川渝前沿论坛 (第六期)

中国·重庆 April 27

High-capacity indoor optical wireless communication enabled by steered infrared beams

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Acknowledgements

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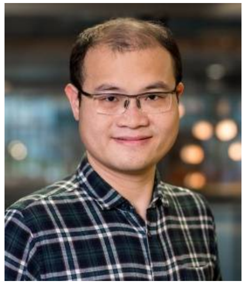

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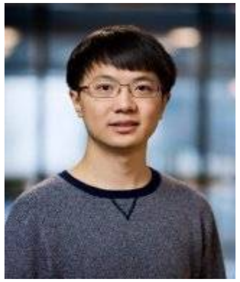

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余少华，中国工程院院士，现任中国通信学会副理事长、国家信息光子技术重点专项专家组组长、国家重点研发计划宽带通信和新型网络重点专项总体专家组副组长、国家第六代移动通信（6G）技术研发总体专家组专家、数字中国产业发展联盟理事长。

□ 研究方向

- 异质异构硅光芯片与系统应用技术（+通信光电子技术研究所）
- 网络通信智能核心芯片与软件技术
- EDA科研条件平台

□ 专业方向

光学工程、光电信息工程、光电子、物理电子学、微电子与固体电子学、电子信息工程、物理学、半导体物理、电磁场与微波光学、人工智能、计算机、射频微波、集成电路、半导体工艺、计算机科学与技术、软件工程、应用数学、计算数学等相关专业硕博(鹏城实验室招聘官网 hr.pcl.ac.cn或公众号-鹏城实验室招聘)。

通信光电子技术研究所人才需求

1) 高速光通信

工作地点：深圳
学　　历：博士/硕士
工作类型：全职

职位描述

1. 从事高速光通信相关领域研究，有光纤或光无线通信、可见光通信、极高频通信研究经验的优先；
2. 有光子集成芯片与系统融合应用研究经历者优先；
3. 承担或参与科研部门高速光通信（包括可见光、空间光、光纤、毫米波太赫兹等）或光电计算领域的科研任务；
4. 负责或参与关键核心技术攻关，完成相应科研指标任务等；

任职要求

1. 在国内外知名高校获得光通信、光学工程、微电子、电子科学与技术、半导体材料和物理电子学相关专业全日制硕博，具有高速光通信系统或相关领域研究经验；
2. 了解国内外高速光通信发展现状，了解最新的光通信系统、均衡技术与均衡算法；
3. 了解光通信系统调制解调方法（OOK、OFDM、CAP、QAM等）；了解高速光通信或光计算等基本知识。
4. 具有一定的光通信、光电子、光学工程相关领域研究经验；
5. 具备较好的沟通、学习能力、英文写作能力等，具有团队合作精神。

通信光电子技术研究所人才需求

2) 通信信号处理算法

工作地点：深圳
学　　历：**博士/硕士**
工作类型：全职

职位描述

1. 负责光通信系统算法需求分析、算法整体方案设计；
2. 负责单载波或多载波无线光/高速光纤通信物理层信号编解码、信号调制、通信信号处理、最优检测算法设计开发；
3. 负责撰写相关文档，包括：算法需求分析，算法开发方案设计；

任职要求

1. 具有统招全日制双一流高校（985/211）或海外知名高校光通信、光学/光学工程/光电子、微电子与物理电子学、半导体物理、电磁场与微波等、数学等相关专业硕博，具有通信信号处理算法相关研究经验；
2. 熟悉通信相关数字信号处理算法开发流程，熟悉人工智能算法在光通信系统中应用者优先；
3. 具有扎实的光通信知识，熟悉OFDM，MIMO，信道编码、同步等；
4. 具有踏实负责的工作态度和良好的沟通、协调能力，责任感强，吃苦耐劳；

Outline

※Background and Motivations

—High-capacity requirement

—Concept of OWC

※Indoor OWC Technologies

—Visible light communication (VLC)

—Infrared light communication (ILC)

※Beam Steered ILC

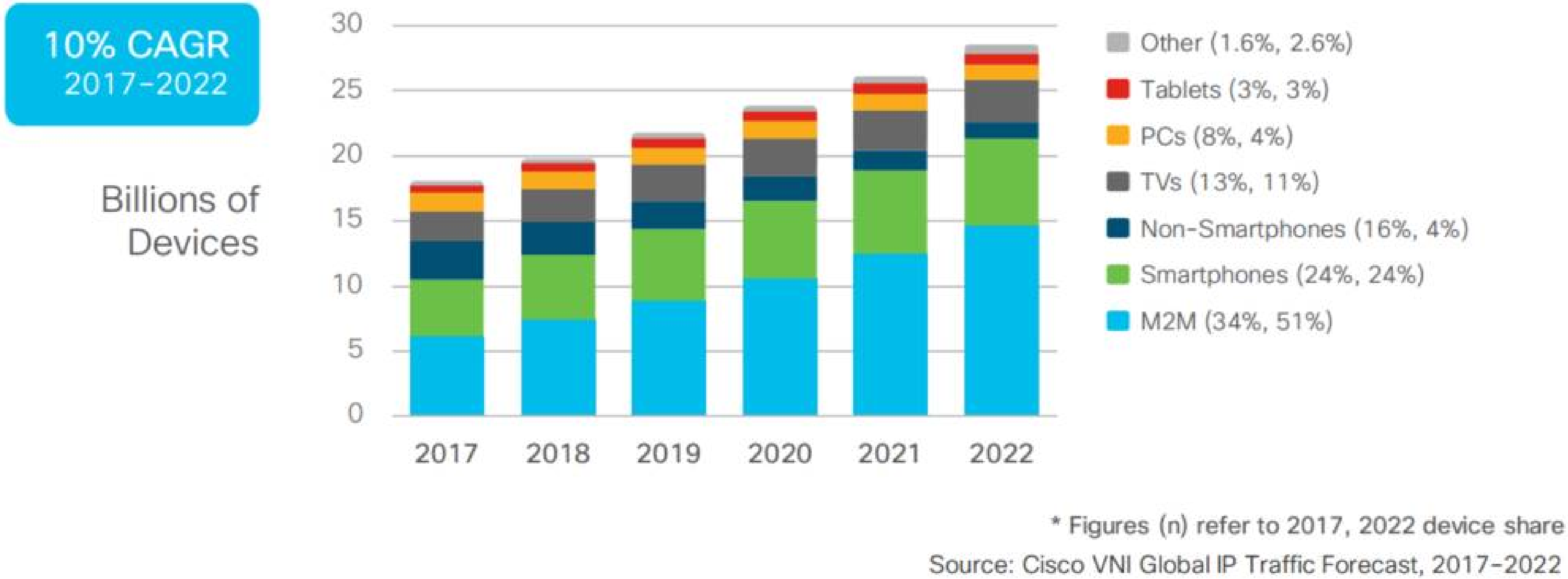
—Line-of-sight

—Non-line-of-sight

※Conclusions

Background

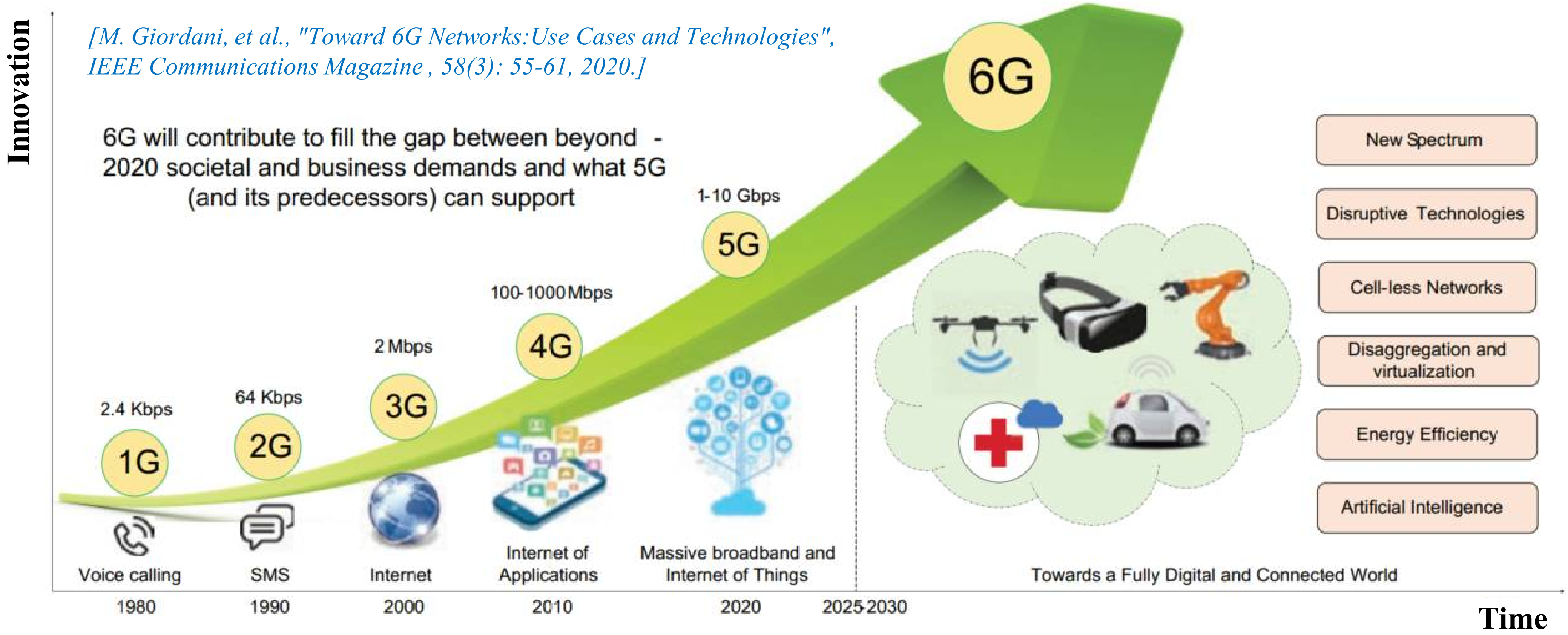
□ Growth of global devices and connections



- **Wireless data traffic: over 50% incensement per year**
- **Fast development of smart terminals: machine to machine (M2M), smartphone, Internet of Thing (IoT), AV, VR, etc.**
- **<8 billion mobile deices, 80% video data, 80% generated indoor**

Background

☐ Evolution of mobile communication: 1G to 6G



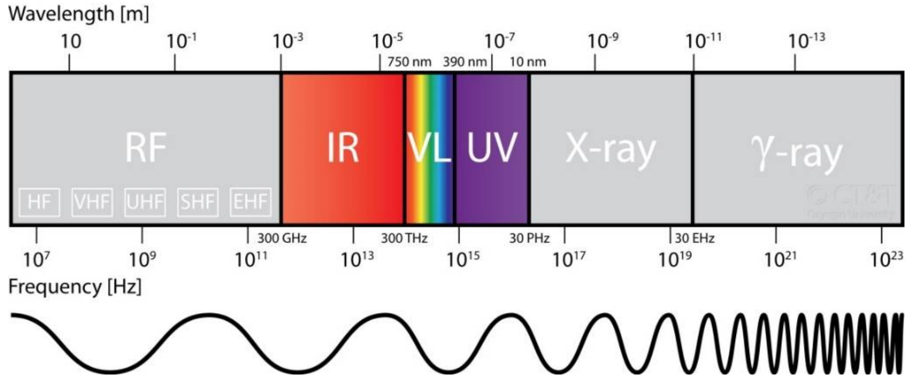
- ✞ New spectrum: light Wave with >300 THz bandwidth
- ✞ Cells: Beamforming and focusing for small cell
- ✞ Technologies: light manipulation for beam steering

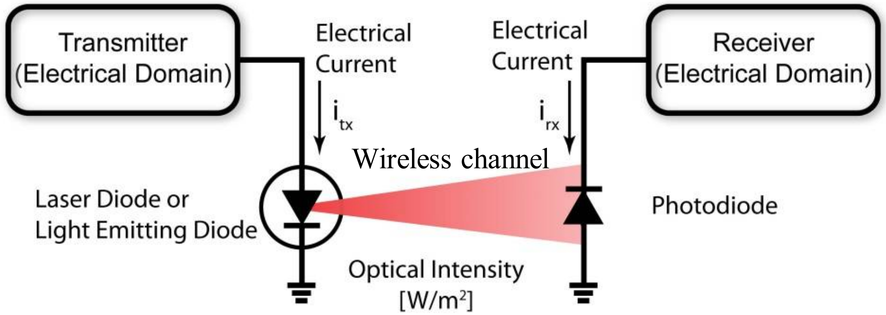
Background

□ Introduction of optical wireless communication (OWC)

✓ **OWC:** Wireless transmission through the deployment of optical frequencies

- Infrared (IR)
- Visible (VL)
- Ultraviolet (UV)





✓ **Transmitter**

- Electrical baseband processing
- E/O Conversion

✓ **Amplitude constraints**

- Non-negativity of the signal
- Eye-safety regulations for laser

✓ **Receiver**

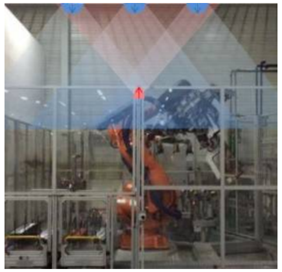
- O/E Conversion
- Electrical baseband processing

Advantages of OWC:

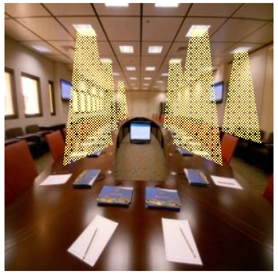
- Large bandwidth capacity
- Unregulated spectrum
- Robustness to EMI: hospitals, airplanes, space crafts, industrial areas etc)

Background

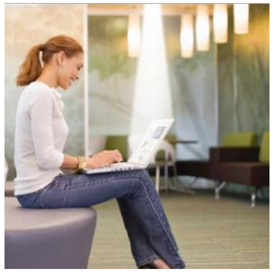
OWC Gb/s User Casers



IoT: Flexible Manufacturing



Conference Rooms

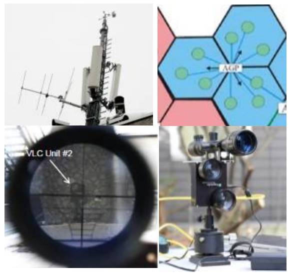


Private Households

In-flight Entertainment

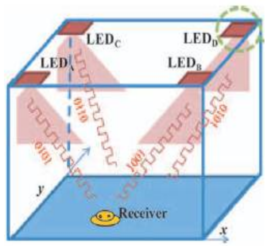
Mass transportation

IoT: Car2Car, Car2Infra



Opt. Backhaul for small cells in 5G

Augmented reality, hospitals, support for disabled people



Precise Indoor Positioning

Secure Wireless

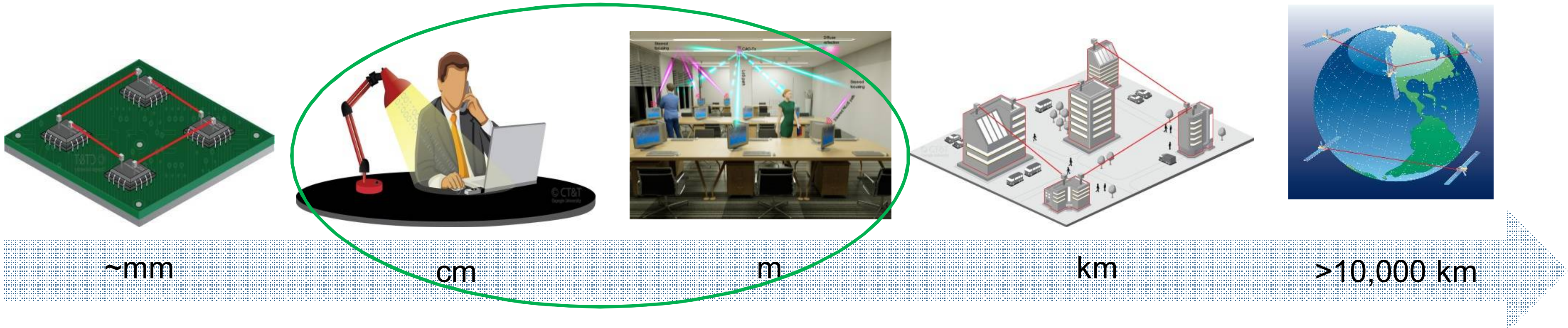
[https://mentor.ieee.org/802.15/dcn/15/15-15-0112-02-007a-short-range-optical-wireless-communications-tutorial.pdf.]

