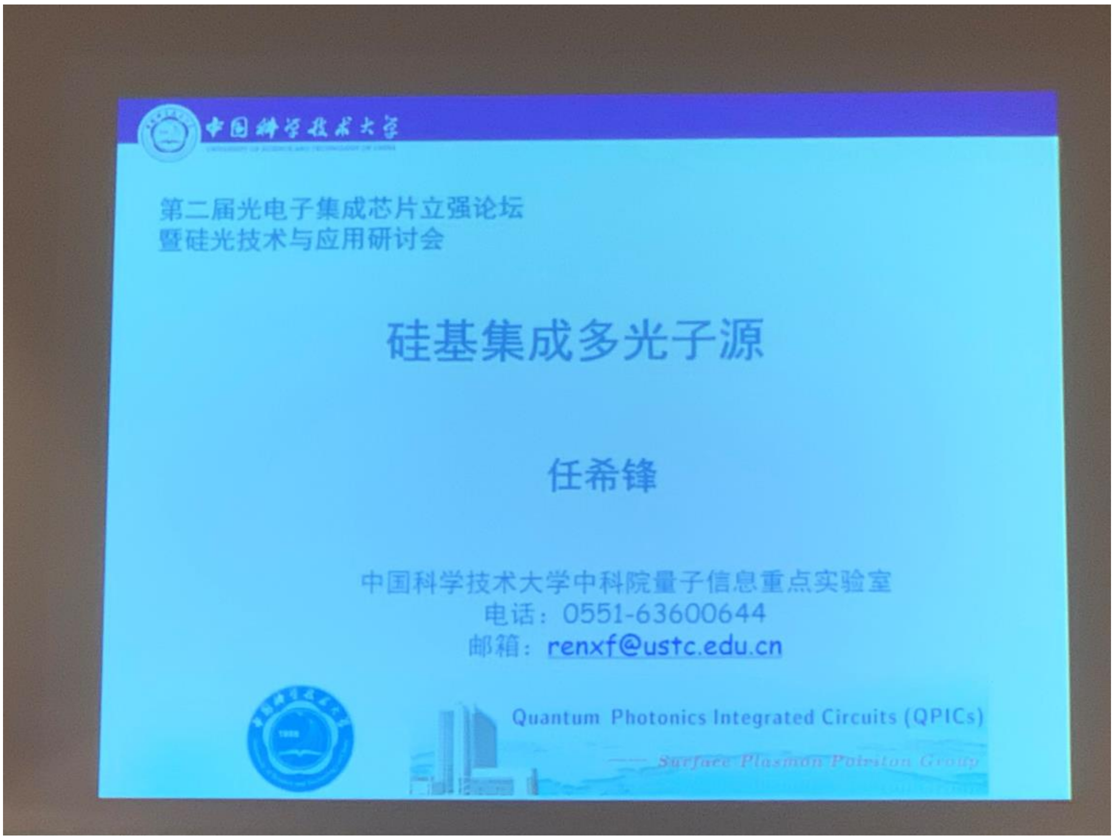
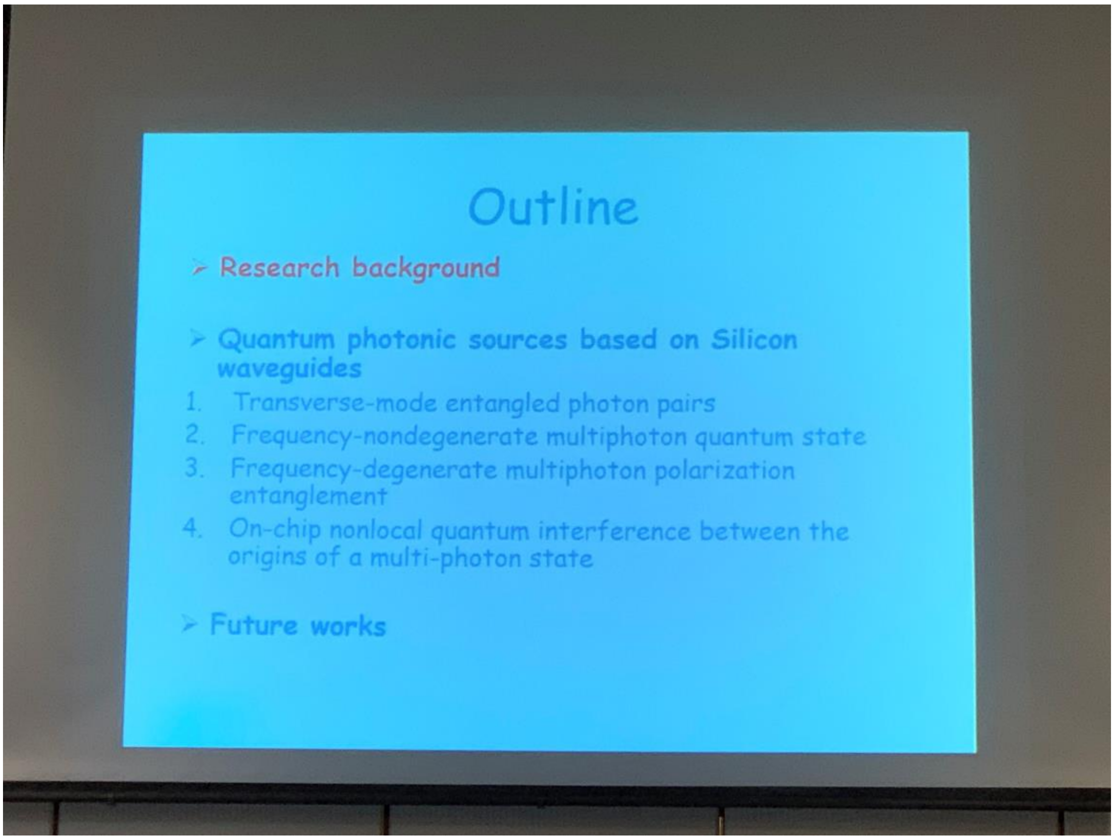
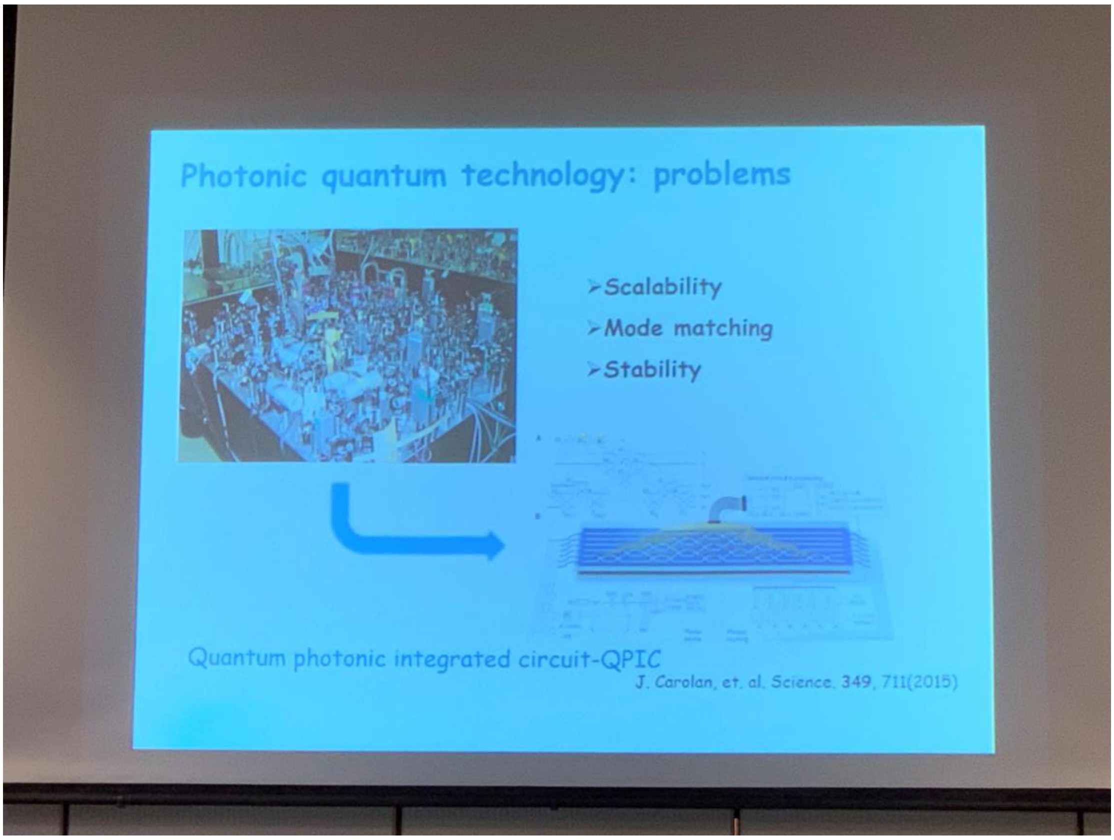
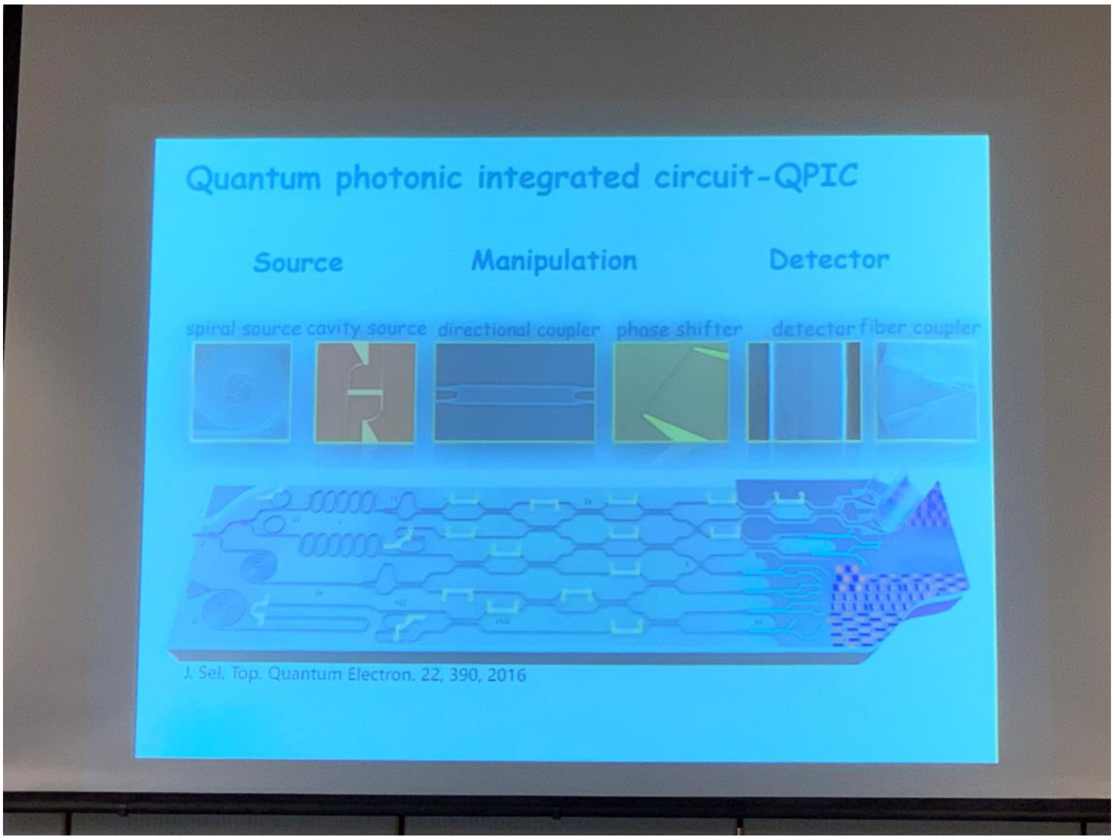
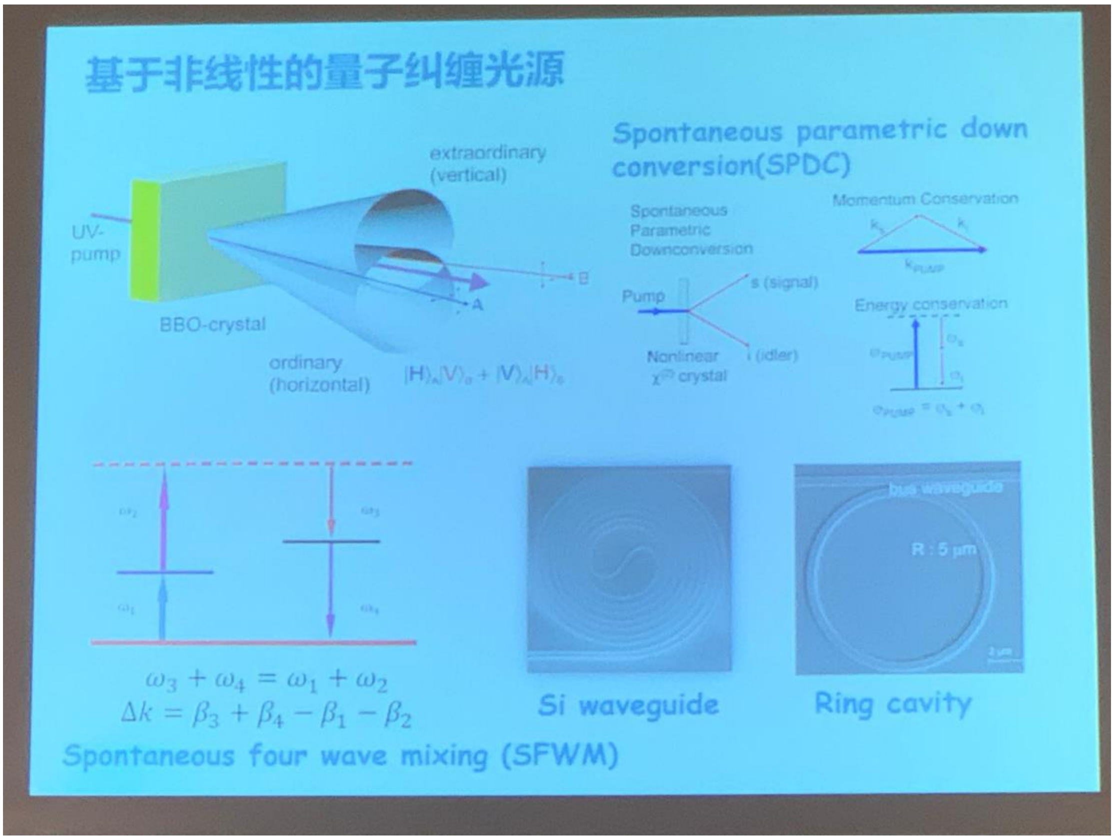
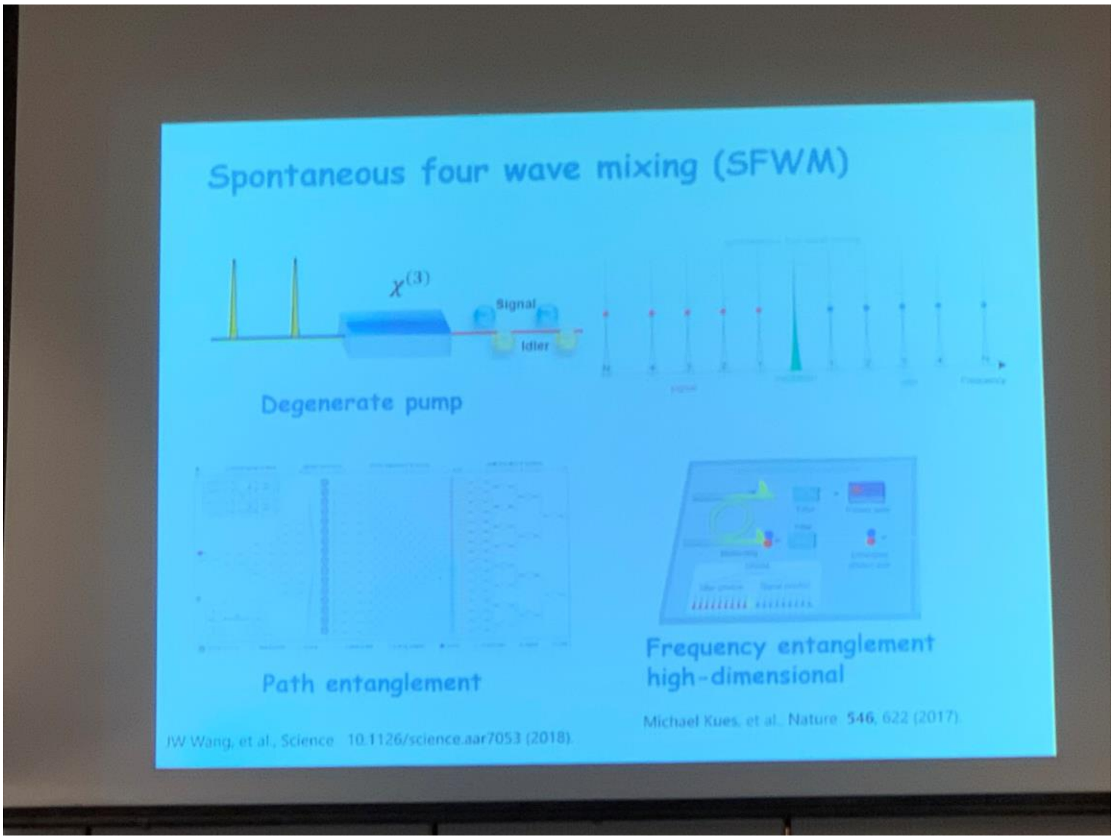

