양자 키 분배 실험의 발전 과정과 최근 동향

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홍 종 철

Quantum Cryptographic Steps - Quantum

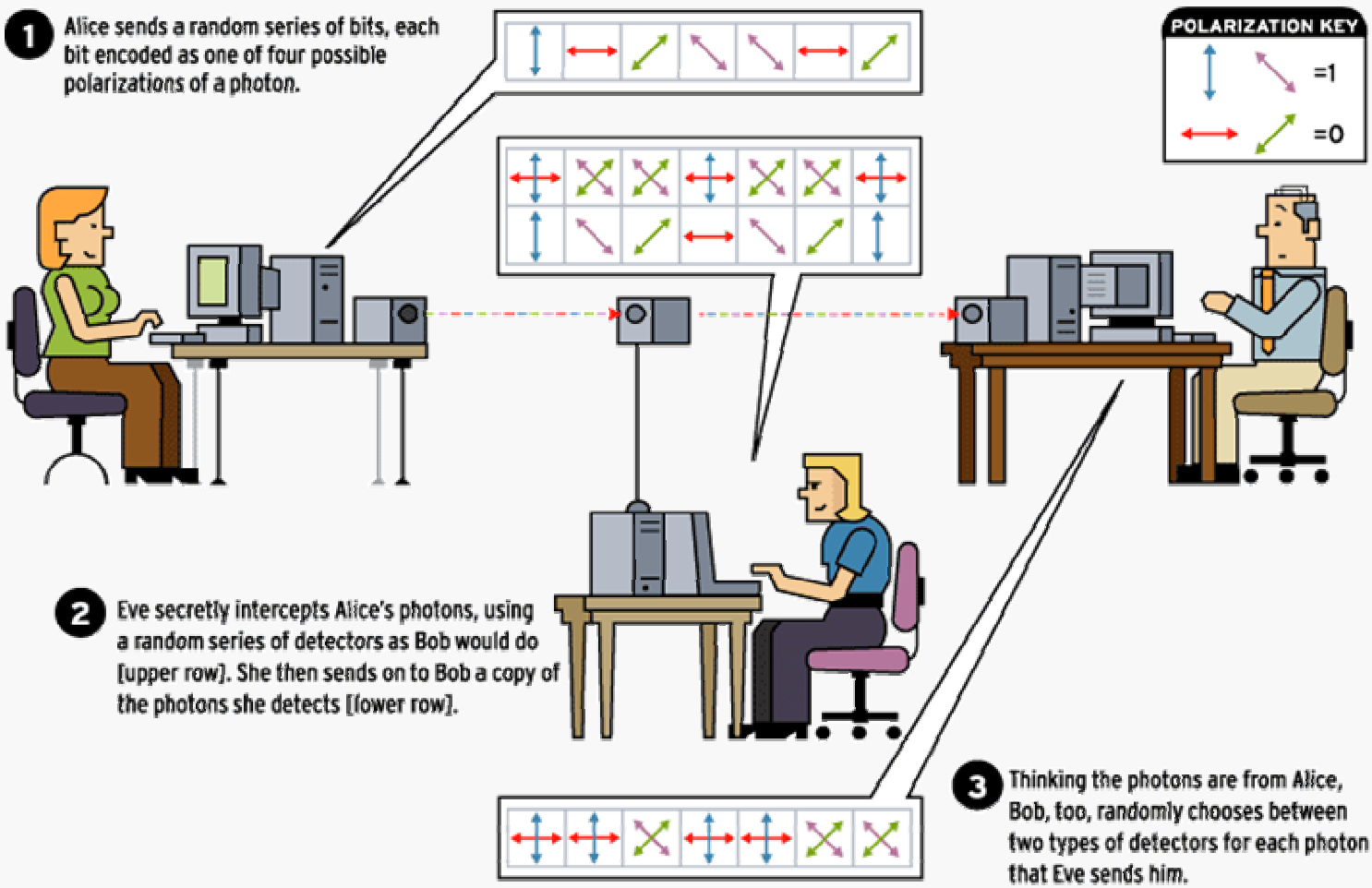
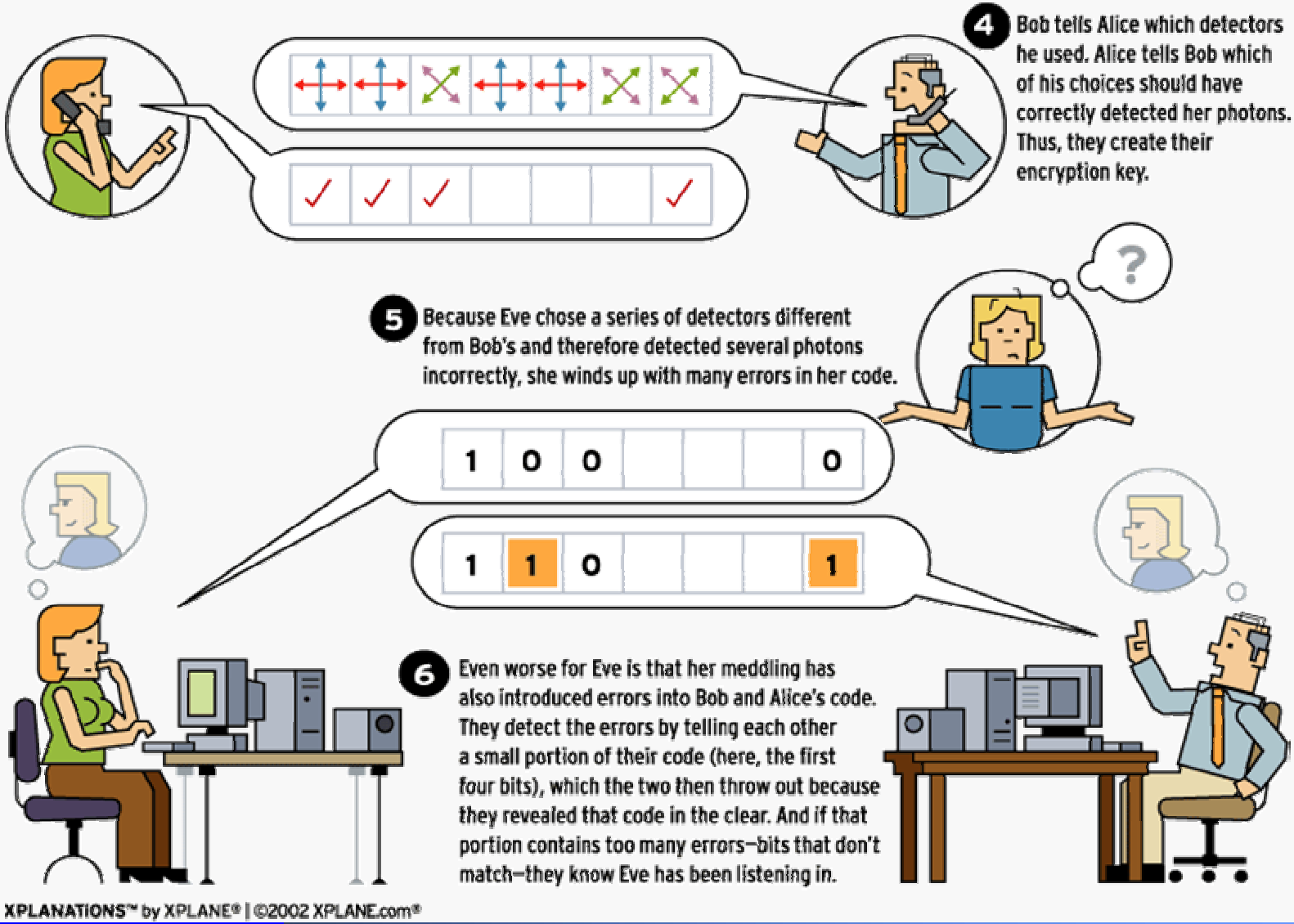