Background

OWC—Domains

✓ Depending on the intended application, variations of OWC (UV, IR, VL) can serve as a powerful alternative, complementary or supportive technology to the existing ones

- **Ultra-short range** (e.g., optical circuit interconnects)
- **Short range** (e.g., WBAN, WPAN)
- **Medium range** (e.g., intra-building connections, WLAN, VANET)
- **Long range** (e.g., inter-building connections)
- **Ultra-long range** (e.g., satellite links)



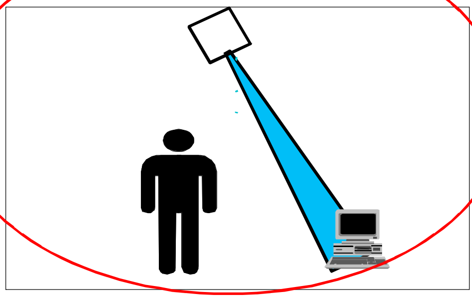
[https://mentor.ieee.org/802.15/dcn/15/15-15-0112-02-007a-short-range-optical-wireless-communications-tutorial.pdf.]

OWC Technologies

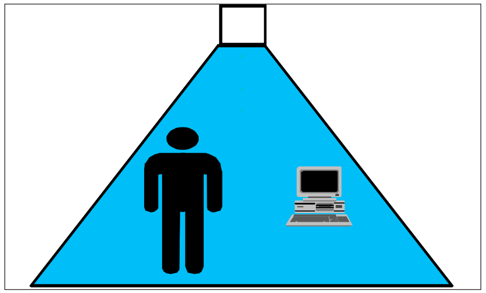
Scenarios of intra-building connections

- Point-to-point LOS link→ coverage, robustness, mobility → steered beams or wide beams
- Blocking → NLOS diffuse link → reconfigurable beams

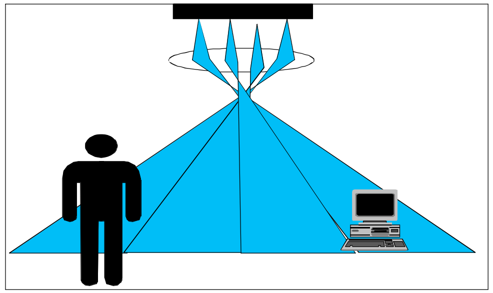
- Directed LOS



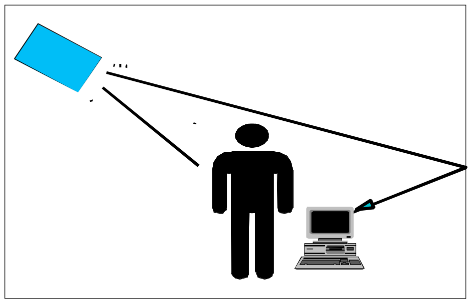
- Non-directed LOS



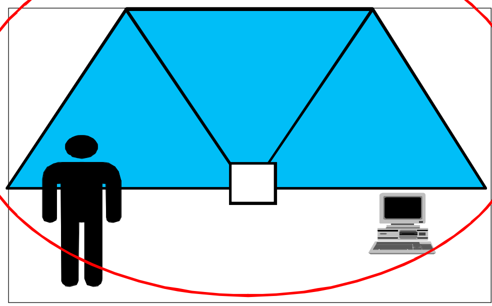
- Switched-beam LOS



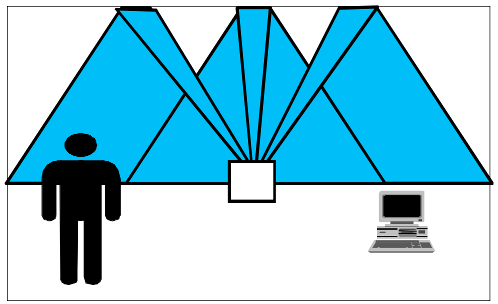
- LOS + NLOS



- Non-directed NLOS



- Multi-spot NLOS

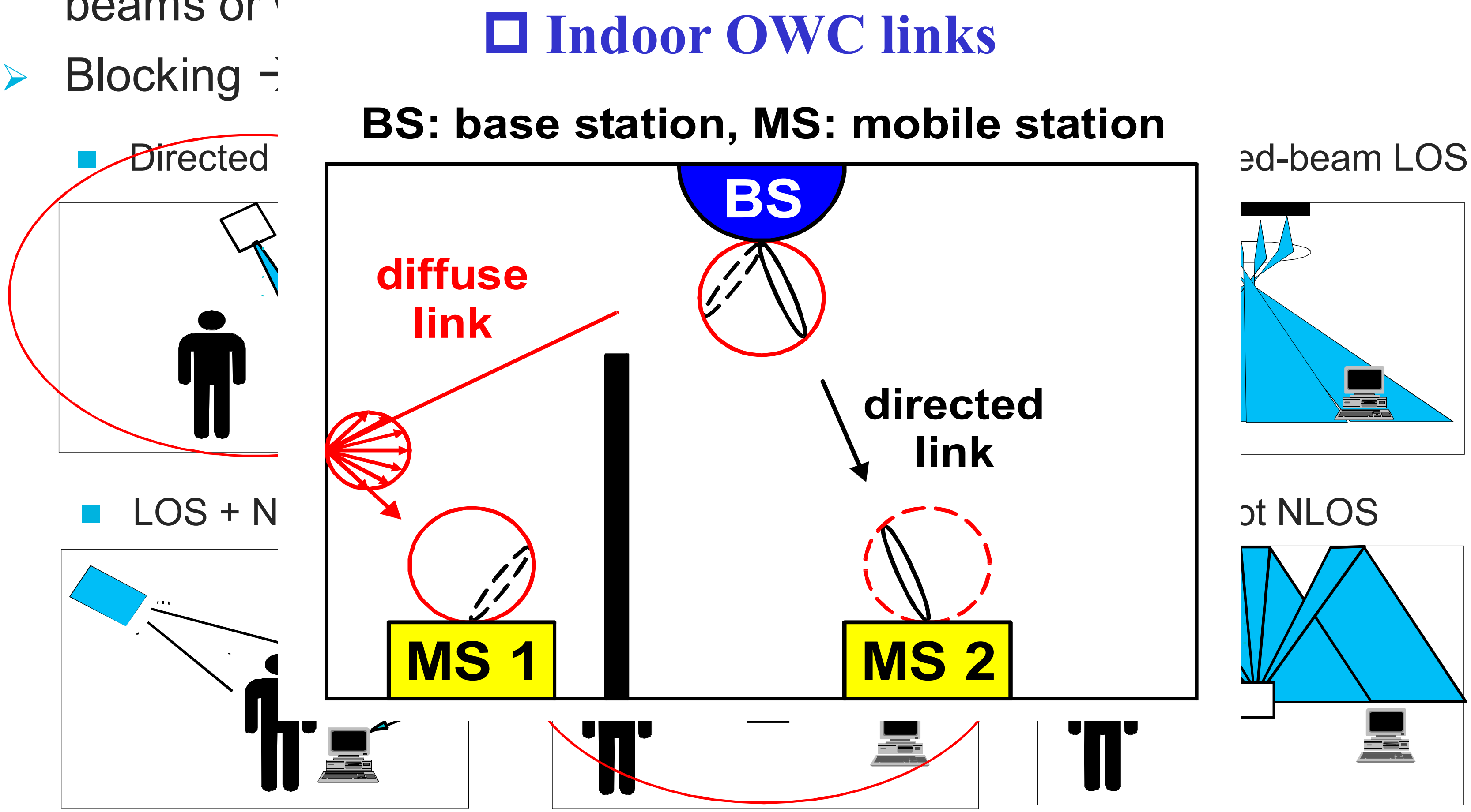


[https://mentor.ieee.org/802.15/dcn/15/15-15-0112-02-007a-short-range-optical-wireless-communications-tutorial.pdf.]

OWC Technologies

□ Scenarios of intra-building connections

- Point-to-point LOS link→ coverage, robustness, mobility → steered beams or
- Blocking →

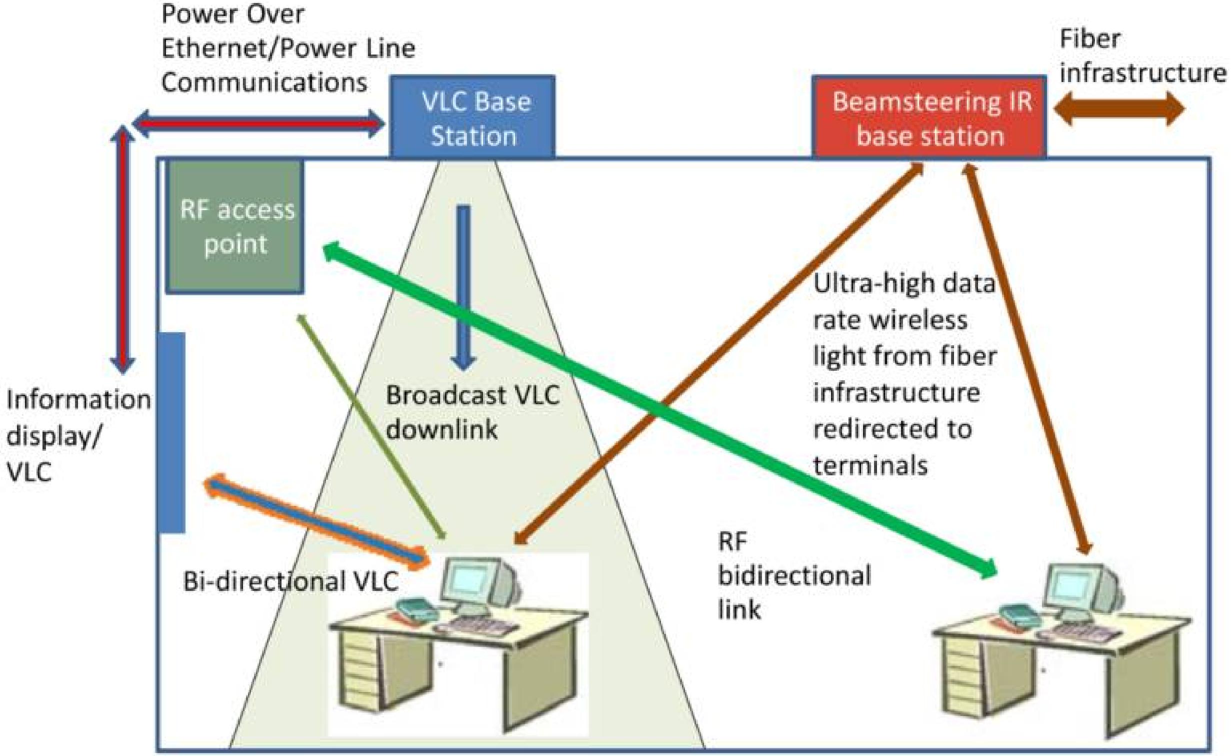


[https://mentor.ieee.org/802.15/dcn/15/15-15-0112-02-007a-short-range-optical-wireless-communications-tutorial.pdf.]

