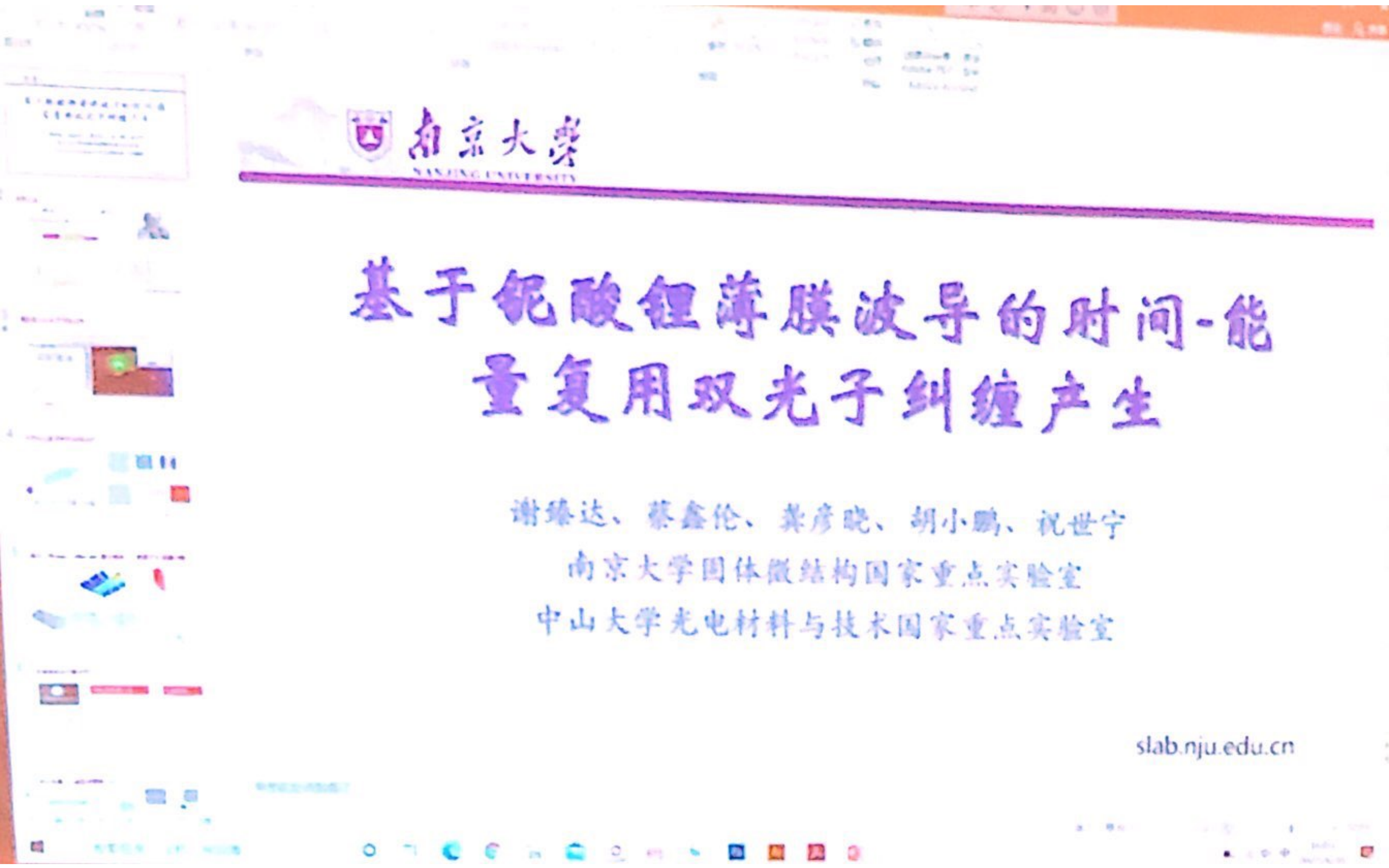
南京大学
NANJING UNIVERSITY
基于铌酸锂薄膜波导的时间-能量复用双光子纠缠产生
谢臻达、蔡鑫伦、龚彦晓、胡小鹏、祝世宁
南京大学固体微结构国家重点实验室
中山大学光电材料与技术国家重点实验室
slab.nju.edu.cn

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背景介绍

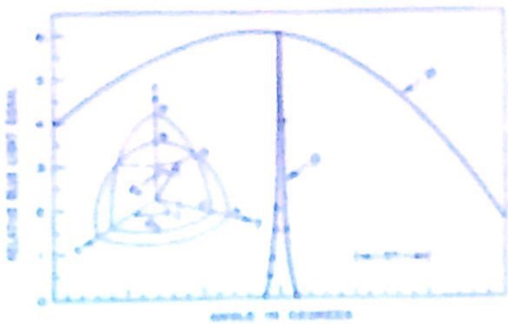
将红宝石 694 nm 激光聚焦到石英晶体上产生 347 nm 紫外光，但效率很低。

(Peter Franken *et al.* 1961)

$$I_{2\omega} = \beta I_{\omega} \sin c^{2}\left(\frac{\Delta kL}{2}\right), \qquad k = \frac{2\pi \bullet n}{\lambda}$$

$$\begin{cases} \Delta\omega = \omega_2 - 2\omega_1 = 0 \\ \Delta k = k_2 - 2k_1 = 0 \end{cases}$$