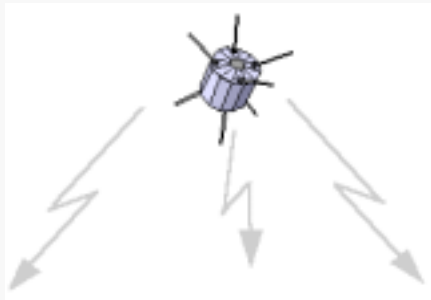
Illustration from **http://www.spectrum.ieee.org/WEBONLY/publicfeature/may02/codef1.html**

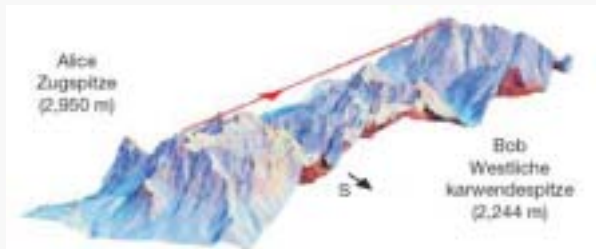
Quantum Cryptographic Steps - Classical

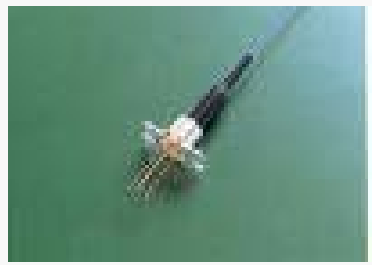


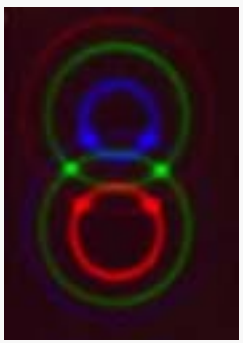
The Quantum Step Components

Coding



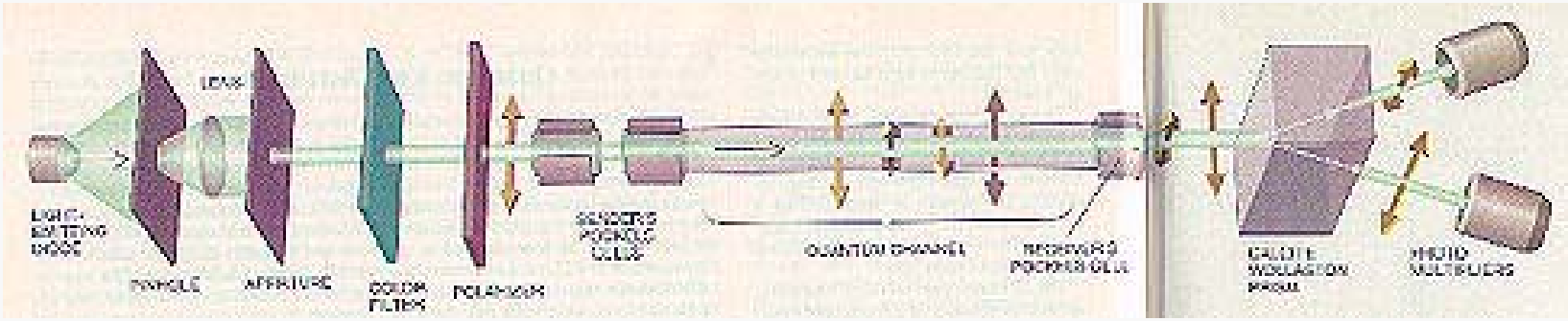






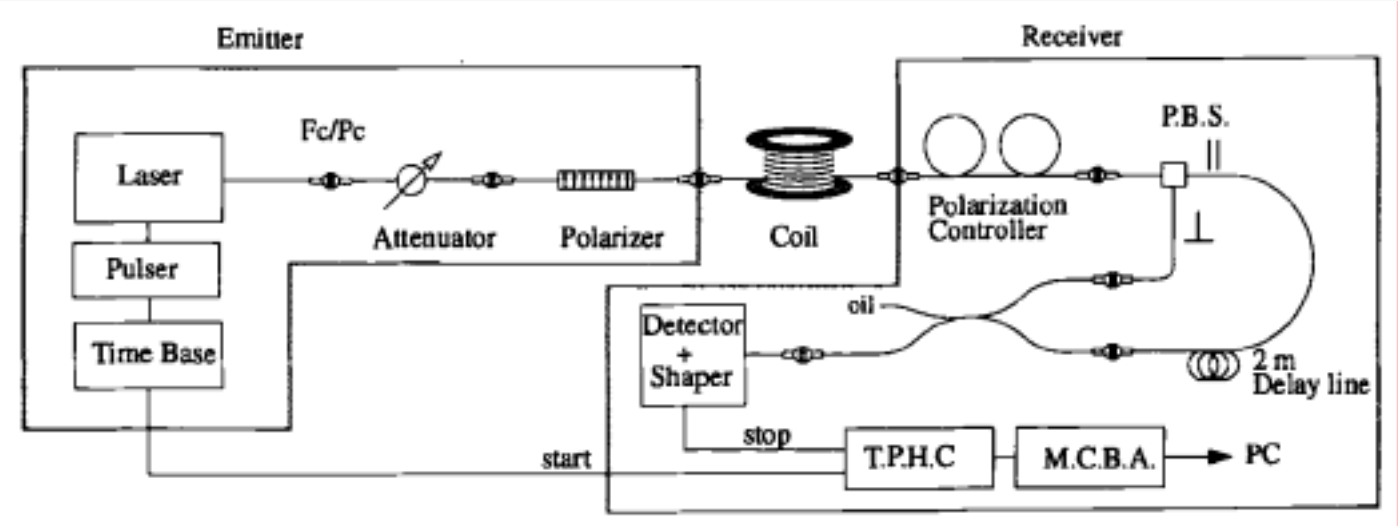
Source — Channel — Detector

The First Experiment



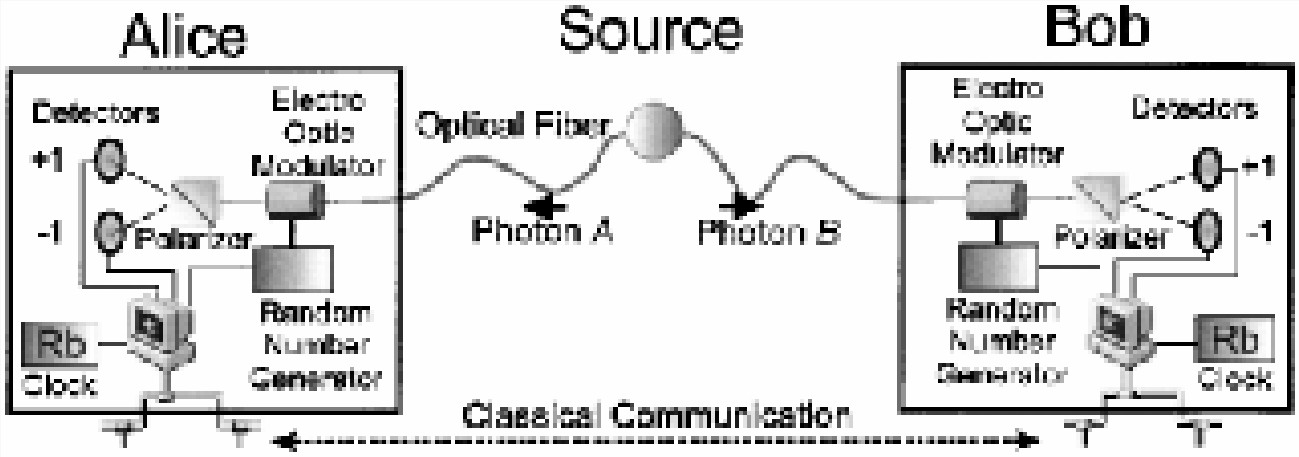
- "Experimental quantum cryptography" , Bennett, et.al. J. Cryptography 5, 3-28 (1992)
  - Green light emitting diode (incoherent source with pinhole)
  - 32 cm free air channel
  - 9% quantum efficiency photomultiplier

