# Optical beams – the next breakthrough in broadband wireless communication

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**KIvI Telecom webinar**

**Oct. 16, 2024, 19.30-21.00 h.**

# Outline

- **Introduction**
  - Indoor optical wireless communication (OWC) vs. RF-based wireless communication (WiFi)
  - LiFi (wide-beam OWC)
  - 2D-steered narrow-beam OWC – the *BROWSE* architecture
- **Optical 2D beam steering**
  - Active non-mechanical steering techniques
  - Passive wavelength-tuned diffractive steering techniques
  - Analog mechanical steering techniques
- **User localization**
  - Beam self-alignment for downstream link
  - Aperture search for upstream link
- **Broadband receiver with wide Field-of-View**
  - 2D matrix of photodiodes
  - Optical beam coupling
- **Bi-directional beam-steered indoor OWC system**
  - System architecture – the BROWSE concept
  - Laboratory demonstrator, with GbE video streaming
- **Concluding remarks**

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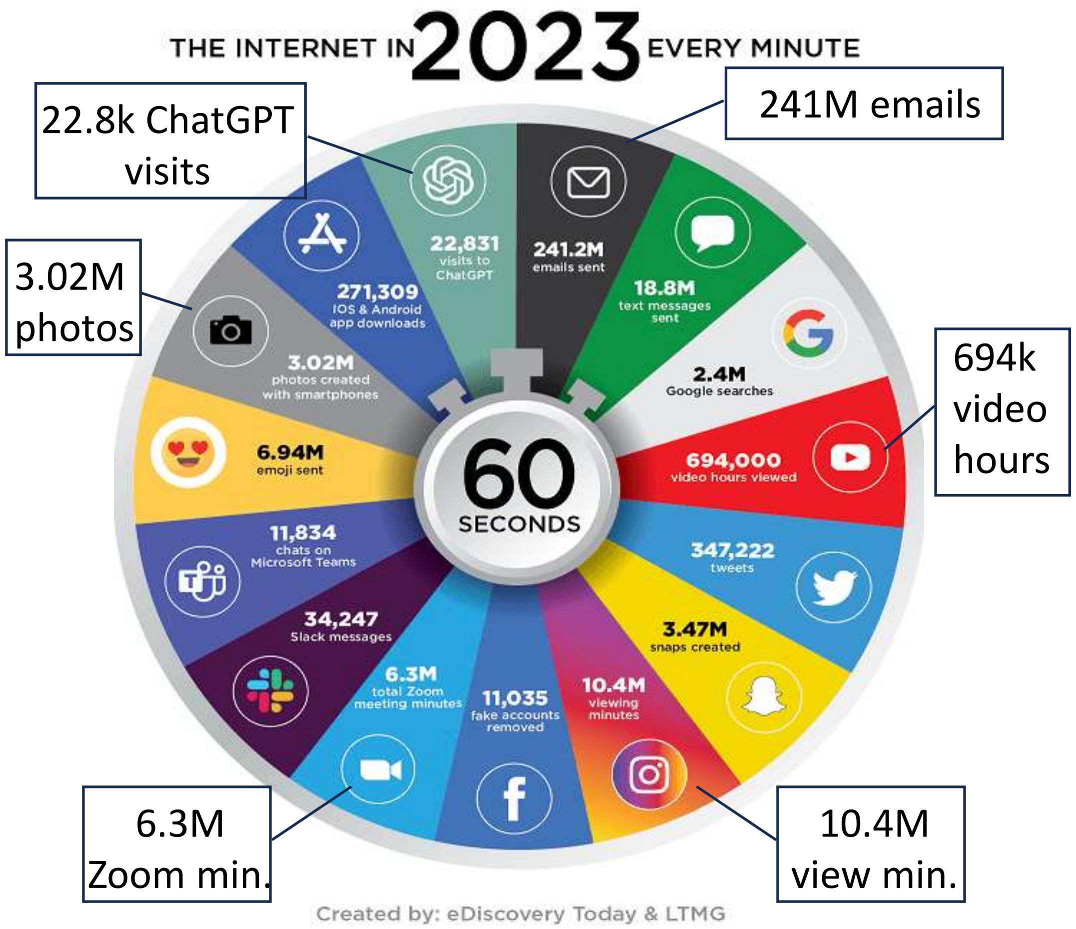
# Motivation for Optical Wireless Communication

- ❑ booming need for wireless connectivity (both data rate and density)
- ❑ driven by the Internet
- ❑ congestion of radio-based wireless (indoor) communication networks (e.g., WiFi)
- ❑ ‘more green’ communication by better energy efficiency

→ Explore **optical wireless communication**, in particular **2D beam-steered OWC** solutions: the ***BROWSE architecture***



22.8k ChatGPT visits

241M emails

3.02M photos

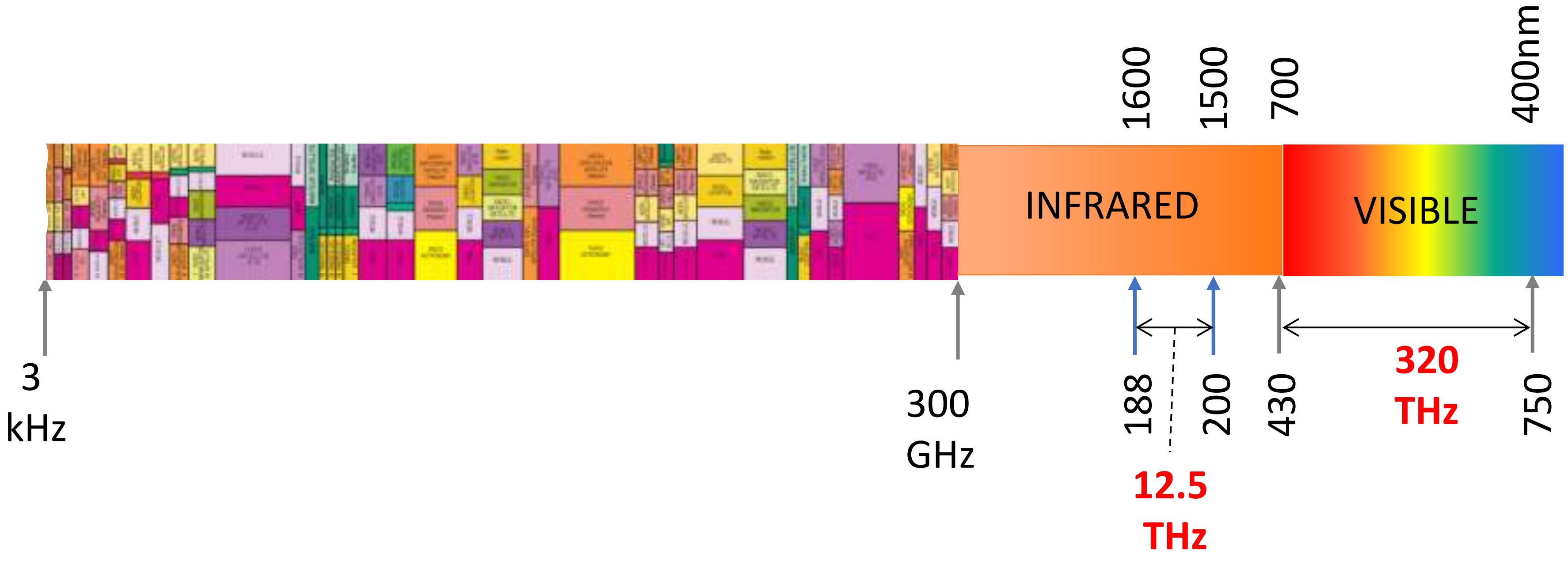
694k video hours

6.3M Zoom min.

10.4M view min.

Created by: eDiscovery Today & LTMG

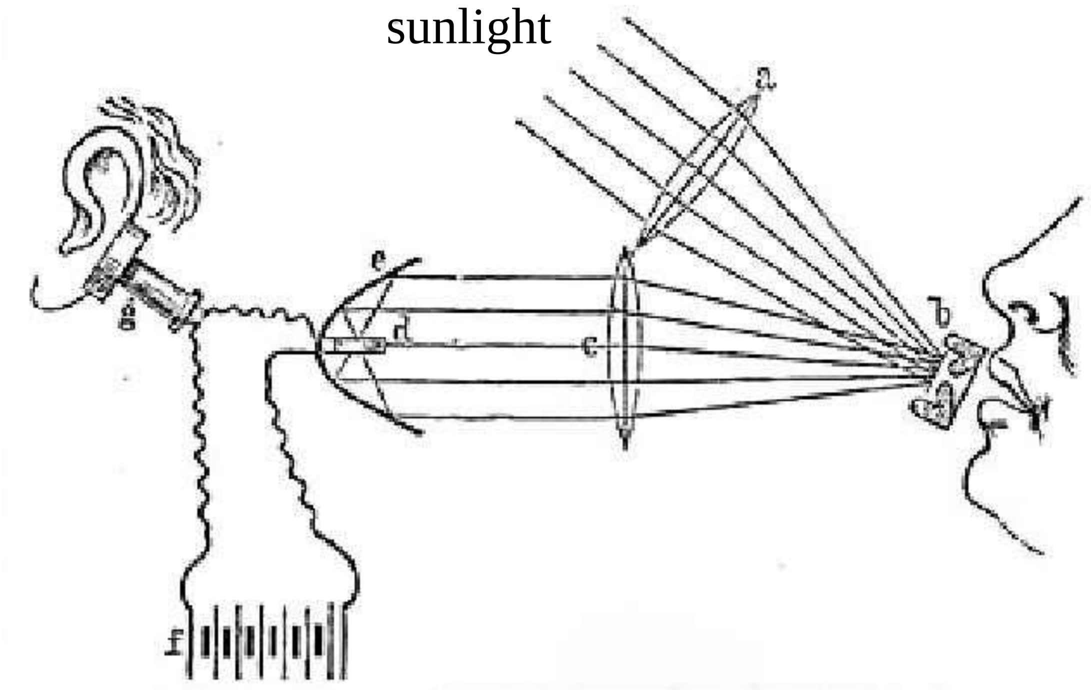
# Booming wireless needs are causing a radio spectrum crunch. The optical domain offers huge extra spectrum.



| | INFRARED | VISIBLE |
|---|---|---|
| Bandwidth | GHz | MHz |
| Eye-safety/Power budget | < 10 mW | < 1 mW |
| Infrastructure | Telecom/Laser | LED Lighting |
| Detector Sensitivity | Higher | - |

[Joanne Oh, PhD defense at TU/e, Mar. 9, 2017]

# Alexander Graham Bell's photophone (1880)

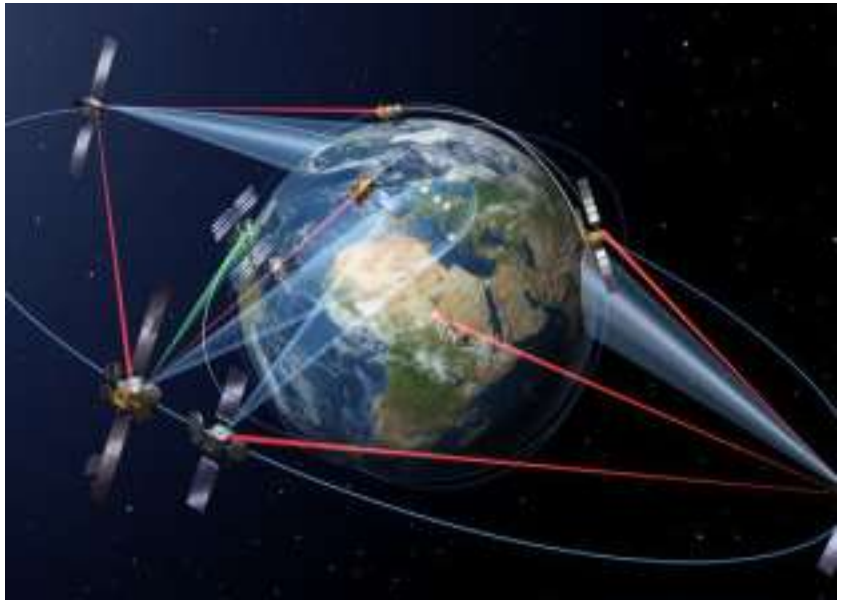


Bell stated that the photophone was 'his greatest, most important invention'. Of his 30 patents, 4 were about the photophone.

# OWC at various length scales

- Fast growing amounts of data, to be transmitted wirelessly at every length scale

. . .

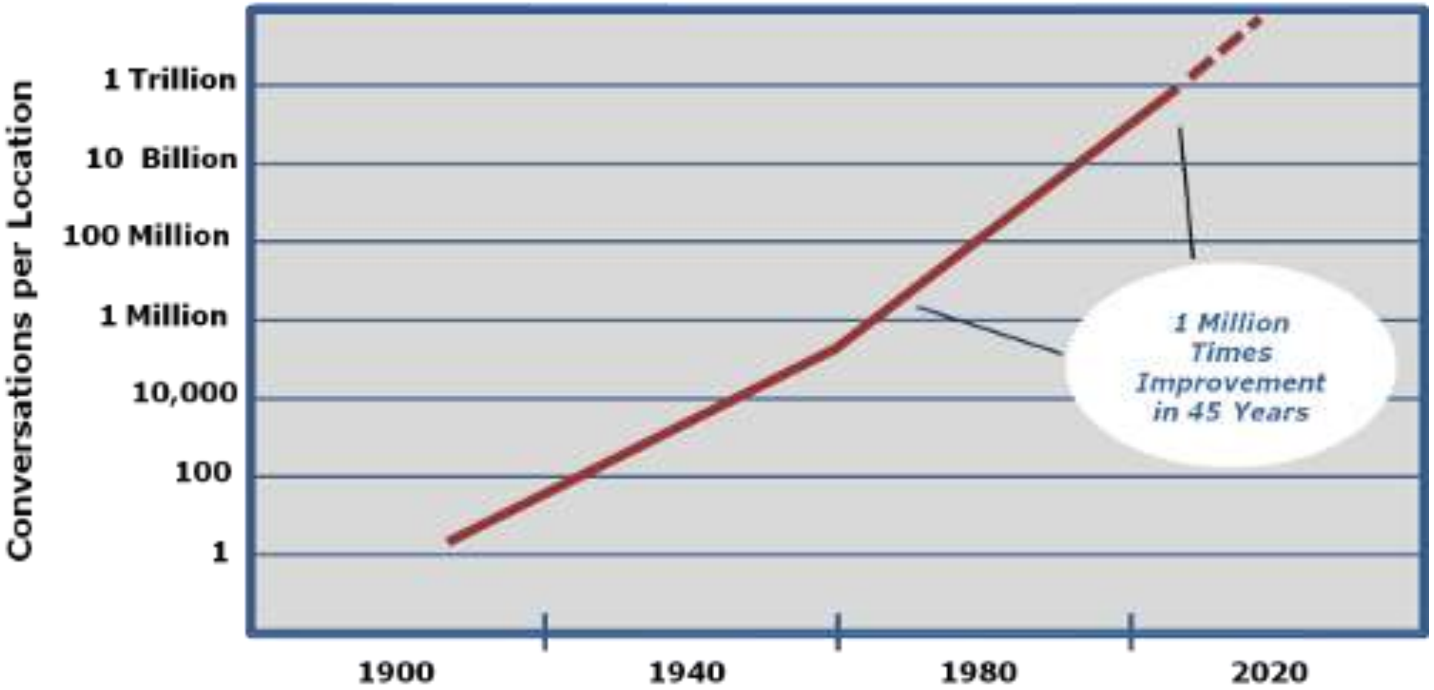


**High-speed short-reach broadband services beyond 5G**

**Inter-satellite and ground-satellite long-reach communication using Laser SatCom**

# Cooper’s law – how wireless capacity grows & the need for atto-cells

*“the maximum number of voice conversations or equivalent data transactions that can be conducted in all of the useful radio spectrum over a given area doubles every 30 months.”* [Martin Cooper, chairman em. ArrayComm]

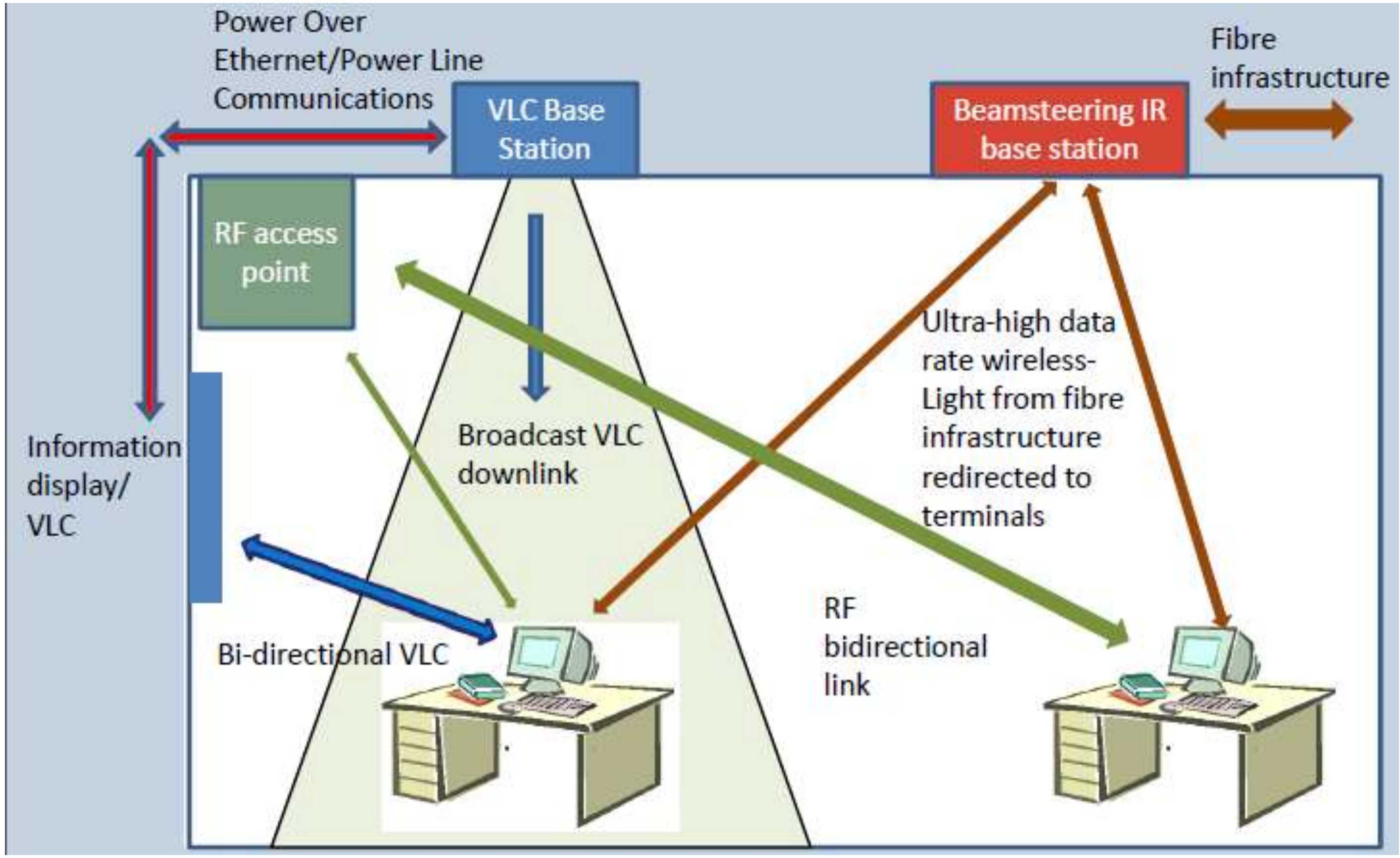


**Cooper’s law of spectral efficiency**

**Radio spectrum efficiency ×$10^6$ in 45 years,** by

| | |
|---|---|
| More spectrum | ×25 |
| Frequency division | ×5 |
| Modulation (FM, SSB, TDM, spread spectrum,…) | ×5 |
| **Spatial division (smaller cells, spectrum re-use)** | **×1600** |

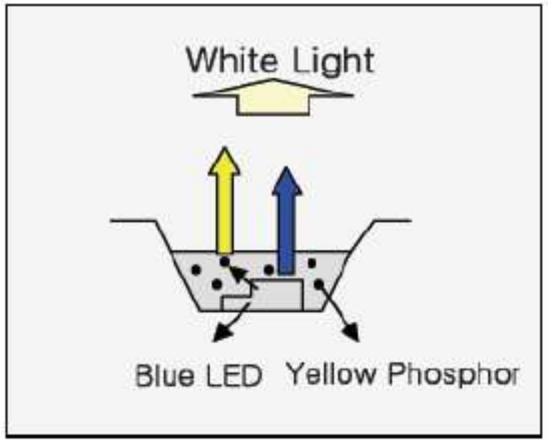
# Indoor optical wireless communication – basic options

