芯片化量子密钥分发

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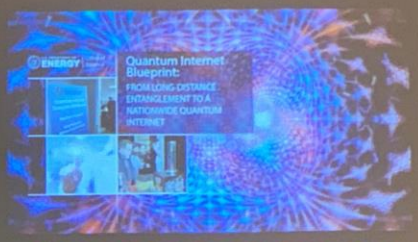
中国科学技术大学(USTC)

量子网络：激烈的国际竞争

Chen et al., Nature 589, 214 (2021)



2020年7月美国能源部计划10年内建成“国家量子互联网”

未来量子网络所面临的挑战

安全性？

⬇

现实安全性

远距离？

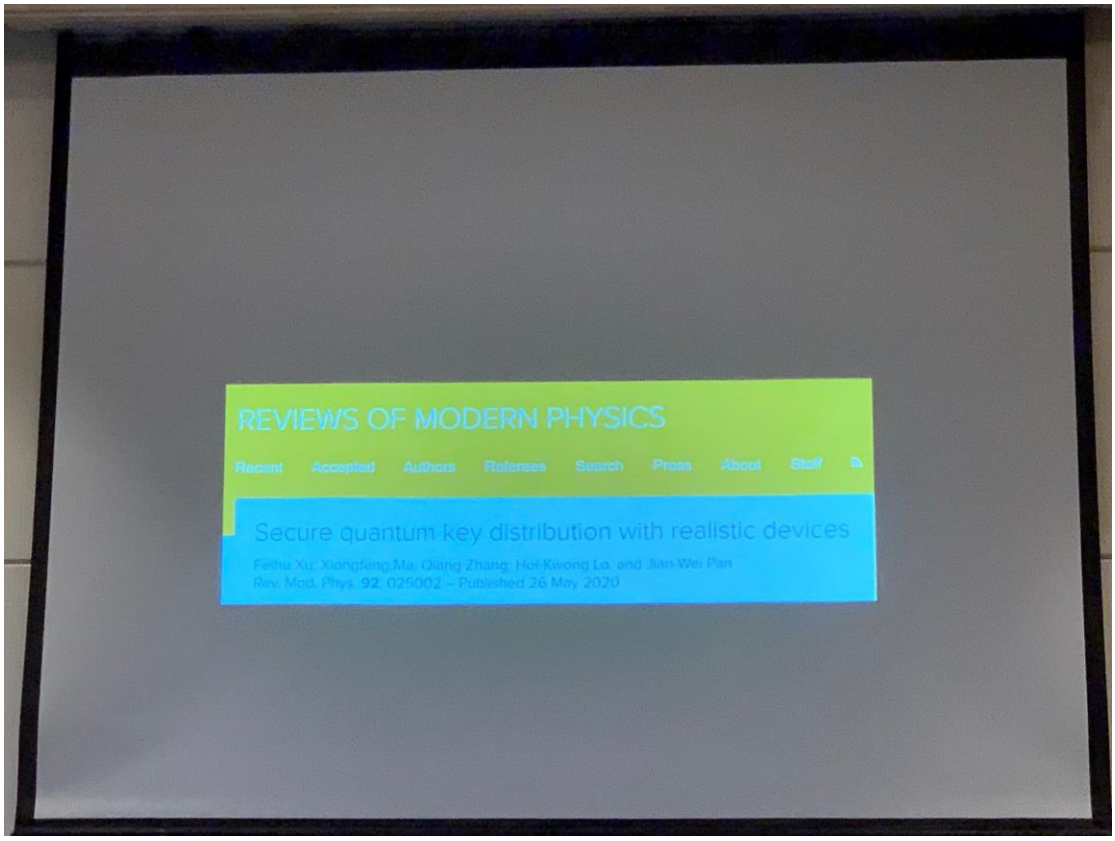
⬇

量子中继

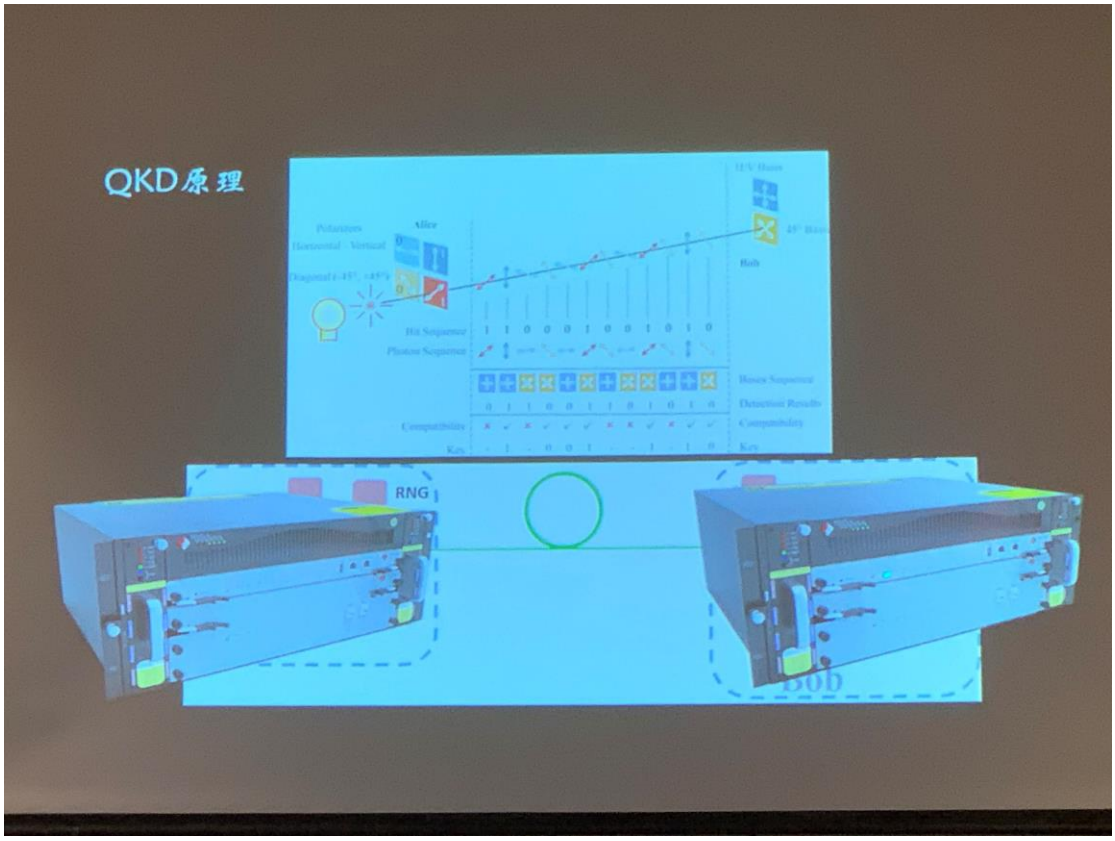
应用？

⬇

低成本、小型化


REVIEWS OF MODERN PHYSICS
Recent Accepted Authors Referees Search Press About Staff
Secure quantum key distribution with realistic devices
Feihu Xu, Xiongfeng Ma, Qiang Zhang, Hoi-Kwong Lo, and Jian-Wei Pan
Rev. Mod. Phys. 92, 025002 – Published 26 May 2020