中国科学技术大学
第二届光电子集成芯片立强论坛
暨硅光技术与应用研讨会
硅基集成多光子源
任希锋
中国科学技术大学中科院量子信息重点实验室
电话：0551-63600644
邮箱：renxf@ustc.edu.cn
Quantum Photonics Integrated Circuits (QPICs)
—— Surface Plasmon Polariton Group

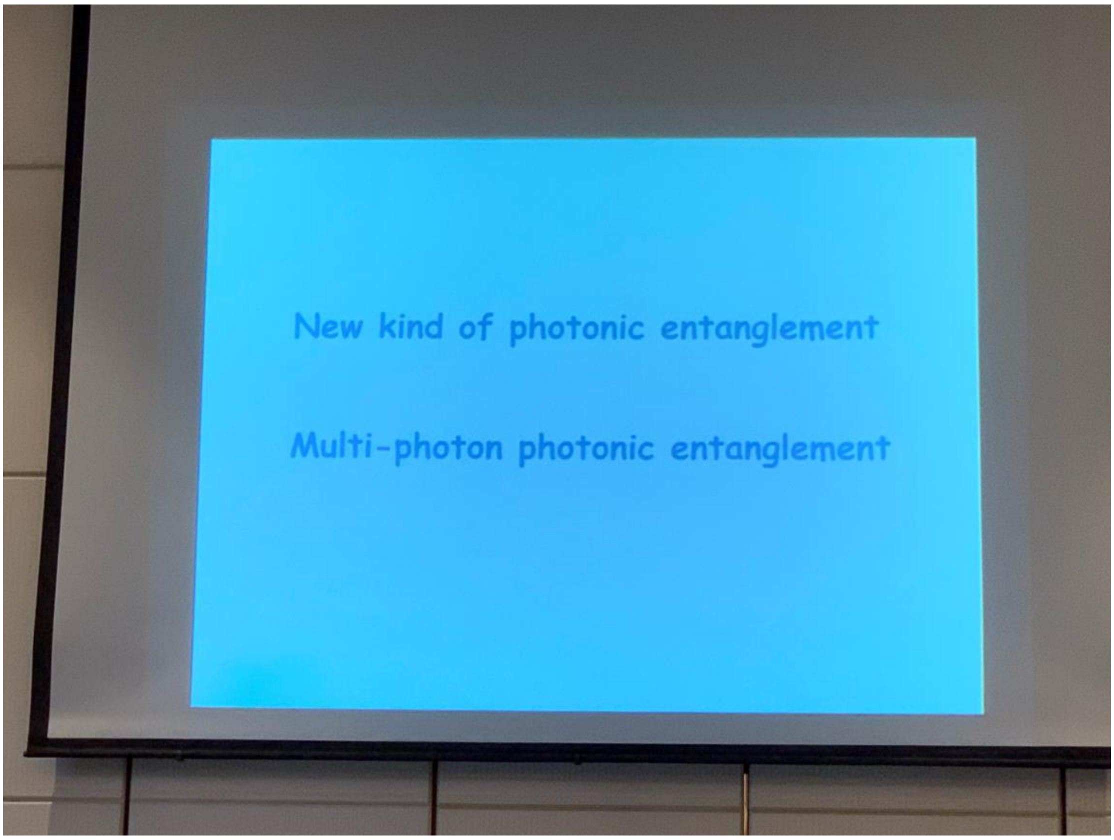

Outline
➢ Research background
➢ Quantum photonic sources based on Silicon waveguides
1. Transverse-mode entangled photon pairs
2. Frequency-nondegenerate multiphoton quantum state
3. Frequency-degenerate multiphoton polarization entanglement
4. On-chip nonlocal quantum interference between the origins of a multi-photon state
➢ Future works

