Optical Wireless GbE Receiver with Large Field-of-View

Ton Koonen, Ketema Mekonnen,
Frans Huijskens, Ngoc Quan Pham, Zizheng Cao, Eduward Tangdiongga

IPI, ECO group
Eindhoven University of Technology

OWCC 2022
Mikrocentrum, Veldhoven, Thu. Nov. 10, 2022

Outline

- **Introduction**
  - Indoor beam-steered OWC – the BROWSE concept
  - OWC receiver requirements
- **2D matrix of photodiodes**
  - characteristics
  - PD biasing
- **Coupling the optical beam to PD matrix**
  - Ray tracing analysis
  - Field-of-View vs. beam coupling efficiency
- **Experiments**
  - OWC receiver performance
  - GbE OWC video streaming
- **Concluding remarks**

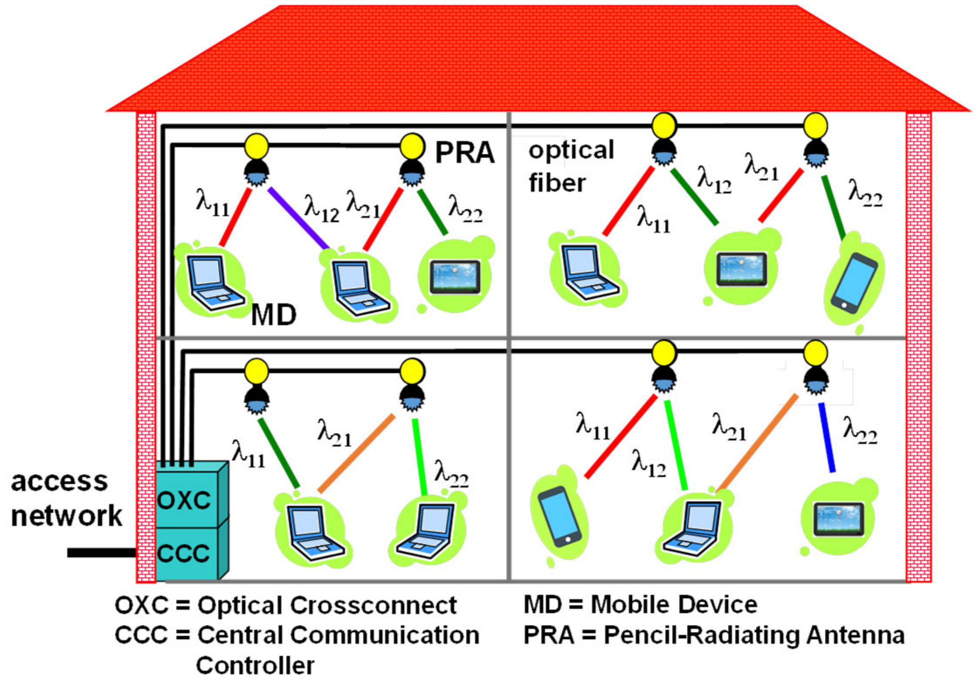
Breaking wireless barriers: free-space beam-steered optical communication

European Research Council

erc

BROWSE's system concept:

- **narrow pencil beams ('*virtual fibres*')**
  → <u>no</u> sharing, high capacity,
  long reach, high level of privacy
- **IR λ>1400nm**
  → <u>eye safe</u>, P_{beam} up to 10mW
- use of **1.5µm fibre-optic components**
  → mature components available
- **passive diffractive beam steerer**
  → no local powering needed, easily scalable
  to many beams (just add λ-s)
- **λ-controlled 2D steering**
  → embedded control channel



[Koonen et al, MWP2014]
[Koonen et al., JLT Oct. 2016, JLT May 2018, JLT Oct. 2018, RSTA Mar. 2020]

EHCI
EINDHOVEN HENDRIK CASIMIR INSTITUTE

USP-s of Indoor beam-steered OWC vs. WiFi, LiFi

WiFi, LiFi

<u>Shared</u> capacity ⇨

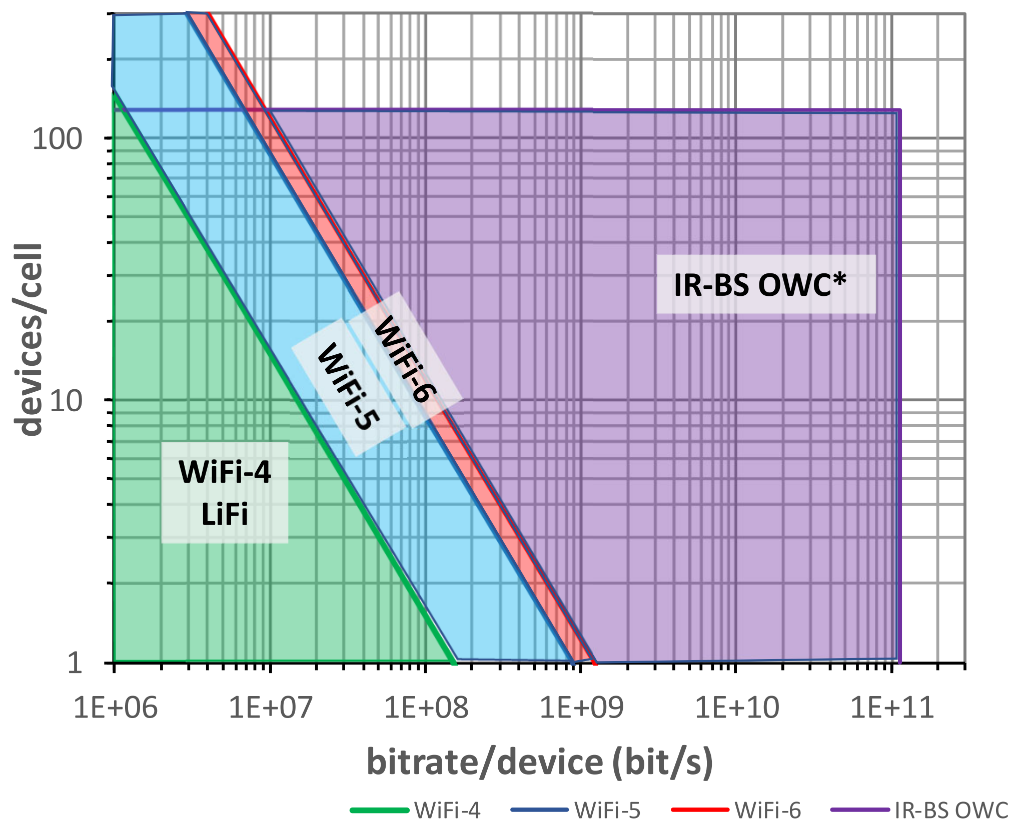
- bitrate × no. devices restricted
- privacy issues
- EMI sensitive (WiFi)