Indoor OWC Technologies

☐ Typical indoor OWC technologies

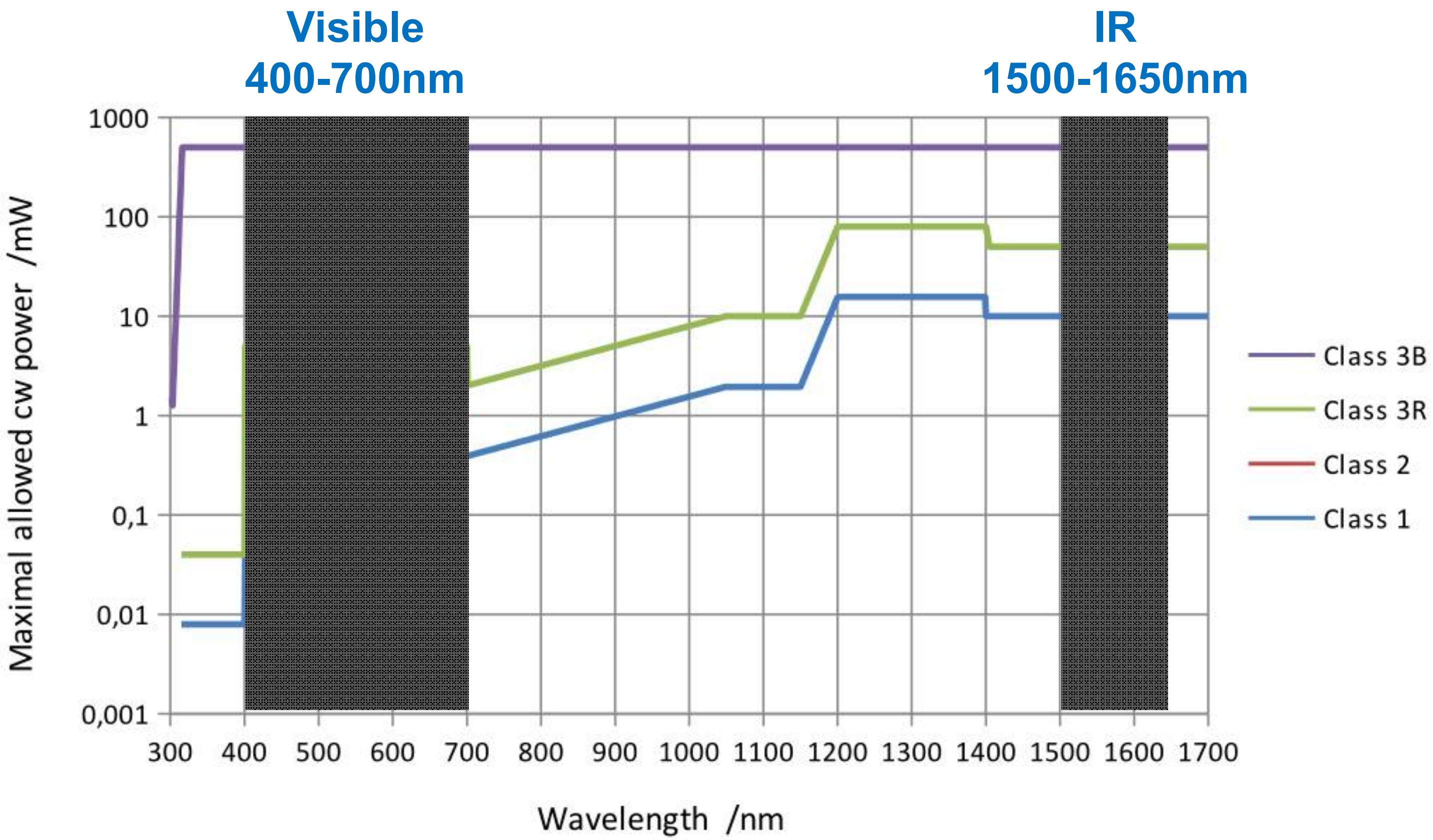
- ✓ Visible Light Communication (VLC), more specifically known as LiFi
- ✓ Beam-steered Infrared Light Communication (BS-ILC)



[D. C. O'Brien, in Proc. IEEE Summer Top., Newport Beach, CA, USA, Jul. 11, 2016.]
[T. Koonen, JLT, 36(8): 1459-1467, 2018.]

Indoor OWC Technologies

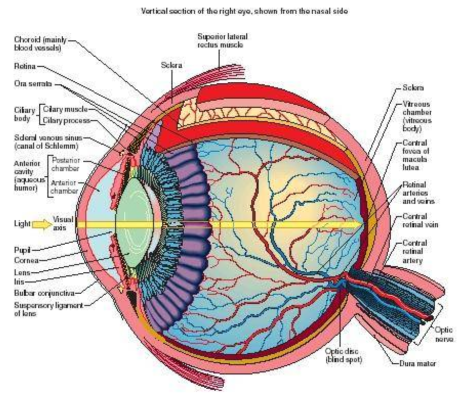
- Acc. to IEC 60825-1:2007
  for static, point-like laser sources (i.e. collimated or weakly divergent laser beams)



- For λ > 1400 nm max. CW beam power of 10mW allowed for class 1 laser
- For λ > 400 nm to 700 nm max. CW beam power of <1mW allowed for class 1 laser

Indoor OWC Technologies

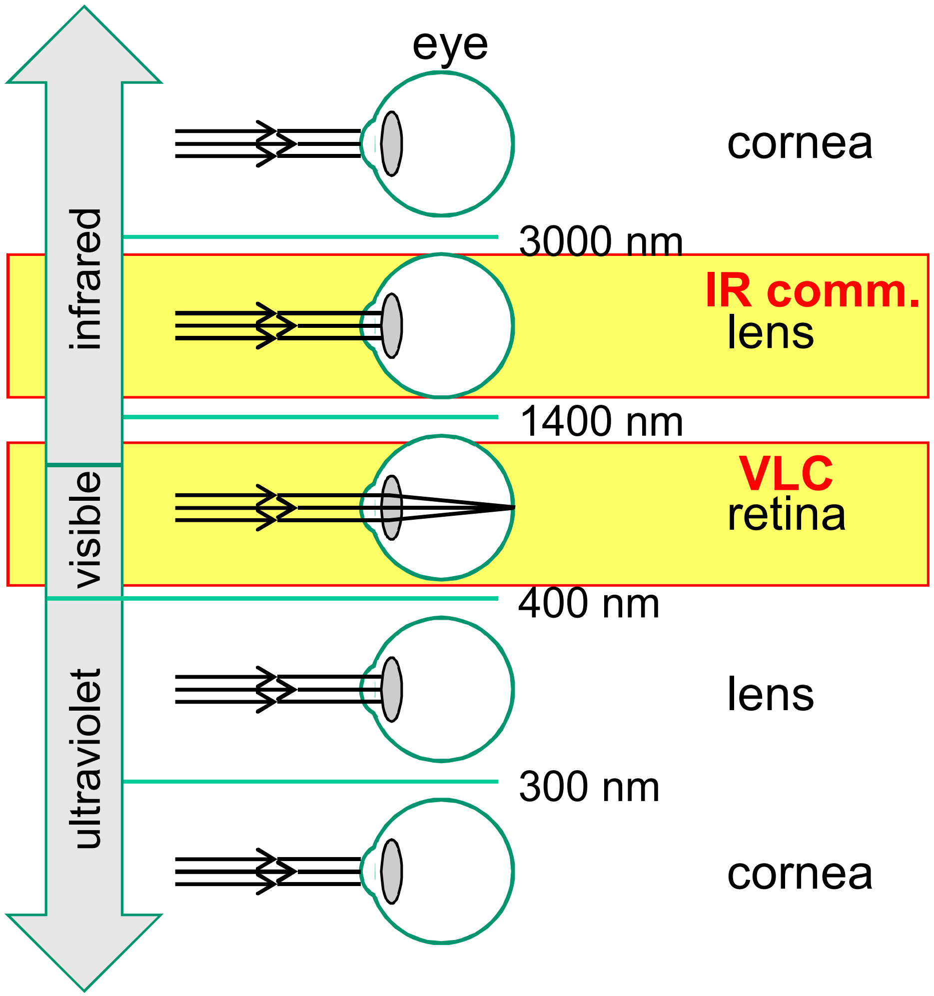
Eye safety consideration



✓ **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 ($R \propto \lambda$)
- less interference from visible light



Indoor OWC Technologies

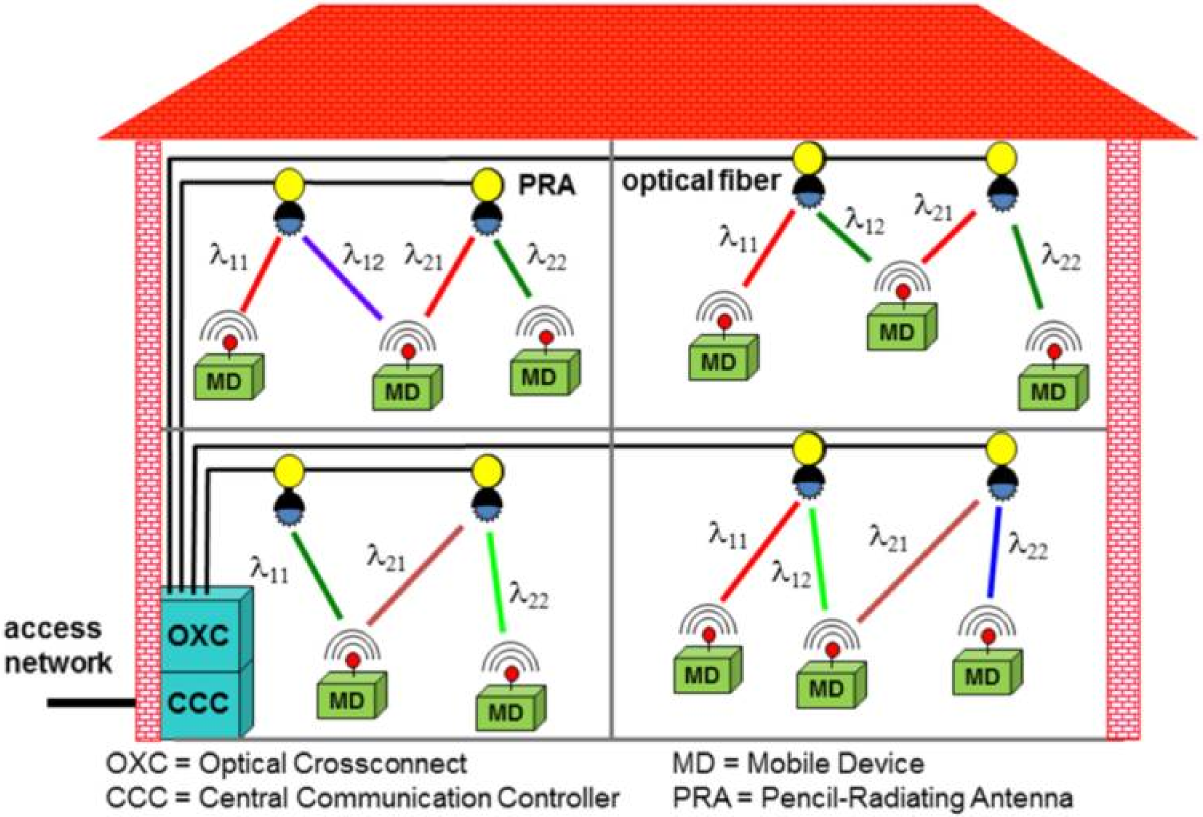
❑ OWC compared with WiFi suite

[T. Koonen, JLT, 36(8): 1459-1467, 2018.]

	BS-ILC	VLC	WiFi IEEE802.11
Carrier Frequency	1460nm-1625nm (width 20.9THz)☺	400nm-700nm (width 320THz) ☺	2.4GHz (83.5MHz); 5GHz (575MHz); 60GHz (7GHz)☹
Typical Capacity per User	**Unshared:** Very high (112Gb/s per beam) ☺	Shared: 9.5Gb/s over 1m ☹	Shared: ☹ 802.11n (2.4GHz):<600Mb/s 802.11ac (5GHz):<6.93Gb/s 802.11ad (60GHz):<7Gb/s
Reach	Medium (10m) ☺	Short (few m) ☺	Medium ☺
Energy consumption	Low (per beam <10mW) ☺	High (Watts): lighting and communication ☹	Base station >100mW ☹
Infrastructure	Share FTTH infra	Share LED illumination	Electrical cable (Cat5) infra
Standardization	Included in IEEE 802.11 bb	First steps made IEEE 802.11 LC	Extensive, mature, keeps evolving
Utilization	Lab phase	Products on market	Very wide-spread, >50% of internet traffic through WiFi

Concept of beam steered ILC

- Concept of indoor OWC deploying 2D beam steering



- Multiple pencil-beam radiating antennas (PRAs) in one room
- Compatible with current fiber system
- λ-controlled
- Wavefront shaping

[T. Koonen, et al., High-Capacity Optical Wireless Communication Using Two-Dimensional IR Beam Steering, JLT, 36(19): 4486-4493, 2018.]

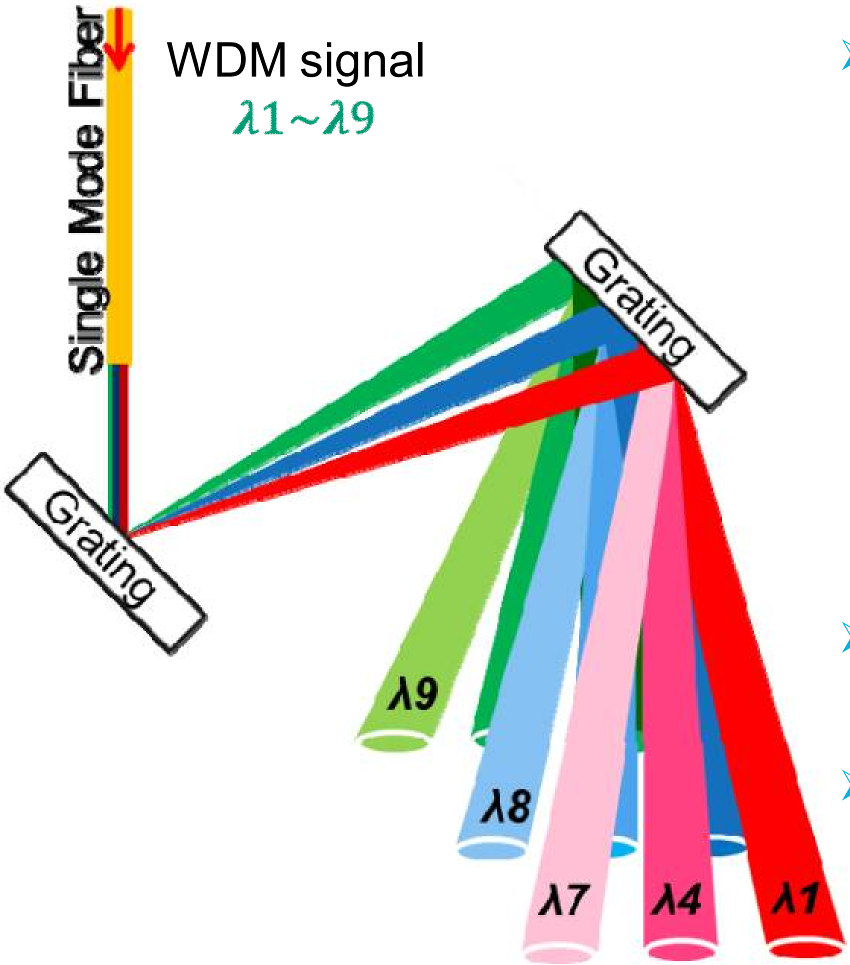
□ Based on Passive Devices (λ-controlled)

① Grating

② AWGR+fiber array

Beam steered ILC under LOS Link

□ 2D steering with cascaded gratings



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

- Diffraction grating: disperse light spatially by wavelength

$$m\lambda = d(sin\theta_i \pm sin\theta_m)$$

λ: wavelength of input beam
d: period of the grating
m: order of diffraction
θ_i: angle of incidence
θ_m : angle of reflectance