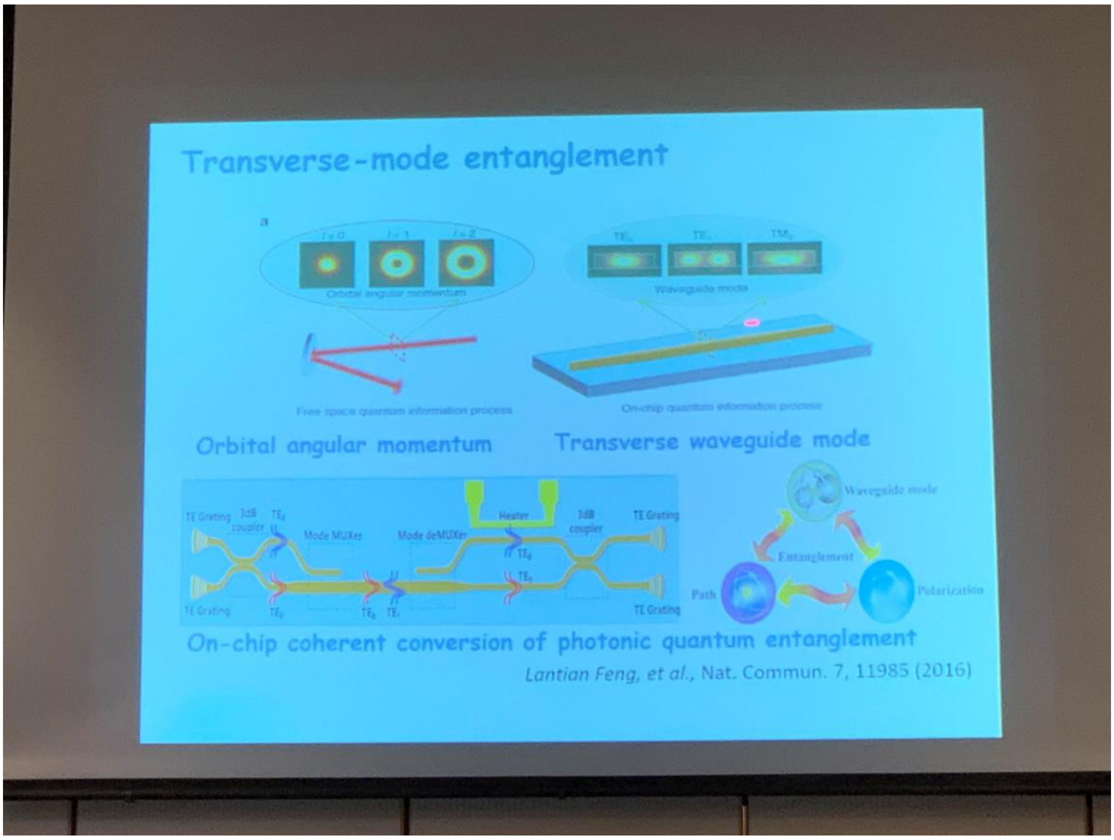

Photonic quantum technology: problems
➢Scalability
➢Mode matching
➢Stability
Quantum photonic integrated circuit-QPIC
J. Carolan, et. al. Science. 349, 711(2015)

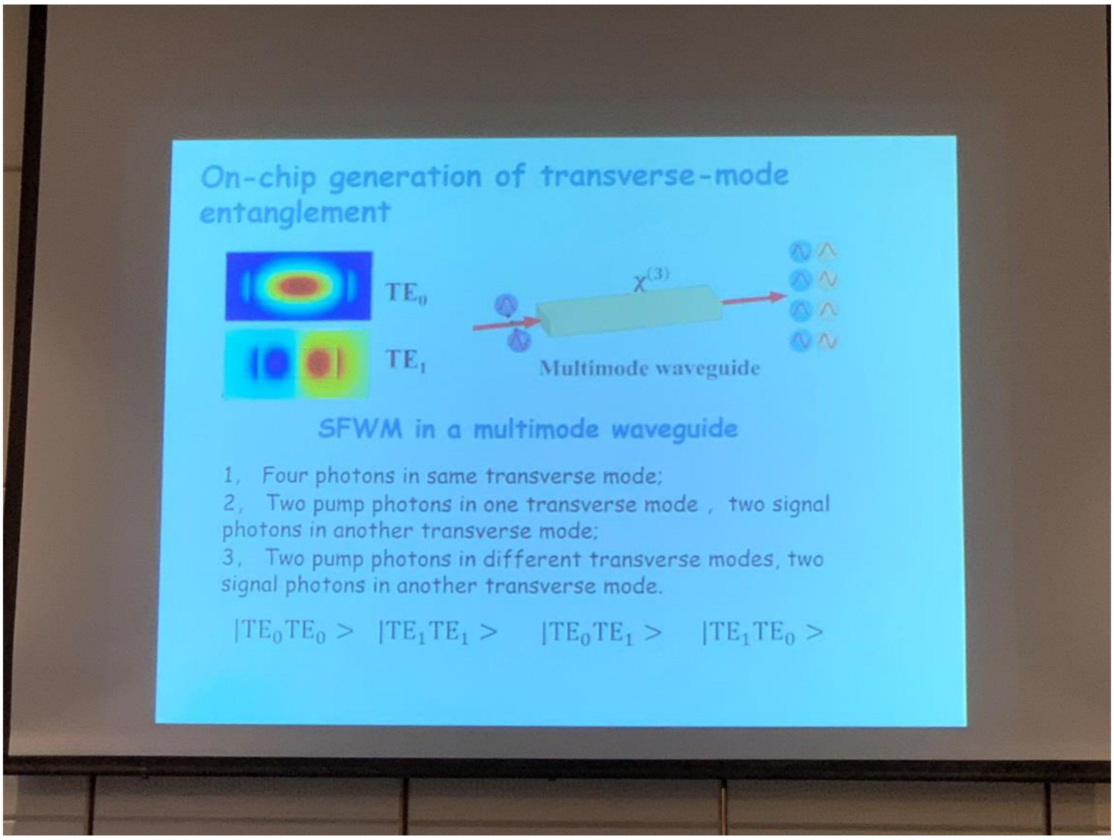

Quantum photonic integrated circuit-QPIC
Source
Manipulation
Detector
spiral source
cavity source
directional coupler
phase shifter
detector
fiber coupler
J. Sel. Top. Quantum Electron. 22, 390, 2016

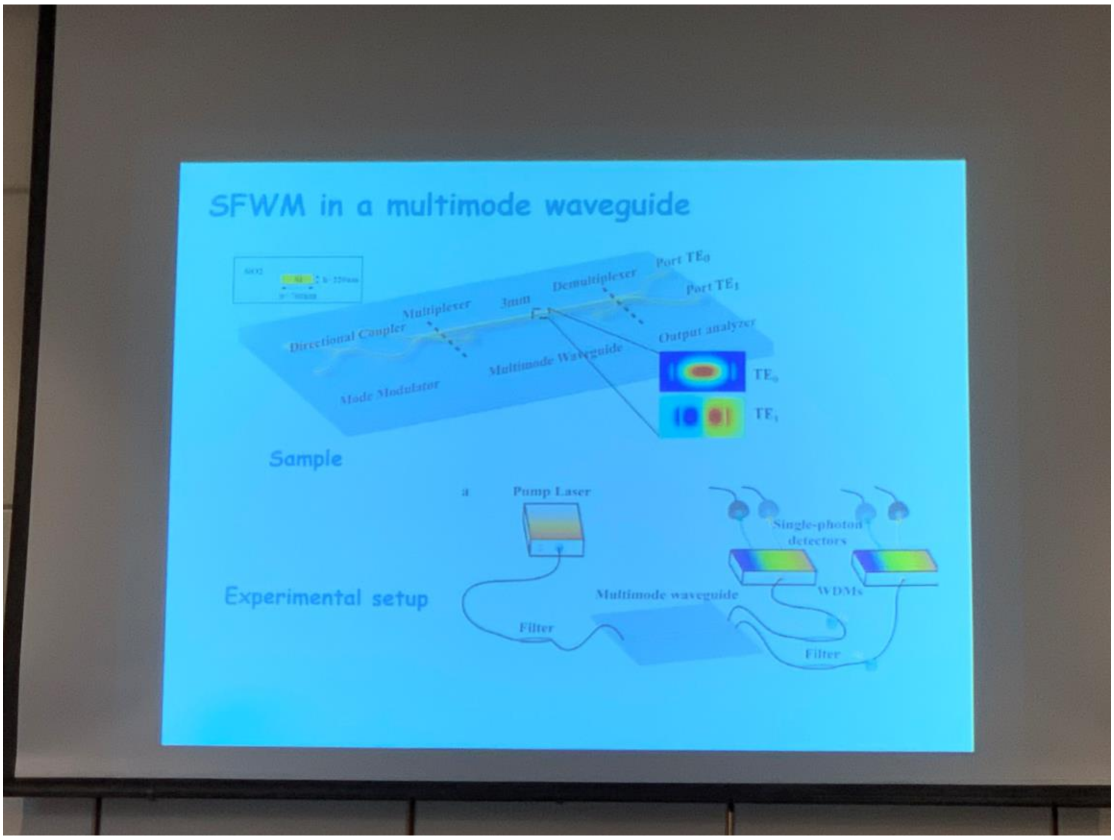

基于非线性的量子纠缠光源
Spontaneous parametric down conversion(SPDC)
extraordinary (vertical)
UV-pump
BBO-crystal
ordinary (horizontal)
Spontaneous Parametric Downconversion
Momentum Conservation
Pump
s (signal)
i (idler)
Nonlinear $\chi^{(2)}$ crystal
Energy conservation
$\omega_{PUMP} = \omega_s + \omega_i$
$\omega_3 + \omega_4 = \omega_1 + \omega_2$
$\Delta k = \beta_3 + \beta_4 - \beta_1 - \beta_2$
Spontaneous four wave mixing (SFWM)
bus waveguide
R : 5 μm
Si waveguide
Ring cavity

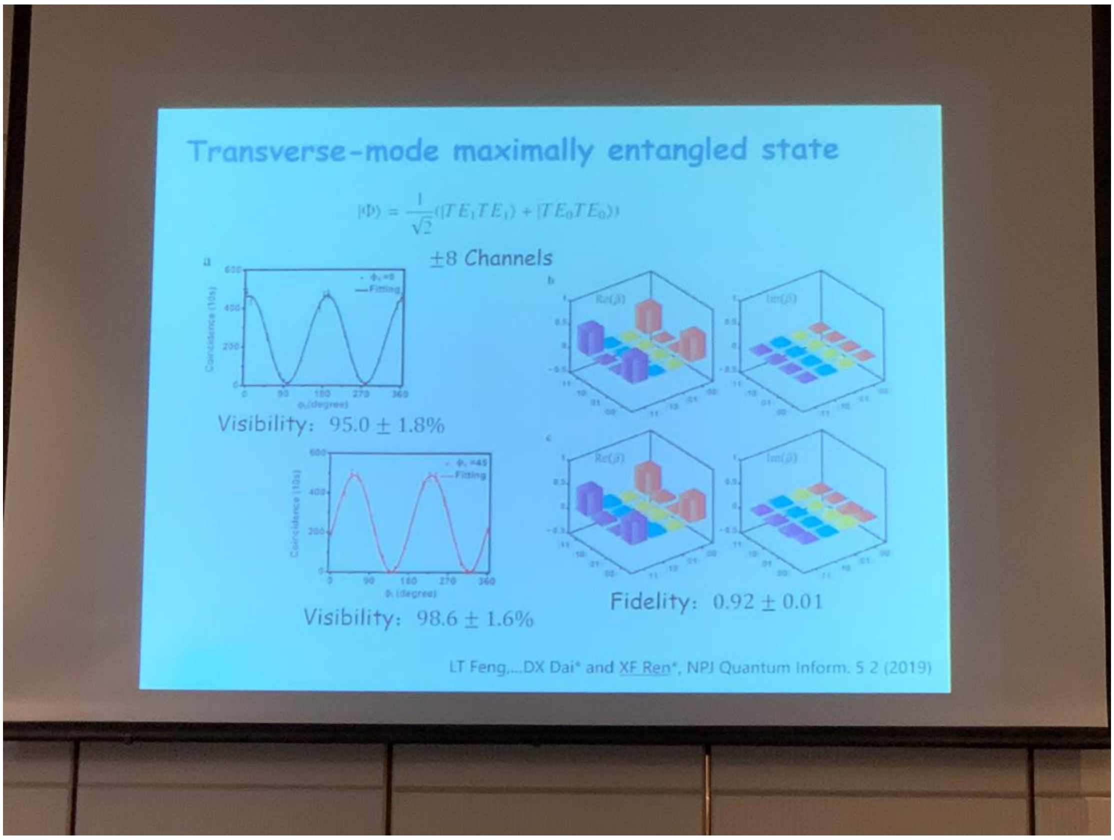

Spontaneous four wave mixing (SFWM)
$\chi^{(3)}$
Signal
Idler
Degenerate pump
Path entanglement
Frequency entanglement high-dimensional
JW Wang, et al., Science 10.1126/science.aar7053 (2018).
Michael Kues, et al., Nature 546, 622 (2017).