QKD原理
Laser
RNG
Decoy
Modulator
Alice
Modulator
SPD1
Bit "1"
SPD0
Bit "0"
Bob


QKD原理
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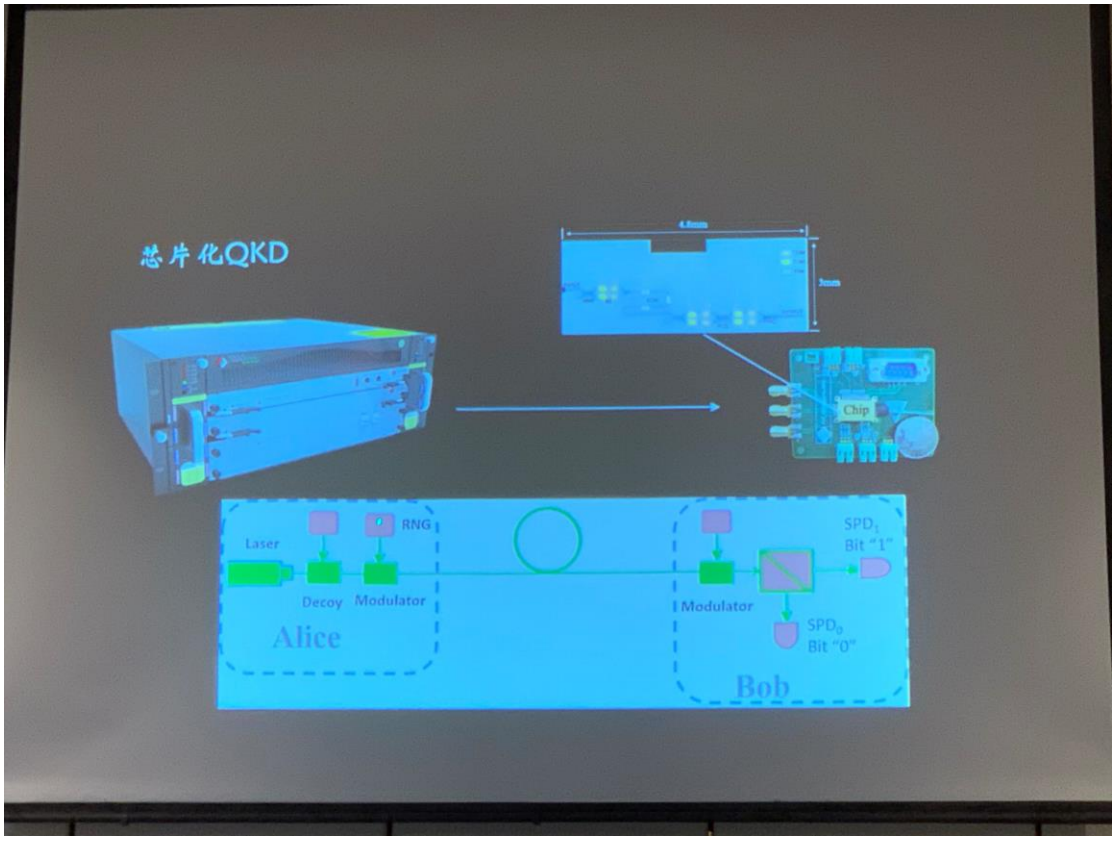
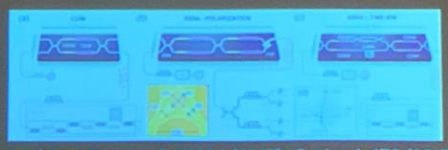
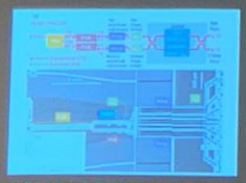

芯片化QKD
Chip
Laser
RNG
Decoy
Modulator
Alice
Modulator
SPD1
Bit "1"
SPD0
Bit "0"
Bob

芯片化QKD近期进展

Toronto: Optica 3, 1274 (2016)



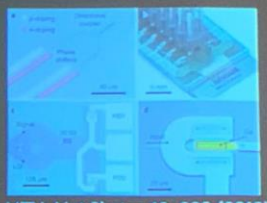
Bristol: Nat Commun 8, 13984 (2017); Optica 4, 172 (2017)



Sandia NL: OE 25, 12282 (2017)

Denmark: npj Quant Inf 3, 25 (2017)

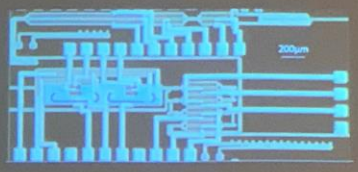
MIT: PRX 8, 021009 (2018)



NTU: Nat Photon 13, 839 (2019)
USTC: PRX 10, 031030 (2020)

举例1：硅光子芯片BB84发射端

与 Joyce Poon 组合作 (Toronto)



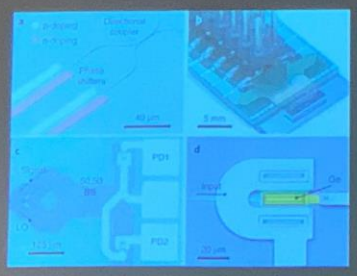
3mm x 1mm

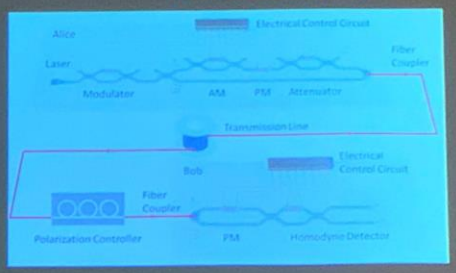
- 高性能器件
  - 环形调制器：20 dB ER，支持 GHz 调制
  - 偏振调制器：>30 dB ER，0.9 dB 功率抖动
- BB84演示
  - QBER: 5.4%；安全密钥率：0.95 kbps

Ma et al., Optica 3, 1274 (2016)

举例2：硅光子芯片连续变量QKD

与 Ai-Qun Liu组合作 (NTU)



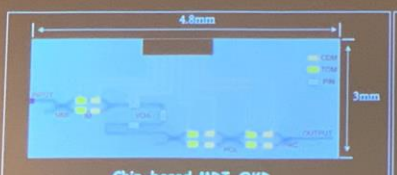


硅芯片上集成低噪声零差探测器
10MHz bandwidth, 5dB shot-noise clearance

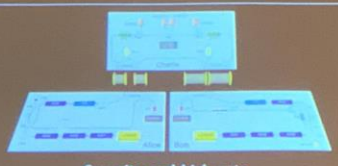
验证性实验演示CV-QKD

Zhang, ..., Xu*, Liu* Nature Photon. 13, 839 (2019)