Beam-steered OWC

<u>No</u> capacity sharing ⇨

- much higher user density
- much higher bitrate/device
- personalized, enhanced privacy
- no EMI disturbances
- high energy efficiency, signal only where and when needed

→ a beam acts as a 'virtual fibre'



WiFi-6 (IEEE 802.11ax, Feb. 2021) OFDMA+1024QAM, PHY max. 1201Mbit/s
WiFi-5 (IEEE 802.11ac-2013) MIMO-8, 256QAM, PHY 867Mbit/s
WiFi-4 (IEEE 802.11n-2009) MIMO-4, 64QAM, PHY 150Mbit/s
IR-BS OWC: 128 beams × 112Gbit/s = 14.3Tbit/s [ECOC2017]

*** a.k.a. 'LiFi 2.0'**

EHCI EINDHOVEN HENDRIK CASIMIR INSTITUTE

OWC receiver design

Requirements:

- Large bandwidth
- Large aperture
- Wide Field-of-View
- Simple
- Compact
- Low power consumption

Solutions reported:

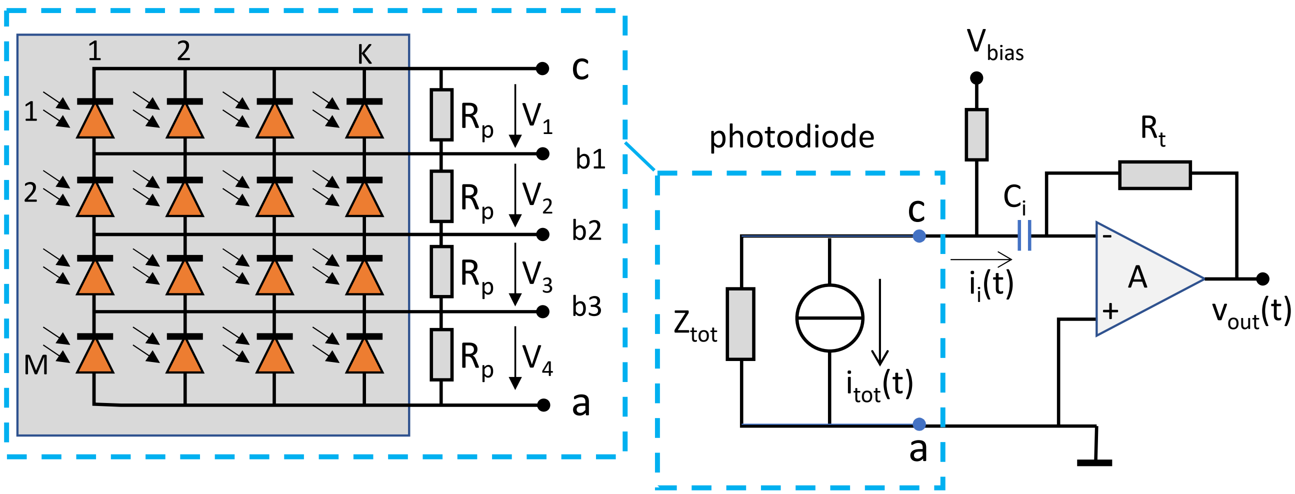
- Non-imaging optics, such as compound parabolic concentrator
- Angular diversity receiver (multiple PD-s and TIA-s)
- PIC with large/multiple surface grating couplers + waveguide-fed UTC-PD
- Wavelength conversion in phosphorent slab waveguide or fibre
- **2D photodiode matrix + single TIA** (first reported at ECOC2020* ; with 4 quad PD-s, not scalable)

* Koonen et al, “Novel broadband OWC receiver with large aperture and wide Field-of-View”, ECOC2020, paper Tu2G.4

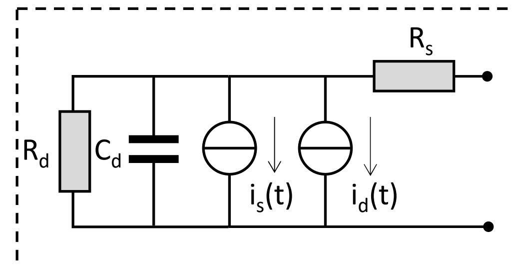
EHCI
EINDHOVEN
HENDRIK
CASIMIR
INSTITUTE

OWC receiver with 2D matrix of photodiodes

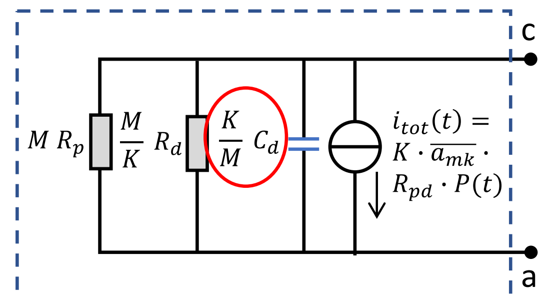
- 2D matrix of photodiodes (i.s.o. single large-area PD)
- Single pre-amplifier



