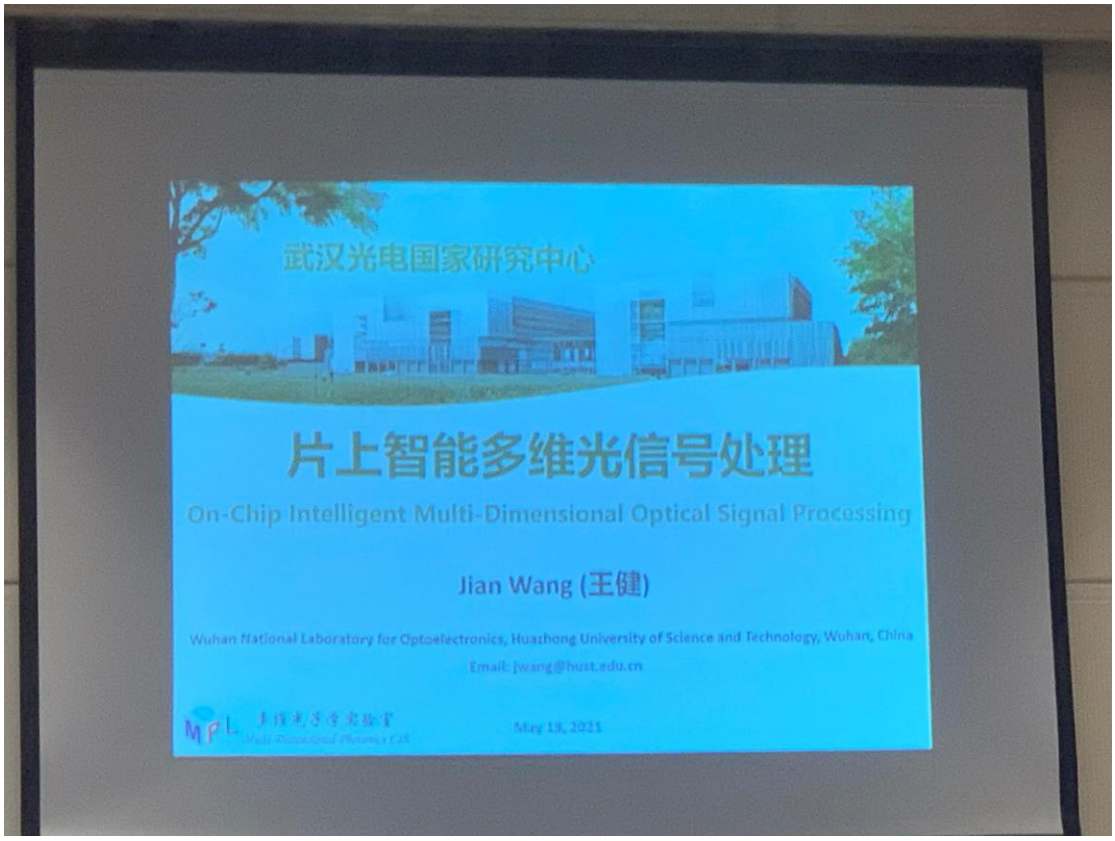
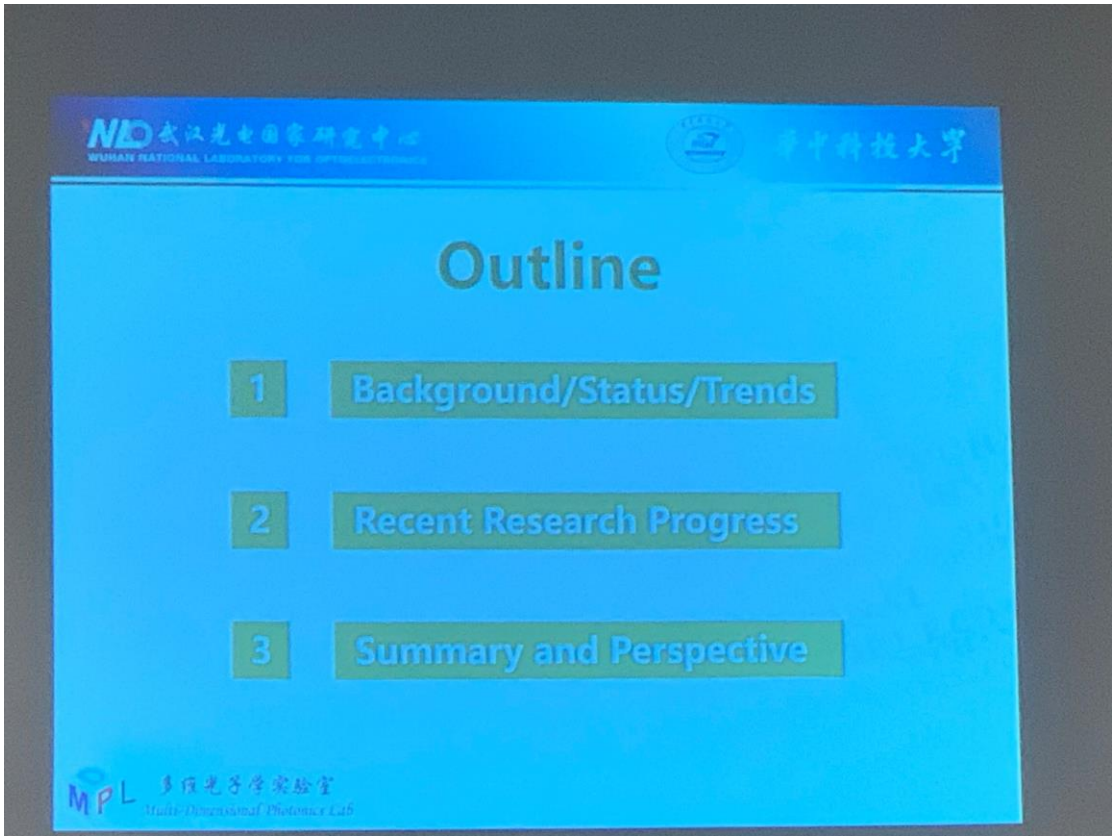
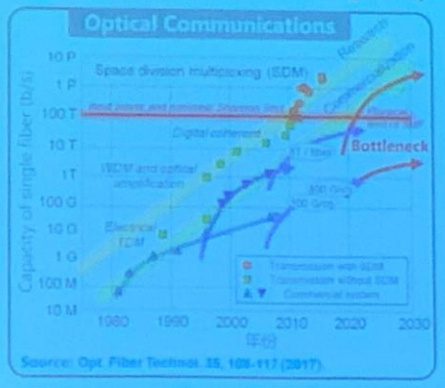
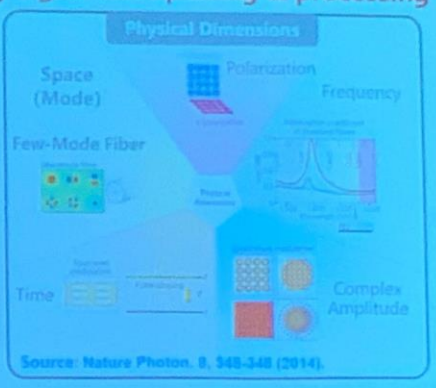

武汉光电国家研究中心
片上智能多维光信号处理
On-Chip Intelligent Multi-Dimensional Optical Signal Processing
Jian Wang (王健)
Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, China
Email: jwang@hust.edu.cn
May 13, 2021


WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS
Outline
1 Background/Status/Trends
2 Recent Research Progress
3 Summary and Perspective

WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS

Big data & 5G era: Ultra-high capacity signal multiplexing & processing





Solution: Multi-Dimensional Multiplexing & Processing of Photons

Bottleneck: Optical Chips

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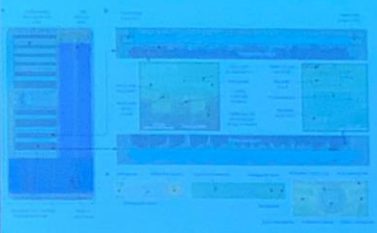
Silicon-Based Optoelectronic Chips: CMOS Compatibility

UC Berkeley: CMOS Compatibility (SOI)



Source: Nature 528, 534-538 (2015).

MIT: Standard CMOS Fabrication Technique

Source: Nature 556, 349-354 (2018).