Polarization Coding QKD via Optical Fiber



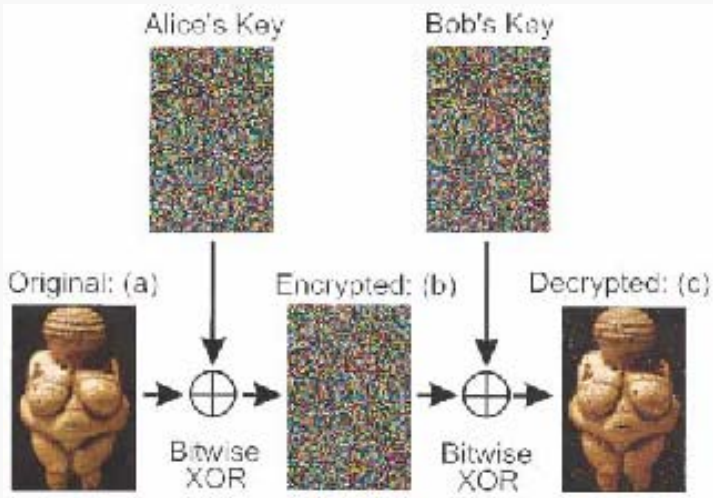
- "Quantum cryptography with polarization photons in optical fibres" , Brequet, et.al. J. Mod. Opt. 41, 2405-2412 (1994)
  - 800nm wavelength, {300m, 1100m} optical fiber channel
  - Si APD(RCA SPCM-100), quantum detection efficiency : 40%
  - Quantum bit rate : order of KHz, error rate : {0.35%,0.54%}

Ekert Protocol via Optical Fiber - I



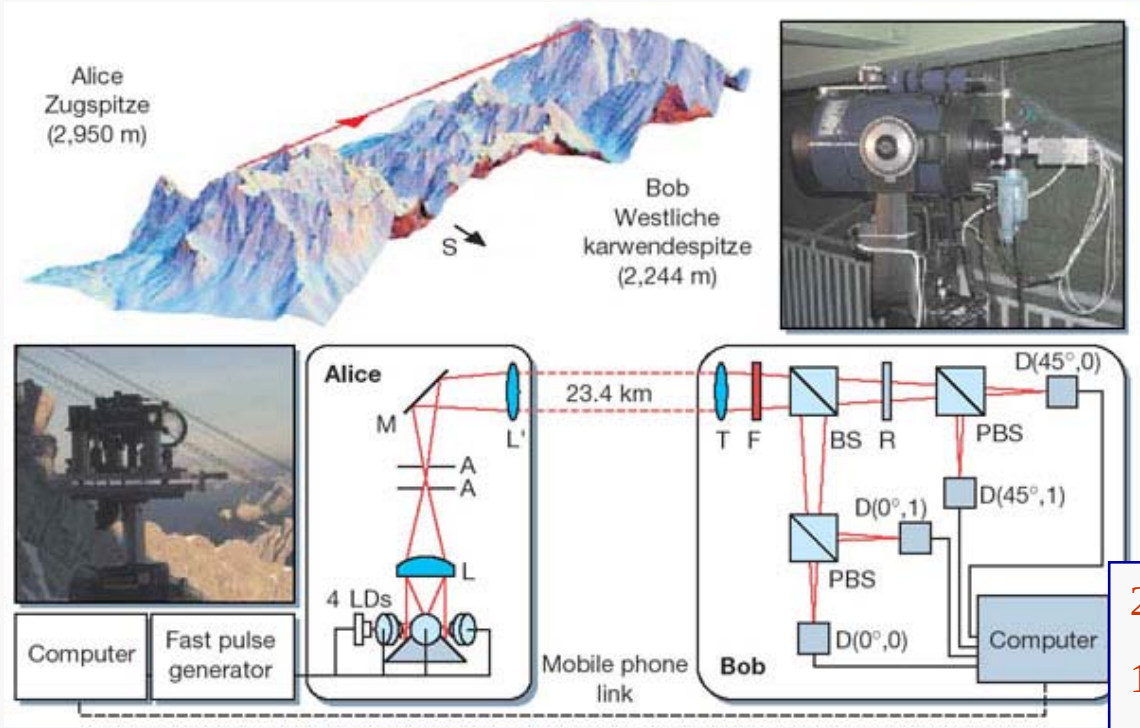
- "Qautnum cryptography with entangled photons" , Jennewein, et.al. Phys. Rev. Lett. 84, 4729-4732 (2000)
  - Type II parametric down conversion using β-barium borate (BBO)
  - Argon-ion laser (351nm) , 350mW
  - 702nm wavelength, 500m long optical fiber channel
  - Si APD

