Defence for the degree *doktor ingeniør*
at the Norwegian University of Science and Technology, April 30, 2007

Quantum cryptography
and
quantum cryptanalysis

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NTNU
Norwegian University of Science and Technology

SPbSPU
St. Petersburg State Polytechnic University

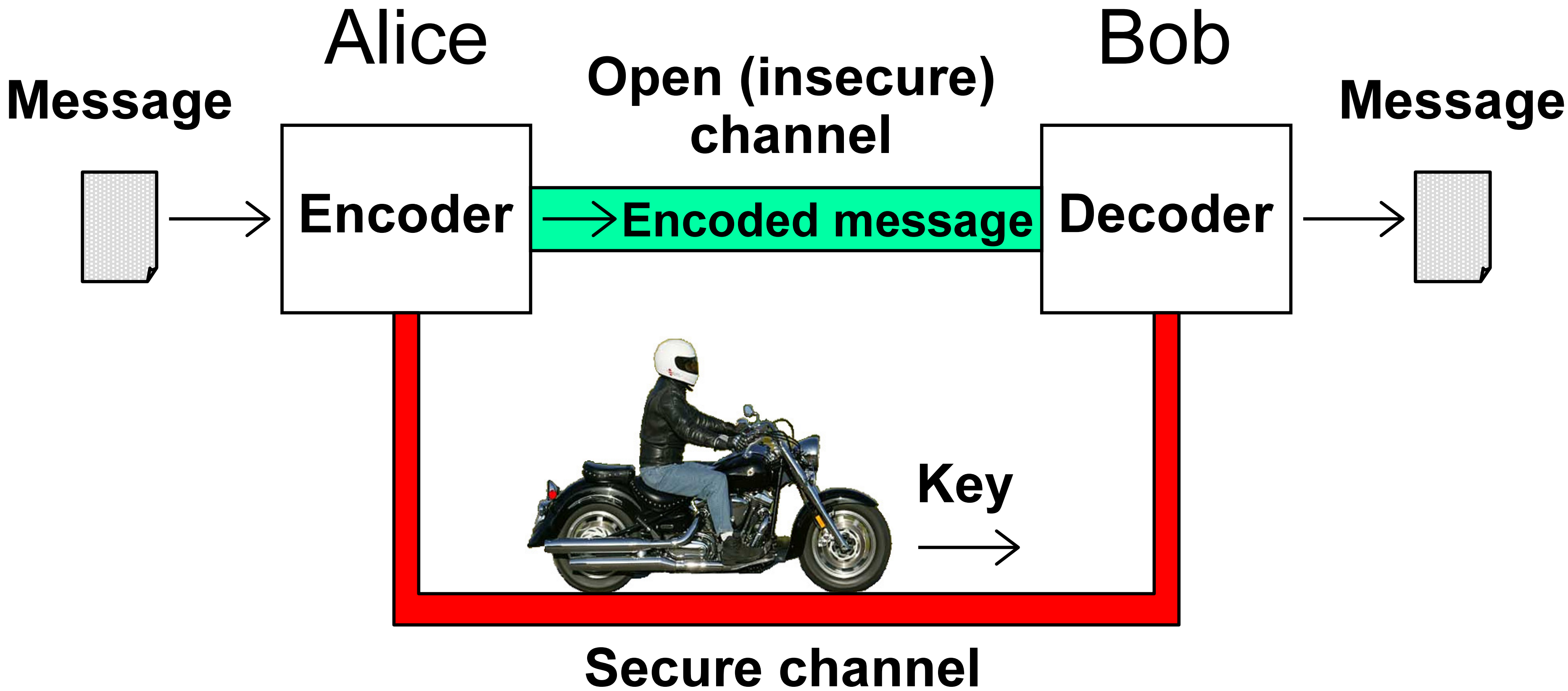
telenor R&D

SINTEF

Quantum cryptography timeline

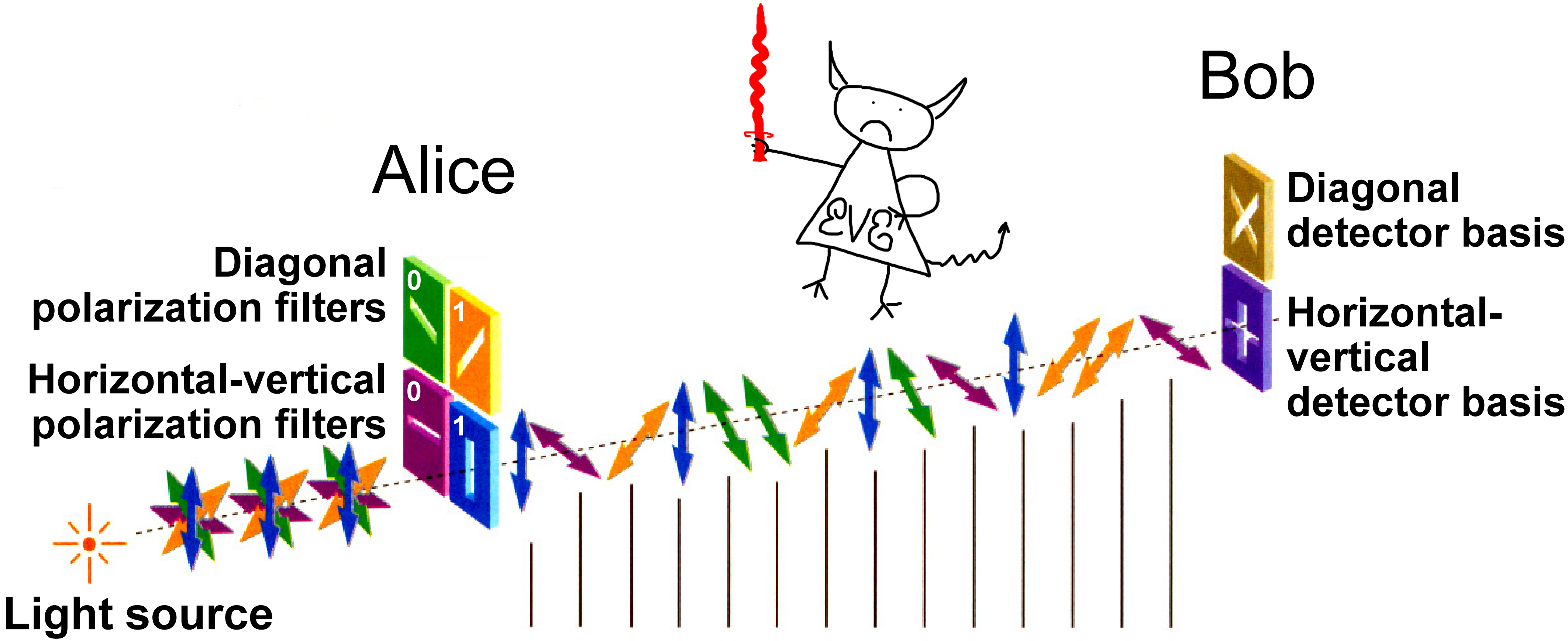
ca. **1970**	Concept ("money physically impossible to counterfeit")
1984	Key distribution protocol (BB84)
1989	Proof-of-the-principle experiment
1993	Key transmission over fiber optic link
2004	First commercial offers
...	Market?

Key distribution



- Secret key cryptography requires secure channel for key distribution.
- Quantum cryptography distributes the key by transmitting quantum states in *open channel*.

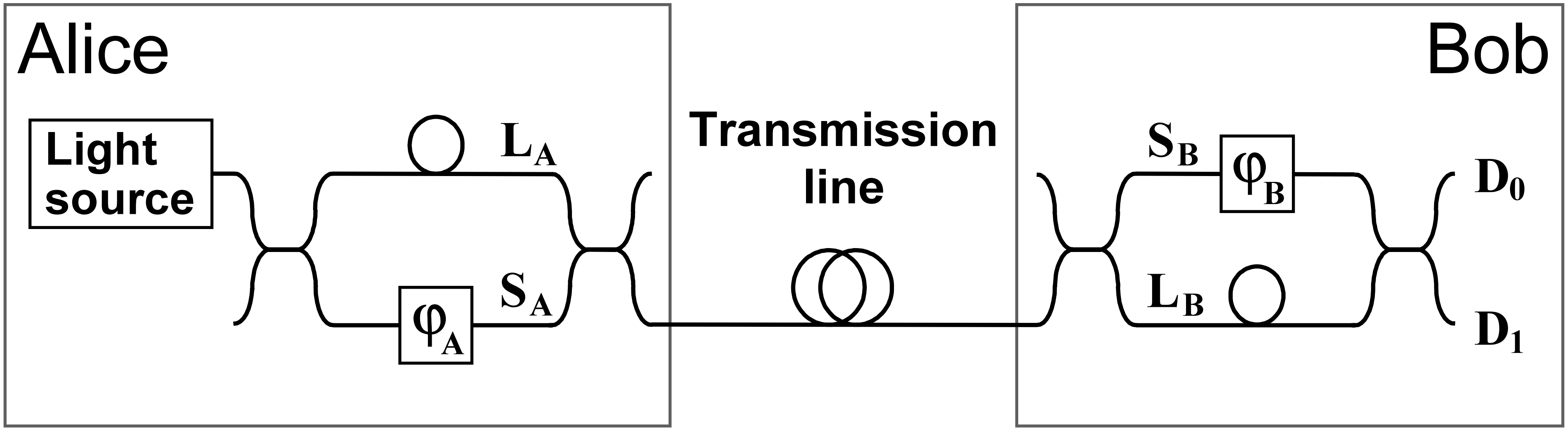
Quantum key distribution



Alice's bit sequence	1	0	1	1	0	0	1	1	0	0	1	1	1	0
Bob's detection basis	+	×	+	+	×	×	+	+	×	+	×	×	+	+
Bob's measurement	1	0	0	1	0	0	1	1	0	0	0	1	0	0
Retained bit sequence	1	–	–	1	0	0	–	1	0	0	–	1	–	0

Image reprinted from article: W. Tittel, G. Ribordy, and N. Gisin, "Quantum cryptography," Physics World, March 1998

Interferometric QKD channel



Detector bases:

$\varphi_A = -45°$ or $+45°$: 0

$\varphi_A = +135°$ or $-135°$: 1

$\varphi_B = -45°$: X

$\varphi_B = +45°$: Z

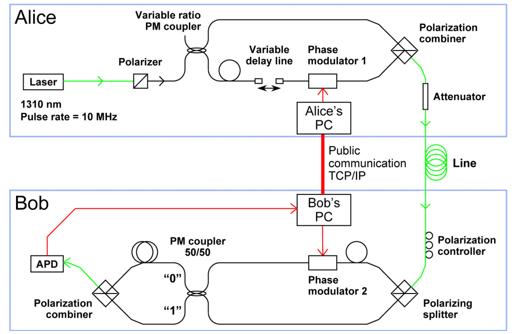
Quantum cryptography at NTNU

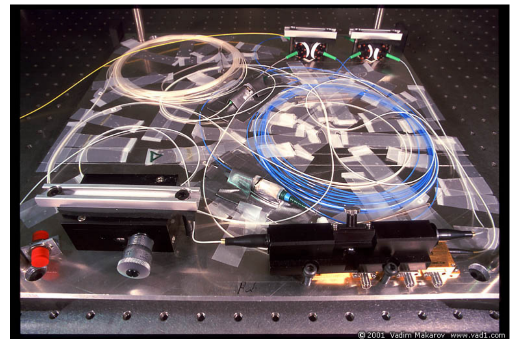
Fiber optic QKD setup

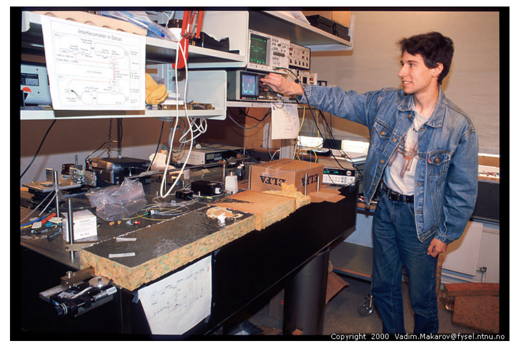
1. Optimal tracking of phase drift
2. Single photon detector with afterpulse blocking

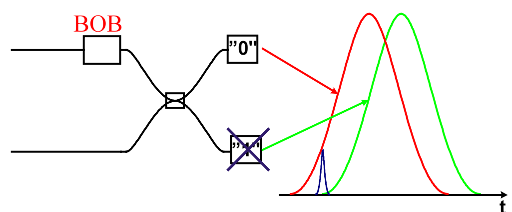
Security against practical attacks

3. Large pulse attack: experiment
4. Faked states attack
5. Detector efficiency mismatch

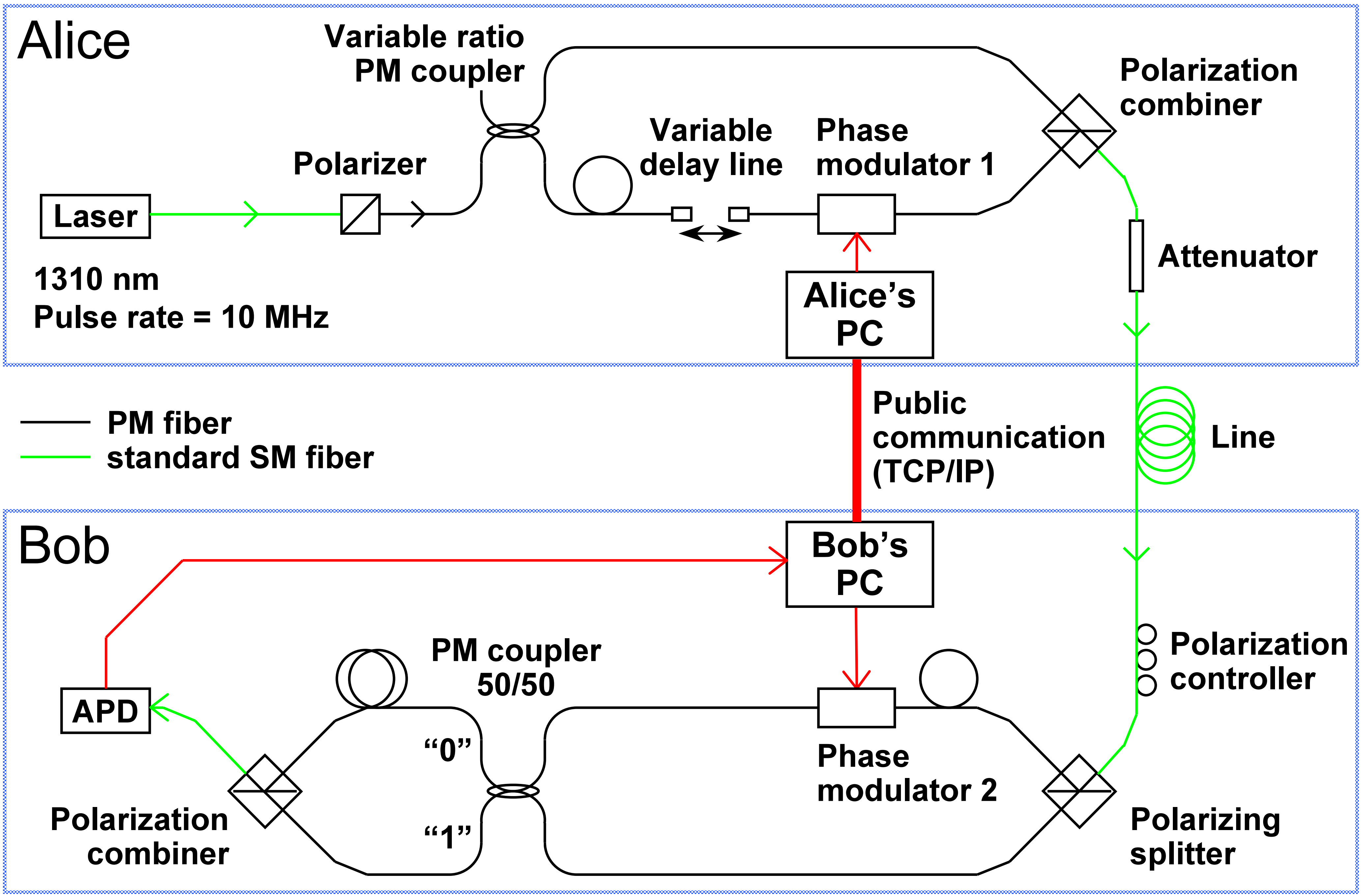








QKD setup


Alice
Variable ratio PM coupler
Polarization combiner
Variable delay line
Phase modulator 1
Polarizer
Laser
1310 nm
Pulse rate = 10 MHz
Attenuator
Alice's PC
PM fiber
standard SM fiber
Public communication (TCP/IP)
Line
Bob
Bob's PC
PM coupler 50/50
Polarization controller
APD
"0"
"1"
Phase modulator 2
Polarization combiner
Polarizing splitter