Fundamental Breakthroughs in Volume, Power consumption & Cost

High-Speed Silicon Optoelectronic Chips

Great Importance for future development of information technology

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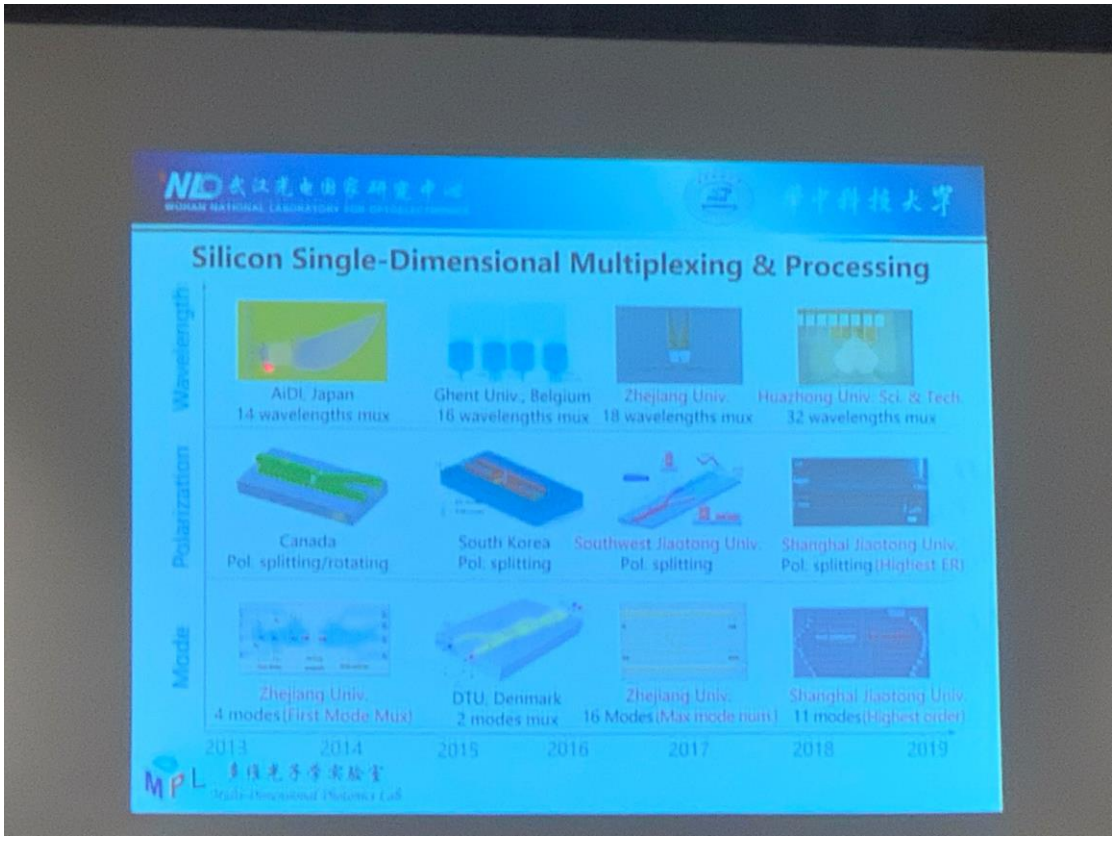
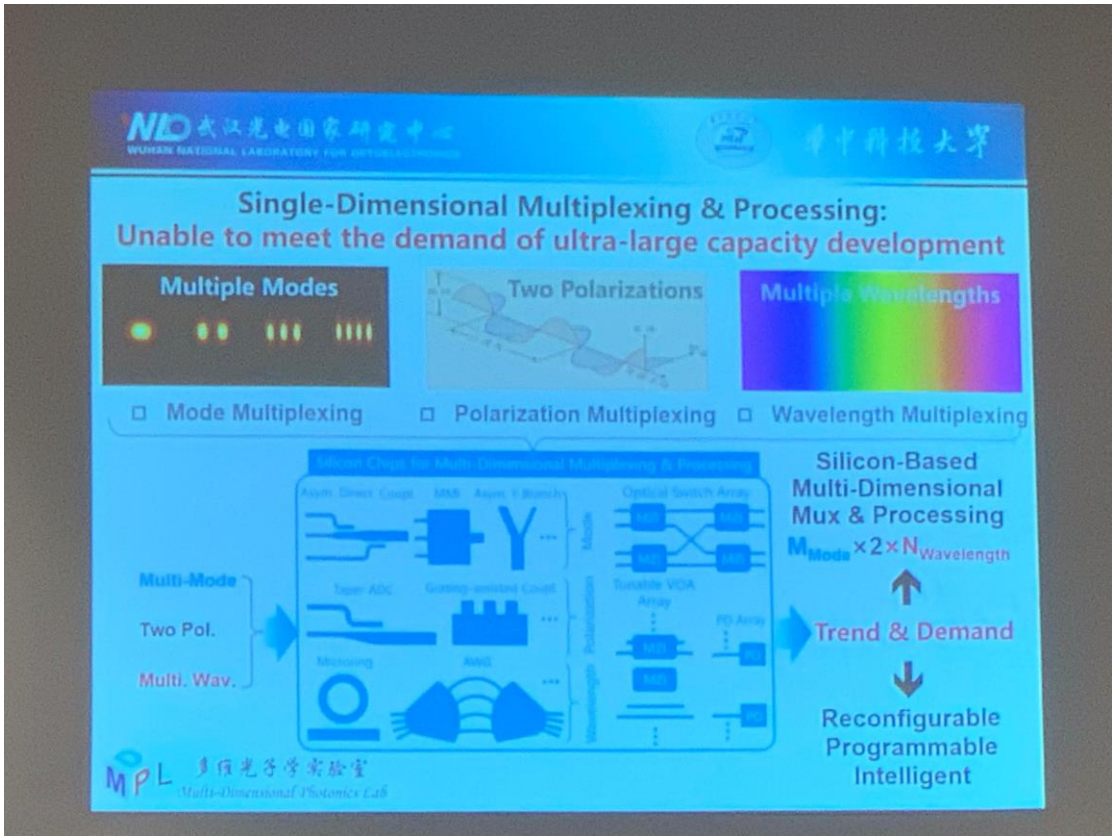
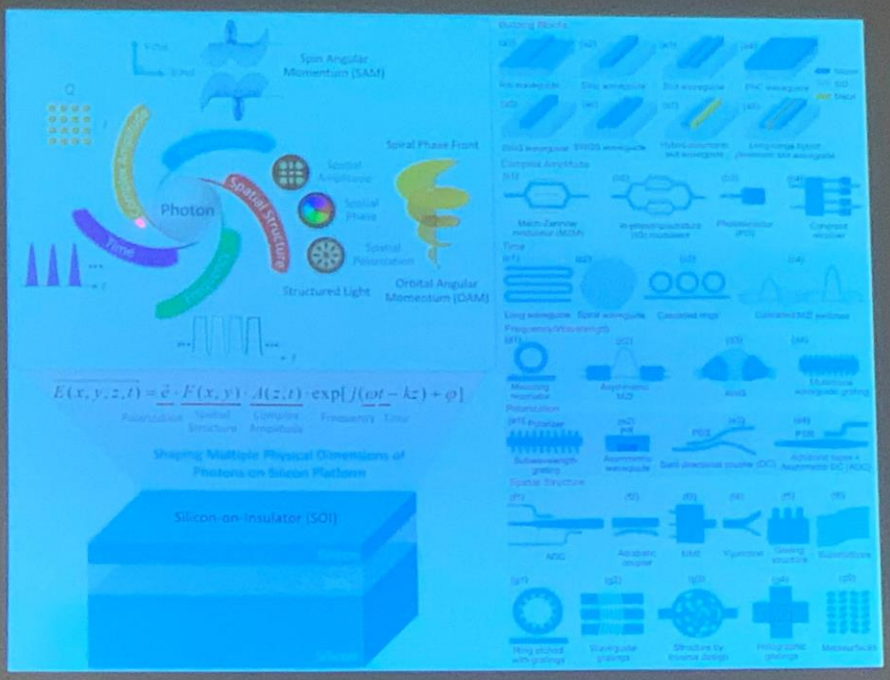
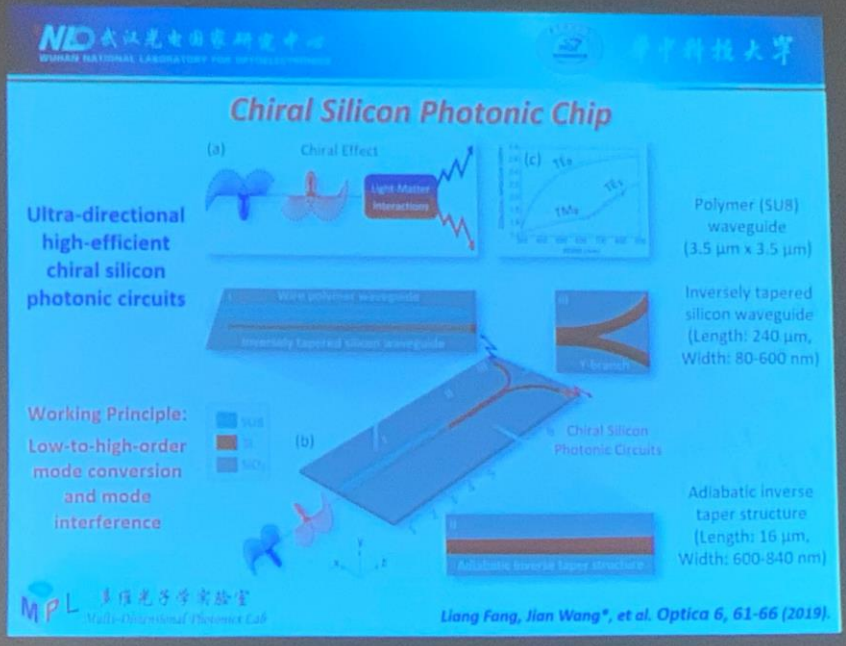