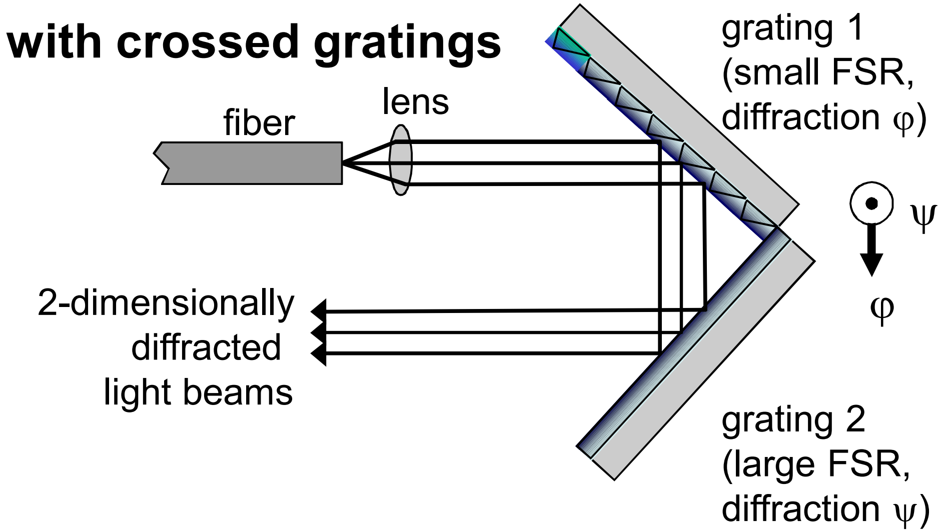
- Blazed grating: maximize optical power in a desired diffraction order or angle
- Orthogonally cascaded two gratings:

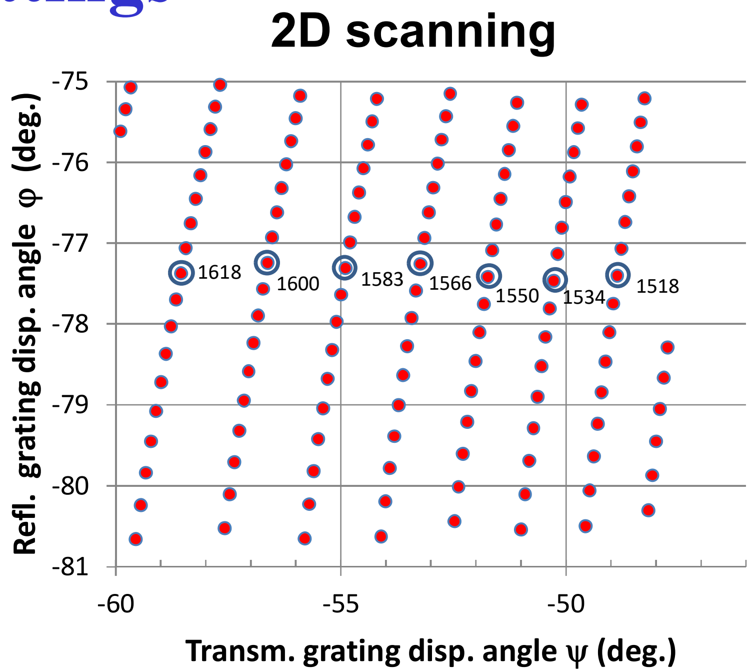
$$FSR = \lambda_m/(m+1)$$

$$FSR1 < 2 \cdot FSR2$$

Beam steered ILC under LOS Link

2D steering with cascaded gratings





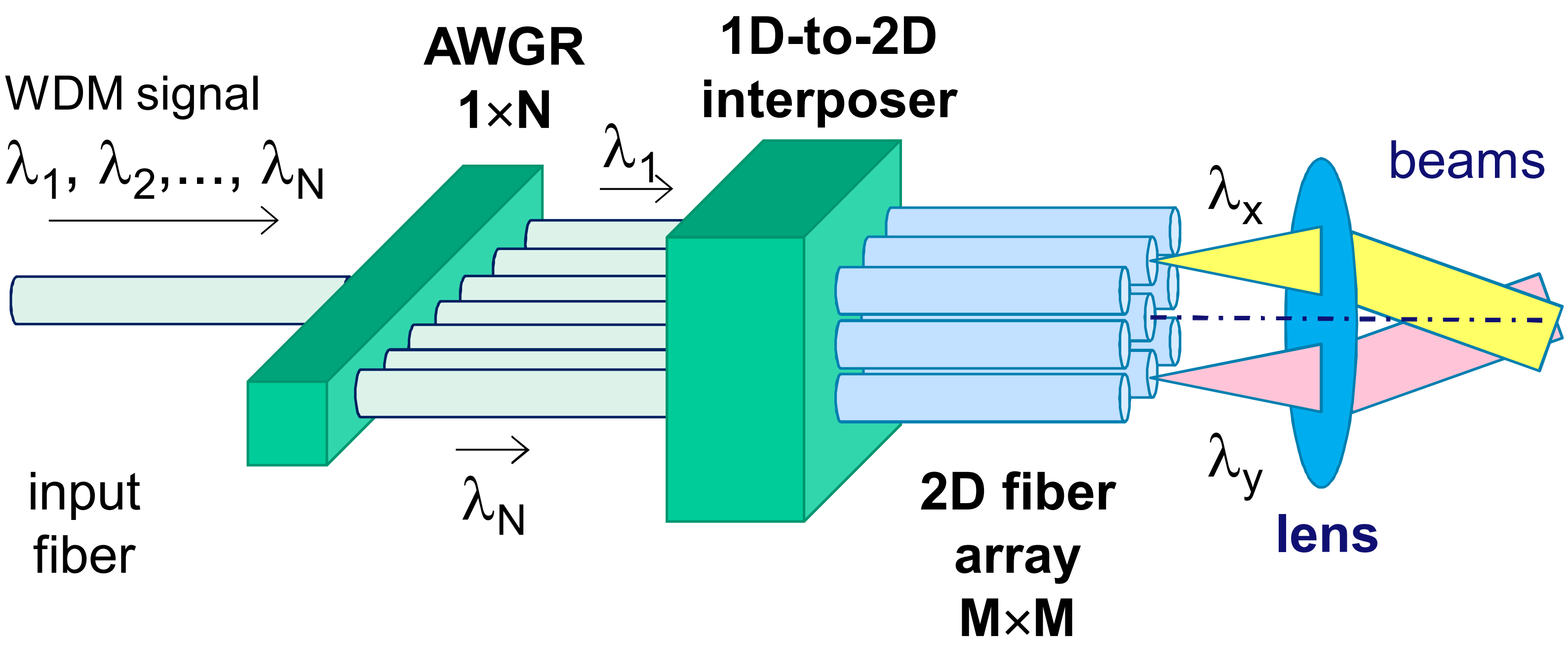
- Fully **passive** device
- Deploys **only wavelength tuning**
- λ scan range is smaller than FSR_2 , and comprises **multiple FSR_1-s**
- May **simultaneously steer multiple beams** (by multi-λ inputs)

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

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

Beam steered ILC under LOS Link

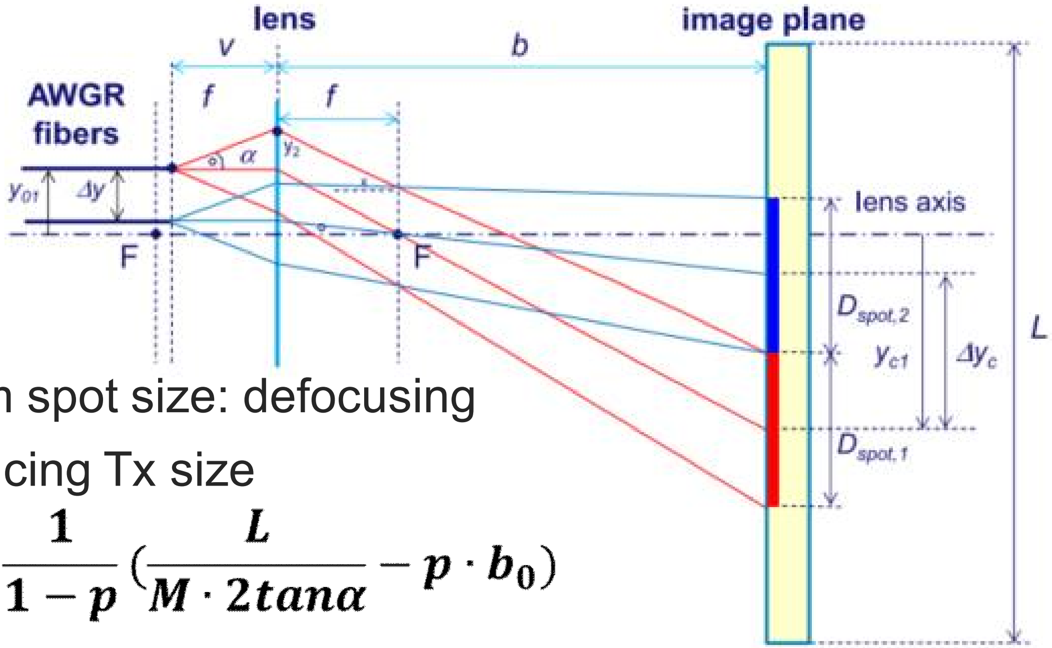
- 2D steering with high port-count Arrayed Waveguide Grating Router (AWGR)



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

Beam steered ILC under LOS Link

□ 2D steering with AWGR+Fiber array



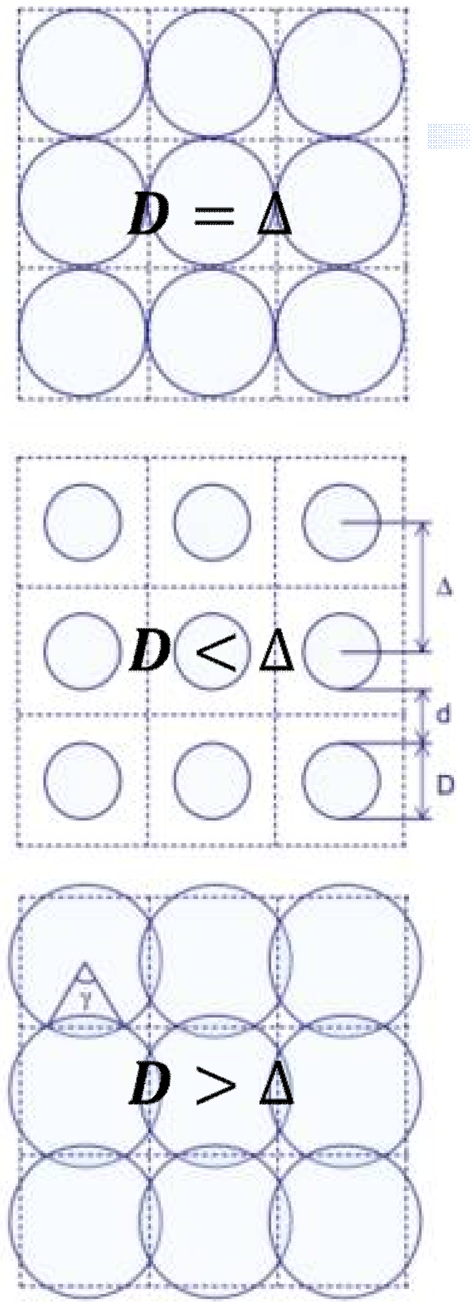
- Beam spot size: defocusing
- Reducing Tx size

$$f = \frac{1}{1-p}\left(\frac{L}{M \cdot 2tan\alpha} - p \cdot b_0\right)$$

$$D_{spot}(b) = 2tan\alpha \cdot \{f + p(b - f)\}$$

$$\frac{dD_{spot}(b)}{db} = 2p \cdot tan\alpha$$

- angular tuning over 17°×17°
- 112 Gb/s per beam, 80 beams



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

□ Based on Active Devices (Wavefront shaping)

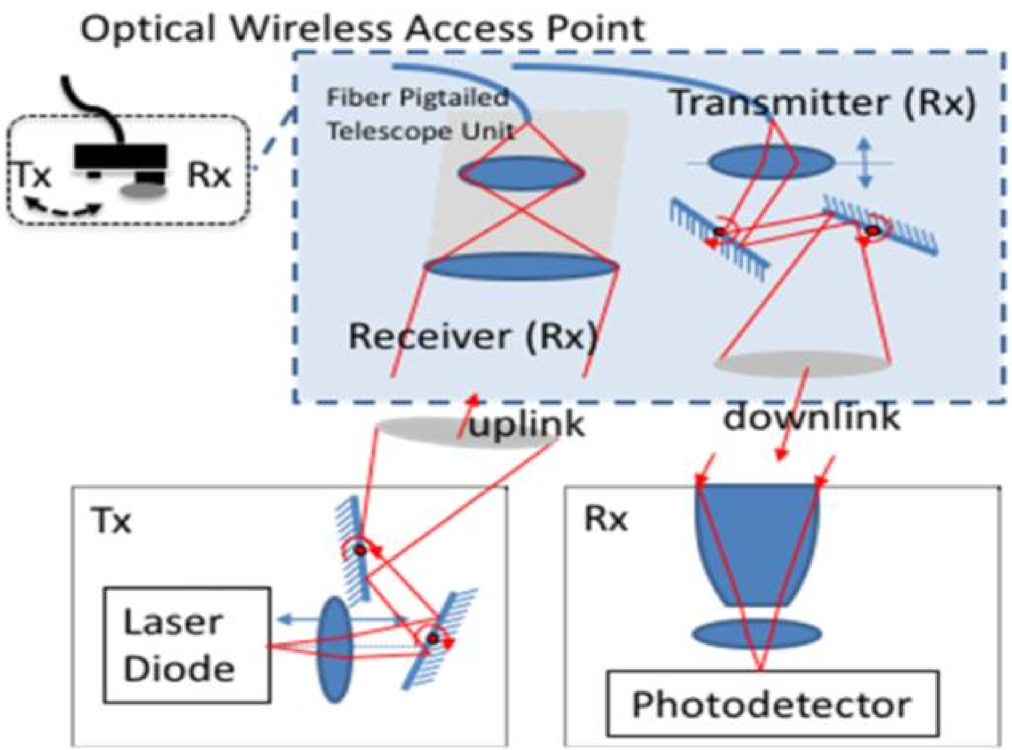
① MEMS

② SLM+Optics

③ MMF+Optics

Beam steered ILC under LOS Link

2D steering with MEMS



Optical wireless access network architecture using a pair of mirrors.