2D matrix of photodiodes applied in transimpedance amplifier



Equivalent circuit of single photodiode



Equivalent circuit of 2D matrix of photodiodes

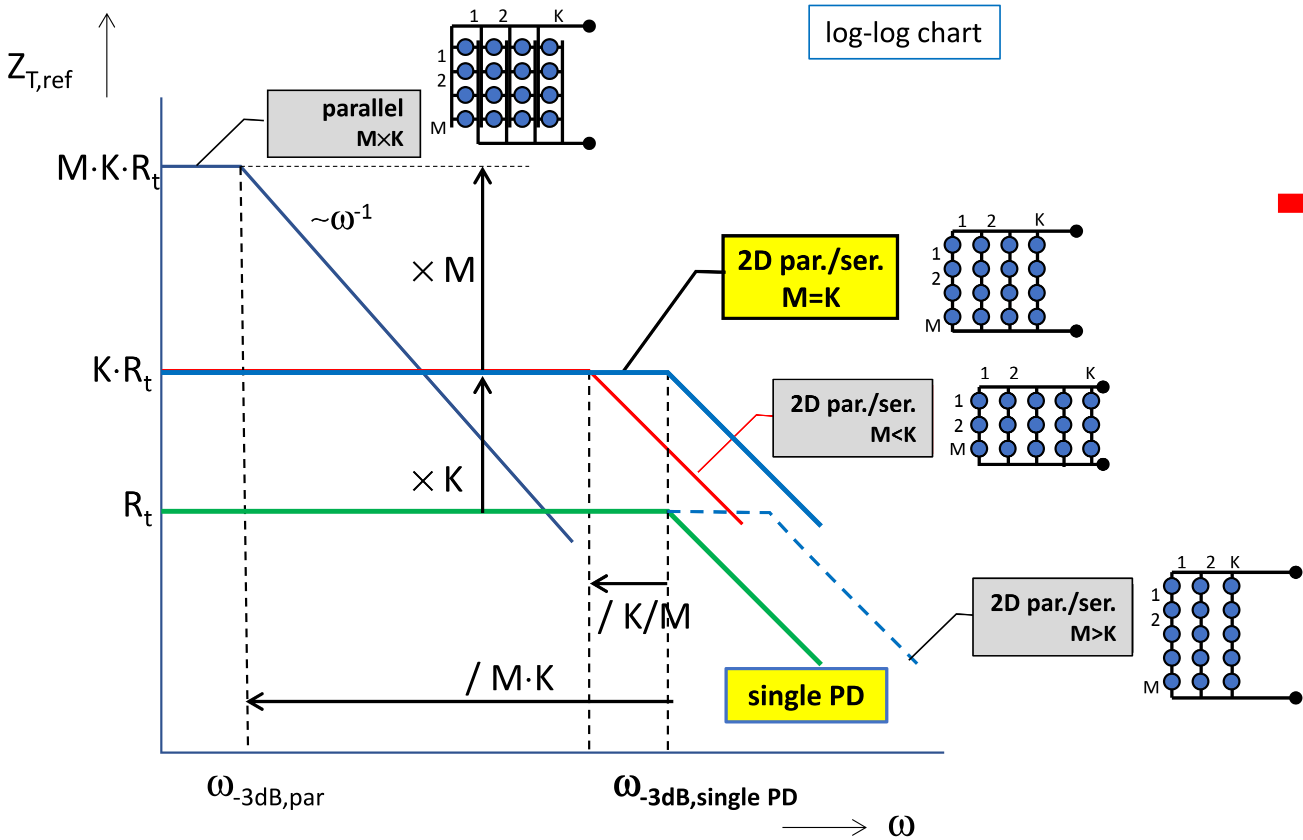
TIA characteristics: $Z_T(\omega = 0) = \left.\frac{v_{out}(t)}{i_{tot}(t)}\right|_{\omega=0} = \frac{A}{1+A} R_t$

$\omega_{-3dB} = \frac{1+A}{C_d \cdot R_t}$ if $Z_{tot} \approx \frac{1}{j\omega\, C_d}$ $\rightarrow$ BW limit due to PD capacitance

Pat. PCT/EP2020/080594 (filed 30 Oct. 2020)

EHCI
EINDHOVEN HENDRIK CASIMIR INSTITUTE

OWC TIA receiver - frequency characteristics



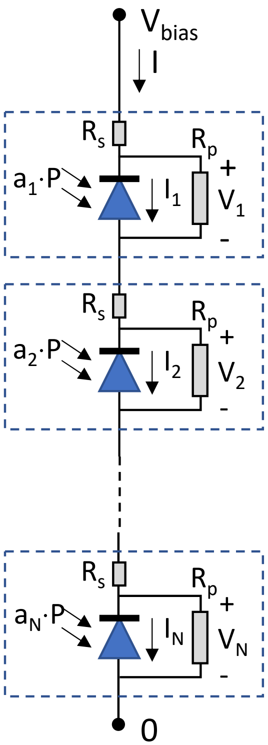
with a **square *M*×*M* matrix** of photodiodes in a TIA the **same** bandwidth is achieved as with a single photodiode, whereas **active area is *M*² times larger**, and **output signal is *M* times larger.**