Silicon Single-Dimensional Multiplexing & Processing
Wavelength
Polarization
Mode
AiDI, Japan
14 wavelengths mux
Ghent Univ., Belgium
16 wavelengths mux
Zhejiang Univ.
18 wavelengths mux
Huazhong Univ. Sci. & Tech.
32 wavelengths mux
Canada
Pol. splitting/rotating
South Korea
Pol. splitting
Southwest Jiaotong Univ.
Pol. splitting
Shanghai Jiaotong Univ.
Pol. splitting(Highest ER)
Zhejiang Univ.
4 modes(First Mode Mux)
DTU, Denmark
2 modes mux
Zhejiang Univ.
16 Modes(Max mode num.)
Shanghai Jiaotong Univ.
11 modes(Highest order)
2013
2014
2015
2016
2017
2018
2019


Single-Dimensional Multiplexing & Processing:
Unable to meet the demand of ultra-large capacity development
Multiple Modes
Two Polarizations
Multiple Wavelengths
Mode Multiplexing
Polarization Multiplexing
Wavelength Multiplexing
Multi-Mode
Two Pol.
Multi. Wav.
Silicon-Based
Multi-Dimensional
Mux & Processing
$M_{Mode} \times 2 \times N_{Wavelength}$
Trend & Demand
Reconfigurable
Programmable
Intelligent


Spin Angular Momentum (SAM)
Spiral Phase Front
Photon
Spatial Structure
Time
Structured Light
Orbital Angular Momentum (OAM)
Shaping Multiple Physical Dimensions of Photons on Silicon Platform
Silicon-on-Insulator (SOI)


Chiral Silicon Photonic Chip
Ultra-directional high-efficient chiral silicon photonic circuits
Chiral Effect
Light Matter Interactions
Polymer (SU8) waveguide (3.5 μm x 3.5 μm)
Inversely tapered silicon waveguide (Length: 240 μm, Width: 80-600 nm)
Working Principle: Low-to-high-order mode conversion and mode interference
Chiral Silicon Photonic Circuits
Adiabatic inverse taper structure (Length: 16 μm, Width: 600-840 nm)
Liang Fang, Jian Wang*, et al. Optica 6, 61-66 (2019).

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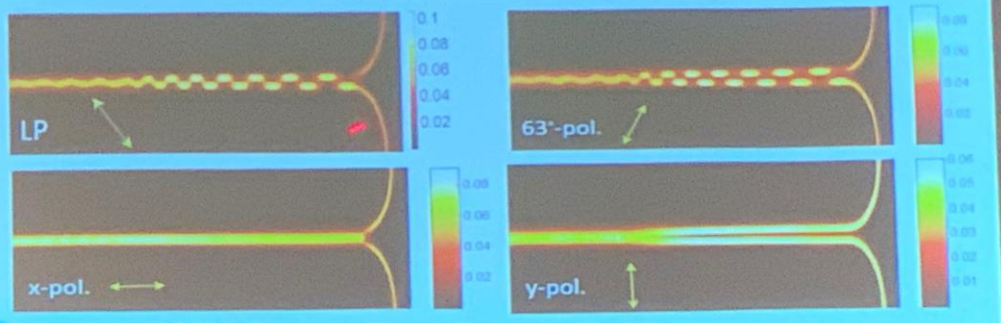
Chiral Silicon Photonic Chip

Perfect 3dB Power Splitter for Arbitrary LP Inputs

LP, LCP, RCP

$$\begin{bmatrix}\cos\alpha \\ \sin\alpha\end{bmatrix} = \frac{1}{2}(\cos\alpha - i\sin\alpha)\begin{bmatrix}1 \\ i\end{bmatrix} + \frac{1}{2}(\cos\alpha + i\sin\alpha)\begin{bmatrix}1 \\ -i\end{bmatrix}$$



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Liang Fang, Jian Wang*, et al. Optica 6, 61-66 (2019).

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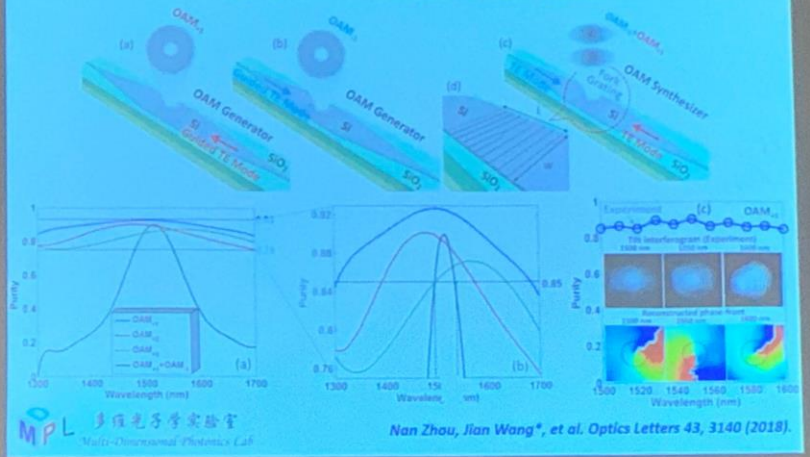
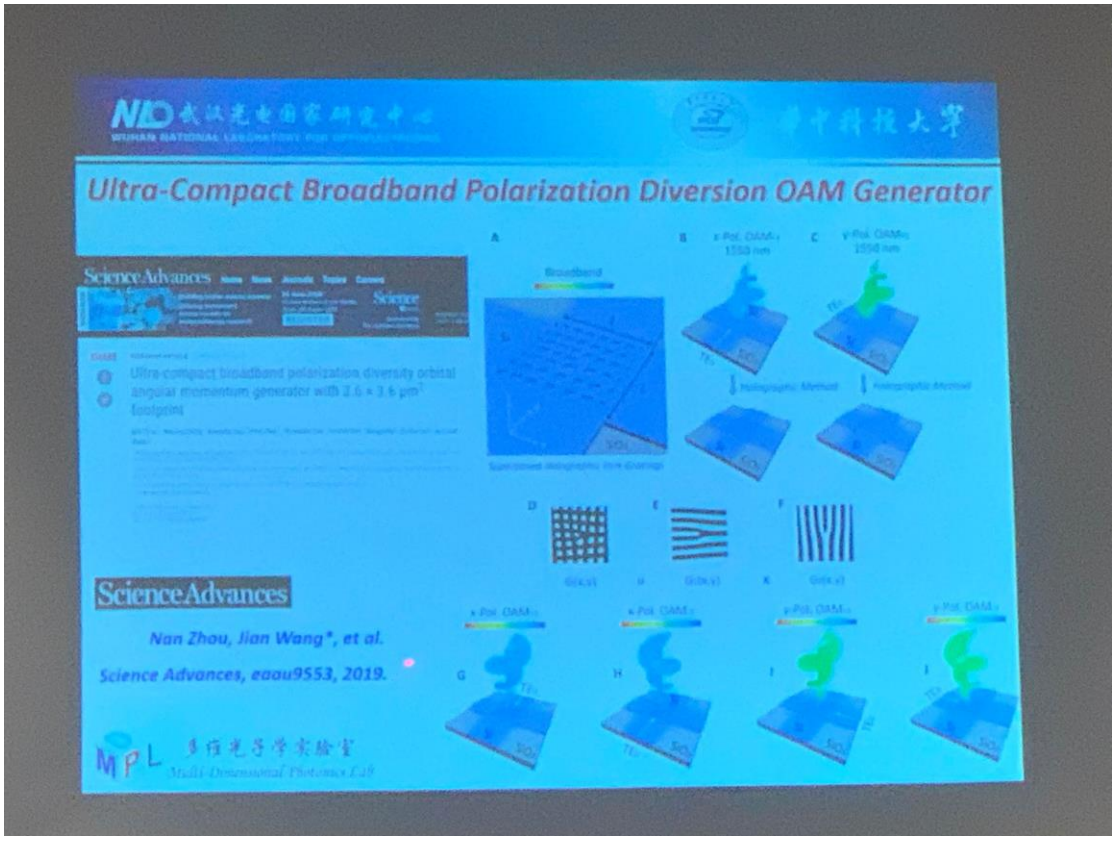
Ultra-Broadband OAM Generation and Synthesization