- Proposed in 2010 by Ke Wang et al., OE, 18(24)
- Integrate an optical fiber-based local area network
- Full duplex transmission
- Downlink: a pair of steering mirrors+Lens, electronically controlled at the Tx

  Lens+CPC at the Rx
- Similar structure for uplink
- 10 Gb/s for downlink and 2Gb/s for uplink
- angular tuning over 20°×20°

[Ke Wang et al., OSA OE, 18(24), 2010; P. Brandl et al., IEEE PTL, 25(15), 2013]

Beam steered ILC under LOS Link

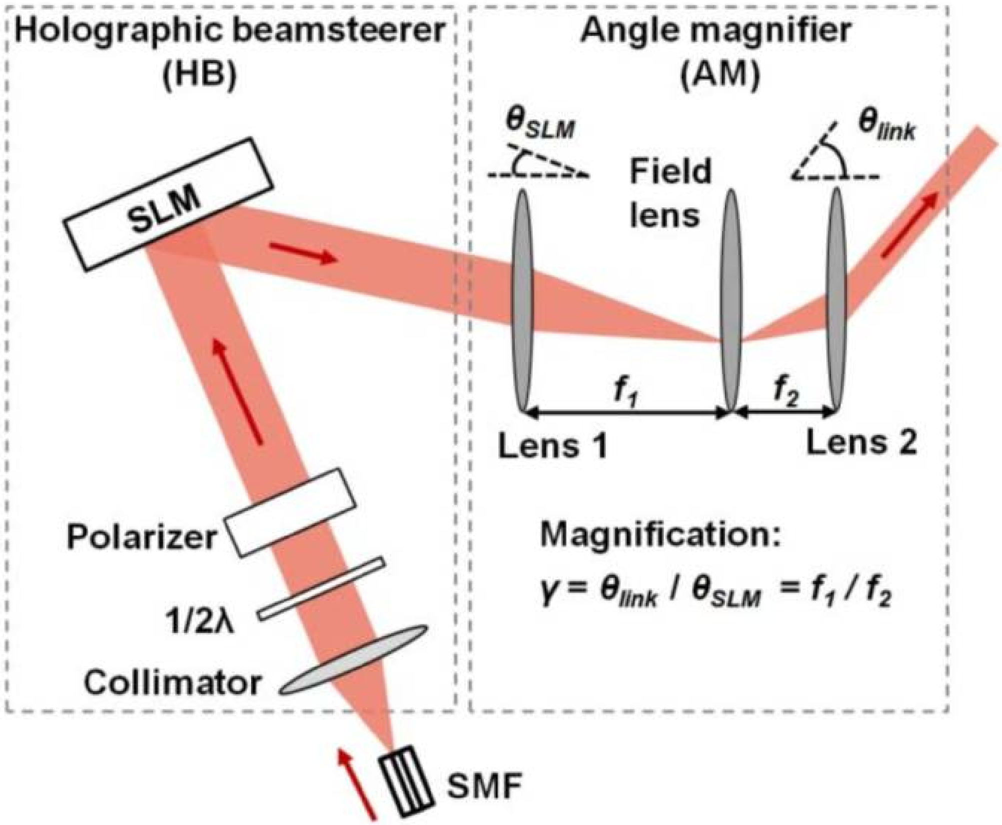
☐ 2D steering with SLM+optics

- Proposed in 2014 by D. O'Brien
- Signal from an optical fiber-based local area network
- Full duplex is feasible
- SLM is used as a blazed grating

$$\theta_{SLM} = \operatorname{asin}\frac{\lambda}{2p}$$

p=15μm, $\theta_{SLM} \approx 3°$; p=4.5μm, $\theta_{SLM} \approx 10°$

- Optical angle magnification (AM) is needed, $\gamma = 10$
- Coherent 400 Gb/s for downlink
- angular tuning over 30°×30°



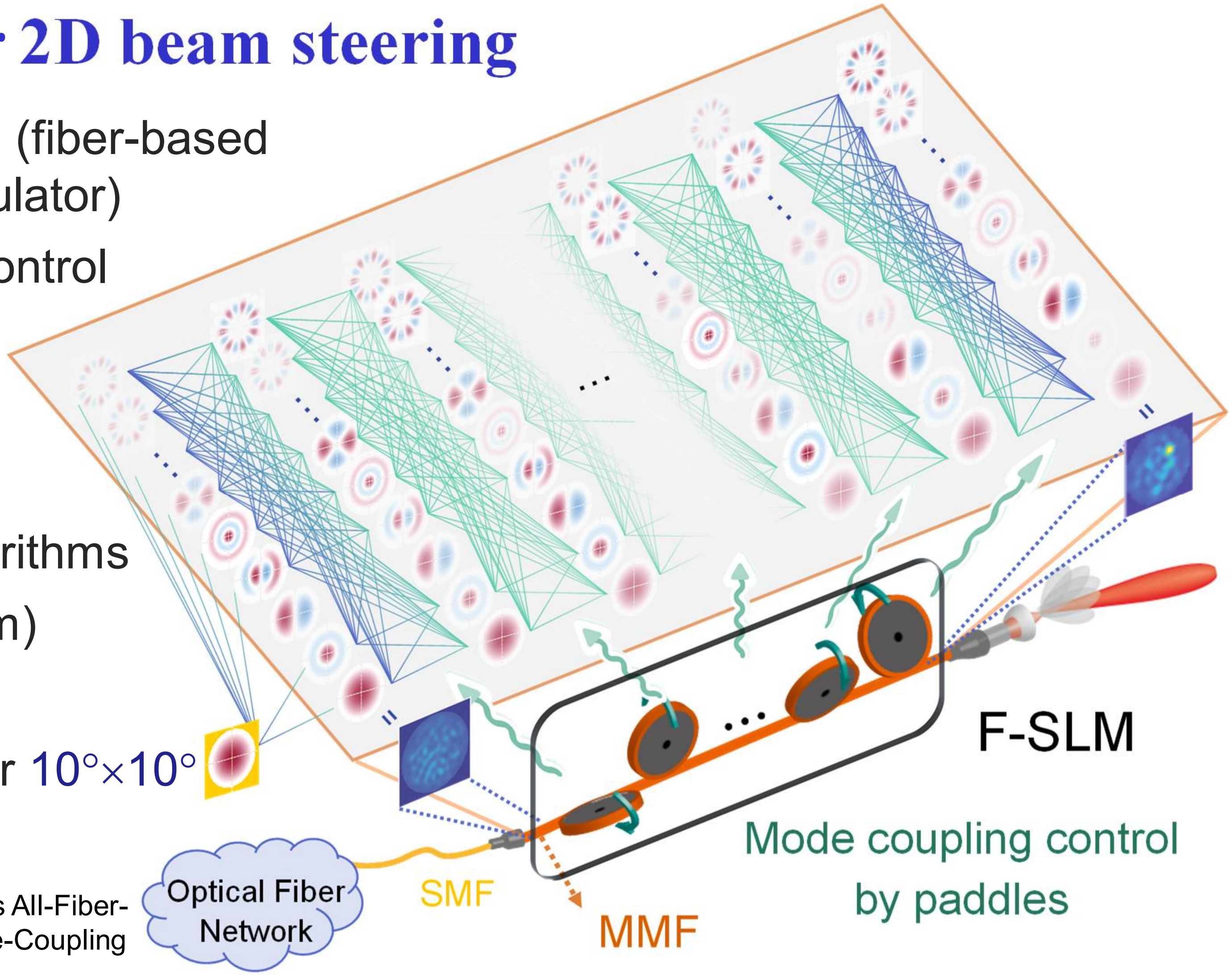
System schematic of SLM-based 2D beam steering

[Dominic O'Brien et al., PTL, 27(4), 2015; JLT, 34(22), 2016]

Beam steered ILC under LOS Link

☐ F-SLM for 2D beam steering

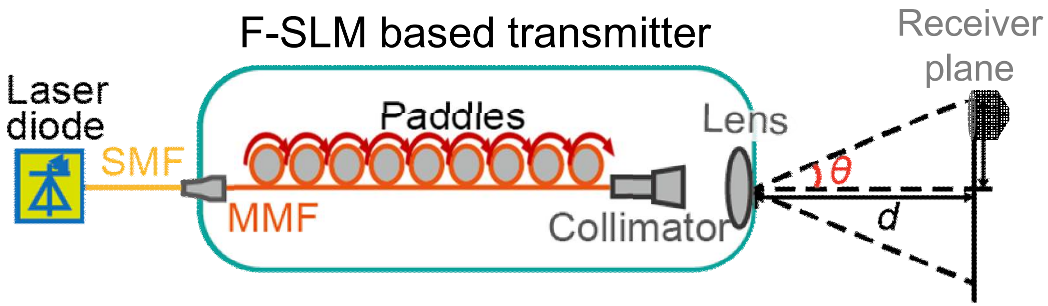
- Proposed F-SLM (fiber-based spatial light modulator)
- Mode coupling control
- Low-cost
- Fiber-compatible
- Combined with optimization algorithms (Genetic Algorithm)
- IM/DD 10 Gb/s
- angular tuning over 10°×10°



[Y. Zhang#, Chao Li#, et al., 10-Gb/s All-Fiber-Beamforming LiFi System via Mode-Coupling Control, CLEO'2021]

Beam steered ILC under LOS Link

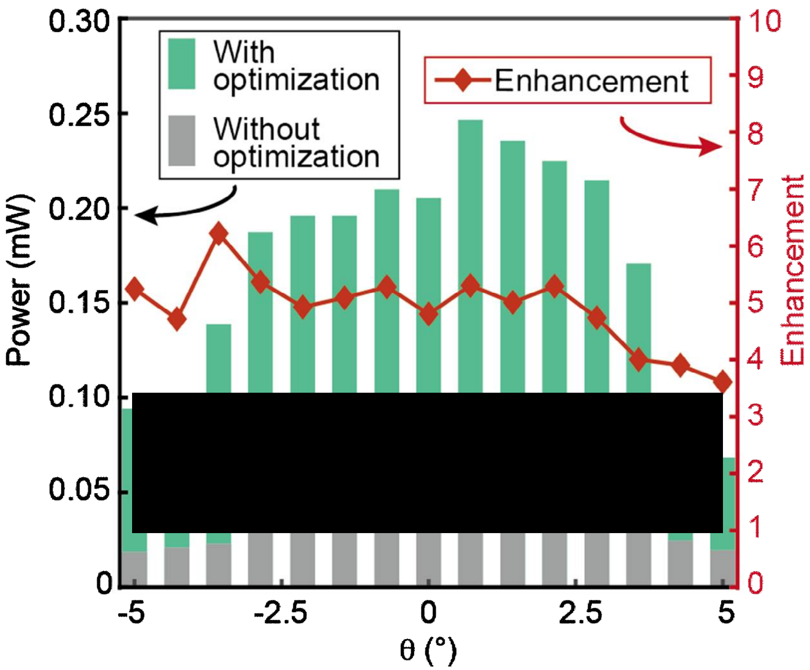
❑ F-SLM for 2D beam steering

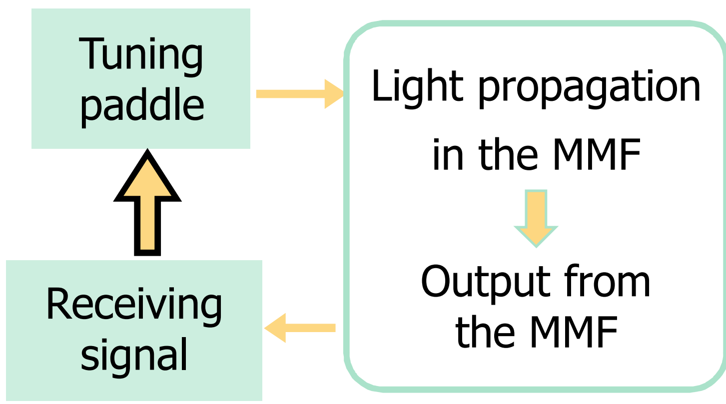


F-SLM with 9-paddle

λ at 1550 nm

$d = 0.8$ m

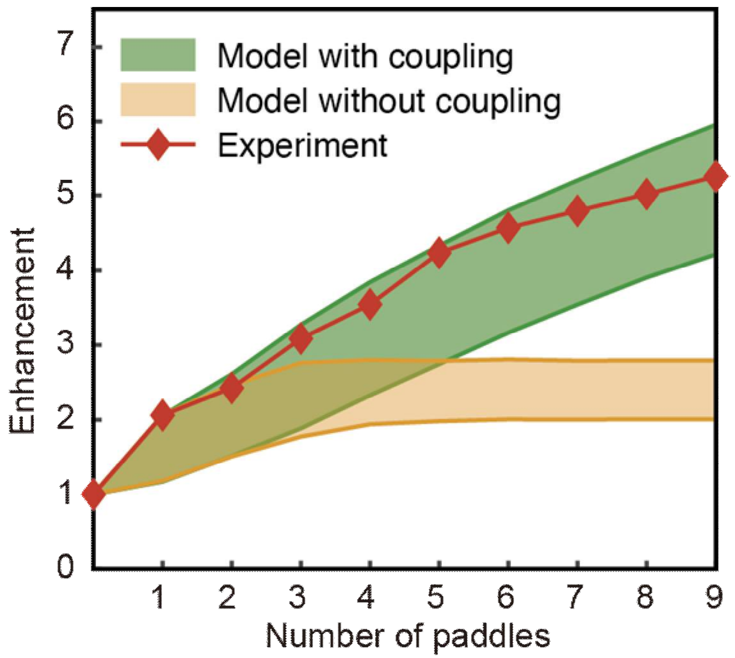




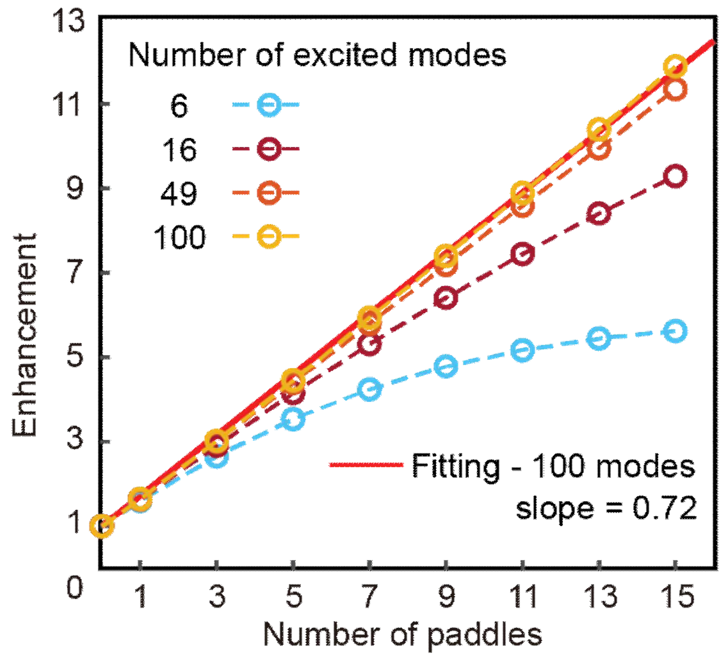
- Feedback-loop optimization

Beam steered ILC under LOS Link

- The enhancement is reliable and scalable
- Mode coupling control is essential
- More paddles → More enhancement ← More modes