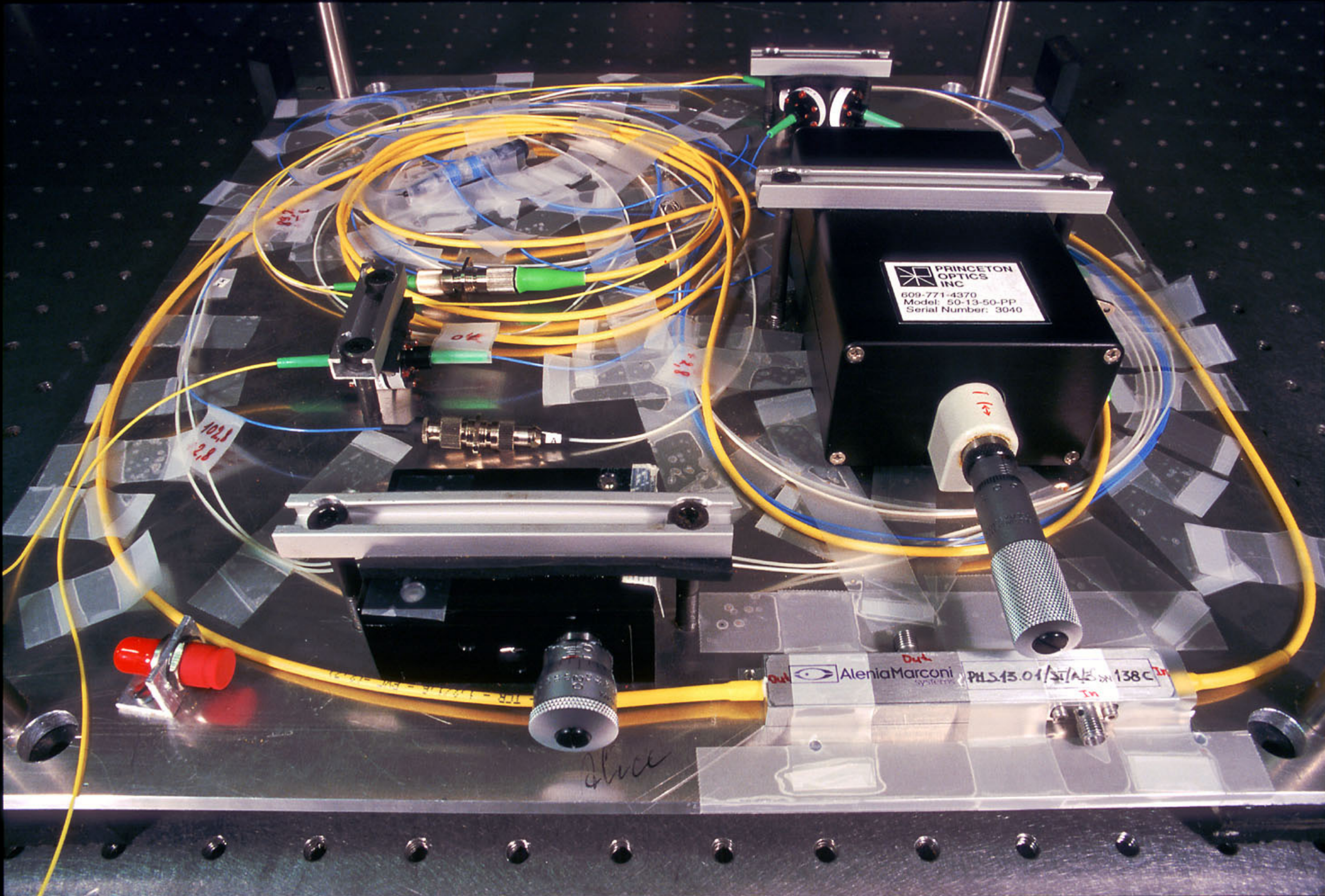


Photo 1. **Alice** (uncovered, no thermoisolation installed)

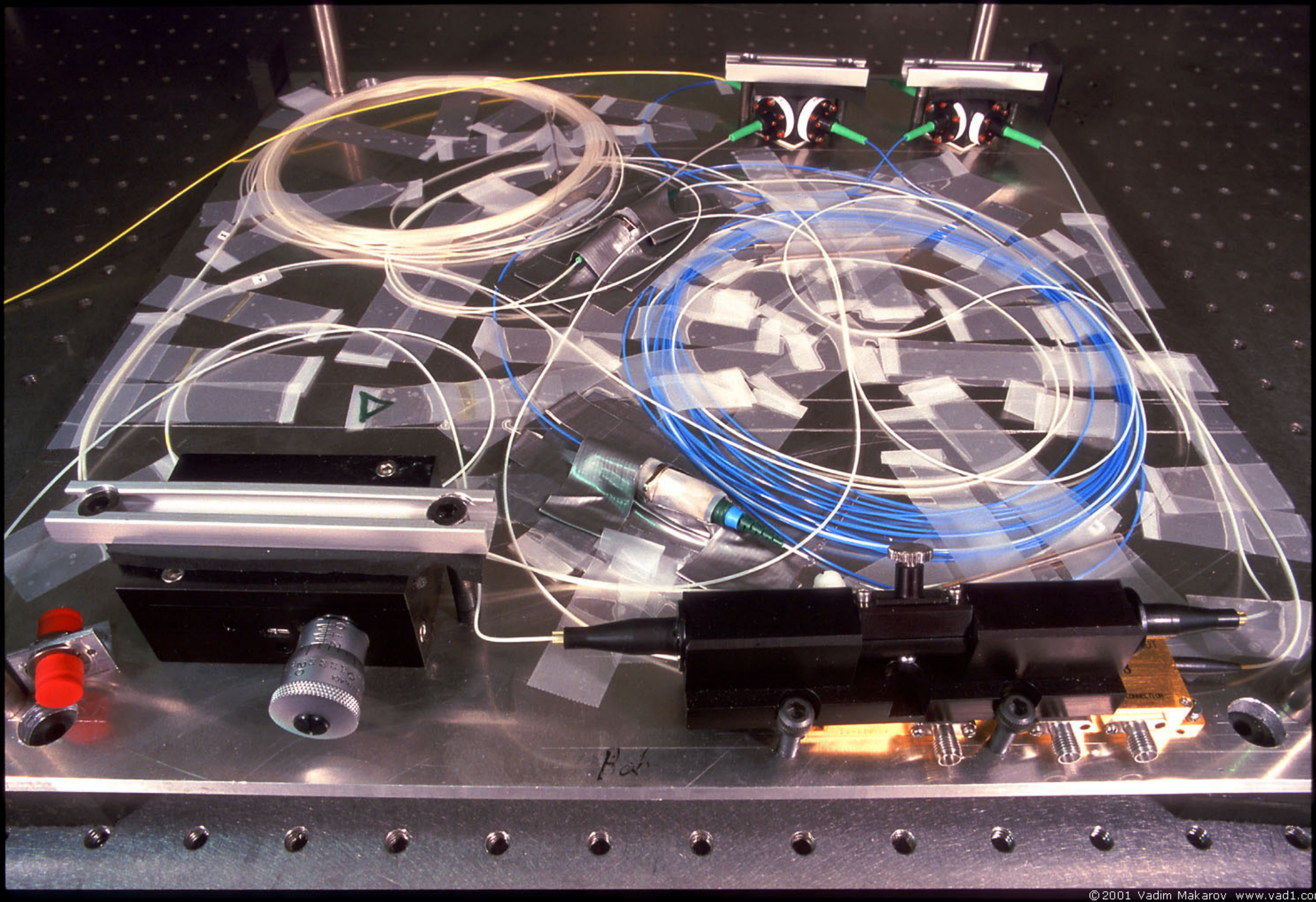


Photo 2. **Bob** (uncovered, no thermoisolation installed)

Tracking phase drift

To get phase accuracy $\Delta\varphi$ within ±10° ($\mathrm{QBER}_{\mathrm{opt}\,\Delta\varphi} < 1\%$), no more than N_a = ~200 detector counts per adjustment are required.

Optimally counted at ±90° points from the extreme of the interference curves. Exact required number of counts

$$N_a = \frac{2k^2}{\Delta\varphi^2}\left(\frac{1}{1-2(\mathrm{QBER})}\right)^2,$$

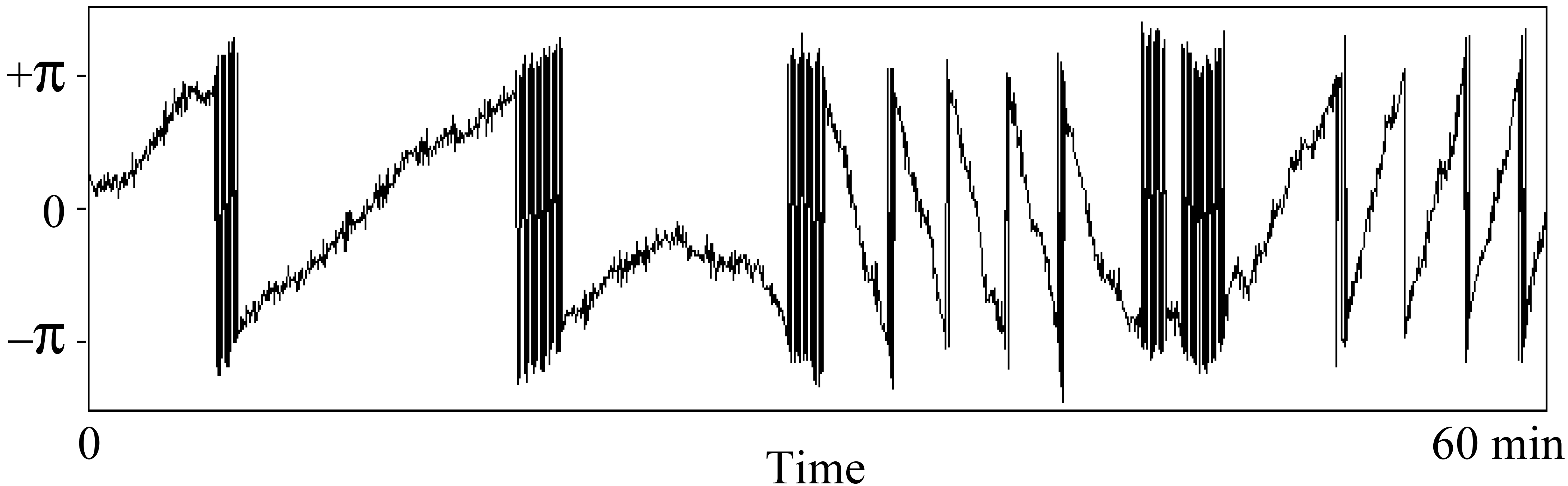
where *k* is the number of standard deviations of not exceeding $\Delta\varphi$.

J. Appl. Opt. **43**, 4385 (2004)

Tracking phase drift

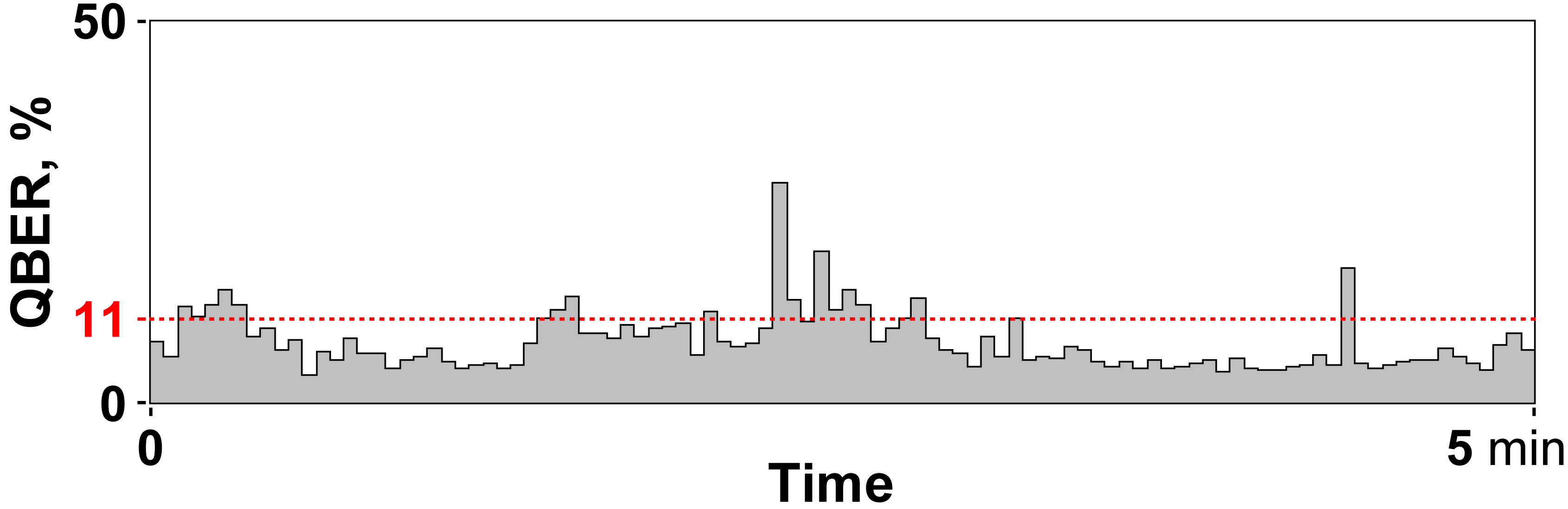
To get phase accuracy $\Delta\varphi$ within ±10° ($QBER_{opt\,\Delta\varphi} < 1\%$), no more than N_a = ~200 detector counts per adjustment are required.