$\bar{a}{\cdot}P(t)$: average power received per PD

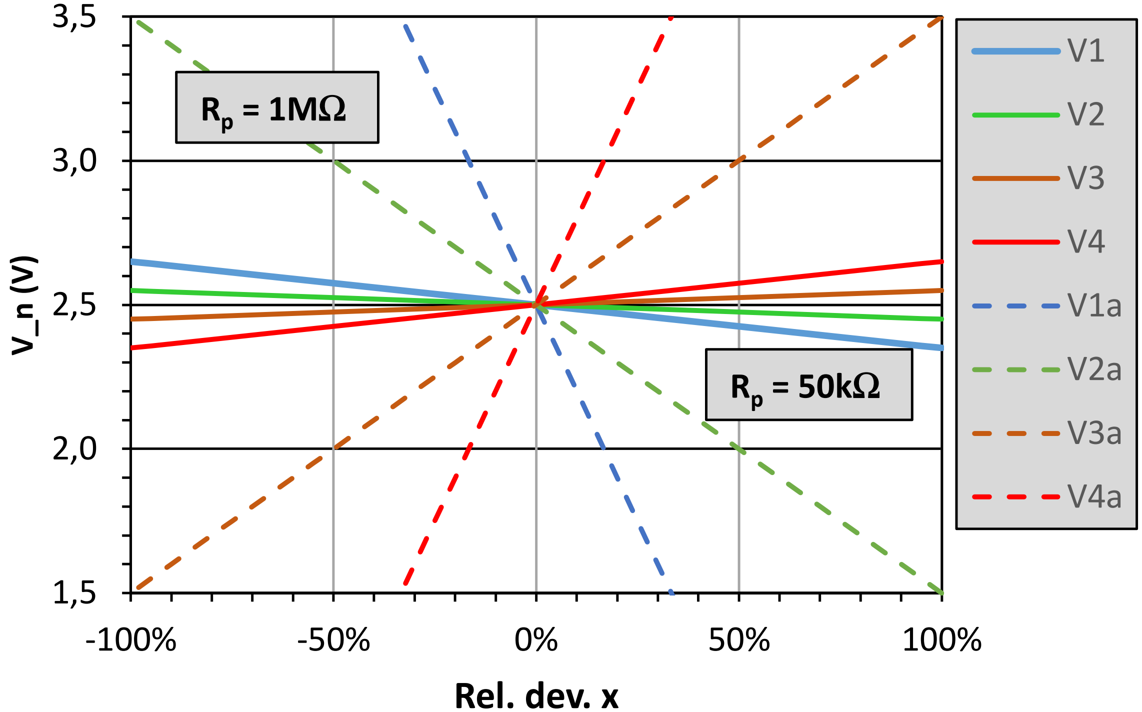
$$Z_{T,ref}(\omega = 0) = \frac{v_o(t)}{\bar{a} \cdot R \cdot P(t)} \approx K \cdot \frac{A}{1+A} \cdot R_t \qquad \omega_{-3dB} \approx \frac{M}{K} \cdot \frac{1+A}{C_d \cdot R_t}$$

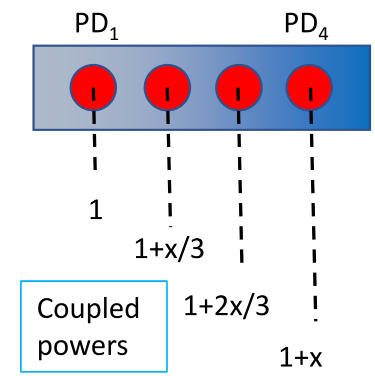
EHCI EINDHOVEN HENDRIK CASIMIR INSTITUTE

Uneven illumination of 2D matrix of photodiodes



Bias voltage unbalances at uneven illumination (V_{bias}=10V, M=4, P=10µW)



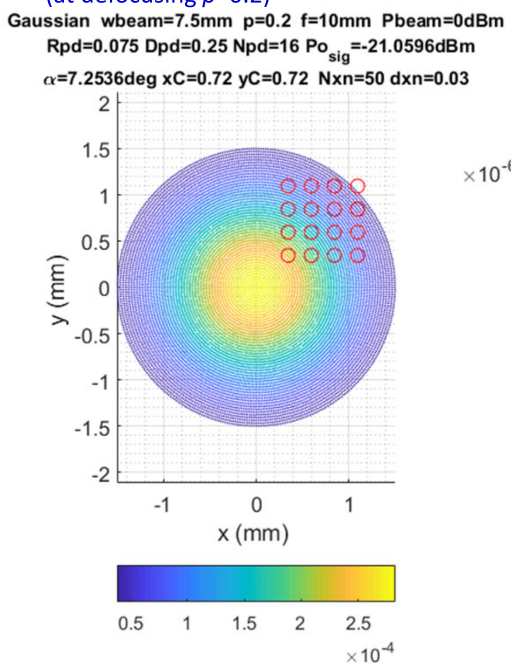


- reducing R_p reduces PD bias unbalances at uneven illumination
- as long as R_p >> R_t / (A+1) , BW of OWC receiver is not affected

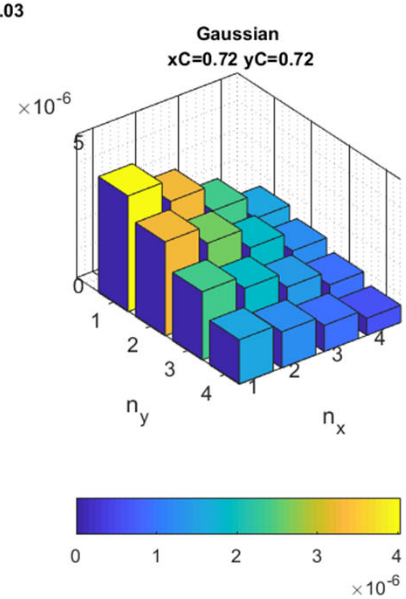
Photodiode matrix – analysis of bias conditions V_m

- **Gaussian beam**
- **4×4 PD array moving diagonally across the beam's footprint**

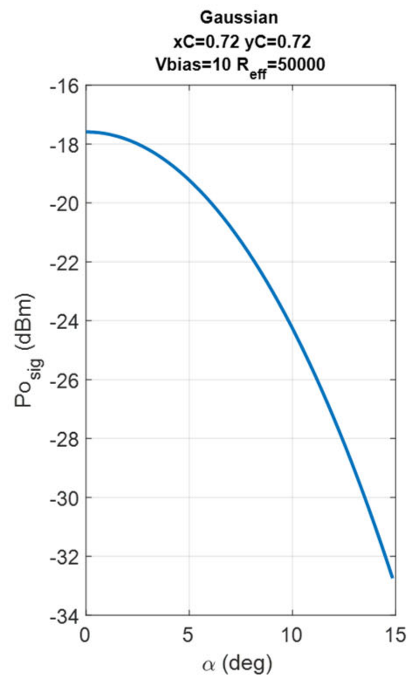
Beam onto PD matrix
(at defocusing *p*=0.2)