Ekert Protocol via Optical Fiber - II



- Total coincidence rate ~ 1700 s^{-1}
- Singles rate ~ 35000 s^{-1}
- Quantum detection efficiency : 5%
- pair production rate : 7 x 10^5 s^{-1}
- Coincidence window : 4ns
- Establish 2162 bits raw keys
- Bit rate : 420 bit/s
- Quantum bit error rate : 3.4 %

Free Space QKD



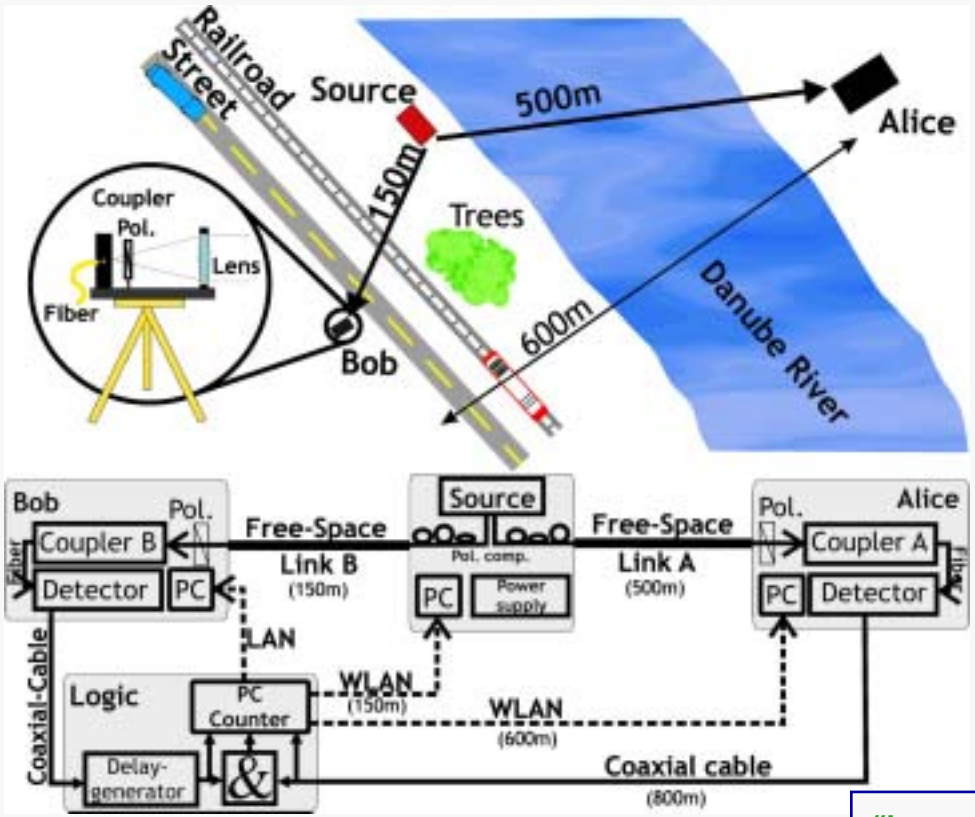
23.4 km free space channel

18-20 dB optical loss

1.5-2 Kbit/s

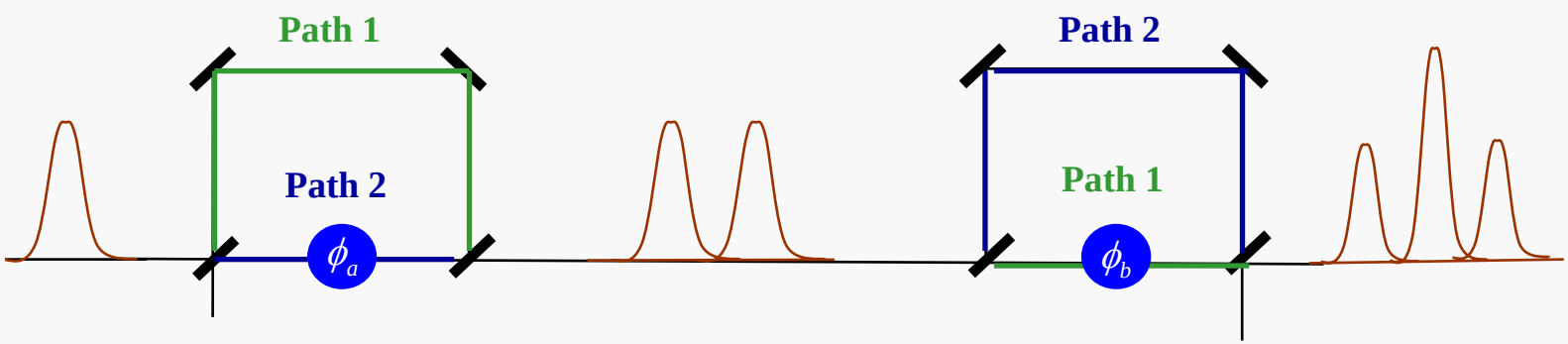
"A step towards global key distribution", Kurtsiefer, et.al. nature 419, 450 (2002)

Free Space Entanglement Distribution



"Long-distance free-space distribution of quantum entanglement" , Zeilinger, et.al. science 301, 621-623 (2003)

New Coding Scheme – Phase Coding



$$e^{i\phi_a}e^{i\phi_b}\left|S,0\right\rangle + ie^{i\phi_a}e^{i\phi_b}\left|S,1\right\rangle + \left|L,0\right\rangle - i\left|L,1\right\rangle$$
$$-\left(e^{i\phi_a}+e^{i\phi_b}\right)\left|C,0\right\rangle + i\left(e^{i\phi_a}-e^{i\phi_b}\right)\left|C,1\right\rangle$$