$n_e(2\omega) = n_o(\omega)$



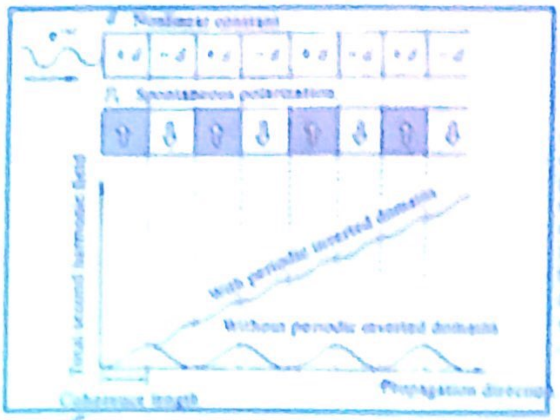
P.D.Maker *et al.*, *PRL* 1962

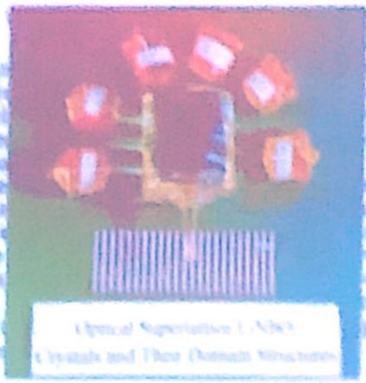
准相位匹配和光学超晶格

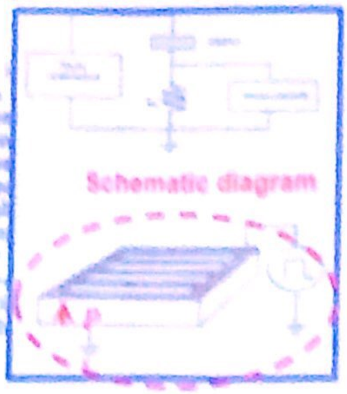
HYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 1

Interactions between Light Waves in a Nonlinear Dielectric*

J. A. ARMSTRONG, N. BLOEMBERGEN, J. DUCUING, AND P. S. PERSHAN
Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts







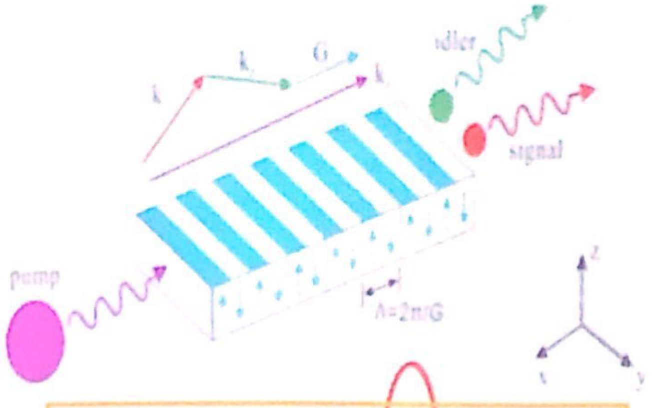
$$\begin{cases} \Delta\omega = \omega_2 - 2\omega_1 = 0 \\ \Delta k = k_2 - 2k_1 - G_m = 0 \end{cases}$$

$G_m = 2\pi m / \Lambda \qquad \Lambda = \dfrac{\lambda}{2(n_{2\omega} - n_\omega)}$

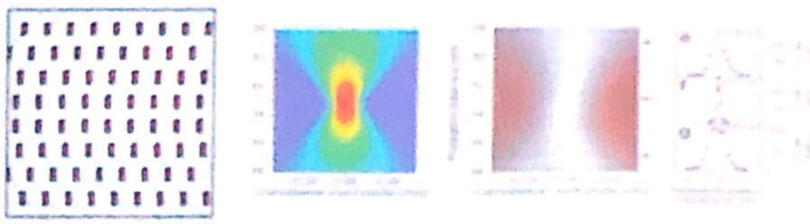
J Mater Sci 17, 1663 (1982)
J Appl Phys 77, 5481 (1995)
Appl Phys Lett 68, 2781 (1995)
Science 278, 843 (1997)

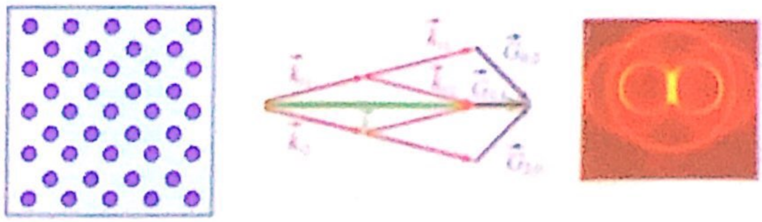
光学超晶格中的光子态调控

自发参量下转换（SPDC）



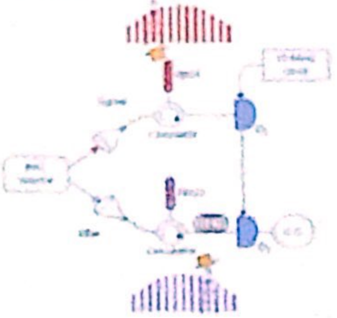
$$\left|\Psi\right\rangle = \psi_0 \sum_{k_s, k_i} \delta(\vec{k}_s + \vec{k}_i + G - \vec{k}_p)\hat{a}_s^{\dagger} \hat{a}_i^{\dagger} \left|0\right\rangle$$



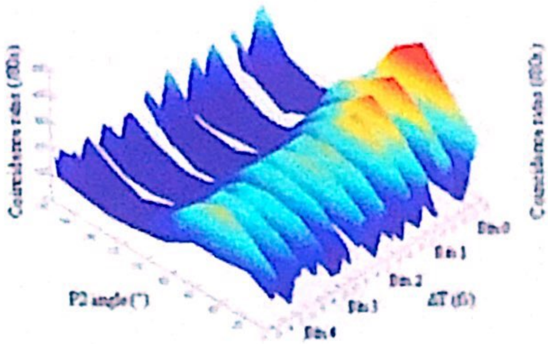


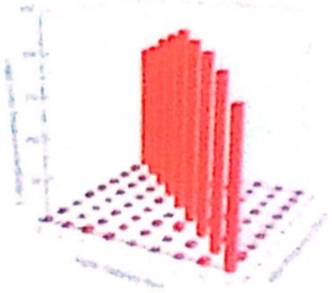
Phys. Rev. Lett. **101**, 233601 (2008)
Nat. Commun. **2**, 429 (2011)
Phys. Rev. Lett. **111**, 023603 (2013)
...