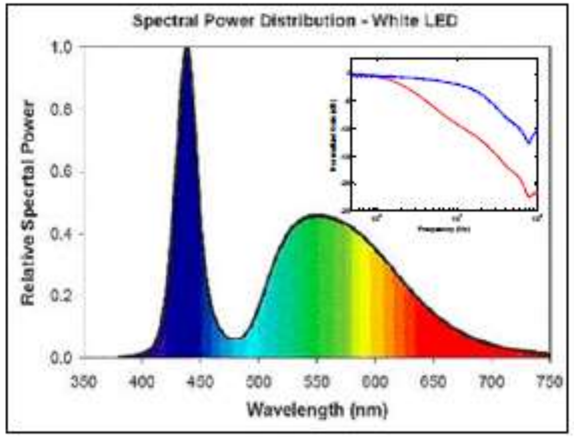


- Visible Light Communication / LiFi with wide-coverage beams (typ. <1Gbit/s, shared)
- Beam-steered IR communication (>10Gbit/s, unshared)
- User environment requirements: scalable to many users, high capacity per user, power efficient, cost-effective, high privacy → beam-steered OWC

Fig.: from Dominic O'Brien, IPS Summer Topicals 2016

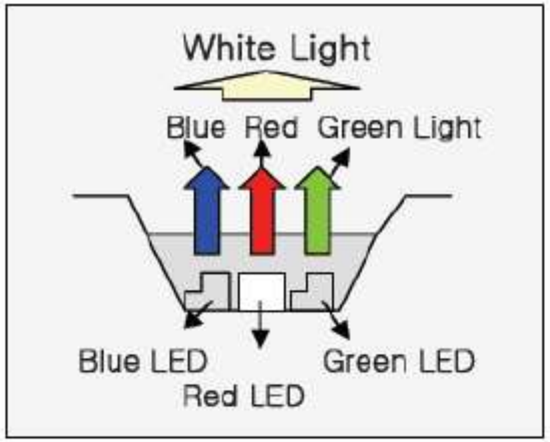
# LED types for VLC

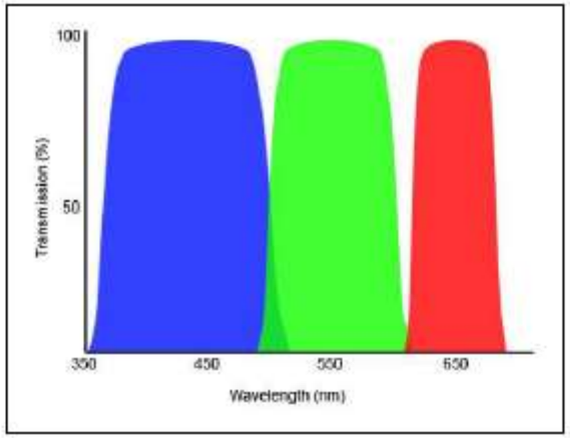




**Blue LED + phosphor**

- LED is fast (BW≈ 20MHz)
- Phosphor is slow (BW ≈ 2MHz)
- Low cost
- Simple driver
- Use blue filter at Rx



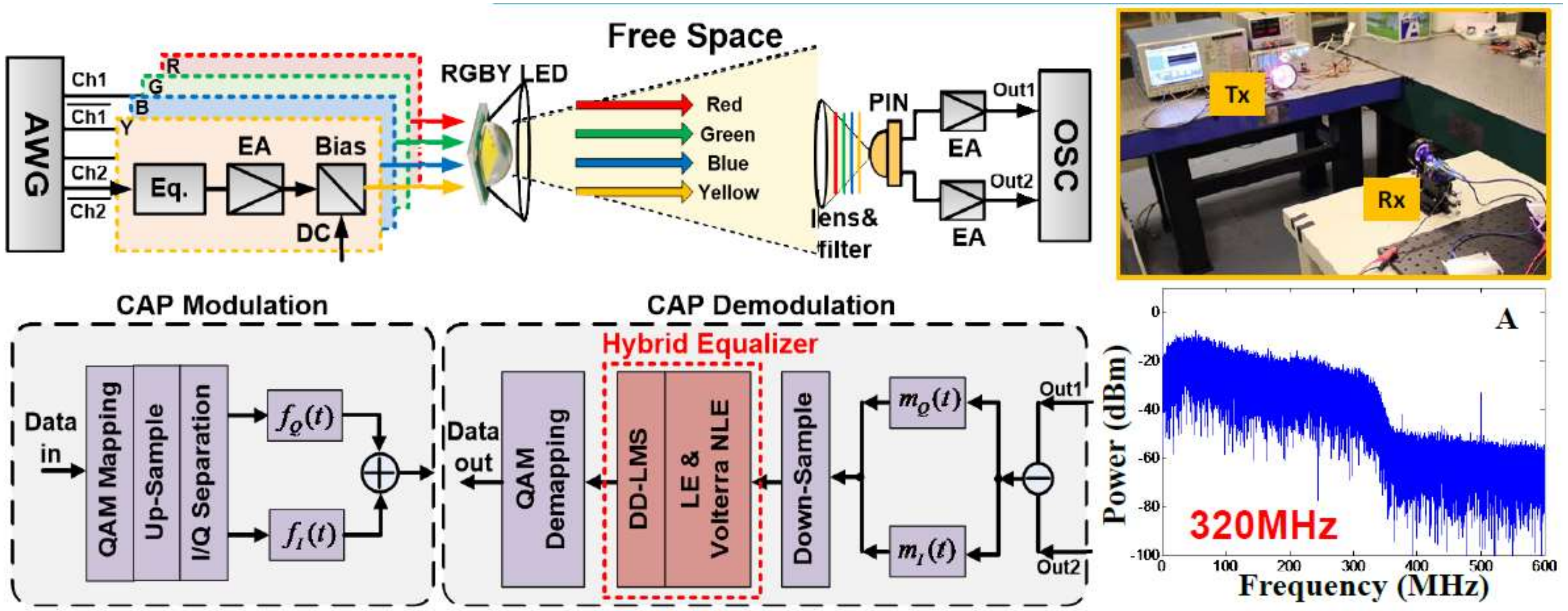


**R+G+B LED**

- 3x data speed by wavelength multiplexing
- BW ≈ 15MHz per colour
- Higher cost
- More complex driver
- One Rx per colour

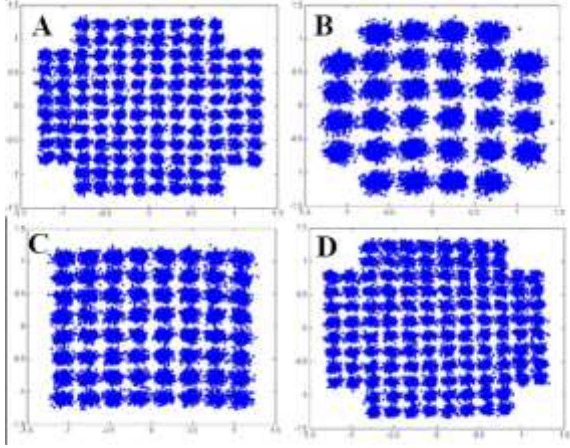
[Volker Jungnickel, IPS Summer Topicals 2016]

# 8Gbit/s VLC system with RGBY LED, CAP mod.



- <u>8Gbit/s aggregate (R+G+B+Y filtered) data rate</u>
- reach 1m
- <u>passive pre-emphasis</u>
  → BW improved from 25 to 320MHz
- reflection cup, with 60° divergence angle
- differential receiver to improve SNR

**Received CAP constellations at BER≈$10^{-3}$**



red
128 CAP

green
32 CAP

blue
64 CAP

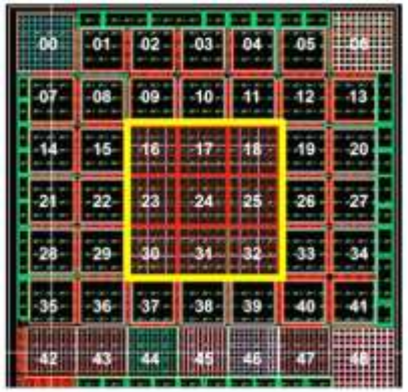
yellow
128 CAP

[Y. Wang et al., IEEE Phot.J. 2015 (Fudan Univ.)]

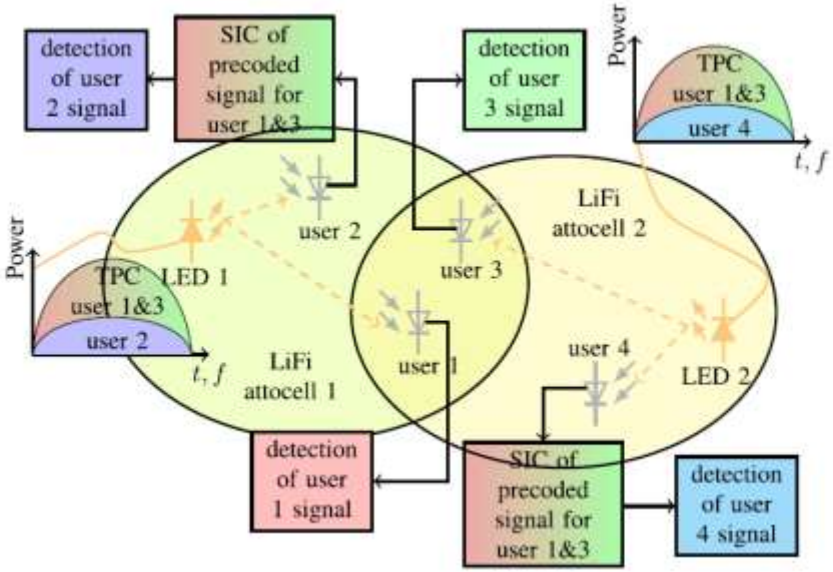
# LiFi system

**Multiple access points, in an atto-cells network architecture**

- uses LEDs
- Seamless handover between atto-cells
- MAC protocols
- Bi-directional, multi-user
- <u>extends VLC (is basically point-to-point) into a fully networked system</u>
- pureLiFi's LiFi-X system:
  40Mbit/s bi-directional full duplex, with USB dongle



**LiFi receiver chip** with 49 APD detectors, each 200×200μm² on 180μm CMOS technology chip (die 3×3 mm² )



**Multi-cell operation** using Non-Orthogonal Multiple Access and Space Division Multiple Access

[H. Haas et al., JLT Mar.2016 (Edinburgh Univ.)]

# Optical Wireless Communication by Directed Beams - KSPs

- Ultra-high capacity
- at high user density (cf. 5G+) if narrow beams
- High power efficiency (a green technology)
- Low latency (lower than silica fiber)
- License-free spectrum
- Immune to EMI
- Complementary to RF, THz
- No infrastructure needed
- High security
- High privacy
- Scalable (to many users, long reach)
- Re-use of mature technologies

**Issues**

- Line-of sight blocking
- No standardization yet…

**Short range (indoor)**

**Long range (inter-satellite)**

# Indoor OWC: Beam-steered OWC vs. WiFi, LiFi

## WiFi, LiFi

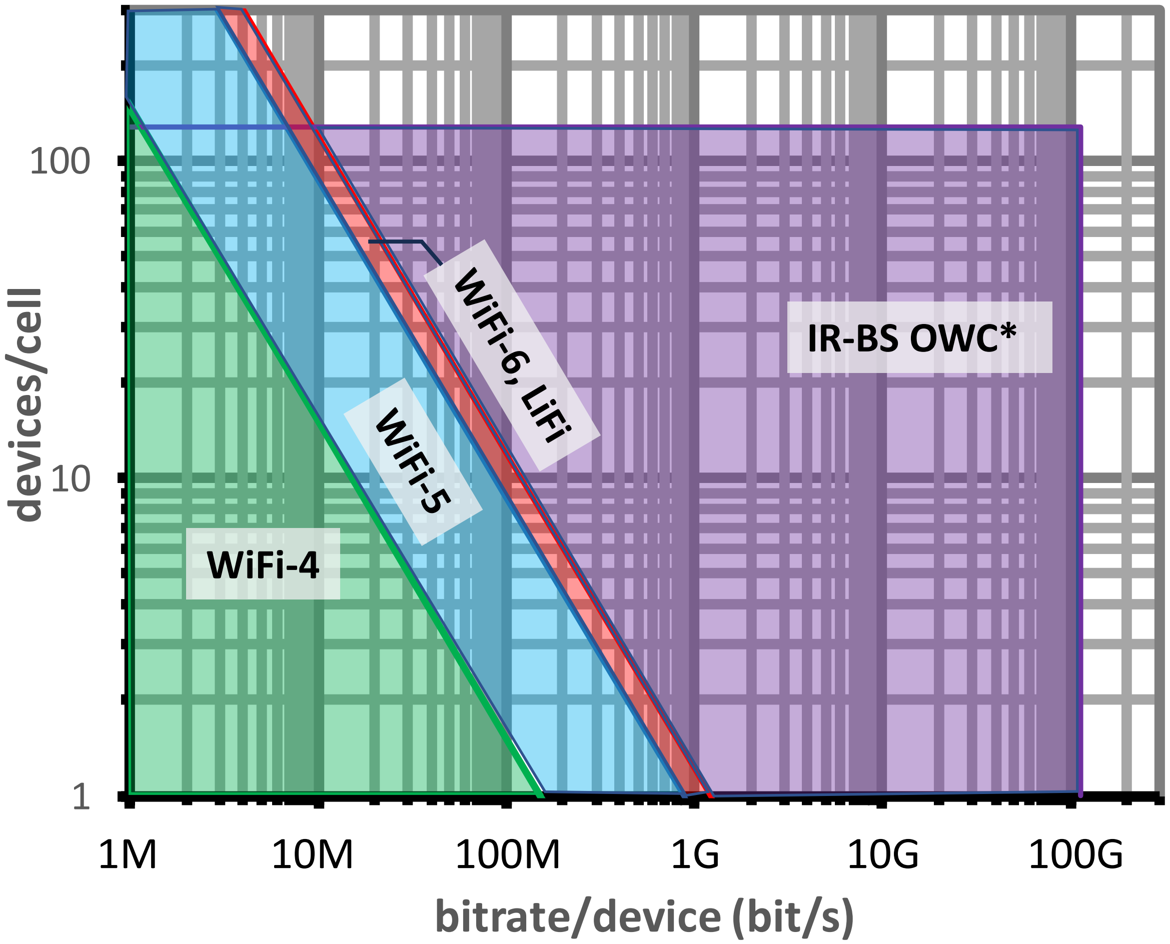
Shared capacity ⇨

- bitrate × no. devices restricted
- privacy issues
- Electro-Magnetic Iinterference sensitive (WiFi)

## Beam-steered OWC

No 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



*** This work, a.k.a. 'LiFi 2.0'**

**→ optical beam acts as a 'virtual fiber': yields high capacity & high user density**

WiFi-6 (IEE
WiFi-5 (IEE
WiFi-4 (IEEE 802.11n-2009) MIMO-4, 64QAM, PHY 150Mbit/s
IR-BS OWC: 128 beams × 112Gbit/s = 14.3Tbit/s [ECOC2017]

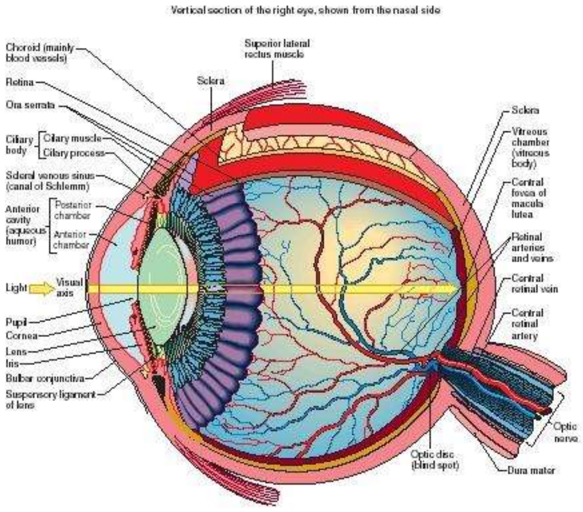
[Koonen et al., J. STQE, Nov./Dec. 2021]

# Beam-steered optical wireless communication – a green technology

Beams with small footprint → **each user gets his/her own beam (‘*virtual fiber*’)**
→ high BW channels → **no/minor signal processing**, low latency
→ beam is steered only when and where needed → **no energy wasted**
→ high privacy → **no/little encryption** needed
→ beams do not penetrate walls, nor address neighbours → **no crosstalk mitigation** needed

| | Beam-steered Optical wireless comm. | Radio wireless comm. |
|---|---|---|
| Beam footprint | small (cm-range; beam collimation by passive lens)<br>large with LiFi / VLC) | medium; beam shaping by high-gain mm-wave antenna<br>• Passive horn antenna (bulky)<br>• Active phased array antenna (complex) |
| Bandwidth | large (1 nm ~ 125GHz @ $\lambda$=1.5$\mu$m) | limited (spectrum congestion; signal bandwidth compression needed) |
| Latency | low | medium |
| Signal modulation complexity | low (OOK, PAM-4) | high (QAM-x, OFDM, …; signal processing needed) |
| EMI sensitivity | none | needs shielding |
| Privacy | high (difficult to tap/jam; does not penetrate walls) | low (encryption needed; crosstalk through walls) |
| Spectrum license needs | none | needed (except ISM bands) |
| Standardisation | none yet (↔ some for LiFi, IEEE 802.11bb) | mature IEEE802.11~ in progress |

# Eye safety

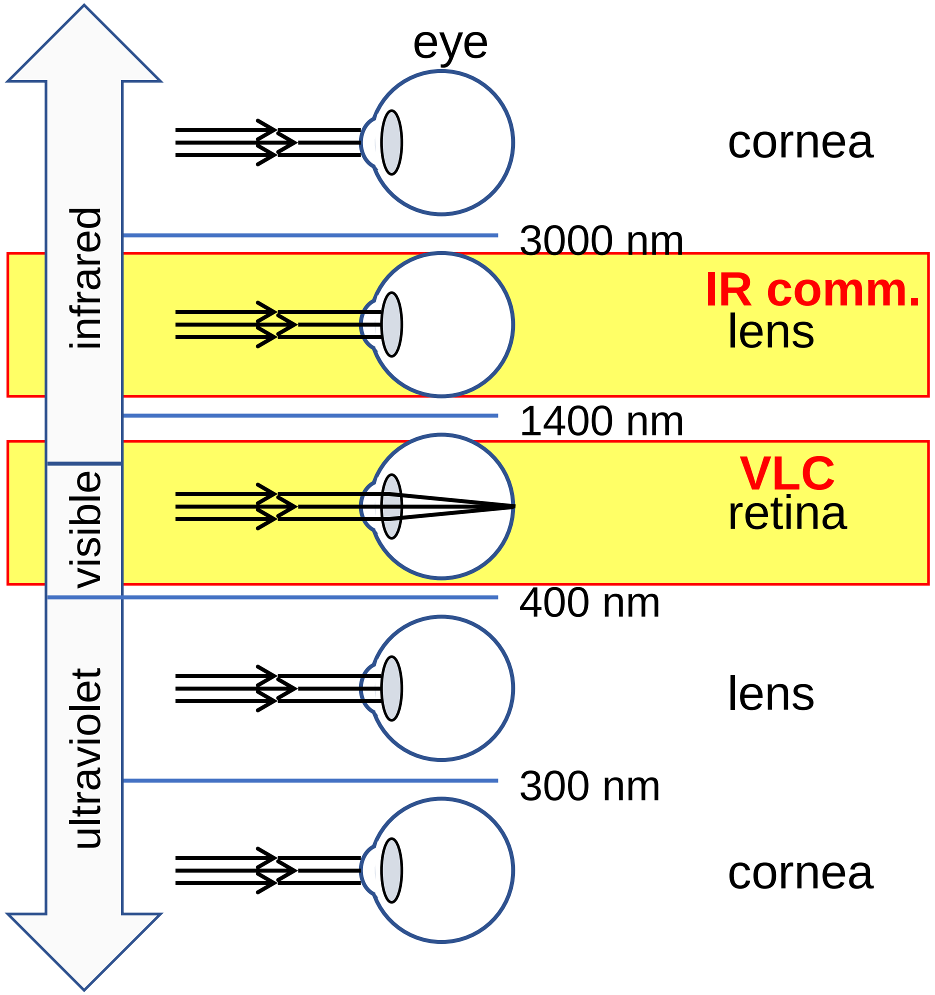

Vertical section of the right eye, shown from the nasal side

**eye safety (ANSI Z-136 series and IEC 825 series)**

| | max. power @ λ=880nm | max. power @ λ=1550nm |
|---|---|---|
| Class 1 | <0.5mW | <10mW |
| Class 1M | <2.5mW | <150mW |
| Class 3R | <500mW | <500mW |

