Optical Wireless Communication with SPAD Receivers

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Outline

- Applications for OWC / VLC
- Spectra of light sources
- OWC with linear-mode APD receivers
- Thin and thick SPADs
- Quantum limit
- Parasitics of SPADs
- SPAD receiver
- OWC with SPAD receiver
- BER model
- Modeling of BER in OWC
- Comparison
- Conclusions

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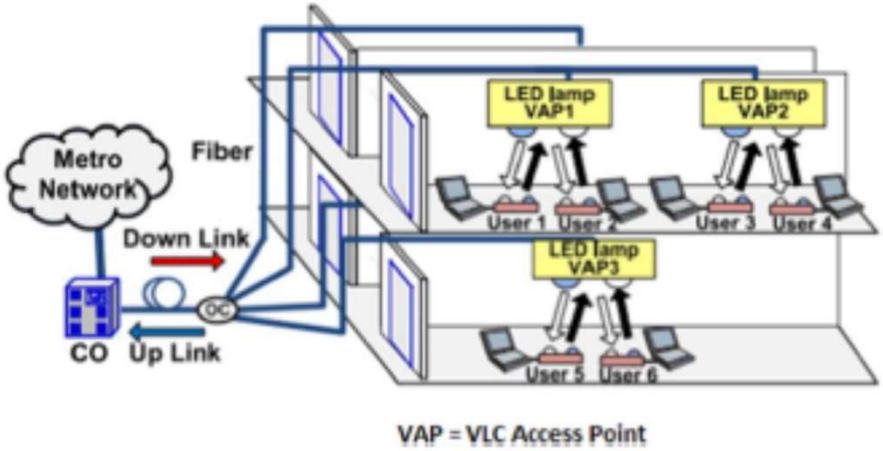
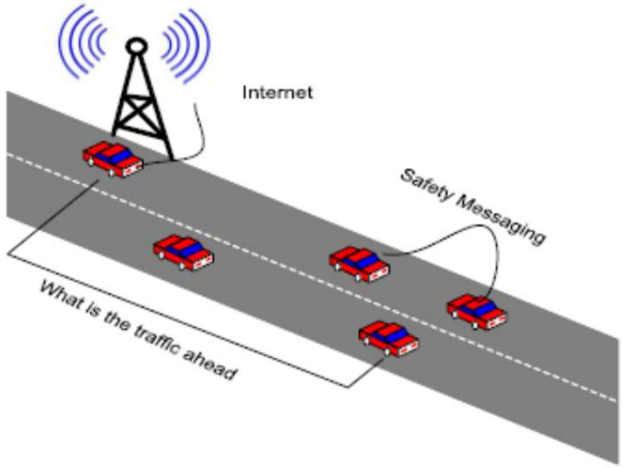
Applications for OWC / VLC



Indoor: usage of blue light spectrum of white LEDs for down stream.
Up stream: seems to be neglected in literature.

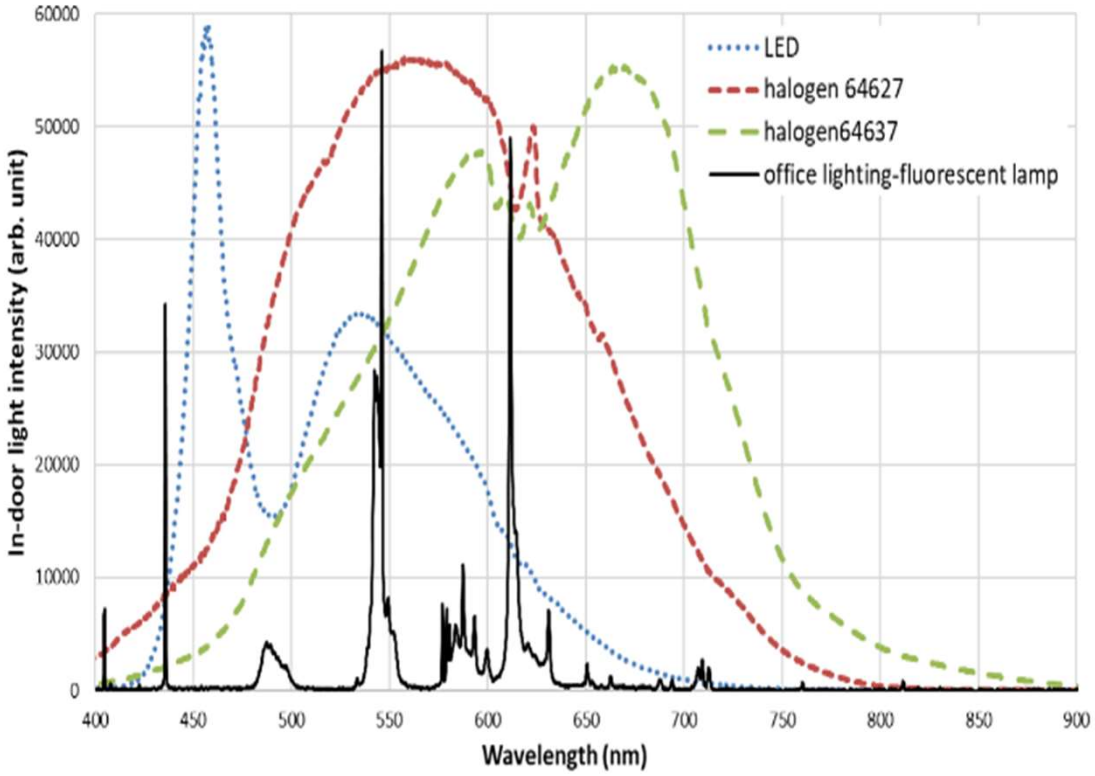
L.U. Khan, Digital Communications and Networks 2016



VLC for vehicular networks C2C/V2V, C2X/V2X

Outdoor: strong ambient light. OWC / VLC difficult.
First camera receivers at about 50Mb/s introduced.

Indoor Light Sources

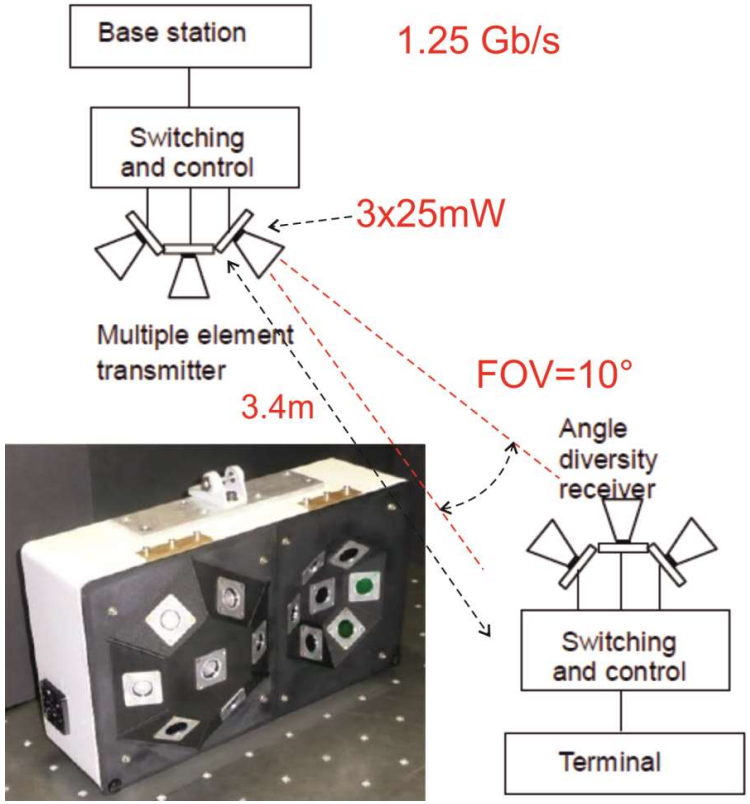


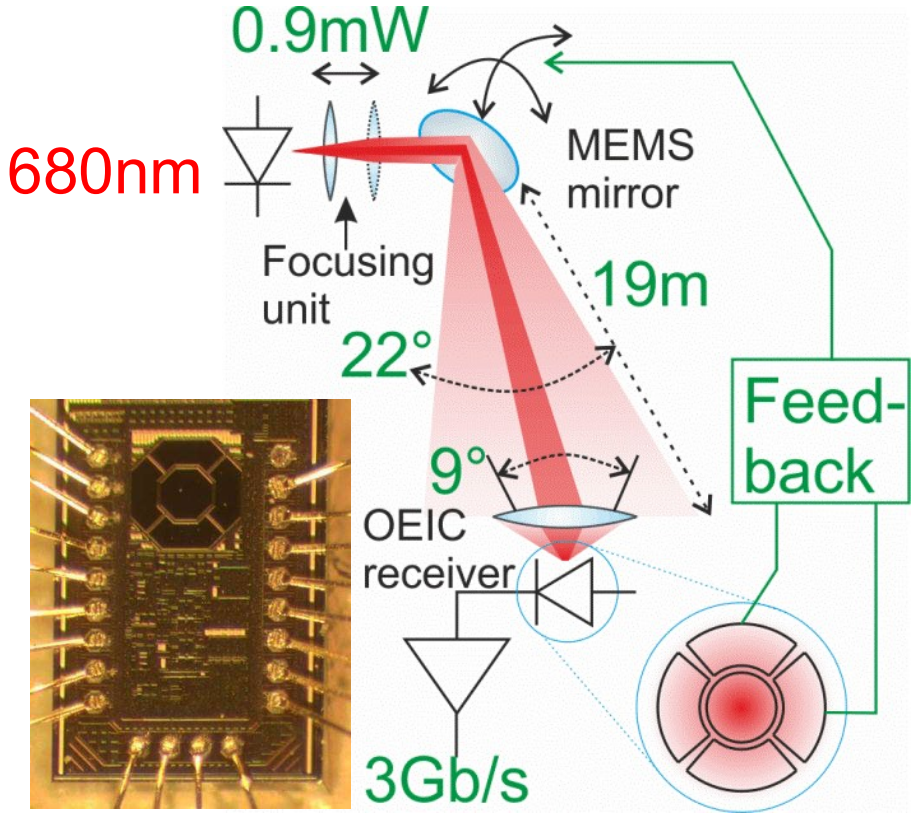
Fluorescent lamps leave wide wavelength ranges for OWC.