高效（Photon-efficient）量子编码——高维时间-能量纠缠

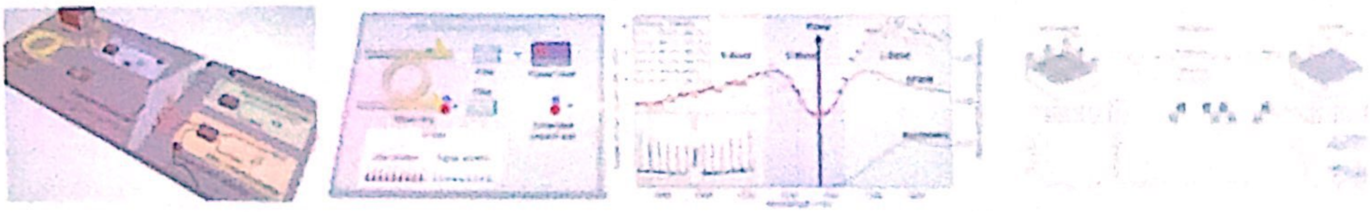


5 qubits/photon



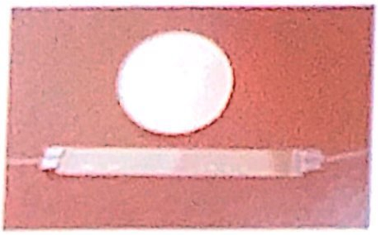


Nature Photonics 9, 536 (2015)



C. Reimer et al. Science **351**, 1176 (2016)
M. Kues et al. Nature **546**,622 (2017)
C.Reimer et al. Nat. Phys. **15**,148 (2019)

铌酸锂有源光量子芯片



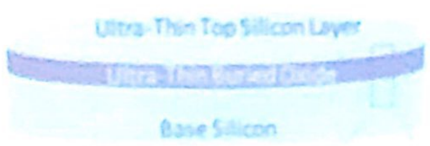
LiNbO$_3$ 微结构量子芯片 V.S. SOI 量子芯片

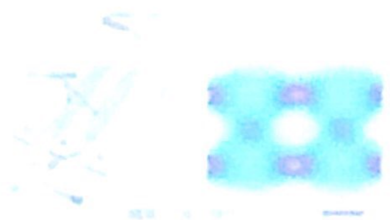
	LiNbO$_3$	SOI
输入功率 (mW)	0.039	15
操作频率	electro-optic ~40 GHz	heating ~kHz
片上光子产率Hz nm^{-1} mW^{-1}	1.1×10[illegible]	2.7×10[illegible]
尺寸 (mm)	10	5.2
纠缠光子频率范围	任意设计 演示108nm调谐	受相位匹配限制， 演示9.6nm 调谐

Phys. Rev. Lett. 113, 103601 (2014)
我们的工作

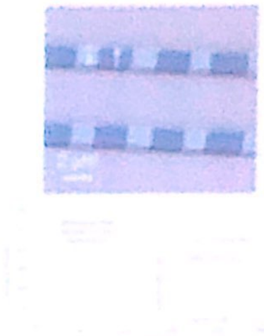
Nat. Photon. 8, 104 (2014)