**IR communication vs. VLC:**

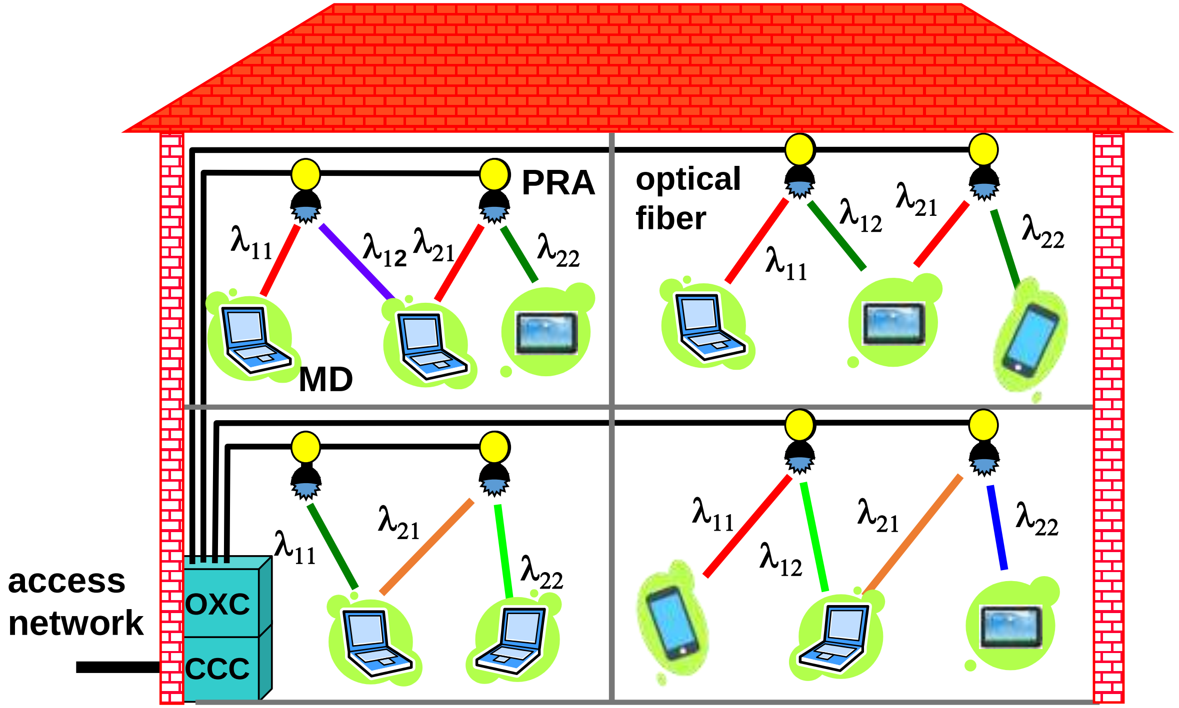
- allows higher optical transmit power
- higher photodiode responsitivity ($\mathcal{R} \propto \lambda$)
- less interference from visible light



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

**BROWSE's system concept:**

- **narrow 'pencil' beams**
  → no sharing, high capacity,
  long reach, high level of privacy
- **IR $\lambda$>1400nm** → eye safe,
  $P_{beam}$ up to 10mW
- use of **mature 1.5$\mu$m fiber-optic components**
- **passive diffractive beam steerer**
  → steering by $\lambda$-tuning → no local powering, easily scalable to many beams (just add $\lambda$-s)
- **$\lambda$-controlled 2D steering**
  → embedded control channel



**OXC = Optical Crossconnect**
**CCC = Central Communication Controller**
**MD = Mobile Device**
**PRA = Pencil-Radiating Antenna**

[Koonen et al, MWP2014, JLT Oct. 2016, JLT May 2018, JLT Oct. 2018, Phil. Trans. Royal Soc. A Mar. 2020, US Pat. 9246589B2, Jan. 20

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  - ❑ Passive wavelength-tuned diffractive 2D beam steering modules
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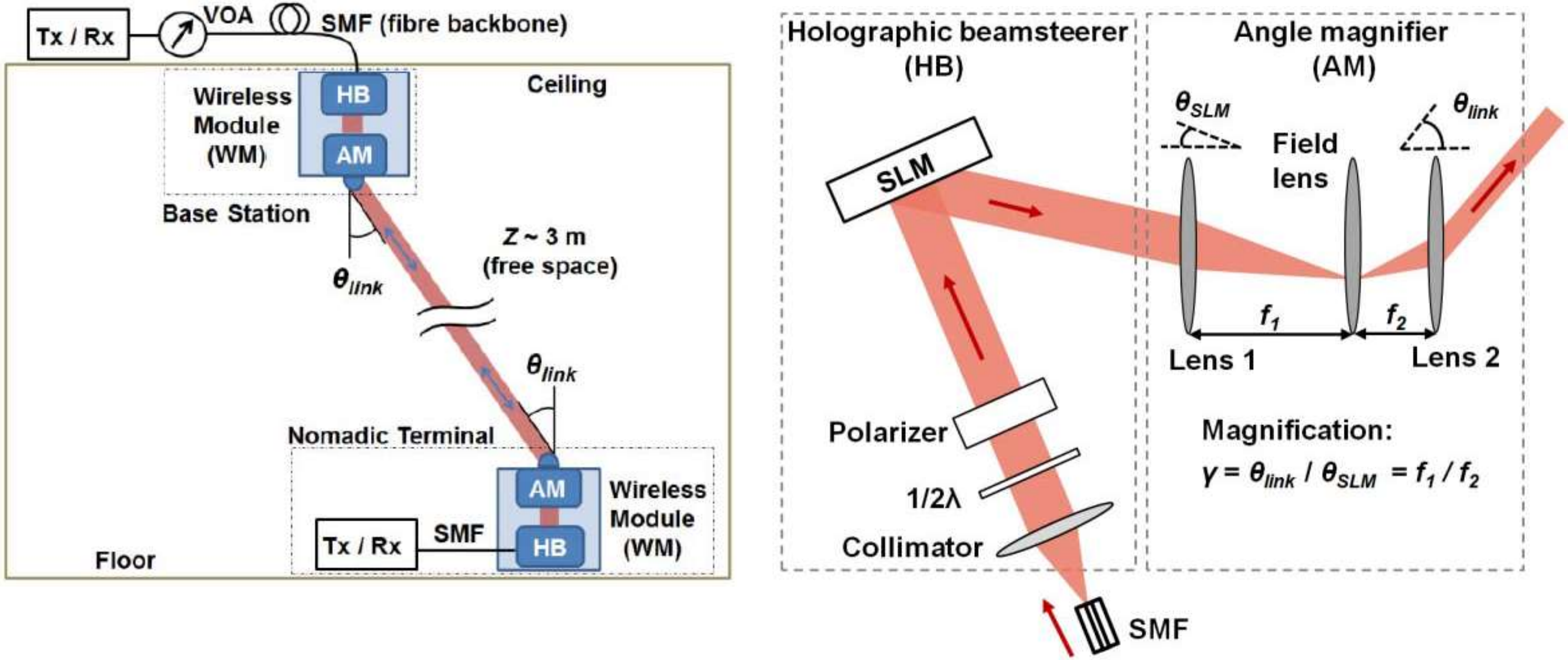
# 2D beam steering with SLM and multiple λ-channels

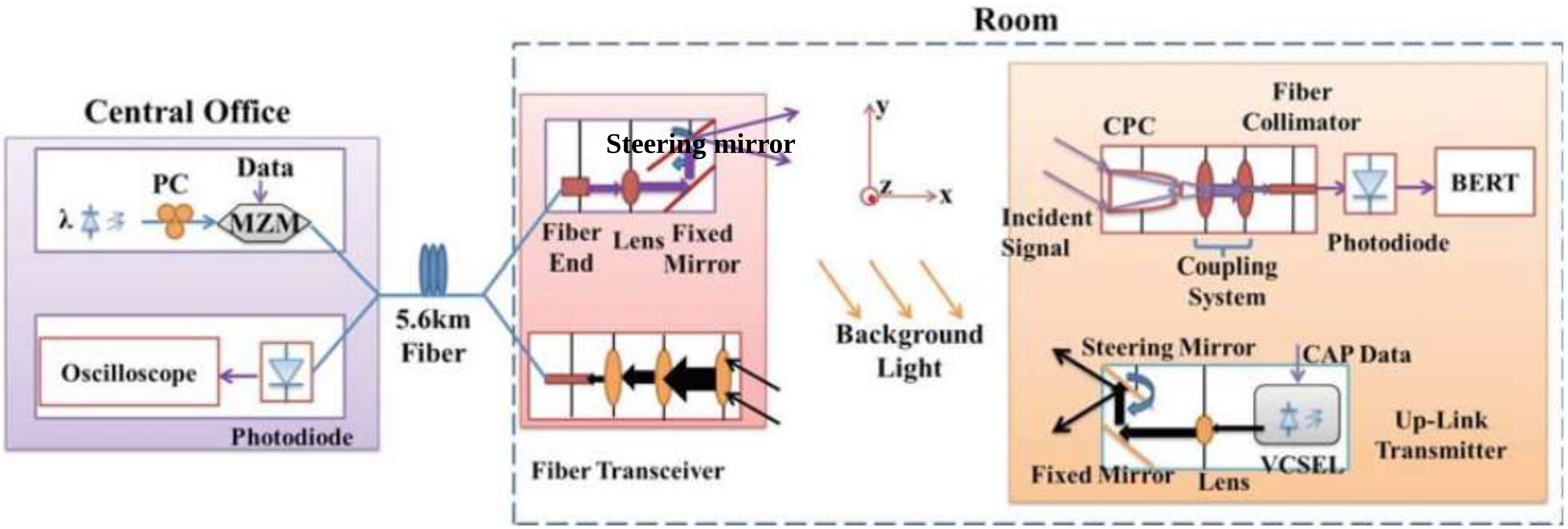


- **Spatial Light Modulator**, 512×512 pixels, 256 phase levels
- Pixel size $p$=15μm → max. steering angle $\theta_{max}=\lambda/2p\approx3°$
- Angle magnifier module, magnification $\gamma=f_1/f_2$
- WDM exper. 3λ × 37.4Gbit/s = 112Gbit/s at 30°, full FoV 60° over 3m  
  6λ × 37.4Gbit/s = 224Gbit/s at 18°, full FoV 36° over 3m

**Each beam needs (part of) an SLM**  
**→ complicates upscaling to many beams**

[A. Gomez et al., PTL Feb. 2014 (Oxford Univ.)]

# 2D beam steering with MEMS mirrors



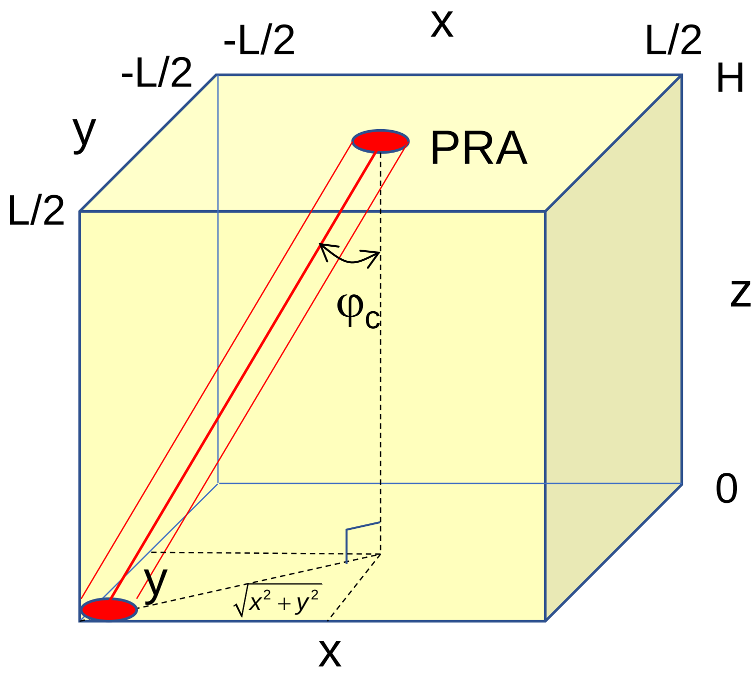
- **MEMS mirror** steering range >20°
- Free-space link 2m, max. coverage area 113cm
- Full duplex
  - downlink 10Gbit/s, λ=1551nm, 7mW
  - uplink 2Gbit/s, VCSEL λ=850nm, 5mW
- CAP-16 modulation (better spectrum efficiency than OOK, simpler than OFDM and QAM)
- Receiver with compound parabolic concentrator to increase FoV

**Each beam needs a MEMS mirror**
**→ complicates upscaling to many beams**

[Ke Wang et al., OFC2015 (Univ. Melbourne)]

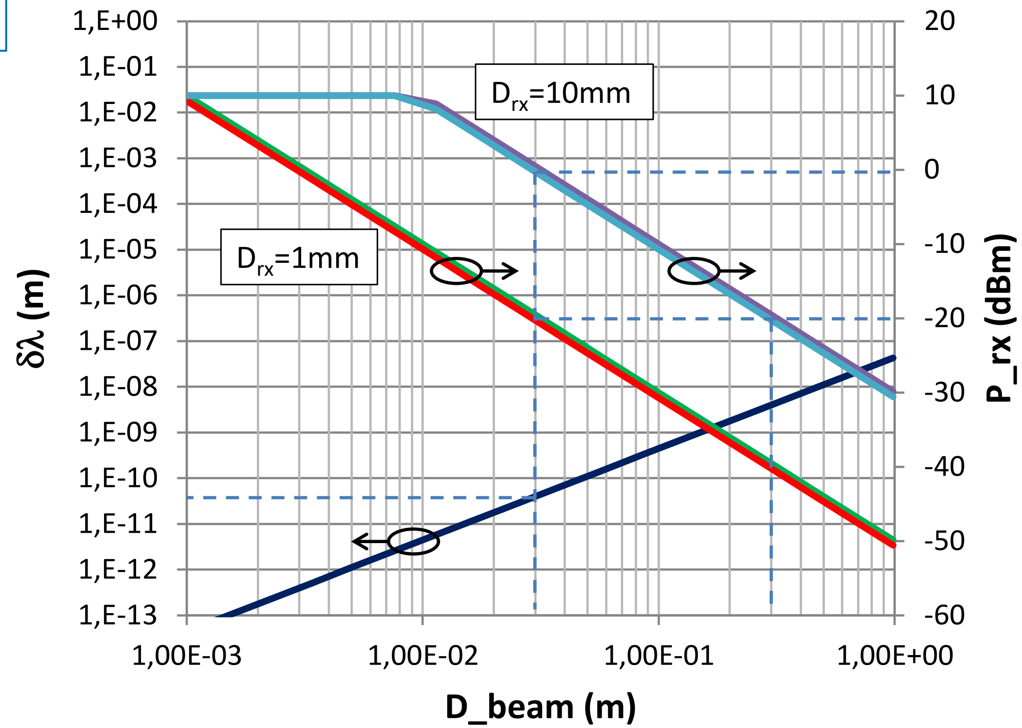
# Diffractive beam steering: steering by wavelength tuning

**Scanning the area**



**Choosing the beam diameter**

**System design**

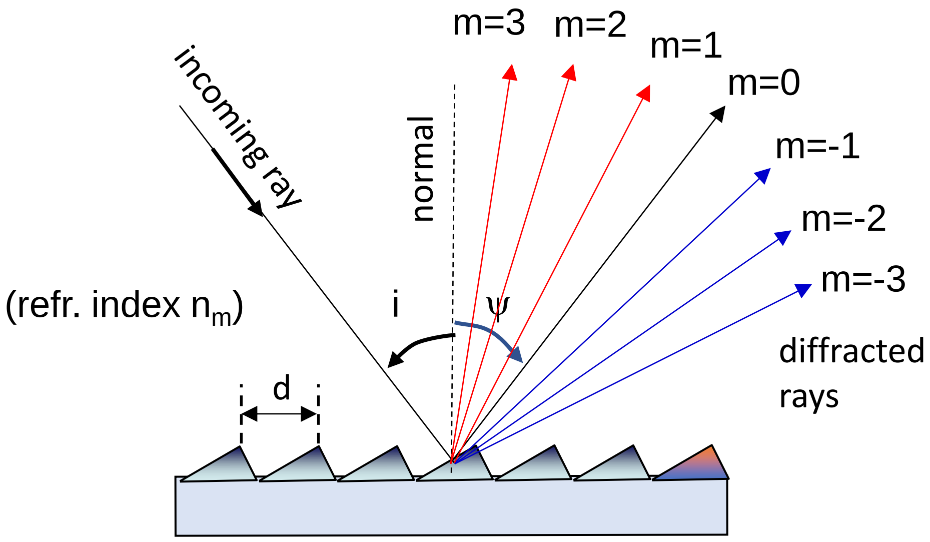


- Beam power $P_{beam}$=10mW
- Area dim. L=1.5m, H=2.5m
- Receiver aperture $D_{rx}$=1mm or =10mm
- Total wavelength tuning range $\Delta\lambda$=100nm
- Tuning step size $\delta\lambda=\Delta\lambda\,(D_{beam}/L)^2$
- Min. received power $P_{rx\_min} = P_{beam}\cos\varphi_c \dfrac{A_{rx}}{A_{spot}} = P_{beam}\left(\dfrac{D_{rx}}{D_{beam}}\right)^2\left(1+\dfrac{L^2}{2H^2}\right)^{-1}$

**Larger beam diameter relaxes steering, increases achievable bandwidth, but reduces received power → Large receiver aperture desired**

[Ton Koonen et al., JLT Oct.2016]

# Reflection grating operating in low order m



Grating equation $\sin\psi_m + \sin i = \frac{m\,\lambda}{n_m\,d}$

Free Spectral Range (for order $m \geq 2$) $\Delta\lambda_{FSR,m} = \frac{\lambda}{m-1}$

Maximum order $m_{max} = \left\lfloor \frac{d}{\lambda}\left(1-\sqrt{1-\frac{2\,\lambda}{d}}\right)\right\rfloor$

**Max. angular tuning range $\Delta\psi_{max}$**

(by tuning over $\Delta\lambda = \Delta\lambda_{FSR}$ , starting at $\lambda$=1500nm)

$$\boxed{\cos\Delta\psi_{max} = 1 - \frac{\lambda}{d}\,\frac{m}{m-1}}$$

achieved for $\psi_m\left(\lambda + \Delta\lambda_{FSR,m}\right) = \frac{\pi}{2}$

**Grating with N grooves/mm, at $\lambda$=1500nm over tuning range $\Delta\lambda_{tun}$ for max. order $m_{max}$ and incidence angle i**

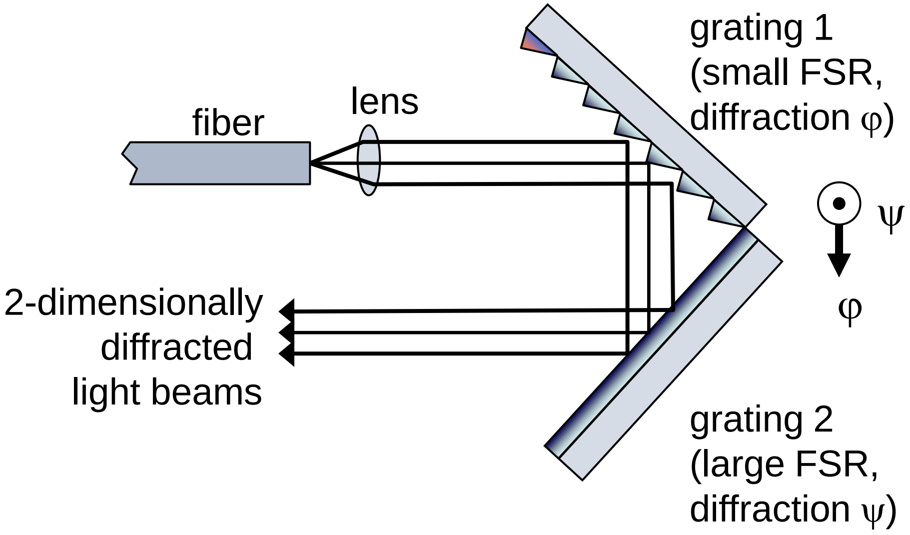
| N (gr/mm) | Δψ_m,max (deg) | order m_max | tuning range Δλ_tun (nm) | i (deg) | Δψ_m,max bound (deg) |
|---|---|---|---|---|---|
| 50 | 22,80 | 25 | 63 | 72,39 | 23,07 |
| 55 | 23,97 | 23 | 68 | 79,66 | 24,07 |
| 60 | 25,11 | 21 | 75 | 79,90 | 25,21 |
| 65 | 26,22 | 19 | 83 | 72,83 | 26,53 |
| 70 | 27,32 | 17 | 94 | 63,71 | 28,07 |
| 75 | 28,36 | 16 | 100 | 66,93 | 28,96 |
| 80 | 29,37 | 15 | 107 | 68,21 | 29,93 |

[Ton Koonen et al., JLT Oct. 2016]