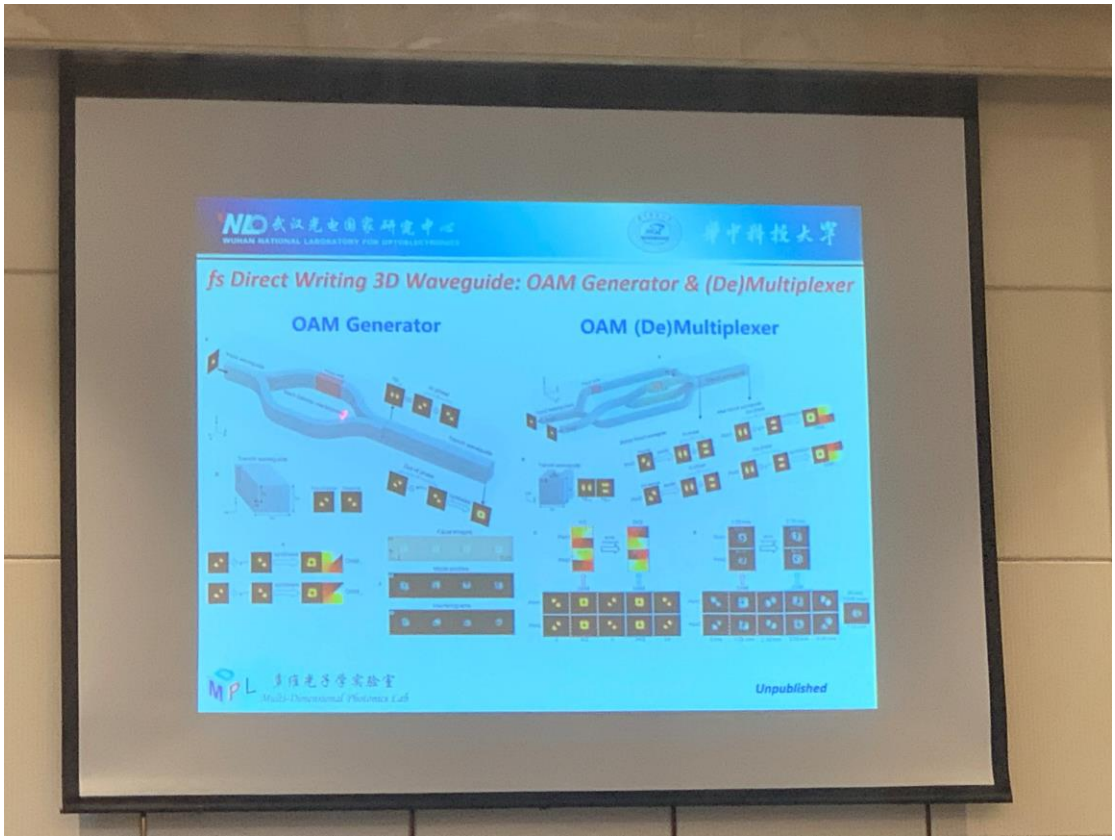
Holographic Fork Grating on Silicon Platform



多维光子学实验室

Nan Zhou, Jian Wang*, et al. Optics Letters 43, 3140 (2018).

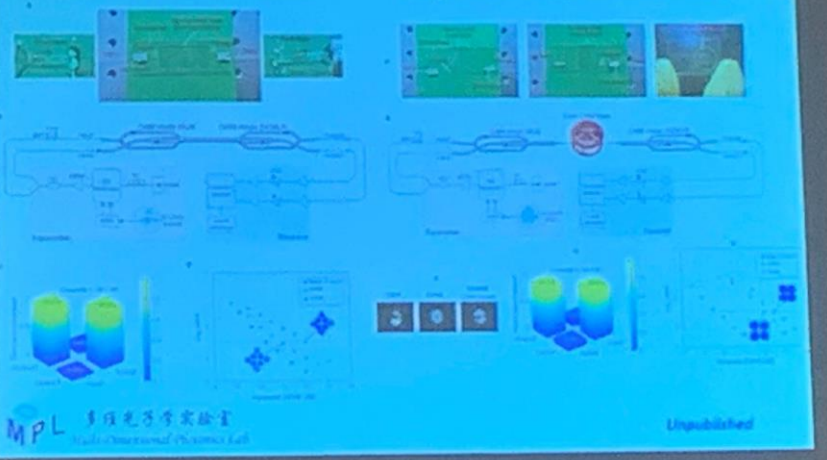

Ultra-Compact Broadband Polarization Diversion OAM Generator
Science Advances
Nan Zhou, Jian Wang*, et al.
Science Advances, eaau9553, 2019.


fs Direct Writing 3D Waveguide: OAM Generator & (De)Multiplexer
OAM Generator
OAM (De)Multiplexer
Unpublished

fs Direct Writing 3D Waveguide: OAM Generator & (De)Multiplexer

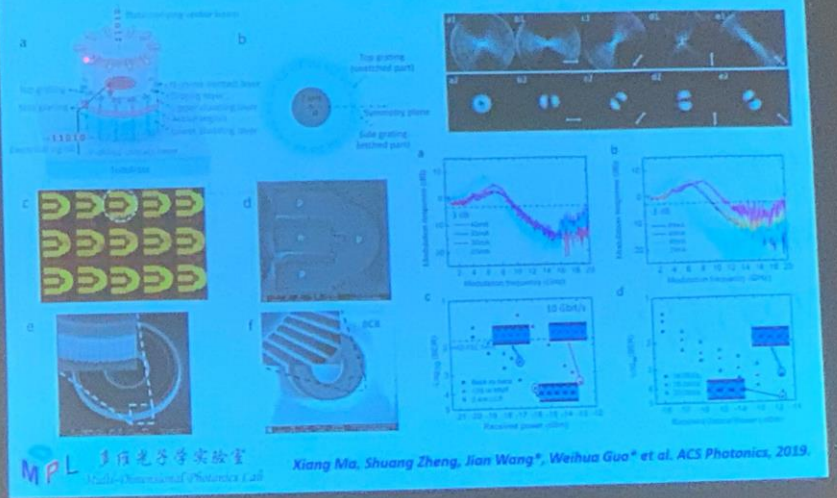
Chip-Chip Interconnects

Chip-Fiber-Chip Interconnects



Unpublished

High-Speed Directly-Modulated Cylindrical Vector Lasers



Xiang Ma, Shuang Zheng, Jian Wang*, Weihua Guo* et al. ACS Photonics, 2019.

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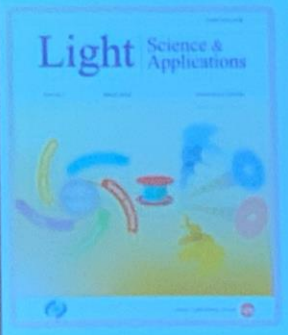
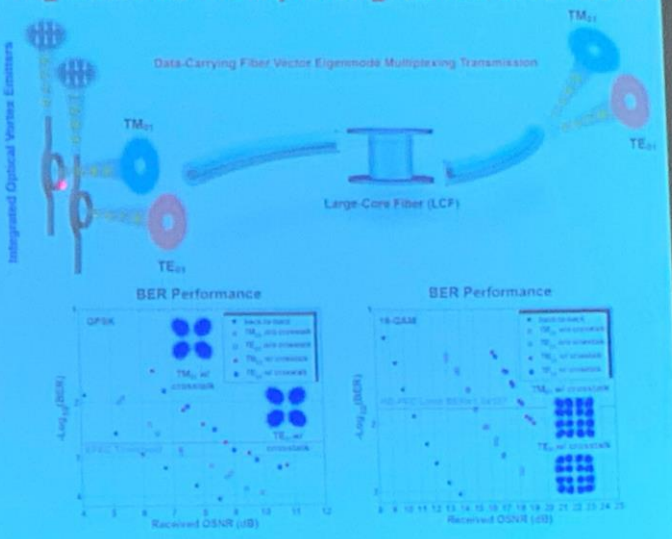
Direct Fiber Vector Eigenmode Multiplexing Communications





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Jun Liu, Jian Wang* et al. Light: Science & Applications, 7, 17148 (2018).