新的发展——铌酸锂薄膜芯片





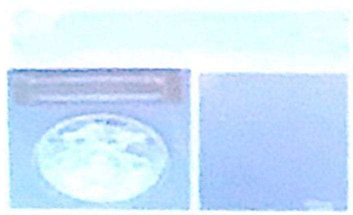
高速、低功耗电光调制器



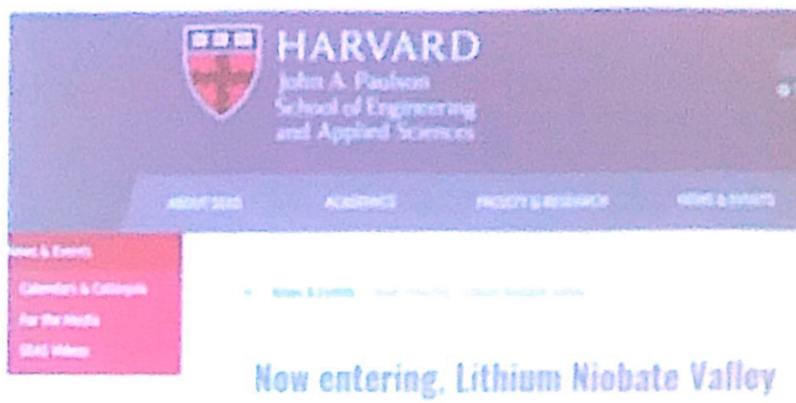
高效率倍频

光频梳产生

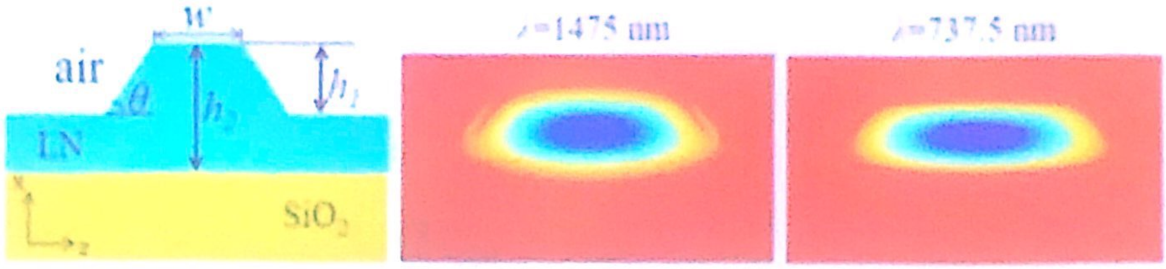
米级延时线



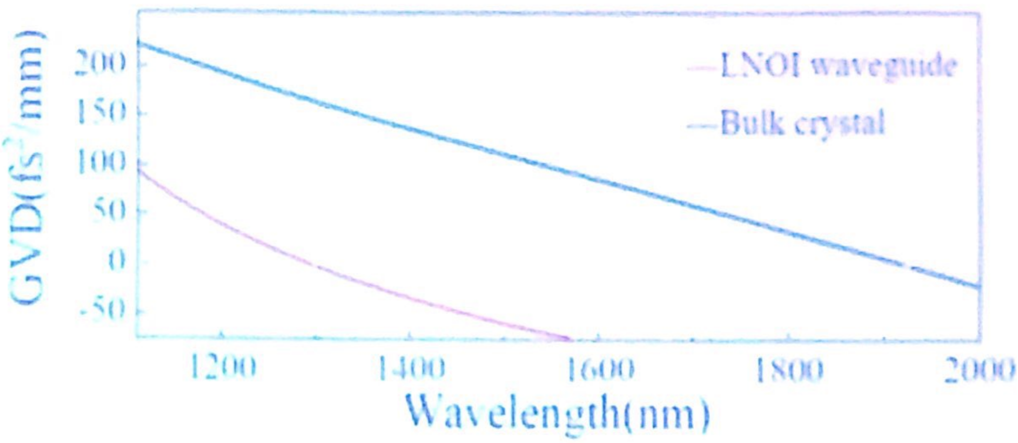
C. Wang et al. Nature **562**, 101 (2018)
M. He et al. Nat. photon. **13**, 359 (2019)
C. Wang et al. Optica **5**, 1438 (2018)
Y. He et al. Optica **6**, 1138 (2019)
J. X. Zhou et al. Chinese Phys. Lett. **37**, 084201 (2020)



LNOI波导设计

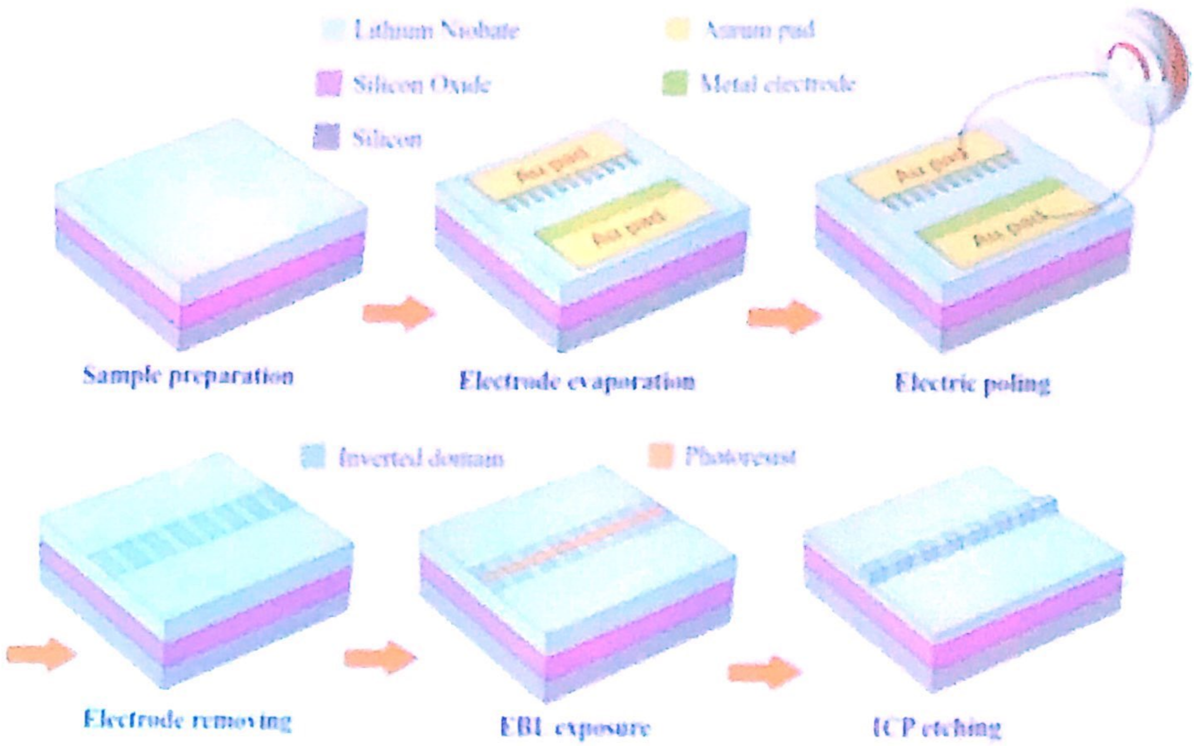


w
air
θ
h_2
h_1
LN
SiO_2
x
z
λ=1475 nm
λ=737.5 nm



GVD(fs²/mm)
200
150
100
50
0
-50
1200
1400
1600
1800
2000
Wavelength(nm)
LNOI waveguide
Bulk crystal