White LEDs: 450nm may be not a good idea for the upstream.

Halogen lamps seem to be a problem for OWC.

Optical Wireless Communication





- High power demand
- Bulky set-up
- Multi lenses receiver

European project OMEGA

Le Minh et al, IEEE PTL, vol. 22, no. 21, 2010

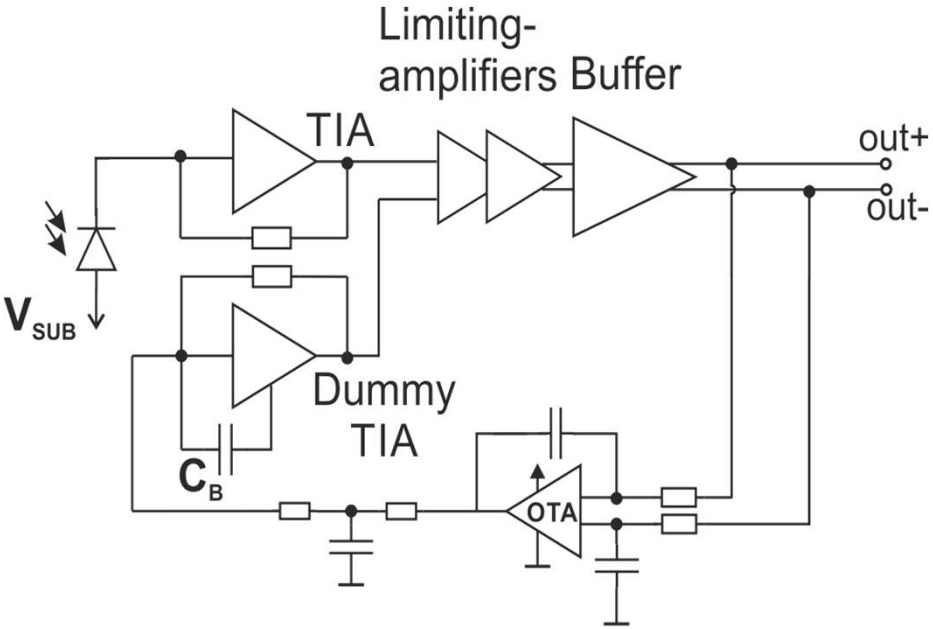
- Power efficient
- Monolithic integrated PIN-photodiode optical receiver in 0.35µm BiCMOS
- Simple optical set-up

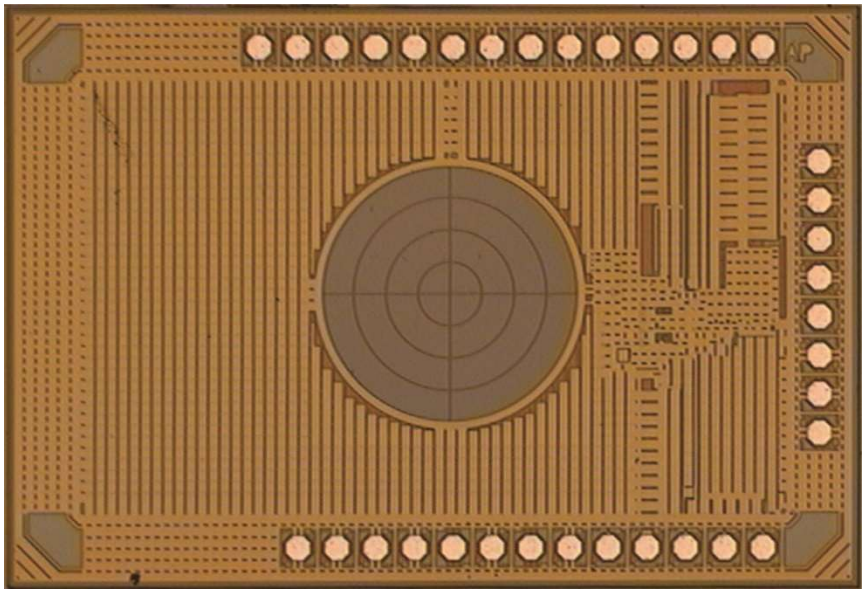
P. Brandl et al, IEEE PTL, 2013; IEEE JSTQE 2014

OWC with APDs

APD receiver in 0.35µm BiCMOS

With APD, no receiver lens is necessary. -> large RX FOV



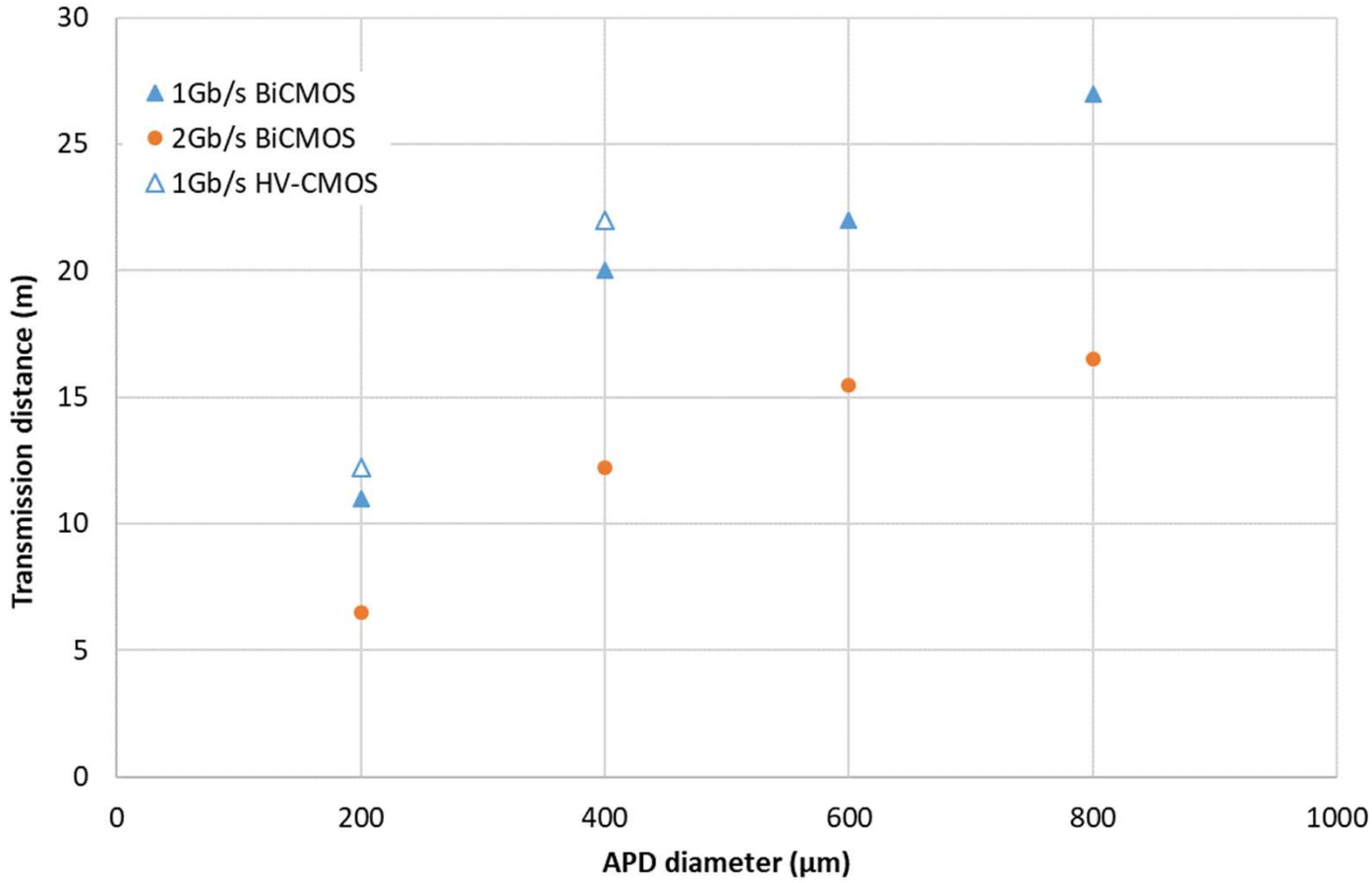


-32.2 dBm at 2Gb/s with 200µm APD, 122 pJ/bit incl. 50Ω driver [Opt. Expr. 2015]

Chip photo of 800µm diameter APD receiver

Chip area with 400µm diameter APD: 960µm×1540µm

Maximum transmission distances with APD receivers



No receiver optics;
No optical filter;
BER=10^{-9}

HV CMOS RX is with ARC.

