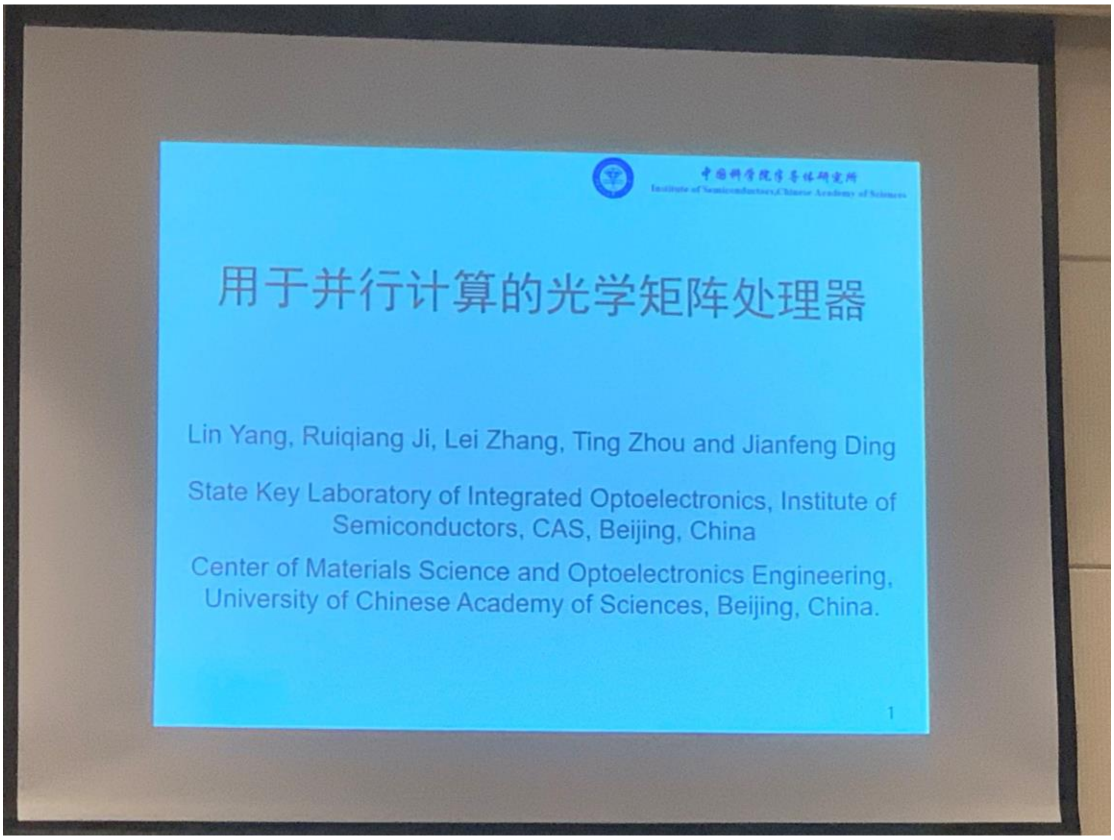
用于并行计算的光学矩阵处理器
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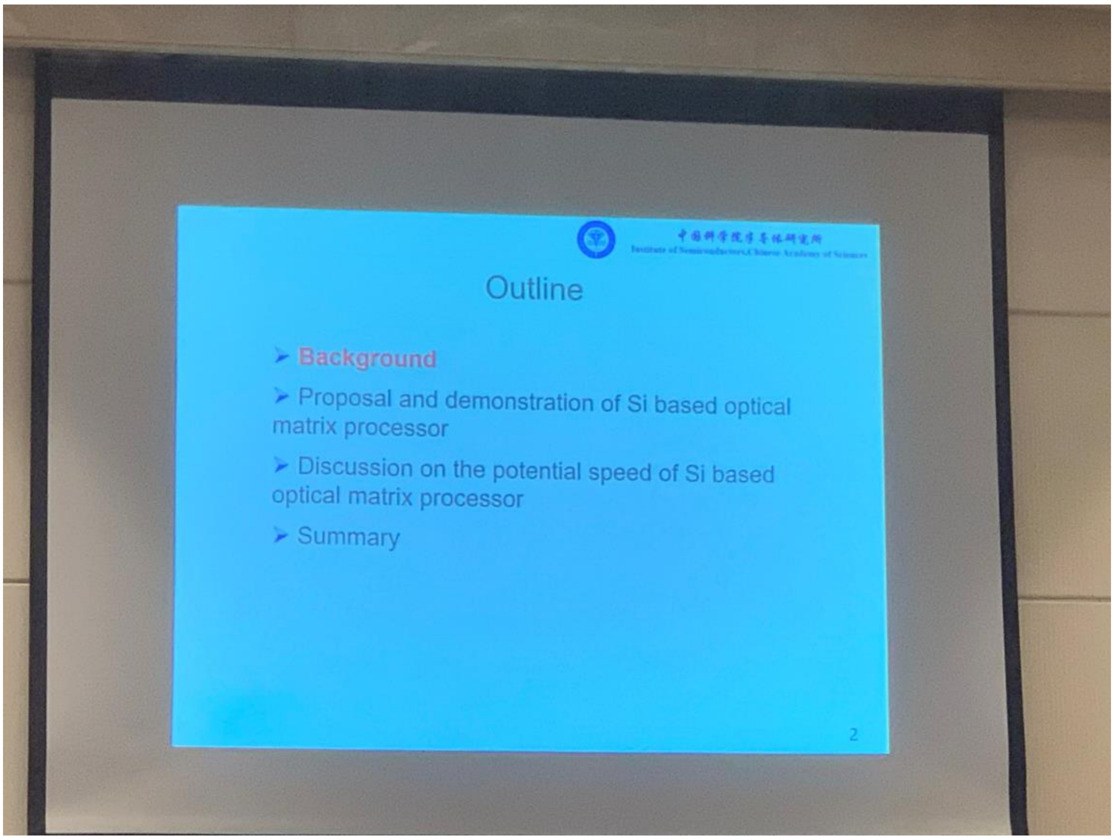
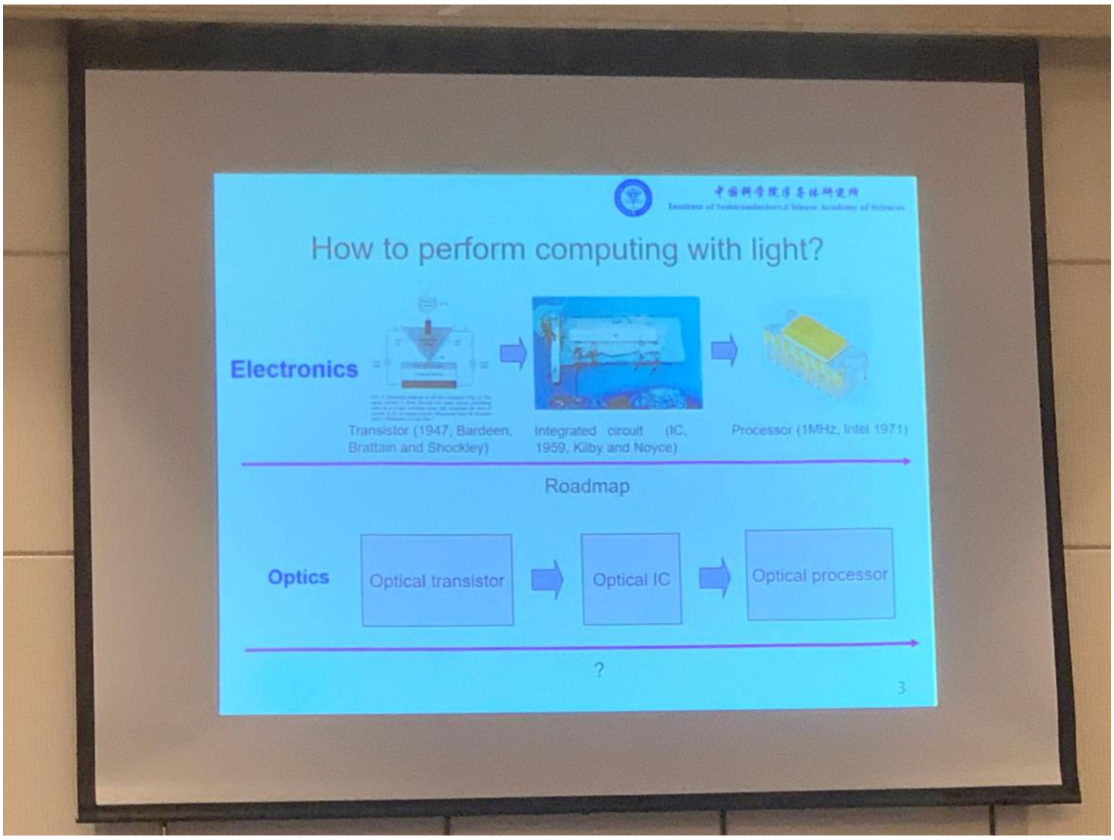
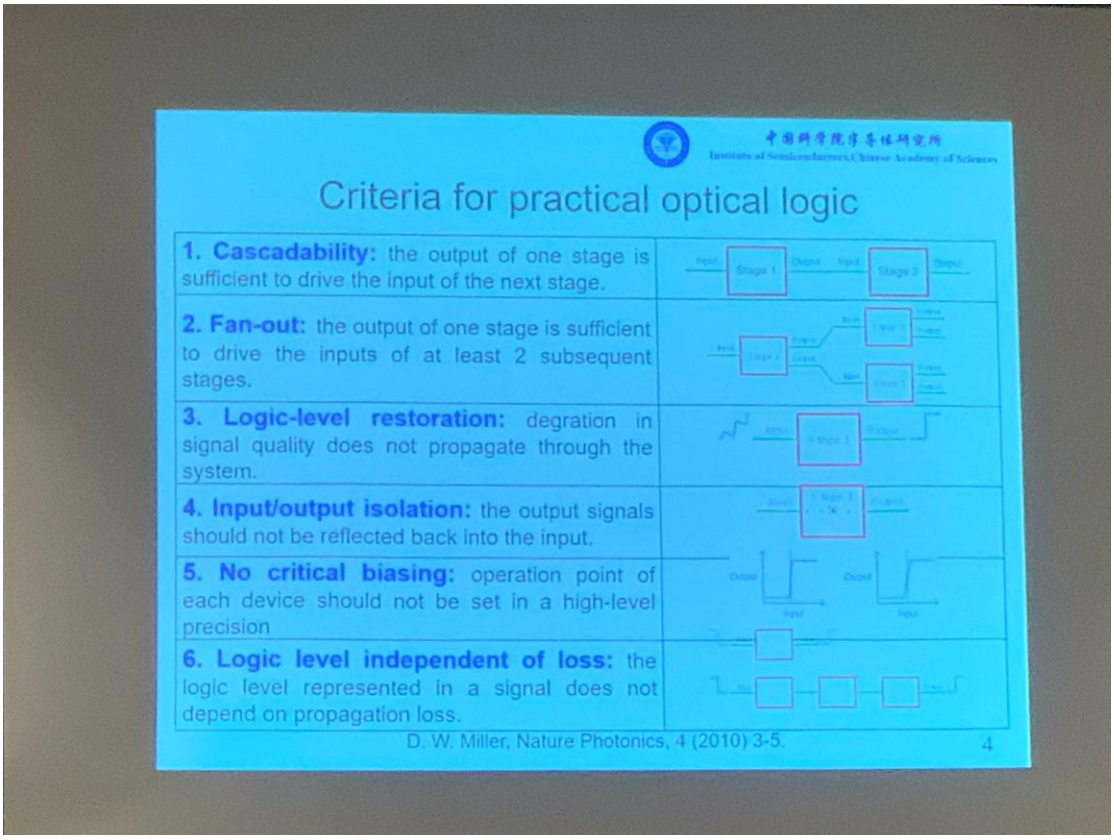
State Key Laboratory of Integrated Optoelectronics, Institute of Semiconductors, CAS, Beijing, China
Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing, China.
1