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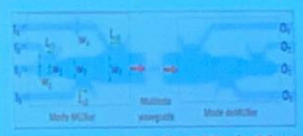
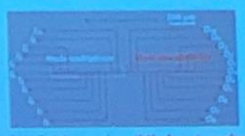
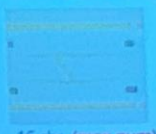
Mode/Polarization/Wavelength Mux/Demux



Asymmetric DC (Earliest Mode Mux)
Opt. Lett. 38, 1422 (2013).

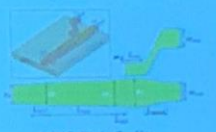


SWG 11 modes (Highest order)
J. Lightwave Technol. 36, 5746 (2018).

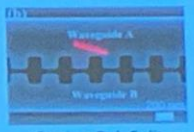


16 chs. (max num)
Opt. Lett. 41, 4515 (2016).

Inverse Design
Opt. Express 2018.



ADC Pol. Split.
Light Sci. Appl. 2012.



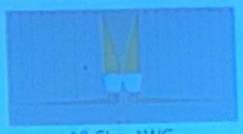
Grating Pol. Split.
Opt. Express 2016.

Bent DC Pol. Split.
APL Photonics 2016.

Subwavelength Pol. Split.(>200nm)
Laser Photon. Rev. 2019.

AWG
Electron. Lett. 42, 400 (2006).

Reflective AWG
Opt. Lett. 35, 2594 (2010).



18 Chs. AWG
J. Lightwave Technol. 2015.

32 Chs. AWG

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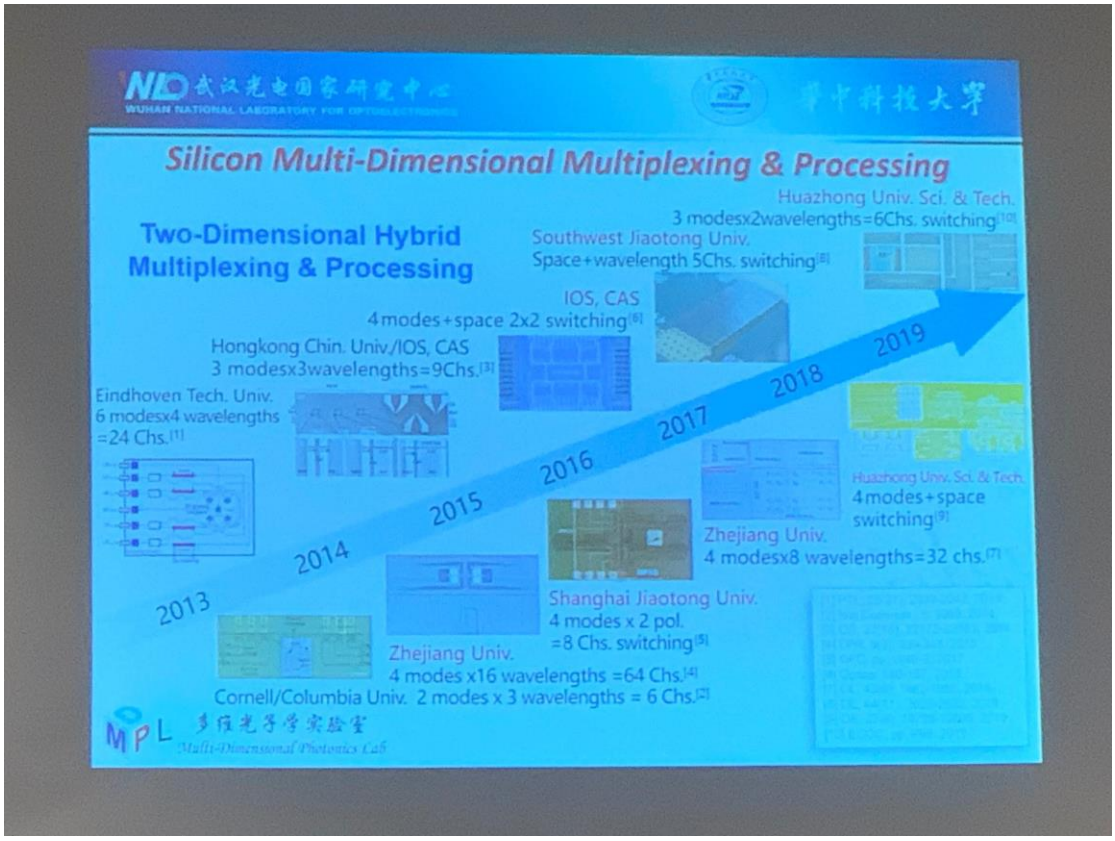
WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS
華中科技大學
Silicon Multi-Dimensional Multiplexing & Processing
Two-Dimensional Hybrid Multiplexing & Processing
Huazhong Univ. Sci. & Tech.
3 modesx2wavelengths=6Chs. switching[10]
Southwest Jiaotong Univ.
Space+wavelength 5Chs. switching[8]
IOS, CAS
4modes+space 2x2 switching[6]
Hongkong Chin. Univ./IOS, CAS
3 modesx3wavelengths=9Chs.[3]
Eindhoven Tech. Univ.
6 modesx4 wavelengths
=24 Chs.[1]
2013
2014
2015
2016
2017
2018
2019
Huazhong Univ. Sci. & Tech.
4modes+space
switching[9]
Zhejiang Univ.
4 modesx8 wavelengths=32 chs.[7]
Shanghai Jiaotong Univ.
4 modes x 2 pol.
=8 Chs. switching[5]
Zhejiang Univ.
4 modes x16 wavelengths =64 Chs.[4]
Cornell/Columbia Univ. 2 modes x 3 wavelengths = 6 Chs.[2]
MPL
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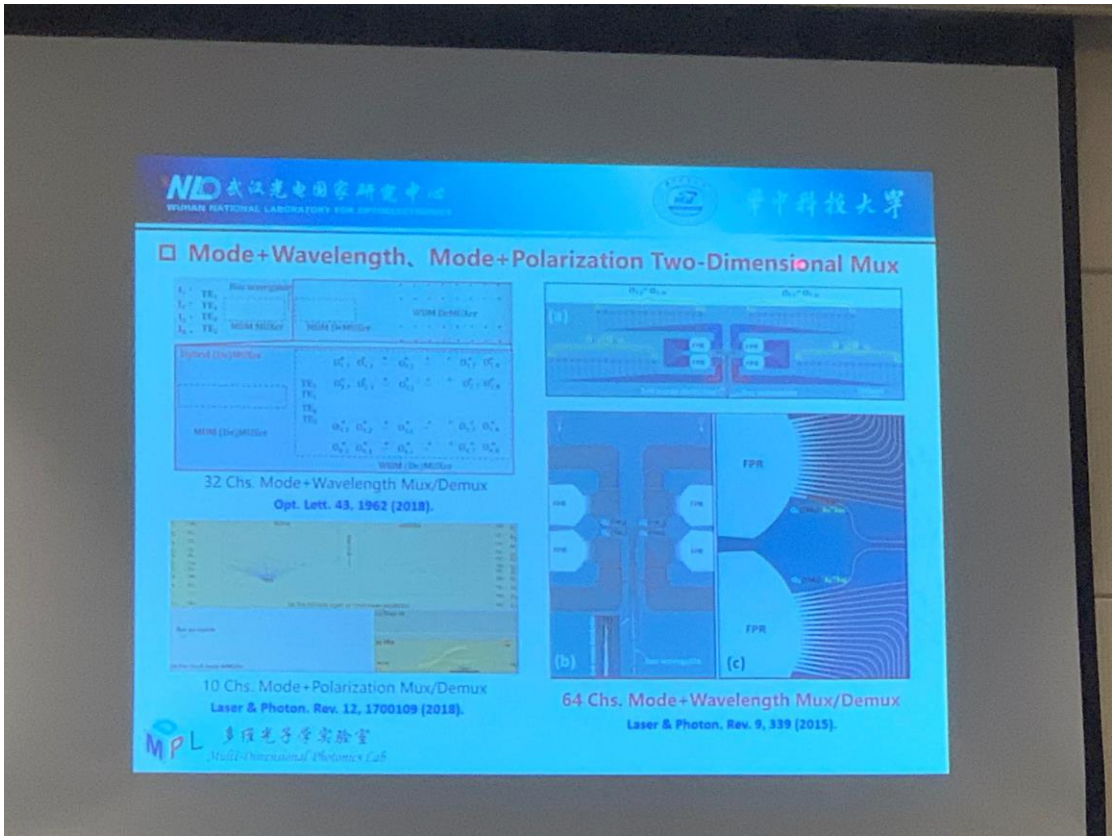
Multi-Dimensional Photonics Lab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華中科技大學
□ Mode+Wavelength、Mode+Polarization Two-Dimensional Mux
32 Chs. Mode+Wavelength Mux/Demux
Opt. Lett. 43, 1962 (2018).
10 Chs. Mode+Polarization Mux/Demux
Laser & Photon. Rev. 12, 1700109 (2018).
64 Chs. Mode+Wavelength Mux/Demux
Laser & Photon. Rev. 9, 339 (2015).
FPR
(b)
(c)
MPL
多维光子学实验室
Multi-Dimensional Photonics Lab