# 2D steering with cascaded gratings

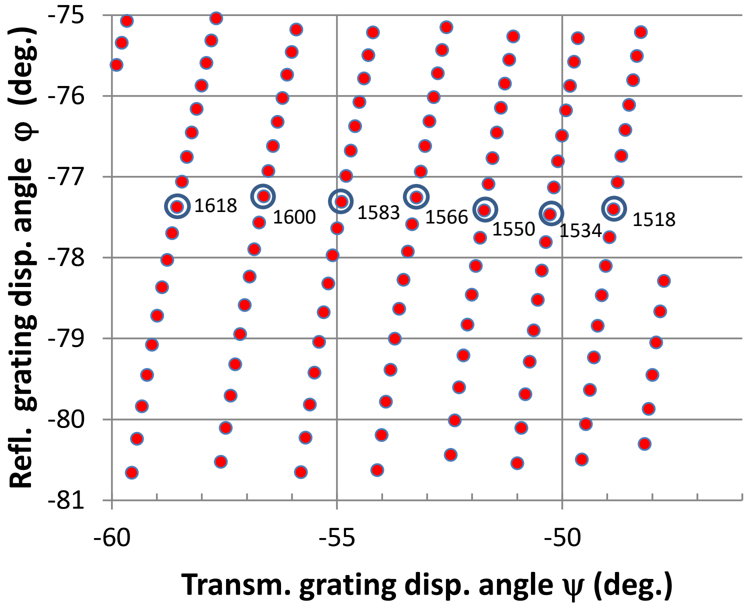
- Continuous/stepwise 2D beam steering by wavelength tuning

## with crossed gratings



- Fully <u>passive</u> device
- Deploys only wavelength tuning
- λ scan range is smaller than $FSR_2$ , and comprises multiple $FSR_1$-s
- May simultaneously steer <u>multiple</u> beams (by multi-λ inputs)

## 2D scanning

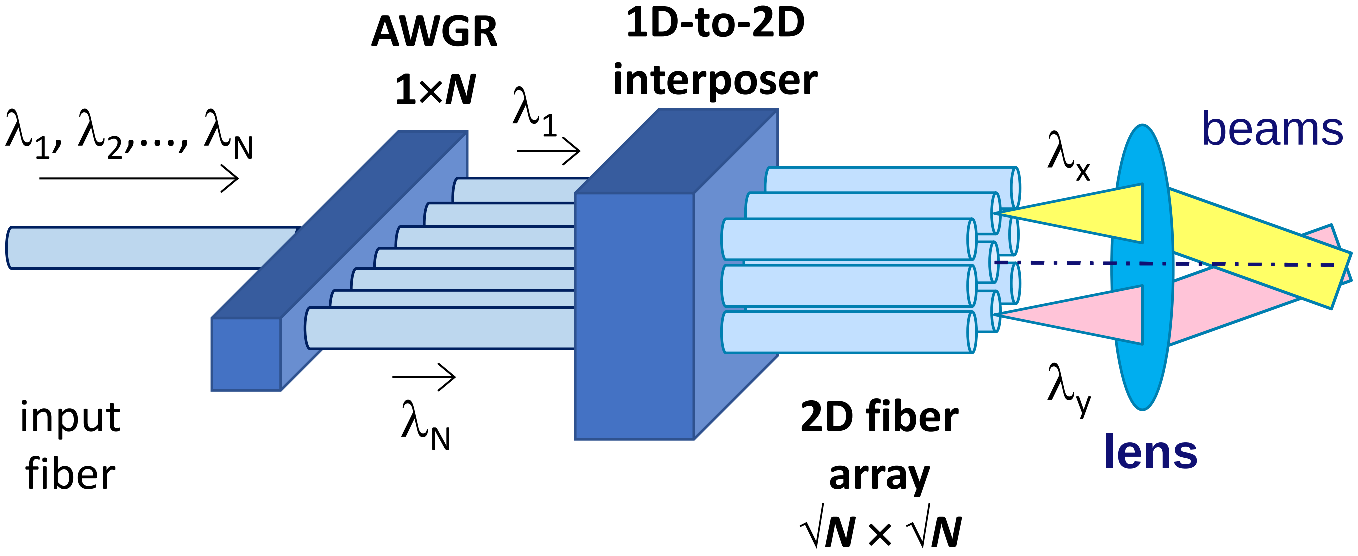


- reflection grating 1: 13.3gr/mm, order *m*=95, incidence $\theta_i$=80.7° ; $FSR_1$=16.3nm
- transmission grating 2: 1000 gr/mm, *m*=1, $\theta_i$=49.9°
- λ-tuning: from λ=1505 to 1630nm (over ~ 8×$FSR_1$)
- angular tuning over 5.6°×12.7°

[Koonen et al, JLT 2016, US Pat. 9246589, d.d. Jan. 20, 2012]

# 2D beam steering with high port count Arrayed Waveguide Grating Router

- Stepwise 2D beam steering by wavelength tuning



- System experiment:
  - ❑ AWGR with 80 ports @ 112Gbit/s PAM-4
  - ❑ OWC link 2.5m, 17°×17° coverage

128 fibers array

+ $f$=50mm large NA lens objective (f/D=0.95)

+ (C+L$^-$ band) AWGR, 144 ports, $\Delta\nu$=50GHz, $BW_{-3dB}$ =35 (/24)GHz

[Koonen et al, Sum. Top. 2016, JLT Oct. 2018, ECOC2017]

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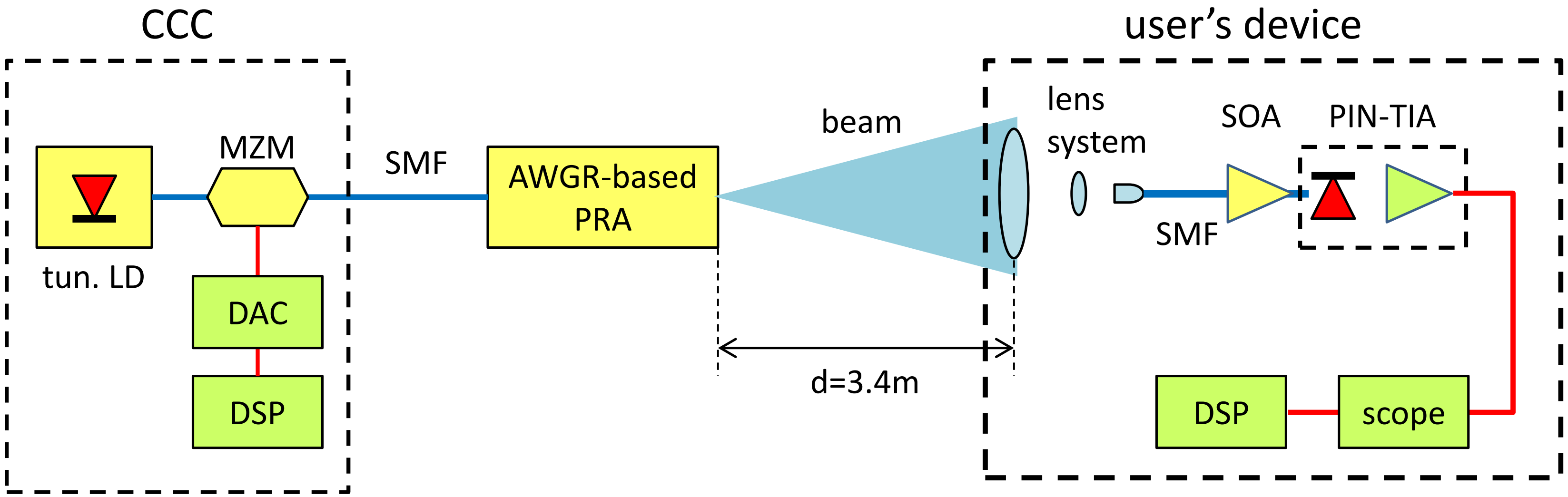
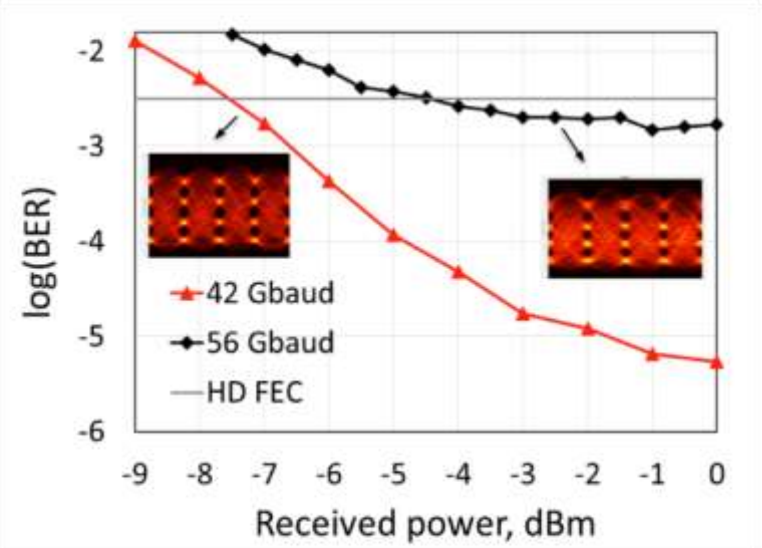
# Experiment: transmitting 112 Gbit/s PAM-4 per beam with AWGR beam steerer





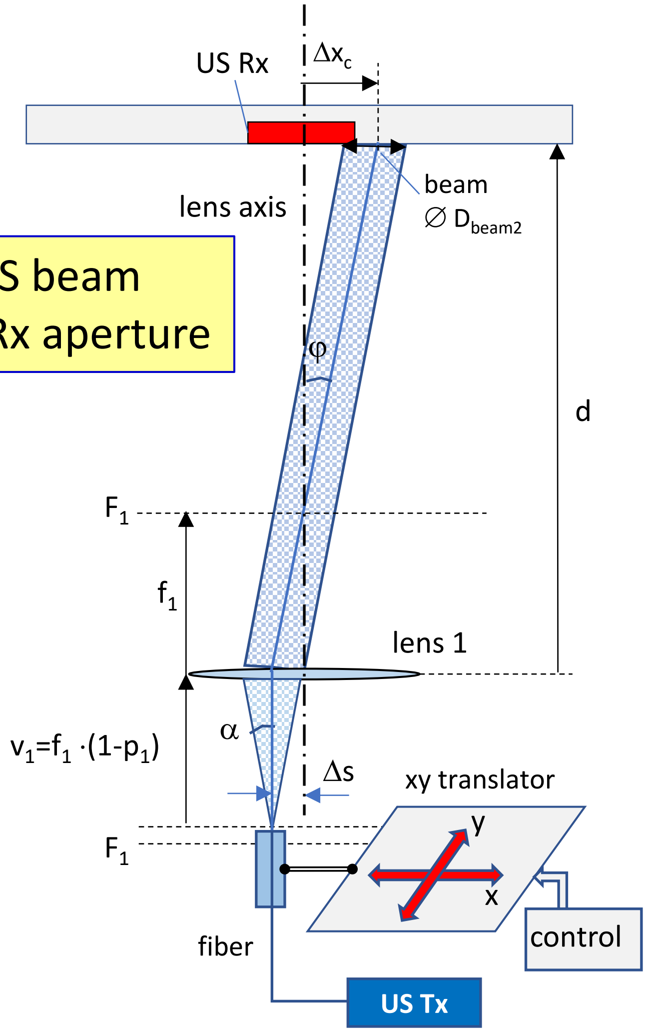
- Beam steerer: AWGR with 9×9 2D fiber array, lens *f*=40mm
- Received beam: +10dBm, ∅8.5cm

[Fausto Gomez-Agis et al., ECOC2017]

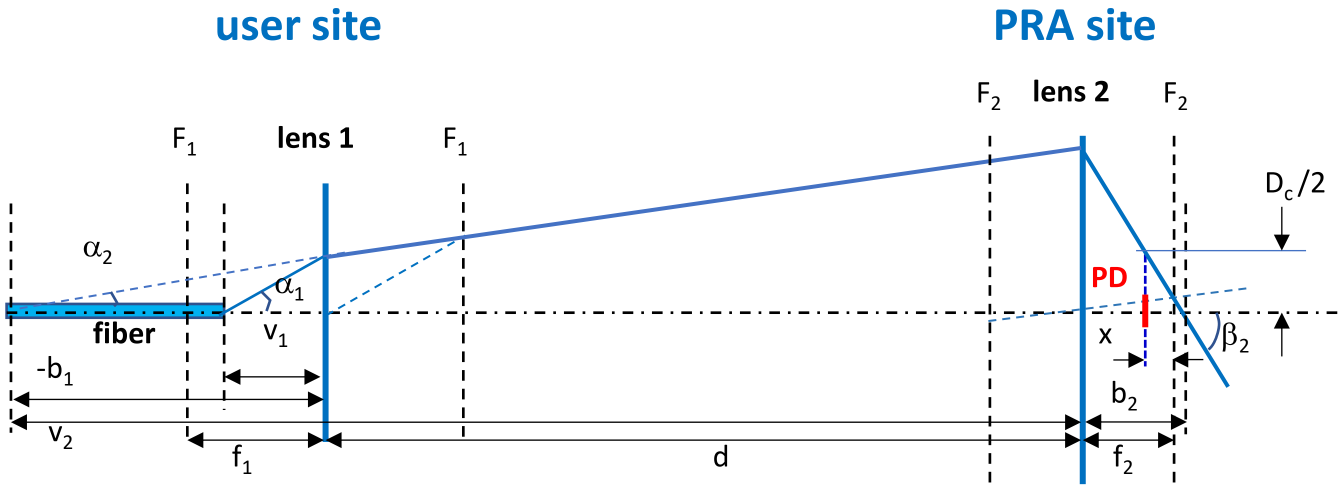
# Stepper motor 2D beam steering

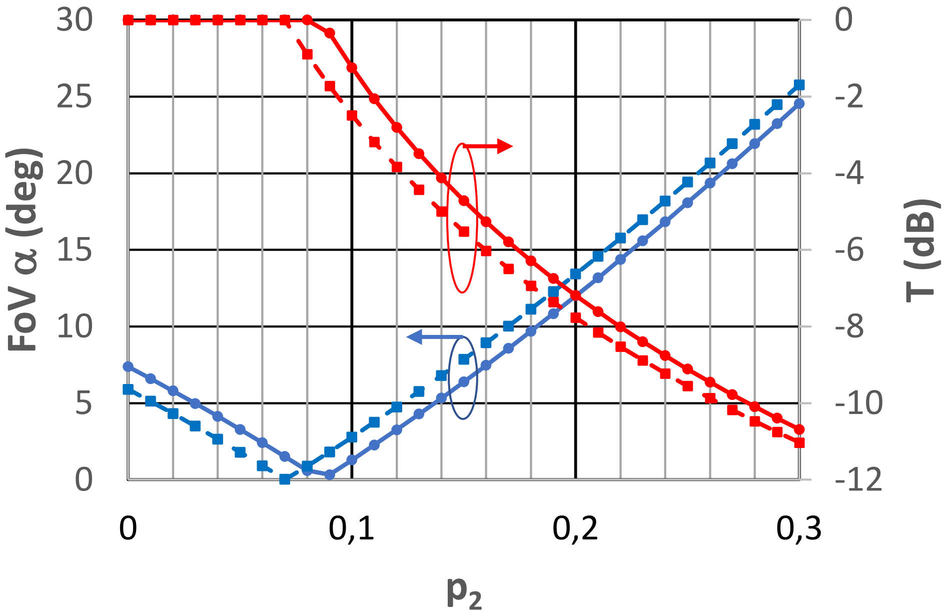
- with arbitrary λ laser and mechanical beam steering at user
- upstream optical path design (in the BROWSE system)

dia. US beam
< US Rx aperture



**2D beam steering by xy-stepper motors (‘set-and-forget’)**
steering angle φ = atan(Δs/f)





**defocusing $p_2=x/f_2$**
- enlarges FoV $\alpha$
- reduces beam-to-PD coupling $T$

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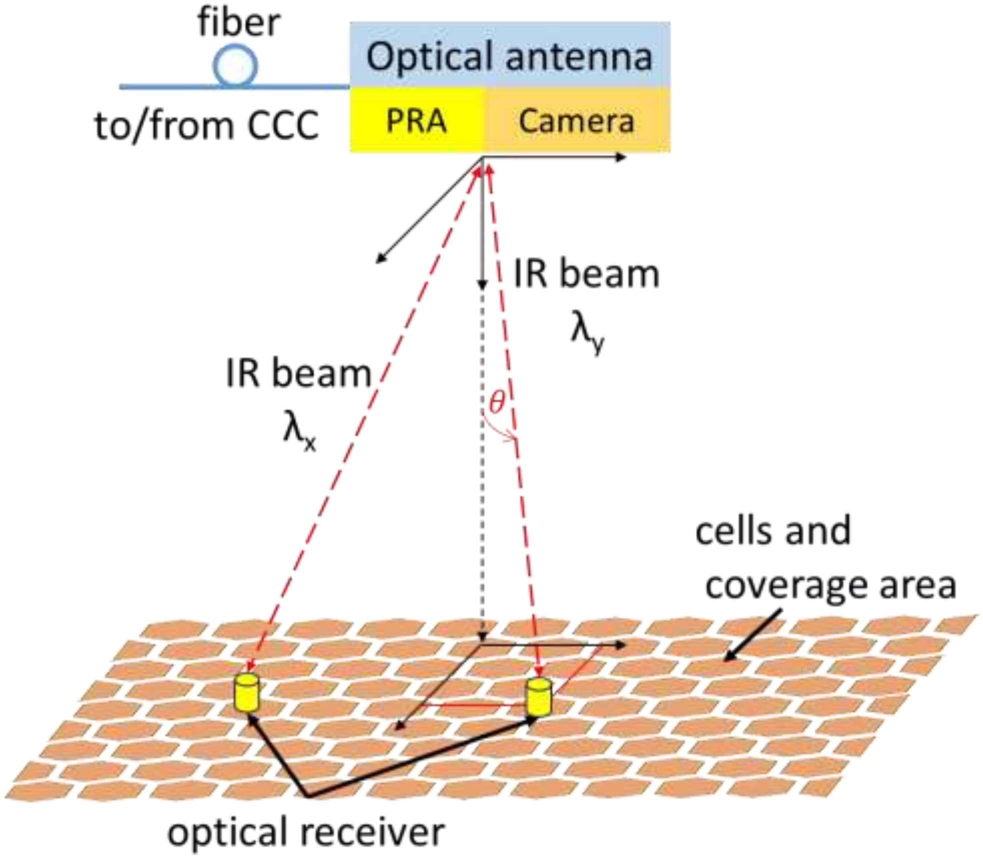
# Localization techniques

## Reported techniques:

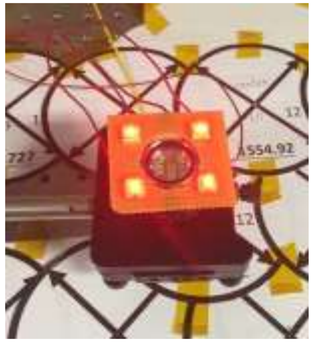
- **Triangular algorithms** for processing RF signals,
    - sent by multiple ceiling units, processed at user device, *or*
    - sent by user device, processed at multiple ceiling units
    - e.g. Received Signal Strength, Angle of Arrival, Time Difference of Arrival
- Similarly with **VLC techniques using multiple luminaires**
- By means of **camera observation**
    - using optical signals sent by user device
    - multiple user devices can be observed and tracked simultaneously
    - localization accuracy within few mm achieved

➔ **Need active functions at user device → extra power consumption, reduces battery life**

# Camera-based localization



- Active 4-LED tag on each user device
- Low-cost (IR) camera
- Image processing by Raspberry Pi
- Multiple user devices localized simultaneously within 25ms with <5mm accuracy at a reach>3m
- Camera-observed positions to be calibrated to $\lambda$-mapped positions