Outline
➤ Background
➤ Proposal and demonstration of Si based optical matrix processor
➤ Discussion on the potential speed of Si based optical matrix processor
➤ Summary
2


中国科学院半导体研究所
How to perform computing with light?
Electronics
Transistor (1947, Bardeen, Brattain and Shockley)
Integrated circuit (IC, 1959, Kilby and Noyce)
Processor (1MHz, Intel 1971)
Roadmap
Optics
Optical transistor
Optical IC
Optical processor
?
3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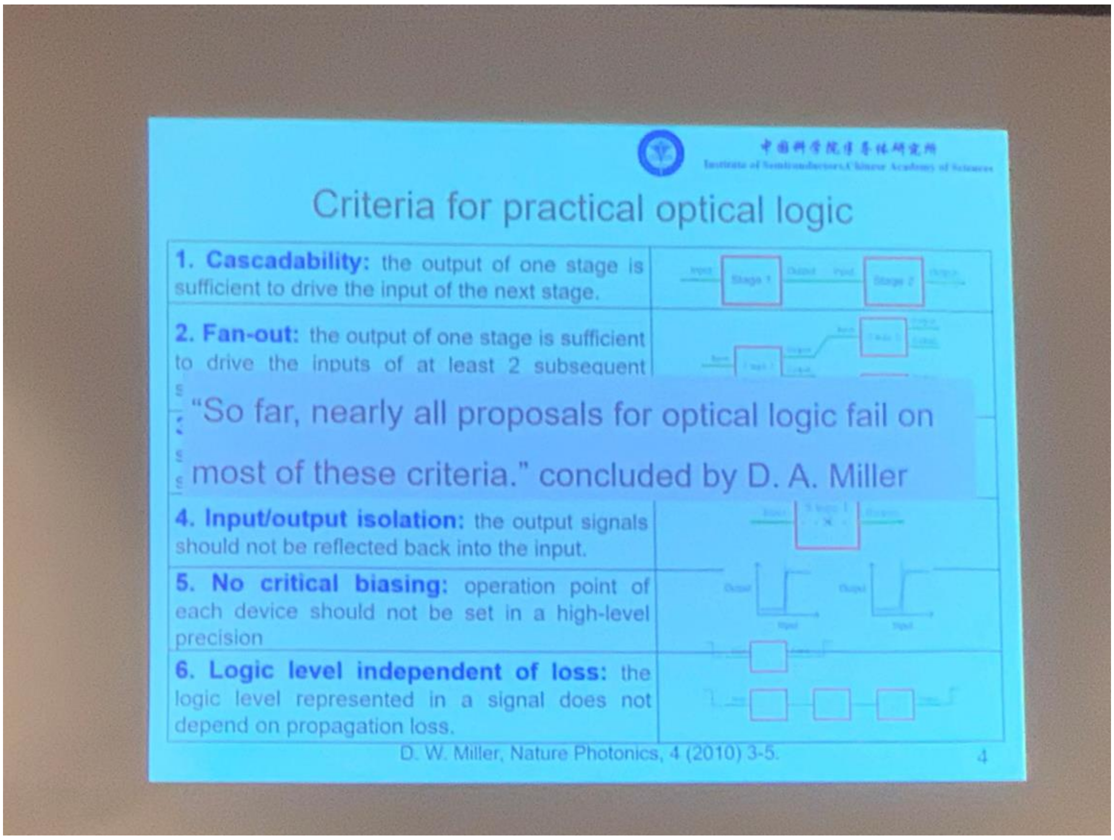
Institute of Semiconductors,Chinese Academy of Sciences
Criteria for practical optical logic
1. Cascadability: the output of one stage is sufficient to drive the input of the next stage.
Input
Stage 1
Output
Input
Stage 2
Output
2. Fan-out: the output of one stage is sufficient to drive the inputs of at least 2 subsequent stages.
3. Logic-level restoration: degration in signal quality does not propagate through the system.
4. Input/output isolation: the output signals should not be reflected back into the input.
5. No critical biasing: operation point of each device should not be set in a high-level precision
6. Logic level independent of loss: the logic level represented in a signal does not depend on propagation loss.
D. W. Miller, Nature Photonics, 4 (2010) 3-5.
4