Chip-based MDI-QKD

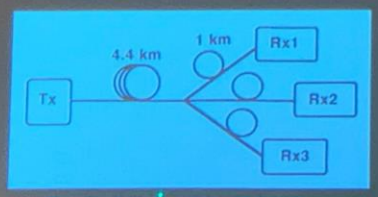


Chip-based MDI-QKD
[Wei, Xu* et al., PRX 10, 031030 (2020)]

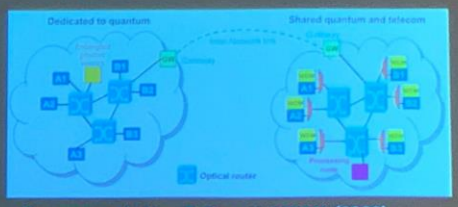


Security and high rate
[Li, Xu* et al., PRAppl. 15, 034081 (2021); submitted]

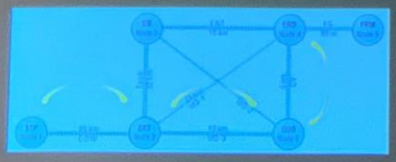
量子通信城域网：下行传输 + 可信中继



Townsend, Nature 385, 47 (1997)



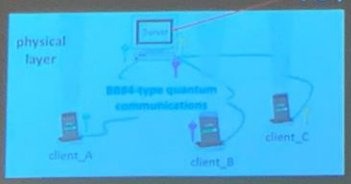
Chapuran et al., New J. Phys. 11, 105001 (2009)



- Elliott, arXiv: quant-ph/0503058 (2005) — USA
- Peev et al., New J. Phys. 11, 075001 (2009) — Europe
- Chen et al., Opt. Express 18, 27217 (2010) — China
  Wang et al. Opt. Lett. 35, 2454 (2010)
  Chen et al., Nature 589, 214 (2021)
- Sasaki et al., Opt. Express 19, 10387 (2011) — Japan

量子接入网

可信中继



Hughes et al., arXiv:1305.0305 (2013)

可信中继

Frohlich et al., Nature 501, 69 (2013)

QKD现实安全性

解决方案：Measurement-device-independent (MDI) QKD，根本上免除任何探测端攻击[Lo, Curty, Qi, PRL 108, 130503 (2012)]

QKD现实安全性

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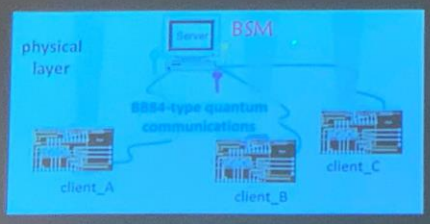
基于不可信中继的量子网络组网方案

芯片化、测量设备无关(MDI)量子接入网

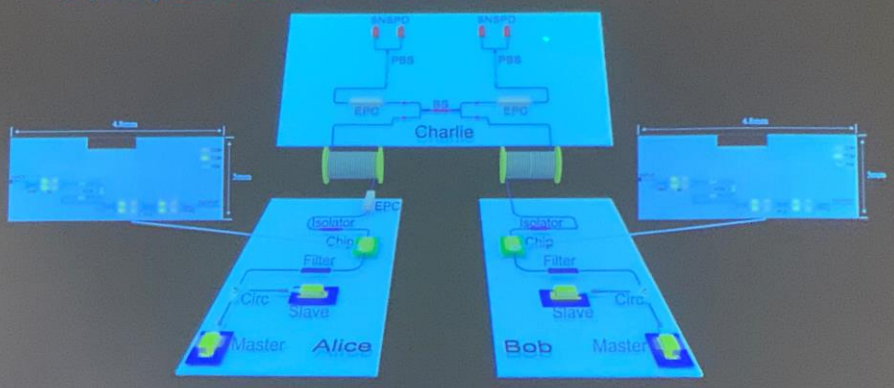


Chip-based MDI-QKD Network

- 高安全性：不可信中继
- 低成本
- 芯片：仅发射端，免受损耗影响
- 可扩展、省资源

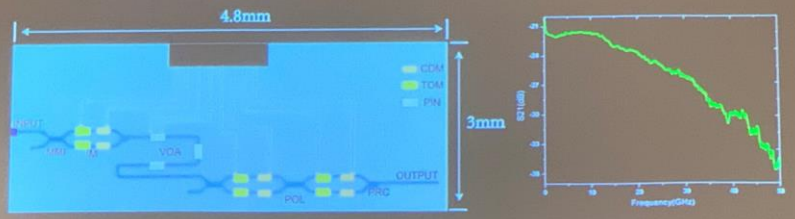
Xu et al., Nat. Photon. 9, 772 (2015)