4 visible LEDs around receiver aperture at user device

- Ngoc Quan Pham et al., paper P45, ECOC 2019
- Ariel Gomez et al., JLT 2016

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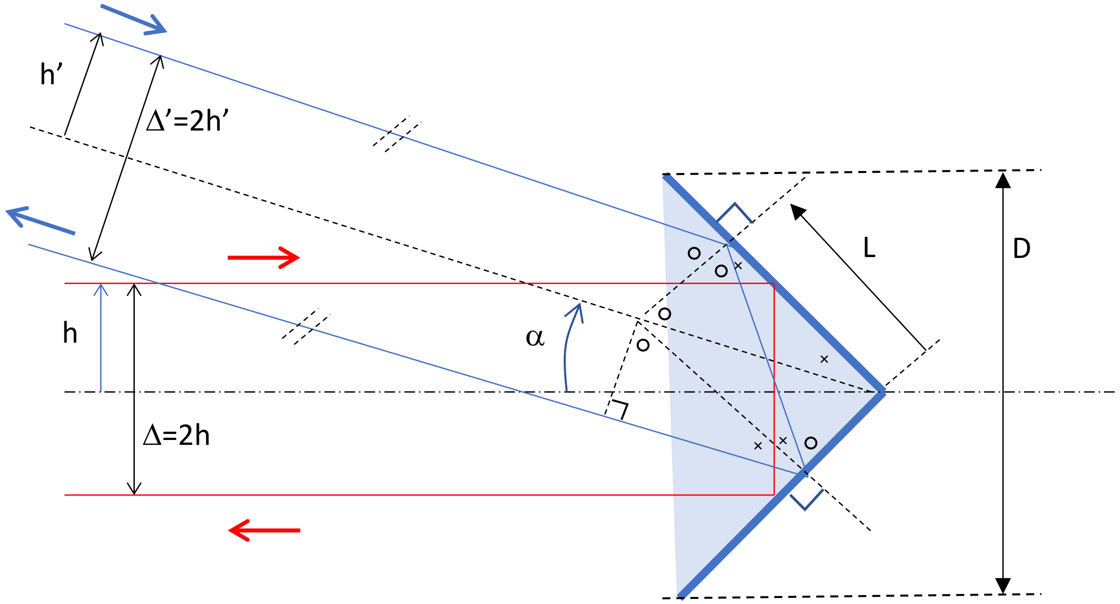
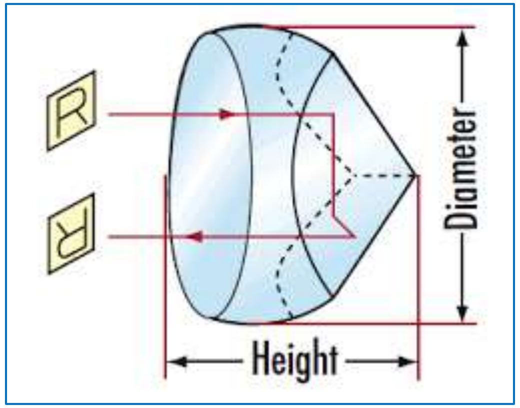
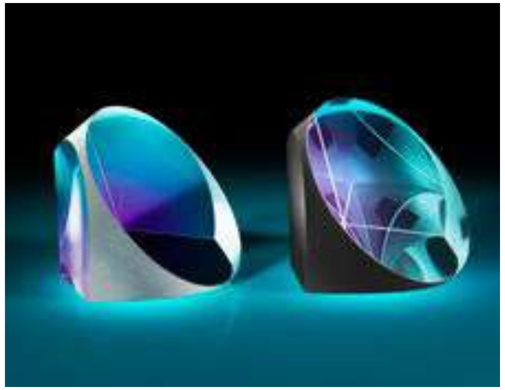
# Corner cube reflector

- CC reflects light ray in same direction it came from but with a lateral offset

$$\Delta = 2h = 2\cdot L\cdot \sin(\pi/4 - \alpha)$$
$$\leq D\cdot\sqrt{2}\cdot\sin(\pi/4 - \alpha)$$

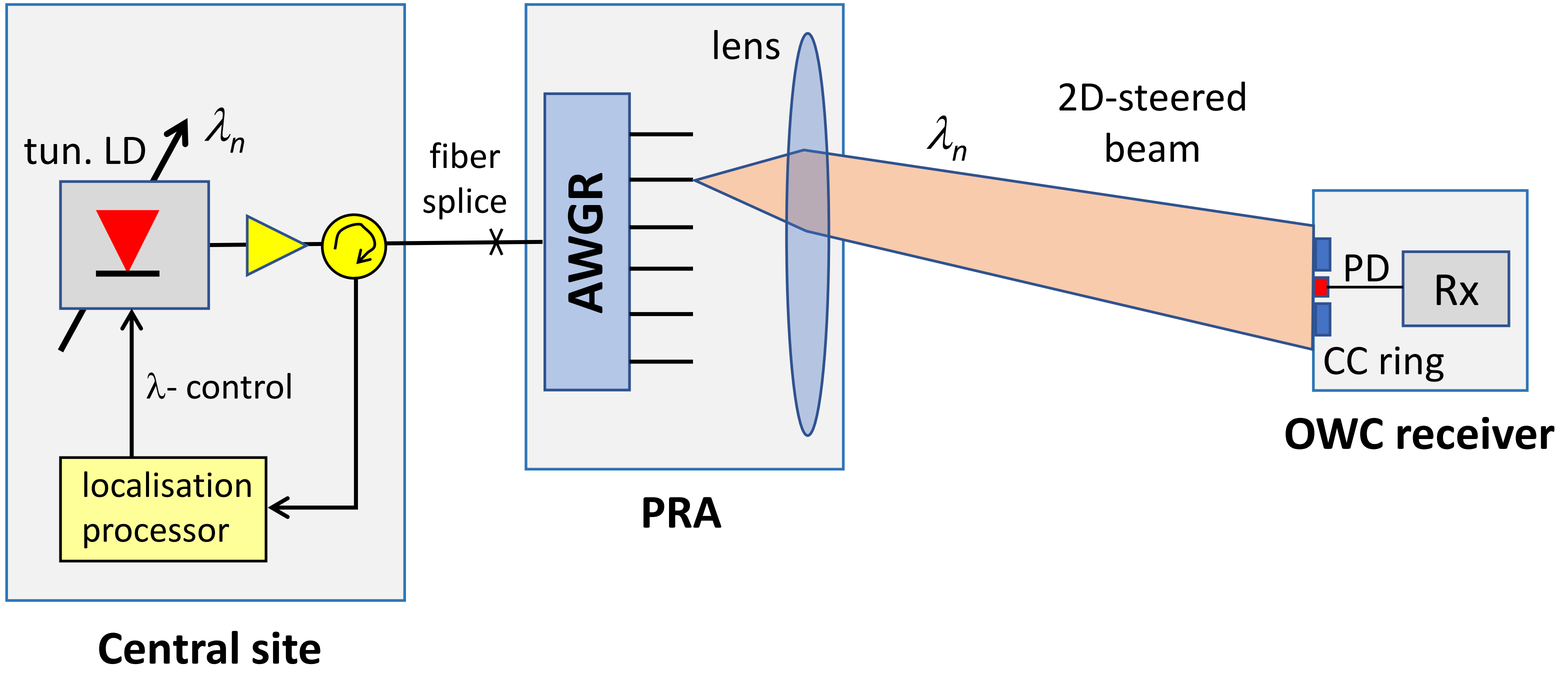






[Edmund Optics]

# User localisation: by passive retro-reflector at user device



CC = corner cube

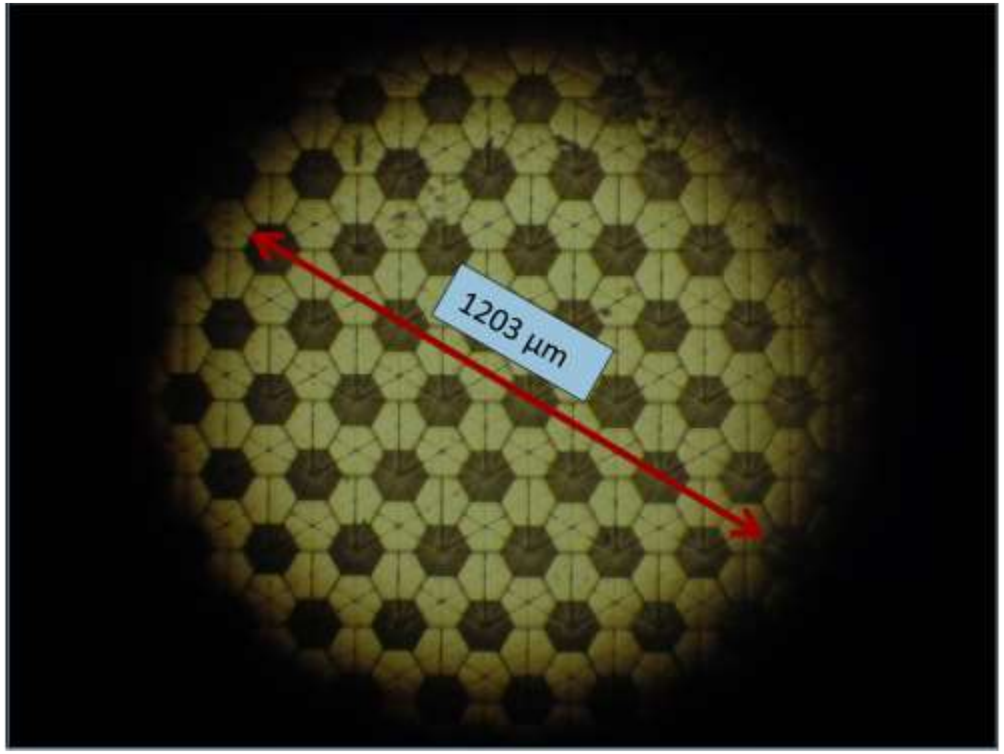
- corner cube retro-reflector ring around PD
- no active function at user
- monitoring at PRA/central site the power of the beam returned by the RR
- auto-calibrates position to wavelength (by λ-scanning)
  *Note*: does not determine the angular orientation of user device.
- Returning beam has lateral offset ∝ CC diameter → **ring containing array of miniature CC-s**

[Koonen et al., JLT May 2020]

# Array of miniature CC-s, each with aperture *D*=100μm

- miniature CC-s molded in retro-reflecting foil
- cheap, robust
- widely used commercially, e.g., for road signage, bikes, …

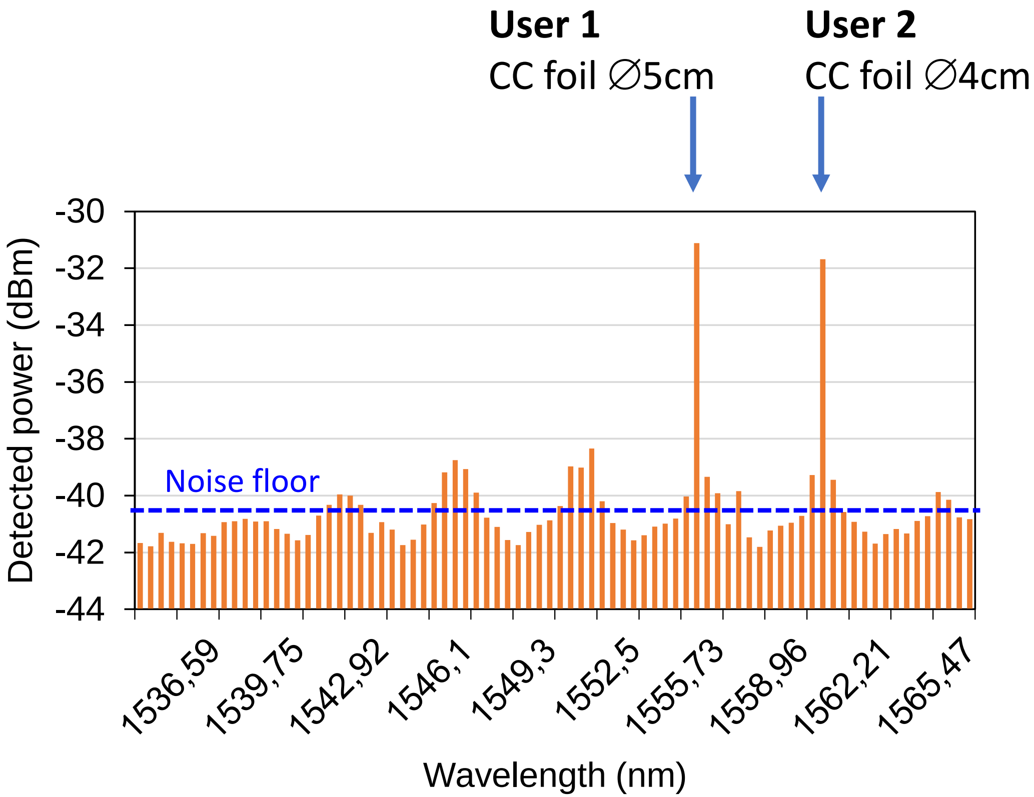
**Corner cube retro-reflector, diameter >10mm**
[Thorlabs]

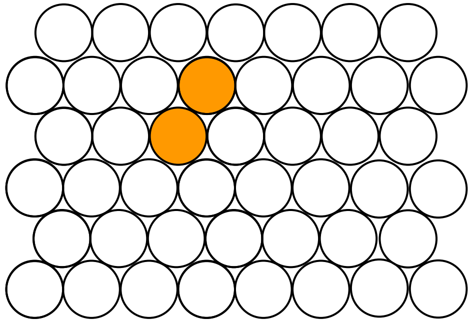


**Retro-reflector array on a bike**

**retroreflecting foil with CC-s, each ∅100μm**
(from Orafol)

# Scanning the user area

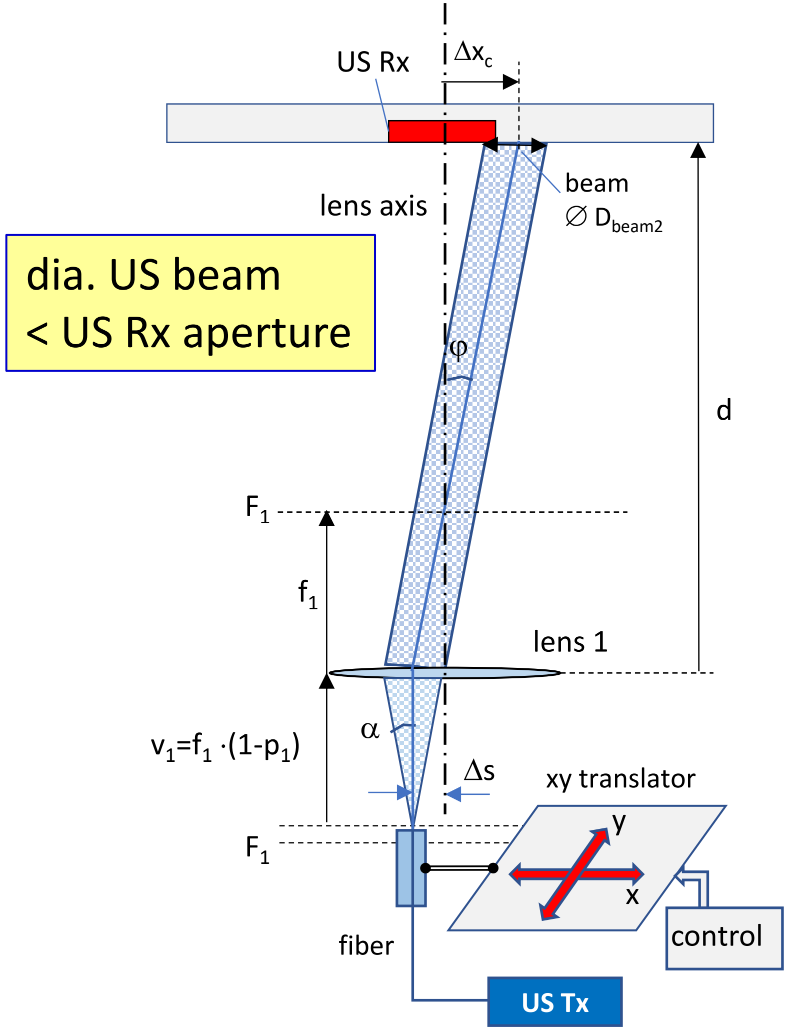




scanned cells
with 2 user devices

- Scanning by wavelength-tuning
- The peaks indicate positions of user devices, mapped to wavelength
- Scanning whole user area took 15 sec. (largely consumed by Labview’s control software and acquisition of the detected signal; 115ms/cell × 128 cells)

# Localization of ceiling receiver: by scanning with upstream beam

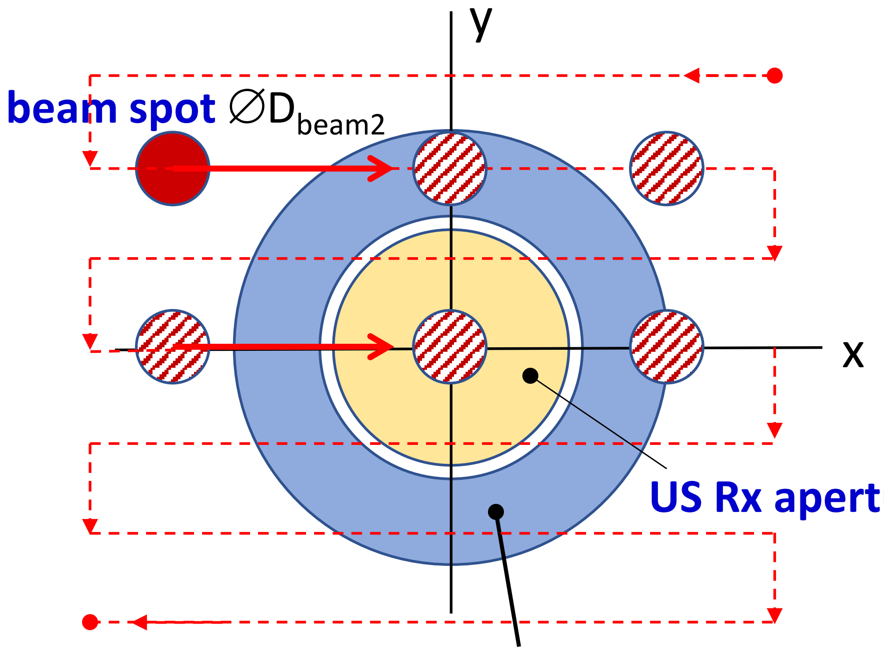


dia. US beam
< US Rx aperture

- 2D beam steering by xy-stepper motors at user
  → no holding current, consume energy only when active (‘set-and-forget’); steering angle $\varphi = \mathrm{atan}(\Delta s/f)$
- arbitrary $\lambda$ laser, with low output power (eye safety near user)
  → low cost; but implies dia. upstream beam < dia. aperture of upstream receiver

**→ upstream beam alignment by mechanical scanning and hole seeking algorithm**

# US beam alignment with ring of miniature retro-reflectors (RR ring)



**beam spot** $\varnothing D_{beam2}$

**US Rx aperture**

**annular RR ring** (inner $\varnothing$ $D_1$ , outer $\varnothing$ $D_2$ )

with monitored reflected power results { $p_i$ }

taken at positions $\overline{r_i} = \begin{pmatrix} x_i \\ y_i \end{pmatrix}$

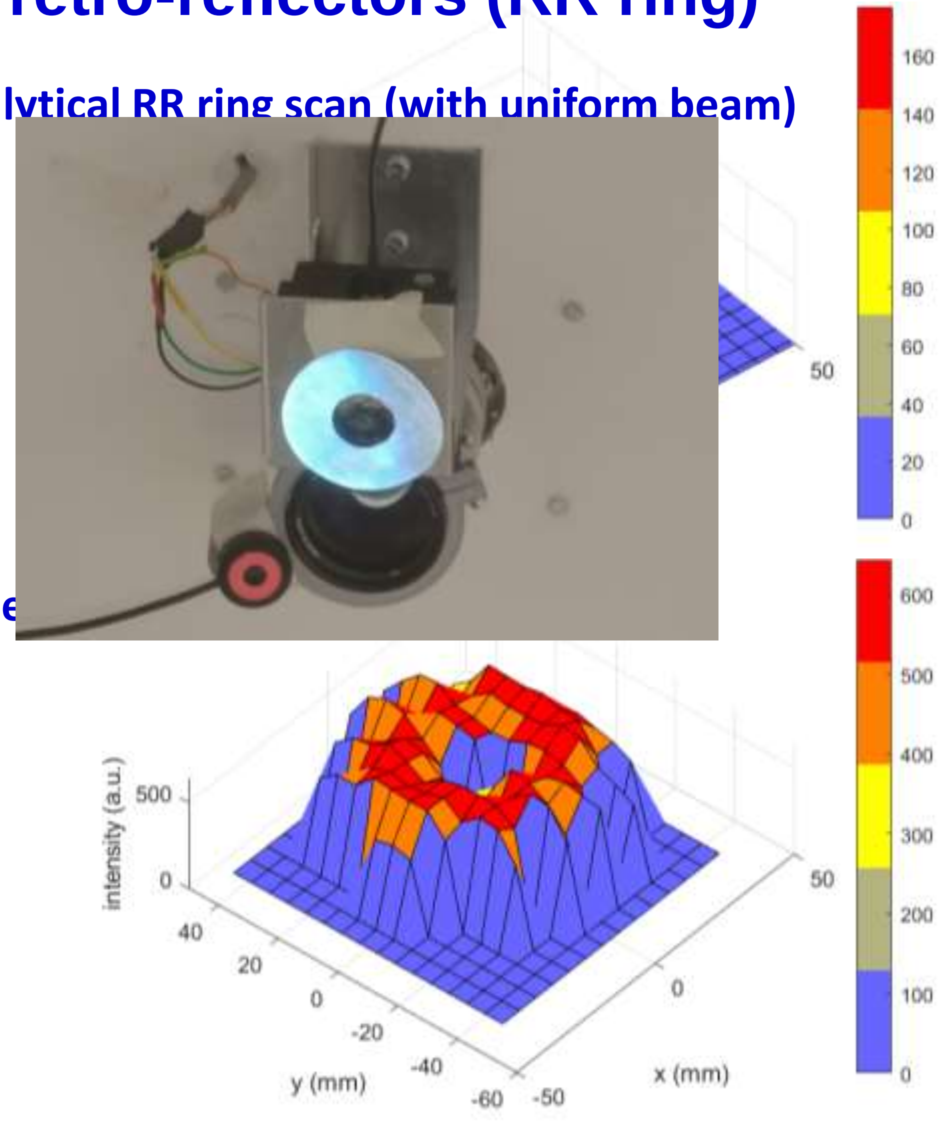
calculate **Center-of-Gravity of the RR ring** by

$$\overline{CoG} = \begin{pmatrix} x_{CoG} \\ y_{CoG} \end{pmatrix} = \frac{1}{P_{tot}} \sum_{i-1}^{N} p_i \begin{pmatrix} x_i \\ y_i \end{pmatrix} \text{with } P_{tot} = \sum_{i=1}^{N} p_i$$