(30 modes are excited)



Beam steered LOS-ILC

☐ Comparison of beam steering technologies

Technology	Scalability of number of beams	FoV coverage	Steering speed	Active/passive module	Cost
2D grating	High	6°×12°	High	Passive	Low
AWGR+fiber array	Medium	17°×17°	High	Passive	Medium
MEMS mirrors	Low	20°×20°	Low	Active	Medium
SLM+optics	Low	3° (w/o Optics) 30°×30°	Medium	Active	High
MMF	Low	10°×10°	Medium	Active	Very Low

□ Integrated circuits in BS-ILC

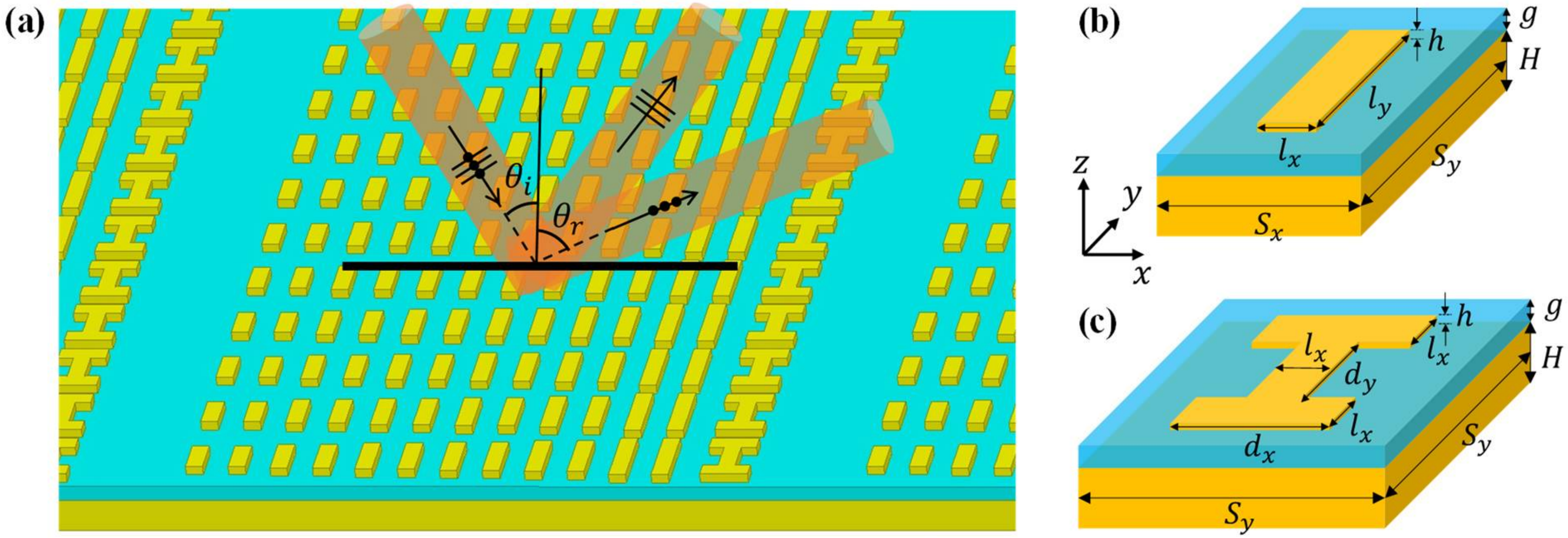
① Metasurface

② Cascaded optical pre-amplifier receiver

③ Ultra-low power consumption OWC receiver

Integrated circuits in BS-ILC

□ Design and frabricate a Metasurface chip

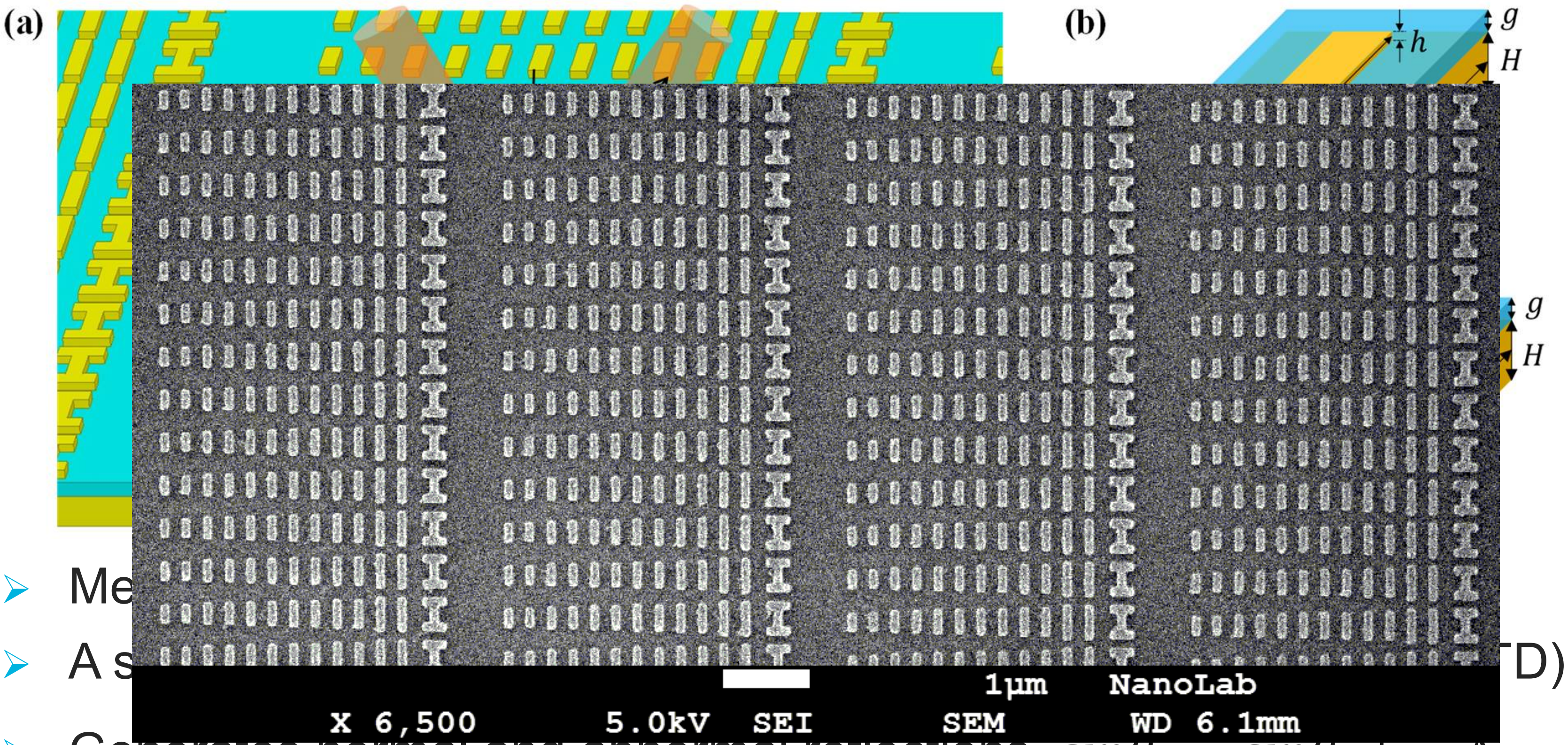


- Metasurface: polarization beam splitter
- A super cell consists of eight phase units to cover 2π phase (FDTD)
- Generates normal and abnormal reflections, $sin\theta_r = sin\theta_i + \frac{\lambda}{\Lambda}$, $\Lambda = 4\mu m$
- Adjust the polarization states to change the power distribution

[J. Huang#, Chao Li#, et al., LPR, 15, 2000266, 2021]

Integrated circuits in BS-ILC

□ Design and frabricate a Metasurface chip



- Me
- A s … TD)
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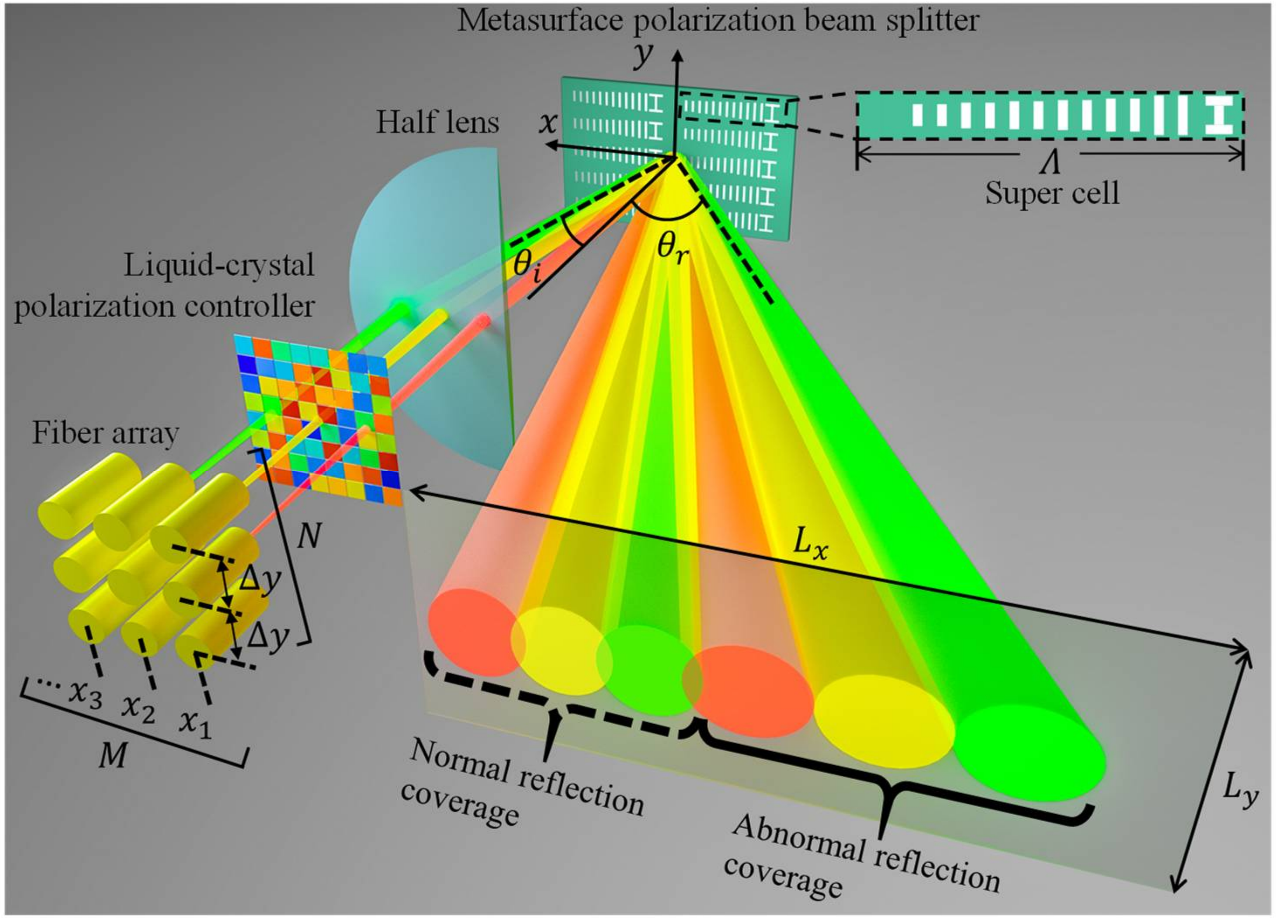
[J. Huang#, Chao Li#, et al., LPR, 15, 2000266, 2021]

Integrated circuits in BS-ILC

□ Implementation on the 2D beam steering system



- Metasurface+AWGR +fiber array
- Double the coverage
- 20 Gb/s per beam

[J. Huang#, Chao Li#, et al., LPR, 15, 2000266, 2021]

Integrated circuits in BS-ILC

□ Design of a two-stage cascaded SOA-PIN receiver

- For a cascaded m-section optical preamplifers, the total noise figure (NF):

$$NF_{total} = NF_1 + \frac{NF_2 - 1}{G_1} + ... + \frac{NF_m - 1}{G_1 G_2 ... G_{m-1}}$$

- Total gain: $G_{total} = G_1 + G_2 + G_3 + ...G_m$

- For the m-th section, the NF_m is:

$$NF_m = 10log_{10}(\frac{2\rho_{ASE}}{G_m hv} + \frac{1}{G_m}) \quad NF_m \approx 10log_{10}\frac{2N_{c,m}}{N_{c,m} - N_{0,m}}$$

- When the NF_{m+1} and G_{m+1} are fixed, increasing injection current in the *m*-th stage will increase G_m. The increased G_m then decrease the contribution of the NF_m in NF_{total}. As a result, by adjusting the injection current of each stage, the total NF is reduced.