2Gb/s only with BiCMOS RX possible.

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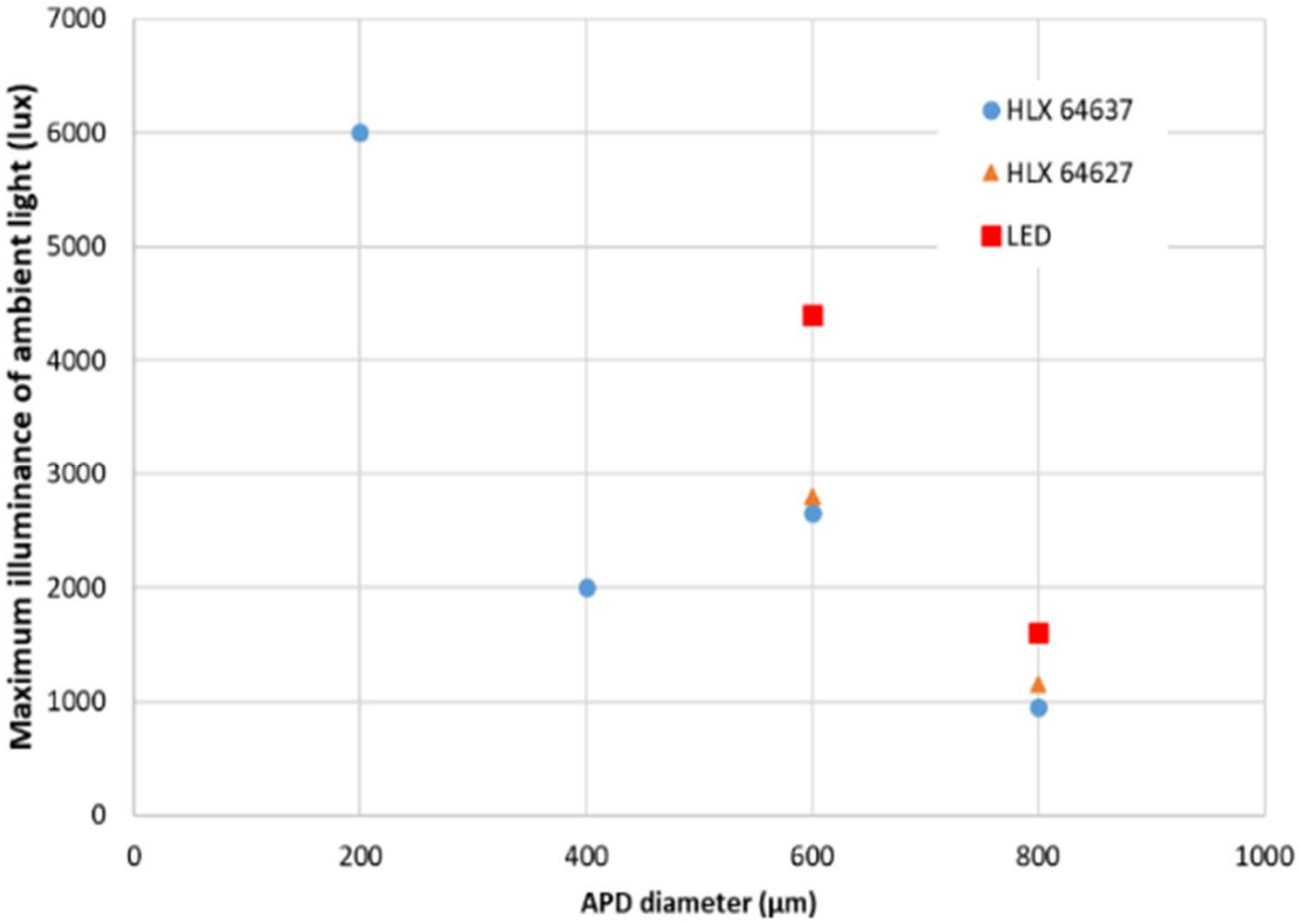
Maximum ambient light illuminance for different light sources with APD receivers



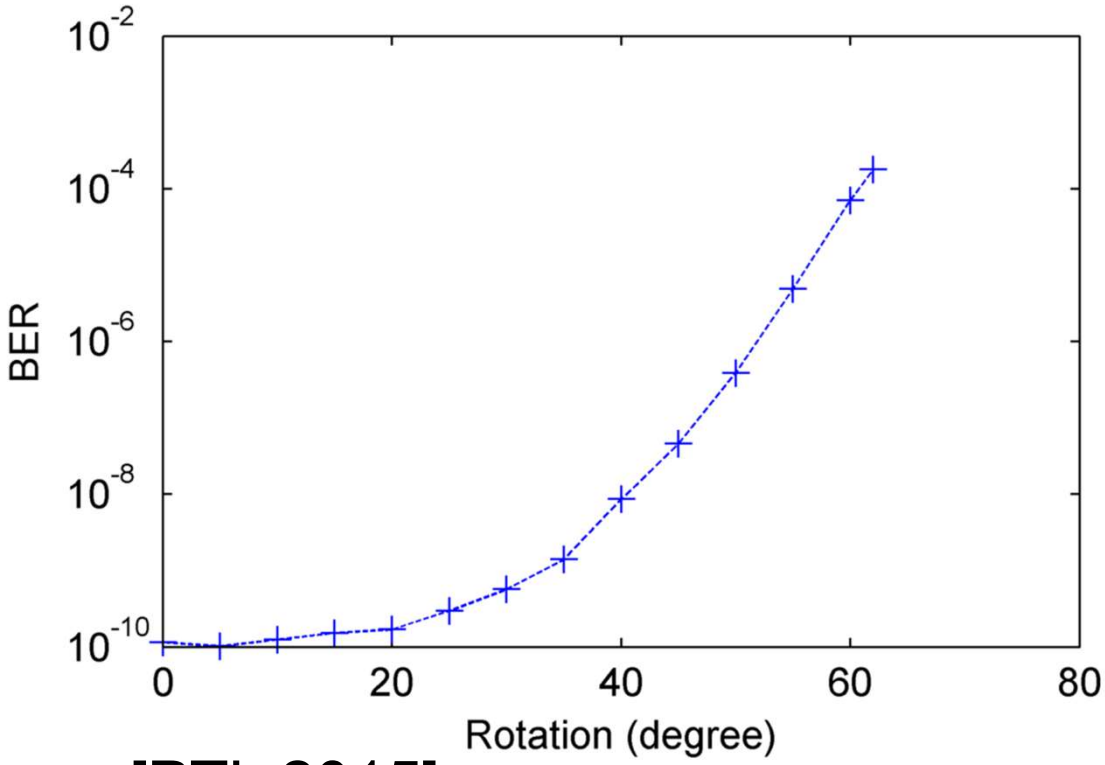
Transmission distances close to the maximum distances

BER=10^{-9}

Halogen lamps are not a problem

BER with linear-mode APD receiver in dependence on light incidence angle

Measured BER



[PTL 2015]

HV-CMOS 0.35µm

200µm APD diameter

With ARC:
Total incidence angle (FOV) for BER=1e-9: 68°

Distance: 3m

Data rate: 1Gb/s

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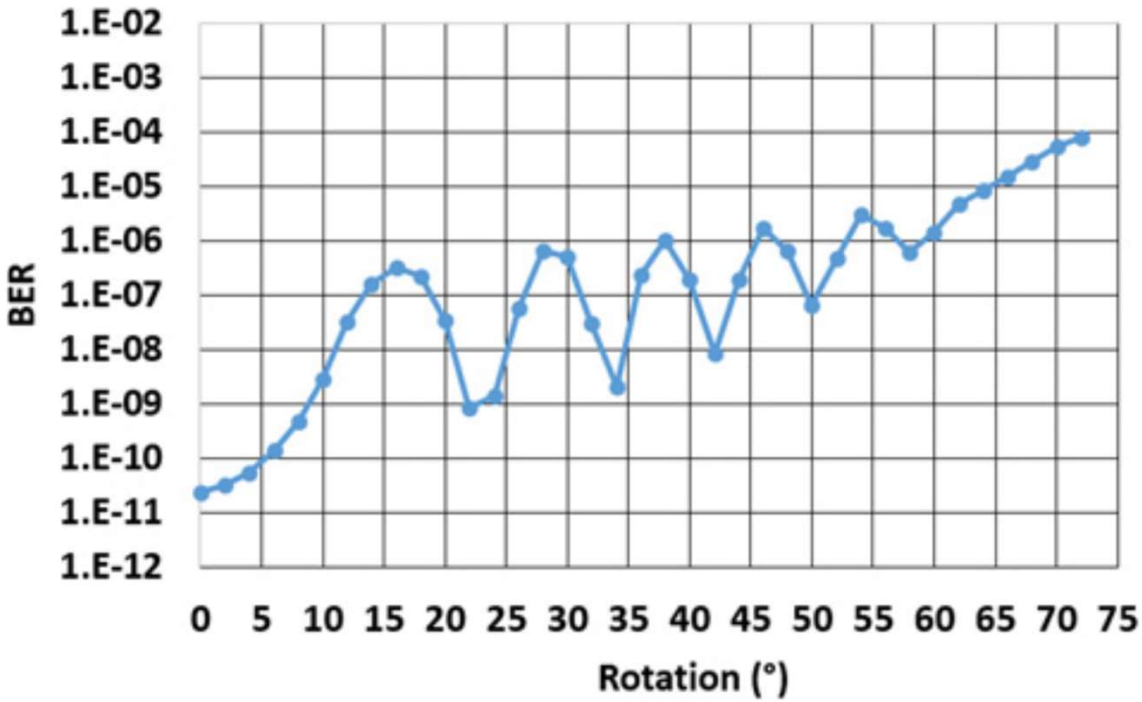
BER with linear-mode APD receiver in dependence on light incidence angle

