2443-22

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

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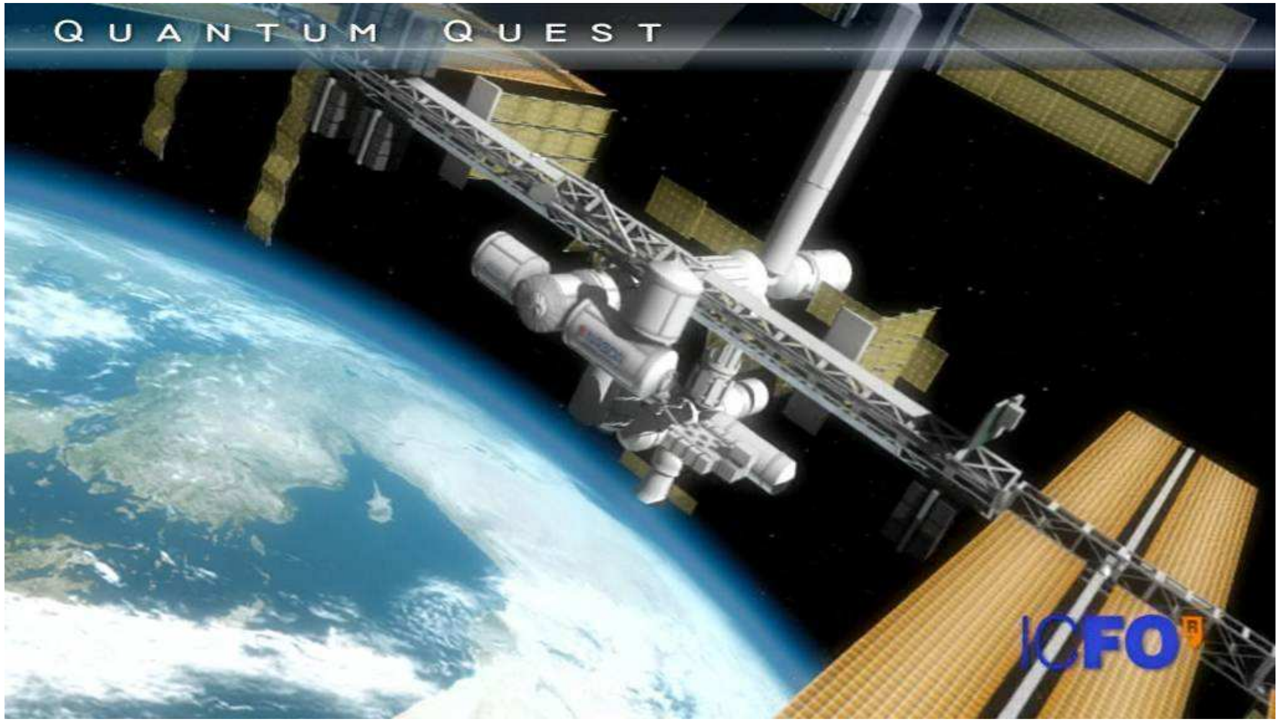
A Photonic Transceiver for Quantum Applications in Space

V. Pruneri
ICFO
Spain

Strada Costiera, 11 - 34151 - Trieste - Italy • Tel. +39 0402240111 • Fax. +39 040224163 • sci_info@ictp.it • www.ictp.it

A Photonic Transceiver for Quantum Applications in Space



Valerio Pruneri

Acknowledments: F. Steinlechner, M. Jofre, M. Mitchell

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Lecture outline:

Faint pulse sources (FPS) and Entangled Photons Sources (EPS) for quantum communication in space

- Quantum cryptography: BB84 + decoy states
- Quantum transceiver for space
- State-of-the-art FPS sources
- $LiNbO_3$ based FPS
- SOA-based FPS
- Quantum random number generators
- State-of-the-art EPS sources
- High-brightness crossed-crystal EPS
- Polarization-flipped linear round-trip EPS

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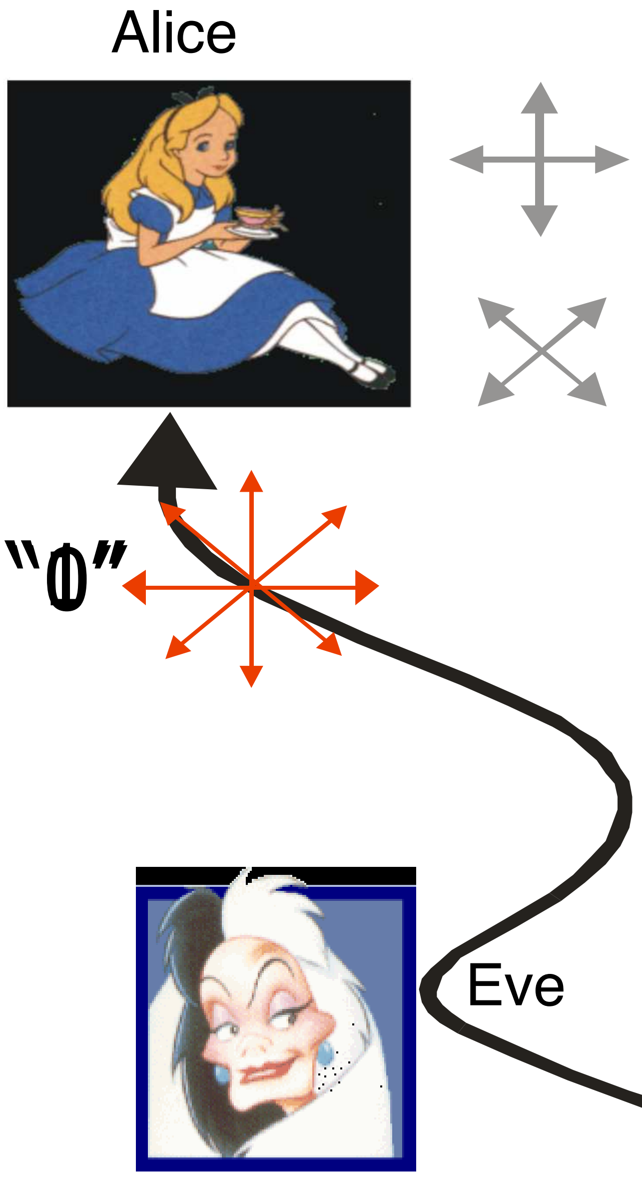
Quantum cryptography