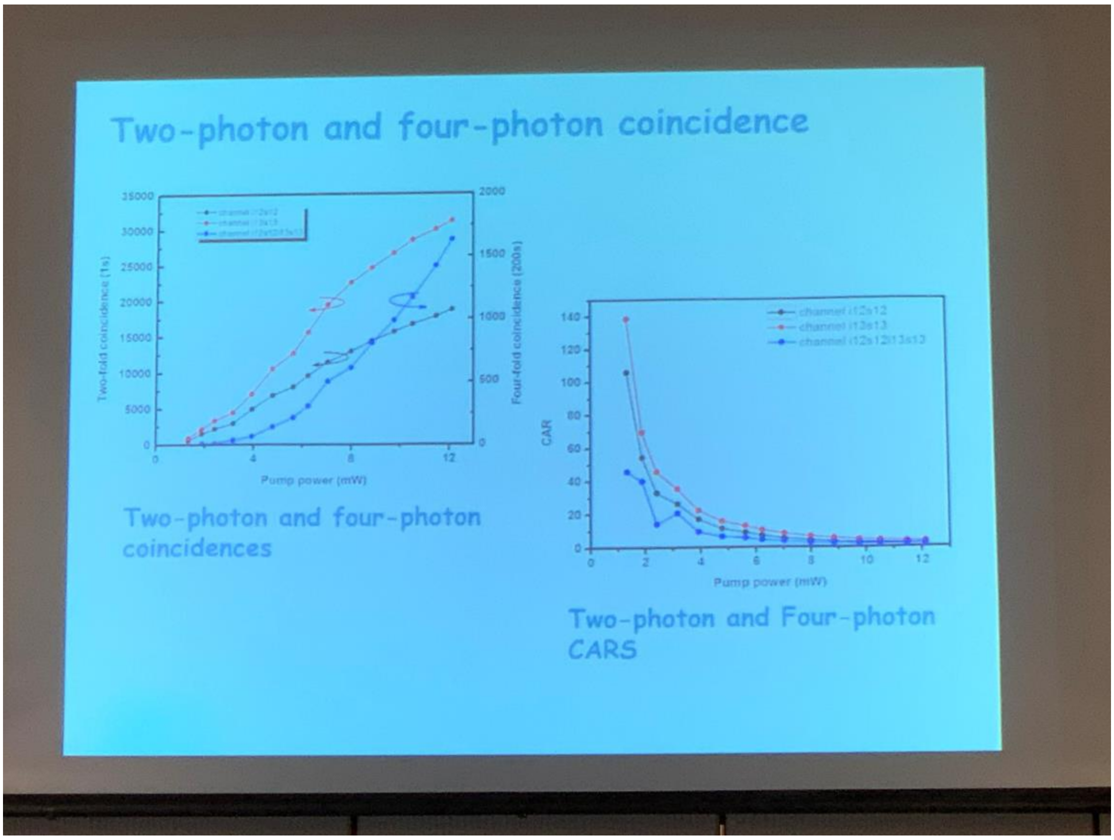

New kind of photonic entanglement
Multi-photon photonic entanglement

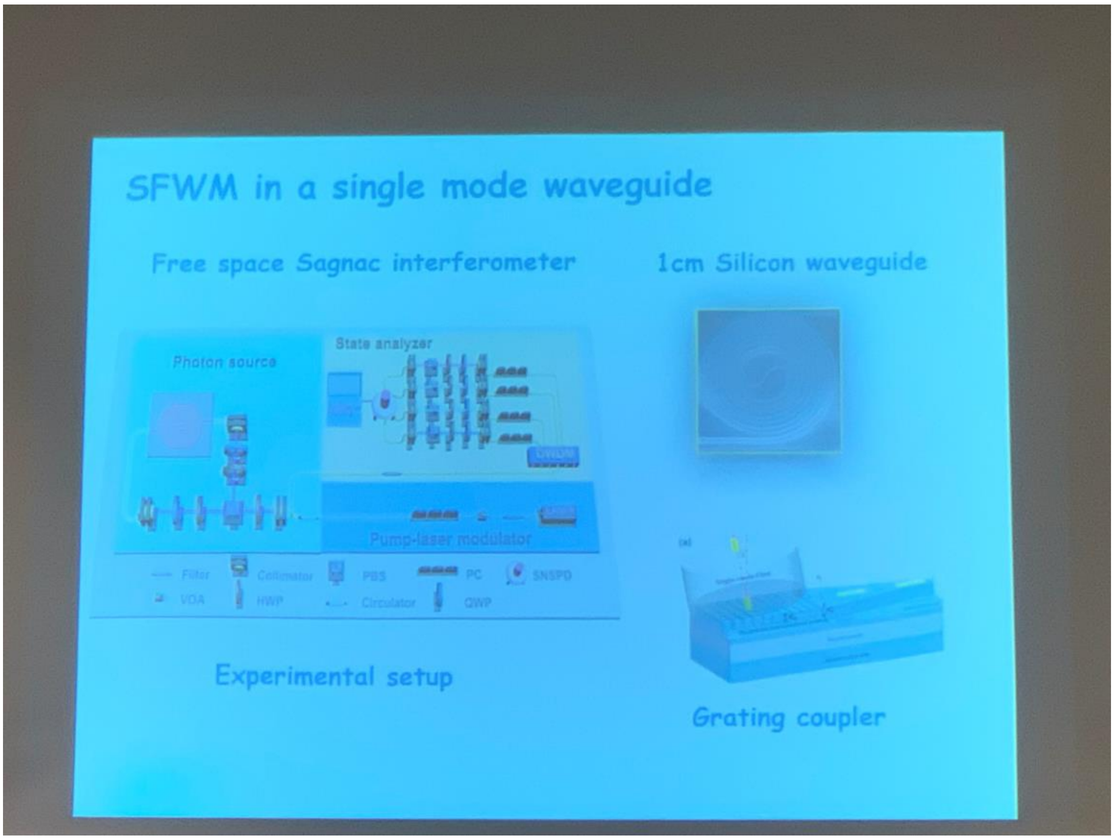

Transverse-mode entanglement
a
Orbital angular momentum
Waveguide mode
Free space quantum information process
On-chip quantum information process
Orbital angular momentum
Transverse waveguide mode
TE Grating
3dB coupler
Mode MUXer
Mode deMUXer
Heater
3dB coupler
TE Grating
TE Grating
TE Grating
Waveguide mode
Entanglement
Path
Polarization
On-chip coherent conversion of photonic quantum entanglement
Lantian Feng, et al., Nat. Commun. 7, 11985 (2016)

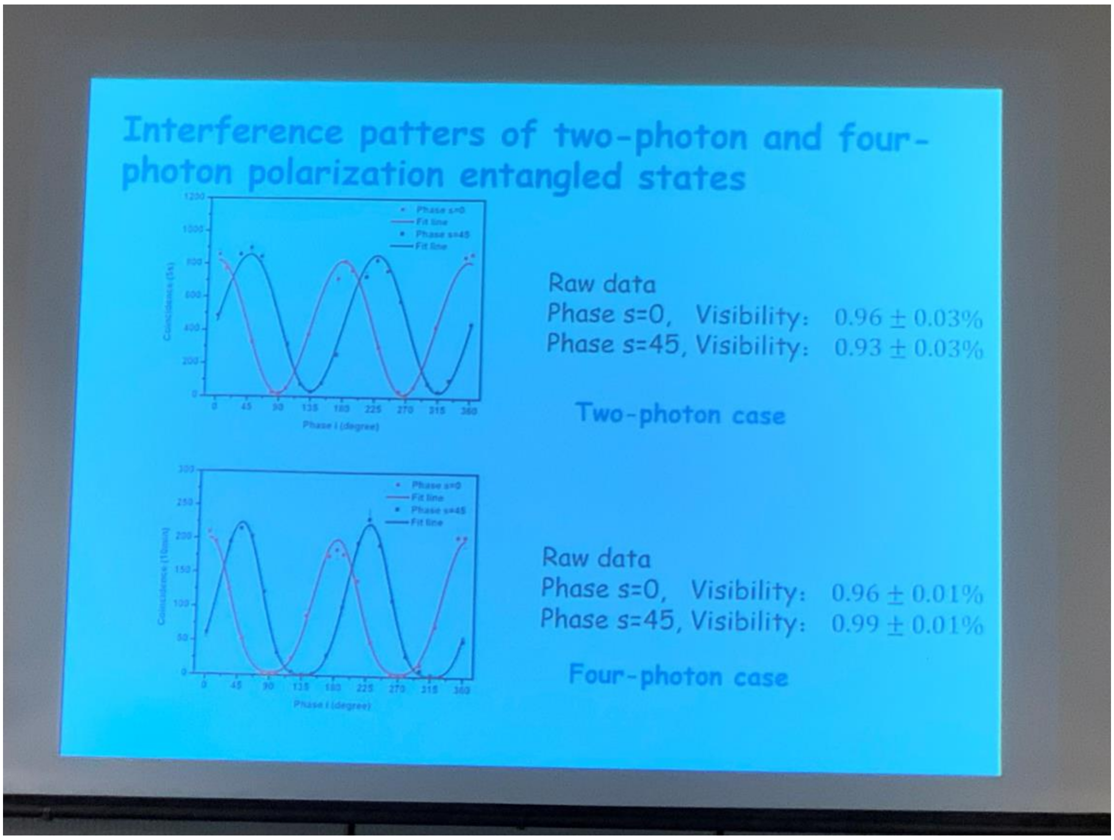

On-chip generation of transverse-mode entanglement
TE_0
TE_1
$\chi^{(3)}$
Multimode waveguide
SFWM in a multimode waveguide
1, Four photons in same transverse mode;
2, Two pump photons in one transverse mode , two signal photons in another transverse mode;
3, Two pump photons in different transverse modes, two signal photons in another transverse mode.
$|TE_0TE_0>$ $|TE_1TE_1>$ $|TE_0TE_1>$ $|TE_1TE_0>$