Measured BER



J. Eng. 2017

BiCMOS 0.35µm

400µm APD diameter

No ARC

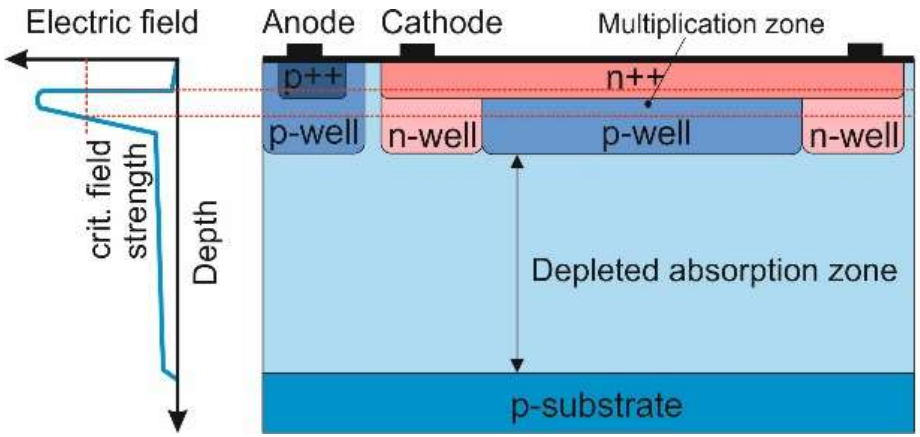
Total incidence angle (FOV) for BER=1e-9: 18° (with ARC: 68°, [PTL 2015])

Distance: 11m

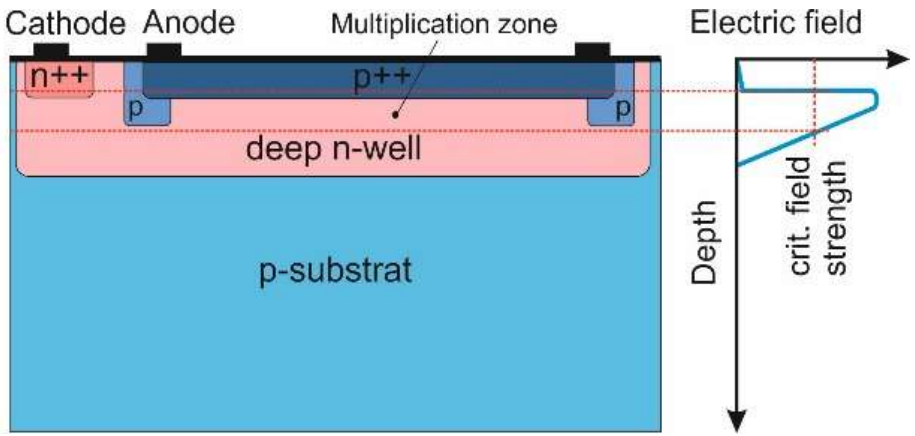
Data rate: 2Gb/s

Thin and Thick SPADs

Thick SPAD



Thin SPAD



Thick fully depleted absorption zone -> high photon detection probability (PDP) for red and near-IR light

PIN-photodiode CMOS with thick low-doped epitaxial layer

Thin multiplication zone acting also as absorption zone -> low PDP for red and near-IR light

Usually triple-well CMOS (DNW) or twin-well CMOS (NW)

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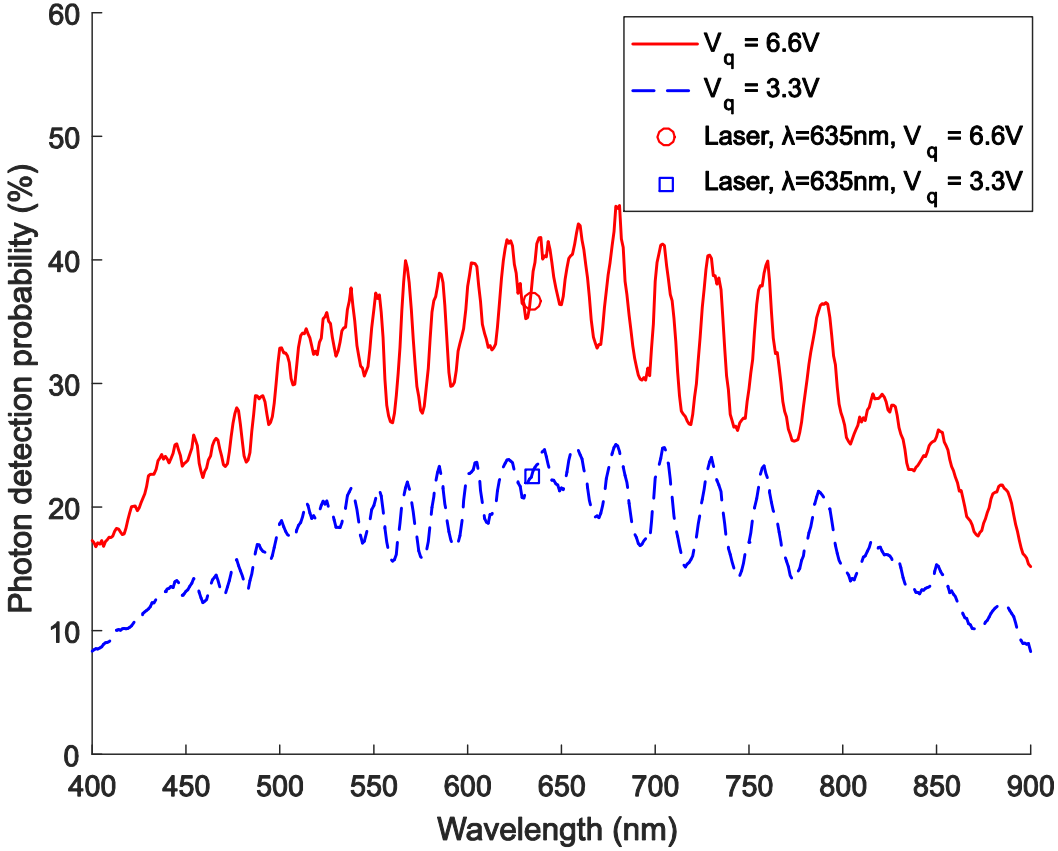
Properties of SPAD in 0.35µm CMOS



Properties for an integrated cascoded active quencher and a dead time of 9ns:

- 3.3V excess bias:
  PDP=22%
  DCR= 21,500s^{-1}
  APP= 0.95%
- 6.6V excess bias:
  PDP=36.7%
  DCR=35,500s^{-1}
  APP=5.1%

Sci. Rep. 2017

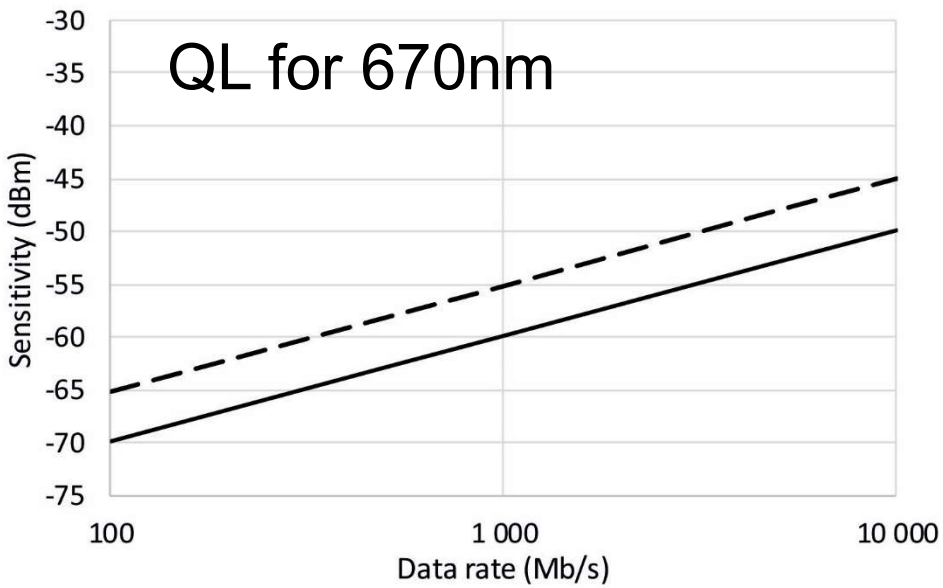
Quantum limit (QL)