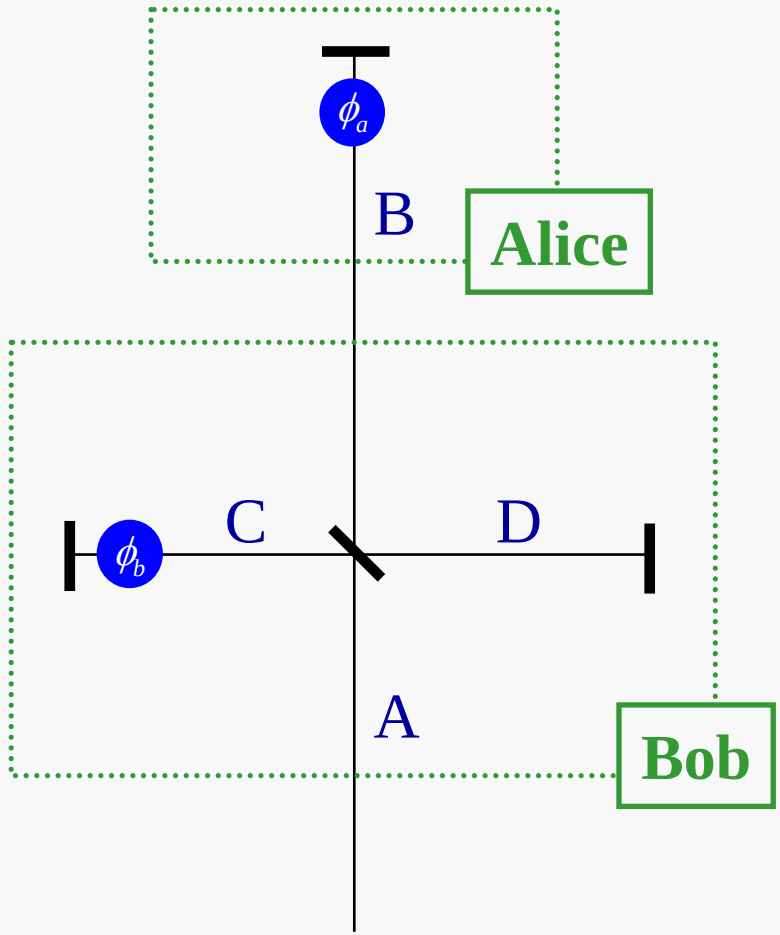
Double Mach-Zehnder Interferometry

QKD with Phase Coding via Optical Fiber

- 0.3 dB/km fiber attenuation
- Typical travel time : 225 μm
- 5ns separation between the different path
- 100kHz laser pulse rate
- Bit error rate (BER) ~ 9.3 %
- 10 Hz key generation rate

- "Quantum key distribution over a 48km optical fibre network" , R.J. Hughes, et.al. J. Mod. Opt. 47, 533-547 (2000)
  - 1300nm wavelength
  - InGaAs APD (efficiency : 10-40%, Dark count : 10-100kHz)
  - $\Delta T \gg T_{coh}$ (the difference between travel time is much higher than the coherence time)

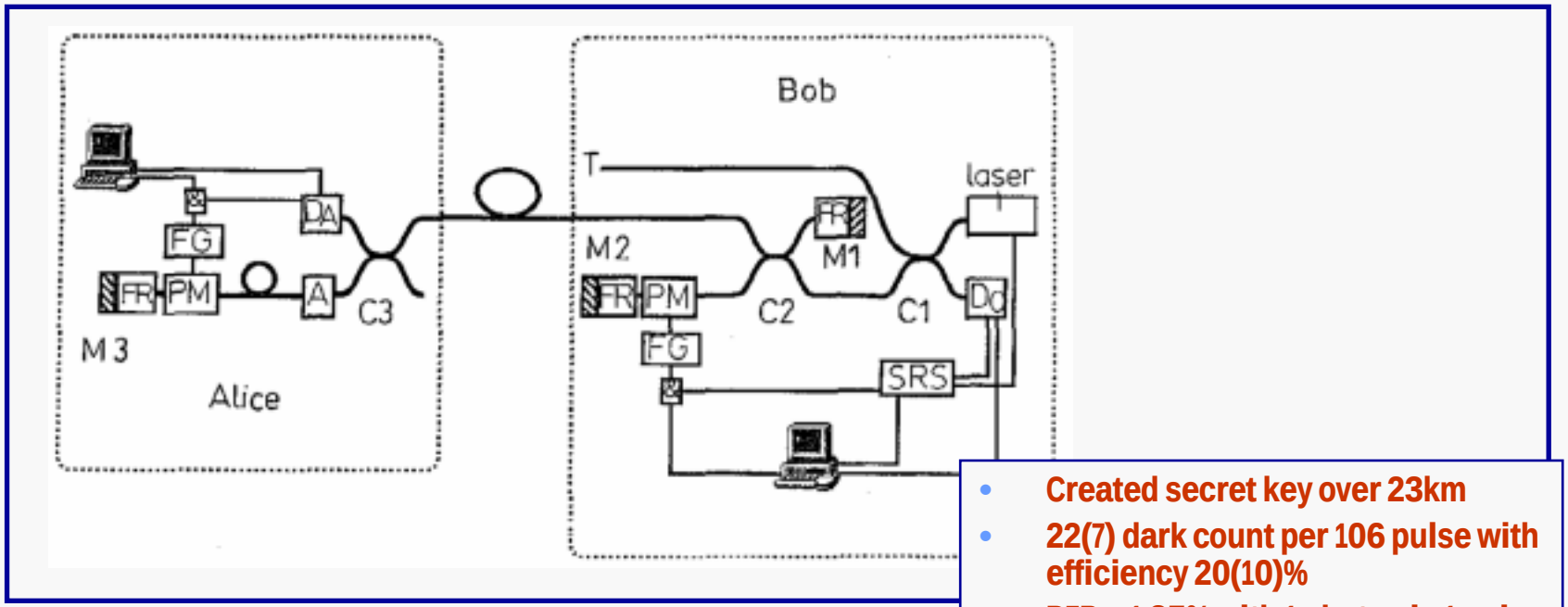
Phase Coding Using Michelson Interferometry



- Interfering paths
  - A → C → C → D → D → B → B → A
  - A → B → B → D → D → C → C → A