**analytical RR ring scan (with uniform beam)**

**Ceiling Rx unit**
**with RR ring**
**∅ 62/25mm**

**expe**



RR ring: inner ∅25mm, outer ∅62mm
Beam spot ∅15mm, scan step size 6mm

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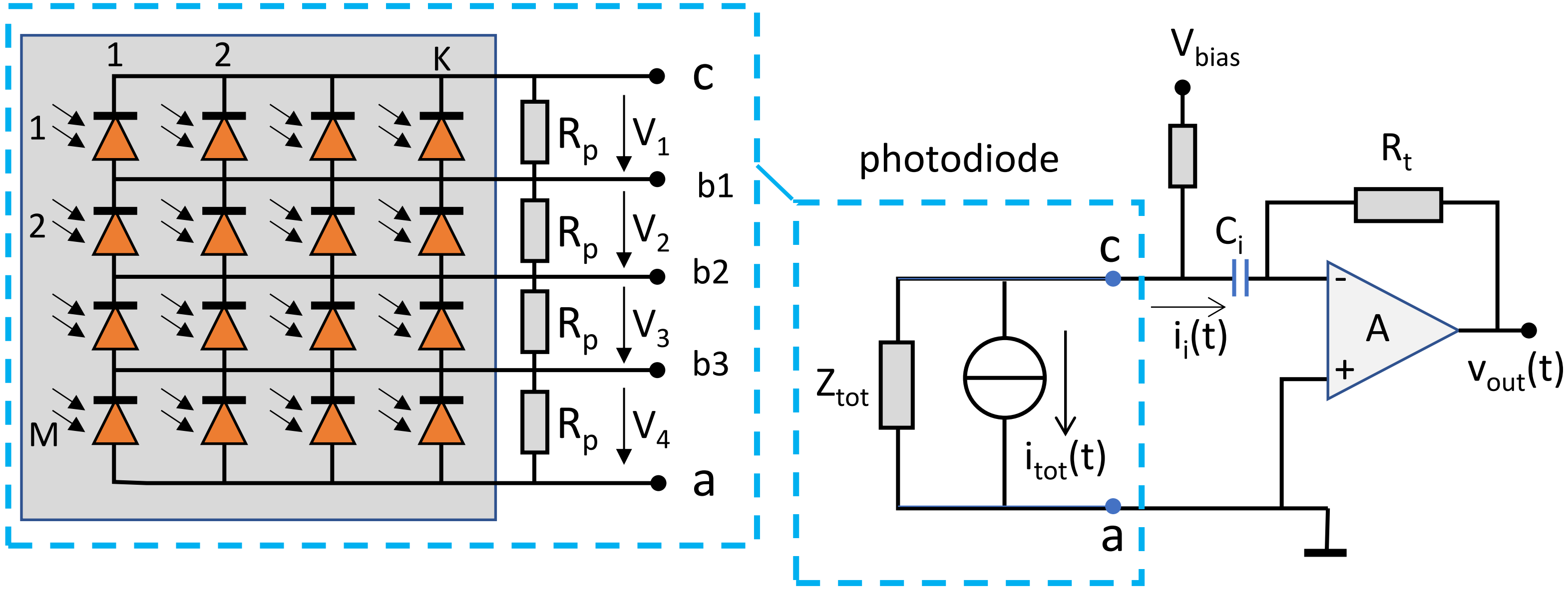
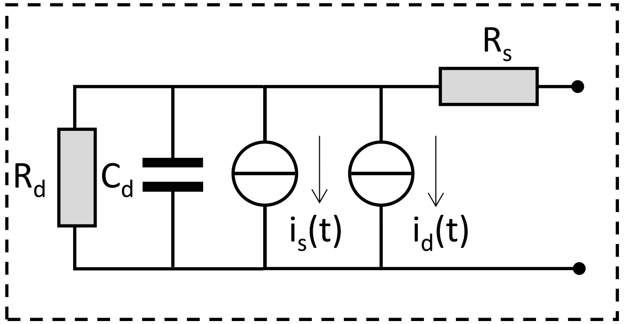
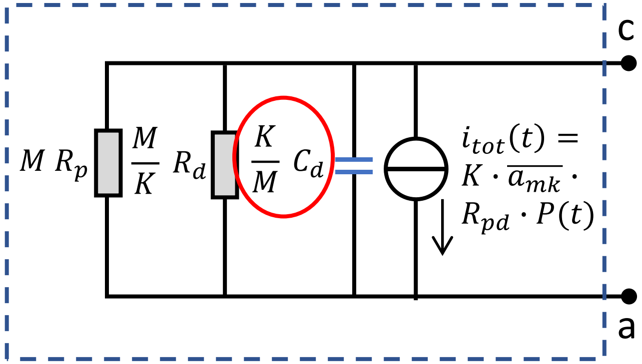
# Wide Field of View OWC receiver

- **2D matrix of photodiodes** (i.s.o. single large-area PD)
- <u>Single</u> pre-amplifier





**Equivalent circuit of single photodiode**



**Equivalent circuit of 2D matrix of photodiodes**

TIA characteristics:

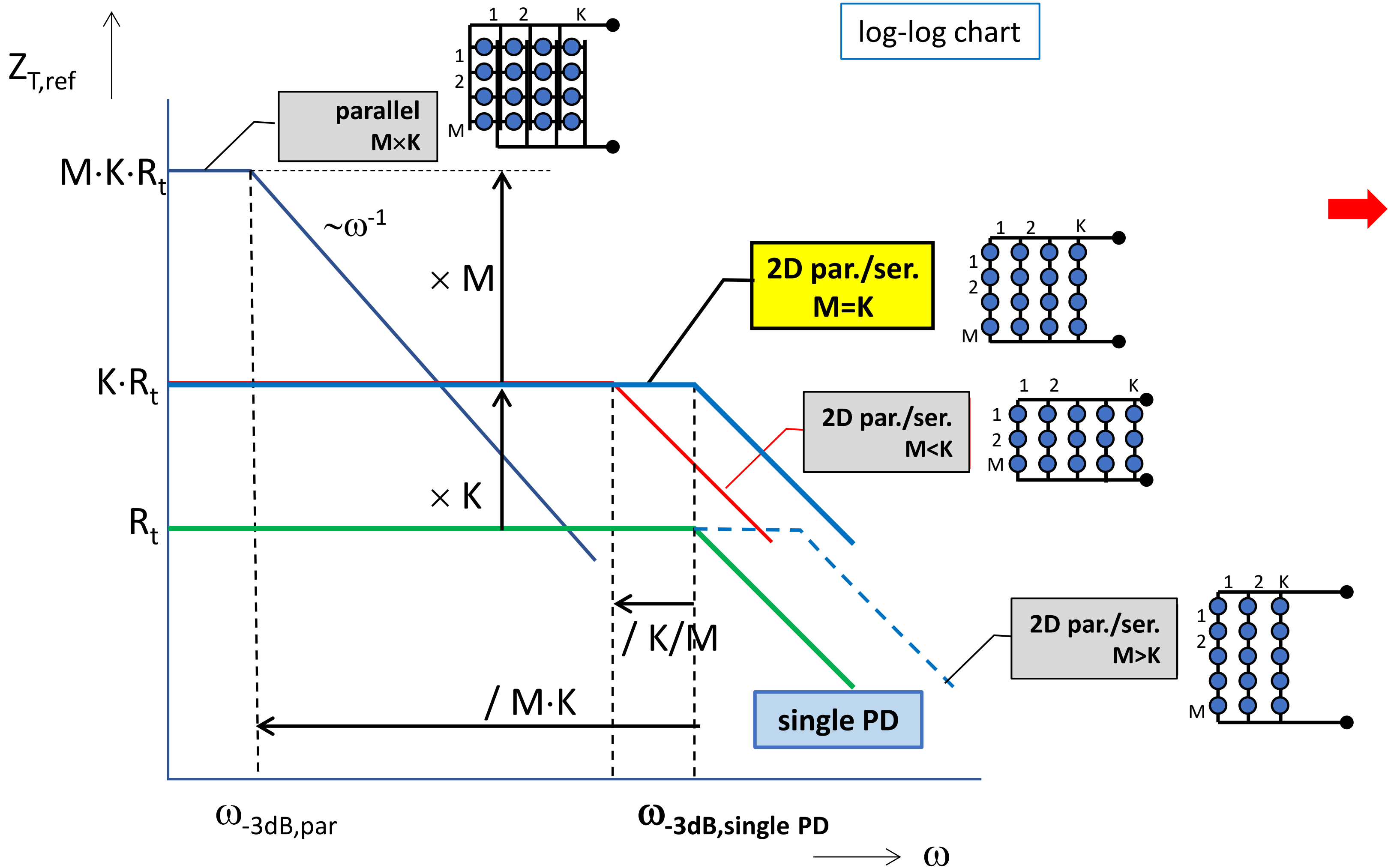
$$Z_T(\omega = 0) = \frac{v_{out}(t)}{i_{tot}(t)}\bigg|_{\omega=0} = \frac{A}{1+A}\,R_t$$

$\omega_{-3dB} = \frac{1+A}{C_d \cdot R_t}$ if $Z_{tot} \approx \frac{1}{j\omega\, C_d}$

→ PD capacitance limits BW ; **enlarge PD area without increasing capacitance with PD matrix**

[Pat. PCT/EP2020/080594 (filed 30 Oct. 2020)]
[Koonen et al., J. STQE, Nov./Dec. 2021]

# OWC TIA receiver using PD matrix : frequency characteristics



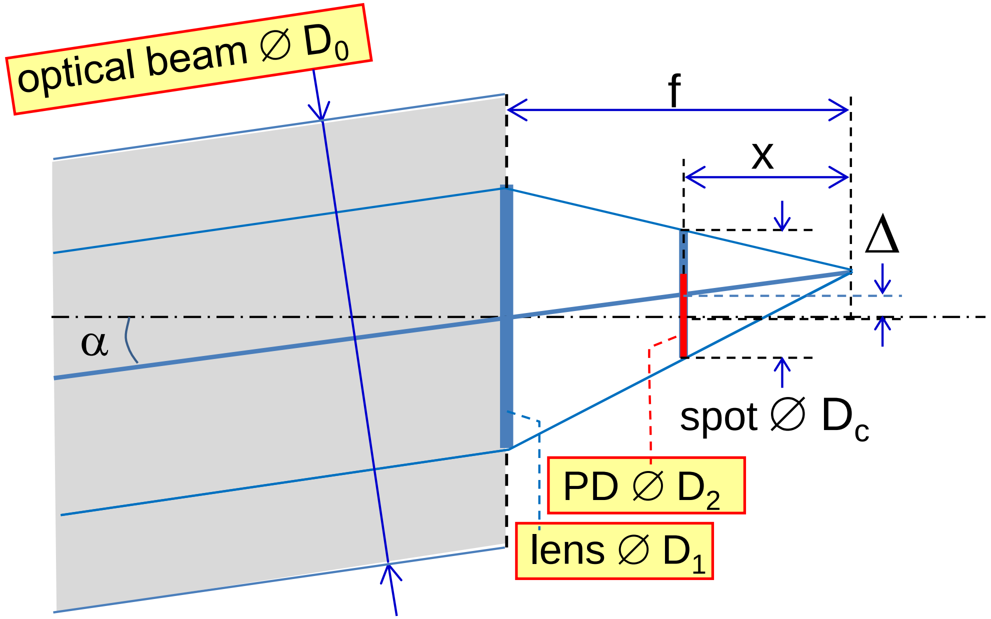
with a **square *M*×*M* matrix** of photodiodes in a TIA the **same** bandwidth is achieved as with a single photodiode, whereas **active area is *M*² times larger**, and **output signal is *M* times larger.**

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

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

# Capturing the beam by the photodiode matrix

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



**Defocusing factor p=x/f:** spot size ∅$D_c$ = p $D_1$ > PD dia. ∅$D_2$

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

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

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

**decreases if p increases**

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

- **FoV half angle $\alpha_{max}$ :**

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

**increases if p increases**

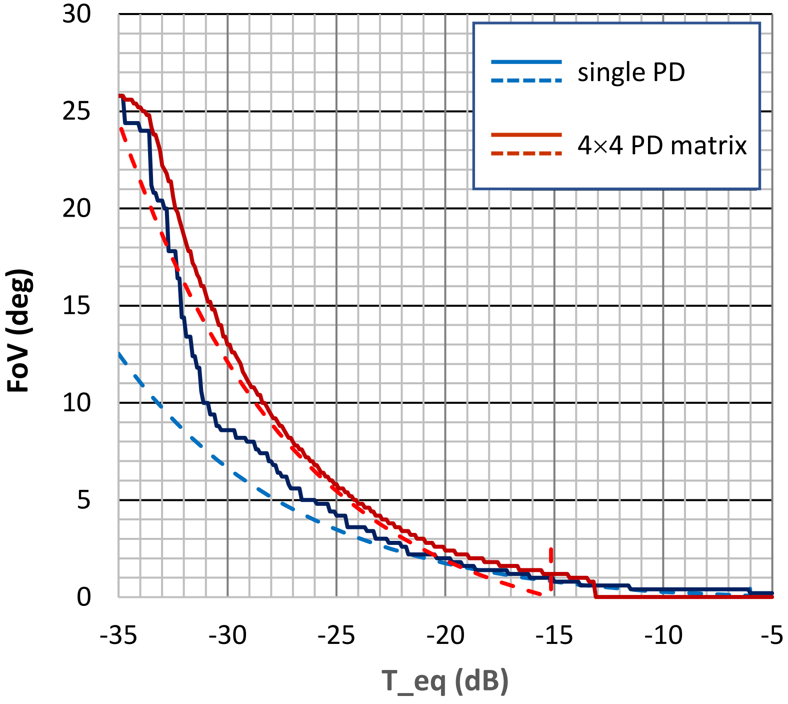
[Koonen et al., IEEE J. STQE, Nov./Dec. 2021]

# Capturing the beam by the photodiode matrix: FoV vs. beam-to-PD coupling

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

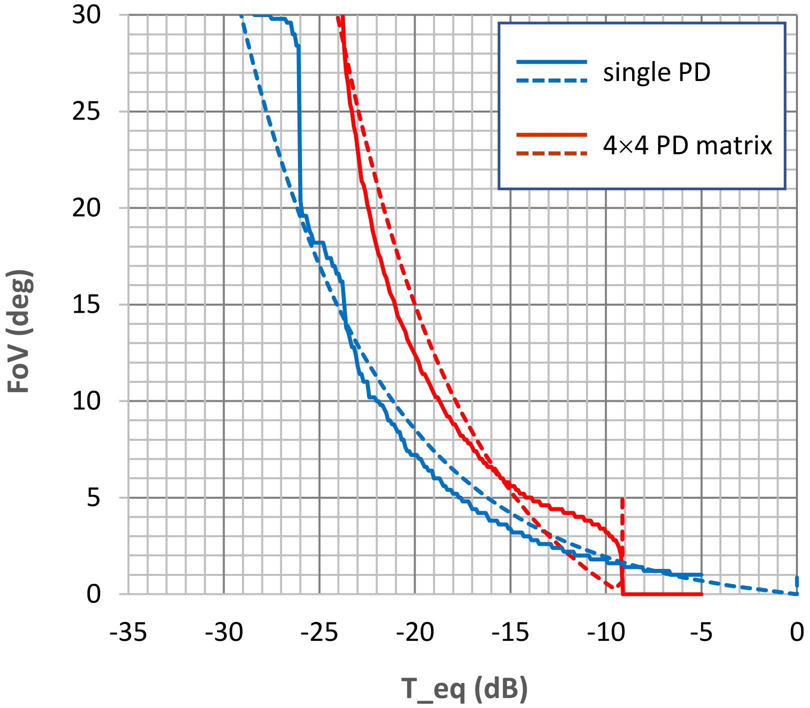
**Downstream**

beam ∅100mm, lens ∅50mm, f=10mm



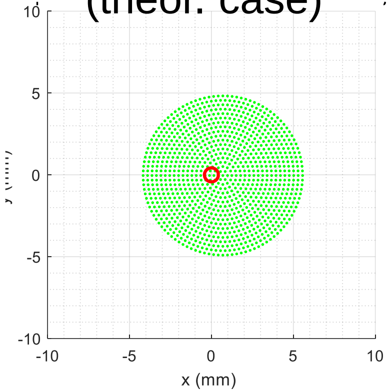
**Upstream**

beam ∅15mm, lens ∅25mm, f=5mm



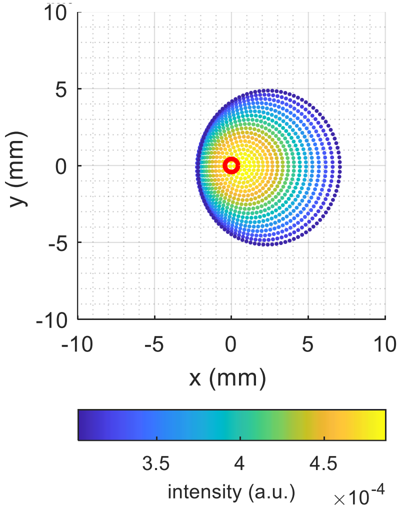
**Thin lens, uniform beam**

(theor. case)



**Fresnel lens, Gaussian beam**

(realistic case)



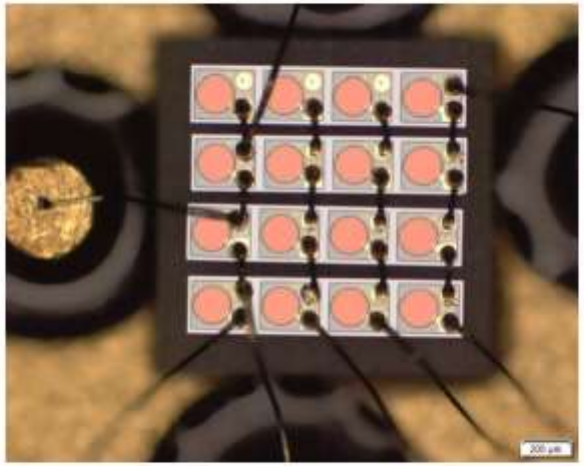
**Gaussian beam $D_0$=∅100mm projected onto photodiode matrix (red) for $\alpha$=5 deg and $p$=20%**
(lenses $D_1$= ∅50mm, $f$=10mm; 1027 rays traced)

- 4×4 matrix ∅0.86mm of ∅150μm PDs, spaced ; single PD ∅150μm
- curves calculated by varying defocusing *p*
- **solid curves**: Gaussian beam, Fresnel lens (25117 rays traced; accu
- **dashed curves:** uniform beam, ideal thin lens (theoretical)

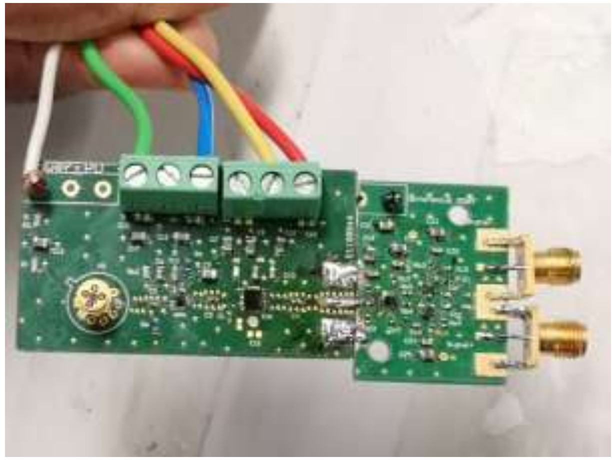
**→ FoV with 4×4 PD matrix clearly larger than with single photodiode**