If we eliminate electronic noise (thermal and shot noise) of amplifiers and excess noise of APDs, the final physical limit is photon noise, because common LEDs and laser diodes are Poissonian emitters.

$$p_m(k)=m^k/k!\ e^{-m}$$

1µW ->

1nW ->



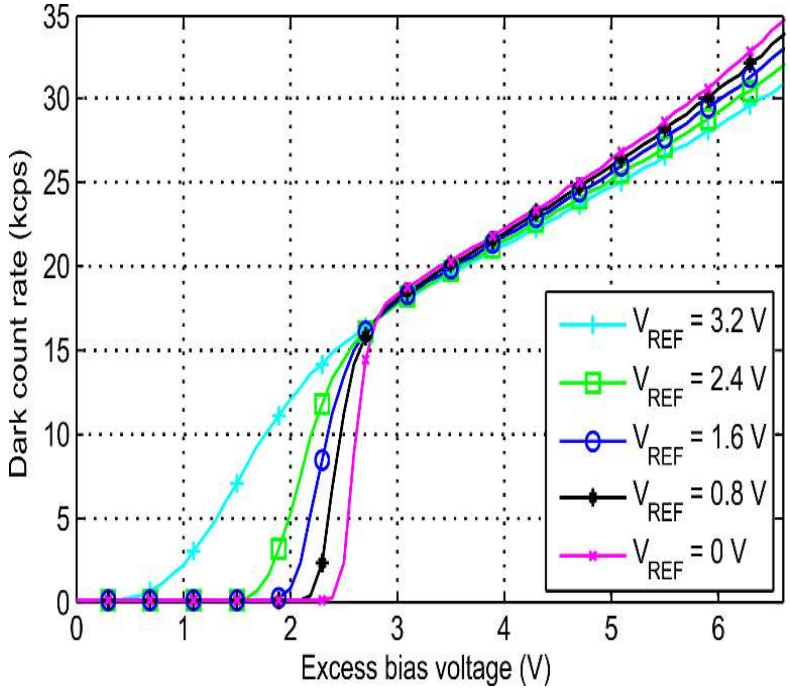
m=20, BER=10^{-9}

m=5.5, BER=2×10^{-3}

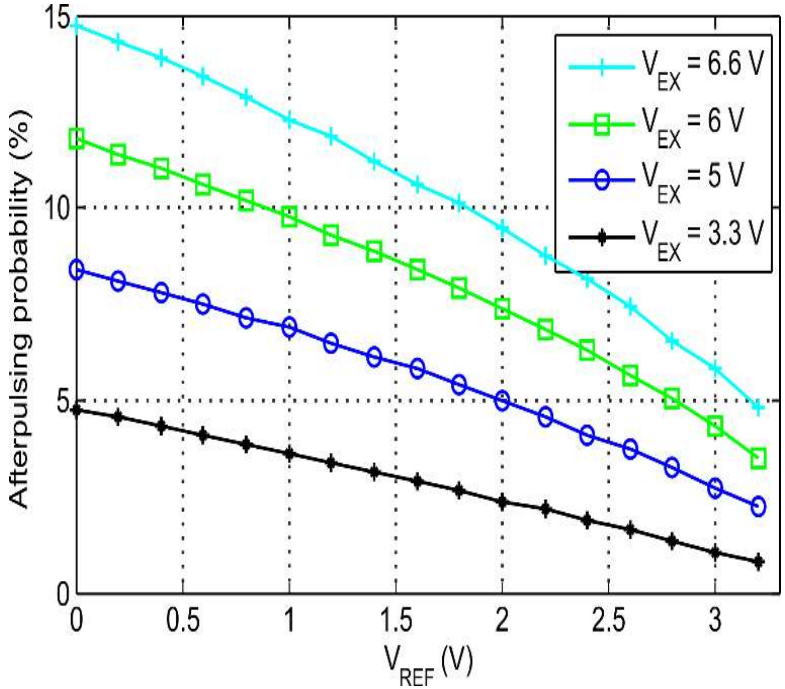
How close can SPADs bring us to the QL?

Parasitics / „Noise“ of SPADs

Dark counts



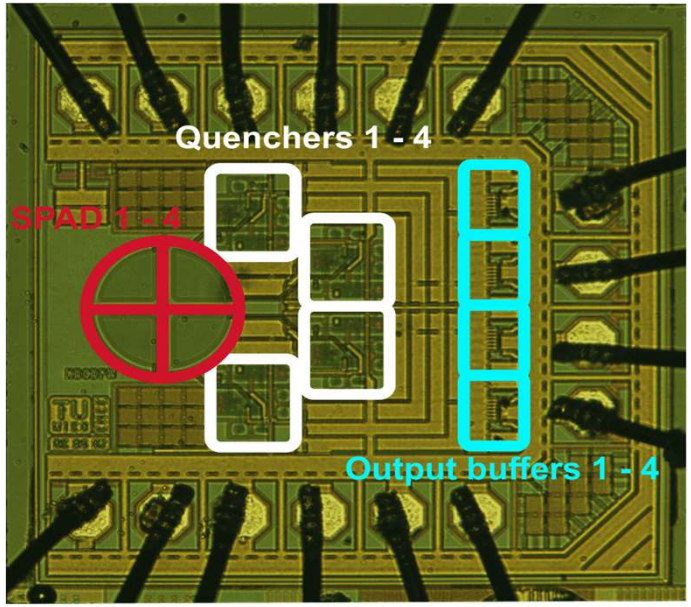
Afterpulsing

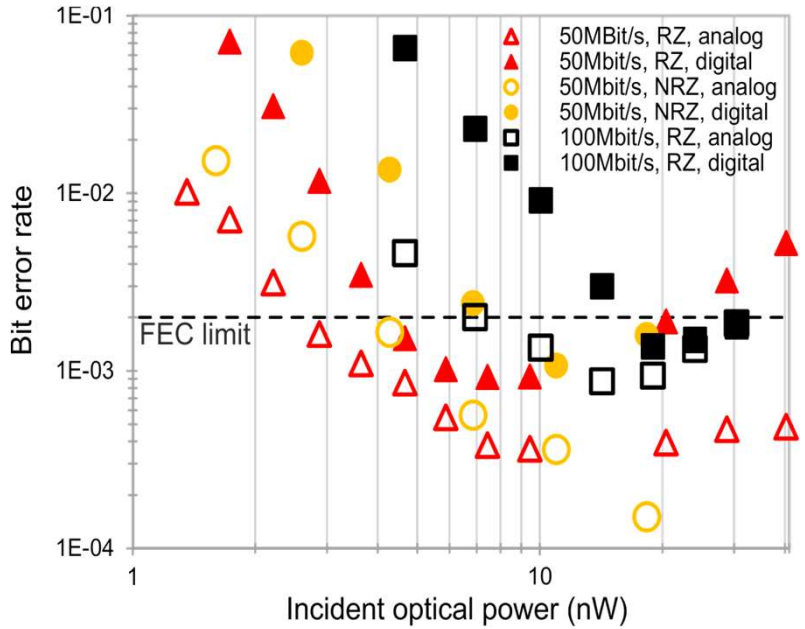


Afterpulsing -> BER > 2×10^{-3}, if only one SPAD is used.

<u>Example:</u> 4 SPADs with a photon detection in each for a „1“ may be enough, if APP=10% -> $BER_{APP} = (APP)^4 = 10^{-4} < 2\times10^{-3}$