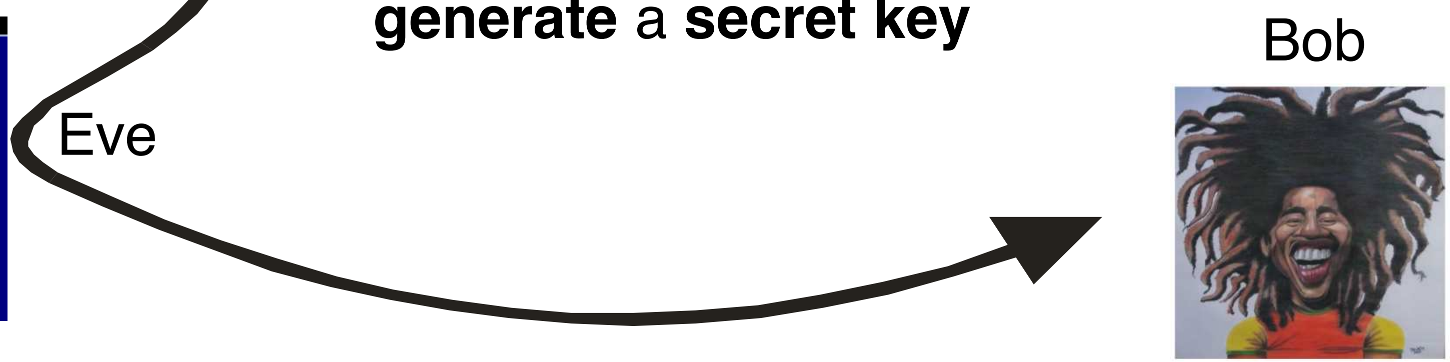


problem: E is evesdropping on A and B's communication

solution: use **secret key** to **encrypt communication** over public channel (one-time pad)

problem: how to distribute key (trust postal service?)

idea: use quantum mechanics to **generate** a **secret key**



Not just QKD…

- Quantum computation.
- Quantum digital signature.
- Quantum auctions.
- Quantum gaming.
- Quantum scheduling and optimization.
- Quantum metrology.
- Quantum imaging.

	Estimated market size[1]
Quantum encryption	$30m by 2008 $300m by 2015 *(pessimistic)* $3bn by 2015 *(assuming annual doubling, approx adoption 30,000 companies).)*
Quantum auctions	$100m through to 2010
	Estimated annual savings from QIP
Scheduling and optimisation	>$2bn *(conservative estimate)*
	Market sizes of areas which QIP can impact[2]
Quantum computing (QC)	
- "Small" quantum simulations	$1.15bn - *the US market for piezoelectric materials*
- Quantum modelling	$540m - *world market for computational flow dynamics software*
- "Large" quantum simulations	*Sell 3 quantum computers at $100m to $10bn each. Expected market: military and national research institutes.*
Spin-offs from QC developments	
- Spintronics	>$100bn - *estimated market value of spintronics*
- MRI	$1.2bn - *estimated market value of MRI contrast-enhancers*
Quantum gaming	$18bn - *current market value of online gaming*
Quantum metrology	
- GPS	$21.5bn - *estimated 2008 market value for GPS technology*
- Precision engineering	$5.6bn - *estimated 2009 market value for photonic components*
- Optical storage	$30.7bn - *estimated 2010 market value for optical data storage*
- Biomedical imaging	$2.6bn - *current market value for ophthalmic diagnostics*

[1] *All figures are in US$*
[2] *From estimated market sizes of comparable conventional analogues*

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Why quantum sources in space?

- Optical fiber losses and photon-detector technology limits QC on Earth to 200 km.
- These problems are less severe in space (line-of-sight limitation).

Technology	Current properties	Future Properties (2020)
Free-space (satellite)	• No commercial suppliers • Distance limit 20km • Limited to line of sight & good weather conditions • Point-to-point only	• Global QKD network • Mobile nodes possible • High fixed cost (satellite required) • Comparable marginal cost to fibre
Fibre	• 3 commercial suppliers • Distance limit 150km • Requires fibre link • Point-to-point only	• Long-distance network capabilities, distance limited by fibre connections • Lower fixed costs, hence lower barriers to entry by competitors

- ***To achieve***
  - New possibilities and unprecedented versatility in communications.
  - Quantum Mechanics over >1000 km.

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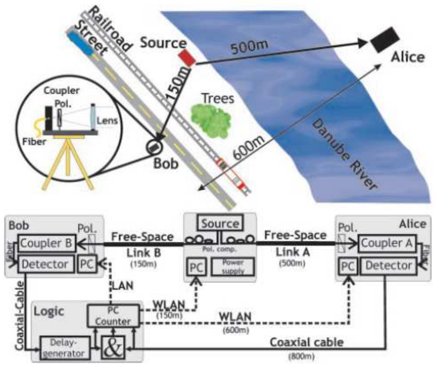
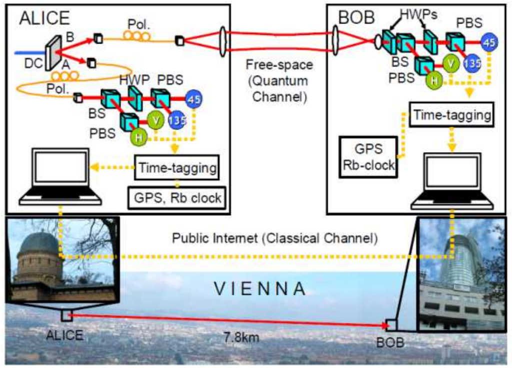
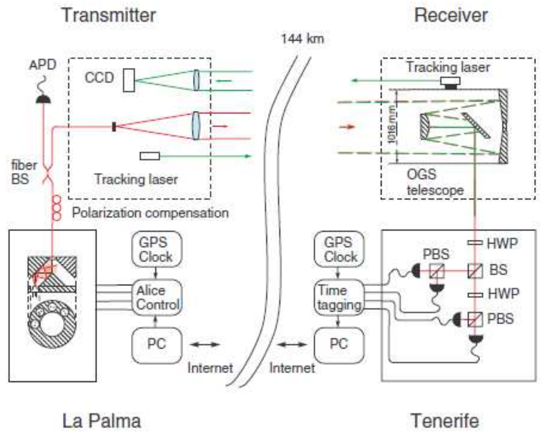
State-of-the-art: Free-space QKD