芯片化高速MDI-QKD - 1.25 GHz



Wei, Xu* et al., PRX 10, 031030 (2020)

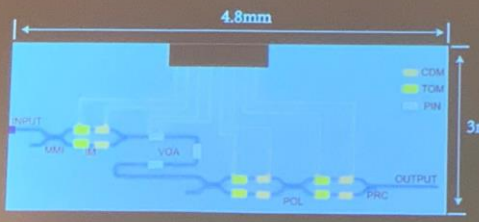
高速硅基集成调制芯片

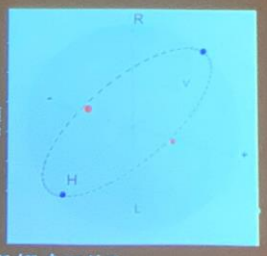


- Carrier depletion modulator (CDM) 和 MZI 结构的偏振/强度调制器
- CDM 的带宽可以达到~21 GHz

Wei, Xu* et al., PRX 10, 031030 (2020)

高速硅基集成调制芯片

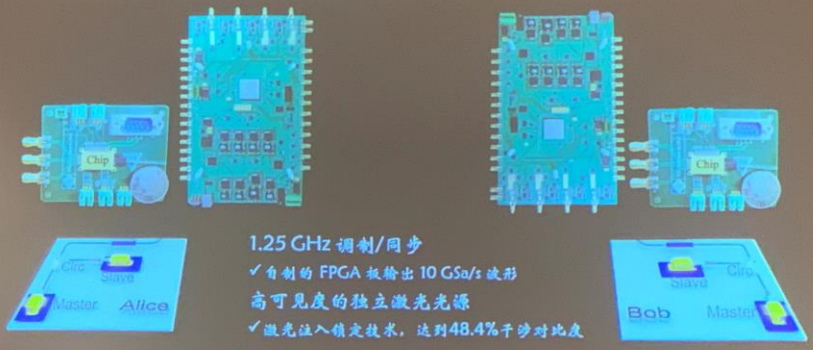




- Carrier depletion modulator (CDM) 和 MZI 结构的偏振/强度调制器
- CDM 的带宽可以达到~21 GHz
- 偏振态对比度达到~26 dB

Wei, Xu* et al., PRX 10, 031030 (2020)

GHz MDI-QKD的主要技术挑战



1.25 GHz 调制/同步

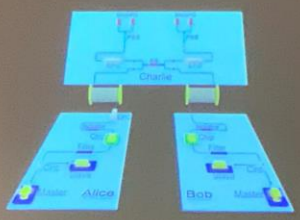
✓自制的 FPGA 板输出 10 GSa/s 波形

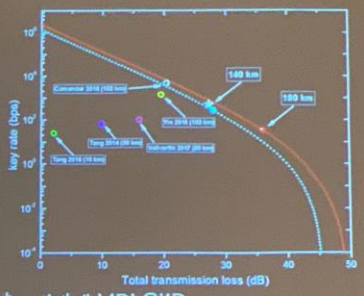
高可见度的独立激光光源

✓激光注入锁定技术，达到48.4%干涉对比度

Wei, Xu* et al., PRX 10, 031030 (2020)

GHz MDI-QKD实验结果





- 1.25 GH、随机调制诱骗态/编码态、芯片化MDI-QKD
- 硅基芯片集成了所有发射端的编码器件
- 高安全码率: 6172 (31) bits/s @ 100-km (180-km) 光纤

Wei, Xu* et al., PRX 10, 031030 (2020)

量子密码的现实安全性 Xu et al., RMP 92, 025002 (2020)

现实安全 = 理论安全 & 系统模型

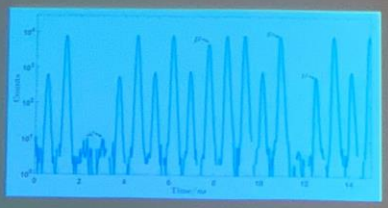
"量子攻击" 解决方案

- Side channels in high-speed QKD?
- Side channels in chip-based QKD?