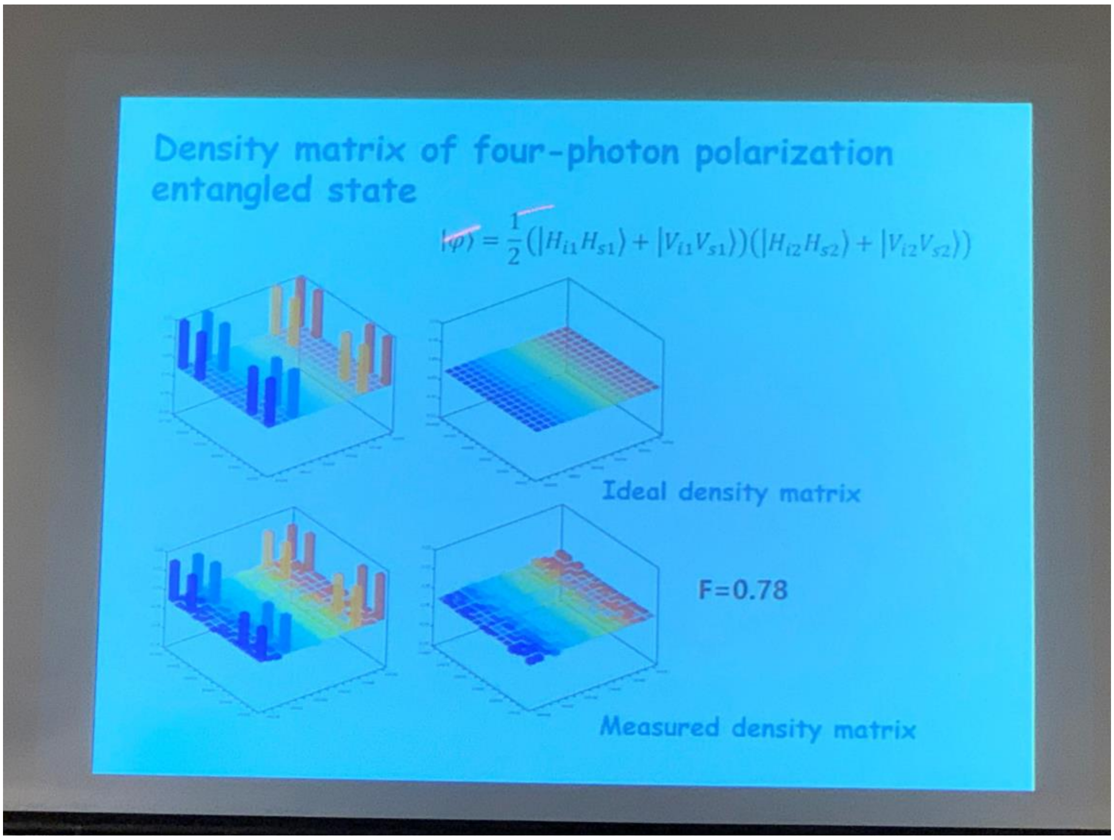

SFWM in a multimode waveguide
Port TE_0
Port TE_1
Demultiplexer
Multiplexer
3mm
Directional Coupler
Output analyzer
Multimode Waveguide
Mode Modulator
TE_0
TE_1
Sample
a
Pump Laser
Single-photon detectors
WDMs
Multimode waveguide
Experimental setup
Filter
Filter

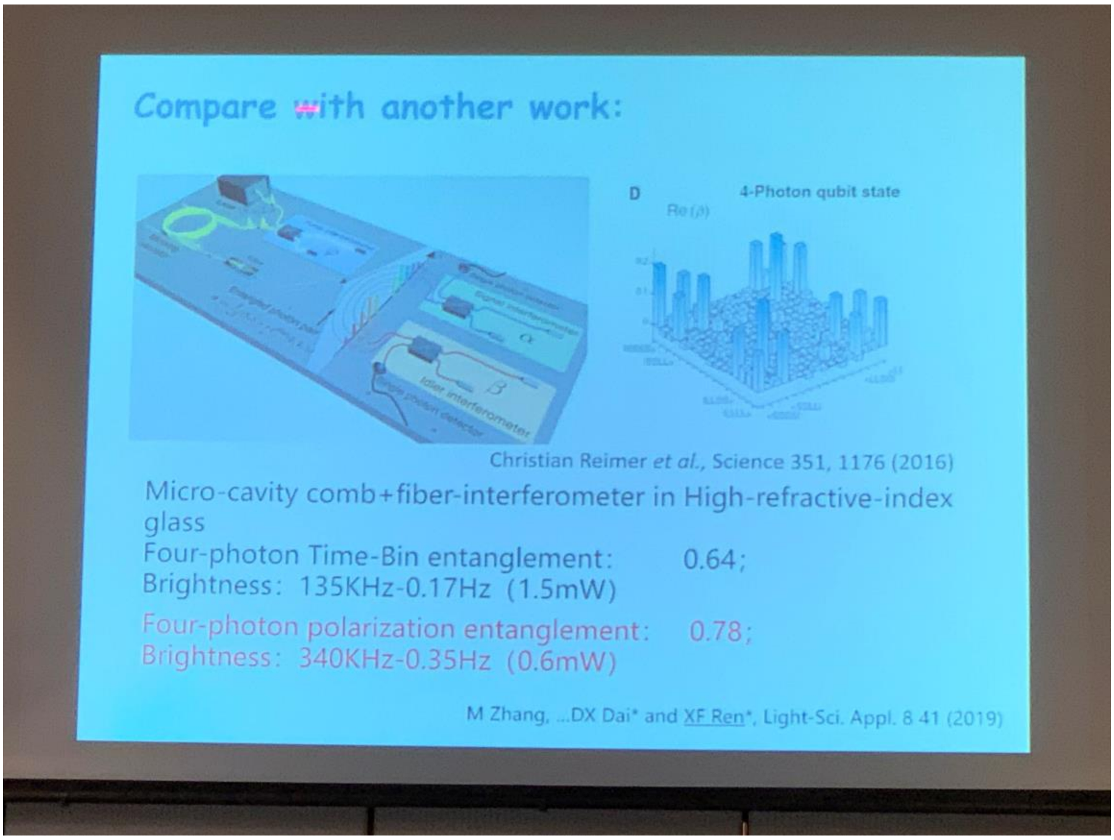

Transverse-mode maximally entangled state
$|\Phi\rangle = \frac{1}{\sqrt{2}}(|TE_1TE_1\rangle + |TE_0TE_0\rangle)$
±8 Channels
Visibility: 95.0 ± 1.8%
Visibility: 98.6 ± 1.6%
Fidelity: 0.92 ± 0.01
LT Feng,...DX Dai* and XF Ren*, NPJ Quantum Inform. 5 2 (2019)

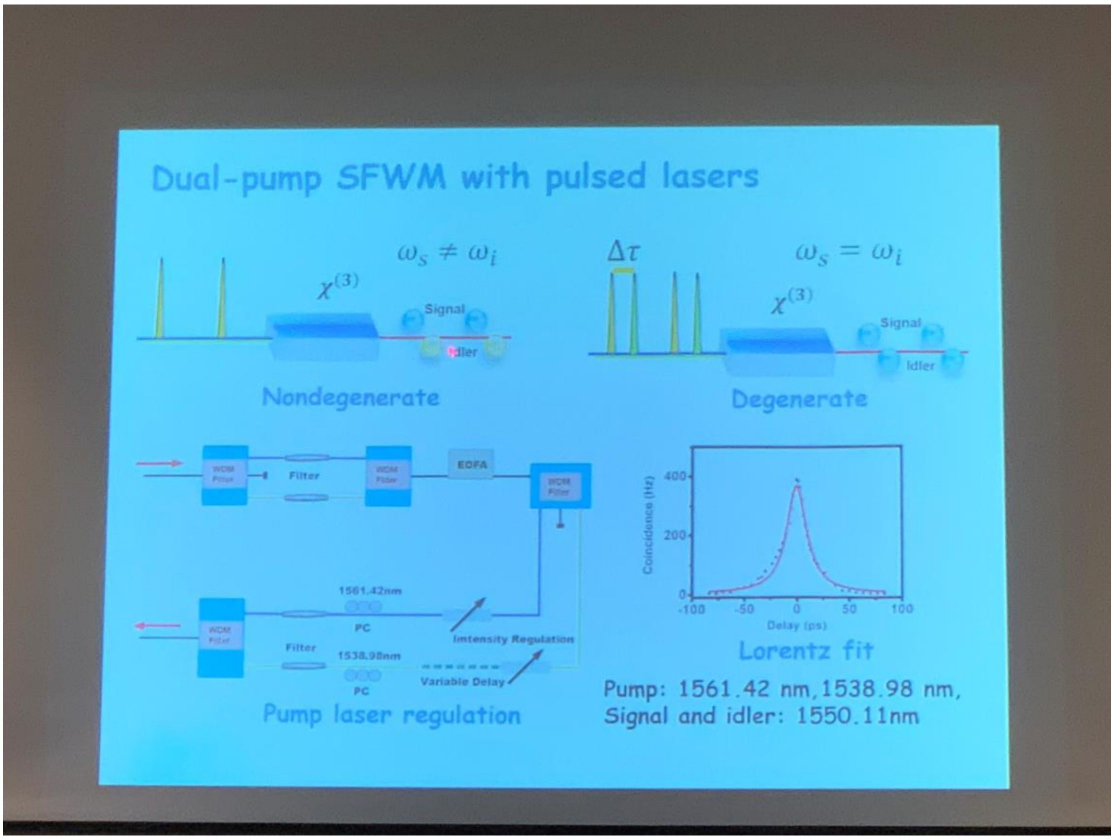

Two-photon and four-photon coincidence
Two-fold coincidence (1s)
Four-fold coincidence (200s)
Pump power (mW)
Two-photon and four-photon coincidences
CAR
Pump power (mW)
Two-photon and Four-photon CARS