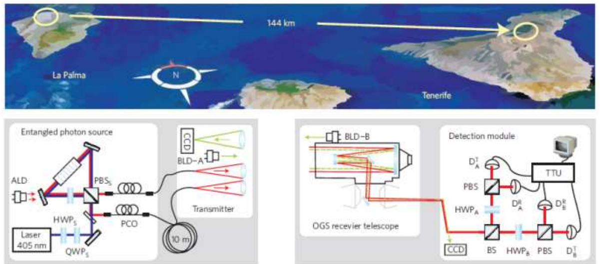
M. Aspelmeyer et al.,
Science 301, 621-623 (2003)



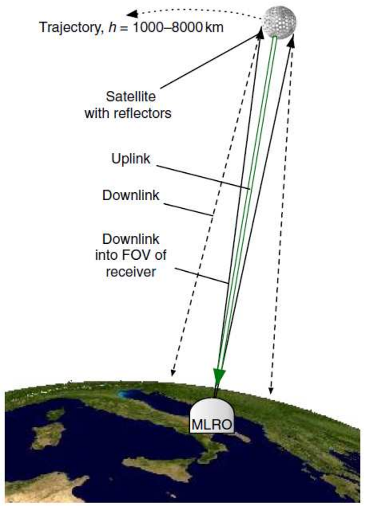
K. Resch et al.,
Opt. Exp. 13, 202-209 (2005)



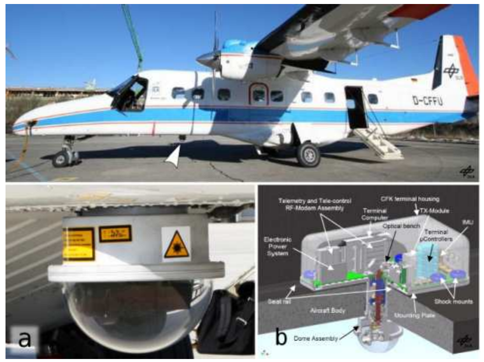
T. Schmitt-Manderbach et al.,
Phys. Rev. Lett. 98, 010504 (2007)



R. Ursin et al.,
Nature Physics 3, 481-486 (2007)



P. Villoresi et al.,
NJP 10, 033038 (2008)



S. Nauerth et al.,
Proc. SPIE 8518 (2012)

Milestone
Satellite link

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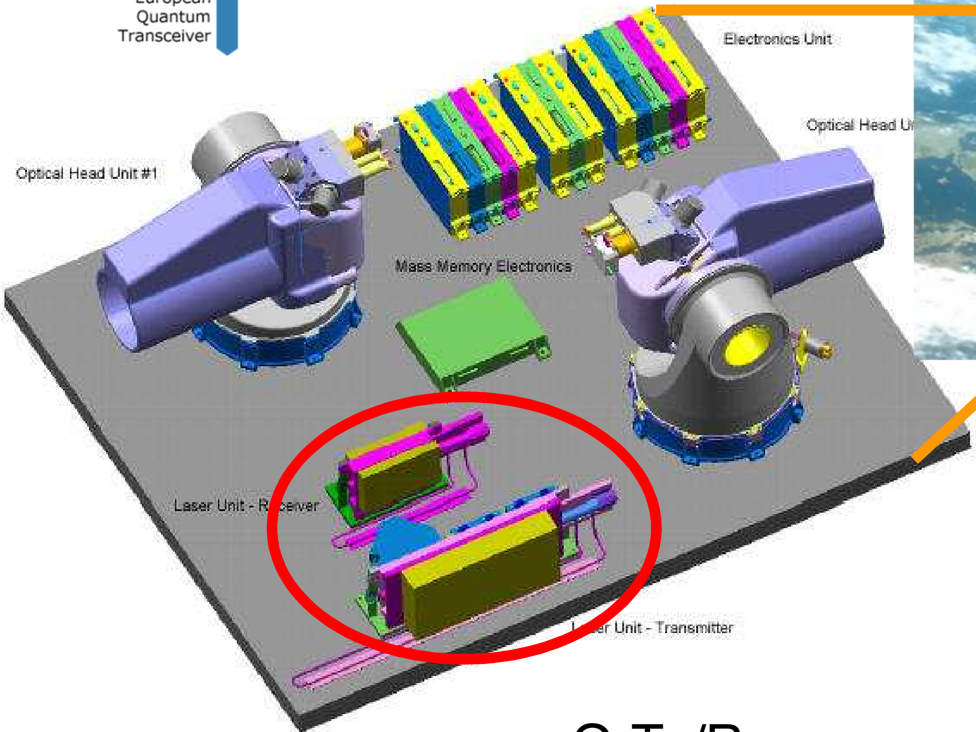
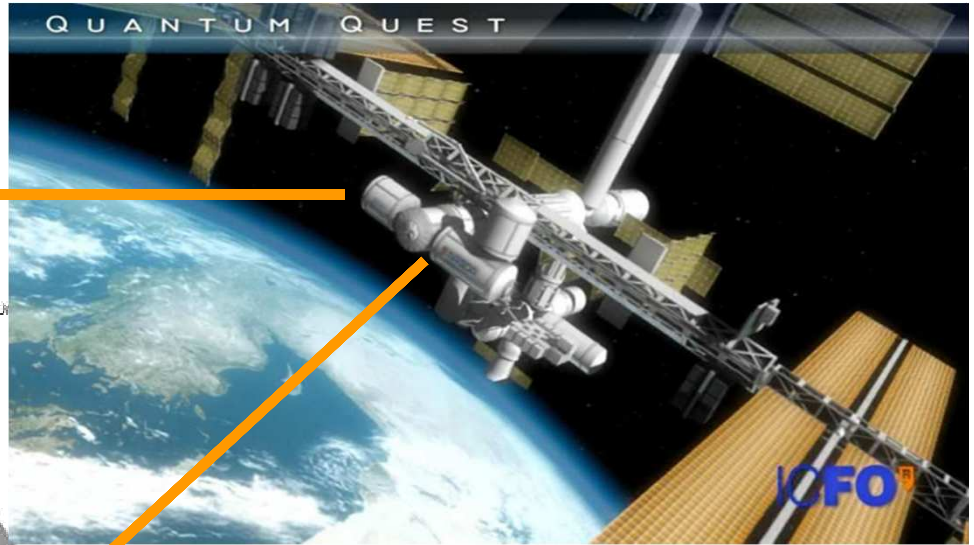
EQT - Quantum Transceiver for Space