Plug & Play System

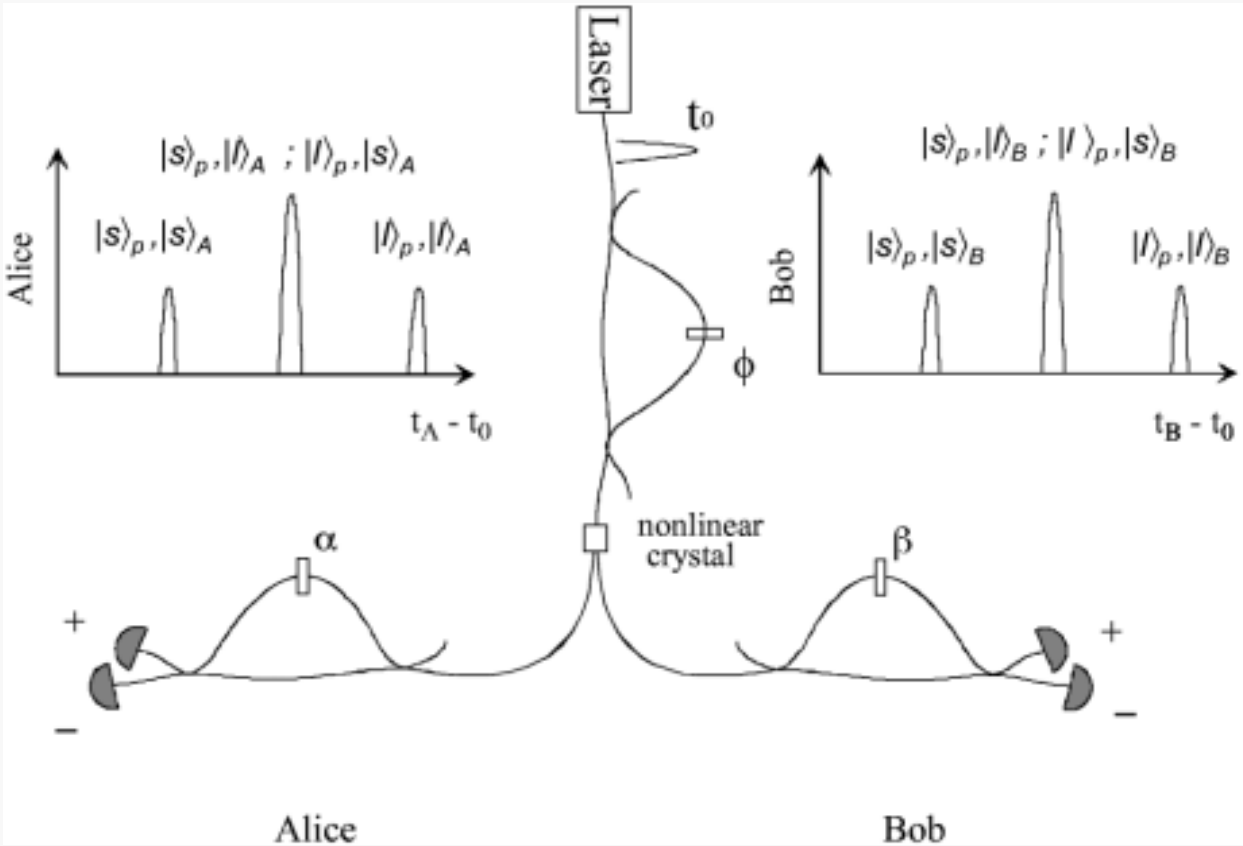
Demonstration of PNP System



- Created secret key over 23km
- 22(7) dark count per 106 pulse with efficiency 20(10)%
- BER = 1.35% with 1 photon in 1 pulse

- "Interferometry with Faraday mirrors for quantum cryptography" , H. Zbinden, et.al. Electron. Lett. 33, 586-588 (1997)
  - LN_2 Cooled Ge APD
  - Faraday mirror : compensate the birefringence of fiber
  - Bob : PZT phase modulator (Modulation freq. ~ 10kHz)
  - Alice : 4GHz $LiNbO_3$ waveguide phase modulator

QKD Using Energy-Time Entanglement - I



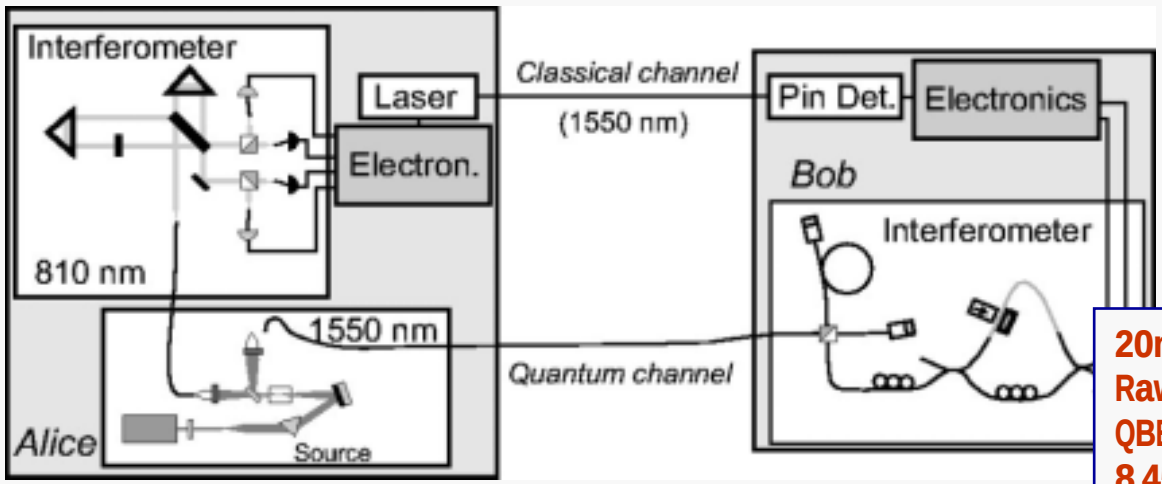
"Quantum cryptography using entangled photons in energy-time Bell state" ,
W. Tittel, et.al. Phys. Rev. Lett. 84, 4737-4740 (1999)

QKD Using Energy-Time Entanglement - II

	++	+-	-+	--
$s_p s_a, s_p s_b$	278±6	197 ±5	187 ±5	147 ±4
$l_p l_a, l_p l_b$	304 ±7	201 ±5	200 ±5	148 ±5
$s_p s_a, l_p l_b$	11 ±0.8	10.4 ±0.8	9.2 ±0.7	9.4 ±0.7
$l_p l_a, s_p s_b$	11.2 ±0.4	8.6 ±0.4	9.1 ±0.4	8.5 ±0.4
QBER (%)	3.7 ±0.2	4.6 ±0.2	4.5 ±0.2	5.7 ±0.3

	++	+-	-+	--
Visibility (%)	92.5±1.8	92.6 ±1.4	89.3 ±1.9	94.5 ±1.6
Max.	518 ±13	416 ±8	359 ±9	279 ±7
Min.	20 ±5	16 ±3	20 ±4	8 ±2
QBER (%)	3.7 ±0.9	3.7 ±0.7	5.3 ±1	2.8 ±0.8