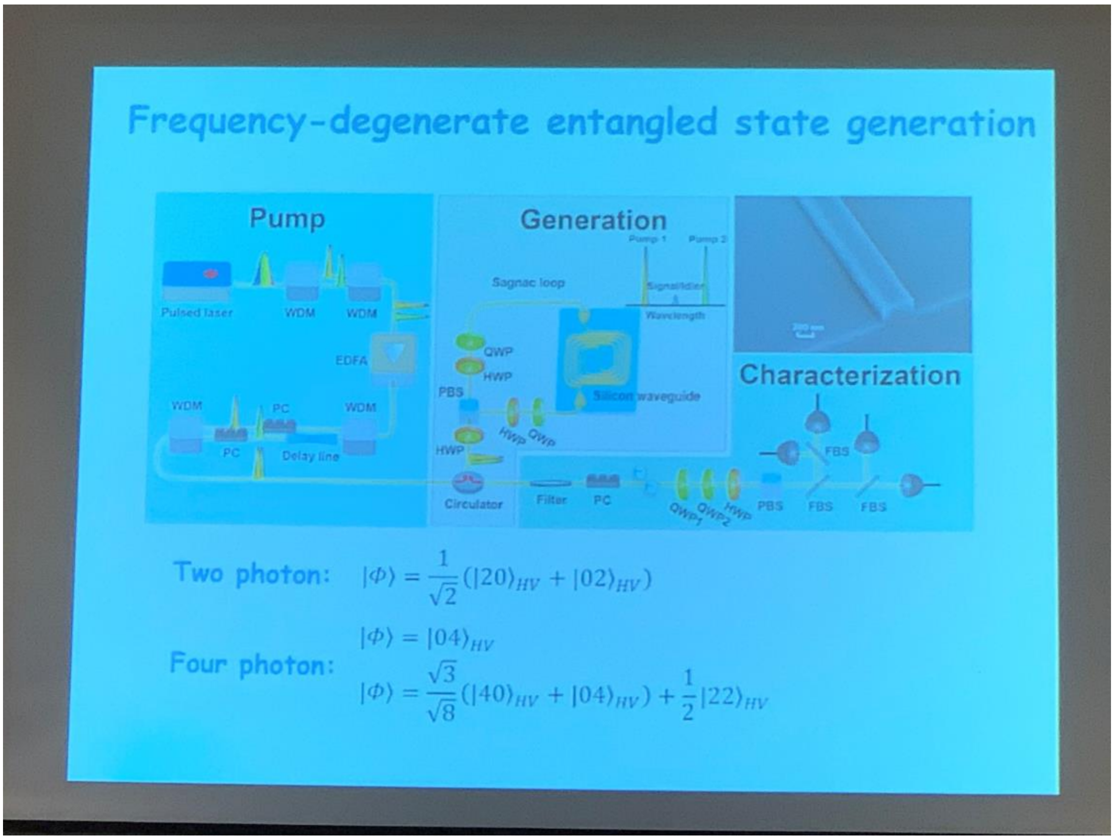

SFWM in a single mode waveguide
Free space Sagnac interferometer
1cm Silicon waveguide
Photon source
State analyzer
Pump-laser modulator
Filter
Collimator
PBS
PC
SNSPD
VOA
HWP
Circulator
QWP
Experimental setup
Grating coupler

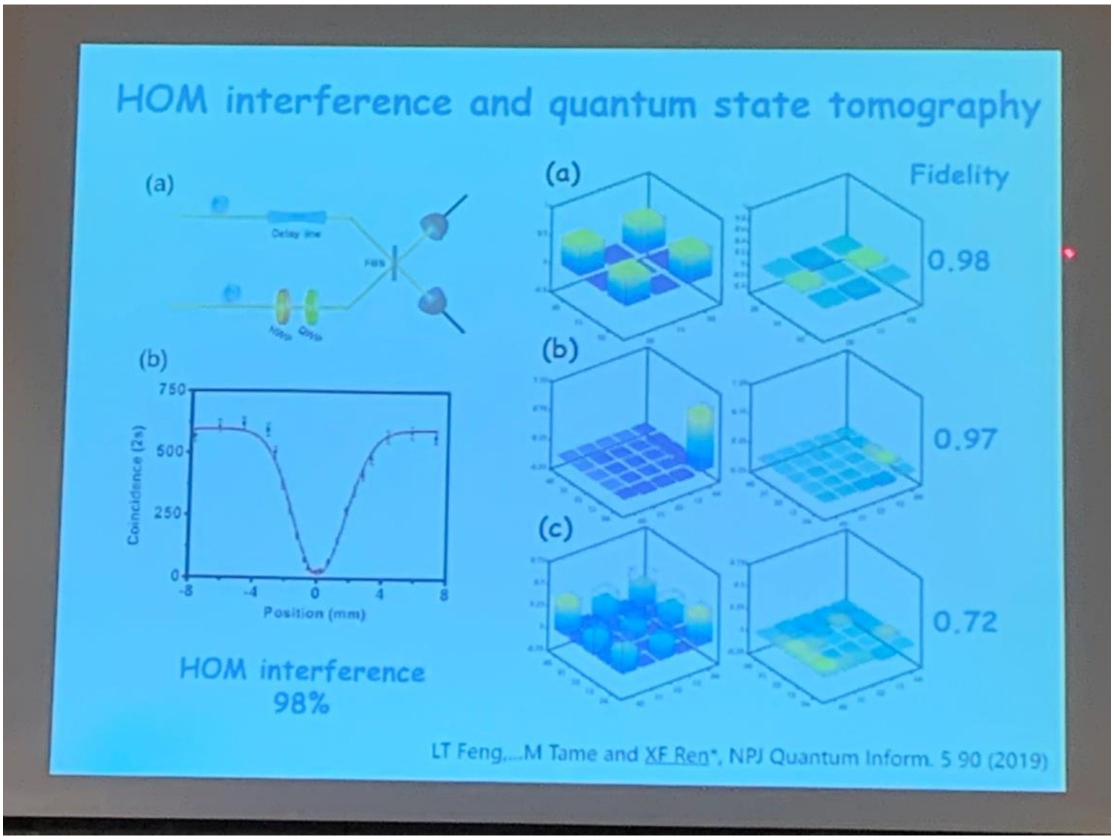

Interference patters of two-photon and four-photon polarization entangled states
Raw data
Phase s=0, Visibility: 0.96 ± 0.03%
Phase s=45, Visibility: 0.93 ± 0.03%
Two-photon case
Raw data
Phase s=0, Visibility: 0.96 ± 0.01%
Phase s=45, Visibility: 0.99 ± 0.01%
Four-photon case

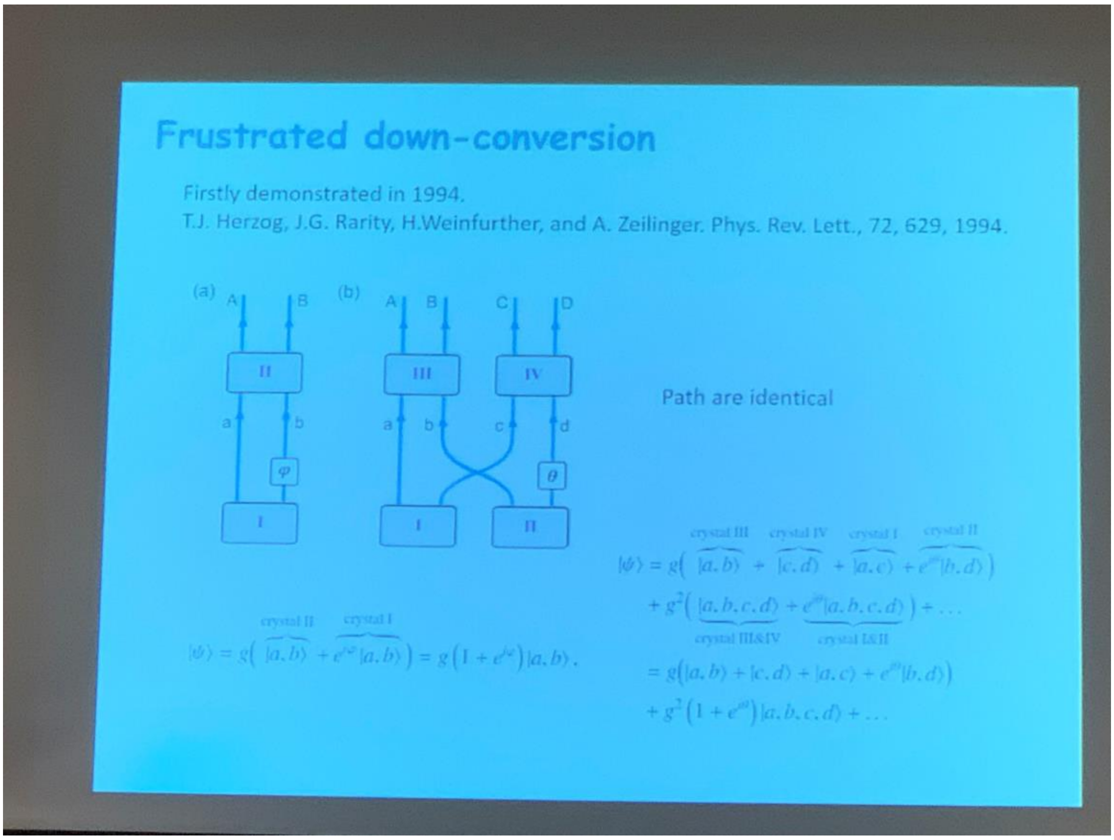

Density matrix of four-photon polarization entangled state
$|\varphi\rangle = \frac{1}{2}(|H_{i1}H_{s1}\rangle + |V_{i1}V_{s1}\rangle)(|H_{i2}H_{s2}\rangle + |V_{i2}V_{s2}\rangle)$
Ideal density matrix
F=0.78
Measured density matrix

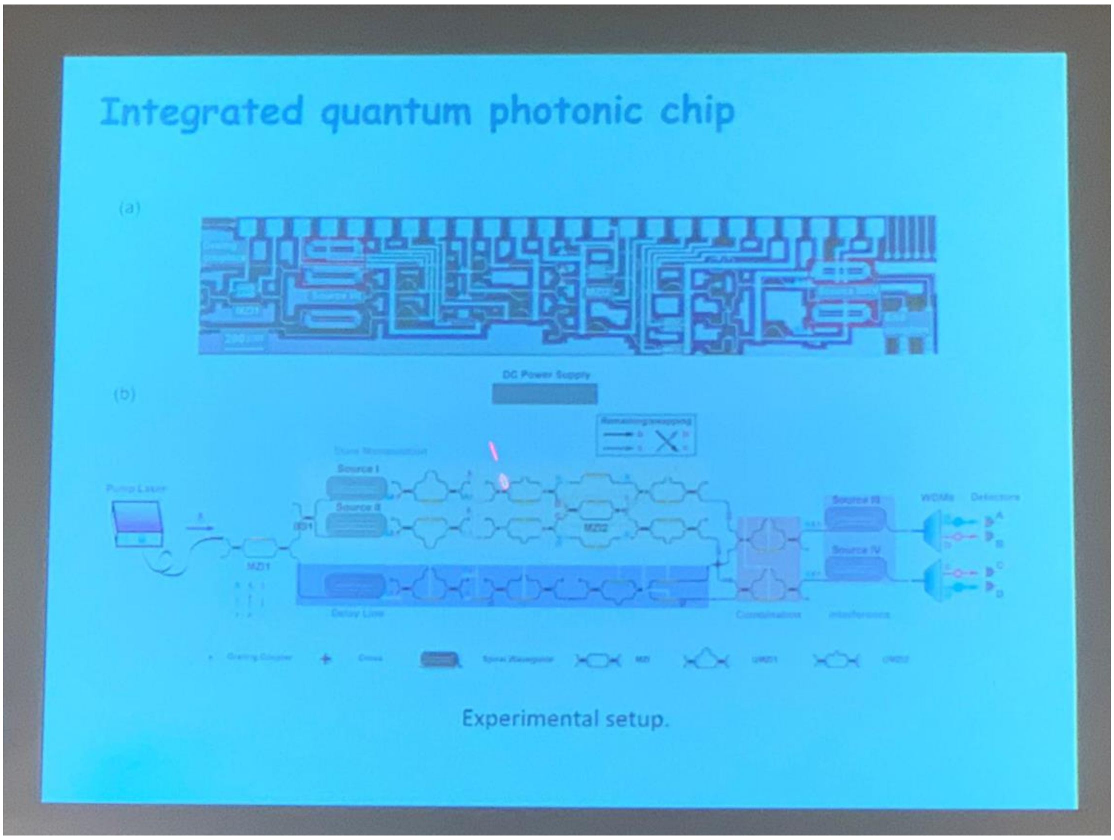

Compare with another work:
D
4-Photon qubit state
Re (ρ)
Idler interferometer
Christian Reimer et al., Science 351, 1176 (2016)
Micro-cavity comb+fiber-interferometer in High-refractive-index glass
Four-photon Time-Bin entanglement: 0.64;
Brightness: 135KHz-0.17Hz (1.5mW)
Four-photon polarization entanglement: 0.78;
Brightness: 340KHz-0.35Hz (0.6mW)
M Zhang, ...DX Dai* and XF Ren*, Light-Sci. Appl. 8 41 (2019)