Experiment: adjustment every 3 s, N_a = 230:



J. Appl. Opt. **43**, 4385 (2004)

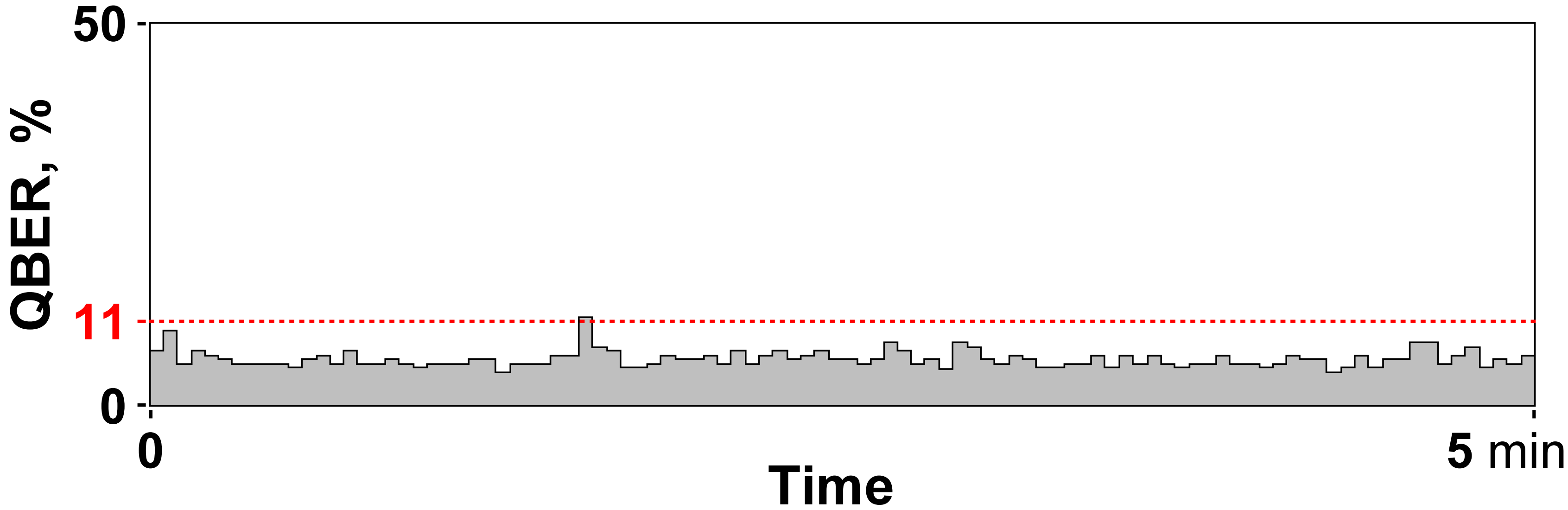
Test of QKD in laboratory conditions



Test run No. 1

best QBER

~ 4%

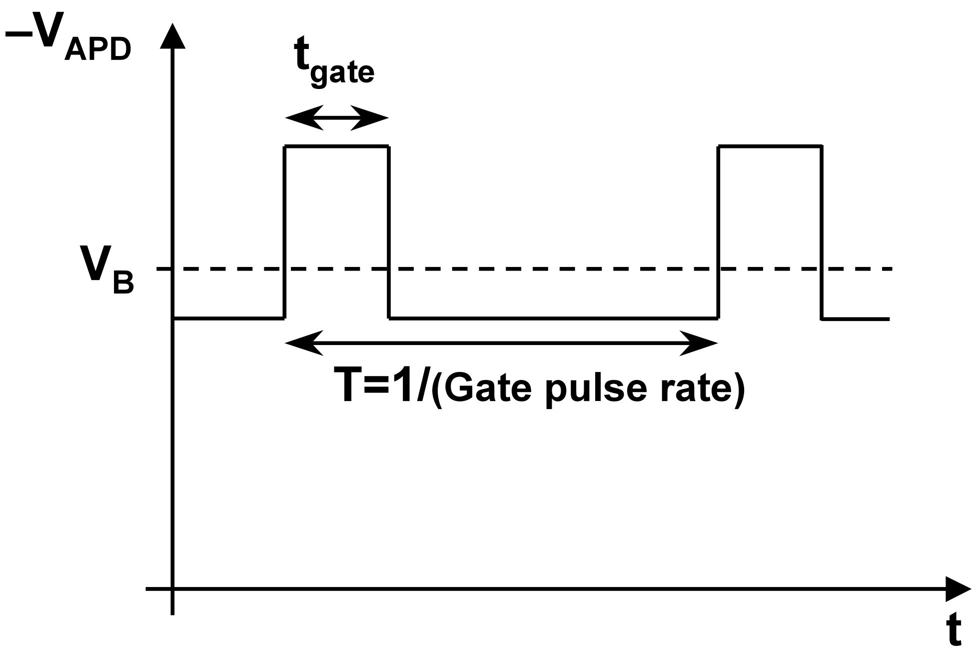


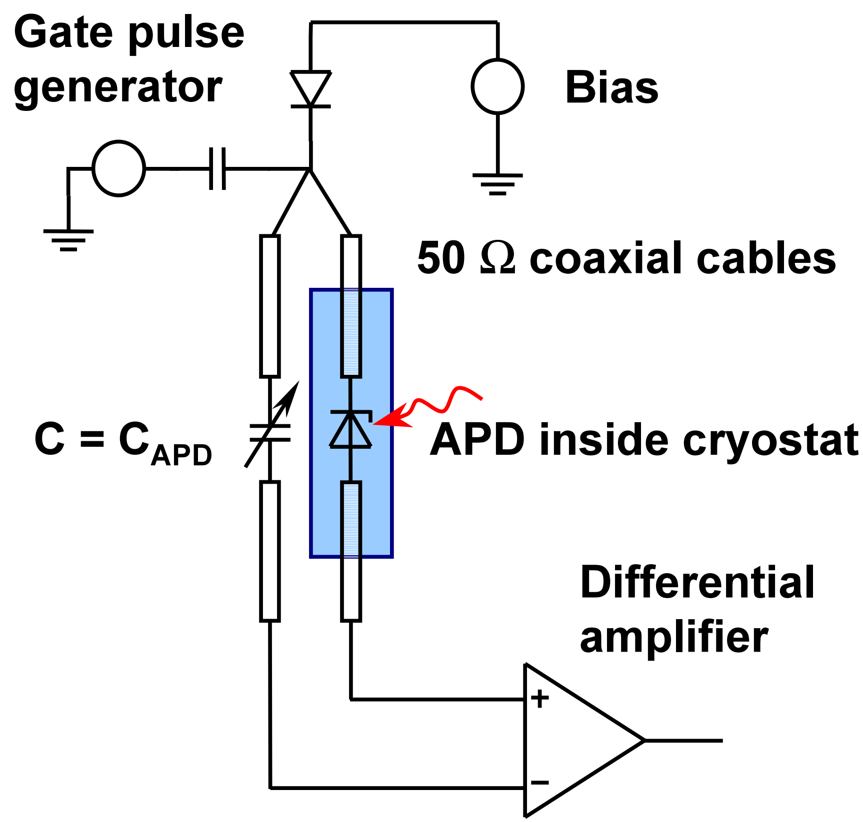
Test run No. 2

QBER =

5.7% average

Single photon detector: avalanche photodiode in Geiger mode





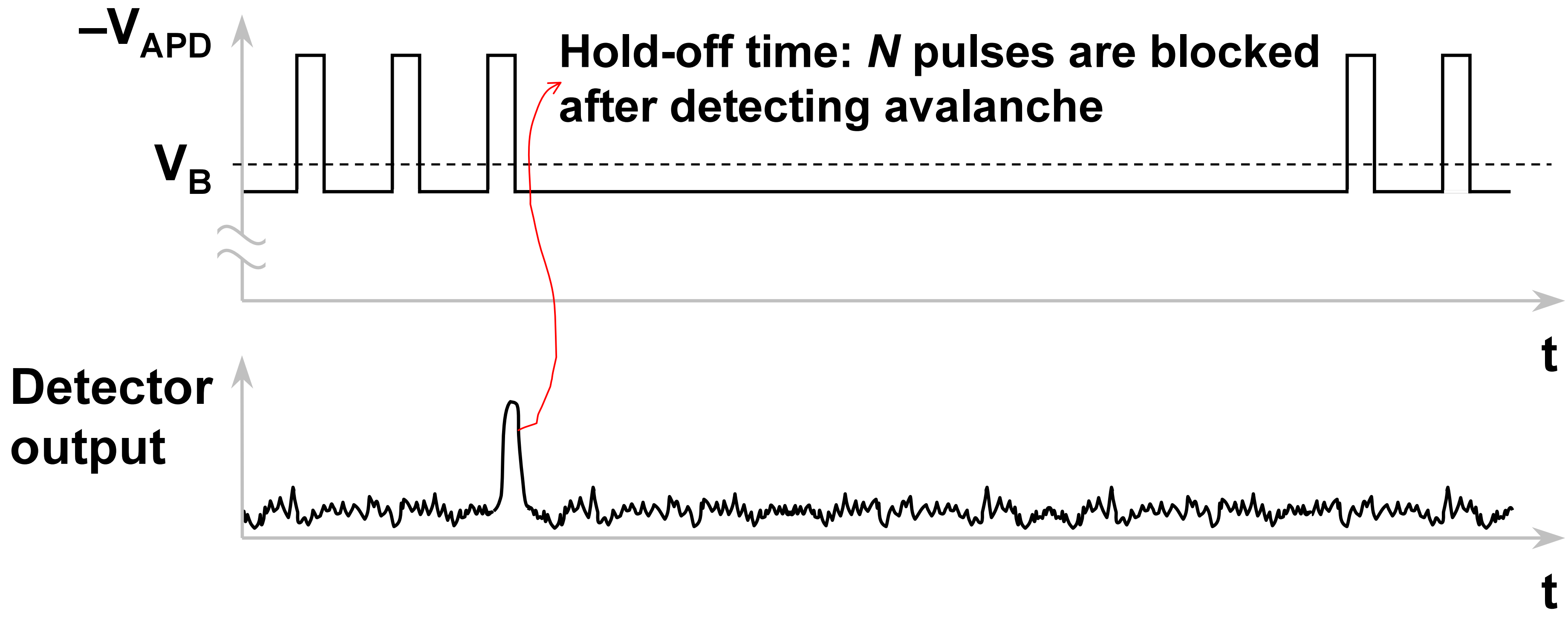
t_{gate} down to 1ns

Gate pulse rate = 20 MHz

APD: Ge FD312L

T=77K, QE=16%, DC=$5 \cdot 10^{-5}$

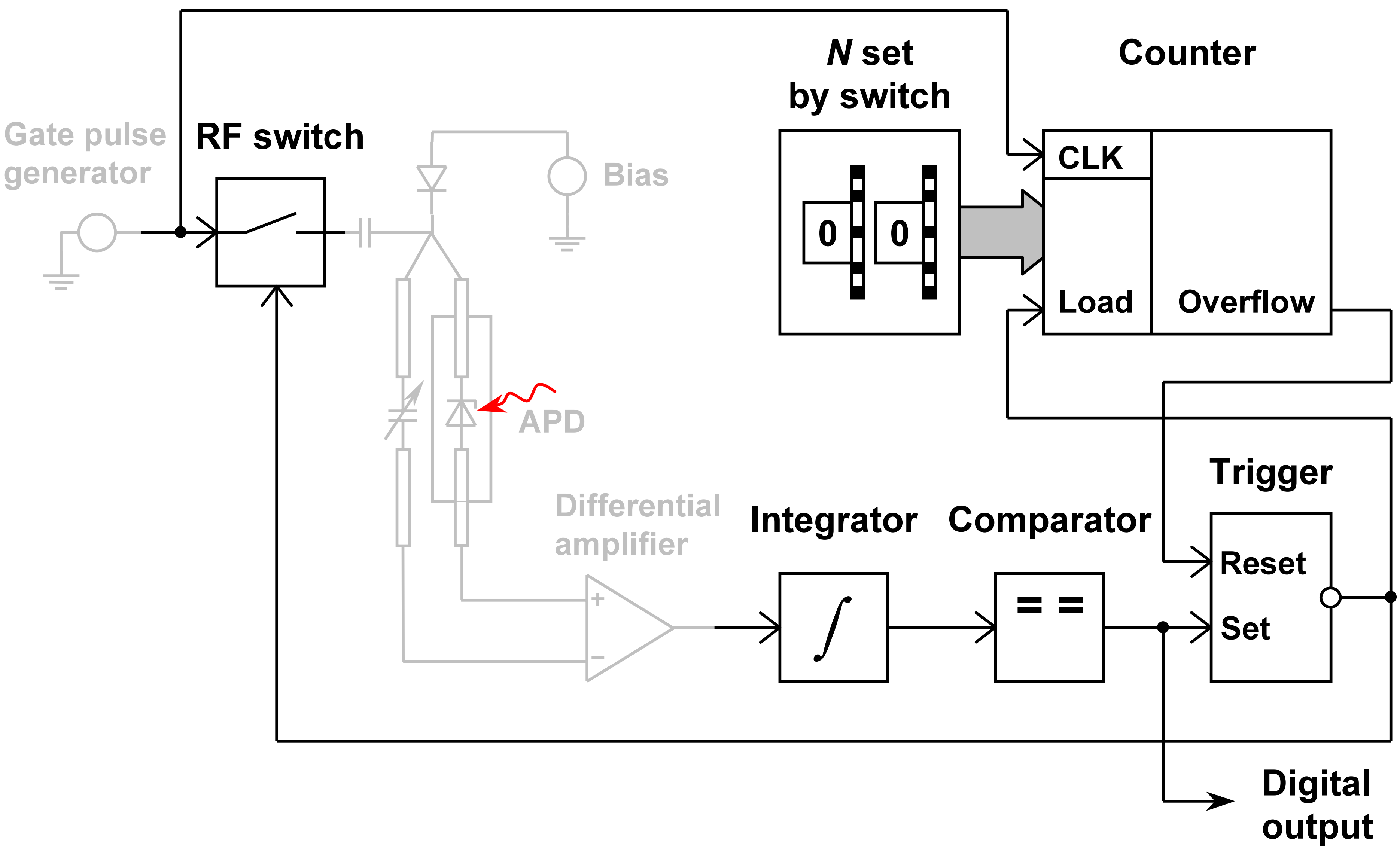
Afterpulse blocking



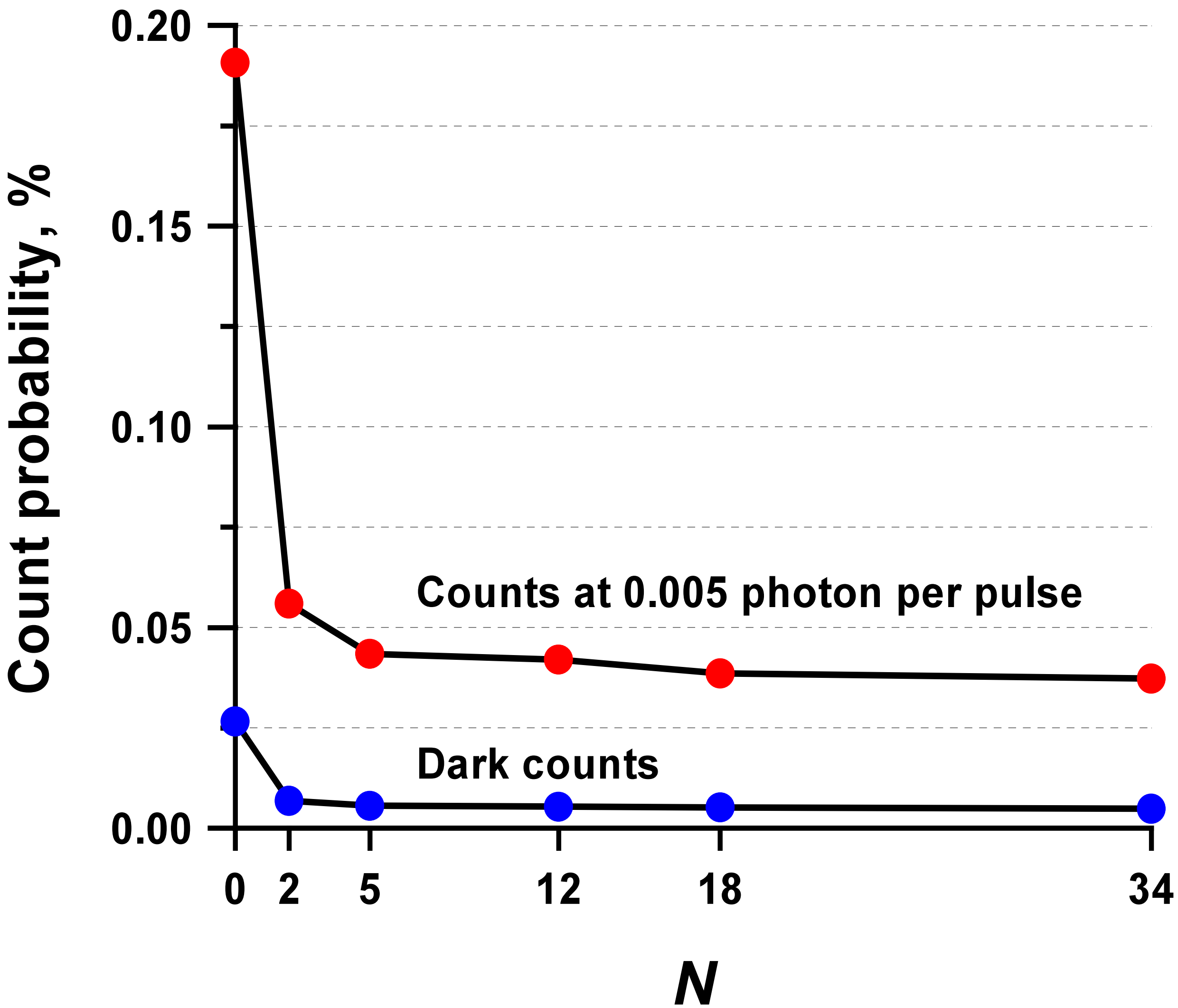
In QKD systems, probability of detecting a photon per pulse is always much lower than 1 (e.g., ~1/1000). This makes afterpulse blocking efficient, allowing without much loss in detection probability:

- **In our QKD system: 20 MHz gate pulse rate**
- **In principle: a few orders of magnitude faster gate pulse rate**

Hardware implementation of afterpulse blocking



Test of afterpulse blocking



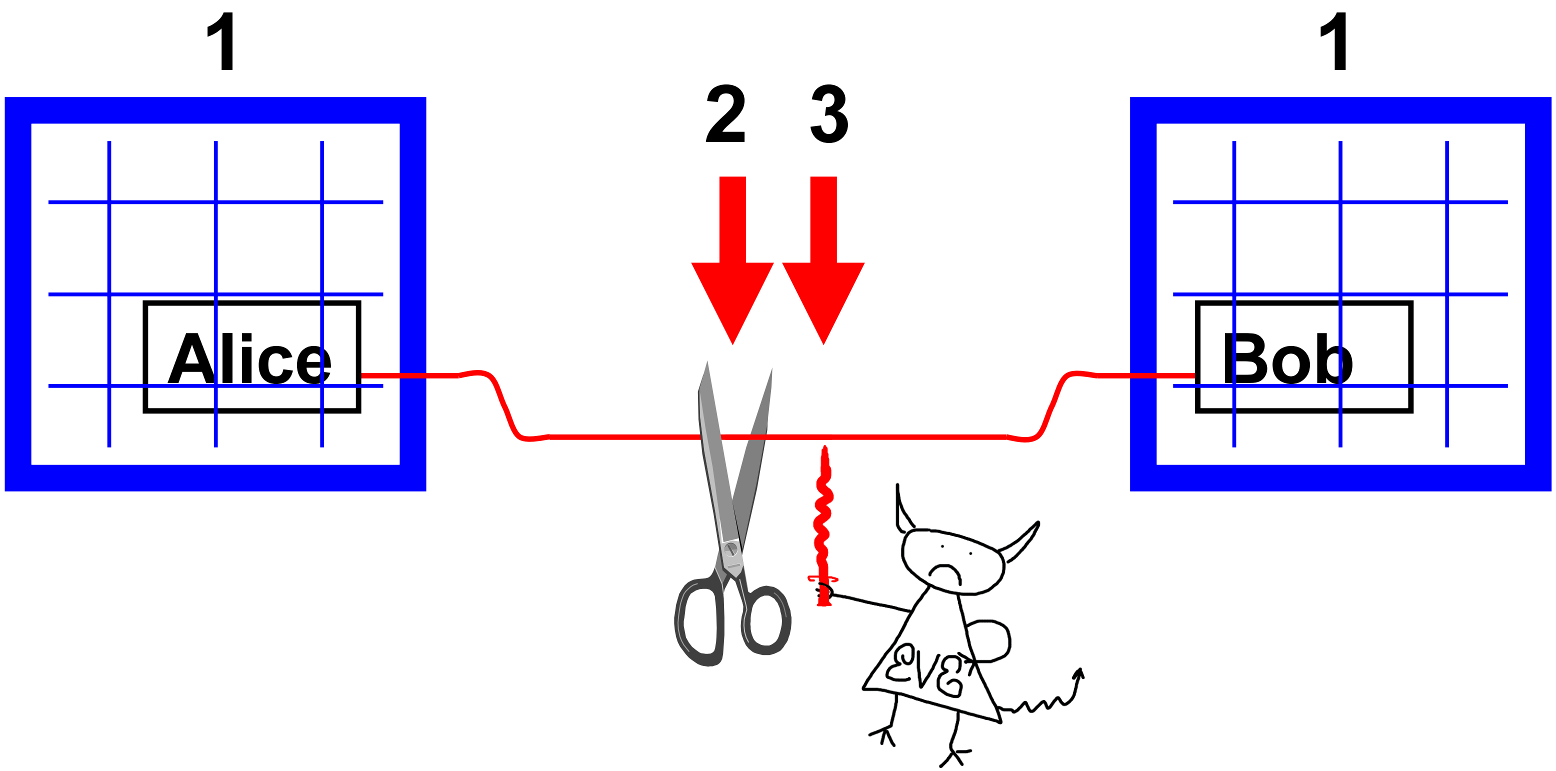
APD: Ge FD312L

Gate pulse rate = 12 MHz

QE = 7%

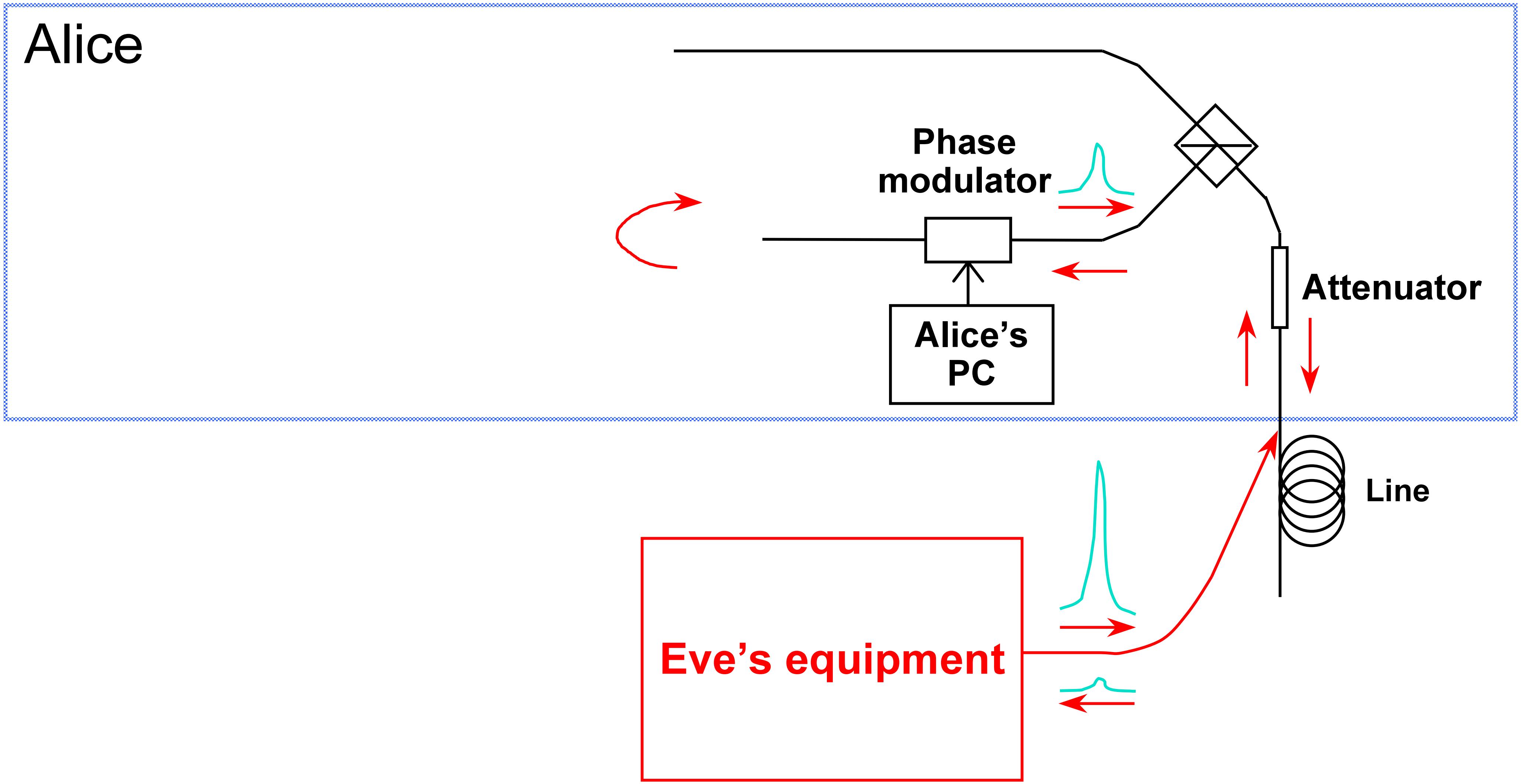
T = 77K

Quantum key distribution: components of security



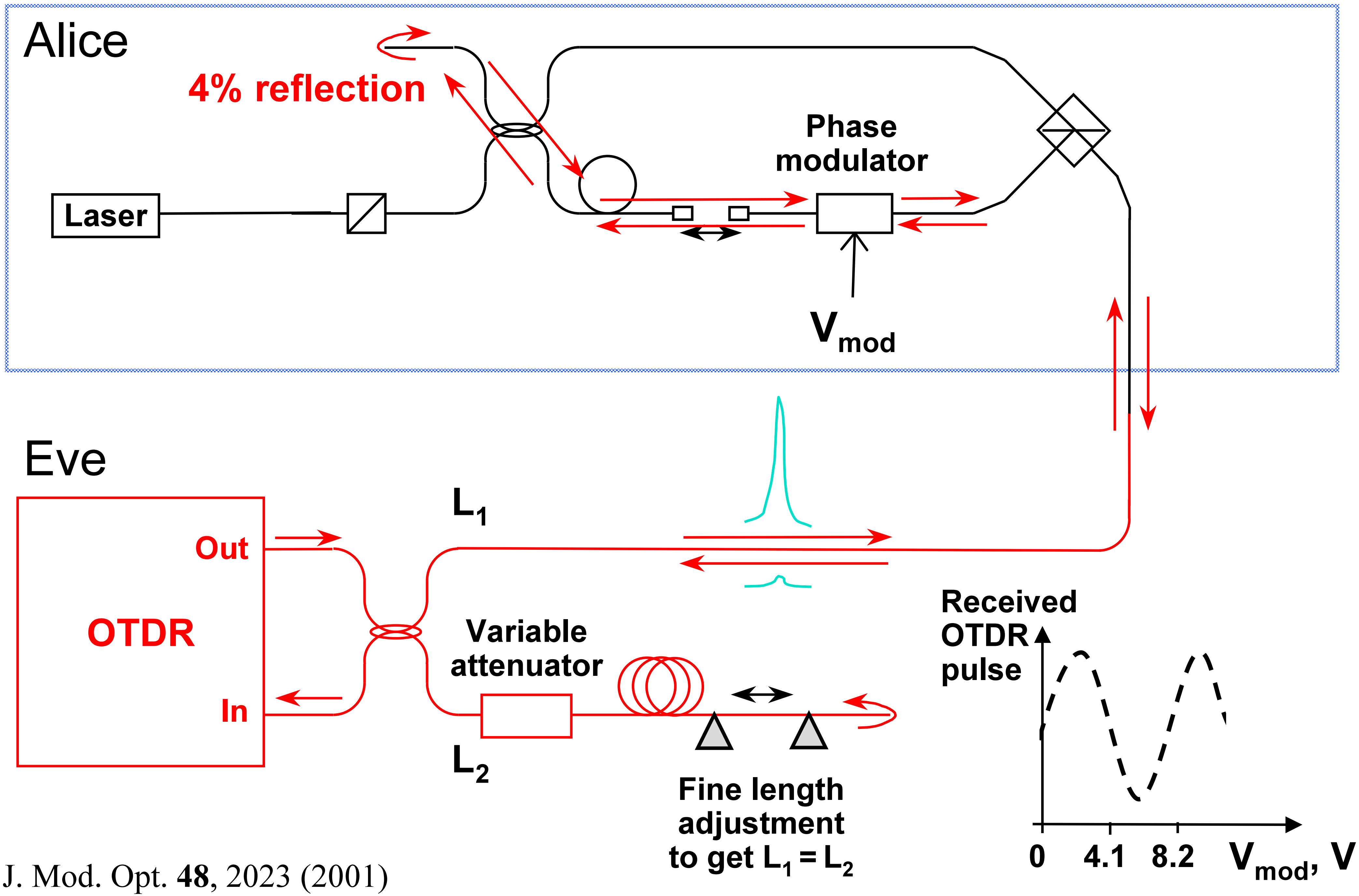
1. Conventional security; trusted equipment manufacturer
2. Security against quantum attacks
   – security proofs for idealized model of equipment
3. Loopholes in optical scheme
   – imperfections not yet accounted in the proof

Large pulse attack



– **interrogating Alice's phase modulator with powerful external pulses (can give Eve bit values directly)**