EQT
European
Quantum
Transceiver





Q-Tx/Rx

Main features Q-Tx/Rx:

-Faint pulse source (FPS) + entangled photon source (EPS).

-Very low power consumption.

-High integration (small footprint).

-Space qualified.

European Space Agency Artes 5 ESTEC 21460/08/NL/IA

J.M. Perdigues Armengol,C. de Matos, “Accomodation of a quantum communication transceiver in an optical terminal”, Proceedings of the International Symposium OPTRO 2005.

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Extreme performance requirements

- General requirements
  - Total mass ≤ 3 kg (goal ≤ 2 kg)
  - Total size ≤ 200x150x100 mm^3 (goal ≤ 150x150x100 mm^3)
  - Total power consumption ≤ 15 W (peak) (goal ≤ 10 W peak)
- Optical requirements
  - Optical bandwidth ≤ 3 nm (goal 1nm)
  - Back to back detected coincidences rate > 10^5 (goal > 10^6)
  - Visibility > 95 % (in 0/90 and +45/-45 basis)
  - QBER < 2.5 % (goal < 1 %)
  - Detection probability > 40 % (goal > 50 %)
  - Weak pulses repetition rate > 10 MHz (goal > 100 MHz)
  - Dark counts < 100 counts/sec (goal < 500 counts/sec)
  - Timing resolution < 1nsec (goal < 0.5 nsec)
- Environmental constraints
  - Operational temperature range -35/+60 deg C
  - Storage temperature range -50/+75 deg C
  - Operational relative humidity range 5-85 %
  - Storage relative humidity range 5-95 %
  - Vacuum environment < 10^{-6} mbar
  - Vibration Resistant
  - Radiations
    - (Gamma) Total ionisation dose up to 150 krad (Si)
    - Displacement damage: cumulative fluence up to $2x10^{10}$ cm^{-2} (65 MeV protons)
    - Single Event Transient up to 60 MeV/mg/cm^{-2} (heavy ions)

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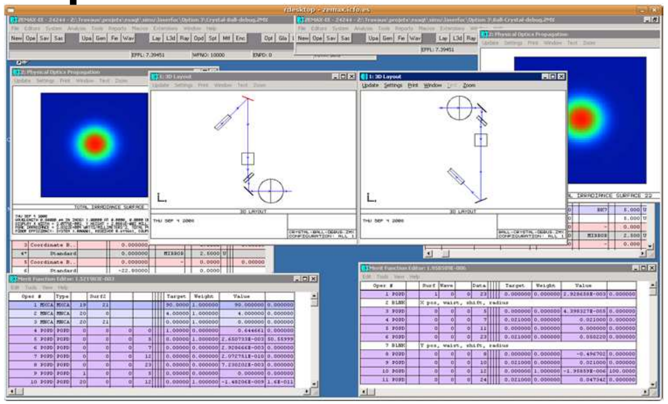
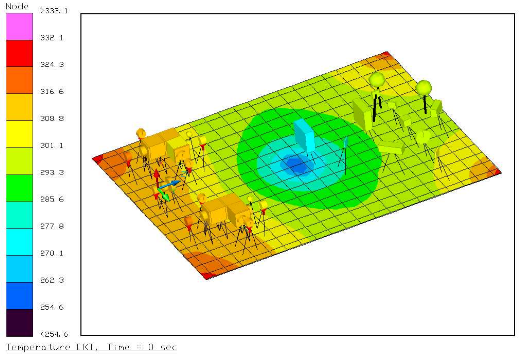
Collaboration requiring combined knowledge