Pattern effect on modulation

Pattern	average intensity of second pulse	deviation from $s \to s$
$s \to s$	1.000	-
$\mu \to s$	1.002	0.24%
$v \to s$	1.003	0.32%
$0 \to s$	1.003	0.27%
$s \to \mu$	0.617	-
$\mu \to \mu$	0.626	1.51%
$v \to \mu$	0.610	-1.08%
$0 \to \mu$	0.632	2.44%
$s \to v$	0.029	-
$\mu \to v$	0.027	-5.57%
$v \to v$	0.025	-11.95%
$0 \to v$	0.027	-5.90%

Intensity deviation is less than 12%

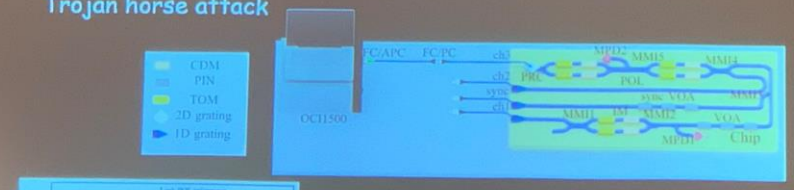


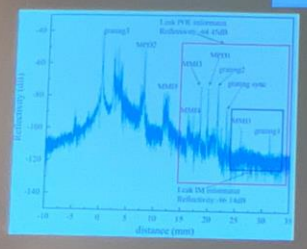
Pattern sifting + alternate key distillation

IID assumption restored

Yoshino et al., npj Quant. Inf. 4, 8 (2018)

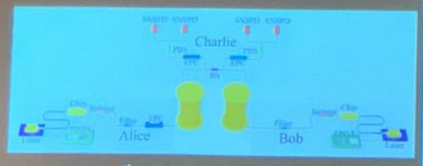
Trojan horse attack



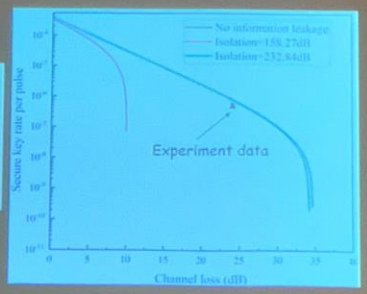


- Total reflectivity that can leak POL and IM modulation is -64.5 dB and -86.1 dB
- Lower reflectivity than fiber-based devices
- Smaller time interval between components

Chip-based MDI-QKD against THA

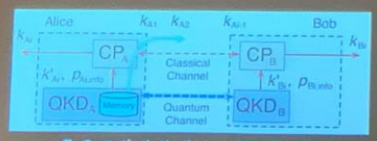


单激光器MDI-QKD

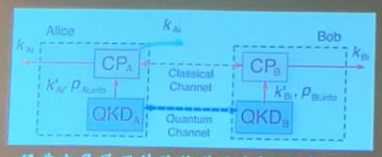


- It requires about 230 dB isolation
- MDI-QKD requires higher isolation than BB84

隐信道攻击

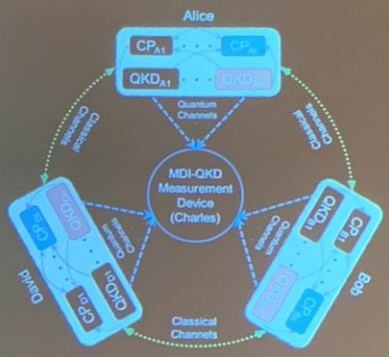


量子器件隐信道攻击(DI-QKD)



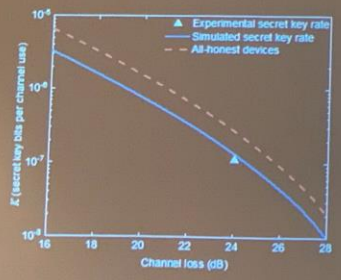
经典电子学器件隐信道攻击(经典密码)

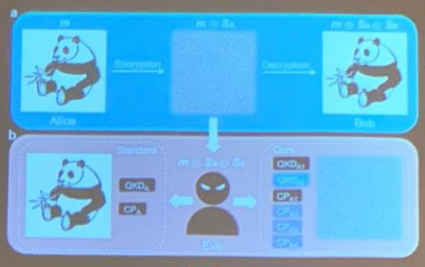
解决方案：冗余设备+多方安全计算



Curty, Lo, npj Quant. Inf. (2019)