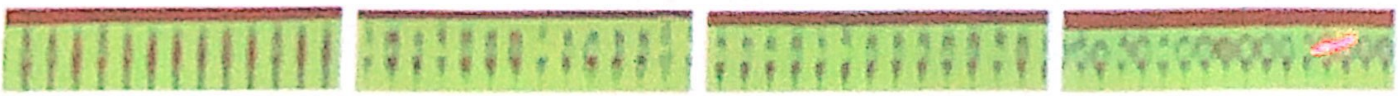
LNOI波导加工



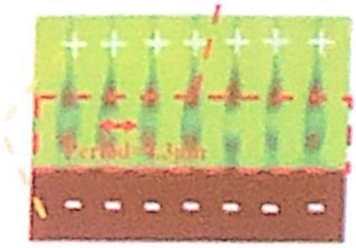
Lithium Niobate
Aurum pad
Silicon Oxide
Metal electrode
Silicon
Au pad
Au pad
Sample preparation
Electrode evaporation
Electric poling
Inverted domain
Photoresist
Electrode removing
EBL exposure
ICP etching

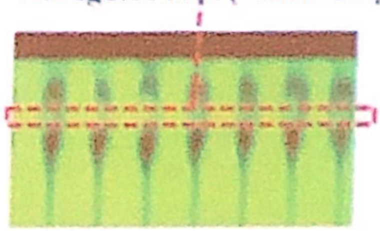
LNOI波导加工

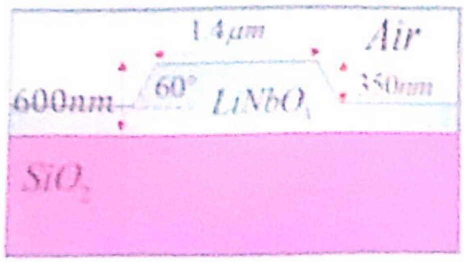
倍频共聚焦显微镜监控极化技术



2 Pulses　　8 Pulses　　12 Pulses　　40 Pulses

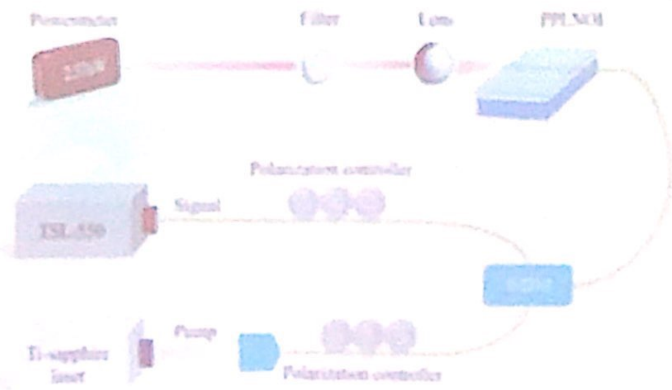




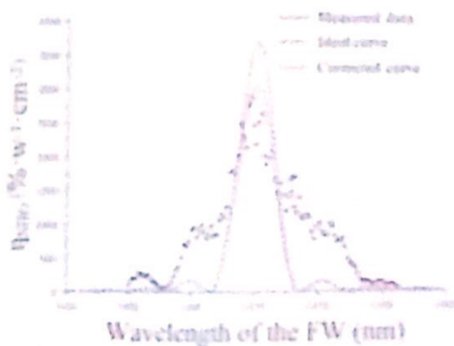


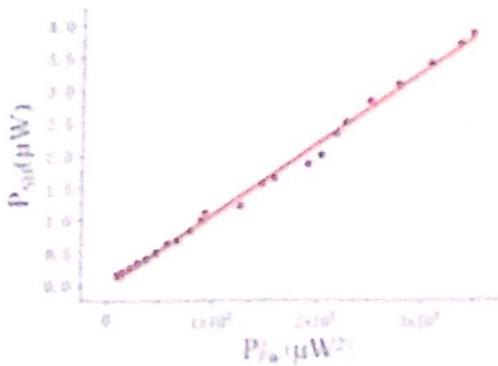
占空比：~50%

倍频测试

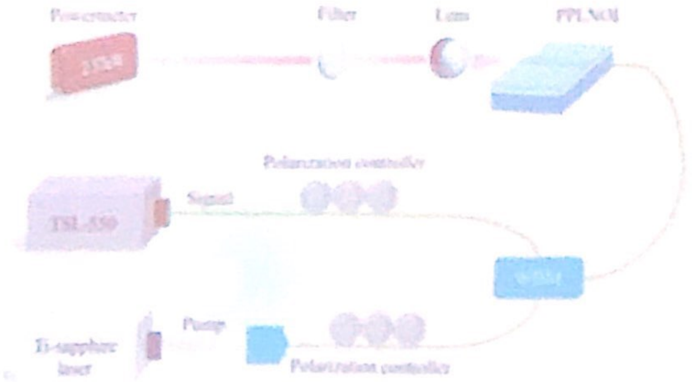


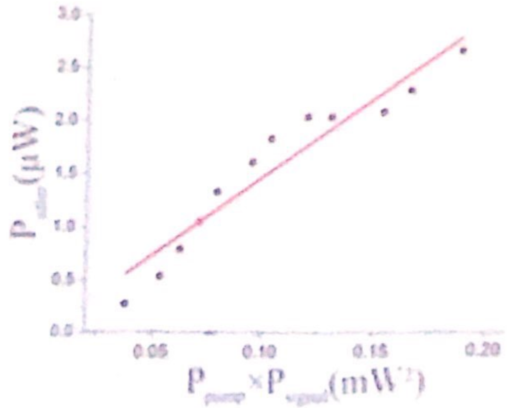
	波导长度	占空比	归一化倍频效率	
			实测值	实测值/理论值
哈佛大学 薄膜铌	4mm	~30%	2600%/(W·cm²)	~60%
南京大学 薄膜铌	6mm	~50%	3061%/(W·cm²)	>80%