Large pulse attack: experiment



J. Mod. Opt. **48**, 2023 (2001)

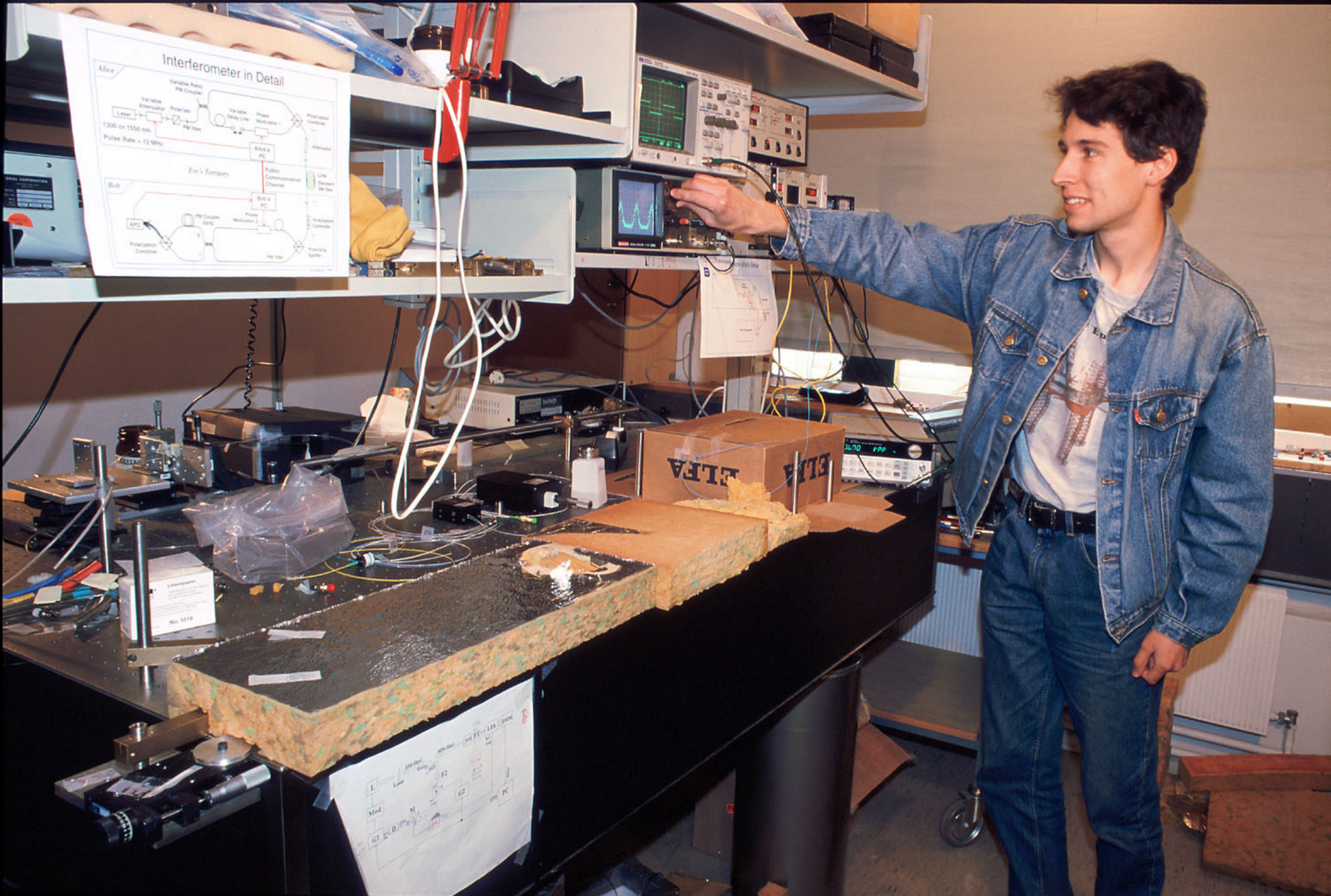
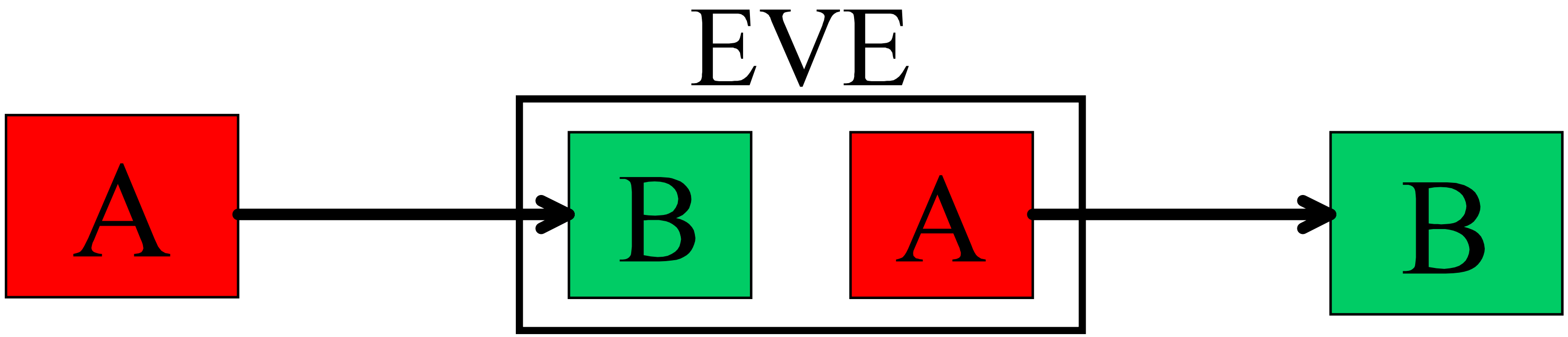


Photo 3. **Artem Vakhitov tunes up Eve's setup**

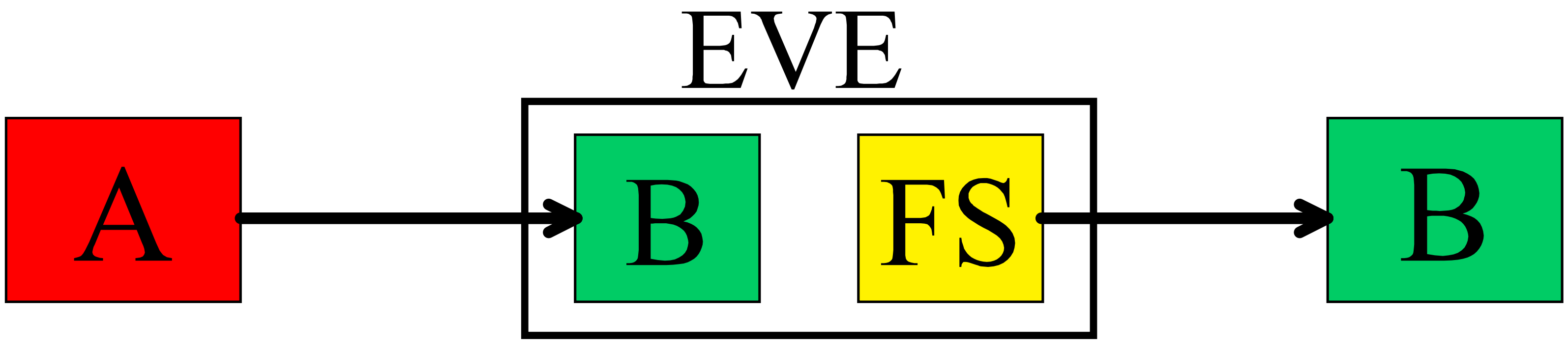
Faked states attack

Conventional intercept-resend:



ALARM!!!

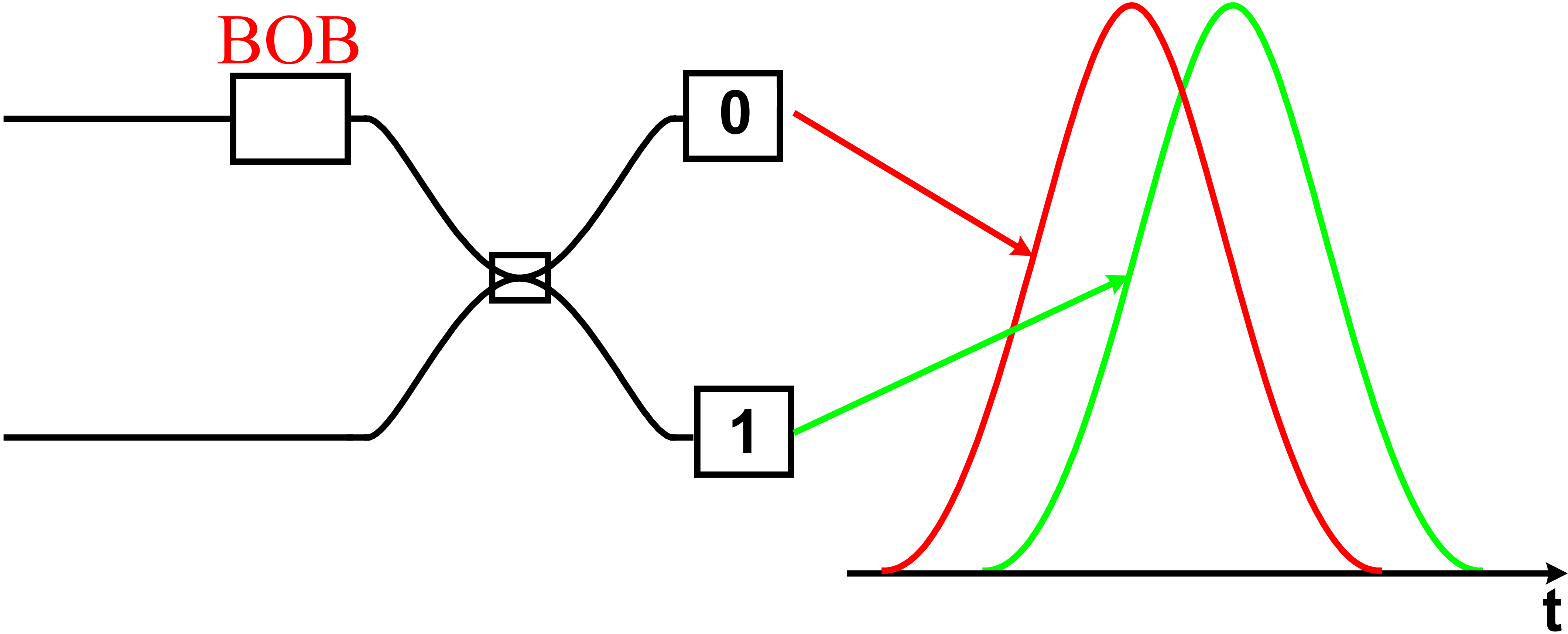
Faked states attack:



(no alarm)

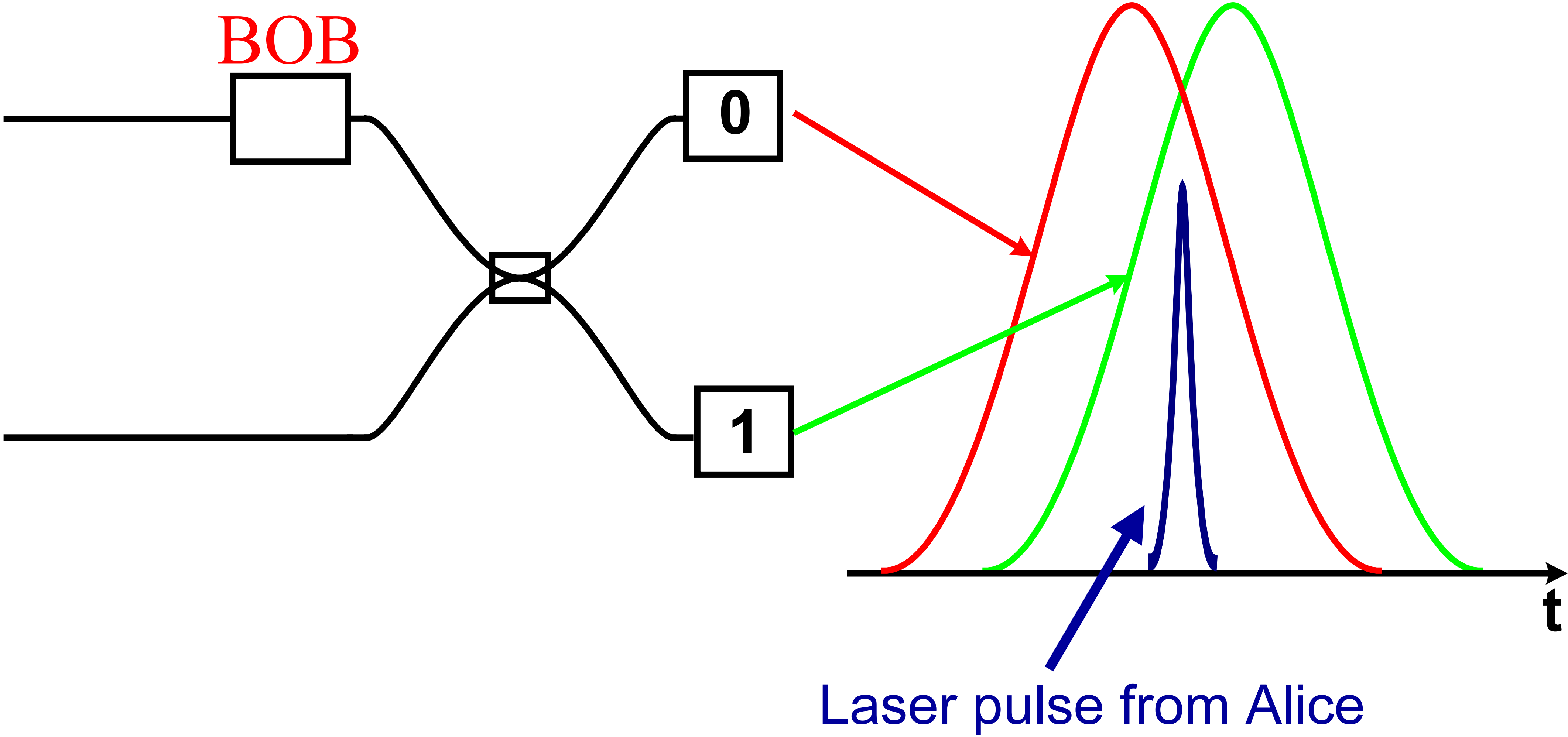
J. Mod. Opt. **52**, 691 (2005)