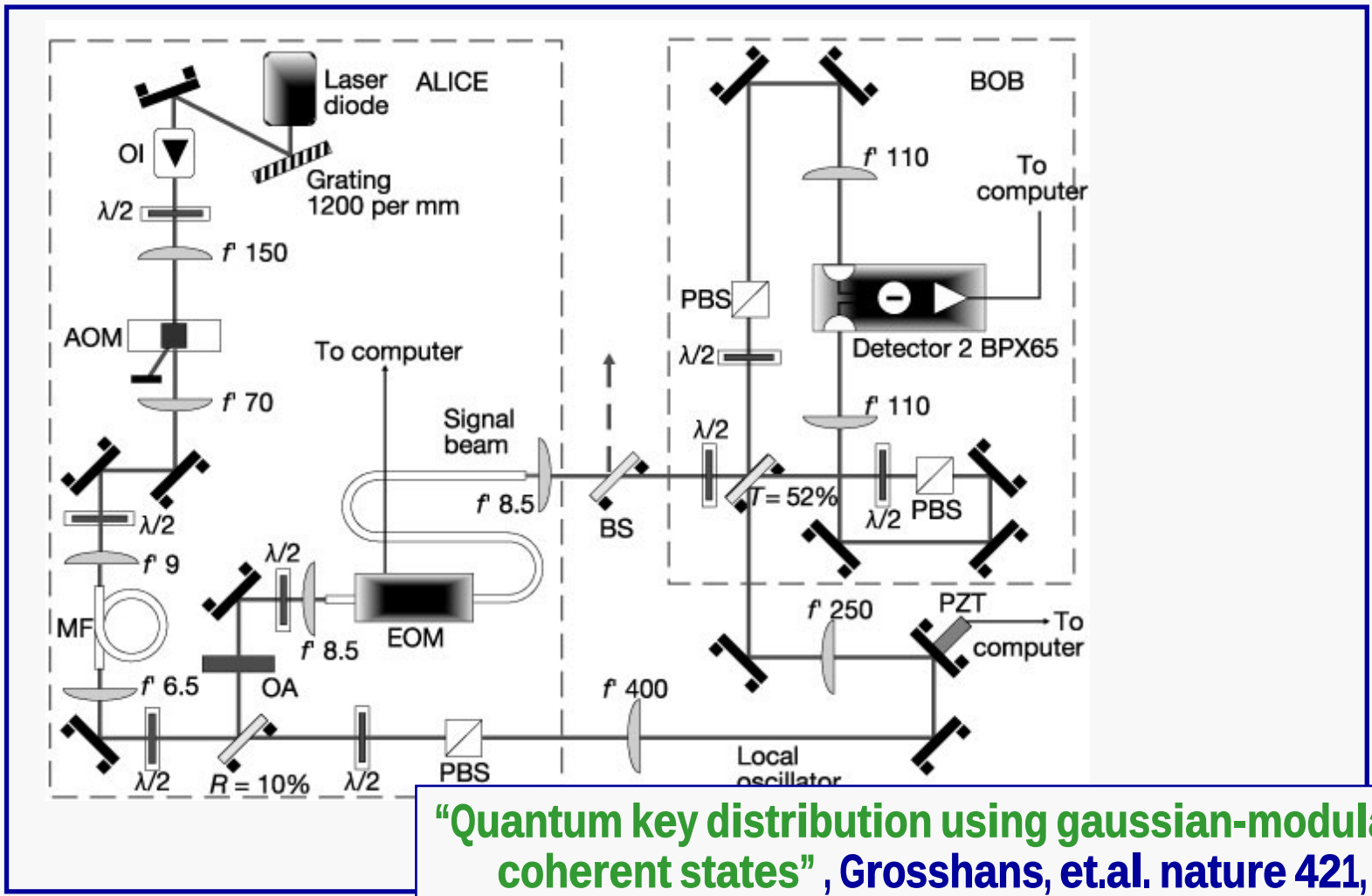
Phase Coding Experiments with Entangled Photons



20m distance
Raw key distribution rate : 450Hz
QBER : 4.7%±0.3%
8.45km distance
Raw key distribution rate : 134Hz
QBER : 6.6%±0.6%

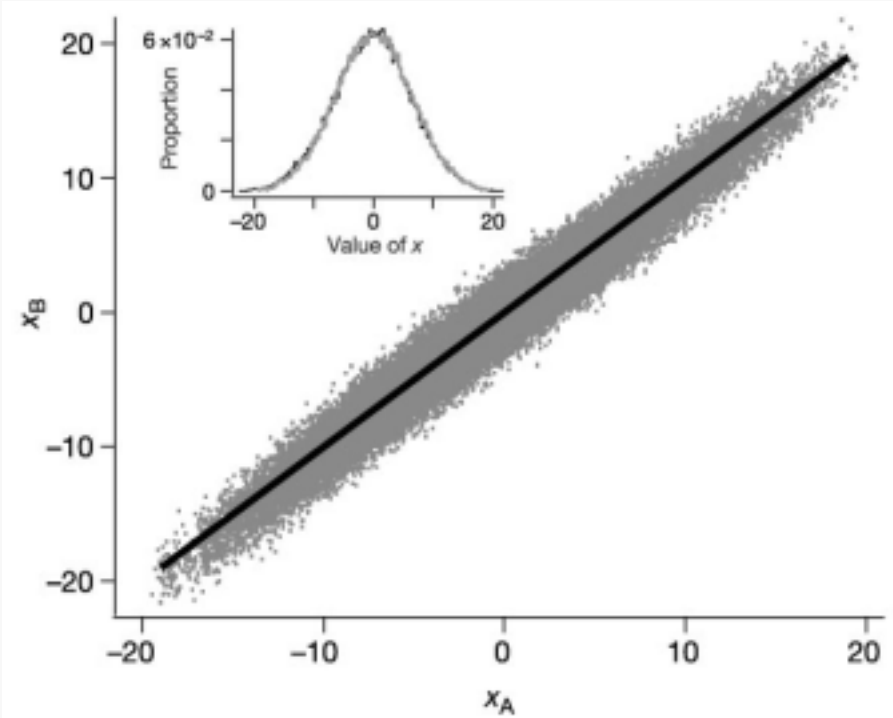
"Long-distance entanglement-based quantum key distribution" , G. Ribordy, et.al. Phys. Rev. A 63, 012309 (2001)