Criteria for practical optical logic
1. Cascadability: the output of one stage is sufficient to drive the input of the next stage.
2. Fan-out: the output of one stage is sufficient to drive the inputs of at least 2 subsequent
"So far, nearly all proposals for optical logic fail on most of these criteria." concluded by D. A. Miller
4. Input/output isolation: the output signals should not be reflected back into the input.
5. No critical biasing: operation point of each device should not be set in a high-level precision
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D. W. Miller, Nature Photonics, 4 (2010) 3-5.
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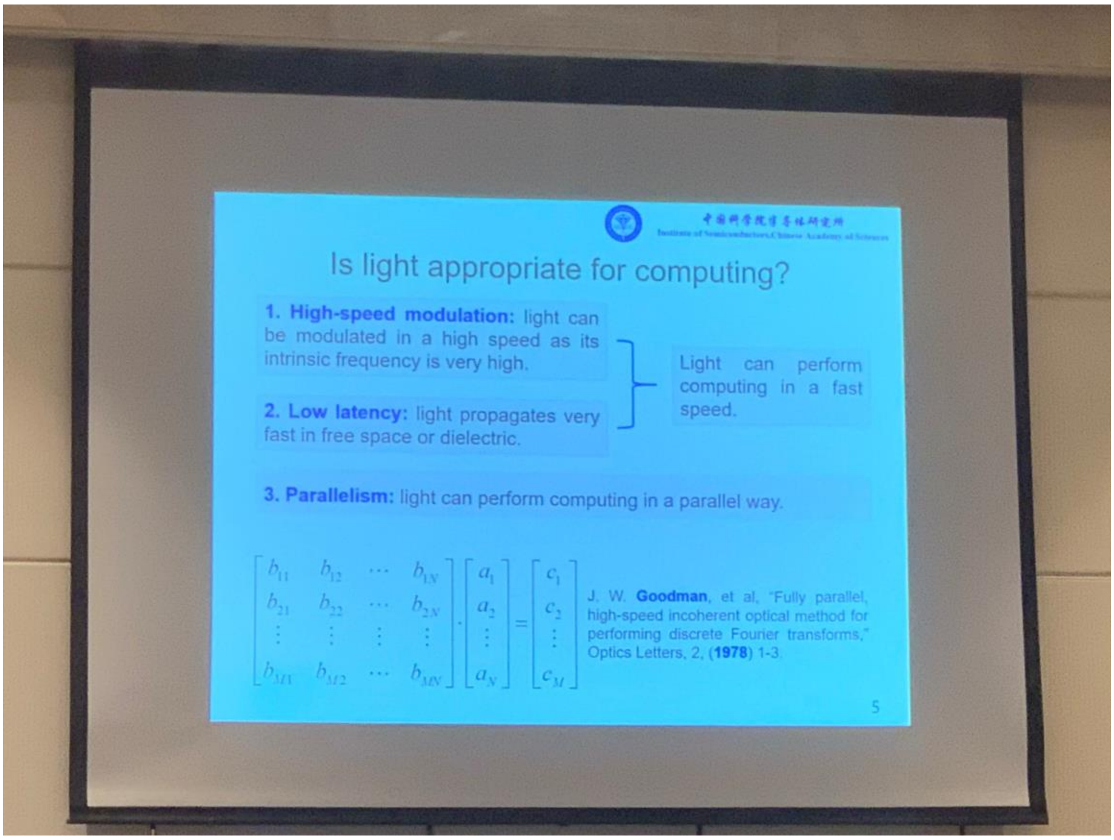
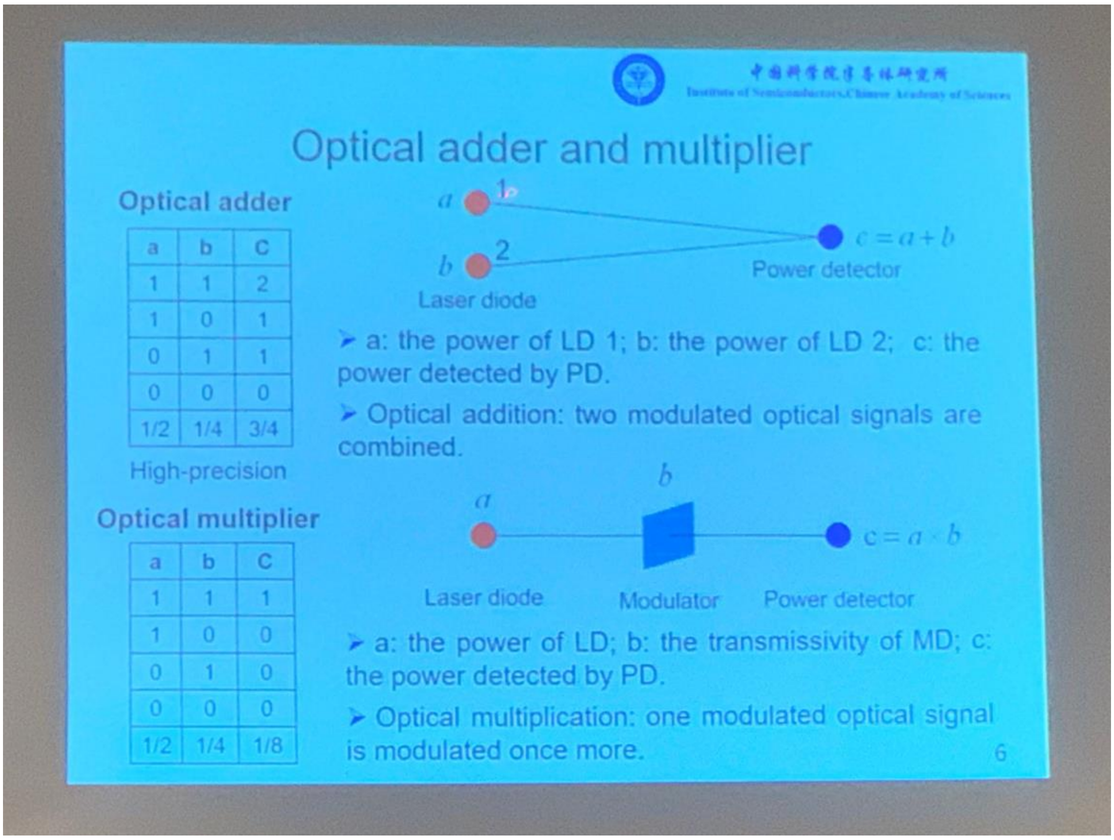
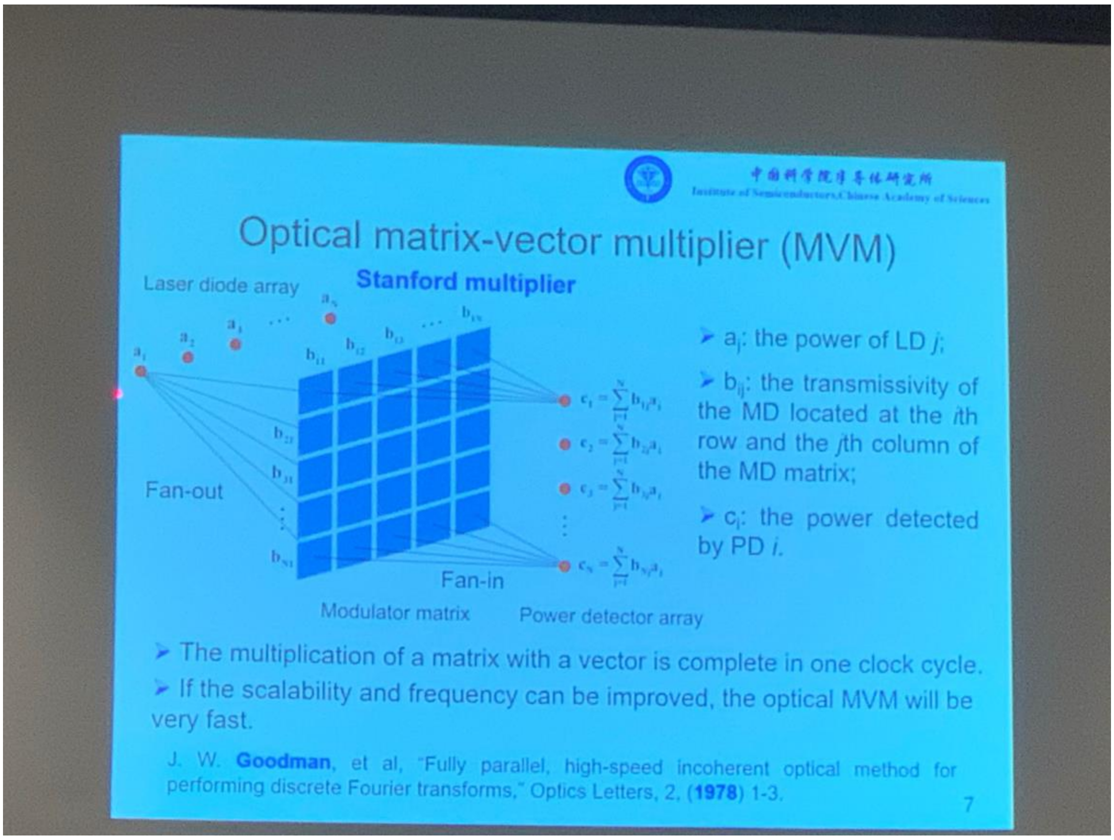
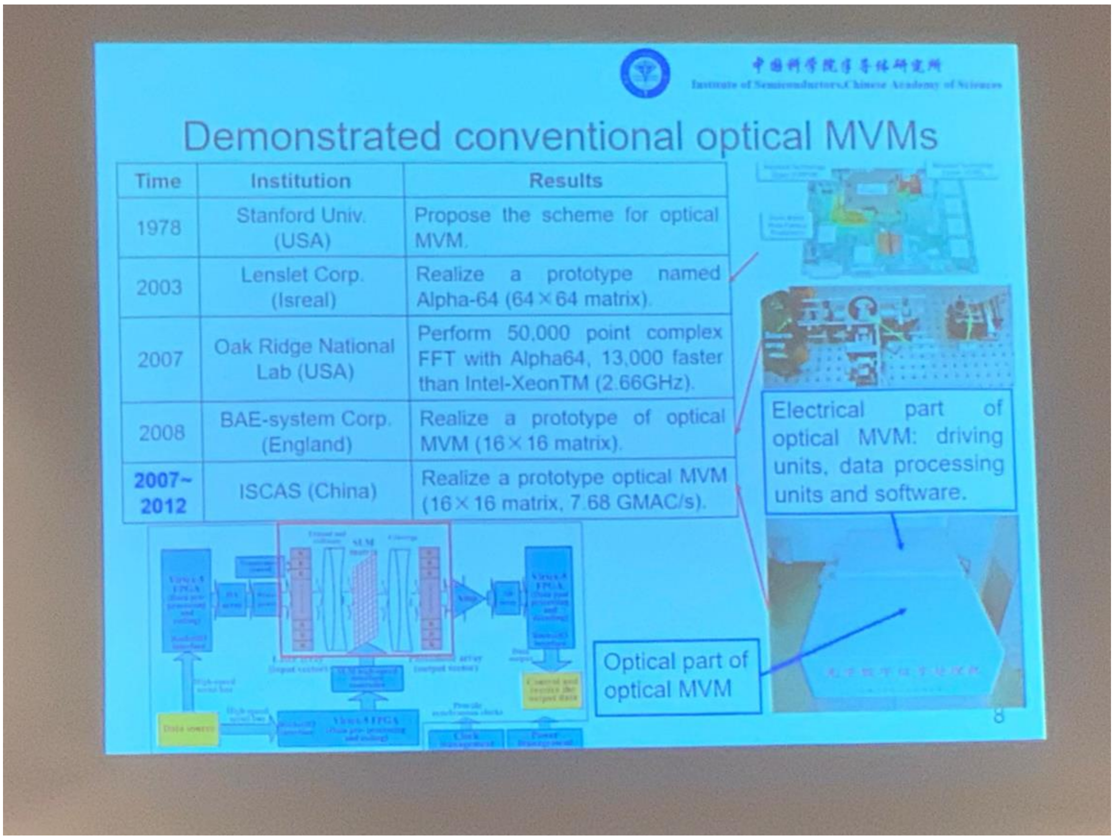
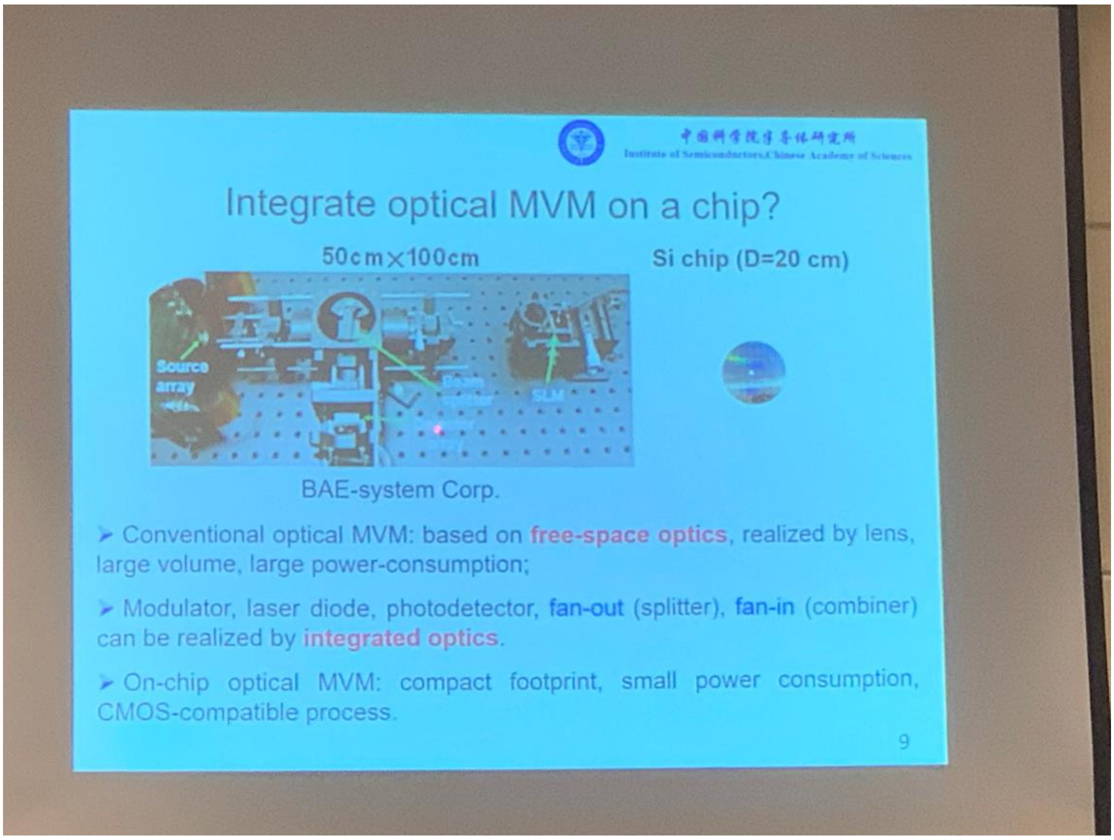