Exploiting common imperfection: detector gate misalignment



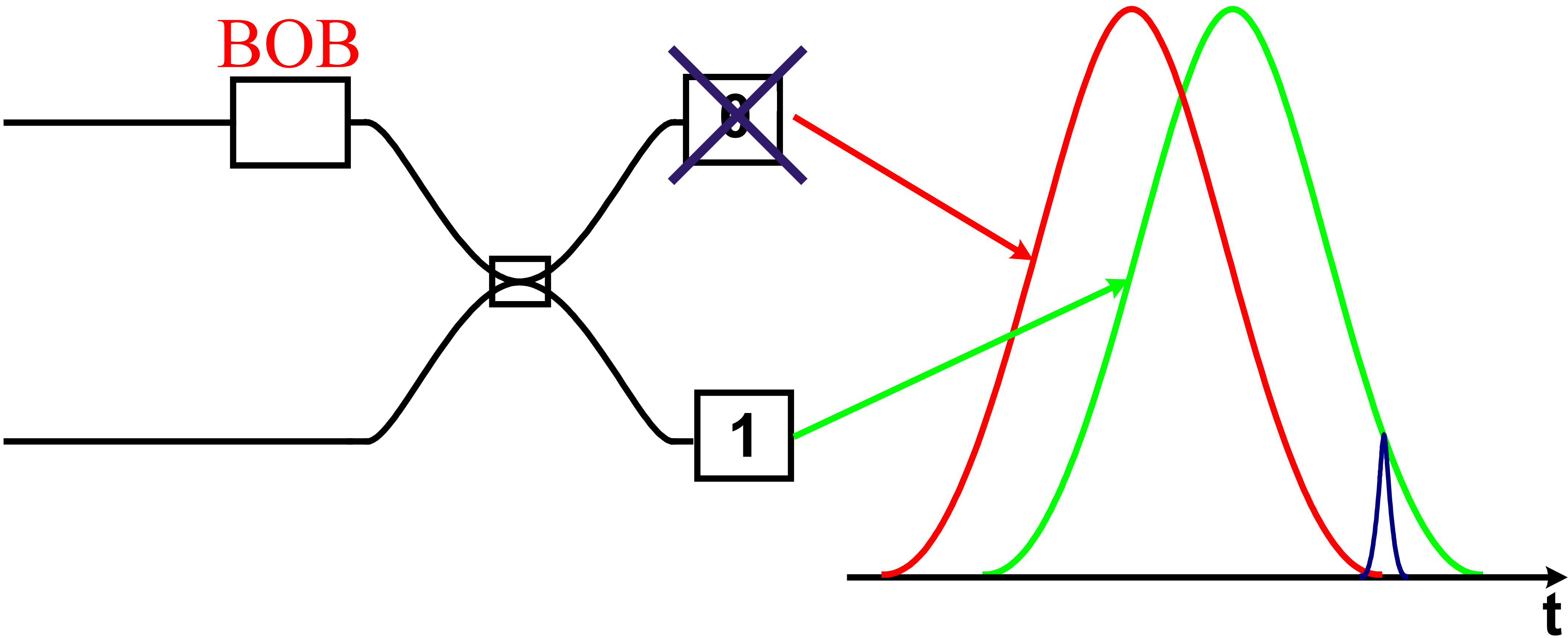
Phys. Rev. A **74**, 022313 (2006)

Detector gate misalignment



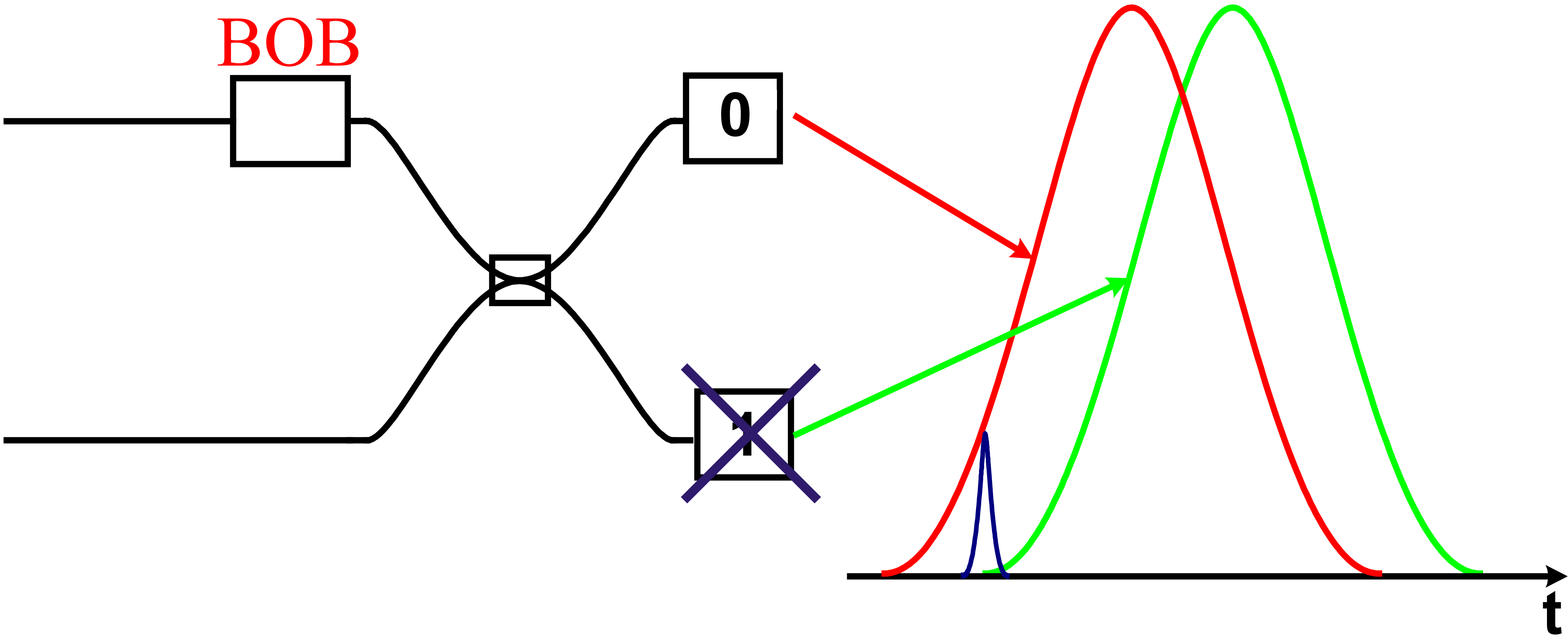
Phys. Rev. A **74**, 022313 (2006)

Detector gate misalignment



Phys. Rev. A **74**, 022313 (2006)

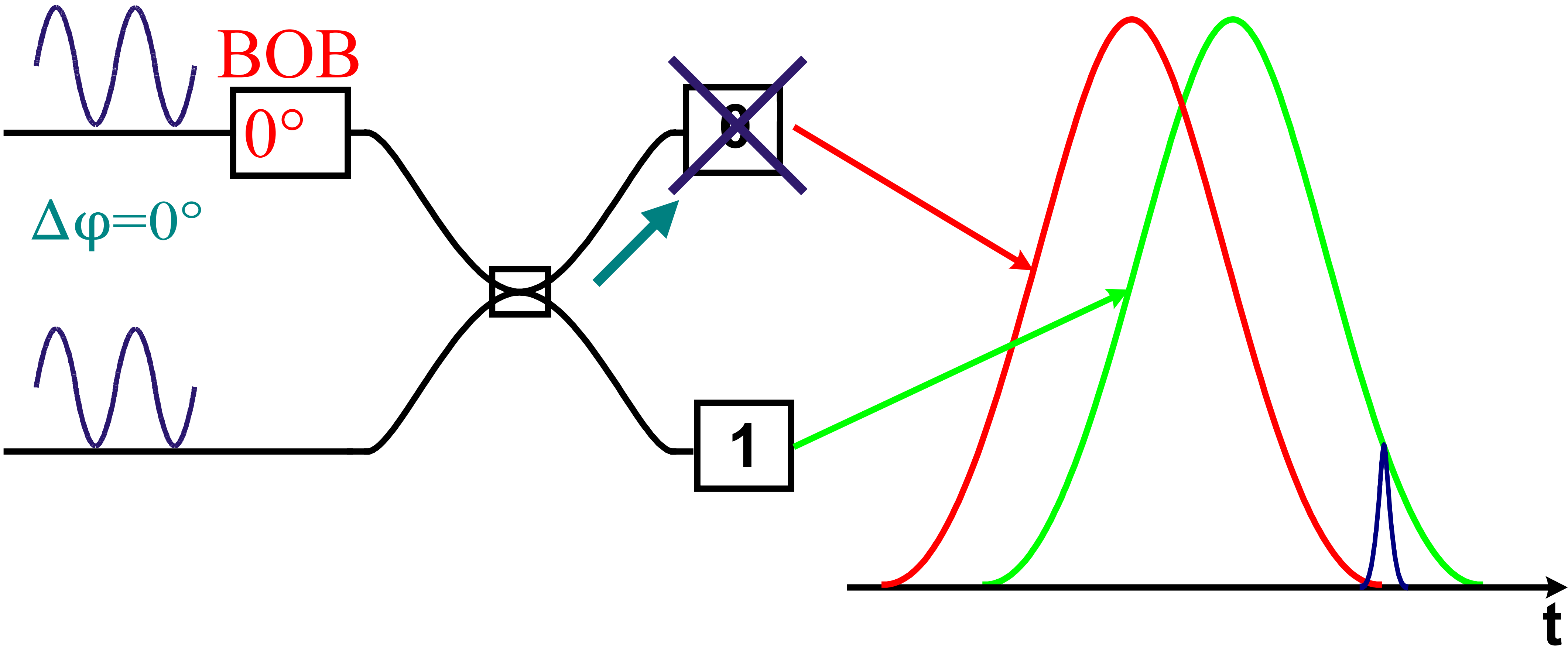
Detector gate misalignment



Phys. Rev. A **74**, 022313 (2006)

Detector gate misalignment

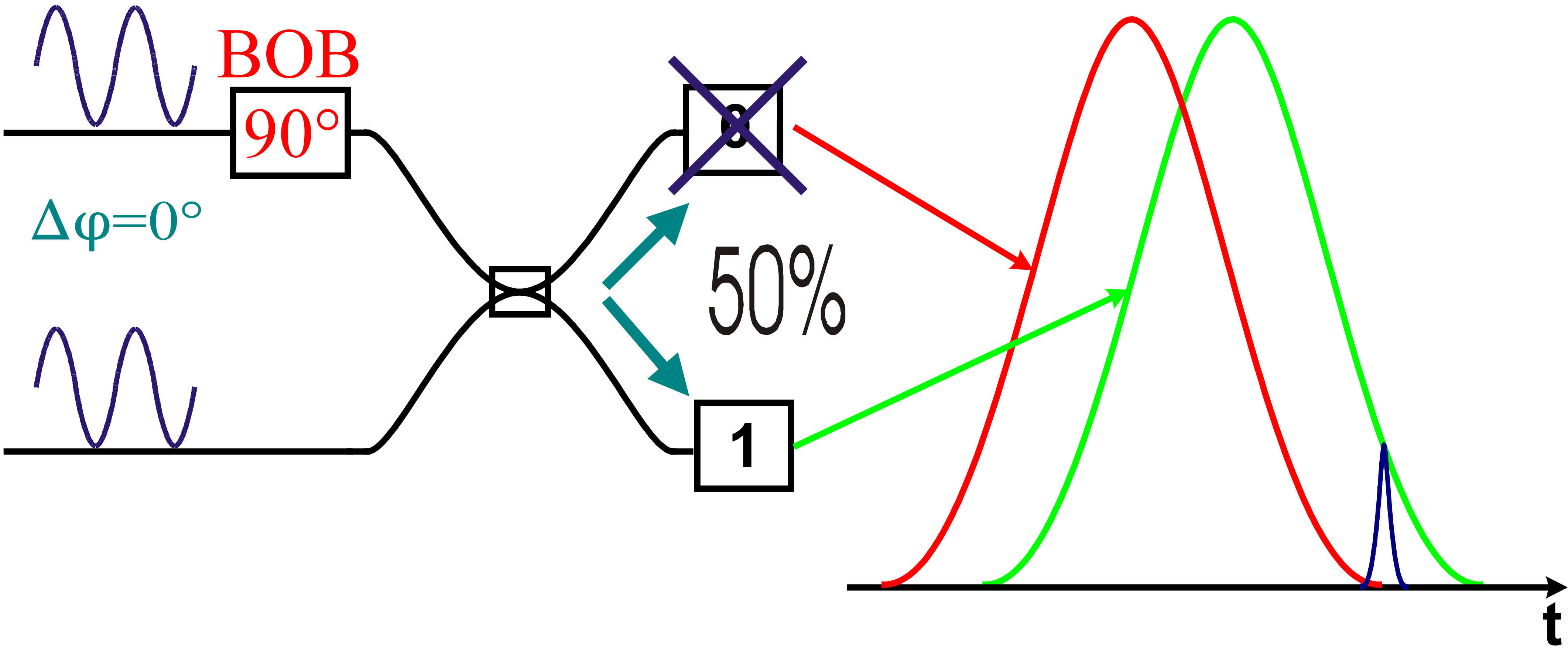
Example: Eve measured with basis Z (90°), obtained bit 1



(Eve resends the opposite bit 0 in the opposite basis X, shifted in time)

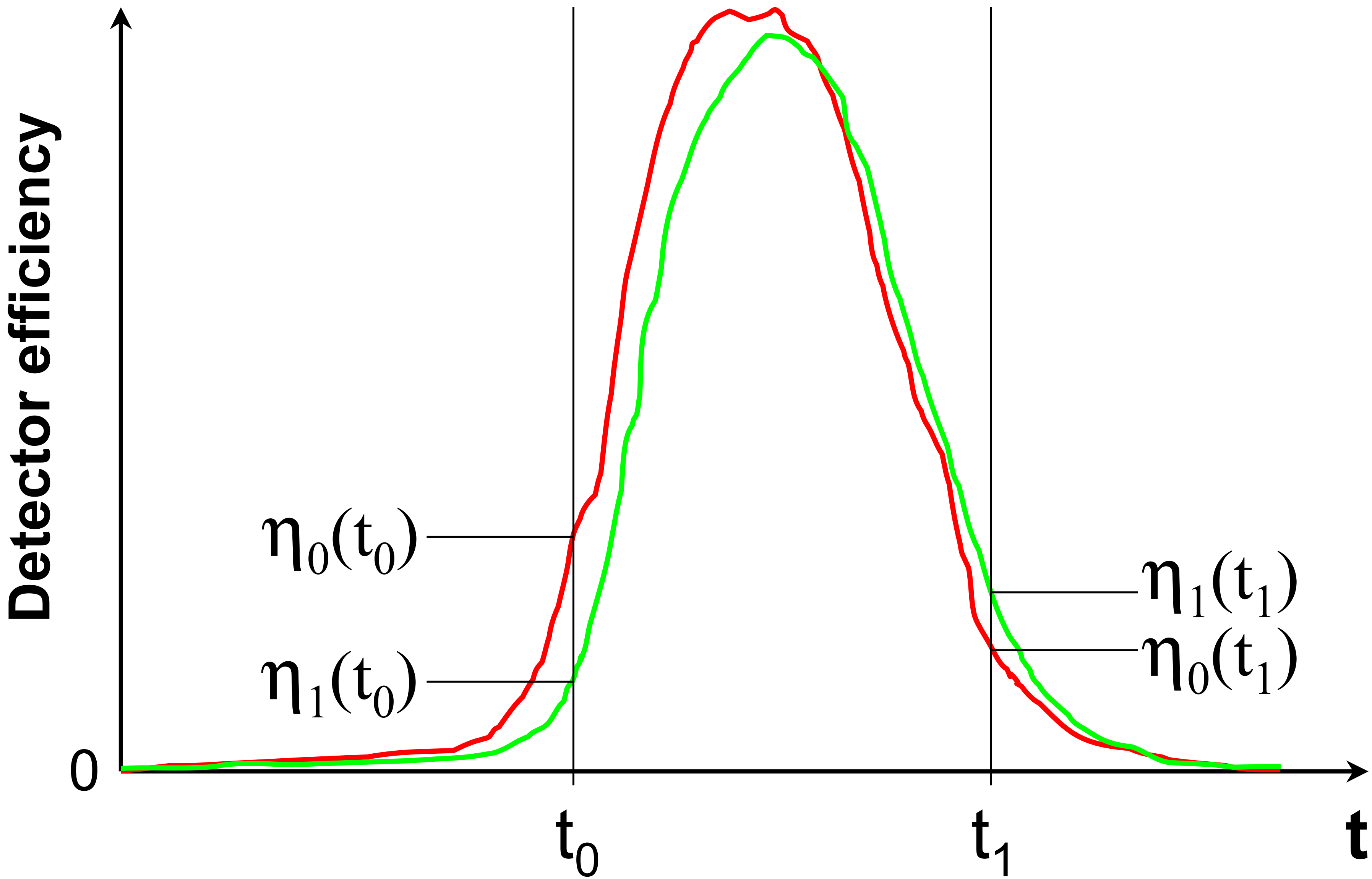
Detector gate misalignment

Example: Eve measured with basis Z (90°), obtained bit 1



- ✓ Eve's attack is not detected
- ✓ Eve obtains 100% information of the key

Partial efficiency mismatch



Partial efficiency mismatch

A. Practical faked states attack:

$$\mathrm{QBER} = \frac{P(\text{error})}{P(\text{arrive})} = \frac{2\eta_0(t_1) + 2\eta_1(t_0)}{\eta_0(t_0) + 3\eta_0(t_1) + 3\eta_1(t_0) + \eta_1(t_1)}$$