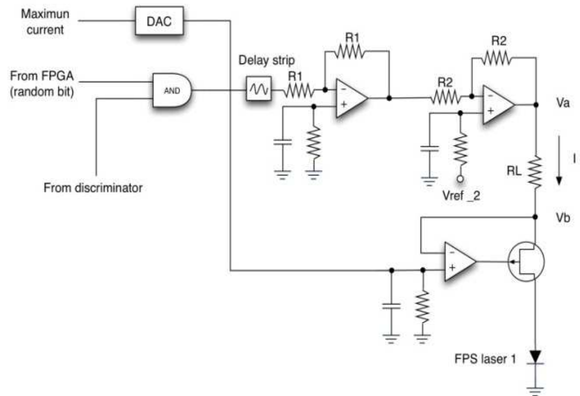
Optical Tolerances



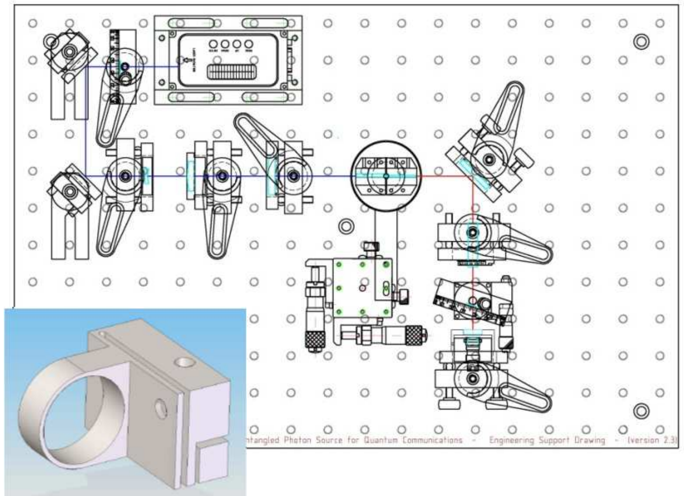
Thermomechanics



Electronics



Mechanical Capabilities



EQT
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Quantum
Transceiver

LIDAX

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IQI

ALTER
TECHNOLOGY GROUP SPAIN

emxys
Embedded Instruments

UNIVERSIDAD
POLITECNICA
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ThalesAlenia
A Thales / Finmeccanica Company Space

+ Thomas Jennewein (IQC)

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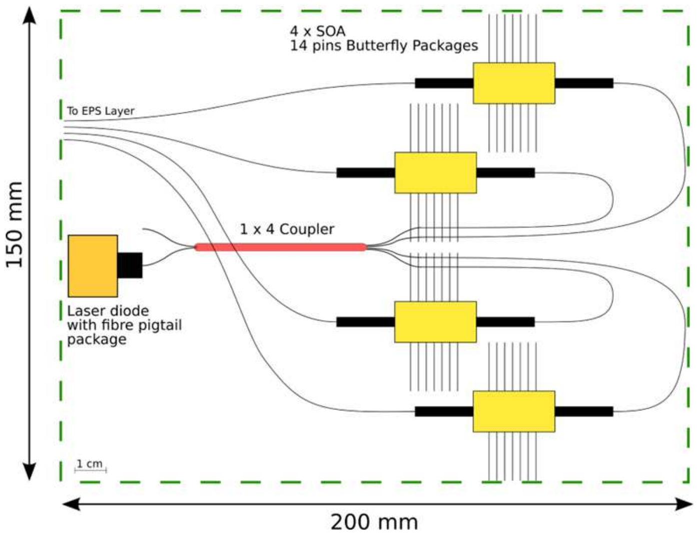
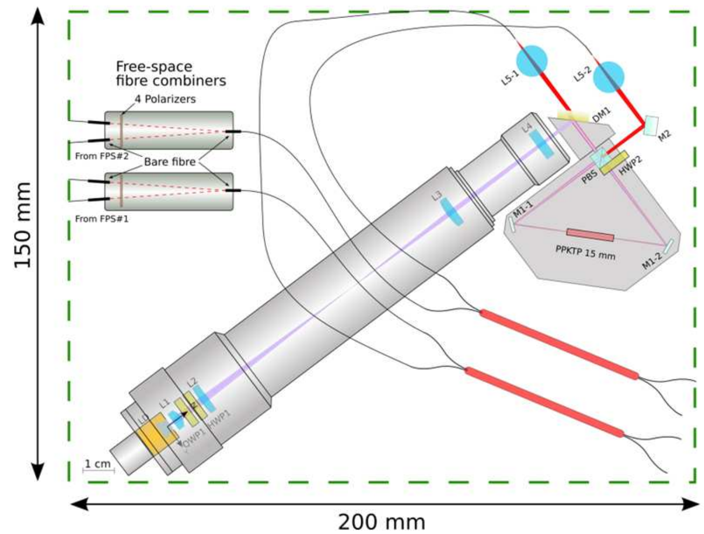
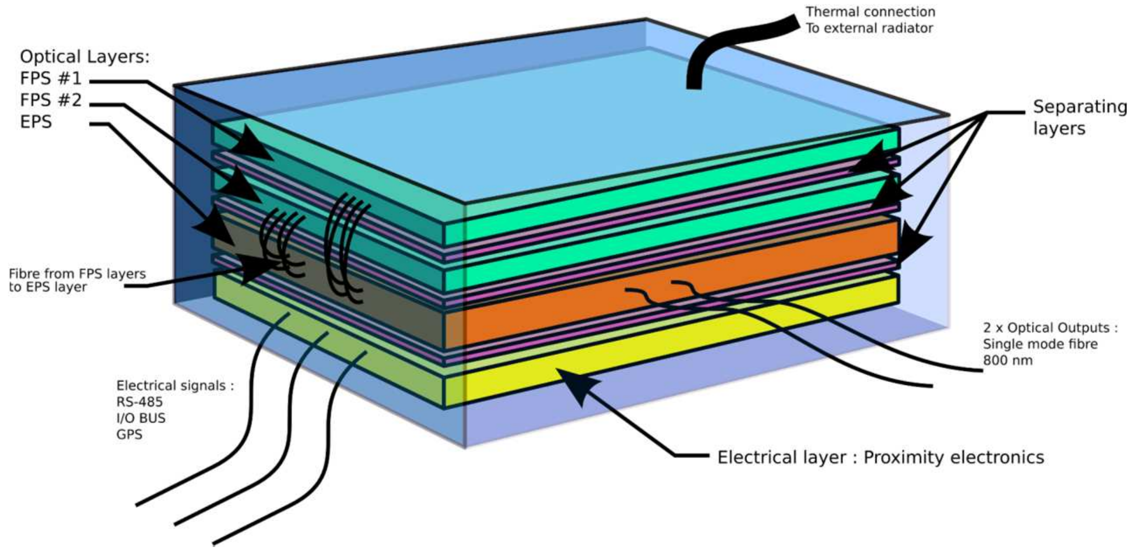
QTx space-proof prototype: potential layout