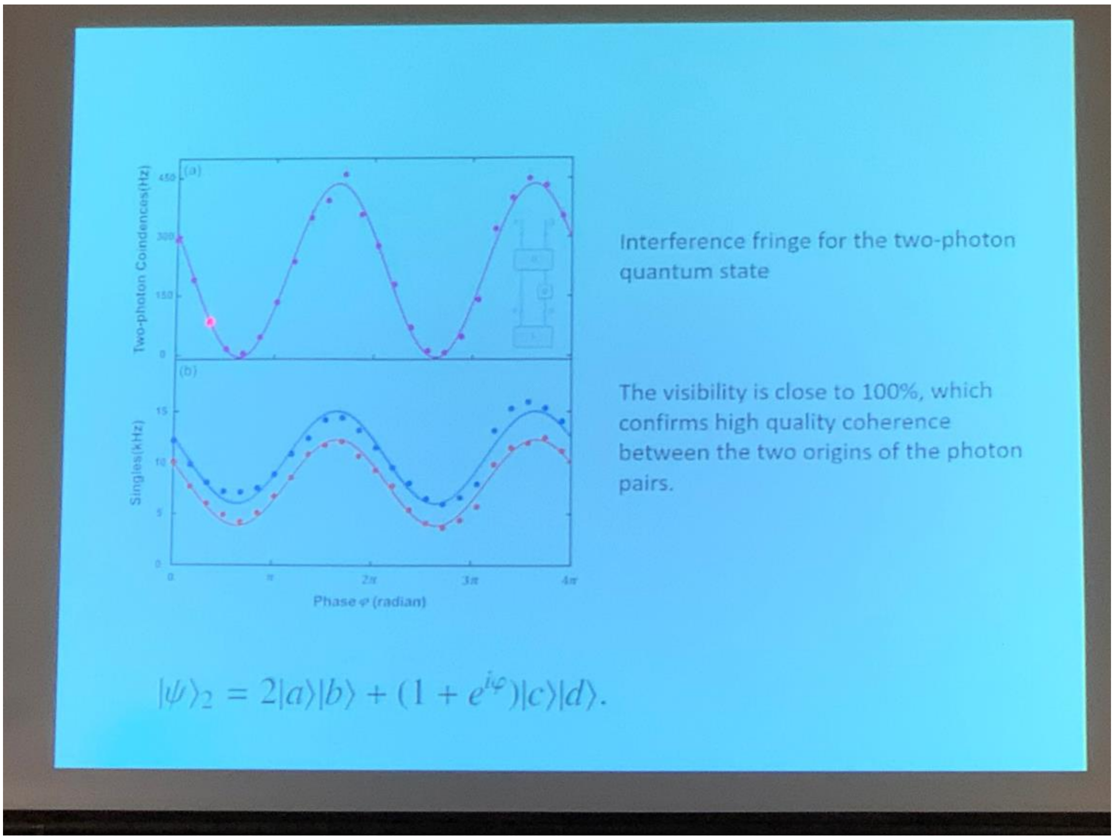

Dual-pump SFWM with pulsed lasers
$\omega_s \neq \omega_i$
$\chi^{(3)}$
Signal
Idler
Nondegenerate
$\Delta\tau$
$\omega_s = \omega_i$
$\chi^{(3)}$
Signal
Idler
Degenerate
WDM Filter
Filter
WDM Filter
EDFA
WDM Filter
1561.42nm
PC
Intensity Regulation
WDM Filter
Filter
1538.98nm
PC
Variable Delay
Pump laser regulation
Coincidence (Hz)
Delay (ps)
Lorentz fit
Pump: 1561.42 nm,1538.98 nm,
Signal and idler: 1550.11nm

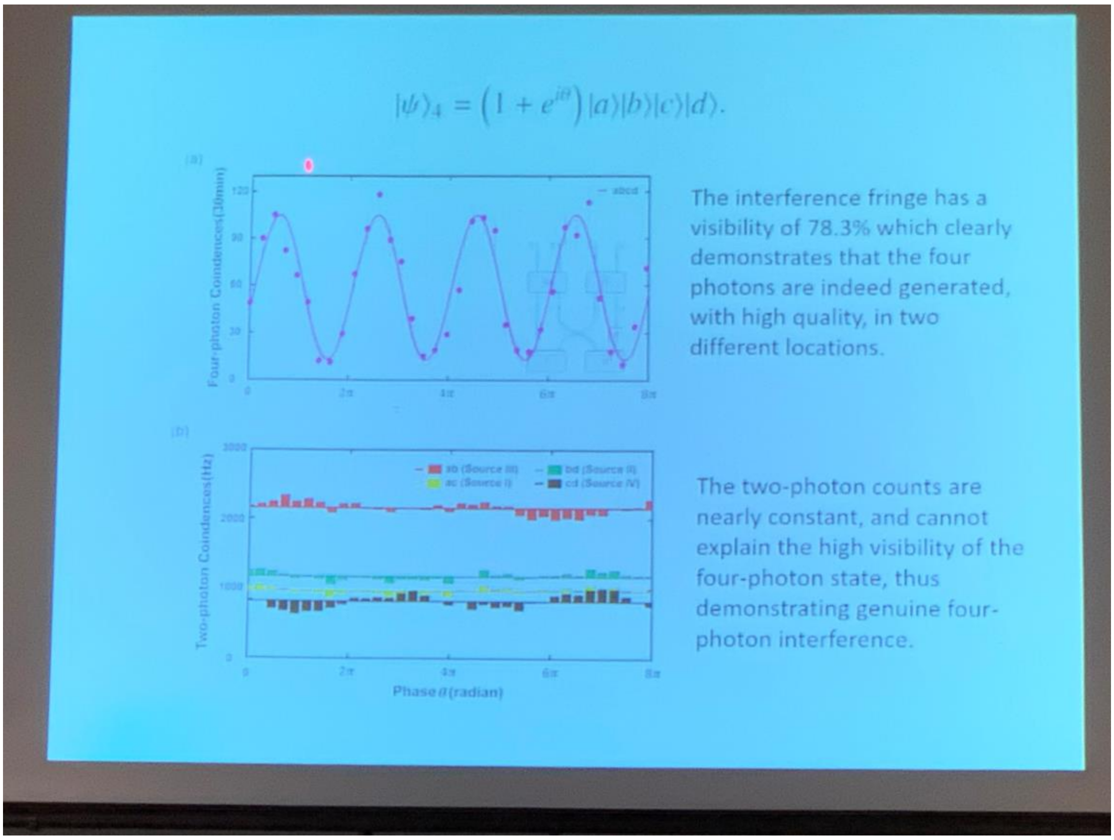

Frequency-degenerate entangled state generation
Pump
Pulsed laser
WDM
WDM
EDFA
WDM
PC
PC
WDM
Delay line
Generation
Pump 1
Pump 2
Signal/idler
Wavelength
Sagnac loop
QWP
HWP
PBS
HWP
HWP
QWP
Silicon waveguide
Circulator
Characterization
FBS
Filter
PC
QWP1
QWP2
HWP
PBS
FBS
FBS
Two photon: $|\Phi\rangle = \frac{1}{\sqrt{2}}(|20\rangle_{HV} + |02\rangle_{HV})$
Four photon:
$|\Phi\rangle = |04\rangle_{HV}$
$|\Phi\rangle = \frac{\sqrt{3}}{\sqrt{8}}(|40\rangle_{HV} + |04\rangle_{HV}) + \frac{1}{2}|22\rangle_{HV}$

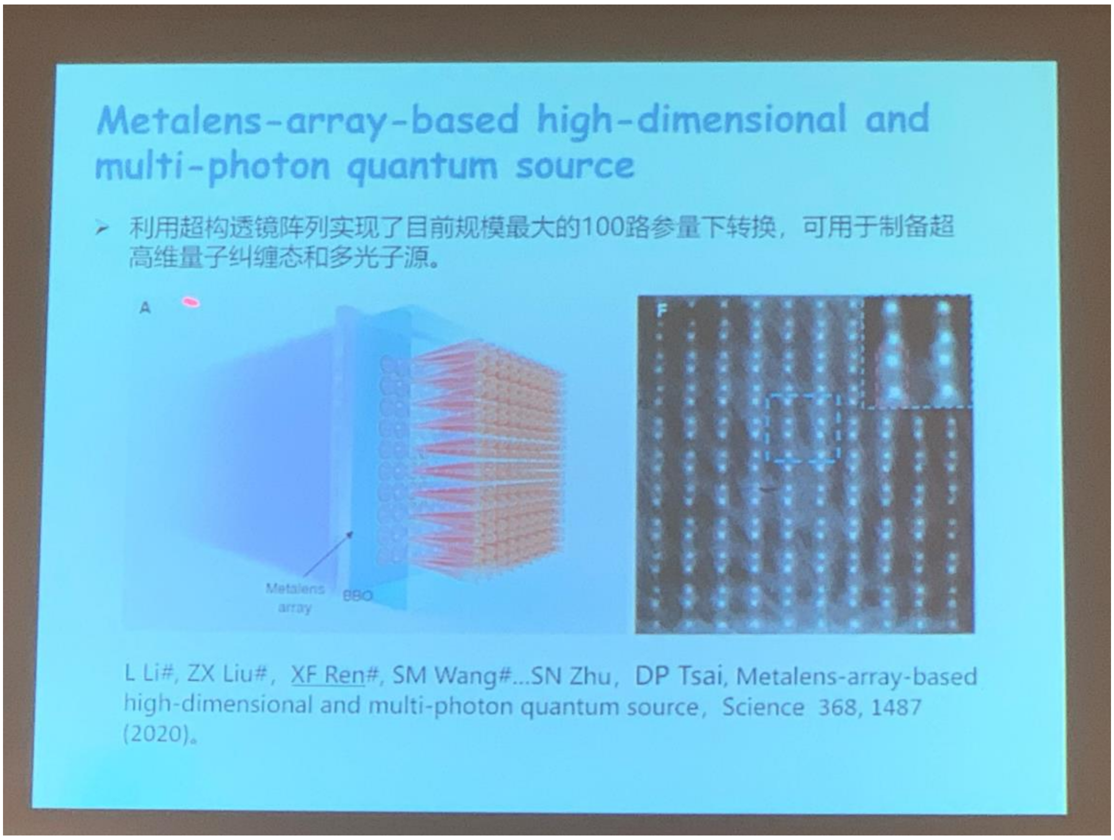

HOM interference and quantum state tomography
(a)
Delay line
PBS
(b)
750
500
250
0
-8
-4
0
4
8
Coincidence (2s)
Position (mm)
HOM interference
98%
(a)
Fidelity
0.98
(b)
0.97
(c)
0.72
LT Feng,...M Tame and XF Ren*, NPJ Quantum Inform. 5 90 (2019)