# OWC broadband receiver module

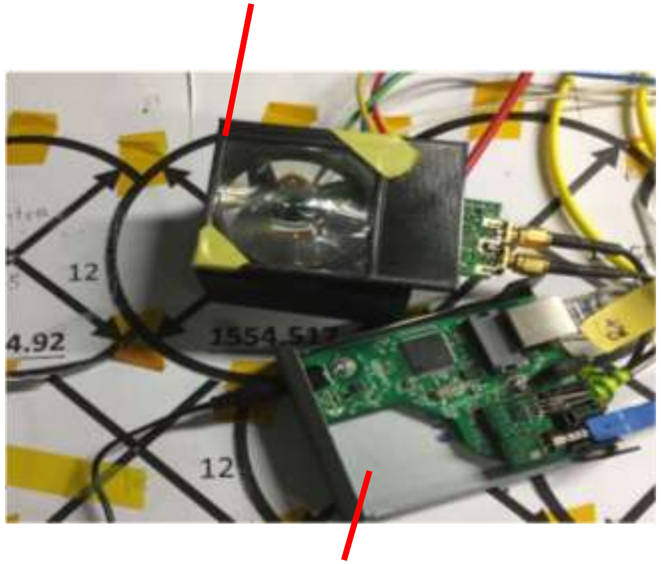
**4×4 PD matrix**
(made by Albis Optoelectronics)



**OWC receiver with differential outputs**

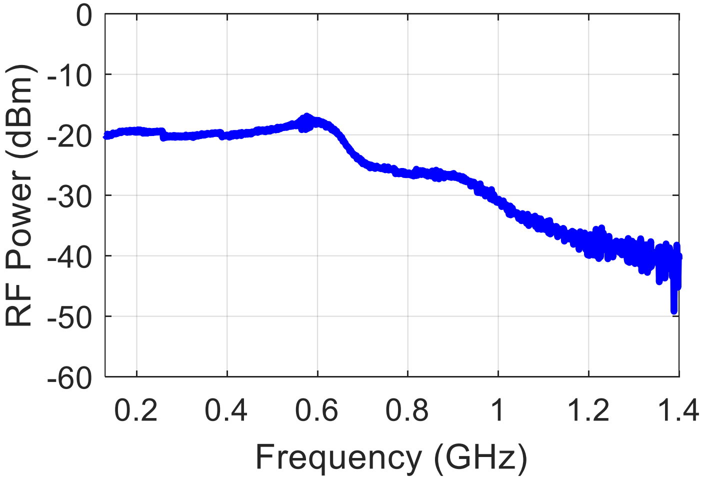


**OWC receiver with ∅2" Fresnel lens**



adapted media converter with
RJ45 output (→ 'OWC dongle')

**Frequency char.**



**$BW_{-3dB}$ = 670MHz**
(incl. commercial TIA, $Z_T$=10k$\Omega$,
$BW_{-3dB}$=750MHz )

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

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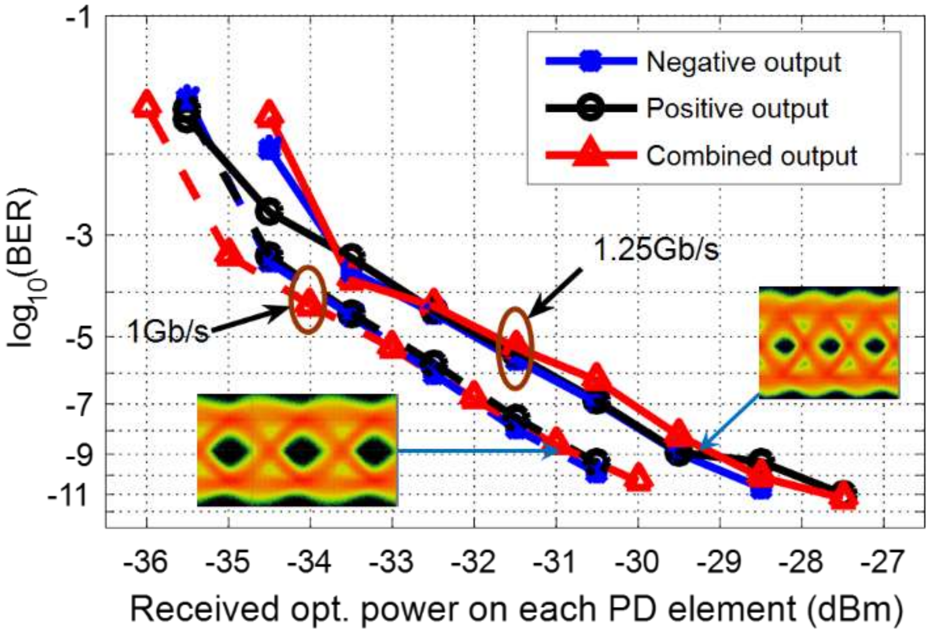
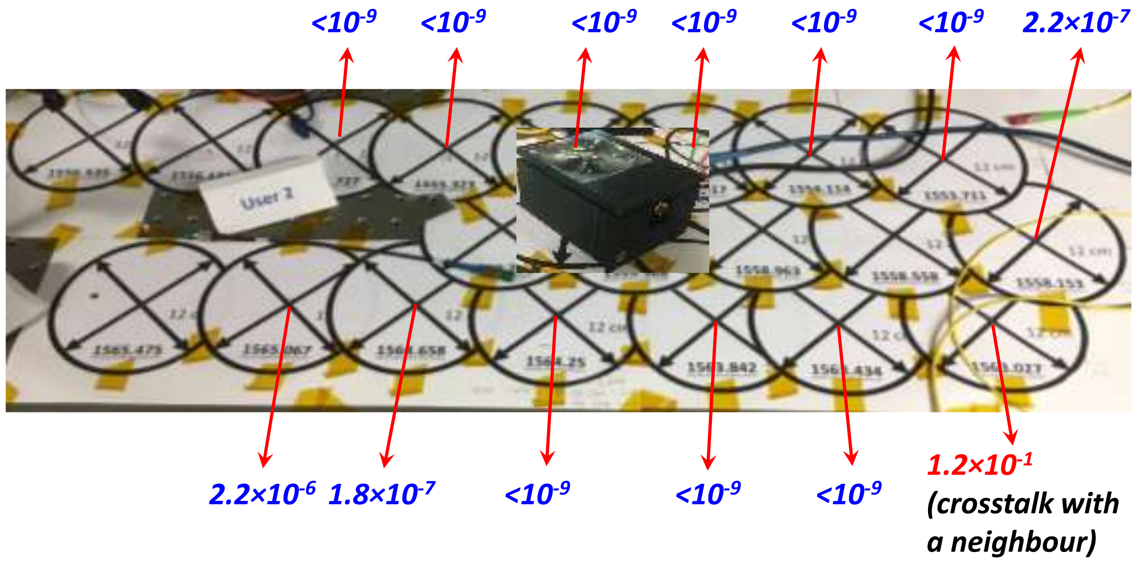
# OWC broadband receiver performance

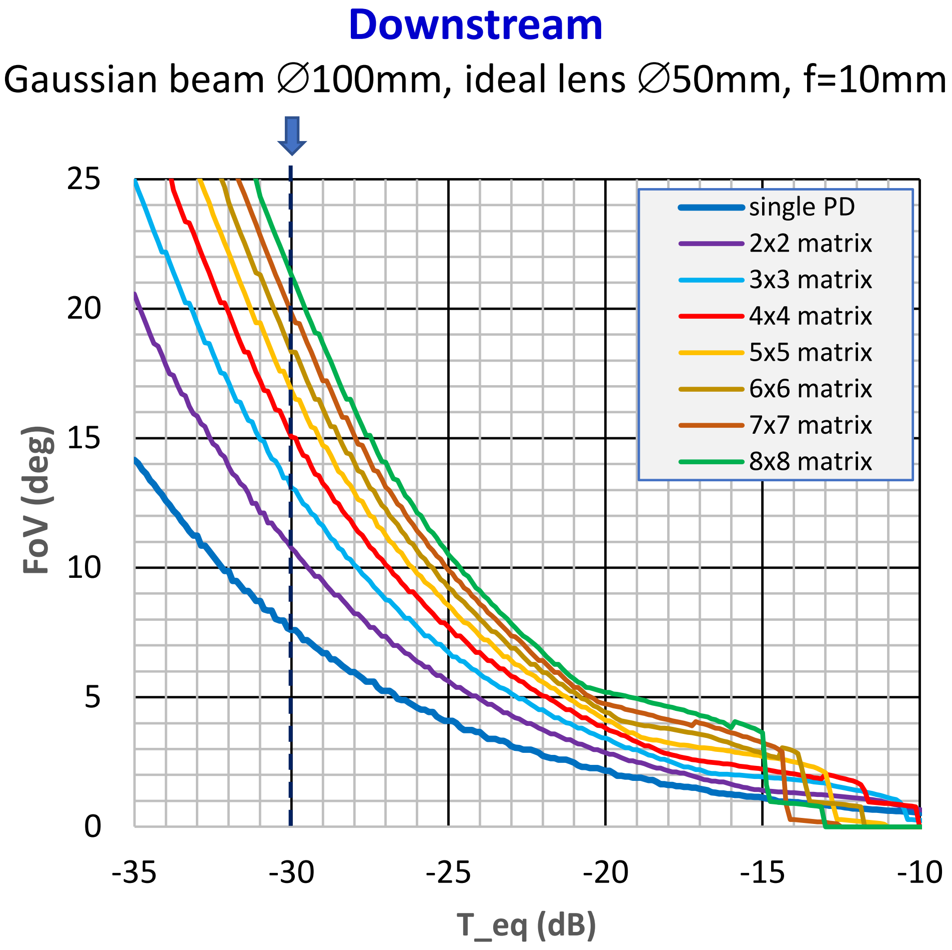


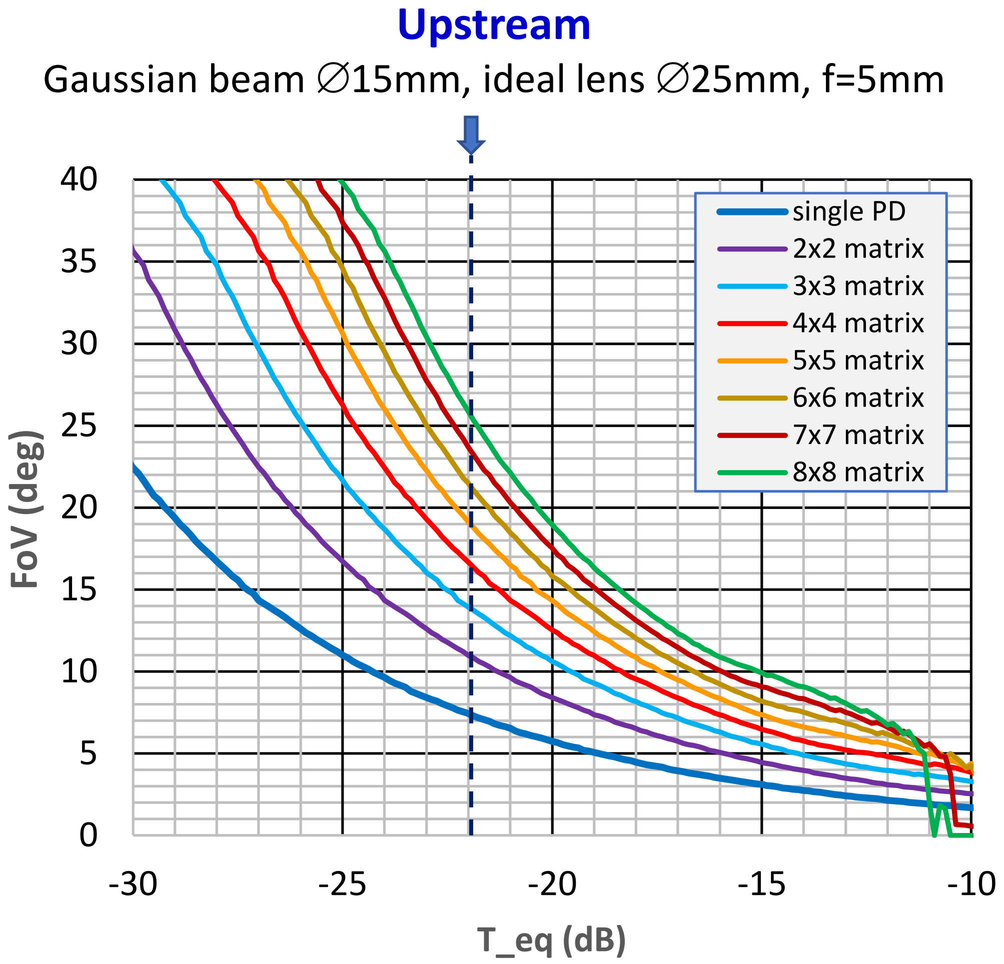


**BER for both single-ended and differential receiver outputs**

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

# Upscaling the PD matrix – impact on the FoV *





$P_{beam}$=10dBm, $P_{rec}$=-20dBm → req. $T_{eq}$> -30dB

$P_{beam}$=2dBm, $P_{rec}$=-20dBm → req. $T_{eq}$> -22dB

* FoV vs. beam-to-PD matrix coupling T_eq

→ Upscaling PD matrix improves FoV performance

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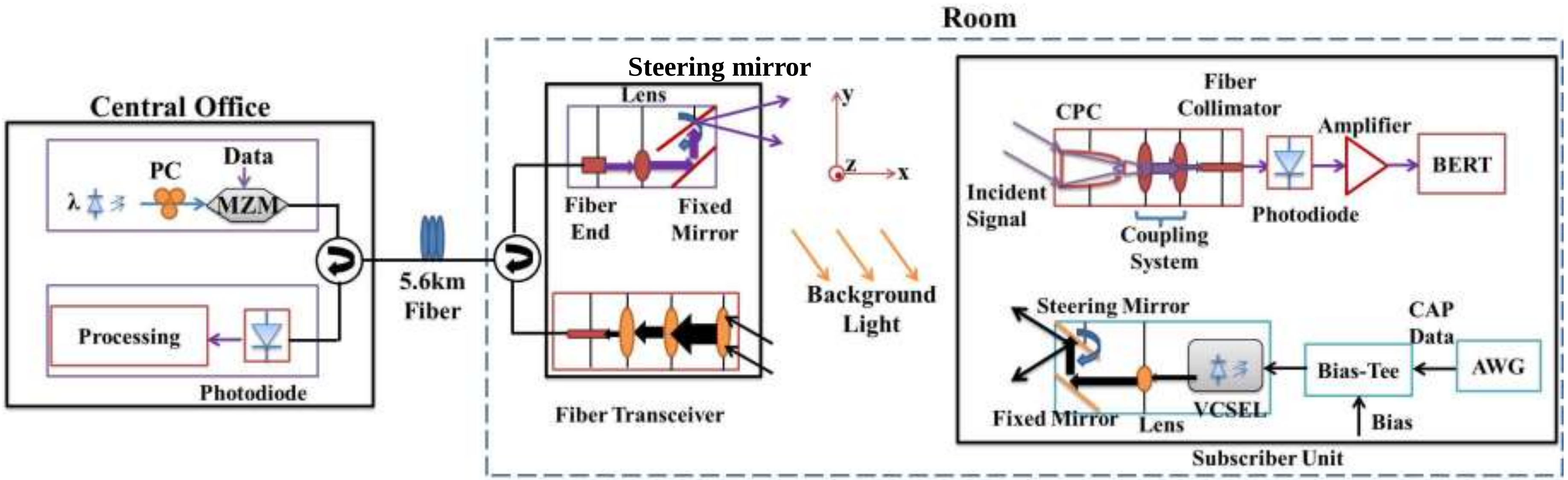
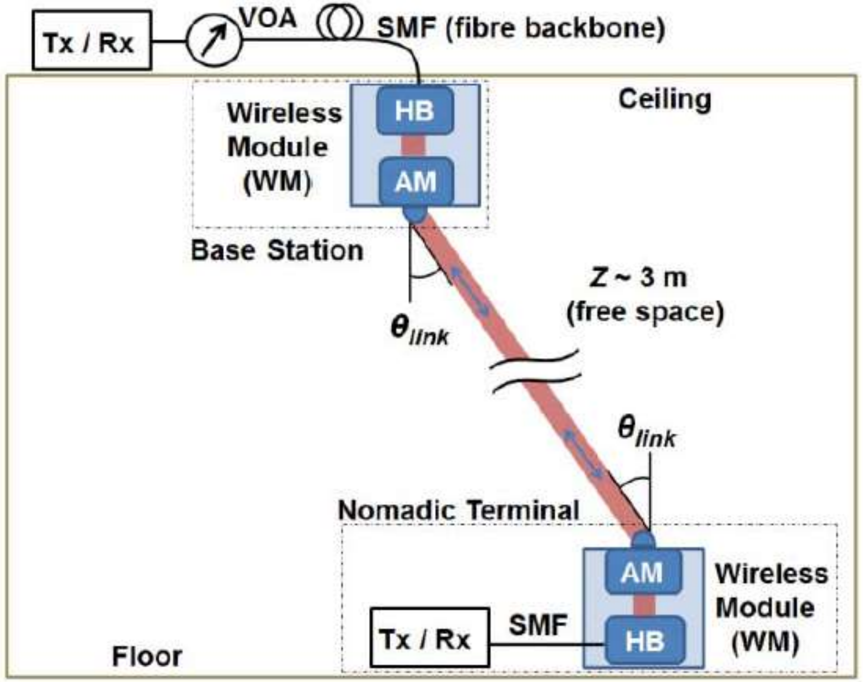
# Ex. 1: Bi-directional OWC: 2D beam steering with MEMS mirrors

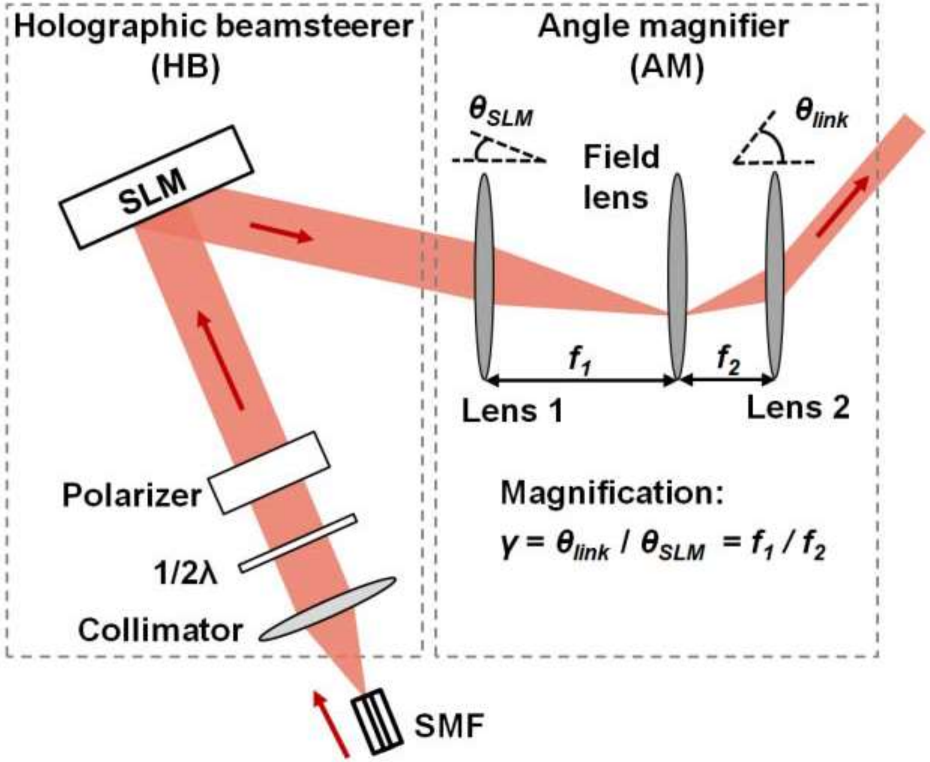


- **MEMS mirror** steering range >20°
- Free-space link 2m, max. coverage area 113cm
- Full duplex
  - downlink 10Gbit/s, λ=1551nm, 7mW
  - uplink 2Gbit/s, VCSEL λ=850nm, 5mW
- CAP-16 modulation (better spectrum efficiency than OOK, simpler than OFDM and QAM)
- Receiver with compound parabolic concentrator to increase FoV

[Ke Wang et al., OFC2015 (PTL, Apr. 2016)]