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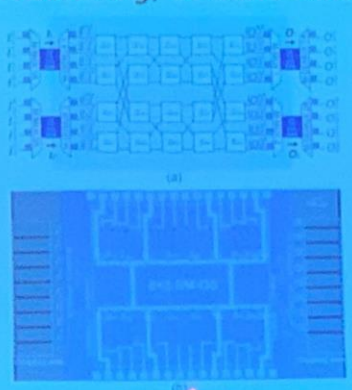
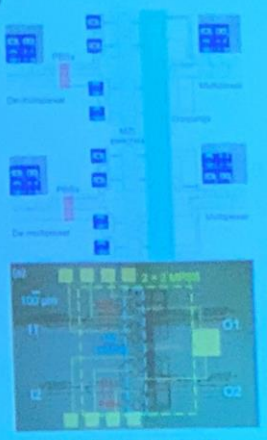
□ Space+Mode, Mode+Polarization Multi-Dimensional Processing (NxN Switching, Selective Switching)



Optica 5, 180 (2018).
Silicon-Based Space+Mode Switching



Photon. Res. 5, 521 (2017).
2x2 Mode+Polarization Selective Switching

MPL Multi-Dimensional Photonics Lab

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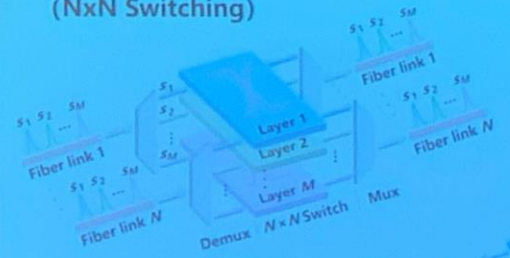
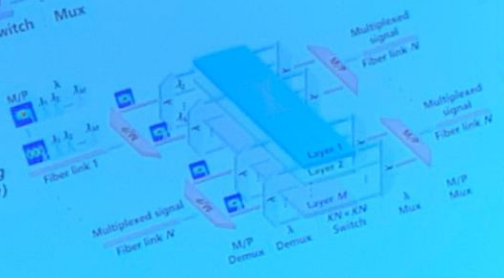
□ Wavelength+Polarization+Mode Multi-Dimensional Processing (NxN Switching)



Single-Dimensional Optical Switching
(Wavelength or Polarization or Mode)



Multi-Dimensional Optical Switching
(Wavelength & Polarization & Mode)

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J. Lightwave Technol. 38, 215 (2020).

Wavelength+Polarization+Mode Multi-Dimensional Processing (Selective Switching)

Silicon-Based 1x4 Multi-Dimensional (Wavelength+Polarization+Mode) Selective Switching

X. Cao, J. Wang*, et al. IEEE J. Quantum Electron. 56, 8400608 (2020).

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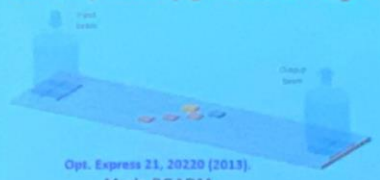
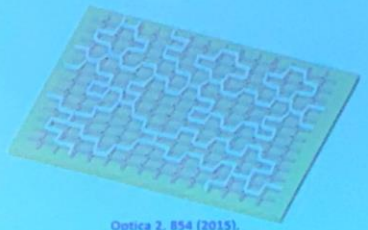
华中科技大学

On-Chip Reconfigurable & Programmable Optical Signal Processing

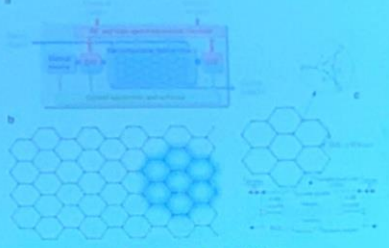


Opt. Express 21, 20220 (2013).
Mode ROADM



Optica 2, 854 (2015).
Programmable Optical FPGA

Nature Commun. 9, 1396 (2018).
Reconfigurable & Programmable Grating Optical Signal Processing



Nature Commun. 8, 636 (2017).
Programmable Multi-Task Optical Signal Processing

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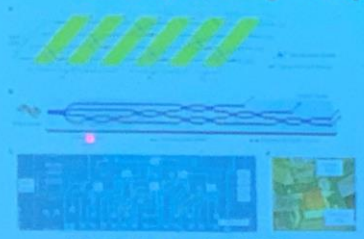
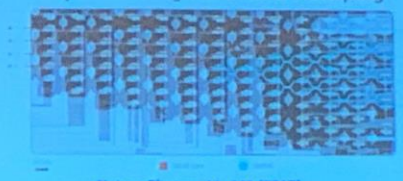
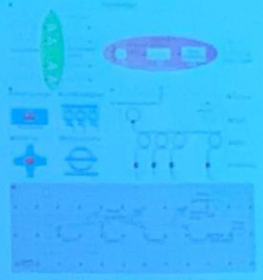
On-Chip Intelligent Optical Signal Processing



Light: Sci. Appl. 6, e17110 (2017).
Adaptive Reconfigurable Mode Decoupling



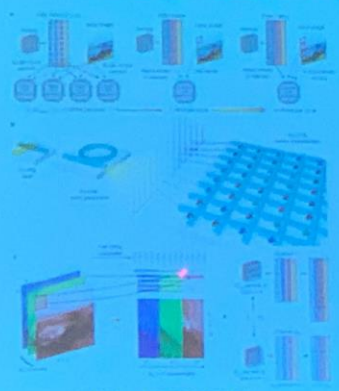
Nature Photon. 11, 441 (2017).
Deep-Learning Photonic Processing (Vowel Recognition)



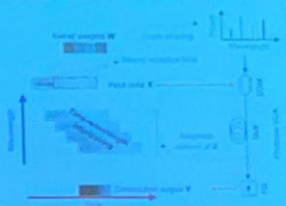
Nature 569, 208 (2019).
Self-Learning All-Optical Spiking Neurosynaptic Networks