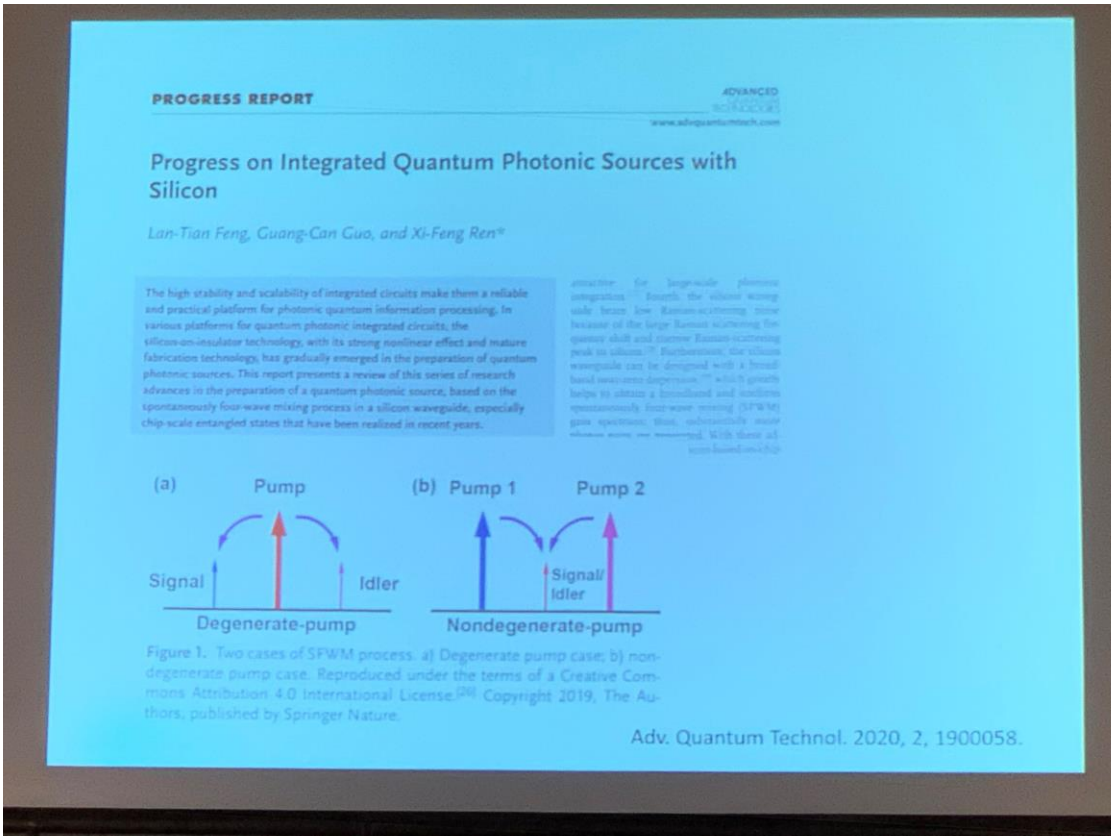

Frustrated down-conversion
Firstly demonstrated in 1994.
T.J. Herzog, J.G. Rarity, H.Weinfurther, and A. Zeilinger. Phys. Rev. Lett., 72, 629, 1994.
(a)
A
B
II
a
b
φ
I
(b)
A
B
C
D
III
IV
a
b
c
d
θ
I
II
Path are identical
$|\psi\rangle = g(\overbrace{|a,b\rangle}^{\text{crystal II}} + \overbrace{e^{i\varphi}|a,b\rangle}^{\text{crystal I}}) = g(1+e^{i\varphi})|a,b\rangle,$
$|\psi\rangle = g(\overbrace{|a,b\rangle}^{\text{crystal III}} + \overbrace{|c,d\rangle}^{\text{crystal IV}} + \overbrace{|a,c\rangle}^{\text{crystal I}} + \overbrace{e^{i\theta}|b,d\rangle}^{\text{crystal II}})$
$+ g^2(\underbrace{|a,b,c,d\rangle}_{\text{crystal III\&IV}} + \underbrace{e^{i\theta}|a,b,c,d\rangle}_{\text{crystal I\&II}}) + \ldots$
$= g(|a,b\rangle + |c,d\rangle + |a,c\rangle + e^{i\theta}|b,d\rangle)$
$+ g^2(1+e^{i\theta})|a,b,c,d\rangle + \ldots$

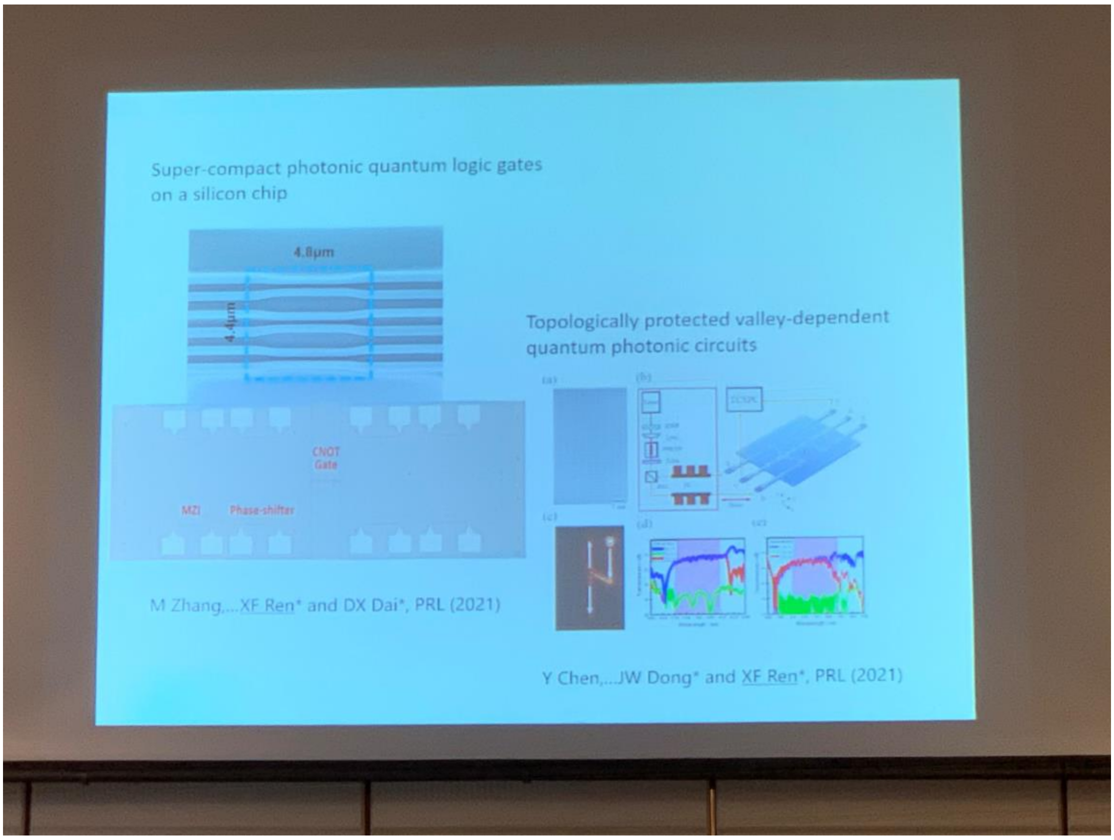

Integrated quantum photonic chip
(a)
(b)
DC Power Supply
Source I
Source II
MZI1
MZI2
Pump Laser
Source III
Source IV
WDMs
Detectors
Delay Line
Combination
Interference
Experimental setup.


(a)
Two-photon Coincidences(Hz)
450
300
150
0
(b)
Singles(kHz)
15
10
5
0
0
π
2π
3π
4π
Phase φ (radian)
Interference fringe for the two-photon quantum state
The visibility is close to 100%, which confirms high quality coherence between the two origins of the photon pairs.
$|\psi\rangle_2 = 2|a\rangle|b\rangle + (1 + e^{i\varphi})|c\rangle|d\rangle.$


$$|\psi\rangle_4 = \left(1 + e^{i\theta}\right)|a\rangle|b\rangle|c\rangle|d\rangle.$$
(a)
Four-photon Coincidences(30min)
abcd
The interference fringe has a visibility of 78.3% which clearly demonstrates that the four photons are indeed generated, with high quality, in two different locations.
(b)
Two-photon Coincidences(Hz)
ab (Source III)
ac (Source I)
bd (Source II)
cd (Source IV)
Phase θ (radian)
The two-photon counts are nearly constant, and cannot explain the high visibility of the four-photon state, thus demonstrating genuine four-photon interference.


Metalens-array-based high-dimensional and multi-photon quantum source
利用超构透镜阵列实现了目前规模最大的100路参量下转换，可用于制备超高维量子纠缠态和多光子源。
A
Metalens array
BBO
F
L Li#, ZX Liu#, XF Ren#, SM Wang#...SN Zhu, DP Tsai, Metalens-array-based high-dimensional and multi-photon quantum source, Science 368, 1487 (2020)。


PROGRESS REPORT
www.advquantumtech.com
Progress on Integrated Quantum Photonic Sources with Silicon
Lan-Tian Feng, Guang-Can Guo, and Xi-Feng Ren*
The high stability and scalability of integrated circuits make them a reliable and practical platform for photonic quantum information processing. In various platforms for quantum photonic integrated circuits, the silicon-on-insulator technology, with its strong nonlinear effect and mature fabrication technology, has gradually emerged in the preparation of quantum photonic sources. This report presents a review of this series of research advances in the preparation of a quantum photonic source, based on the spontaneously four-wave mixing process in a silicon waveguide, especially chip-scale entangled states that have been realized in recent years.
(a)
Pump
Signal
Idler
Degenerate-pump
(b)
Pump 1
Pump 2
Signal/
Idler
Nondegenerate-pump
Figure 1. Two cases of SFWM process. a) Degenerate pump case; b) non-degenerate pump case. Reproduced under the terms of a Creative Commons Attribution 4.0 International License. Copyright 2019, The Authors, published by Springer Nature.
Adv. Quantum Technol. 2020, 2, 1900058.


Super-compact photonic quantum logic gates
on a silicon chip
4.8μm
4.4μm
CNOT
Gate
MZI
Phase-shifter
M Zhang,...XF Ren* and DX Dai*, PRL (2021)
Topologically protected valley-dependent
quantum photonic circuits
Y Chen,...JW Dong* and XF Ren*, PRL (2021)