实验演示抵制隐信道攻击

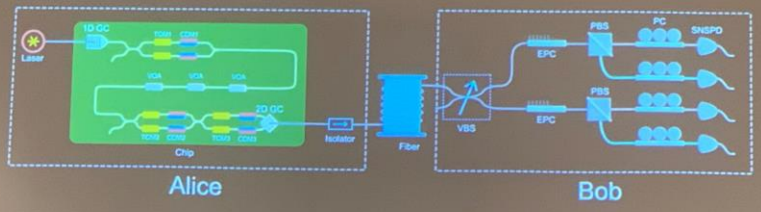




冗余设备
+
多方安全计算协议

Li, Xu* et al., PRAppl. 15, 034081 (2021)

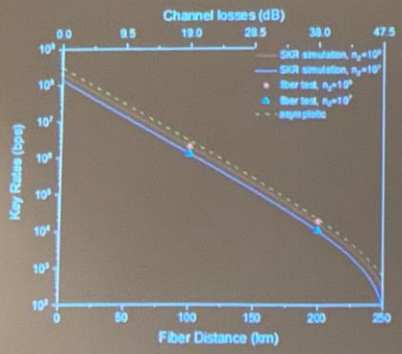
High-rate chip-based QKD



集成化：硅基发送端芯片
高速率：2.5 GHz
低误码率：0.49%
更优的BB84协议：四态、两强度

Li, Xu[a] et al., submitted (2021)