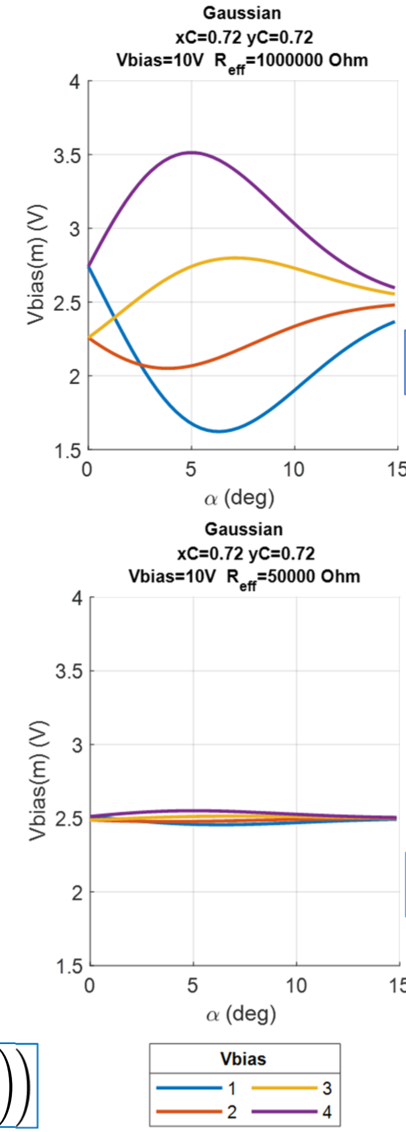


Received power per PD



Moving beam across PD matrix





bias voltage per PD

R_{eff}=1MΩ

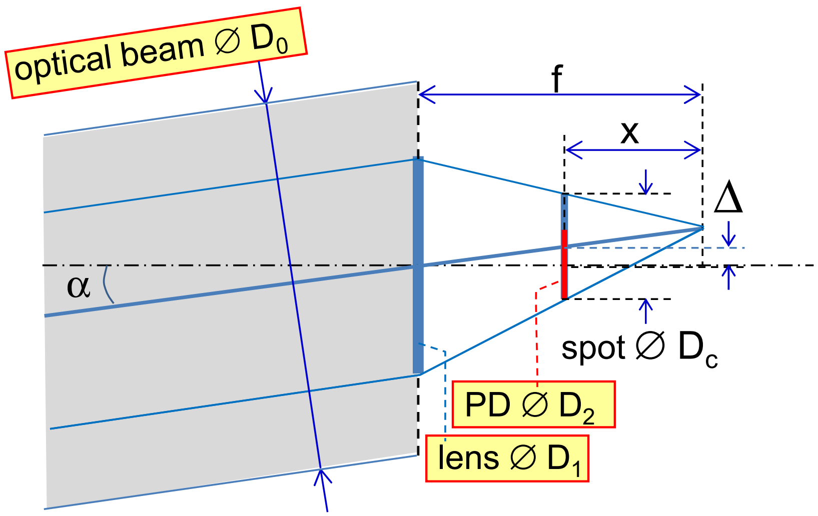
R_{eff}=50kΩ

$$\tan(\alpha) = \frac{\Delta s}{f\,(1-p)}$$

$$R_{eff} = \left(Z_d \,\Big\|\, \left(\frac{K \cdot R_p}{1 + R_s/Z_d}\right)\right)$$

Capturing the beam by the photodiode matrix

- **ideal case : uniform beam, thin aberration-free lens**



Defocusing factor p=x/f: spot size $\varnothing D_c = p\, D_1$ > PD dia. $\varnothing D_2$

With **ideal thin lens $\varnothing D_1$ and uniform beam $\varnothing D_0$** :

- **Coupling fraction T** of beam's power into all photodiodes (matrix fill factor η)

$$T = \cos\alpha \cdot \eta \cdot \left(\frac{D_2}{p\, D_0}\right)^2$$ for $p > D_2 / D_1$ **decreases if p increases**

$$T = \cos\alpha \cdot \eta \cdot \left(\frac{D_1}{D_0}\right)^2$$ for $0 < p \leq D_2 / D_1$

- **FoV half angle α_{max} :**

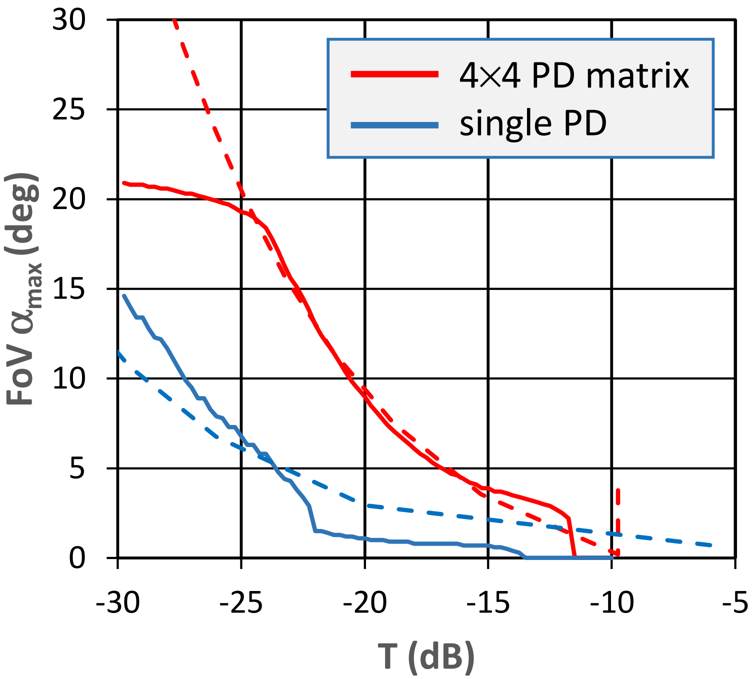
$$\tan\alpha_{max} = \frac{|p \cdot D_1 - D_2|}{2\, f\, (1-p)}$$ **increases if p increases**