Continuous Variable QKD - I



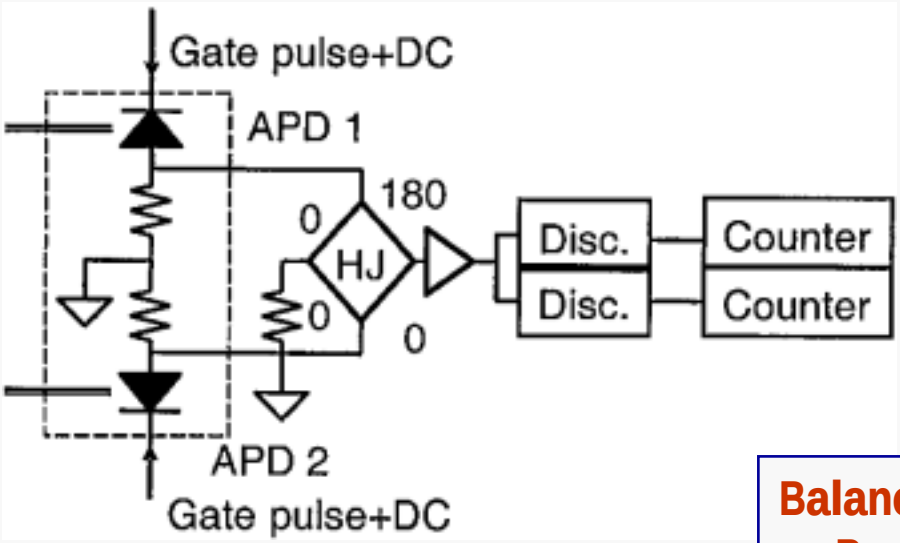
"Quantum key distribution using gaussian-modulated coherent states" , Grosshans, et.al. nature 421, 238-241 (2003)

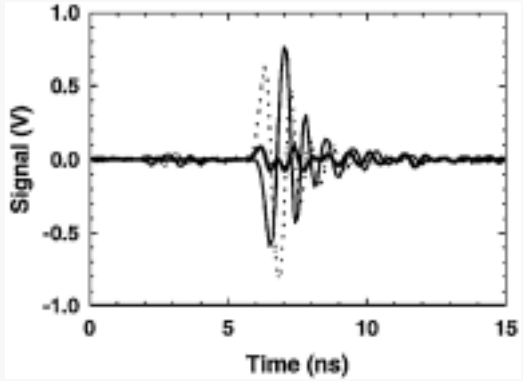
Continuous Variable QKD - II



1690 bps at 1dB channel loss

QKD over 100km - I

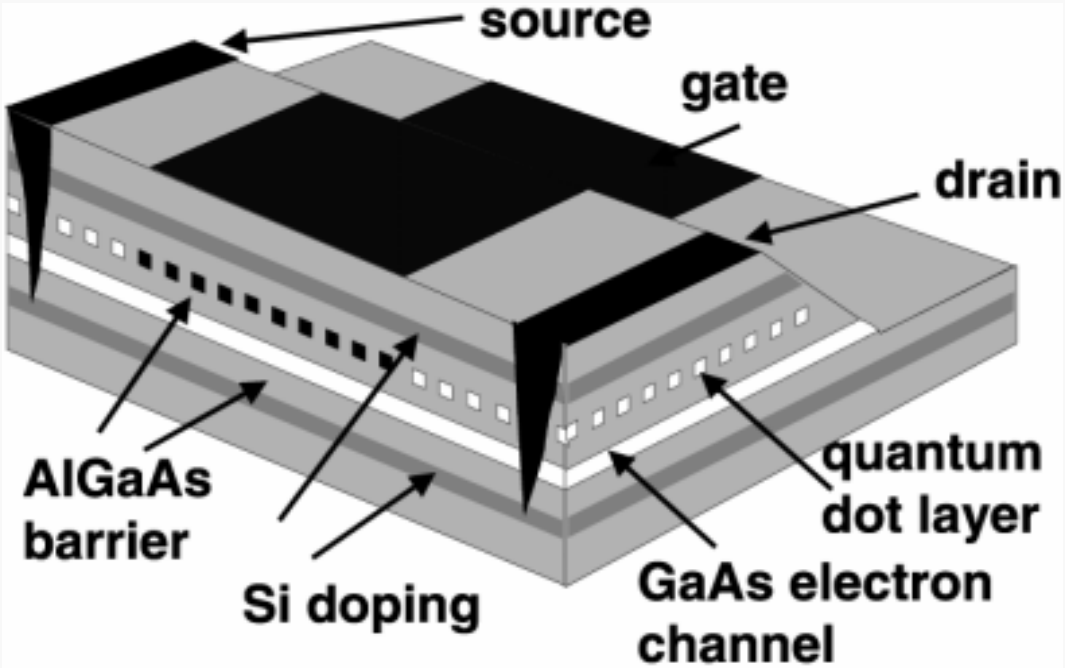


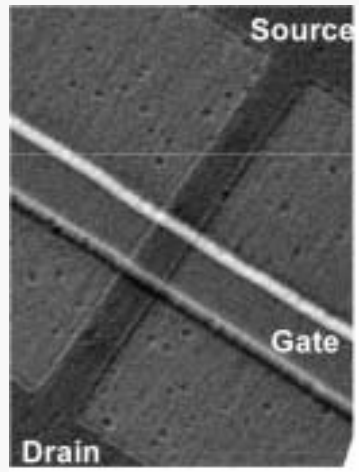


Balanced Gated Mode APD & PNP System
→ Reduce the transient spikes
→ Reduce the quantum threshold

"Single photon interference experiment over 100km for quantum cryptography system using a balanced gated-mode photon detector" , H. Kosaka, A. Tomita, Y. Nambu, T. Kimura, and K. Nakamura, quant-ph/0306066 (2003)

QKD over 100km - II





Reported by Shields, et.al. (Toshiba Research Europe) at CLEO 2003 (Baltimore, US)

Improving single photon detector other than APD : "Detection of single photons using a field effect transistor with a layer of quantum dots", Kardynal, et.al. Meas. Sci. Technol. 13, 1721-1726 (2002)

Error Sources in QKD Experiments

- **Source error**
  - Multi-photon pulse
- **Detector error**
  - Dark count
  - Gate spikes
  - After pulse
- **Channel error**
  - Dispersion
  - Back scattering
  - Polarization rotation & dispersion
  - Attenuation

Conclusion & ETRI Experiment Plan

- Current State
  - Several Hz key rate via 100km length optical fiber channel
  - Several kHz key rate via 23.4km length free space line of sight link
  - Proposing satellite key distribution
- ETRI Experiment Plan
  - Achieve a few kHz raw key distribution via a few 10 km optical fiber channel within 3 years
  - Develop new QKD protocol
  - Improve photon detector

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