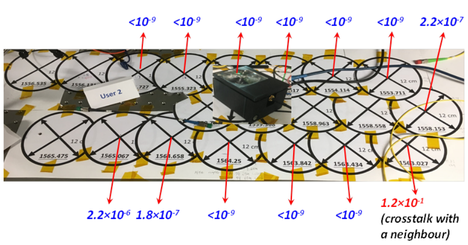


b) OWC receiver with 4×4 PD module and differential amplifier outputs

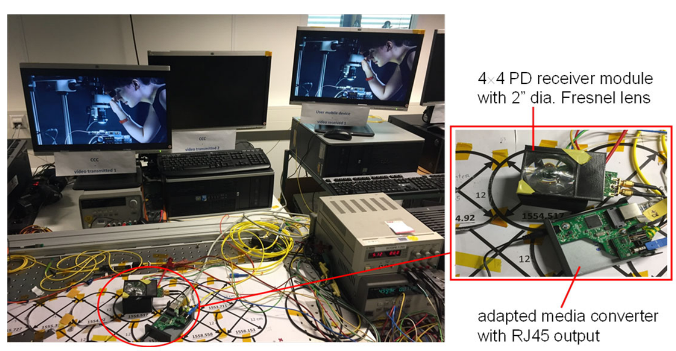


c) BER performance for both single-ended and differential outputs (*inset*: eye diagrams)

Fig. 4 OWC receiver with packaged 4×4 photodiode matrix



a) FoV measurements at 1Gb/s (error-free transmission within 10 deg. from the center cell)



b) GbE video streaming demo using OWC receiver and GbE media converter (*inset*: 4×4 PD receiver module and media converter)

Fig. 5 Lab demo of real-time GbE video transmission using Gigabit-Ethernet media converter

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