Is light appropriate for computing?
1. High-speed modulation: light can be modulated in a high speed as its intrinsic frequency is very high.
2. Low latency: light propagates very fast in free space or dielectric.
Light can perform computing in a fast speed.
3. Parallelism: light can perform computing in a parallel way.
J. W. Goodman, et al, "Fully parallel, high-speed incoherent optical method for performing discrete Fourier transforms," Optics Letters, 2, (1978) 1-3.
5

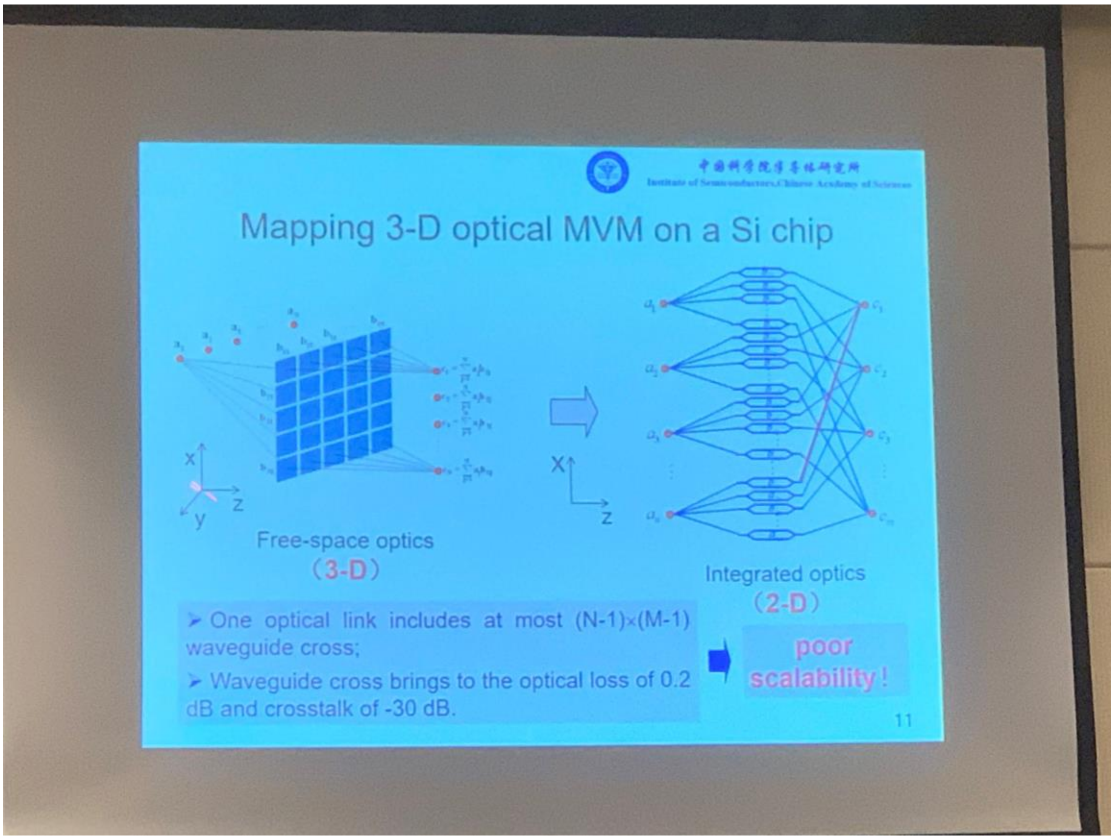

Optical adder and multiplier
Optical adder
a b c
1 1 2
1 0 1
0 1 1
0 0 0
1/2 1/4 3/4
High-precision
a
1
b
2
Laser diode
c = a + b
Power detector
➢ a: the power of LD 1; b: the power of LD 2; c: the power detected by PD.
➢ Optical addition: two modulated optical signals are combined.
Optical multiplier
a b c
1 1 1
1 0 0
0 1 0
0 0 0
1/2 1/4 1/8
a
b
c = a · b
Laser diode
Modulator
Power detector
➢ a: the power of LD; b: the transmissivity of MD; c: the power detected by PD.
➢ Optical multiplication: one modulated optical signal is modulated once more.
6

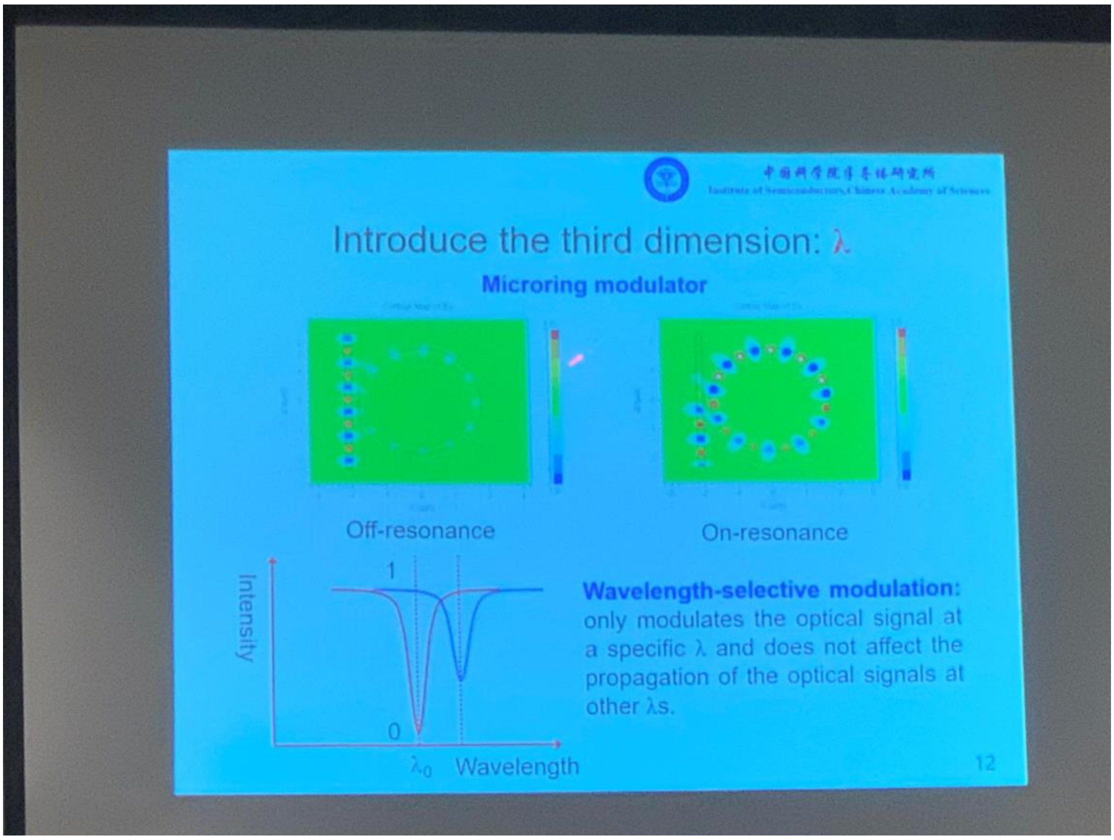

Optical matrix-vector multiplier (MVM)
Laser diode array
Stanford multiplier
Fan-out
Fan-in
Modulator matrix
Power detector array
➢ aj: the power of LD j;
➢ bij: the transmissivity of the MD located at the ith row and the jth column of the MD matrix;
➢ ci: the power detected by PD i.
➢ The multiplication of a matrix with a vector is complete in one clock cycle.
➢ If the scalability and frequency can be improved, the optical MVM will be very fast.
J. W. Goodman, et al, "Fully parallel, high-speed incoherent optical method for performing discrete Fourier transforms," Optics Letters, 2, (1978) 1-3.
7