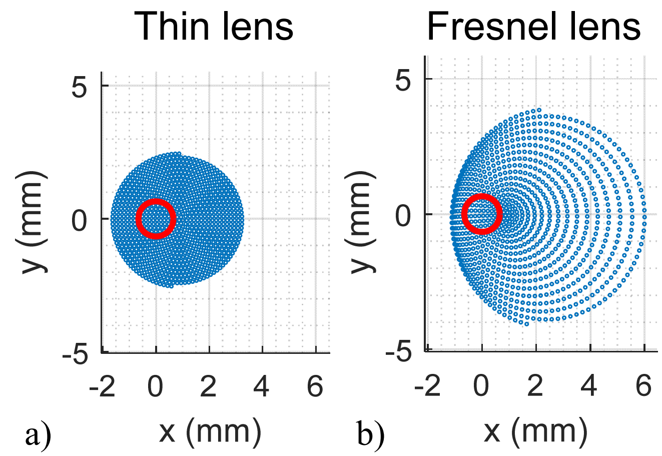
EHCI EINDHOVEN HENDRIK CASIMIR INSTITUTE

Capturing the beam by the photodiode matrix

- **realistic case : Gaussian beam, Fresnel lens with aberrations**

FoV α_{max} vs. beam-to-PD coupling T





Gaussian beam D_0=∅100mm projected onto photodiode matrix ∅1.32mm (red) for α=5 deg and defocusing p=10%
(both lenses D_1= ∅50mm, f=10mm; 1027 rays traced)

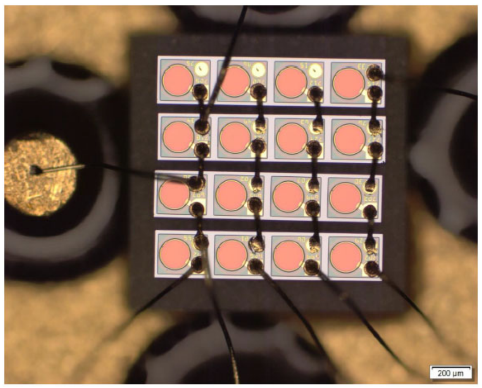
→ FoV with 4×4 PD matrix is substantially larger than with single photodiode

- 4×4 matrix ∅1.32mm of ∅150µm PDs; single PD ∅250µm
- curves calculated by varying p
- **solid curves**: Gaussian beam, Fresnel lens (25117 rays traced; accurate for T> -24 dB)
- **dashed curves:** uniform beam, ideal thin lens (theoretical)

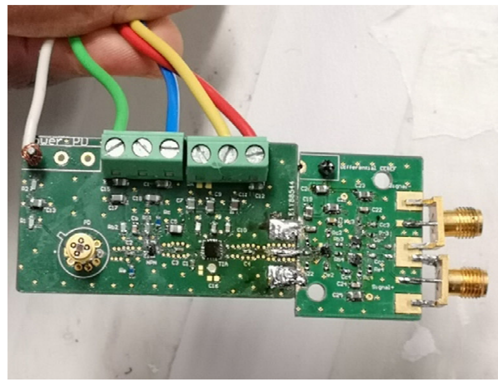
EHCI
EINDHOVEN HENDRIK CASIMIR INSTITUTE

OWC broadband receiver module

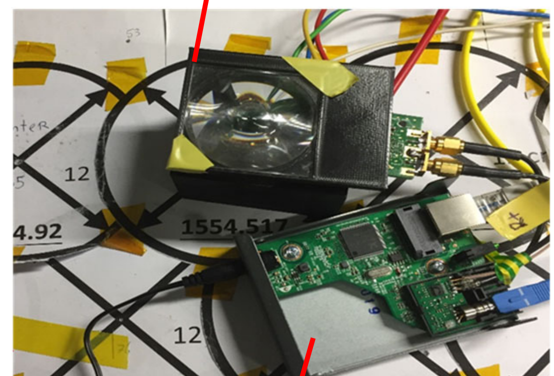
4×4 PD matrix
(made by Albis Optoelectronics)



OWC receiver with differential outputs

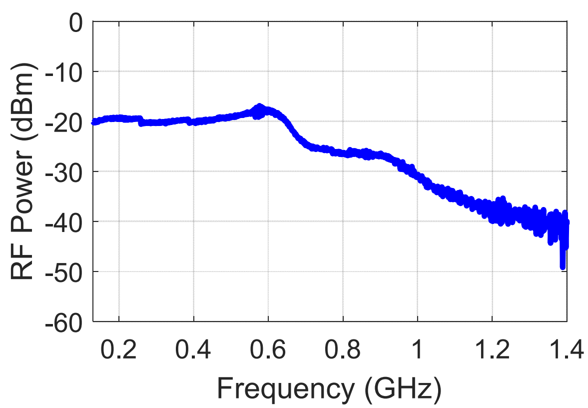


OWC receiver with ∅2” Fresnel lens



adapted media converter with RJ45 output (→ ‘OWC dongle’)

Frequency char.