4-SPAD Receiver

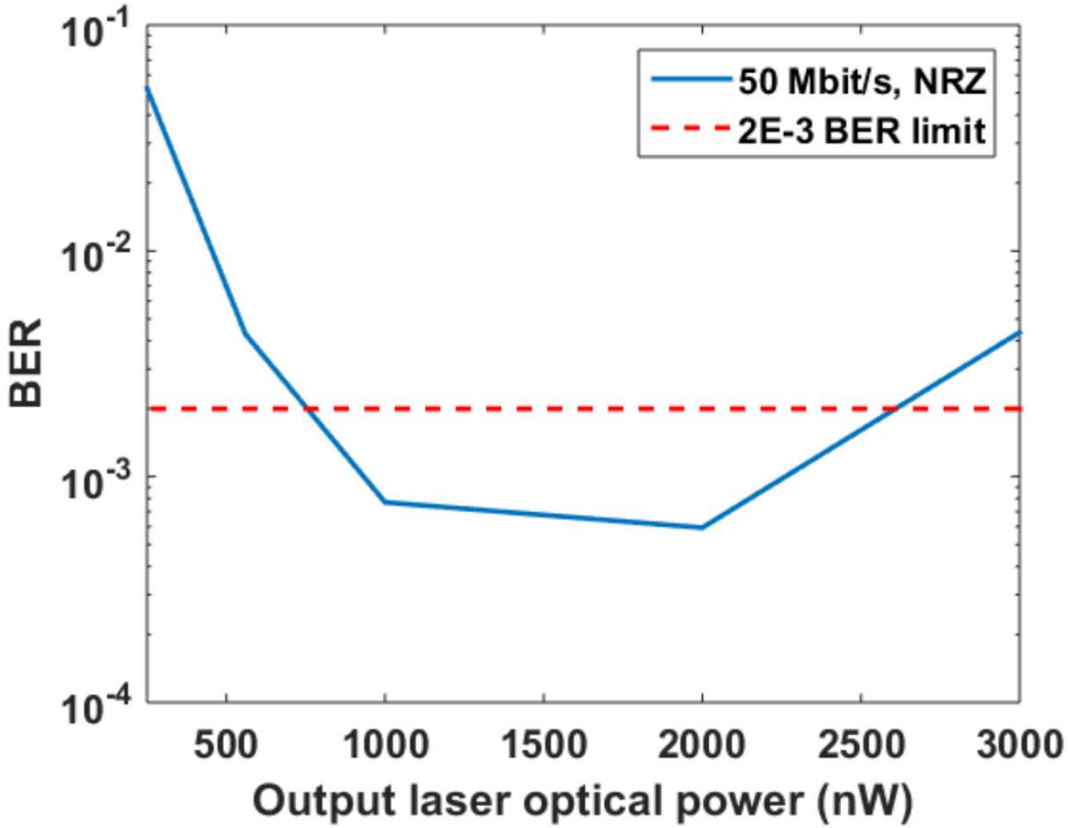




0.35 µm CMOS IC with 6.6 V active quenchers:
-55.7 dBm sensitivity at 50 Mbit/s [Sci. Rep. 2017]
-46.3 dBm at 100 Mbit/s [IEEE JSTQE 2018 (invited)]

50 Mb/s over 2 m OWC distance with 635 nm laser with external modulator having <1µW transmitter power [IPC 2017]

BER of 4-SPAD receiver over 2m distance



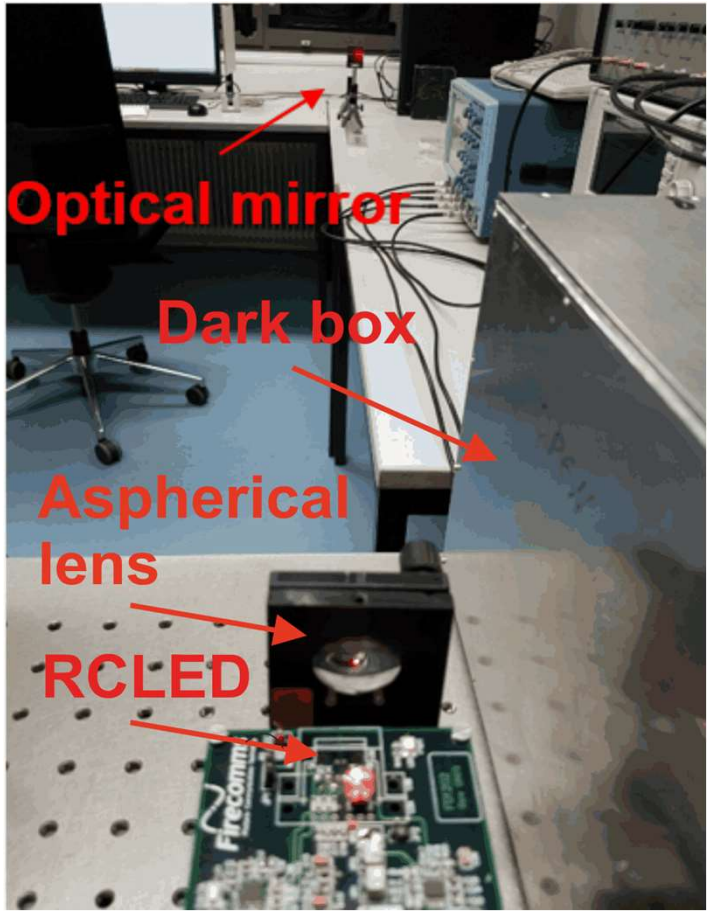
635 nm laser with external modulator;
Collimator with 0.01° beam divergence;
NRZ;

Interference filter Thorlabs FL635-10.

A laser output power of less than 1µm was sufficient for BER<2e-3.

[IPC 2017]

OWC Set-up with SPAD RX



Light sources:

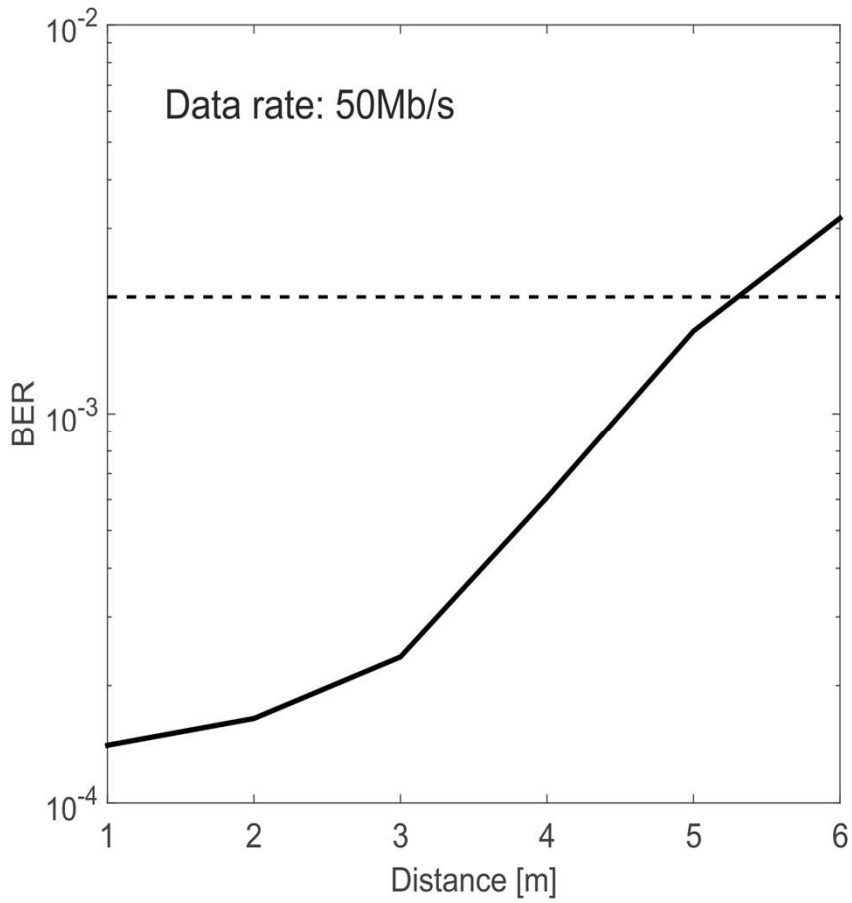
- 635 nm CW laser with modulator
- 650 nm RC-LED

Interference filter in optical window of dark box with $\Delta\lambda$ = 10 nm, FWHM

Mirror for doubling the distance

OWC with 4-SPAD RX

BER for different OWC distances



650 nm RC-LED: 1.1 mW;
Collimator with 0.038 rad beam divergence;
NRZ;

Max. OWC distance at 500 lx room light: 5.3 m;

Max. ambient light 2 klx at 5 m OWC distance

[CSNDSP18]

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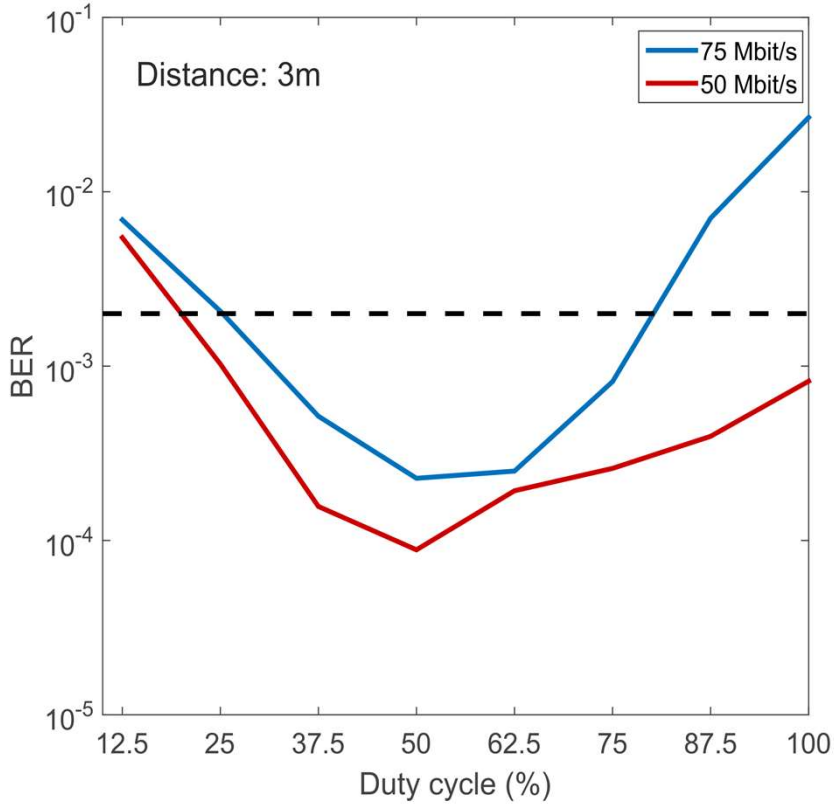
Influence of duty cycle



OWC distance: 3 m;
650 nm RC-LED;
RZ, 500 lx room light

Data rate raised to 75 Mb/s

Duty cycles around 50% are best.