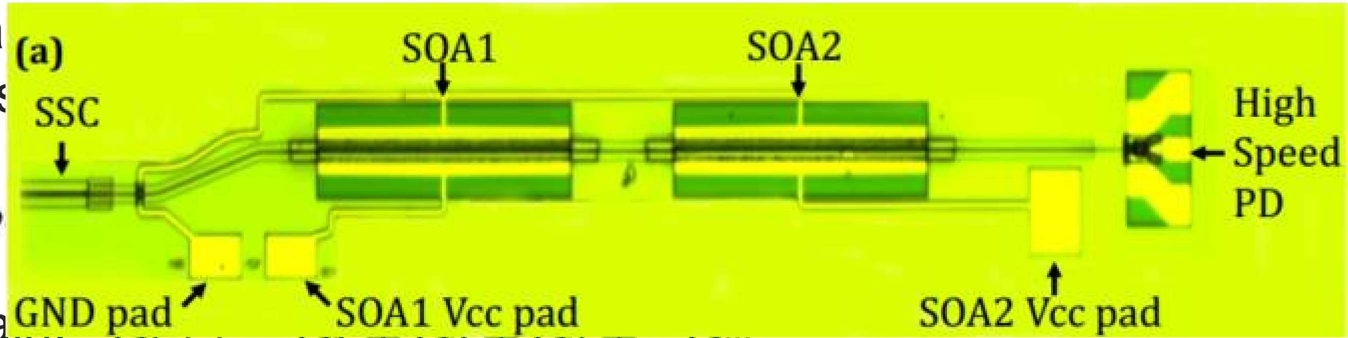
[Y. Lei, Chao Li*, et al., Accepted by OL]

Integrated circuits in BS-ILC

Design of a two-stage cascaded SOA-PIN receiver

- For a ca
total nois

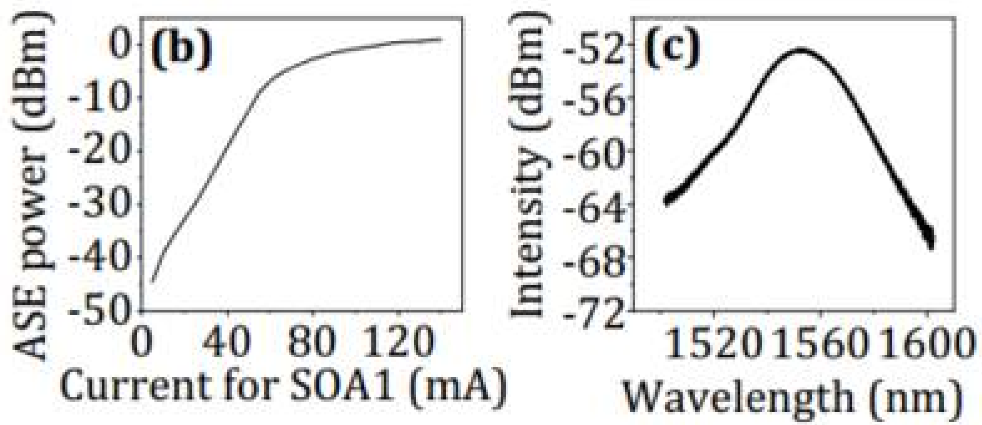
NF_{to}



- Total ga... $G_{total} = G_1 + G_2 + G_3 + \ldots G_m$

- For the m-th s

$NF_m = 10l$



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[Y. Lei, Chao Li*, et al., Accepted by OL]

Integrated circuits in BS-ILC

System performance for a 10 Gb/s OWC link

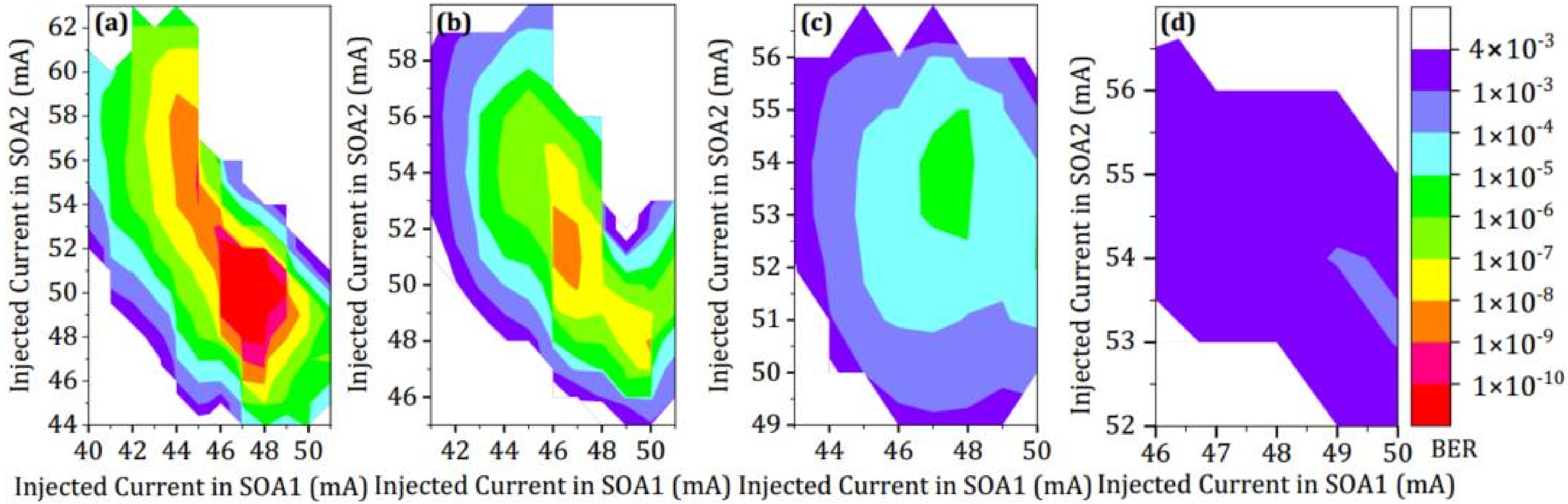


Table 1. BER performance at different combination schemes

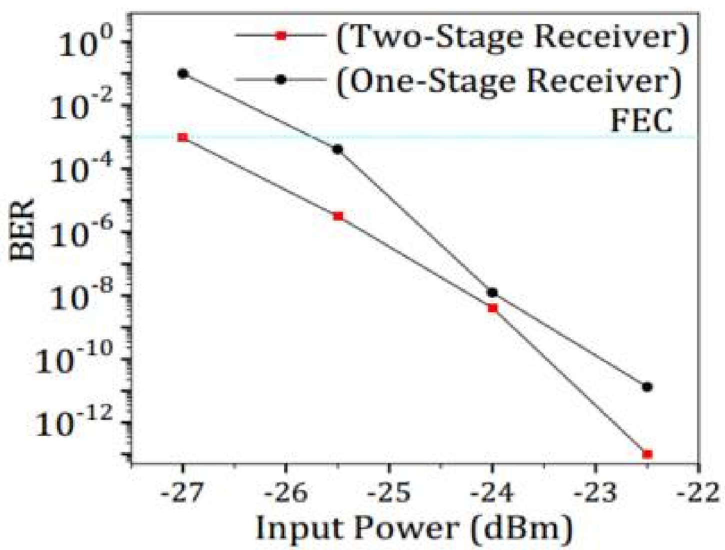
Input Power (dBm)	SOA1+SOA2 (mA)	BER
-22.5	47+50	1×10^{-13}
	41+50.2	1×10^{-3}
-24	46+52	4.15×10^{-9}
	43+49.5	1×10^{-3}
-25.5	47+54	3.17×10^{-6}
	45+50	9.75×10^{-4}
-27	50+53	9.22×10^{-4}

- Maximizing the Receiver's Power Efficiency
- Maximizing the Receiver's Sensitivity

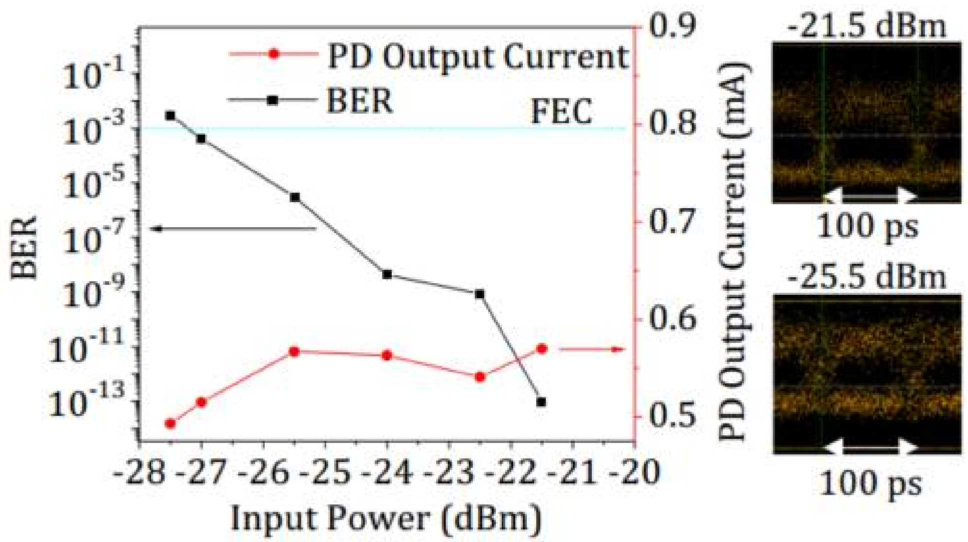
Integrated circuits in BS-ILC

☐ BER performance for a 10 Gb/s OWC link

- 1.5 dB receiver sensitivity improvement



- -27.5 dB receiver sensitivity @ BER=3.1×10^{-3}



□ NLOS BS-ILC Using

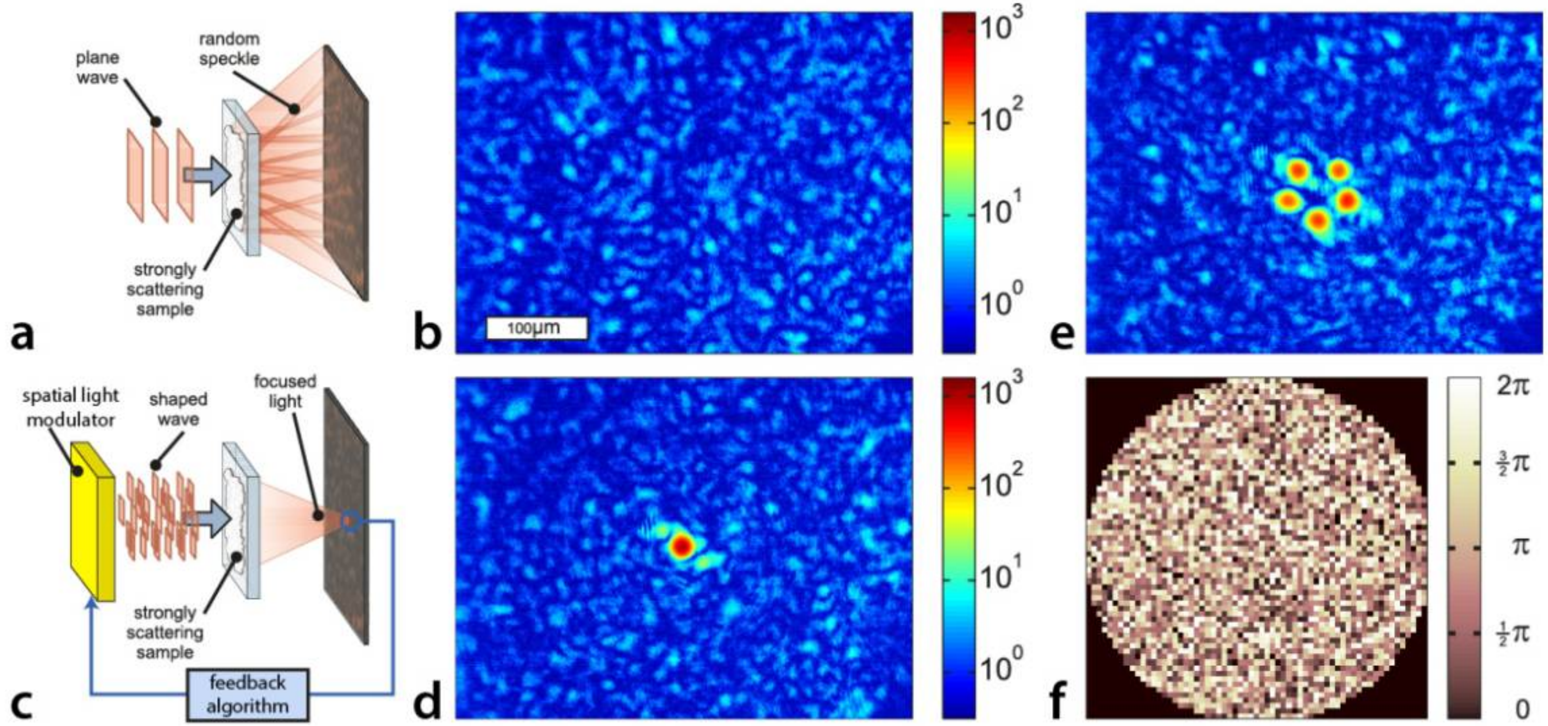
SLM + Genetic Algorithm (GA)

for Wavefront Shaping

Beam steered ILC under NLOS Link

- Light focusing through scattering media （散射成像）
- Proposed by Vellekoop in 2007

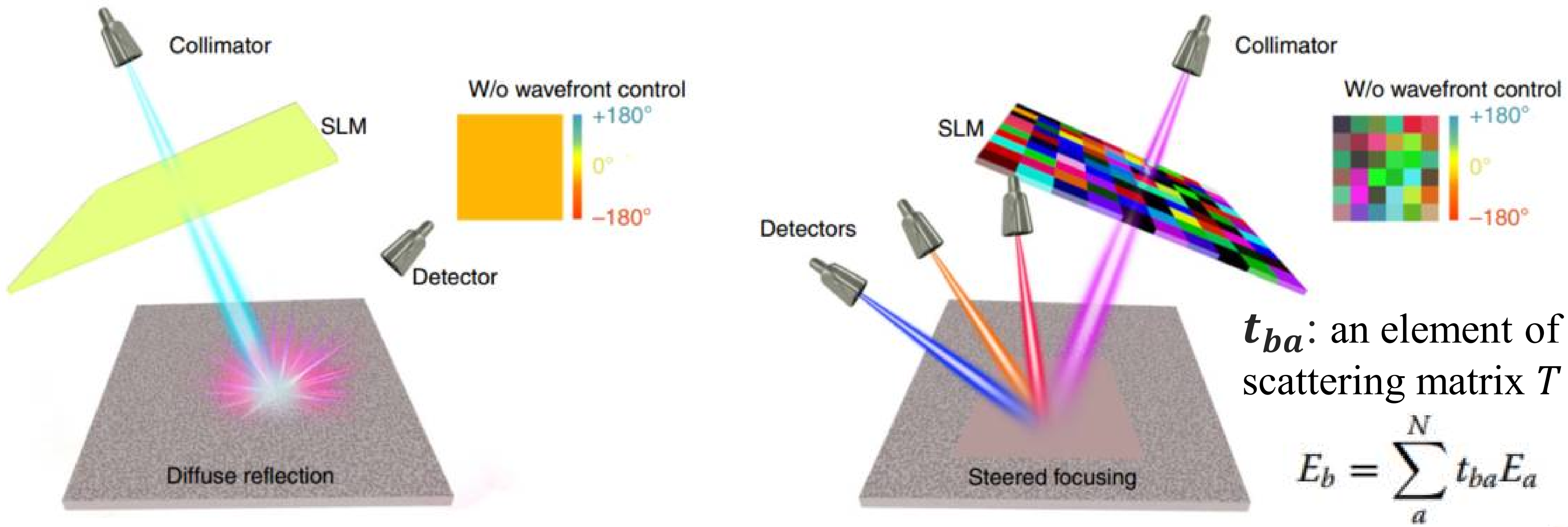
	citations	years
Focusing coherent light through opaque strongly scattering media IM Vellekoop, AP Mosk Optics letters 32 (16), 2309-2311	1487	2007