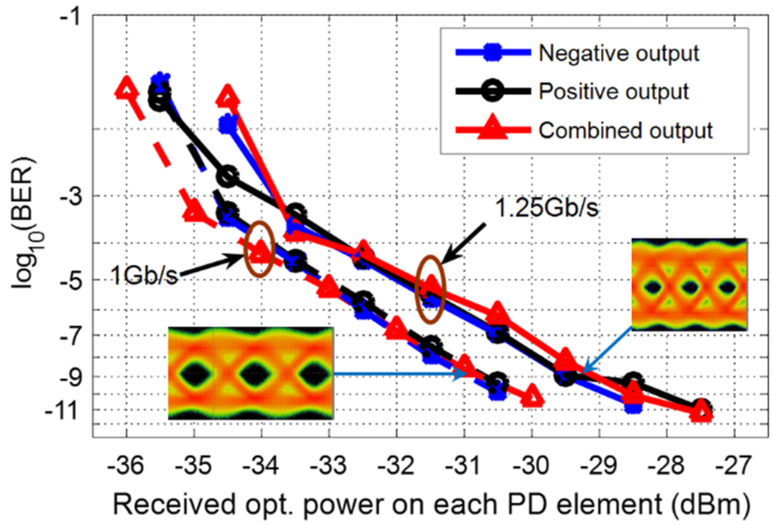


BW_{-3dB} = 670MHz

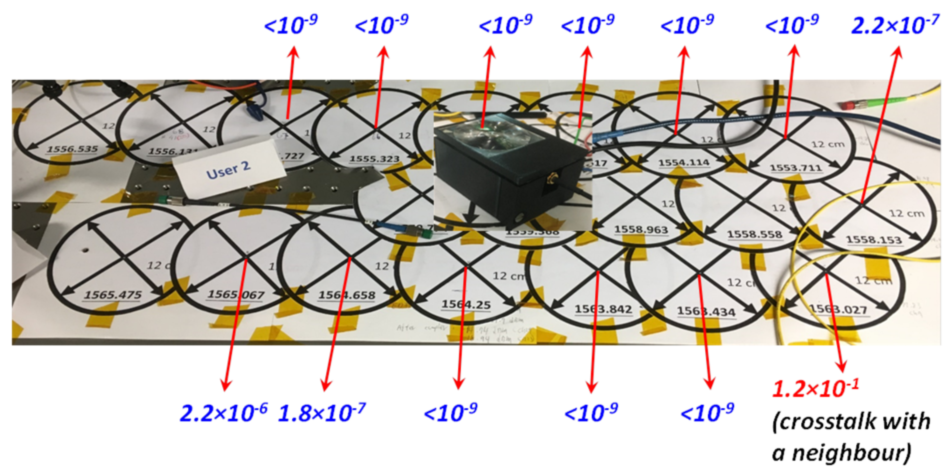
Pat. PCT/EP2020/080594 (filed 30 Oct. 2020)

EHCI
EINDHOVEN HENDRIK CASIMIR INSTITUTE

OWC broadband receiver performance



BER for both single-ended and differential receiver outputs

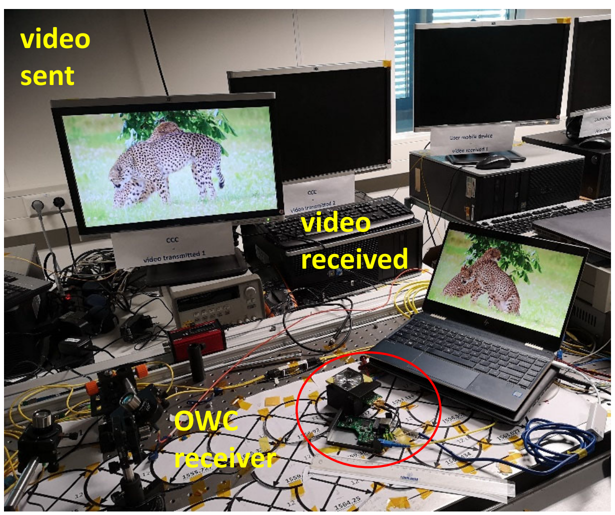


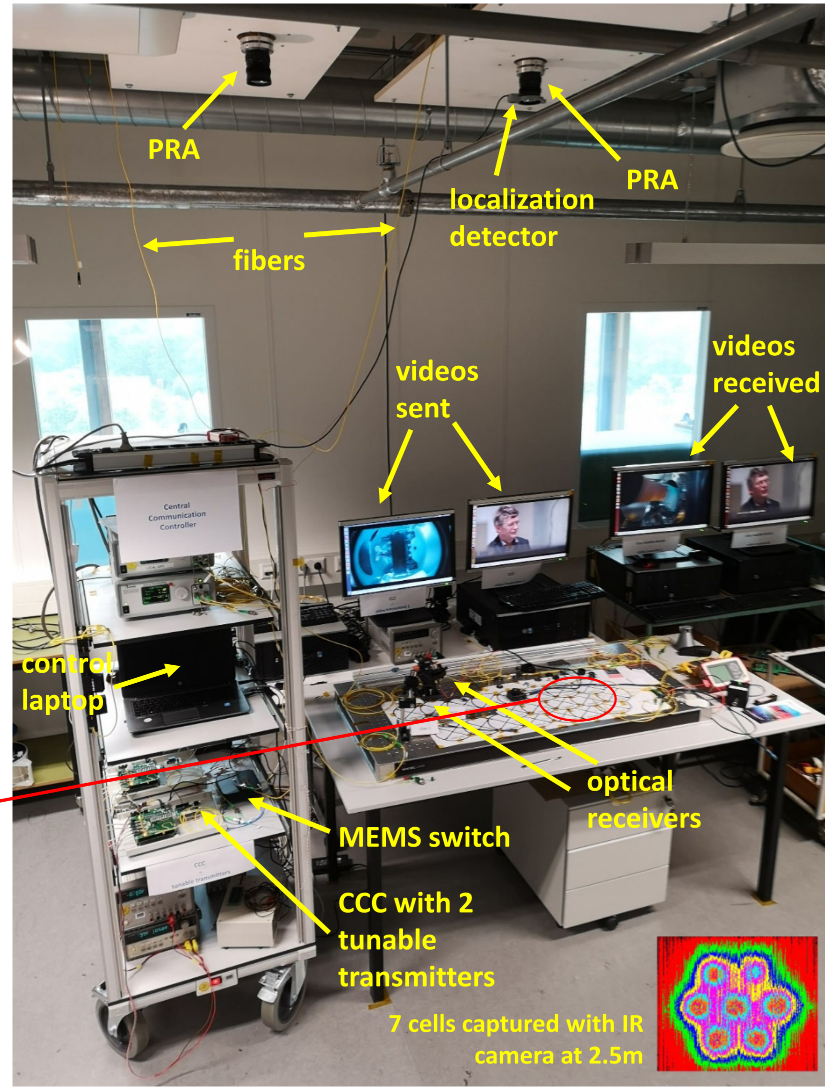
FoV measurements at 1Gbit/s
→ error-free within FoV=10° from center cell