$\Rightarrow$ In the symmetric case (when $\eta_1(t_0)/\eta_0(t_0) = \eta_0(t_1)/\eta_1(t_1)$),
Eve causes less than 11% QBER if mismatch is larger than 1:15

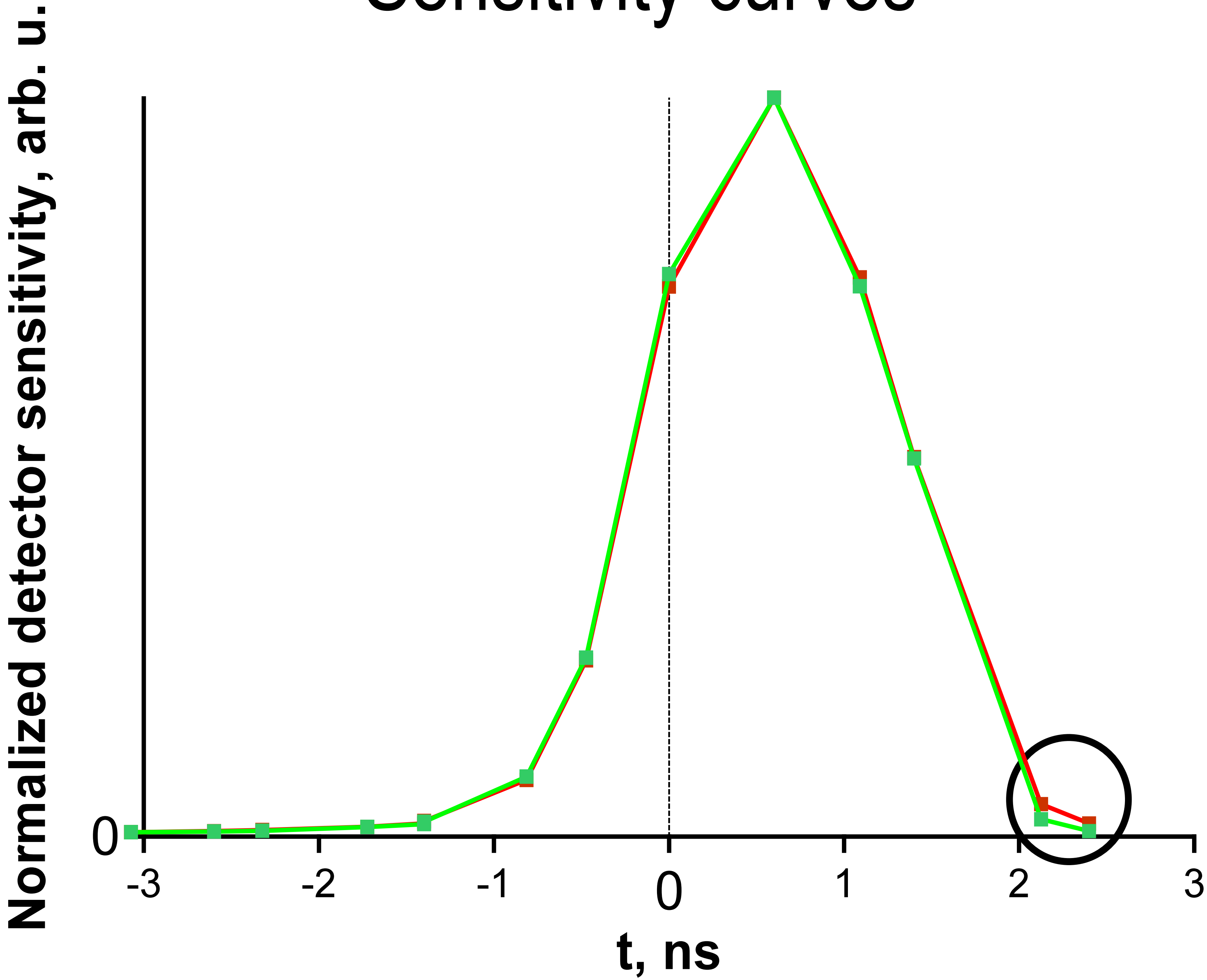
B. General security bound (incomplete):

$$\mathrm{QBER} = \frac{\eta\delta}{1 + \eta\delta - \delta} \approx \eta\delta,$$

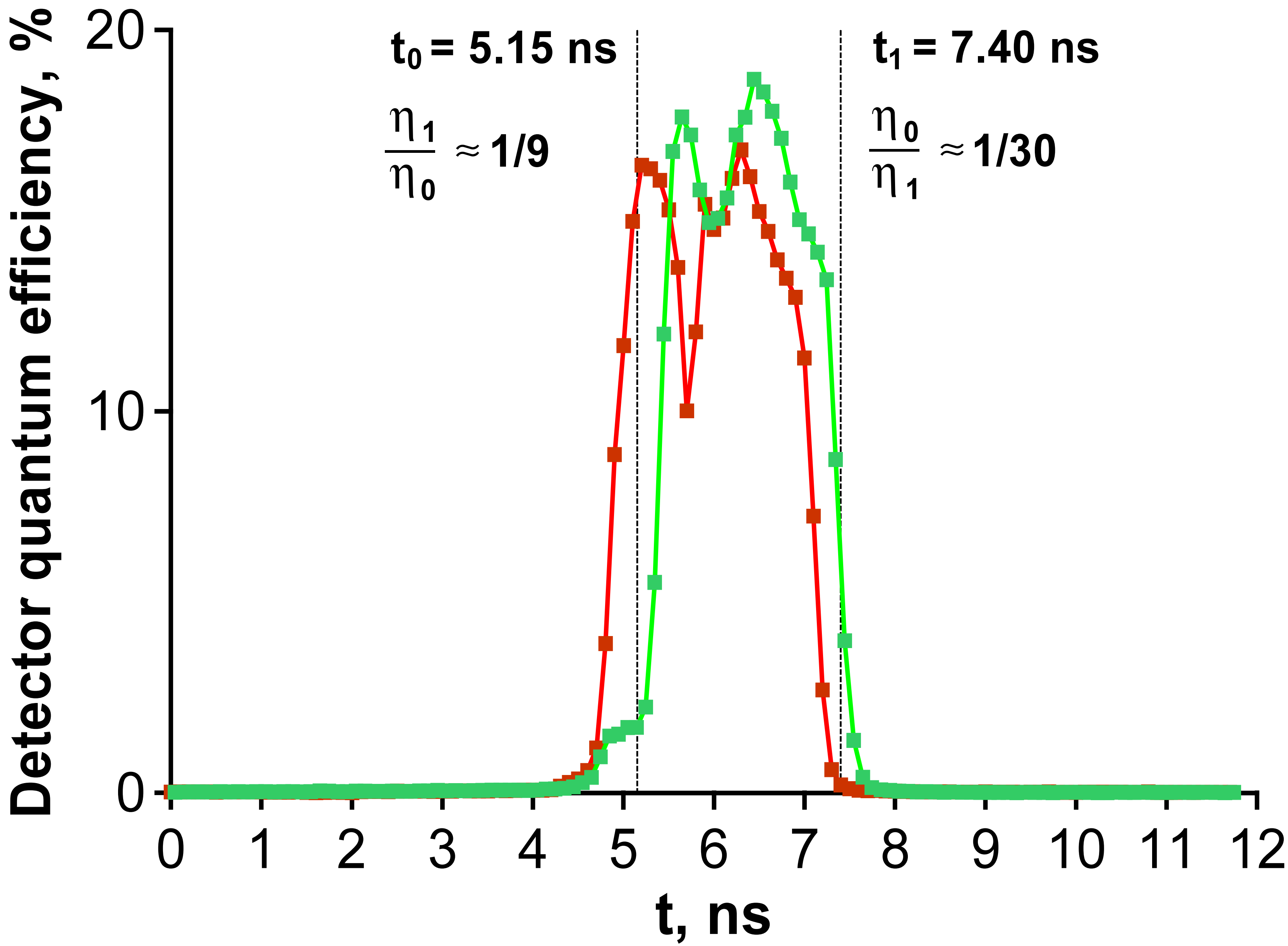
where

$$\eta = \min\left\{ \min_t \frac{\eta_1(t)}{\eta_0(t)}, \min_t \frac{\eta_0(t)}{\eta_1(t)} \right\}$$

Detector model 1.
Sensitivity curves



Detector model 2.
Sensitivity curves at low photon number μ=0.5



Detector efficiency mismatch

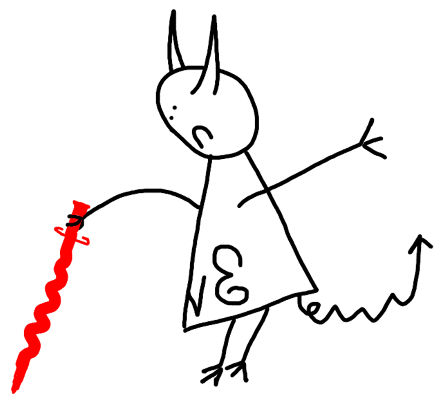
- **Detector efficiency mismatch is a problem for many protocols and encodings: BB84 (considered above), SARG04, phase-time, DPSK and Ekert protocols.**
  [quant-ph/0702262]

- **Control parameter *t* that changes detector efficiencies shall not be necessarily timing; it can be, e.g., wavelength or polarization.**

- **The worst-case mismatch, no matter how small, must be characterized and accounted for during privacy amplification.**

Conclusion

- **A phase tracking technique and detector with afterpulse blocking were successfully developed. (QKD was demonstrated with a very limited success.)**



- **Our group has built *unique expertise* in quantum cryptanalysis of attacks via optical loopholes. Several attacks have been proposed, studied in detail, and protection measures suggested.**

Possible future research

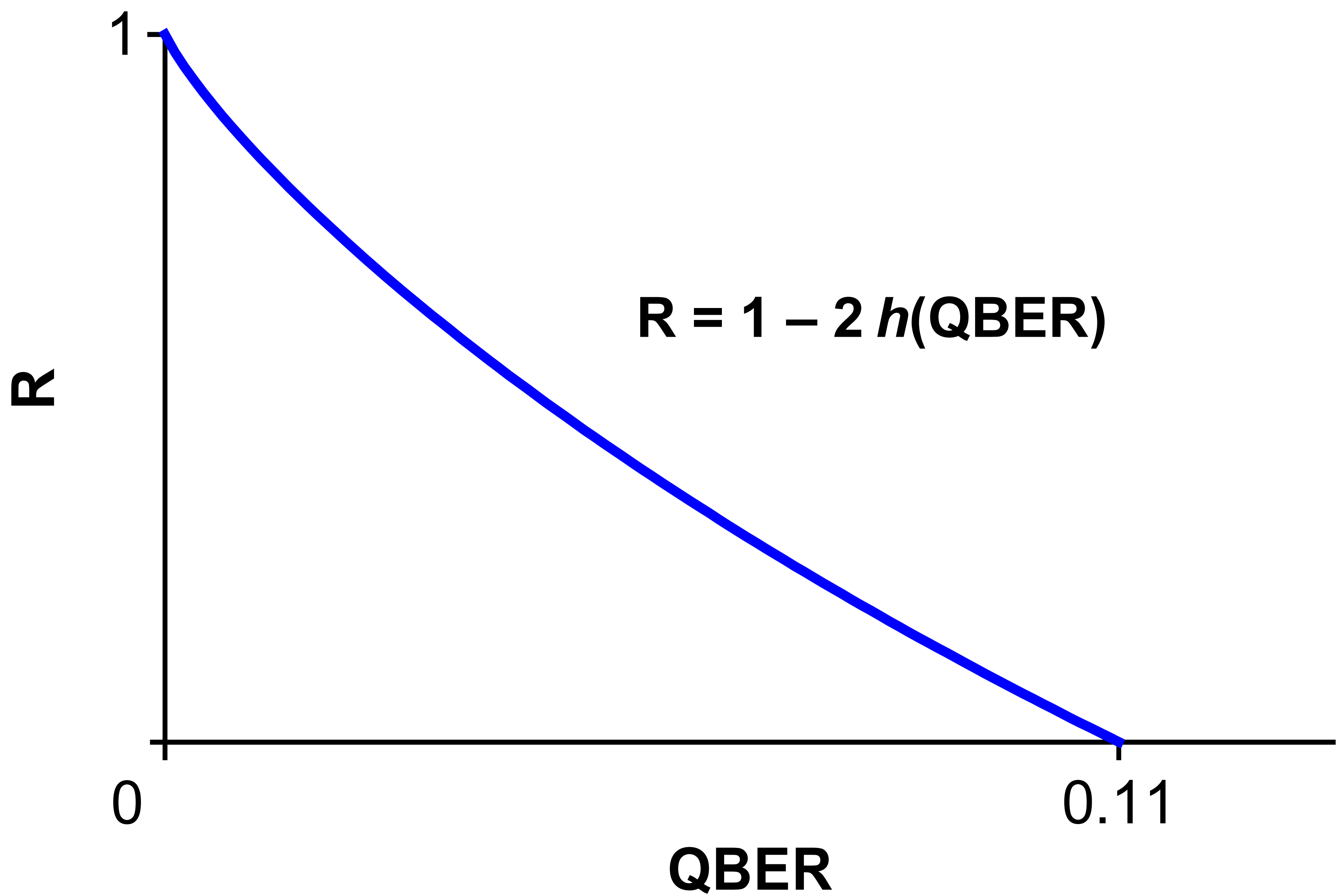
- **Continuing security studies beyond those presented in the thesis; we have experimented with passively-quenched Si APD; we are trying to incorporate detector efficiency mismatch into general proof... With sufficient financing, a study of high-power damage can be attempted.**

- **Improving the QKD experiment, demonstrating it over at least ~20 km distance. Performance of detector and phase tracking can be more accurately characterized.**

- **The QKD field is abound with novel ideas that can be tried...**

Optional slides

Handling errors in raw key



Commercial offers (as of late 2006)