Sci. Adv. 3, e1700160 (2017).
Photonic Synapses on Silicon

On-Chip Intelligent Optical Signal Processing

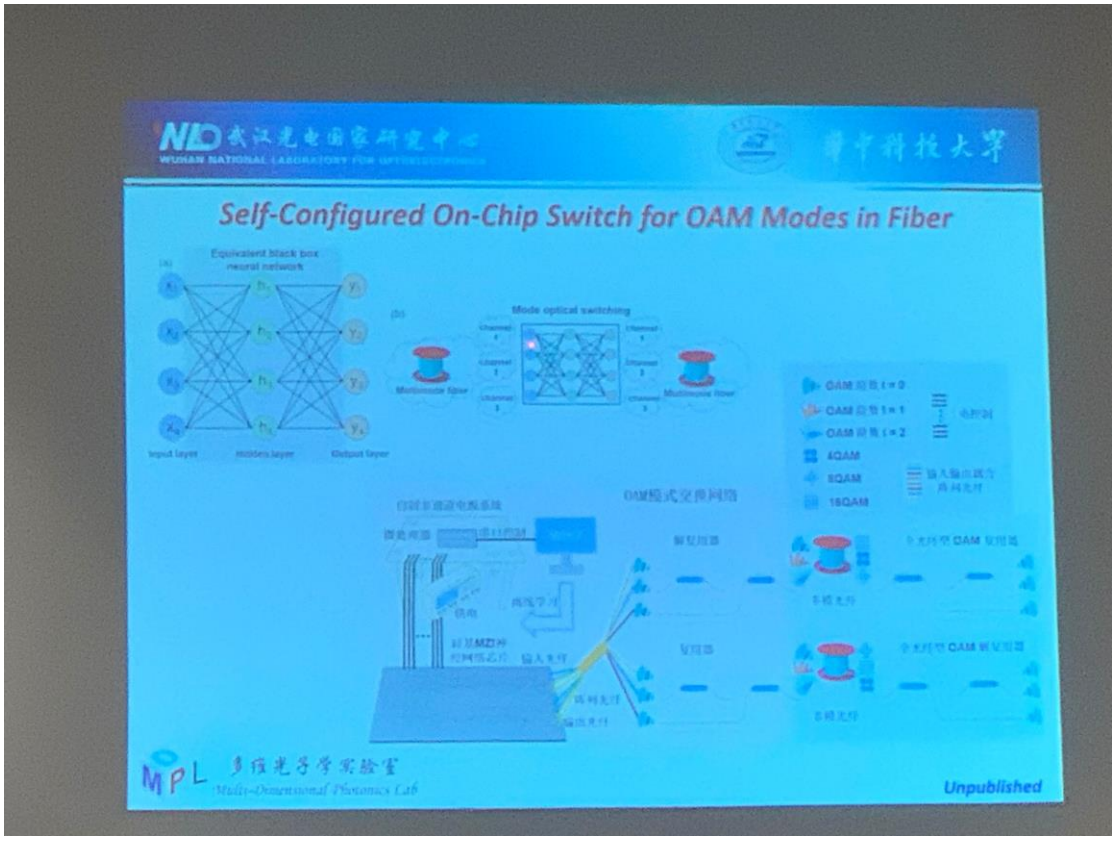


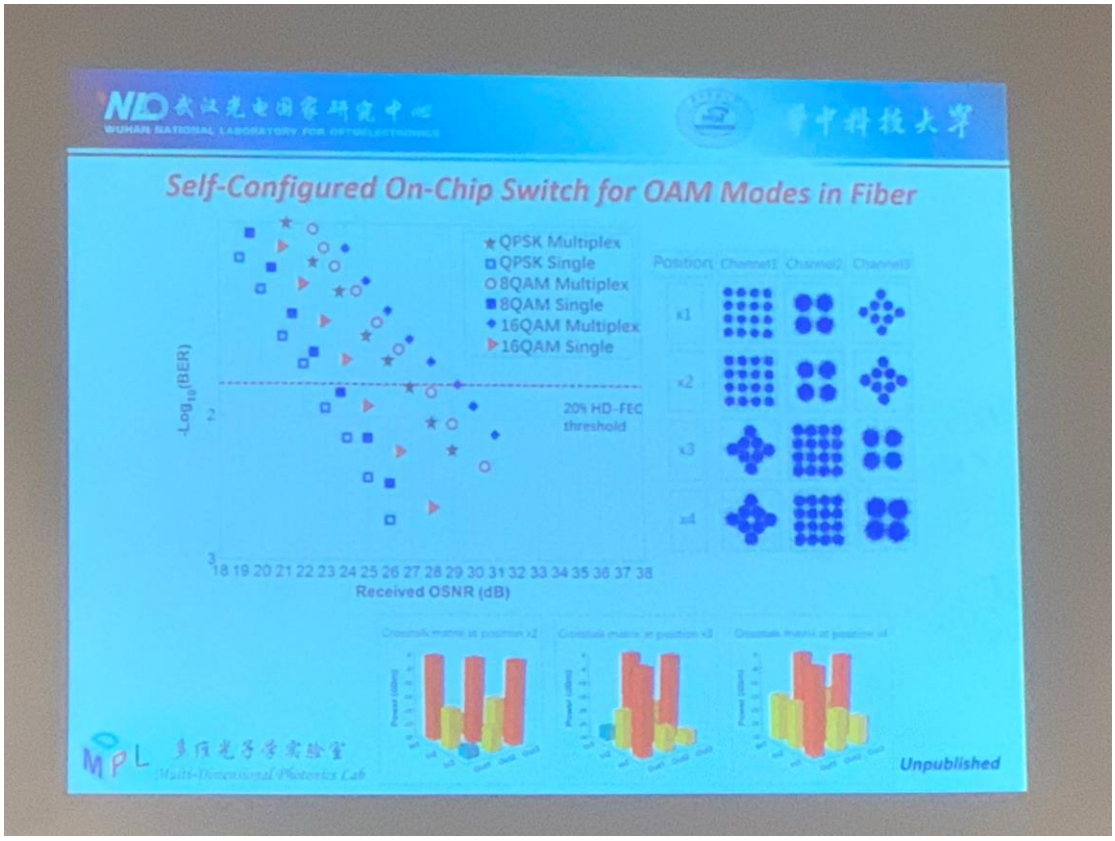
Nature 589, 52 (2021).
Parallel Convolutional Processing using an Integrated Photonic Tensor Core



Nature 589, 44 (2021).
11 TOPS Photonic Convolutional Accelerator

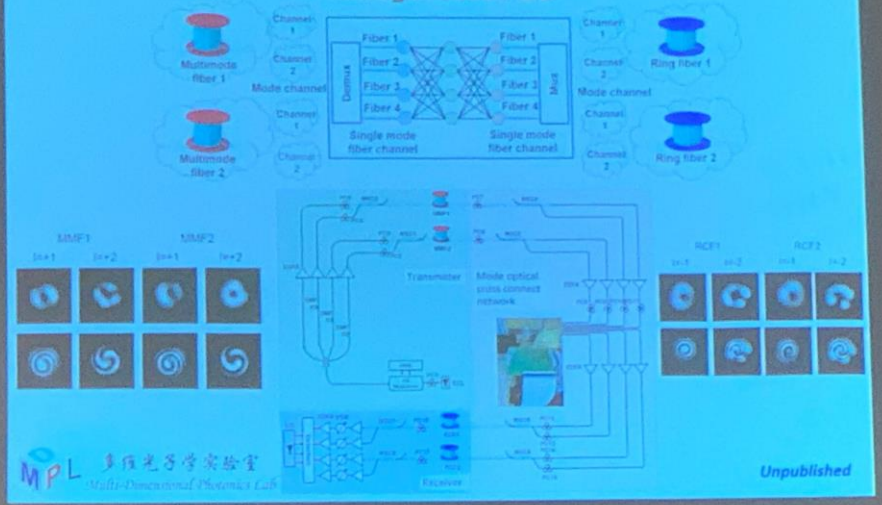
Nature Communications 12, 96 (2021).
Multimode Photonic Convolutional Neural Network


WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS
華中科技大學
Self-Configured On-Chip Switch for OAM Modes in Fiber
Equivalent black box neural network
Input layer
Hidden layer
Output layer
Mode optical switching
Multimode fiber
Multimode fiber
OAM模式空分网络
MPL
多维光子学实验室
Multi-Dimensional Photonics Lab
Unpublished


WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS
華中科技大學
Self-Configured On-Chip Switch for OAM Modes in Fiber
QPSK Multiplex
QPSK Single
8QAM Multiplex
8QAM Single
16QAM Multiplex
16QAM Single
20% HD-FEC threshold
-Log10(BER)
Received OSNR (dB)
Position
Channel1
Channel2
Channel3
x1
x2
x3
x4
MPL
多维光子学实验室
Multi-Dimensional Photonics Lab
Unpublished

WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS

Self-Configured On-Chip Selective Switch for OAM Modes in Heterogeneous Fiber



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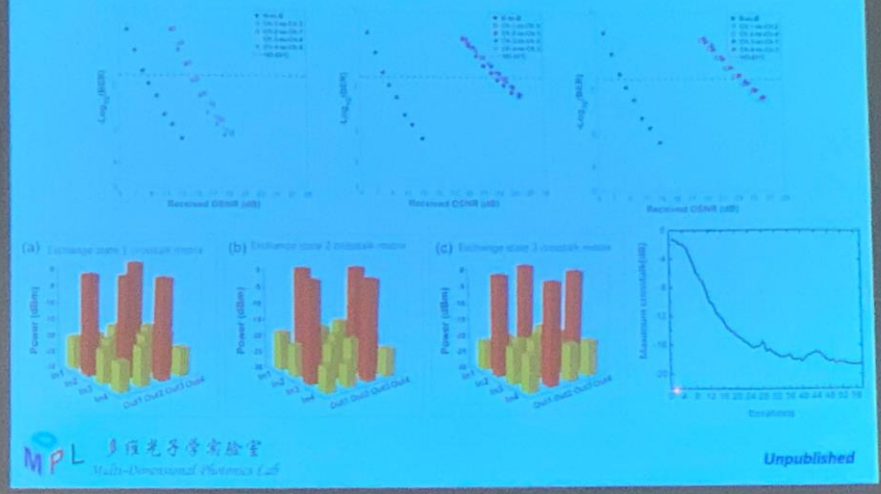
Self-Configured On-Chip Selective Switch for OAM Modes in Heterogeneous Fiber