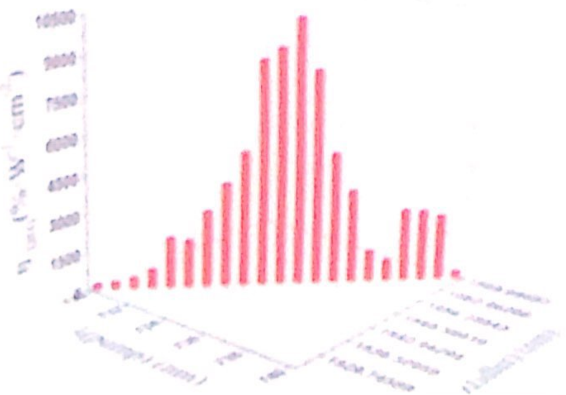




差频测试

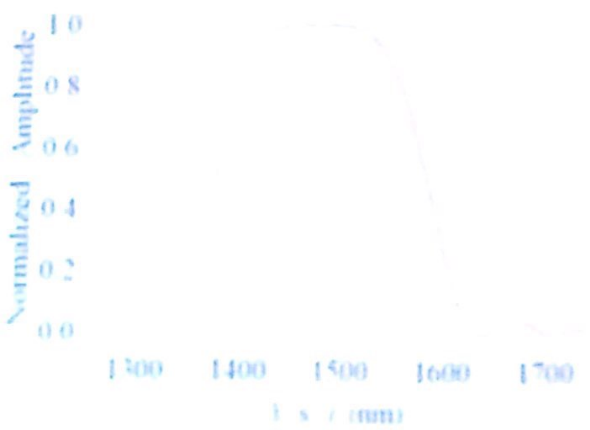

Filter
Lens
PPLNOI
Polarization controller
TSL-550
Signal
Pump
Ti-sapphire laser
Polarization controller


3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.05
0.10
0.15
0.20
$P_{idler}(\mu W)$
$P_{pump}\times P_{signal}(mW^2)$