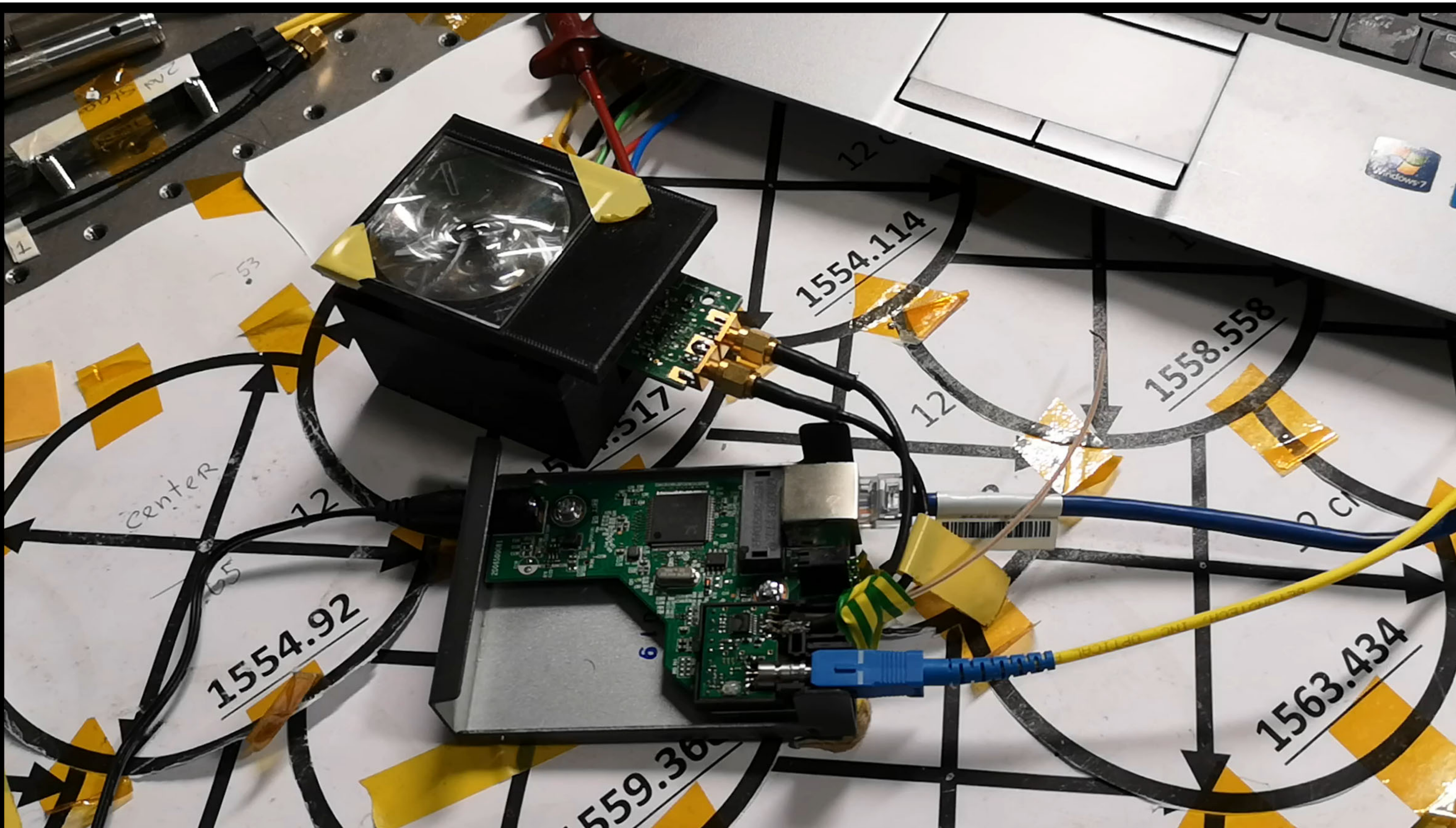
Lab demonstrator @ TU/e

- Transfer of high-def video streams at GbE speed
- Two PRA-s + MEMS switch enabling path diversity for avoiding LoS blocking
- Up to 128 beams, ∅10cm

GbE receiver, streaming video to a laptop






1554.114
1558.558
1554.92
1563.434
center
12

Concluding remarks

- An **OWC receiver** must have a wide aperture, wide FoV, large bandwidth, low power consumption (at user side) without being highly complex.
- A **scalable 2D photodiode matrix** has been presented, which offers larger aperture, wider FoV and same bandwidth as a single PD, without complex power-consuming electronics (only single TIA needed).
- **GbE live video streaming** to laptop with a OWC receiver 'dongle' has been demonstrated in laboratory setup to multiple users, with FoV≈10 deg.

Funding by the European Research Council in the Advanced Grant project BROWSE and Proof-of-Concept project BROWSE+ is gratefully acknowledged. We also gratefully acknowledge Albis Optoelectronics for realizing the packaged photodiodes matrix.

European Research Council erc

EHCI EINDHOVEN HENDRIK CASIMIR INSTITUTE

Thank you for your attention!
Any questions?