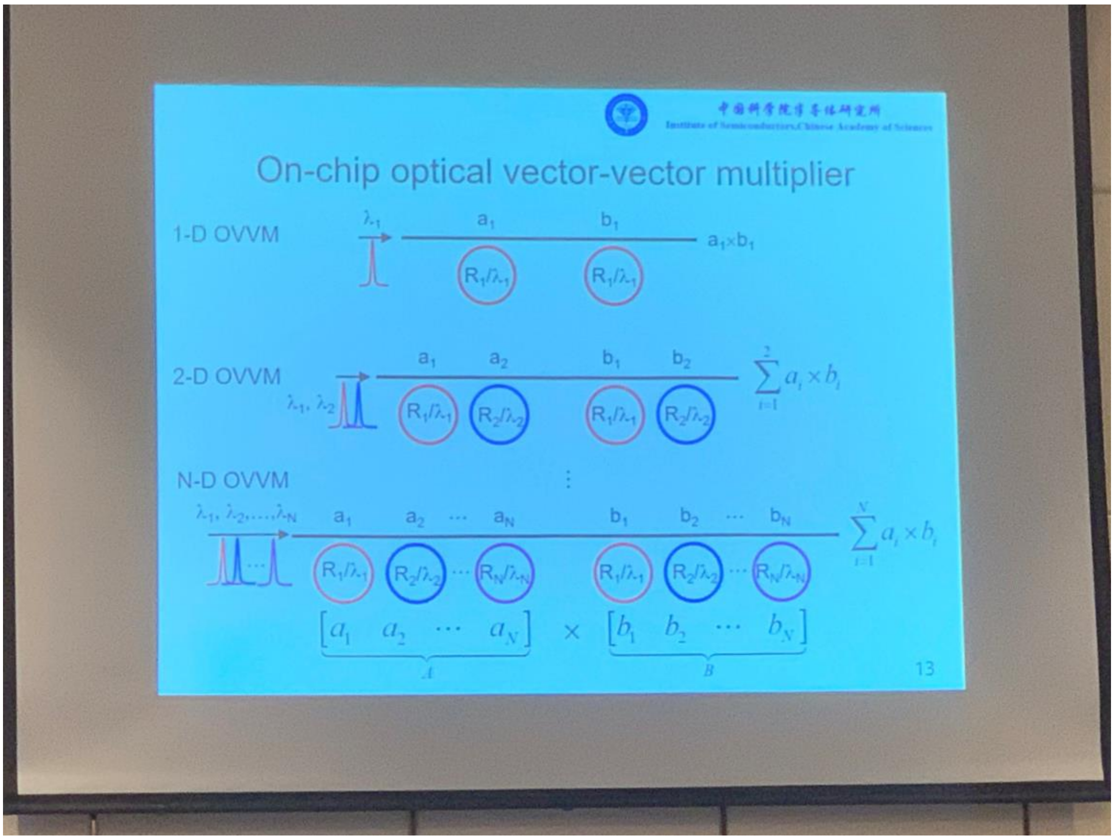


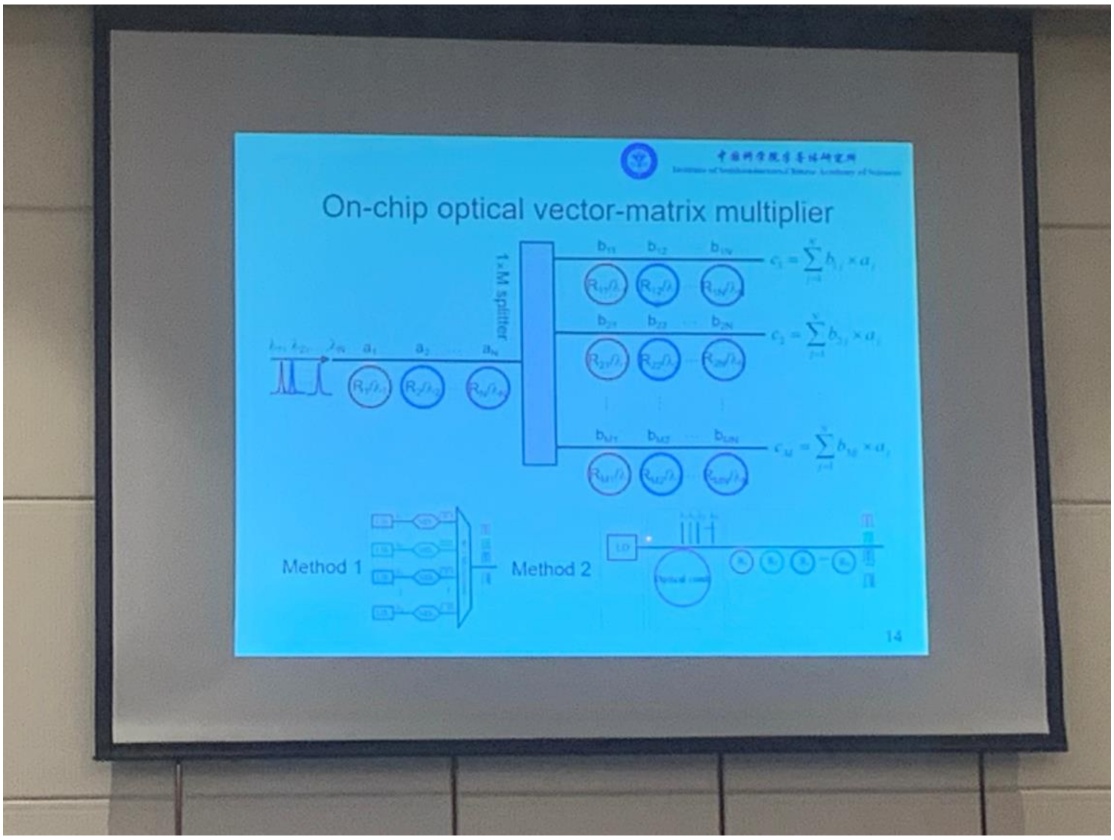
Time	Institution	Results
1978	Stanford Univ. (USA)	Propose the scheme for optical MVM.
2003	Lenslet Corp. (Isreal)	Realize a prototype named Alpha-64 (64×64 matrix).
2007	Oak Ridge National Lab (USA)	Perform 50,000 point complex FFT with Alpha64, 13,000 faster than Intel-XeonTM (2.66GHz).
2008	BAE-system Corp. (England)	Realize a prototype of optical MVM (16×16 matrix).
2007~2012	ISCAS (China)	Realize a prototype optical MVM (16×16 matrix, 7.68 GMAC/s).