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Quantum key distribution (QKD) with polarization of single photon – BB84

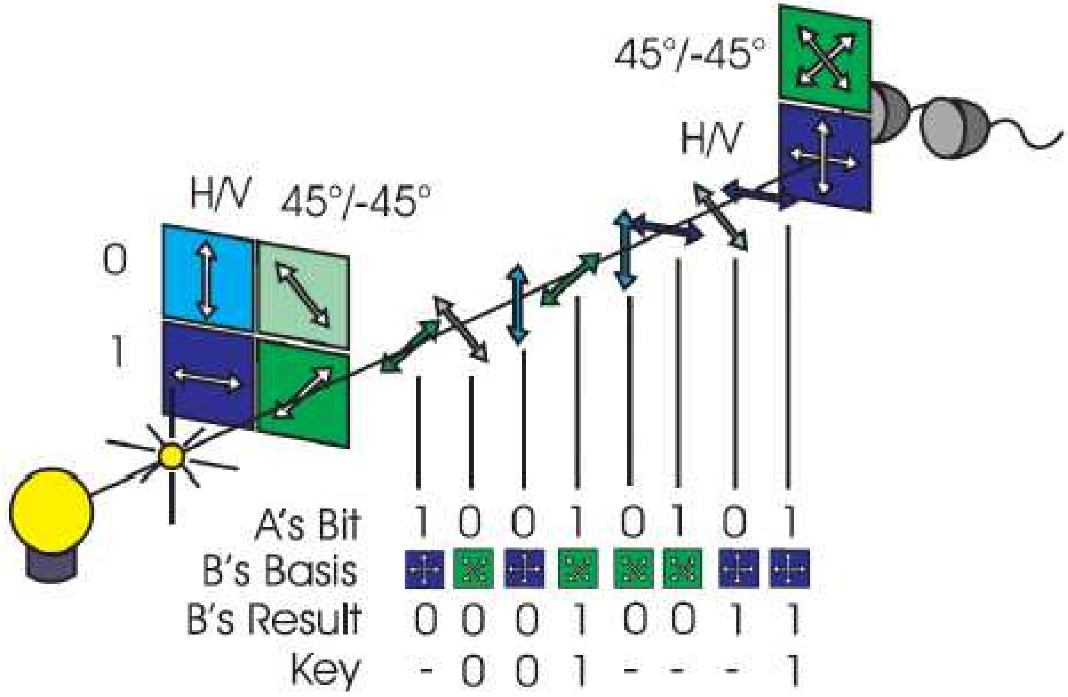
Bennet Brassard 84 **(BB84)**

security is based on
fundamental principles
of physics **(single photon)**

Heisenberg principle +

no-cloning theorem

= **unconditional security**



Eavesdropper can be detected via Errors introduced :

$$\begin{aligned}\mathcal{P}_{\text{error}} &= \mathcal{P}_{\text{Eve has wrong basis}} \times \mathcal{P}_{\text{Bob gets wrong result}} \\ &= 50\% \times 50\%, \\ &= 25\%.\end{aligned}$$

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Faint Pulse Sources (FPS) can be used to approximate truly single-photon source

true- single-photon sources hard to realize… more practical choice is an attenuated laser-pulse that on average it emits < 1photon per pulse.

$$|\text{Faintpulse}\rangle =$$

$$0.8|0-\text{photons}\rangle + 0.1|1-\text{photons}\rangle + 0.01|2-\text{photons}\rangle \ldots$$

Multiple photons open door to eavesdropping. In practical QKD systems, the security can be improved using a **decoy-state protocol.**

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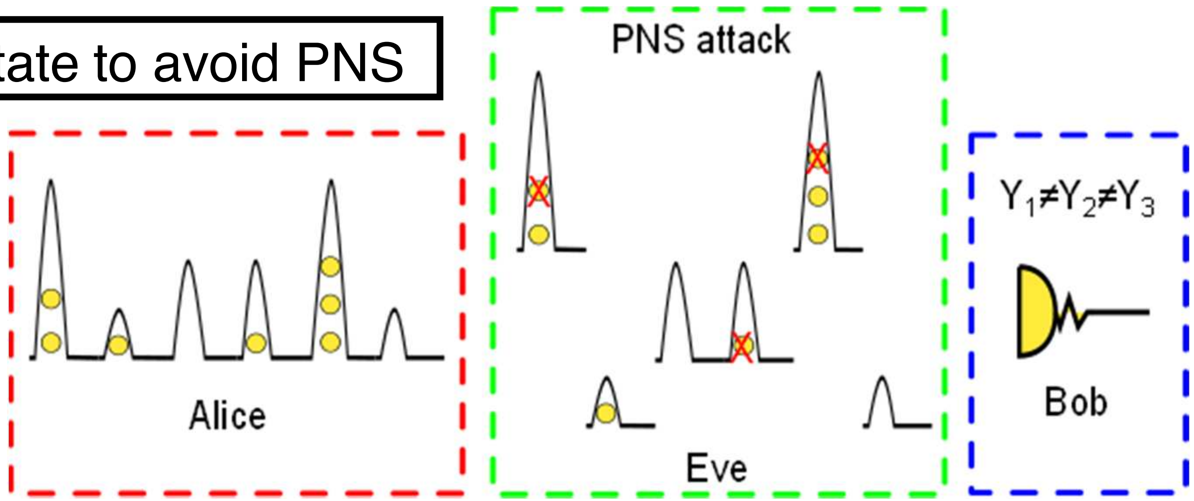
Decoy state protocol

- Principle
  - Alice sends pulses containing N photons, N chosen in {1/2, 1/8,0} (example), each pulse can be either signal or decoy state.
  - Bob announces his detection events.
  - Alice broadcasts which signals were indeed signals or decoy states.
- Any eavesdropper suppressing photons (photon number splitting attack) will be detected by computing the gain (# of detection events/# of signals sent).