MagiQ Tecnologies

USA

id Quantique

Switzerland

Standard VPN router + QKD equipment for frequent key changes

Several other companies also have the QKD technology, but are not selling yet

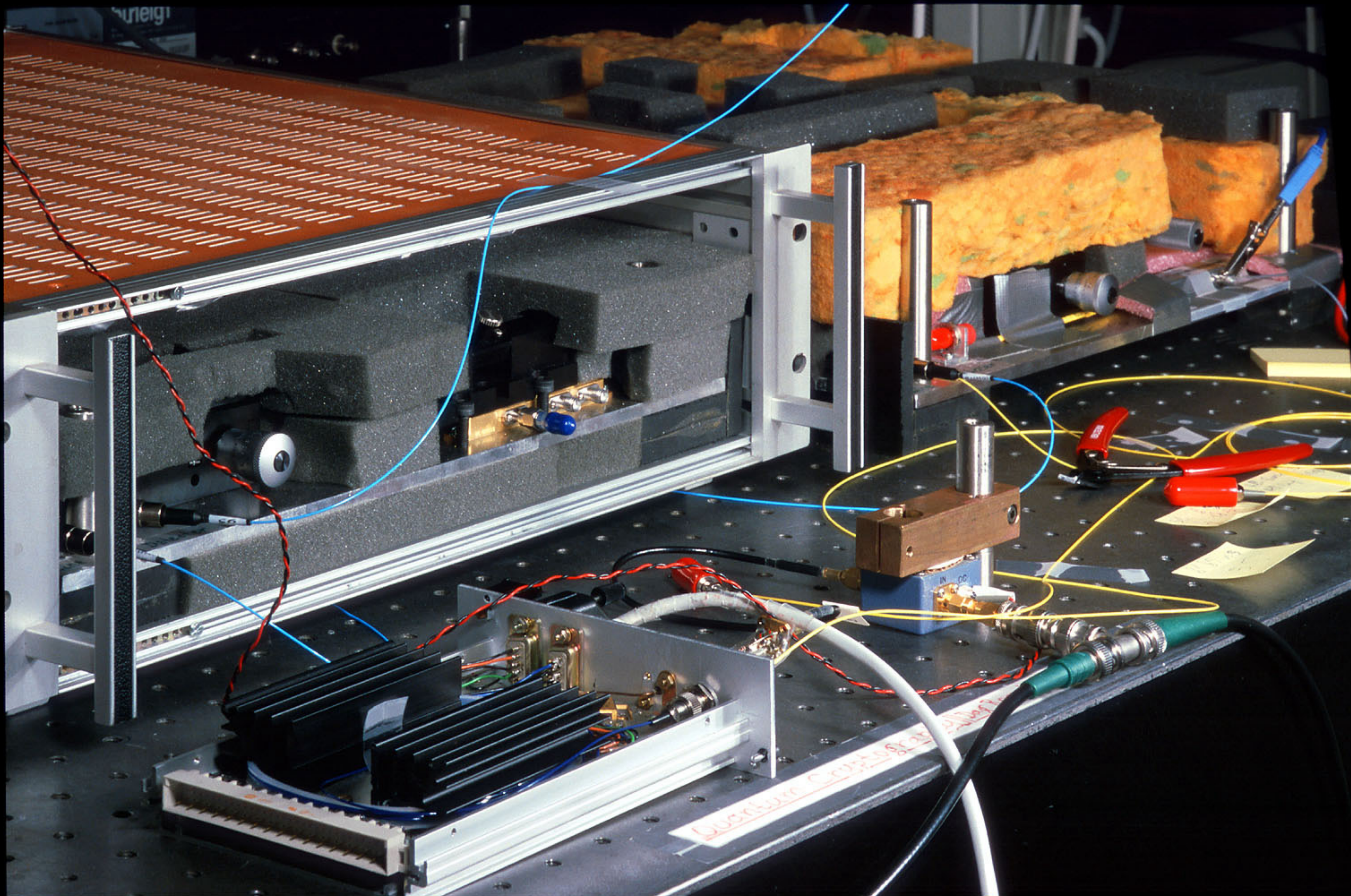
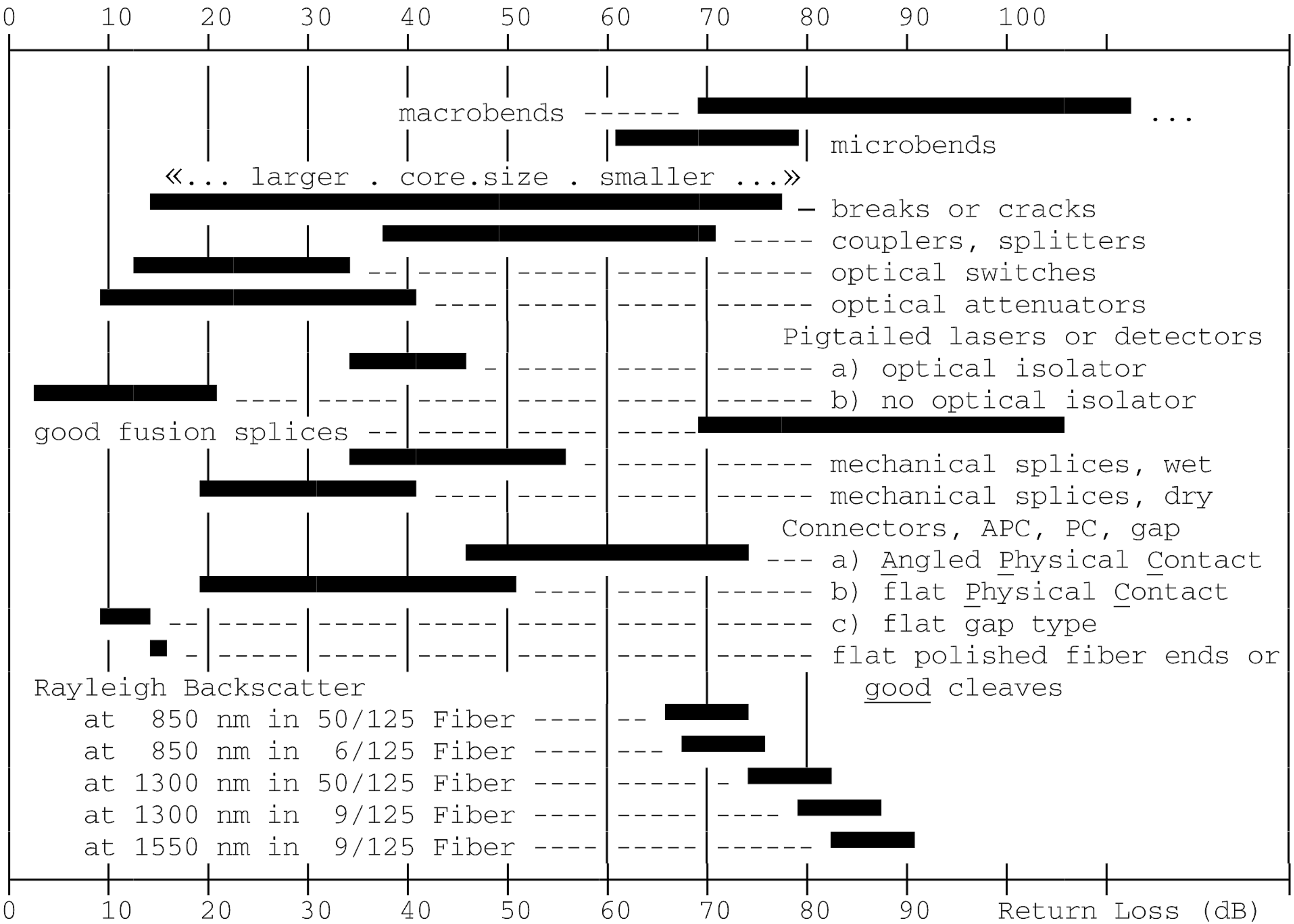


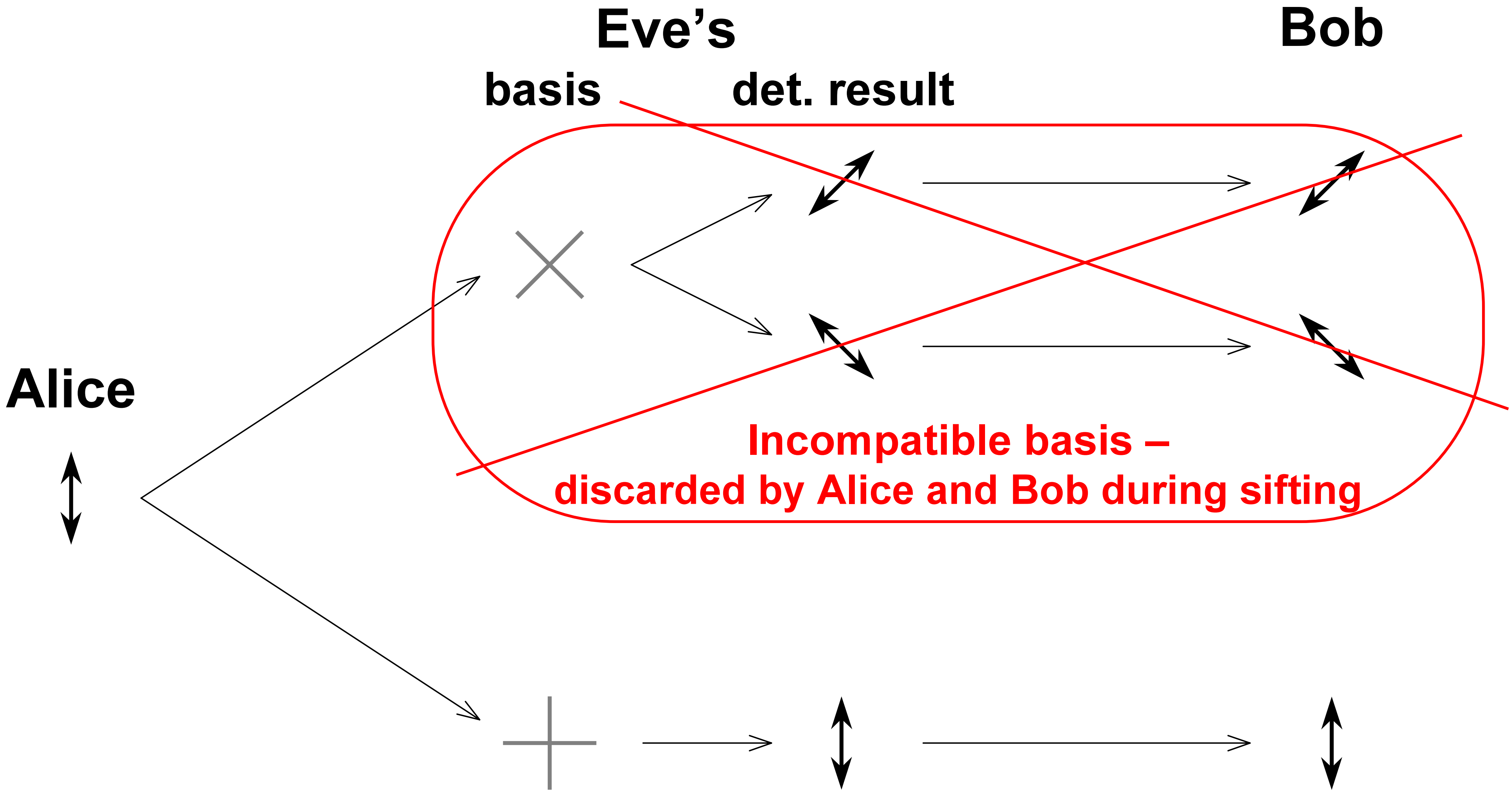
Photo 4. **Bob** (left) and **Alice** (right), thermoisolation partially installed



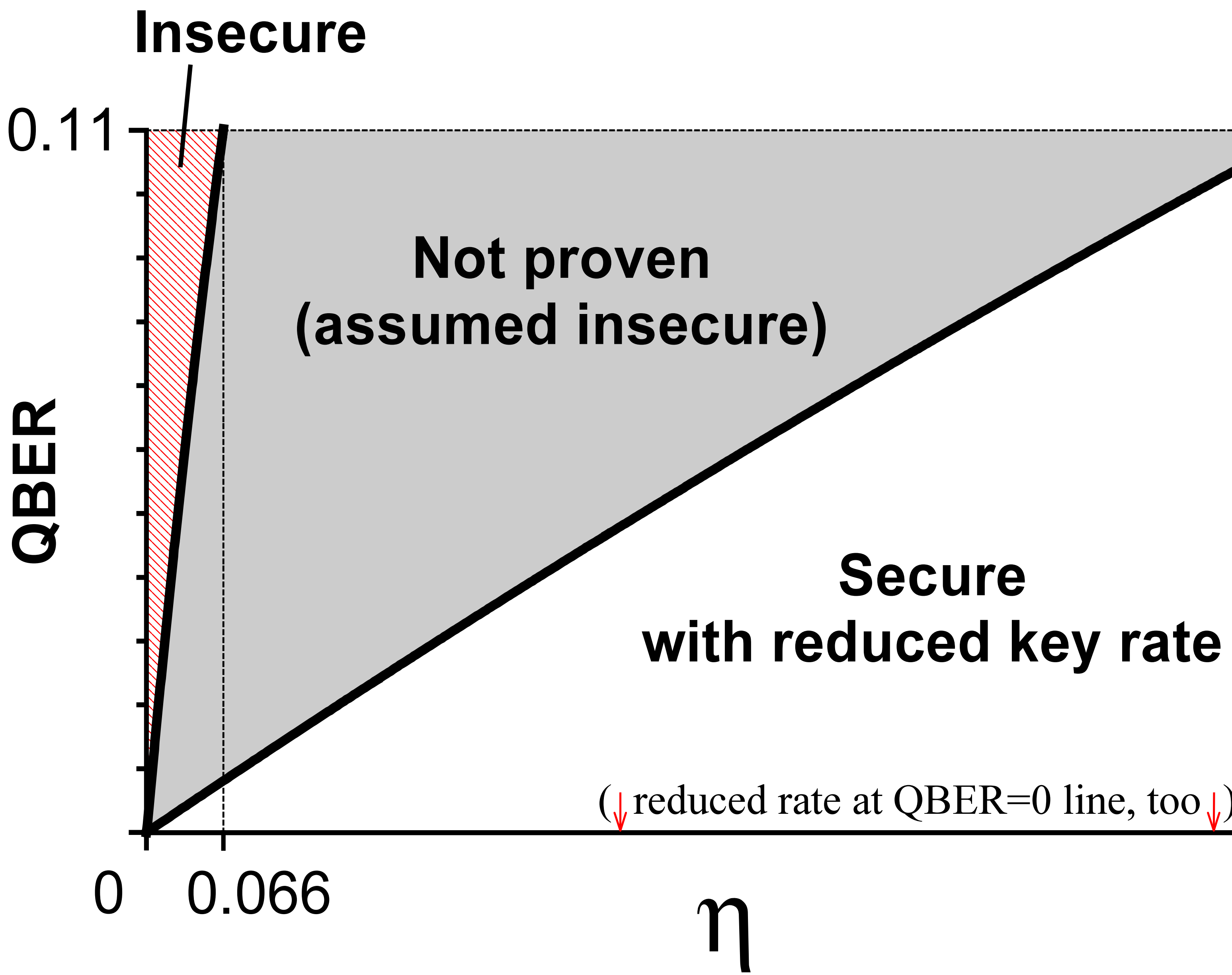
Typical values of reflection coefficients for different fiber-optic components

(courtesy Opto-Electronics, Inc.)

(Eve's basis = Bob's basis) is sufficient for eavesdropping



Security state of QKD system

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