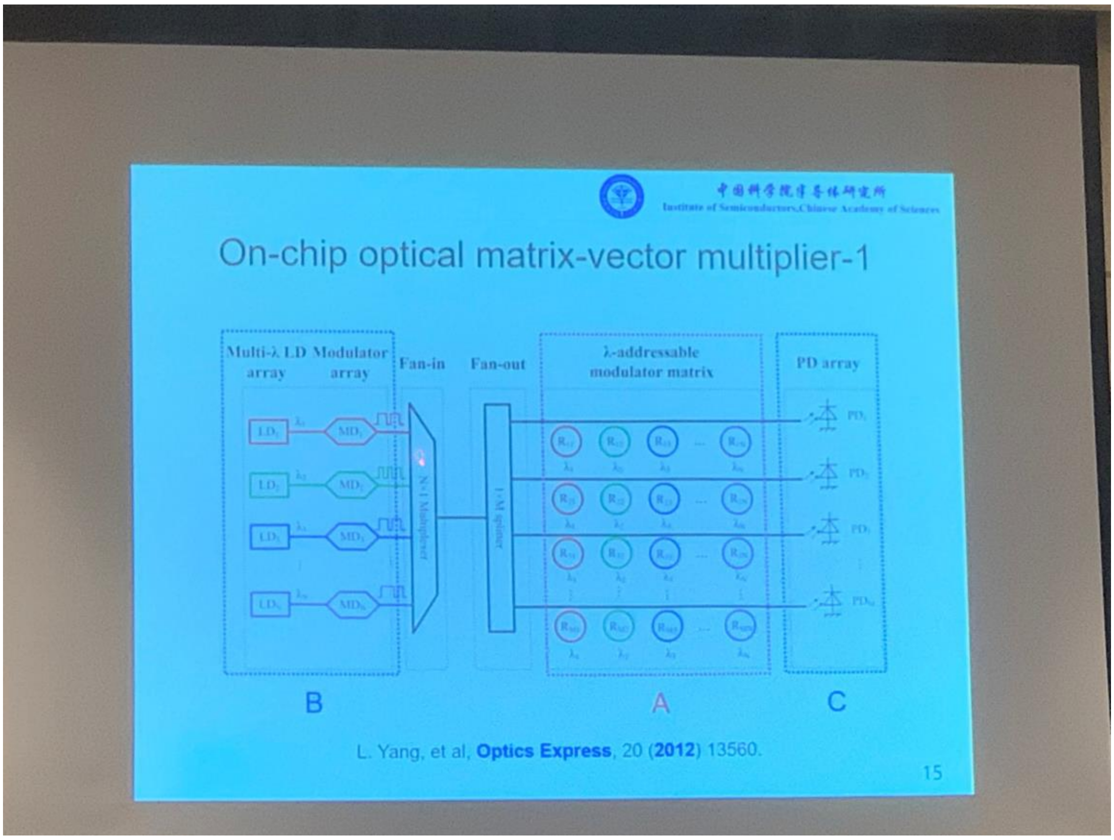


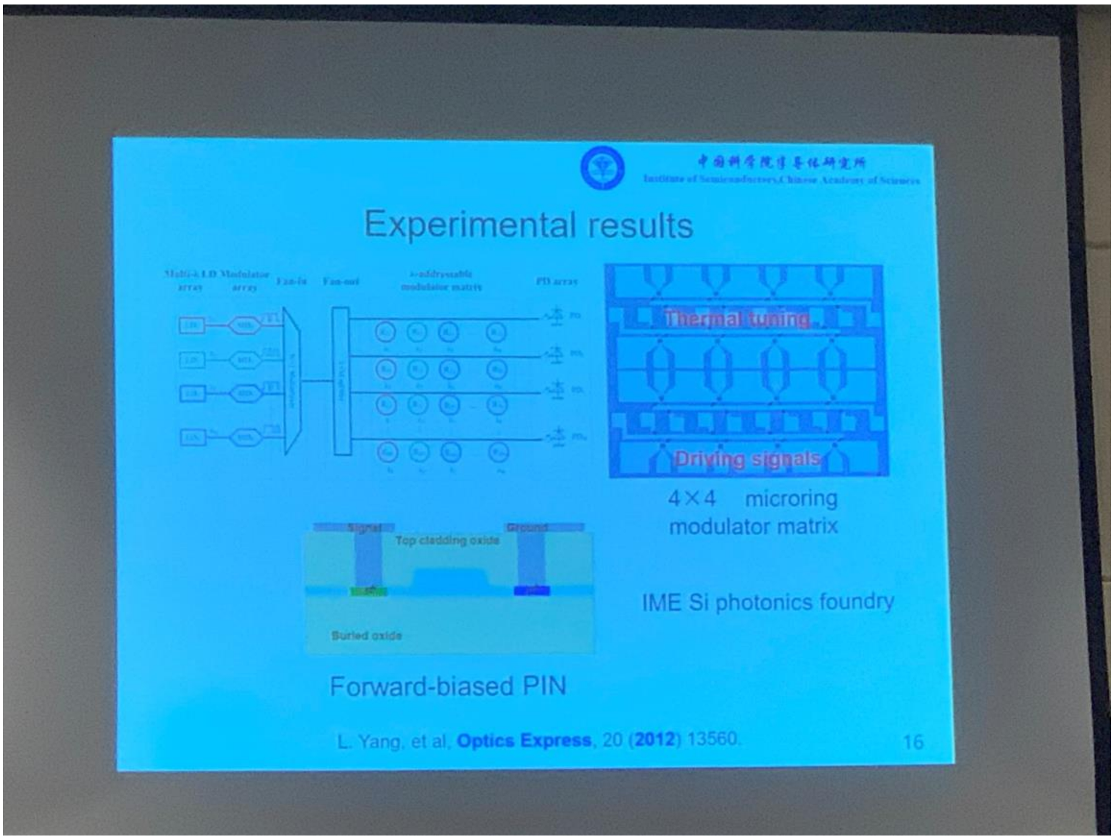

Mapping 3-D optical MVM on a Si chip
Free-space optics
（3-D）
Integrated optics
（2-D）
➢ One optical link includes at most (N-1)×(M-1) waveguide cross;
➢ Waveguide cross brings to the optical loss of 0.2 dB and crosstalk of -30 dB.
poor scalability !
11

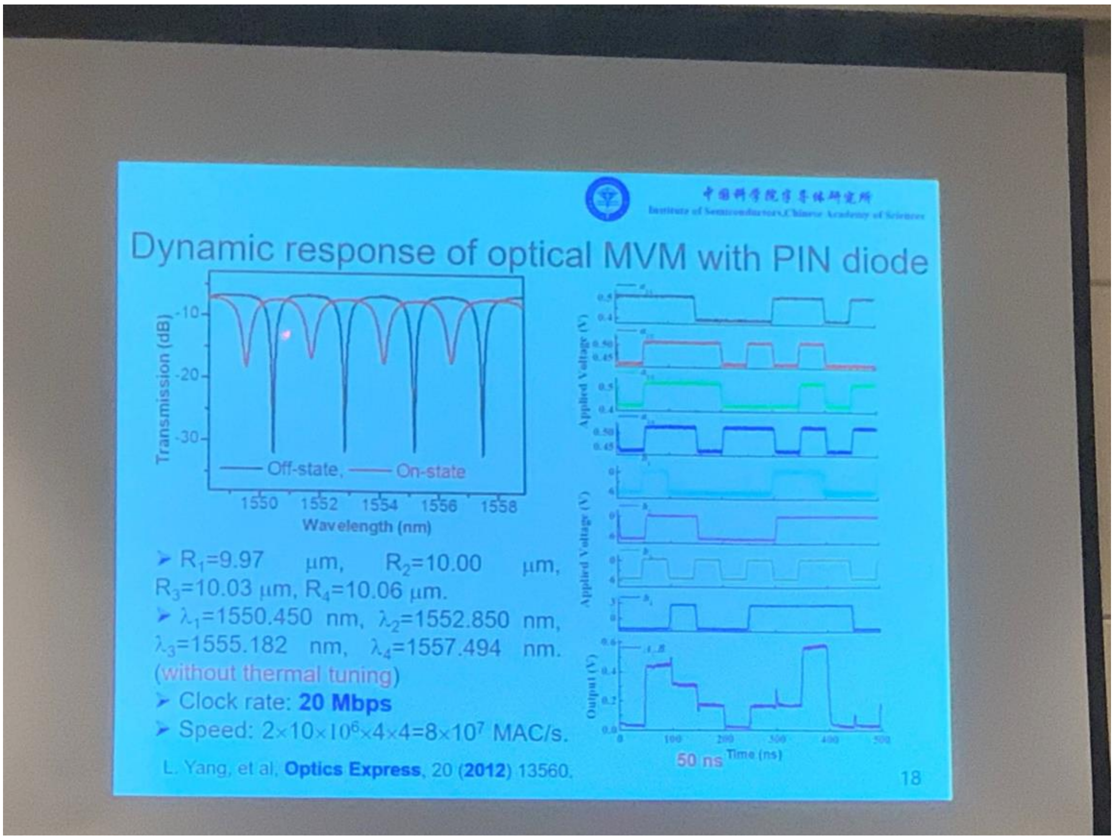

Introduce the third dimension: λ
Microring modulator
Off-resonance
On-resonance
Intensity
1
0
λ0
Wavelength
Wavelength-selective modulation:
only modulates the optical signal at a specific λ and does not affect the propagation of the optical signals at other λs.
12