Decoy-state to avoid PNS



comparable QKD security and performance with less complexity than single photon sources.

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Key generation rate

QKD experiments, interested in maximizing:

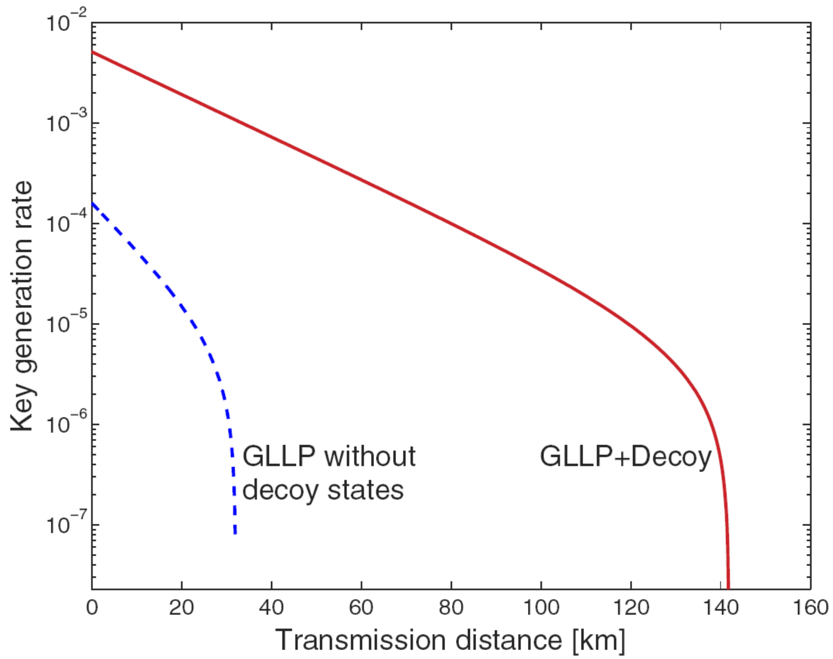
- The secure key generation rate.
- The tolerable error rate (QBER).
- The secure distance.

Channel:

- In optical fibers, loss can be derived from the loss coefficient (α) and the length of the fiber (L).
- Channel transmittance:

$$t_{AB} = 10^{-\frac{\alpha L}{10}}$$

Secure key rate decreases with loss



Gottesman-Lo-Lütkenhaus-Preskill (GLLP) security proof

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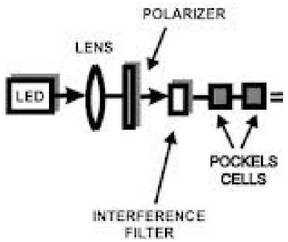
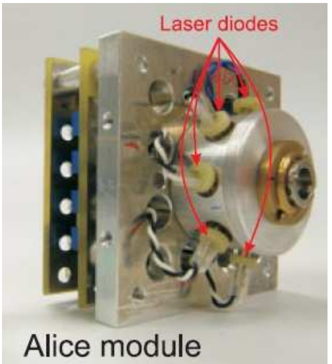
State-of-the-art: FPS

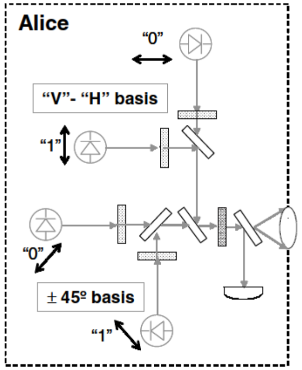
Polarization encoded sources



C. H. Bennett, et al.,
J. Crypt. 5, 3-28 (1992).



H. Weier, et al.,
Fortschr. Phys. 54, 840-845 (2006).



R. J. Hughes, et al.,
New J. Phys. 4, 43 (2002).

- Common limitations of current implementations:
  - Information leackage:
    - Phase coherence.
    - Different qubits prepared
      by different light sources.

- The highest secure key rates reported to date:
  - Optical fiber: 1.02 Mb/s (over 20 km) and 14.1 b/s (over 200 km).
  - Free-space: 50 Kb/s (over 480 m) and 12.8 Kb/s (over 144 km).