[COBCOM 2018]

BER Model

$$
\begin{aligned}
P_{\mathrm{e}} &= P_{\mathrm{e}}(\text{'1'}) + P_{\mathrm{e}}(\text{'0'}) \\
&= \sum_{i_{\mathrm{t}}=0}^{n_{\mathrm{th}}-1} P_{\mathrm{t}}(i_{\mathrm{t}}|\text{'1'})P_{\mathrm{b}}(\text{'1'}) + \sum_{i_{\mathrm{t}}=n_{\mathrm{th}}}^{n_{\mathrm{s}}} P_{\mathrm{t}}(i_{\mathrm{t}}|\text{'0'})P_{\mathrm{b}}(\text{'0'}) \\
&= \frac{1}{2}\left[\sum_{i_{\mathrm{t}}=0}^{n_{\mathrm{th}}-1} P_{\mathrm{t}}(i_{\mathrm{t}}|\text{'1'}) + \sum_{i_{\mathrm{t}}=n_{\mathrm{th}}}^{n_{\mathrm{s}}} P_{\mathrm{t}}(i_{\mathrm{t}}|\text{'0'})\right]
\end{aligned}
$$

$$
P_{\mathrm{t}}(i_{\mathrm{t}}|\text{'b'}) = \sum_{i_{\mathrm{p}}=0}^{i_{\mathrm{t}}} \sum_{i_{\mathrm{d}}=0}^{i_{\mathrm{t}}-i_{\mathrm{p}}} \sum_{i_{\mathrm{a}}=0}^{i_{\mathrm{t}}-i_{\mathrm{p}}-i_{\mathrm{d}}} P(i_{\mathrm{p}}, i_{\mathrm{d}}, i_{\mathrm{a}}, i_{\mathrm{c}}|\text{'b'})
$$

$$
\begin{aligned}
P(i_{\mathrm{p}}, i_{\mathrm{d}}, i_{\mathrm{a}}, i_{\mathrm{c}}|\text{'b'}) &= P_{\mathrm{p}}(i_{\mathrm{p}}|\text{'b'})P_{\mathrm{d}}(i_{\mathrm{d}}|i_{\mathrm{p}}, \text{'b'})P_{\mathrm{a}}(i_{\mathrm{a}}|i_{\mathrm{p}}, i_{\mathrm{d}}, \text{'b'})P_{\mathrm{c}}(i_{\mathrm{c}}|i_{\mathrm{p}}, i_{\mathrm{d}}, i_{\mathrm{a}}, \text{'b'}) \\
&= \underbrace{P_{\mathrm{p}}(i_{\mathrm{p}}|\text{'b'})}\underbrace{P_{\mathrm{d}}(i_{\mathrm{d}}|i_{\mathrm{p}})P_{\mathrm{a}}(i_{\mathrm{a}}|i_{\mathrm{p}}+i_{\mathrm{d}})P_{\mathrm{c}}(i_{\mathrm{c}}|i_{\mathrm{p}}+i_{\mathrm{d}}+i_{\mathrm{a}})}
\end{aligned}
$$

Photo-count statistics modeling

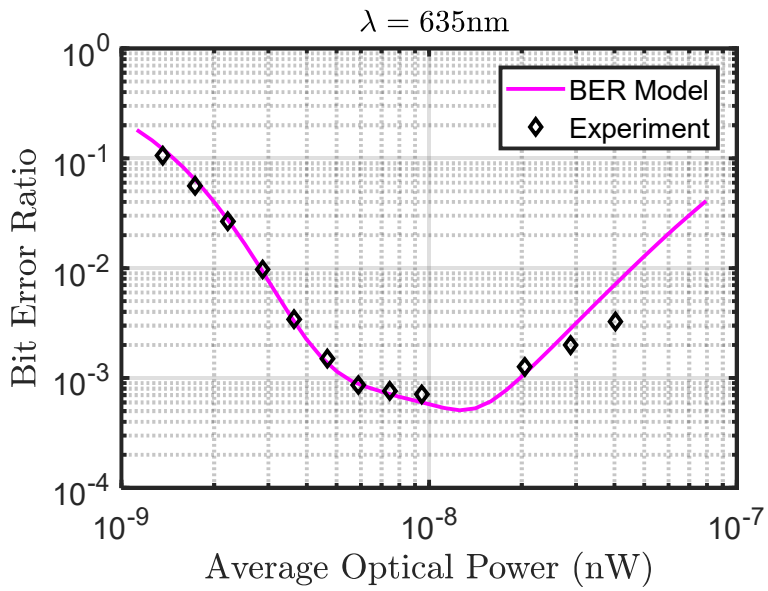
H. Mahmoudi et al., IEEE Photonics J.
Vol. 10, pp.1-11, 2018

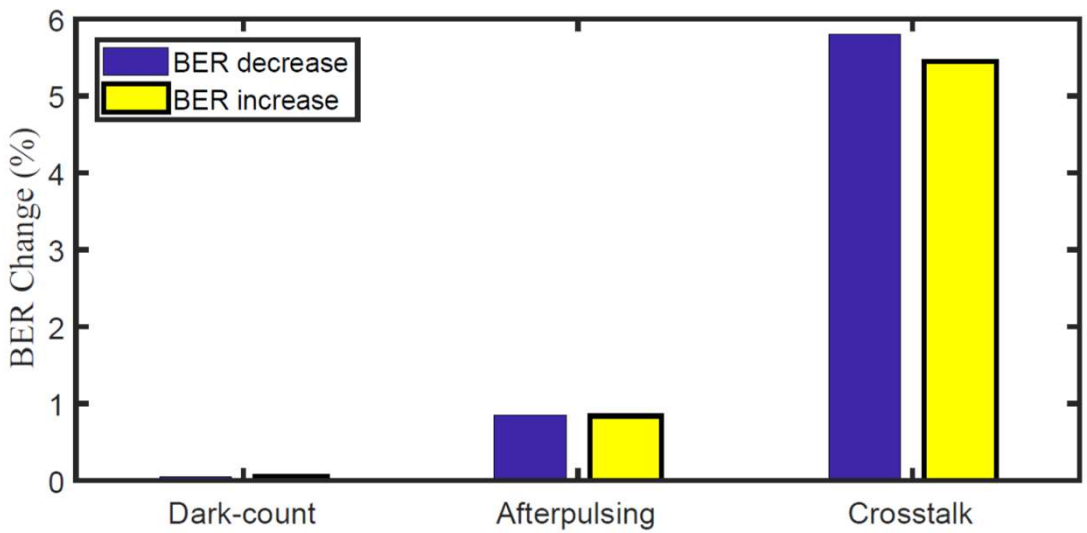
Statistical characterization of parasitics
based on dark measurement
(DCR, APP, OCTP)

H. Mahmoudi et al., IEEE T-ED,
Vol. 66, 497-504, 2019

BER Model - Results

Measured (light coupled via an optical fiber, perpendicular light incidence) and model fitting results of the BER performance at 50Mbit/s





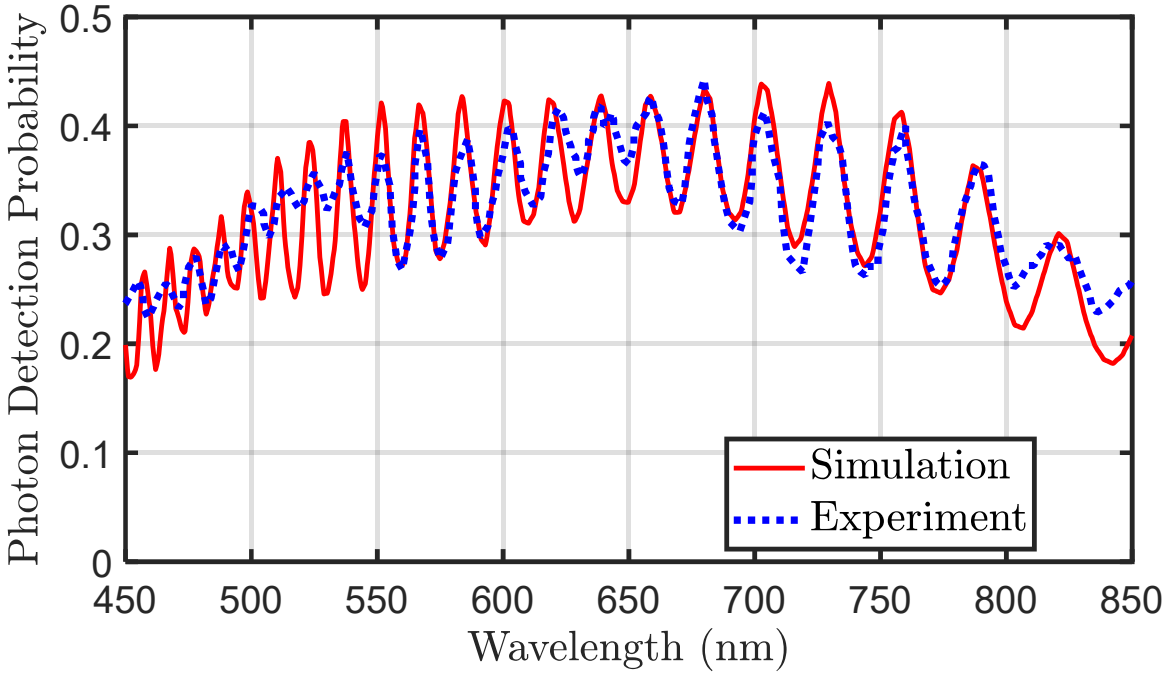
OFAT sensitivity analysis of the minimum BER at 50Mbit/s plotted for ±10% change in the avalanche probabilities of parasitics