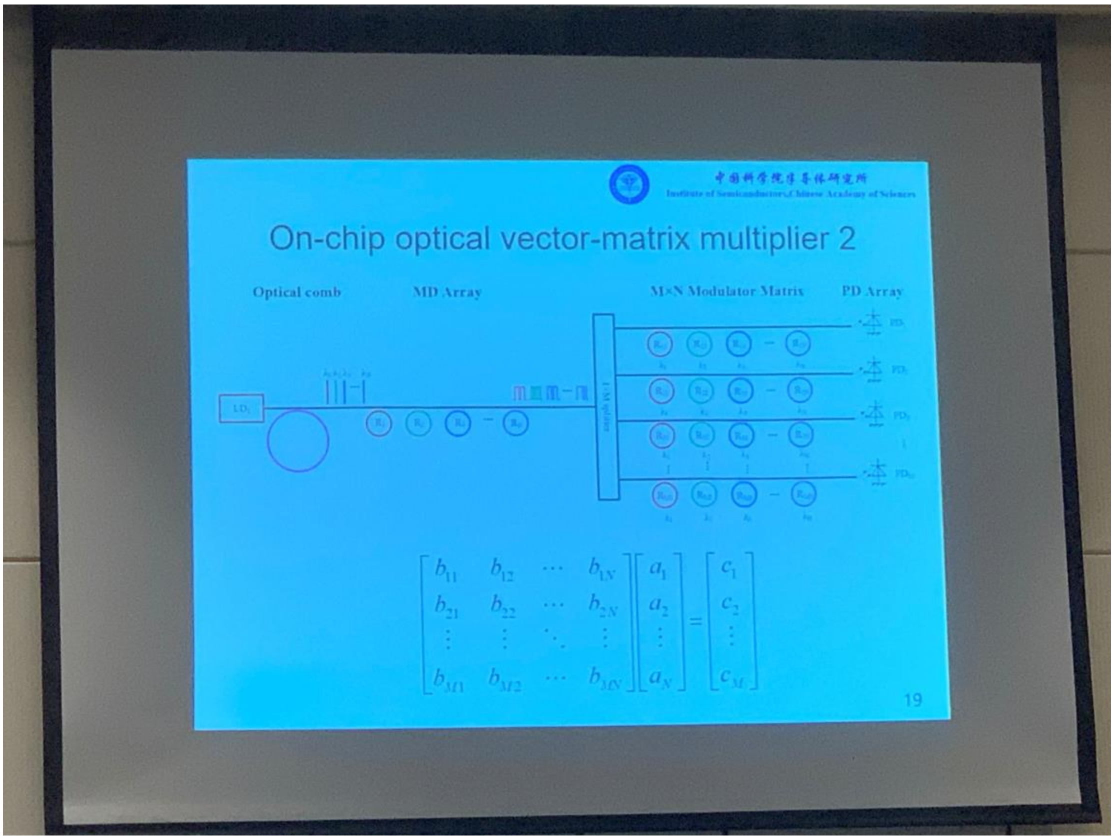

On-chip optical vector-vector multiplier
1-D OVVM
2-D OVVM
N-D OVVM
13

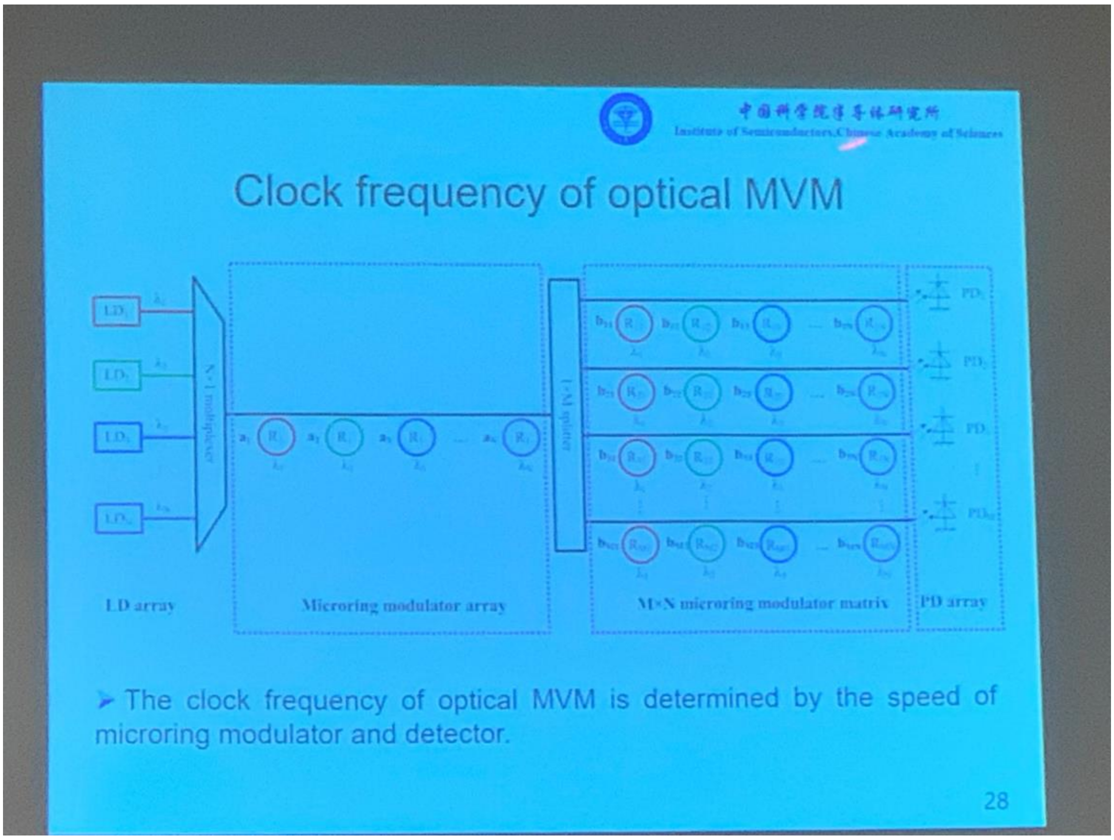

On-chip optical vector-matrix multiplier
1×M splitter
Method 1
Method 2
14

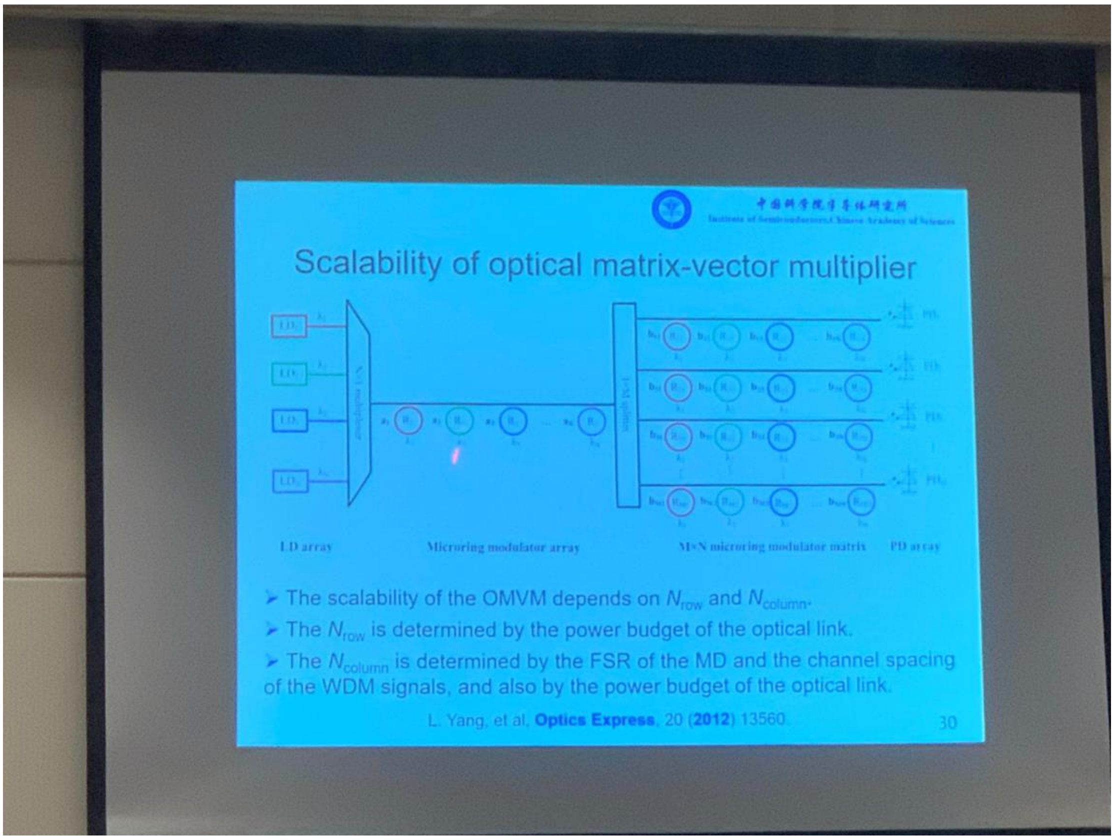

Institute of Semiconductors, Chinese Academy of Sciences
On-chip optical matrix-vector multiplier-1
Multi-λ LD array
Modulator array
Fan-in
Fan-out
λ-addressable modulator matrix
PD array
B
A
C
L. Yang, et al, Optics Express, 20 (2012) 13560.
15


Experimental results
Thermal tuning
Driving signals
4×4 microring modulator matrix
Signal
Ground
Top cladding oxide
Buried oxide
IME Si photonics foundry
Forward-biased PIN
L. Yang, et al, Optics Express, 20 (2012) 13560.
16


中国科学院半导体研究所
Institute of Semiconductors,Chinese Academy of Sciences
Dynamic response of optical MVM with PIN diode
Transmission (dB)
-10
-20
-30
Off-state, On-state
1550 1552 1554 1556 1558
Wavelength (nm)
➢ R1=9.97 μm, R2=10.00 μm, R3=10.03 μm, R4=10.06 μm.
➢ λ1=1550.450 nm, λ2=1552.850 nm, λ3=1555.182 nm, λ4=1557.494 nm. (without thermal tuning)
➢ Clock rate: 20 Mbps
➢ Speed: 2×10×10^6×4×4=8×10^7 MAC/s.
L. Yang, et al, Optics Express, 20 (2012) 13560.
Applied Voltage (V)
Applied Voltage (V)
Output (V)
0 100 200 300 400 500
50 ns
Time (ns)
18


中国科学院半导体研究所
Institute of Semiconductors,Chinese Academy of Sciences
On-chip optical vector-matrix multiplier 2
Optical comb
MD Array
M×N Modulator Matrix
PD Array
LD
$\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1N} \\ b_{21} & b_{22} & \cdots & b_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ b_{M1} & b_{M2} & \cdots & b_{MN} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_M \end{bmatrix}$
19


中国科学院半导体研究所
Institute of Semiconductors,Chinese Academy of Sciences
Clock frequency of optical MVM
LD array
Microring modulator array
M×N microring modulator matrix
PD array
➤ The clock frequency of optical MVM is determined by the speed of microring modulator and detector.
28


中国科学院半导体研究所
Institute of Semiconductors,Chinese Academy of Sciences
Scalability of optical matrix-vector multiplier
LD array
Microring modulator array
M×N microring modulator matrix
PD array
➤ The scalability of the OMVM depends on N_{row} and N_{column}.
➤ The N_{row} is determined by the power budget of the optical link.
➤ The N_{column} is determined by the FSR of the MD and the channel spacing of the WDM signals, and also by the power budget of the optical link.
L. Yang, et al, Optics Express, 20 (2012) 13560.
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Summary
➢ We propose an on-chip optical MVM and demonstrate a prototype with the speed of 1.6×10^{10} MAC/s. We also discuss its potential speed.
➢ There is still a long road to go for the application of optical processor.
Electronics
Transistor (1947)
IC (1959, Kilby and Noyce)
Processor (1MHz, Intel 1971)
Optics
Original idea
Optical processor (8×10^{7} MAC/s) 2012
Optical processor (1.6×10^{10} MAC/s) 2016
L. Zhang, et al, CN200810116741.0, (2008.7.16)
L. Yang*, et al, Optics Express, 20 (2012) 13560.
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