- I. Vellekoop Grpup: NP, **4**, 320, 2010; Nature, **491** (7423), 2012; NP, **6**, 283, 2012
- Researchers: NC, **1**, 2010; NP, **5**, 335, 2011; NP, **7**, 188, 2013; NP, **8**, 784, 2014;

Beam steered ILC under NLOS Link

☐ Building a NLOS link based on scattering focusing



$\boldsymbol{t_{ba}}$: an element of scattering matrix T

$$E_b = \sum_{a}^{N} t_{ba} E_a$$

$$I_b(\theta_a) \equiv |E_b|^2 = \left| E_{ref} + t_{ba} E_a e^{i\theta_a} \right|^2$$

- The transmitted beam is blocked
- NLOS: the light directed to a diffuse reflection ceiling or wall
- SLM: control over the phase of field E_a

$\boldsymbol{E_a}$: field of input beam

$\boldsymbol{E_b}$: field of scattered beam

$\boldsymbol{\theta_a}$: phase of a single segment on SLM $\in [0\ 2\pi]$

[Z. Cao, et al., **8**, 69, 2019; X. Zhang, et al., **38**, 6801, 2020]

Beam steered ILC under NLOS Link

□ Building a NLOS link based on scattering focusing

Cao et al. *Light: Science & Applications* (2019)8:69
https://doi.org/10.1038/s41377-019-0177-3

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ARTICLE **Open Access**

Reconfigurable beam system for non-line-of-sight free-space optical communication

Zizheng Cao[1], Xuebing Zhang[1], Gerwin Osnabrugge[2], Juhao Li[3], Ivo M. Vellekoop[2] and Antonius M. J. Koonen[1]

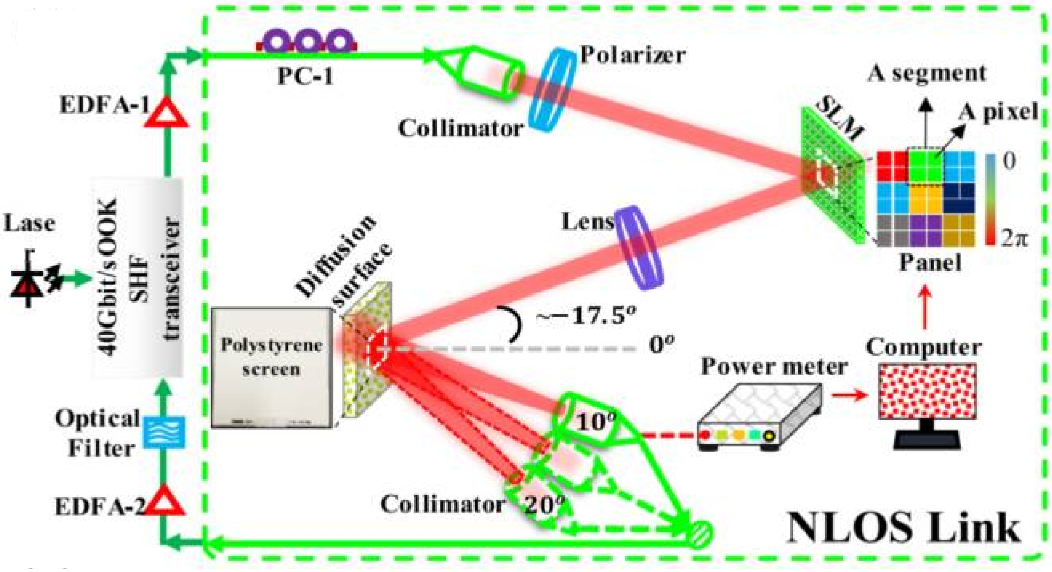
Abstract

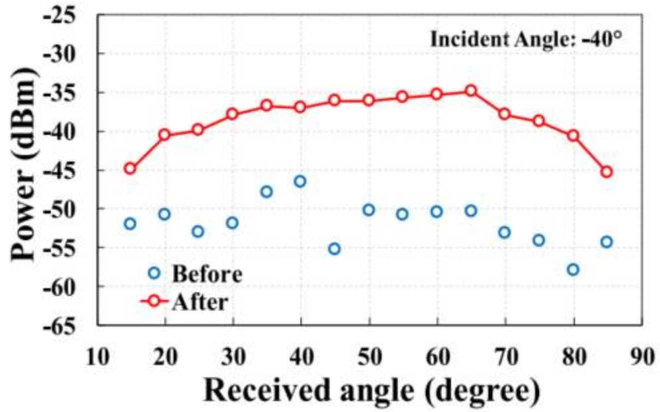
➢ In this paper, we propose a reconfigurable beam-shaping system to permit energy-efficient non-line-of-sight (NLOS) free-space optical communication. ➢ Light is steered around obstacles blocking the direct communication pathway and reaches a receiver after reflecting off of a diffuse surface. A coherent array optical transmitter (CAO-Tx) is used to spatially shape the wavefront of the light incident on a diffuse surface. Wavefront shaping is used to enhance the amount of diffusely reflected light reaching the optical receiver. Synthetic NLOS experiments for a signal reflected over ➢ an angular range of 20° are presented. A record-breaking 30-Gbit/s orthogonal frequency-division multiplexing signal is transmitted over a diffused optical wireless link with a >17-dB gain.

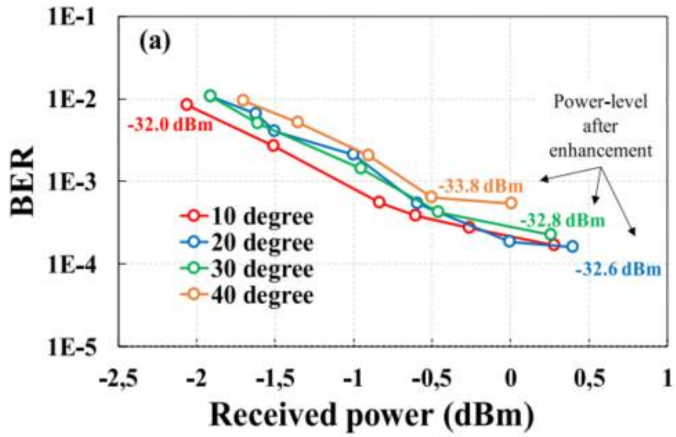
[Z. Cao, et al., **8**, 69, 2019; X. Zhang, et al., **38**, 6801, 2020]

Beam steered ILC under NLOS Link

40 Gb/s NLOS link with wide FoV





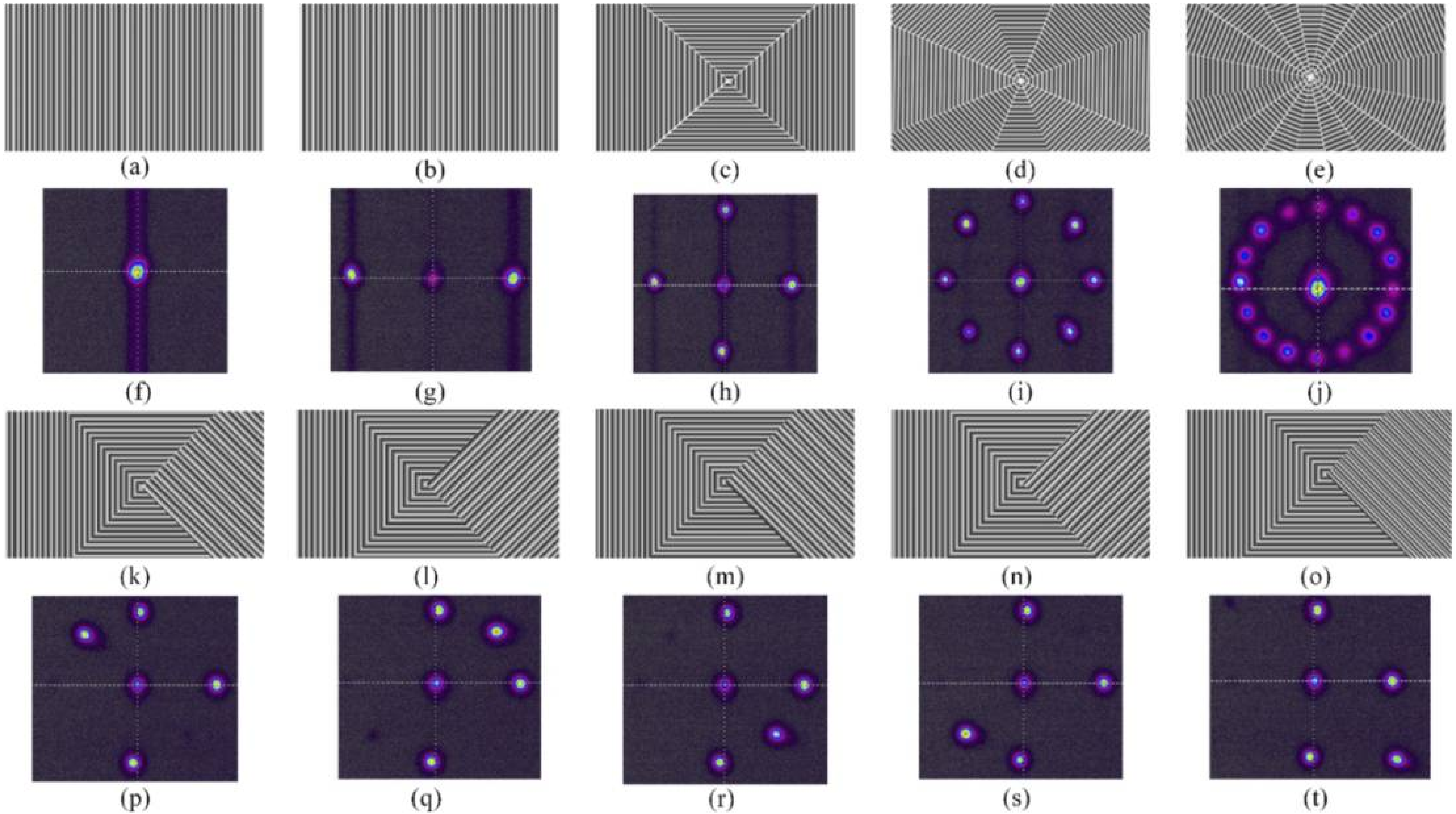


- 40 Gb/s IM/DD OOK signal
- Proposed transfer matrix (TM) algorithm
- 18 dB enhancement
- ±40° FoV

[Z. Cao, et al., **8**, 69, 2019; X. Zhang, et al., **38**, 6801, 2020]

GA algorithm for 2D 92Gb/s x16 broadcasting

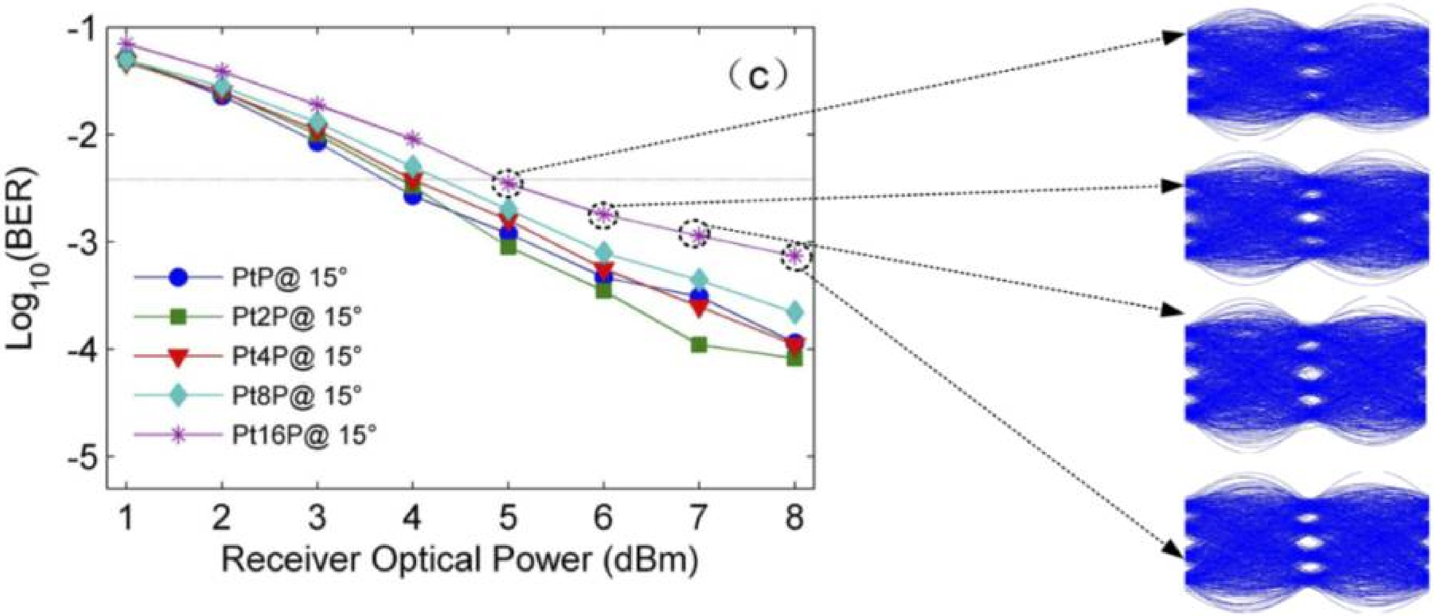
- rotated-splitting-SLM (RSS) algorithm based on GA



[Q. You, Chao Li*, et al., OE, **29**, 19373, 2021; OE, **28**, 30851, 2020]

GA algorithm for 2D 92Gb/s x16 broadcasting

- 1-to-16 broadcasting
- Steering angle at ±15°
- BER performance of 92 Gb/s IM/DD PAM-4



Conclusions

- **Beam steered infrared light communications (BS-ILC) are discussed based on**
  - **Passive devices: Gratings, AWGR+fiber array**
  - **Active devices: MEMS mirors, SLM, MMF based F-SLM**
- **Integrated circuits in BS-ILC**
  - **Field-Programmable Metasurface**
  - **Cascaded optical pre-amplifier receiver (SOA/PIN)**
  - **No-bias monolithic integration optical receiver**
- **Non-line-of-sight (NLOS) BS-ILC**
  - **SLM**
  - **Genetic Algorithm (GA)**

李超

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