PDP Model

$$\mathrm{PDP}(\lambda) = \int_0^{\infty} \mathrm{P_{ab}}(\lambda, x) \times \mathrm{P_{av}}(x)\, dx$$

Absorption probability
(Optical Simulation)

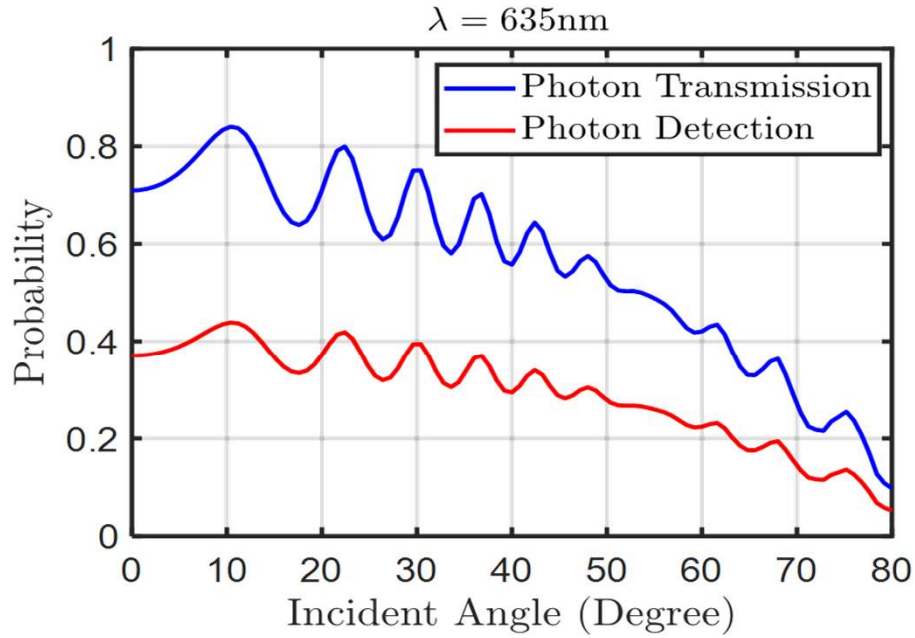
Avalanche probability
(TCAD Simulation)

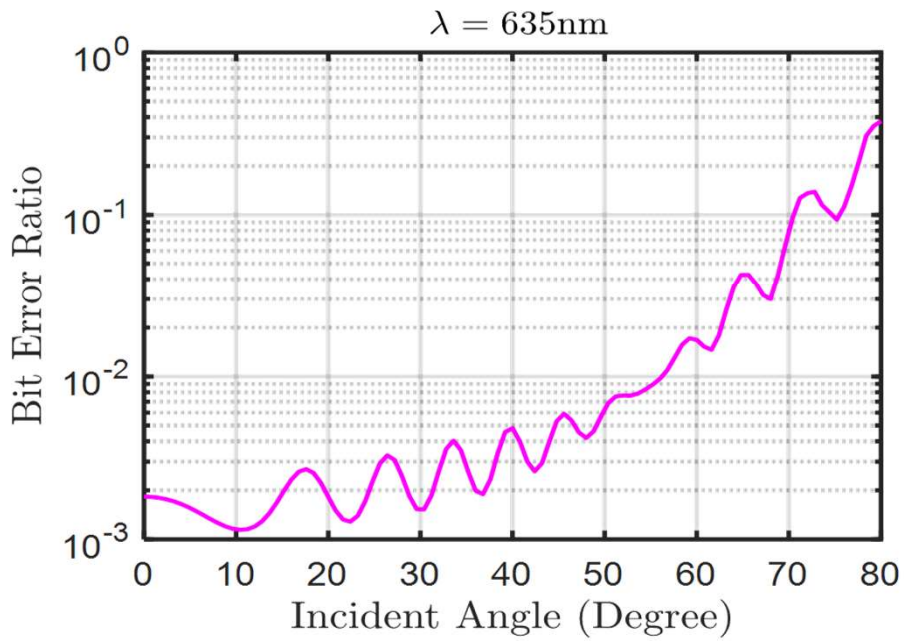


BER Model Results (Angle)

Optical transmission through isolation and passivation stack

PDP

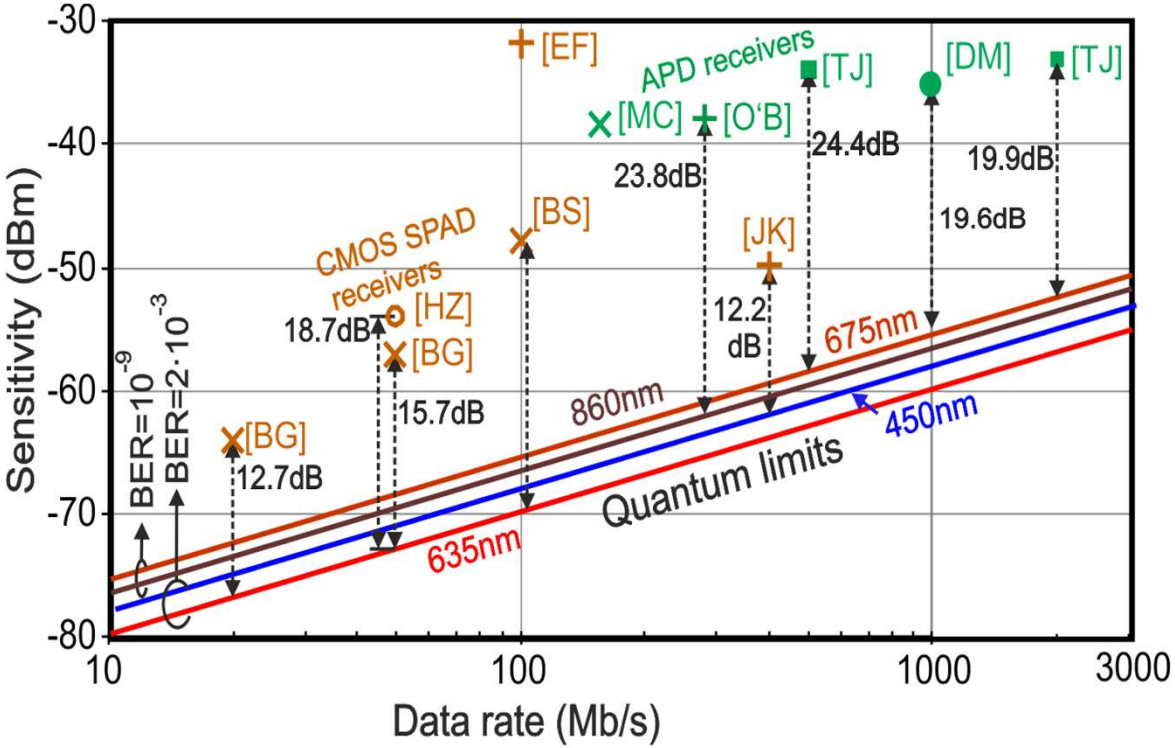




BER model including angular-dependent PDP (DCR, APP and OCTP held constant.)

Total incidence angle (FOV) for BER=2e-3 is 30 degree.

Comparison APD - SPAD RX



APD RX: BER=10^{-9}
SPAD RX: BER=2×10^{-3}

APD RX achieve gaps to the quantum limit of 20dB at 1 and 2Gb/s.

SPAD RX achieve gaps to the quantum limit of 12.7dB [BG 2018] and 12.2 dB [JK 2019]

Conclusions

- In-door OWC is well possible with APD and SPAD receivers.
- Maximum OWC distances of 27m at 1Gb/s and 16.5m at 2Gb/s are possible with APD receivers in 0.35µm technologies without receiver lens and without optical filter.
- SPAD receivers are not so mature yet.
- The data rate with SPAD receivers is much smaller than that of APD receivers. Optical filters are necessary for OWC with SPAD receivers. Error correction is necessary for SPAD RXs.
- BER of SPAD receivers without anti-reflection coating suffers from non-perpendicular light incidence.
- Dark counts, afterpulsing and optical crosstalk represent a barrier for further improving the sensitivity and for increasing the data rate of SPAD receivers.

Acknowledgements

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- Nemanja Vokic
- Paul Brandl
- Bernhard Steindl