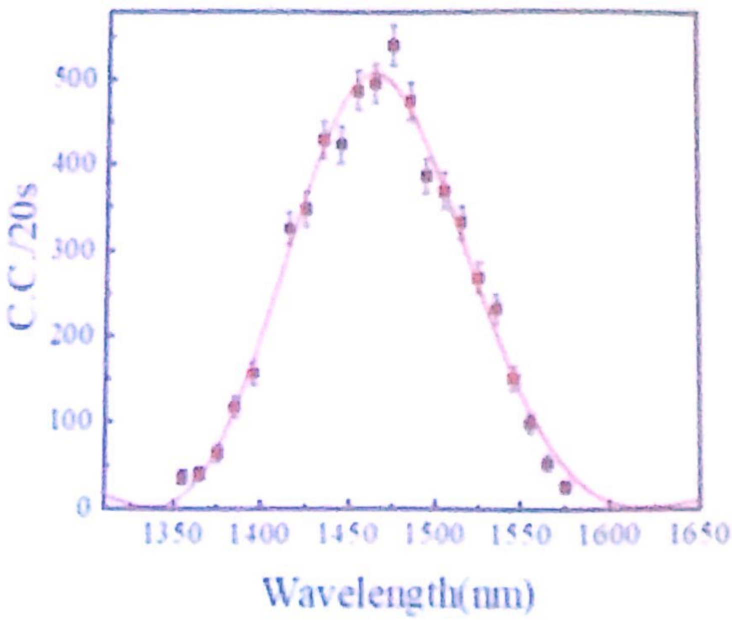


SPDC光谱

理论模拟



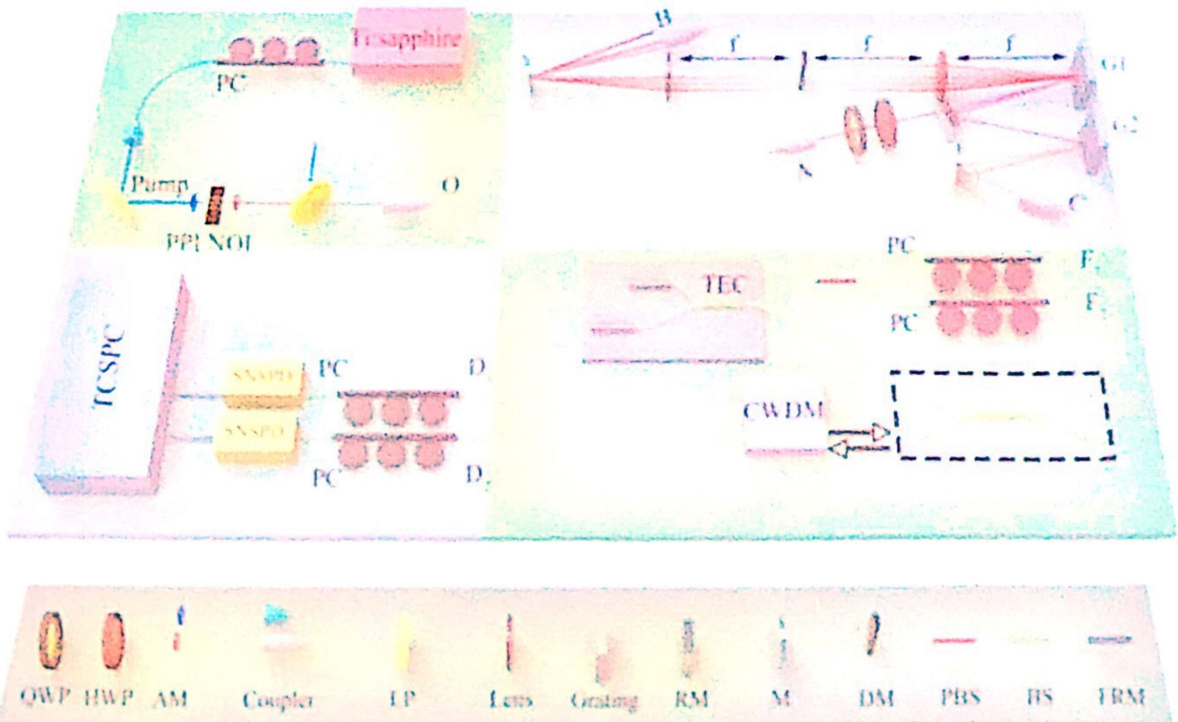
实验测量



相位匹配带宽超过130nm

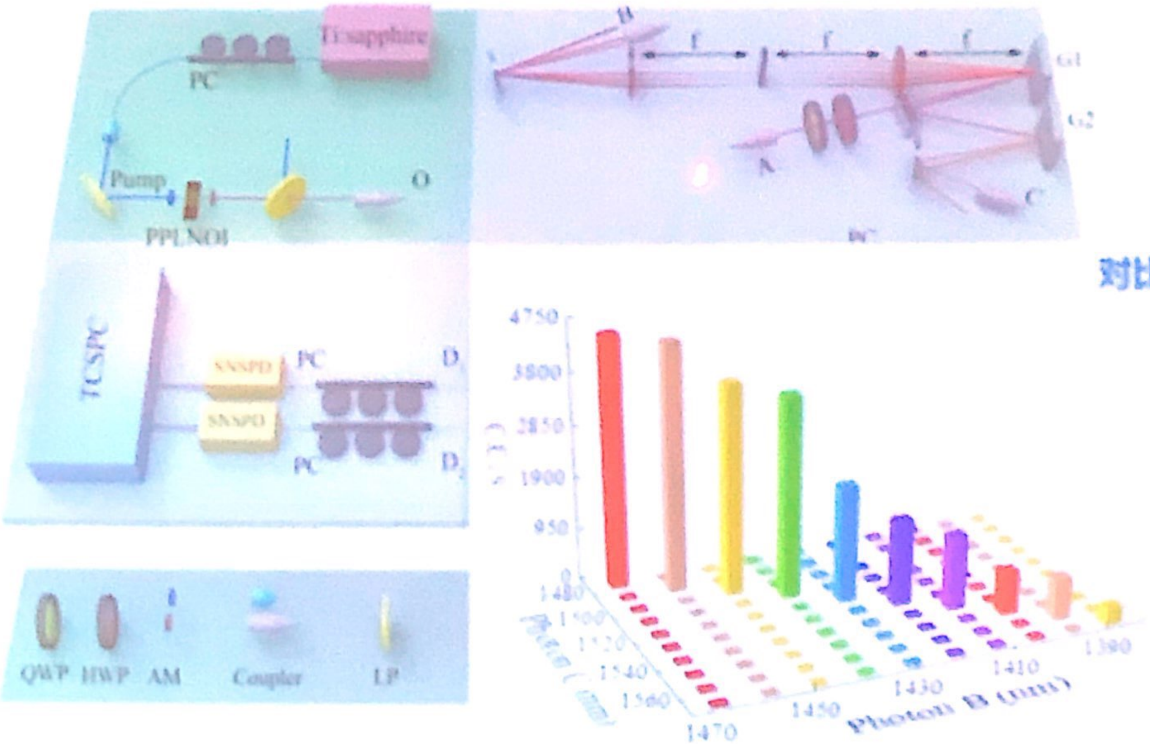
时间-能量复用（>100通道DWDM）

实验装置



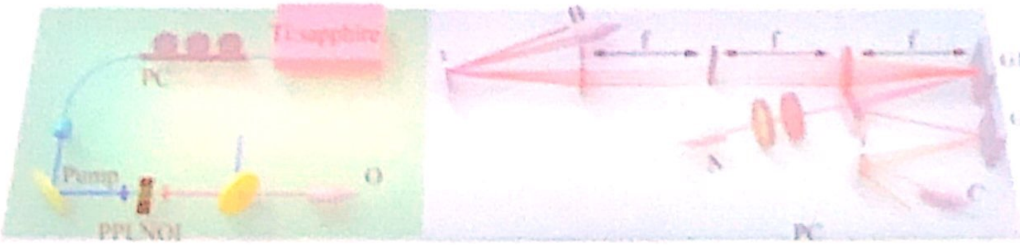
Ti:sapphire
PC
Pump
B
f
f
f
C
O
TEC
PC
PC
TCSPC
SNSPD
SNSPD
PC
PC
CWDM
QWP
HWP
AM
Coupler
LP
Lens
Grating
RM
M
DM
PBS
BS
FRM