# Ex. 2: Bi-directional OWC: 2D beam steering with SLM

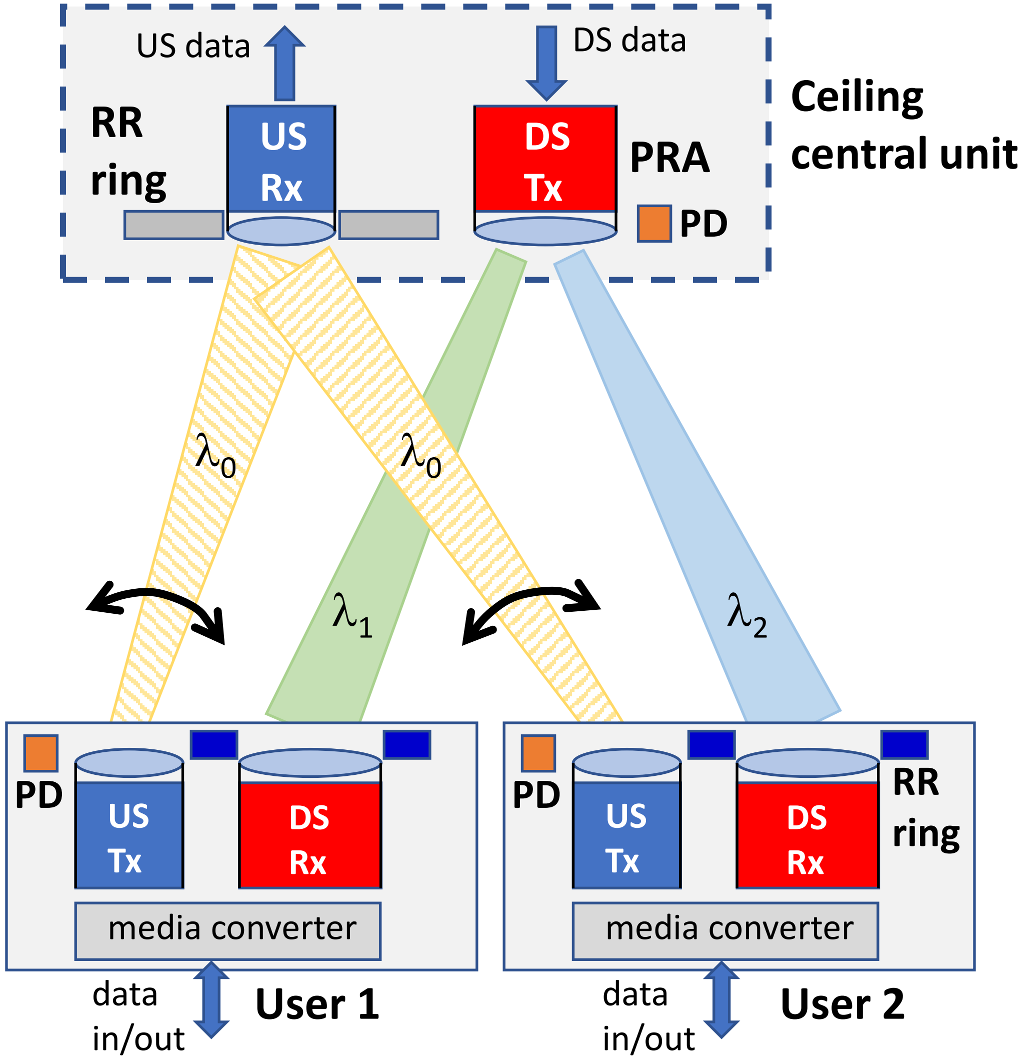




- **Spatial Light Modulator**, 512×512 pixels, 256 phase levels
- Pixel size $p$=15$\mu$m → max. steering angle $\theta_{\max}=\lambda/2p\approx 3^\circ$
- Angle magnifier module, magnification $\gamma=f_1/f_2$
- WDM exper. 3λ × 37.4Gbit/s = 112Gbit/s at 30°, full FoV 60° over 3m
  6λ × 37.4Gbit/s = 224Gbit/s at 18°, full FoV 36° over 3m

[A. Gomez et al., PTL Feb. 2015 (Oxford Univ.)]

# Bidirectional beam-steered OWC system acc. to BROWSE concept



## Downstream

- λ-controlled beam steering
- each user gets his individual beam (single user access, P2P)
- beam alignment by **ring of miniature retro-reflectors** (RR ring) at user

## Upstream

- mechanically controlled beam steering
- arbitrary λ for every user (→ multiple user access, MP2P, e.g. with TDMA MAC, cf. GPON)
- beam alignment: using RR ring at US Rx, *no pre-existing return path needed for monitoring*

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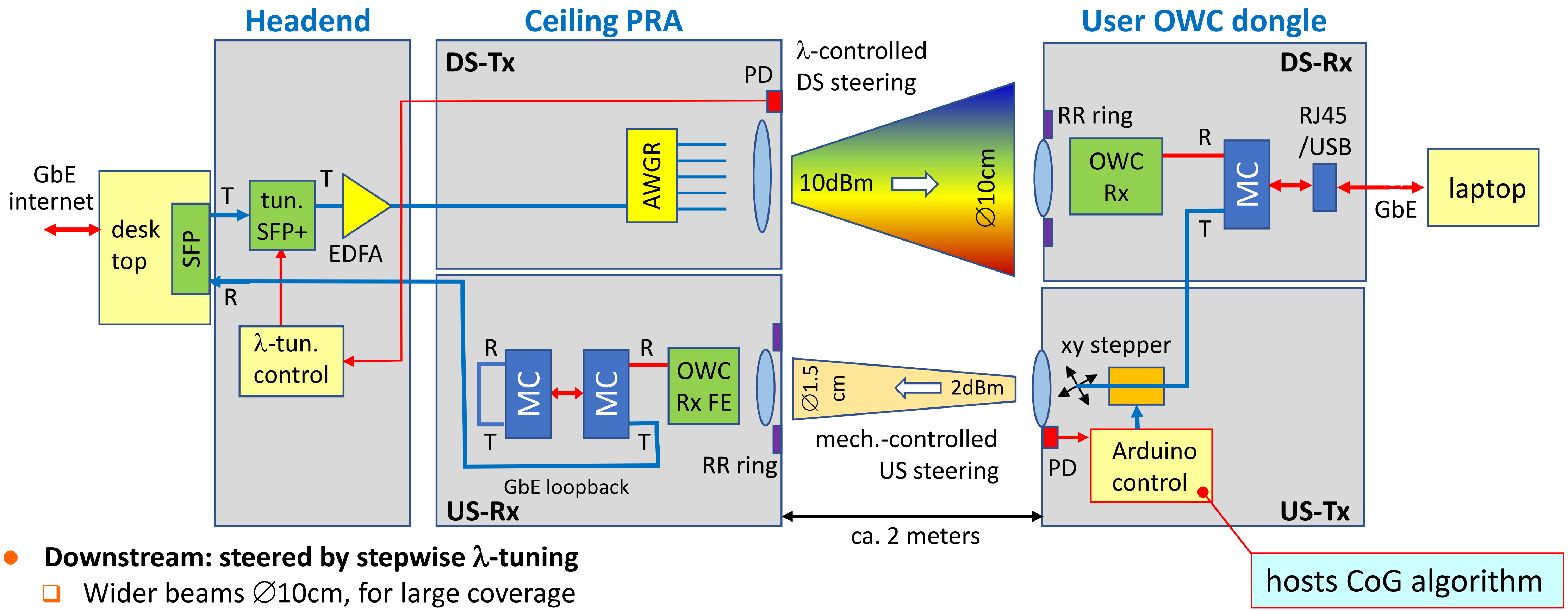
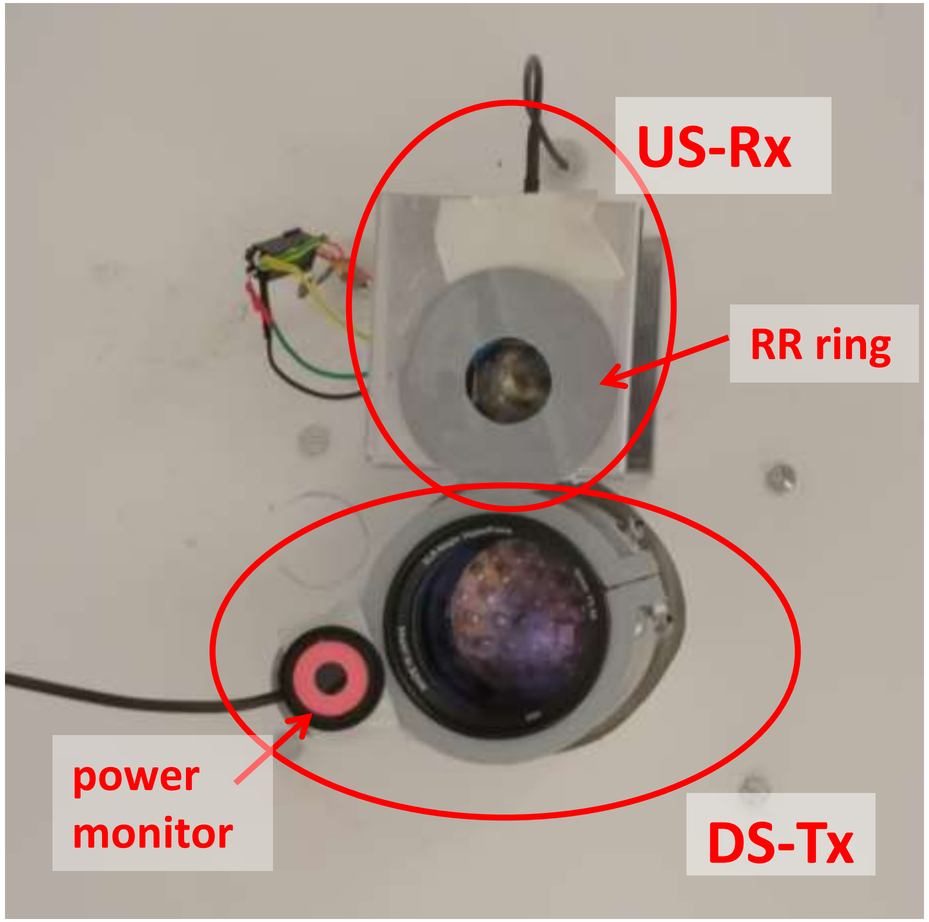
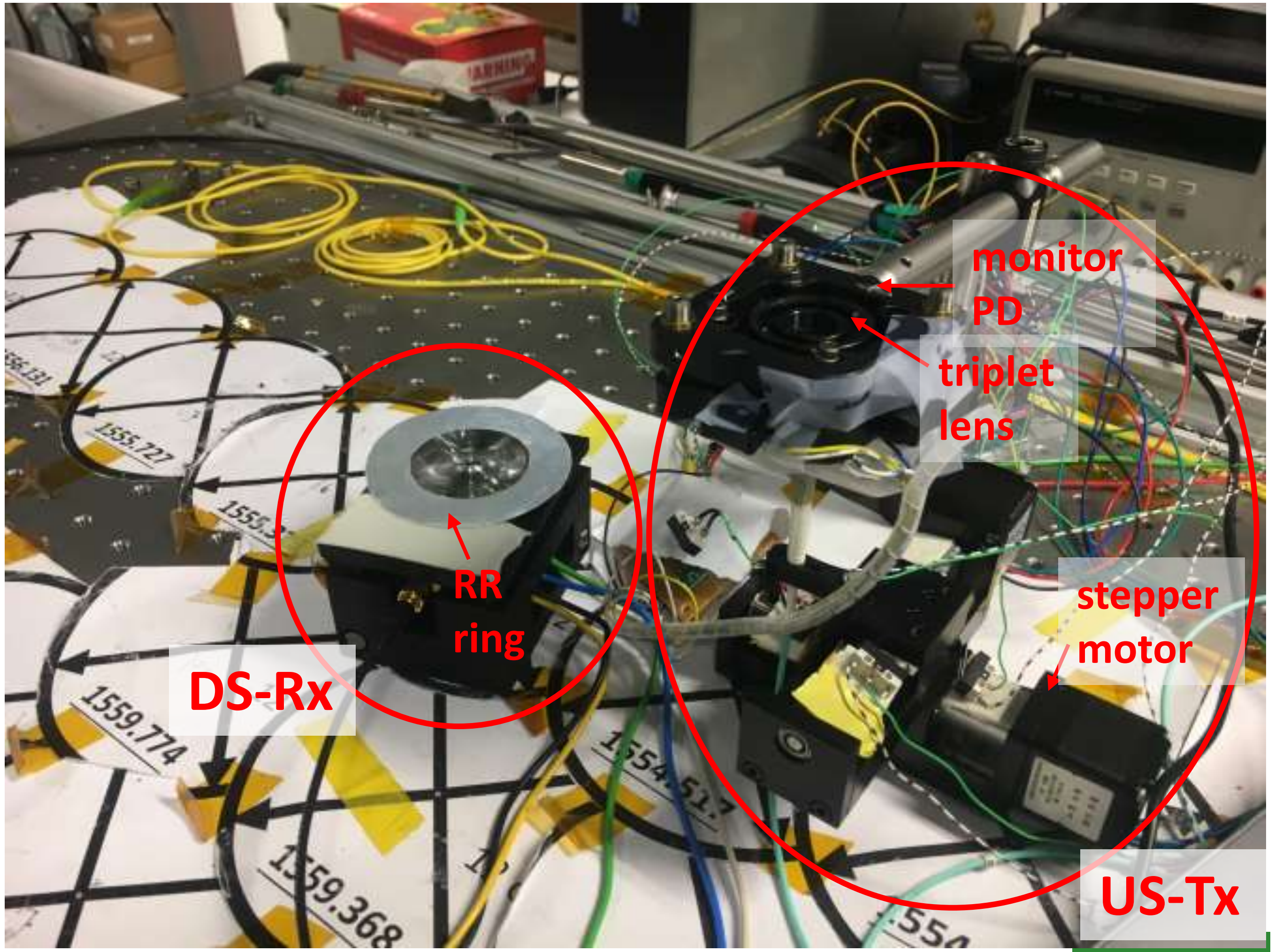
# Bidirectional beam-steered OWC system with US and DS beam alignment



- **Downstream: steered by stepwise λ-tuning**
  - Wider beams ∅10cm, for large coverage
  - Multiple λ-s, P2P link per λ → no MAC needed
  - Beam alignment: self-calibrating, by RR ring at user Rx, λ-tuned scanning and reflected-power monitor at PRA [ECOC2019]
  - Receiver: with FoV≈±10 deg., using 4×4 PD array + ∅50mm f=10mm Fresnel lens [ECOC2020, ECOC2021]
- **Upstream: steered by mechanical tuning**
  - Narrower beams ∅1.5cm → lower upstream power needed (1mW available from MC)
  - λ unspecified, 1 Rx at PRA → MP2P → upstream MAC needed (cf. TDMA-PON )
  - Beam alignment: by RR ring at PRA Rx, stepper scanning, with the hole-seeking CoG algorithm

# Lab demonstration: PRA site and user site

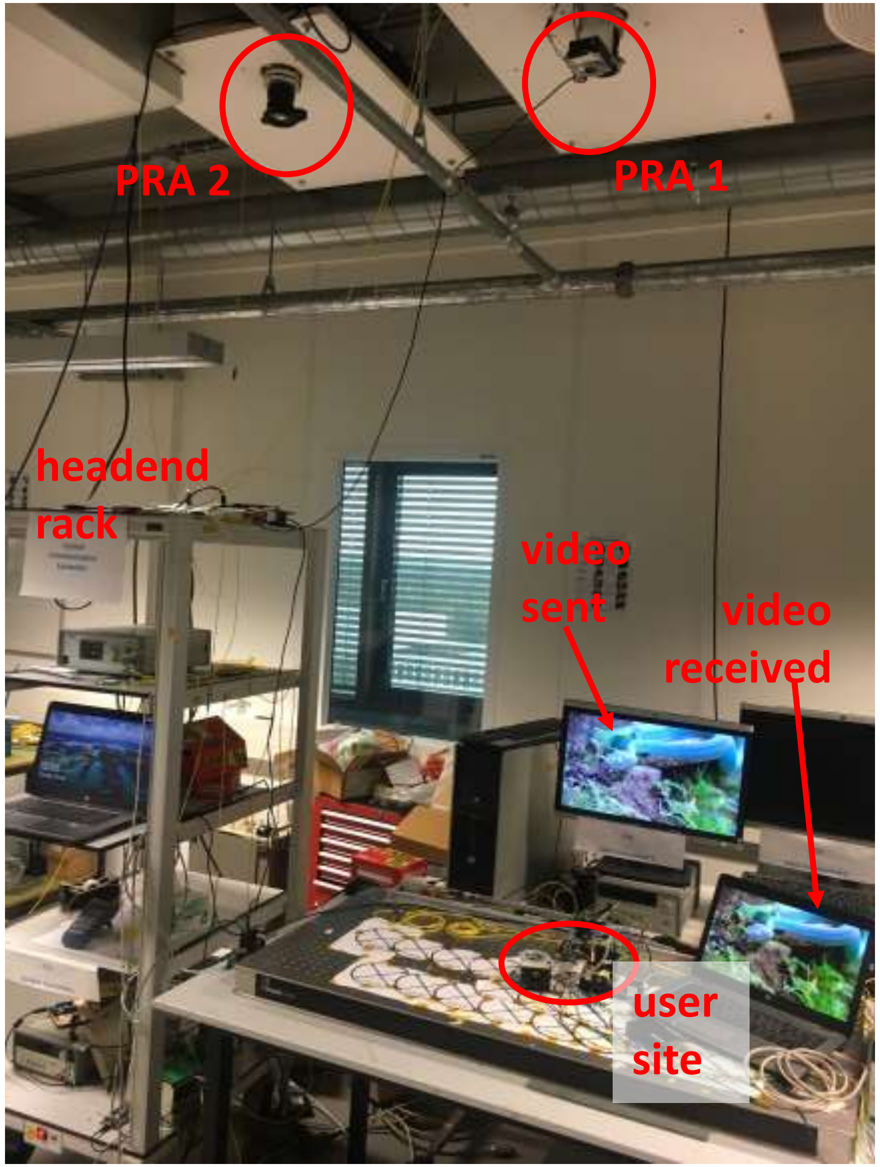




**DS-Tx:** camera lens, f=50mm, F/0.9;
power monitor ∅10mm
**US-Rx**: FoV≈± 12deg.; Fresnel lens ∅25mm , f=5mm;
RR ring inner ∅25mm, outer ∅62mm

**DS-Rx:** FoV≈±10deg.; Fresnel lens ∅50mm, f=10mm; RR ring inner ∅30mm, outer ∅40mm
**US-Tx**: 2 NEMA11 stepper motors, triplet lens f=20mm;
3 monitor PDs ∅1mm

# Lab demonstration: GbE video streaming to/from laptop



- Performance measurements with Iperf
  - TCP tests: ~940Mbit/s downstream, ~939 Mbit/s upstream, with no packet loss
  - UDP: ~958Mbit/s upstream with 0.18% packet loss
- FoV ≈ ± 10 deg.
- Beam alignment time
  - downstream: within 15 sec., limited by Labview control program for λ-tuning
  - upstream: within 10 sec., limited by stepper motor speed


CCC
-
video transmitted 1
CCC
-
video transmitted 2
User mobile device
-
video received 1
User mobile device
-
video received 2

# End users envisaged

- **airline companies** in airplane cabins for in-flight entertainment/internet;
- similarly, **public transport operators**: in train carriages, metro lines, and bus operators in their cabins;
- **hospitals**, for EMI-free patient monitoring and diagnostics;
- **industry 4.0 halls** with autonomously acting robots requiring low-latency control in manufacturing and logistic transport lines;
- **exhibition halls** with exhibition settings which typically change overnight, to connect booths flexibly and individually;
- **virtual gaming rooms** with wearable wireless VR glasses for mobile games, or for training (e.g., of rescue teams).
- **conference rooms, lecture halls**; e.g., at universities such as TU/e
- **intra-DC networks**, e.g., for top-of-the-rack low-latency dense interconnects
- and others…

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# Concluding remarks

- **Optical Wireless Communication by means of narrow infrared beams** offers many advantages: **‘virtual fiber connectivity’** → high capacity per individual user, high privacy, immunity to EMI, high energy efficiency
- **Key functions**: beam steering by passive diffractive module, self-calibrated localization using array of miniature retroreflectors, wide FoV receiver using PD matrix
- A **bi-directional all-optical OWC system** with automatic self-calibrating alignment of both downstream and upstream beams is proposed.
- **GbE video streaming** to/from a laptop computer with TCP transfer speeds ~940Mbit/s and FoV≈±10deg. has been demonstrated.
- **Future outlook**
  - ❑ Explore the indoor OWC key functions m.m. also for *medium/long reach*
  - ❑ *Photonic integration* of beam steerer and PD matrix receiver, upscaling number of beams and PDs to increase FoV, coverage area; adaptive beam shaping by tunable lenses;
  - ❑ *OWC networking*, beam relaying to circumvent line-of-sight blocking

⇒ ***The bi-directional automatically-aligned beam-steered OWC system is very promising for providing high capacity per user, at high user density.***

Upcoming book: Ton Koonen, “Short-Reach Optical Wireless Communication: by Directed Narrow Beams,” John Wiley & Sons

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# Thank you for your attention!