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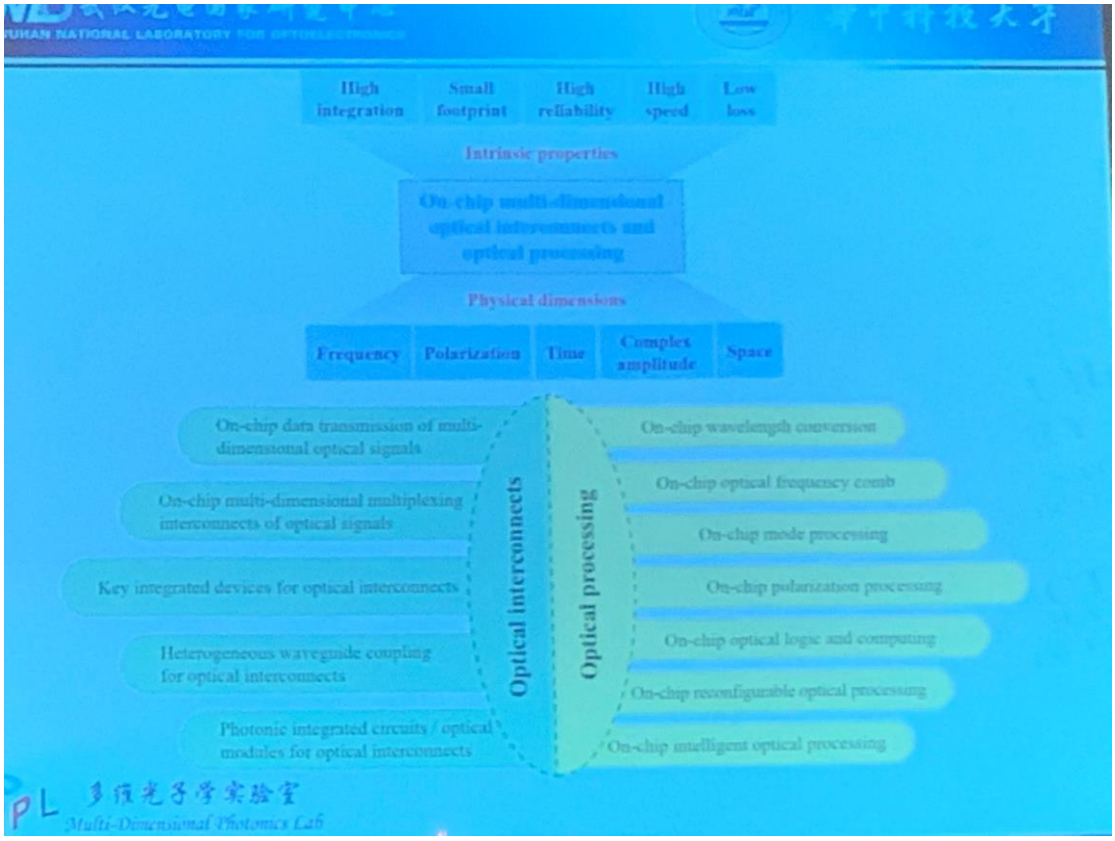
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High integration
Small footprint
High reliability
High speed
Low loss
Intrinsic properties
On-chip multi-dimensional optical interconnects and optical processing
Physical dimensions
Frequency
Polarization
Time
Complex amplitude
Space
On-chip data transmission of multi-dimensional optical signals
On-chip multi-dimensional multiplexing interconnects of optical signals
Key integrated devices for optical interconnects
Heterogeneous waveguide coupling for optical interconnects
Photonic integrated circuits / optical modules for optical interconnects
Optical interconnects
Optical processing
On-chip wavelength conversion
On-chip optical frequency comb
On-chip mode processing
On-chip polarization processing
On-chip optical logic and computing
On-chip reconfigurable optical processing
On-chip intelligent optical processing
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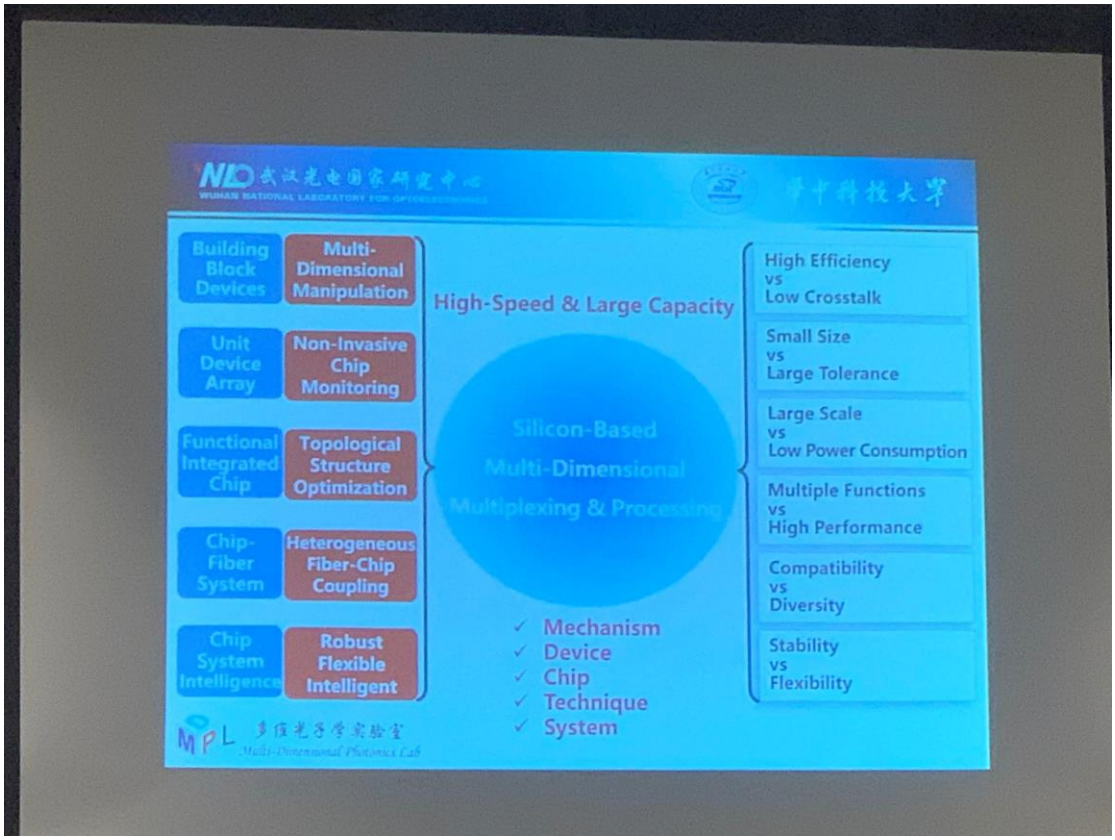
WUHAN NATIONAL LABORATORY FOR OPTOELECTRONICS
Building Block Devices
Multi-Dimensional Manipulation
Unit Device Array
Non-Invasive Chip Monitoring
Functional Integrated Chip
Topological Structure Optimization
Chip-Fiber System
Heterogeneous Fiber-Chip Coupling
Chip System Intelligence
Robust Flexible Intelligent
High-Speed & Large Capacity
Silicon-Based Multi-Dimensional Multiplexing & Processing
✓ Mechanism
✓ Device
✓ Chip
✓ Technique
✓ System
High Efficiency vs Low Crosstalk
Small Size vs Large Tolerance
Large Scale vs Low Power Consumption
Multiple Functions vs High Performance
Compatibility vs Diversity
Stability vs Flexibility
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Multi-Dimensional Photonics Lab

多维光子学实验室：研究方向

多维光子学实验室

Multi-Dimensional Photonics Lab

围绕光子多物理维度（频率、时间、偏振、复振幅、空间），特别是光子空间新维度开展基础研究及在光通信、光处理、光集成、光操控、光测量、光成像、光量子等领域交叉应用研究

- ✓ 光场调控（涡旋光、矢量光、结构光、时空光、全维度调控等）
- ✓ 光子集成（硅基光子学、表面等离子体、超表面、飞秒加工等）
- ✓ 新型光纤（涡旋/全矢量光纤、半导体功能光纤、全光纤器件等）
- ✓ 互连通信（自由空间/水下/光纤中短距光互连和长距光通信等）
- ✓ 信号处理（线性/非线性光信号处理、光计算、光子人工智能等）
- ✓ 前沿交叉（光镊、传感测量、显微成像、量子信息、生命科学等）