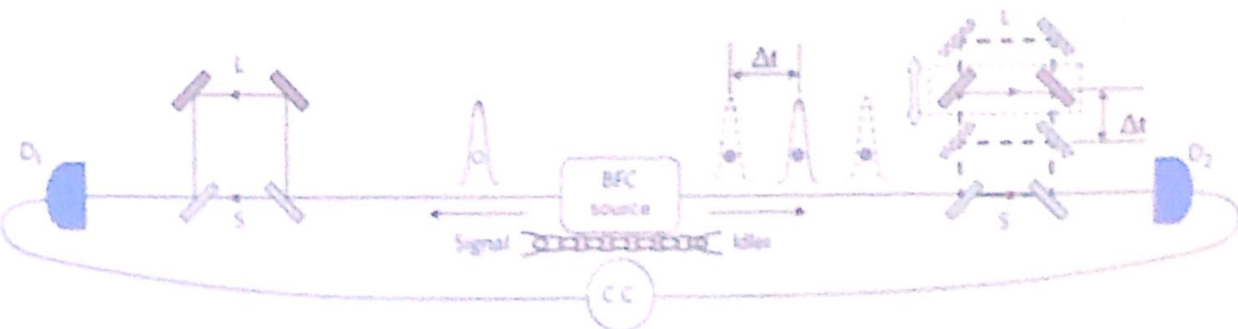
频率关联测量



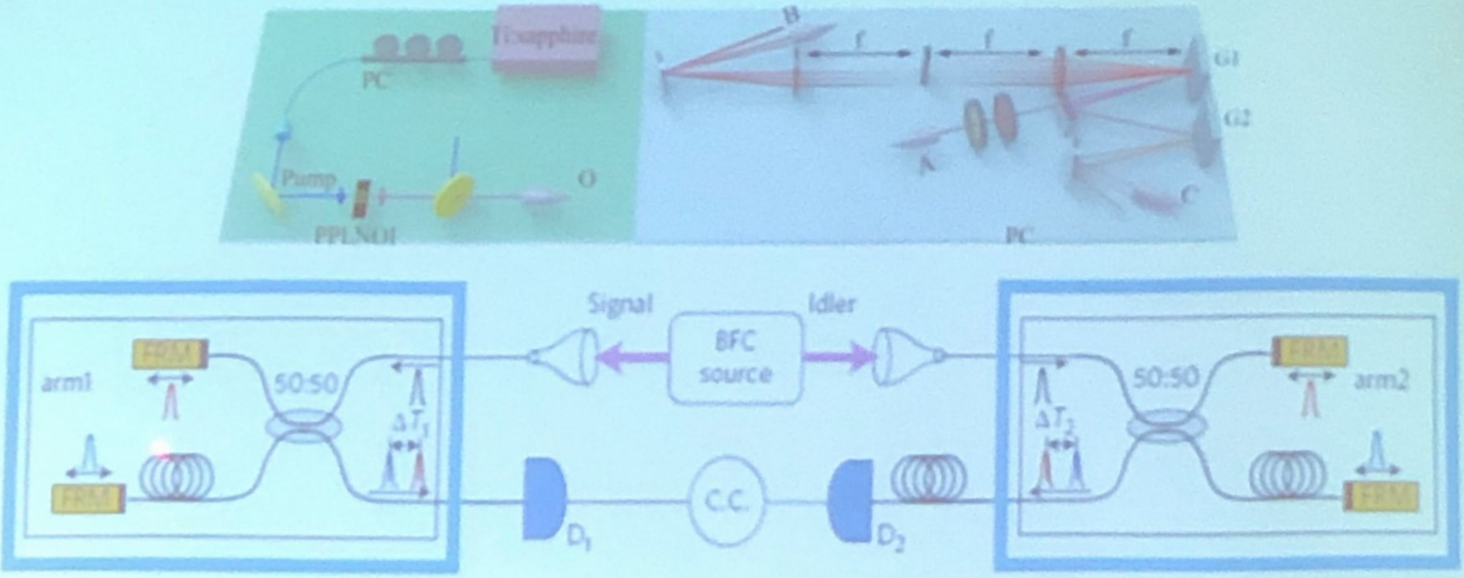
对比度：>32d

Franson干涉

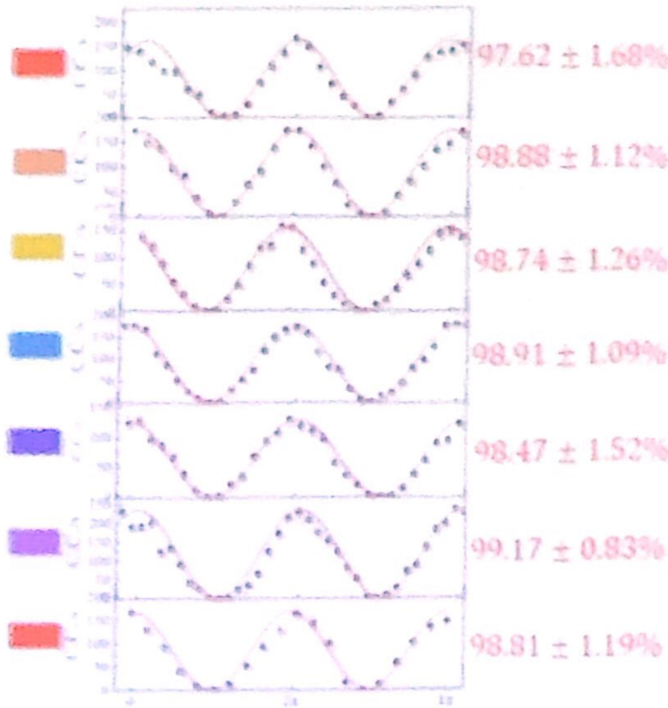

PC
Ti:sapphire
Pump
f
f
f
O
PC


L
S
D_1
D_2
Δt
Δt
BFC
source
Signal
Idler
CC

Franson干涉


Ti:sapphire
PC
Pump
PPLN
OI
O
B
f
G1
G2
A
C
PC
Signal
Idler
BFC source
arm1
arm2
FRM
50:50
ΔT_1
ΔT_2
C.C.
D_1
D_2

频率复用Franson干涉测量



光子产率：2.34×10^{11} Hz/mW
产率提高3个量级以上
复用维度：9 (100+)
干涉可见度：> 97%

初步展示了高码率的铌酸锂薄膜光源及其色散调控能力。

展望

——铌酸锂基有源光量子芯片