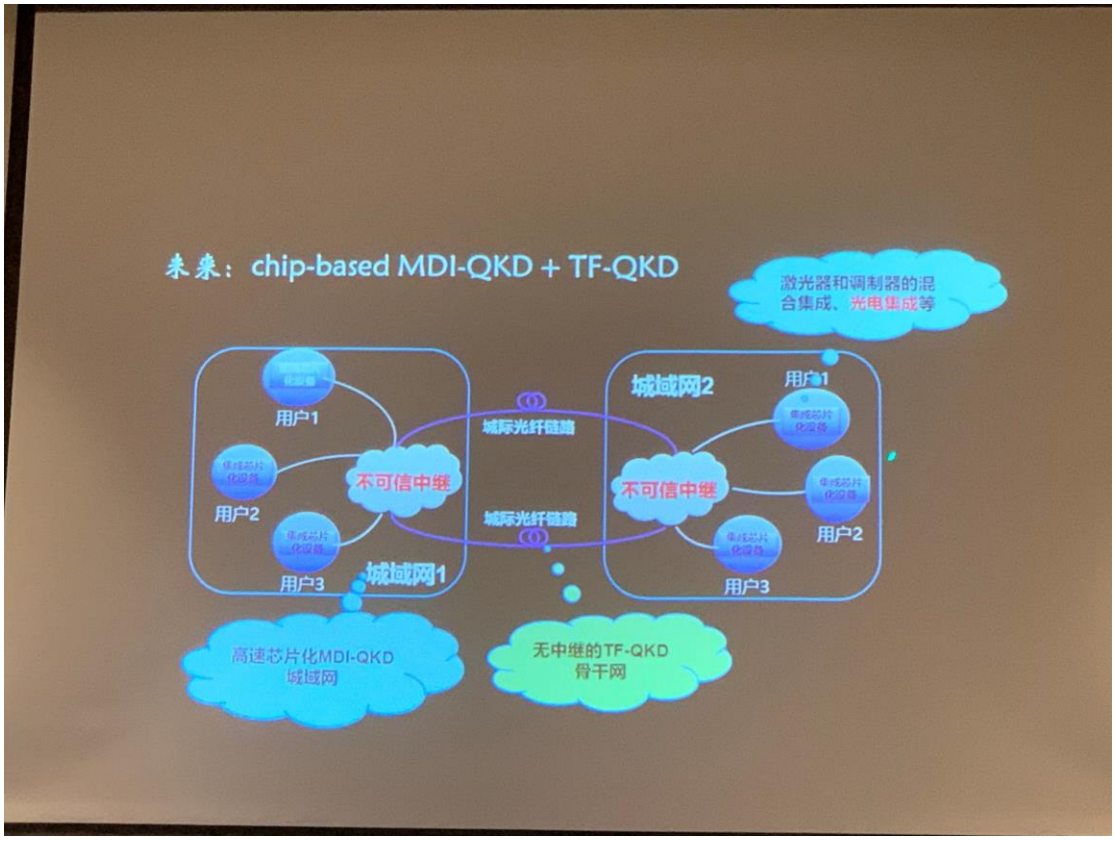
High-rate chip-based QKD

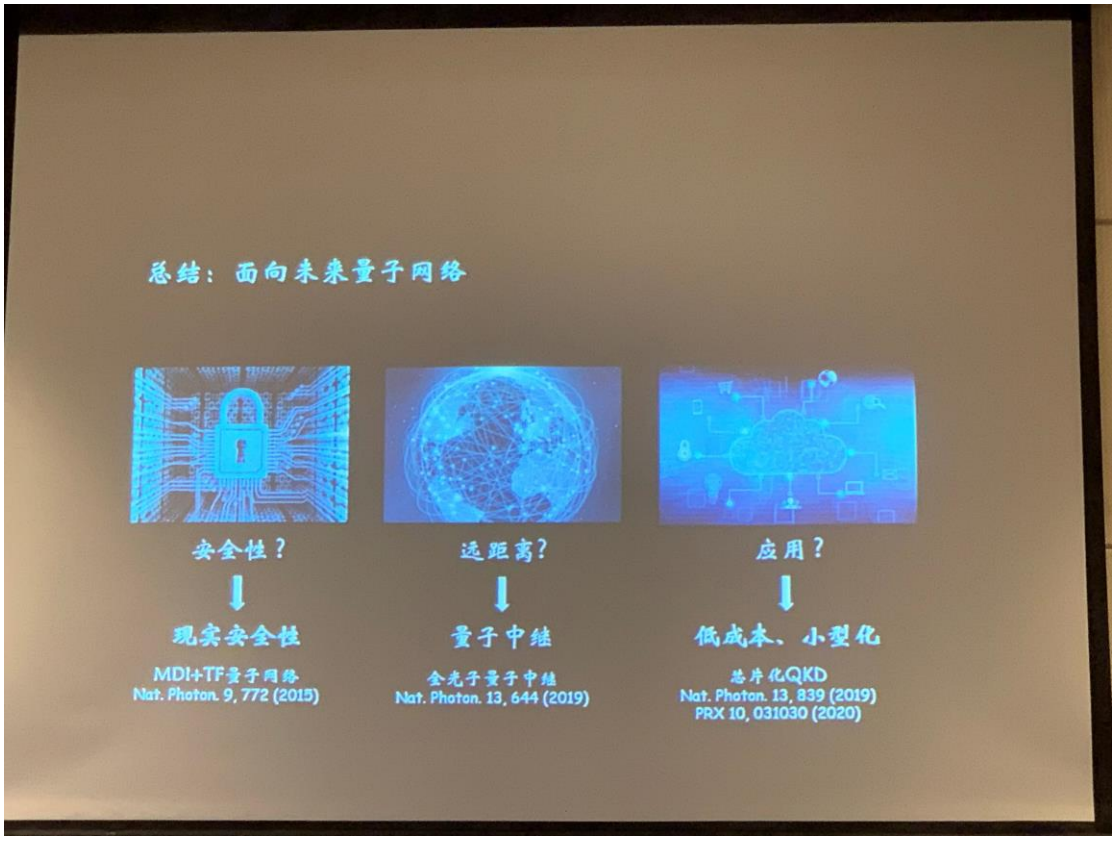


文献	协议	时钟频率	探测器	误码率	码率	码率(归一化到10 dB, Mbps)
Lucamarini et al. 2013	BB84	1 GHz	InGaAs APD(净20.5%)	4%	1.09 Mbps @50 km	1.09
Sibson et al. 2017	BB84	1 GHz	SNSPD(净40%)	1%	329 kbps @20 km	0.08
Bunandar et al. 2018	BB84	625 MHz	SNSPD(净>85%)	2%	1.039 Mbps @ 9.2 dB	0.86
Grunenfelder et al. 2020	BB84	5 GHz	SNSPD(净80%)	1.93%	392.7 kps @101 km	4.08
Islam et al. 2017	High dimension	2.5 GHz	SNSPD(净>70%)	4%	7.71 Mbps @10 dB	7.71
This work	BB84	2.5 GHz	SNSPD(净36%)	0.499%	2.4 Mbps @101 km	23.22

已报道实验中最高码率：2.4 Mbps@100km

Li, Xu[a] et al., submitted (2021)


未来：chip-based MDI-QKD + TF-QKD
激光器和调制器的混合集成、光电集成等
用户1
用户2
用户3
不可信中继
城域网1
城际光纤链路
城际光纤链路
城域网2
用户1
不可信中继
用户2
用户3
高速芯片化MDI-QKD城域网
无中继的TF-QKD骨干网


总结：面向未来量子网络
安全性？
现实安全性
MDI+TF量子网络
Nat. Photon. 9, 772 (2015)
远距离？
量子中继
全光子量子中继
Nat. Photon. 13, 644 (2019)
应用？
低成本、小型化
芯片化QKD
Nat. Photon. 13, 839 (2019)
PRX 10, 031030 (2020)