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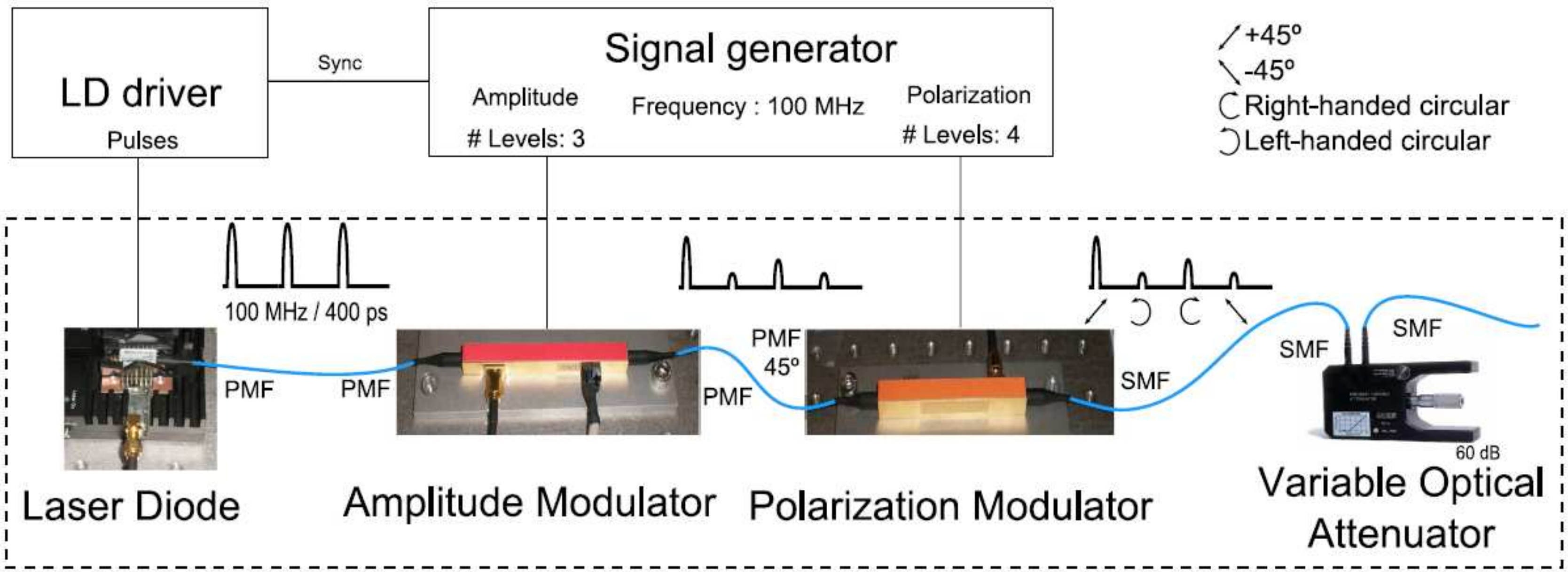
Integrated FPS

- Single laser diode followed by integrated (waveguide) amplitude and polarization $LiNbO_3$ modulators (having):
  - Indistinguishability.
  - High bit rates (100Mb/s).
  - 850nm (free space).
  - Space-qualified.
  - Low power consumption (5W).
  - High integration.



Allows to install the source on a low orbit satellite

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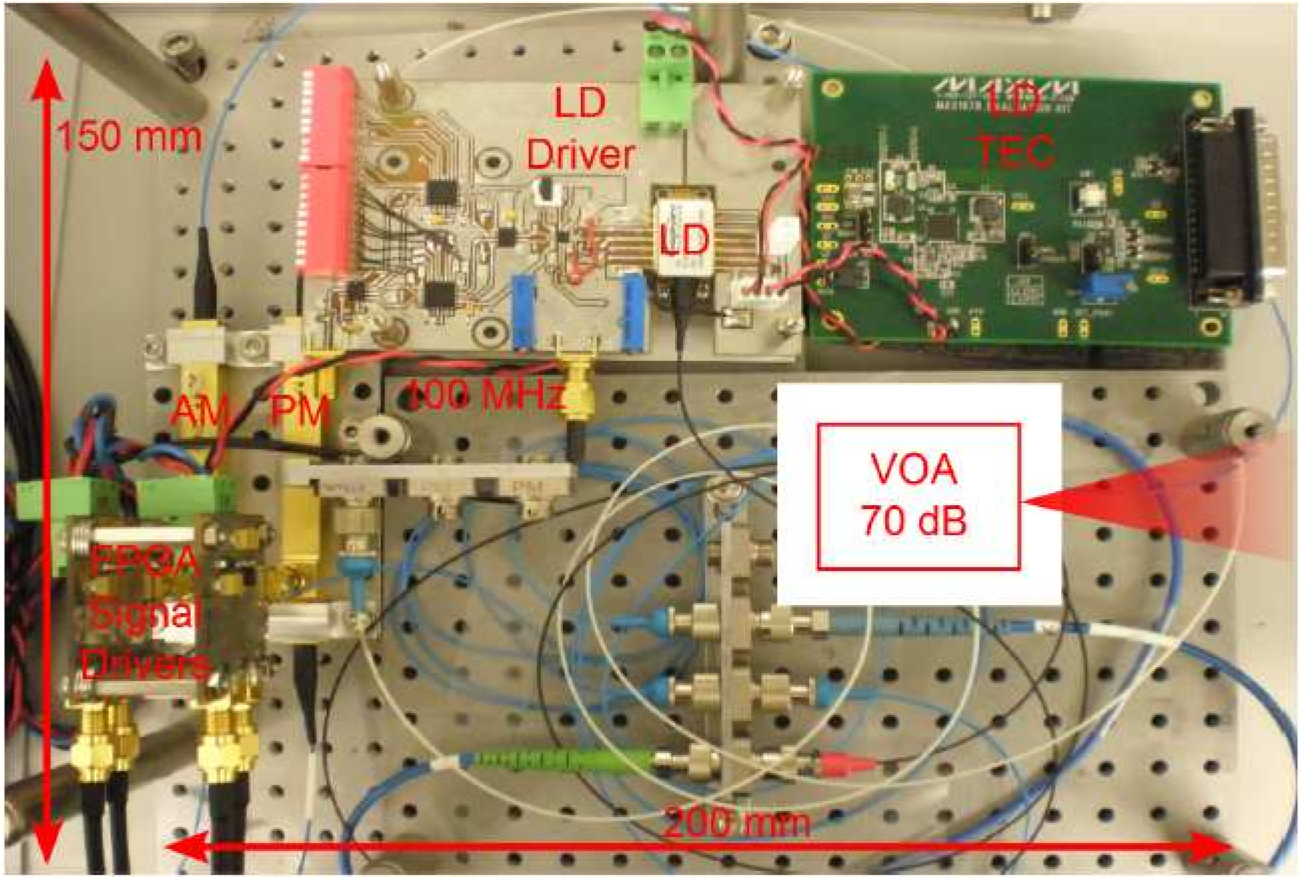
$LiNbO_3$ based FPS



M. Jofre, et al., “100 MHz Amplitude and Polarization Modulated Optical Source for Free-Space Quantum Key Distribution at 850 nm”, J. Lightwave Tech., **28**, 2572-2578 (2010).

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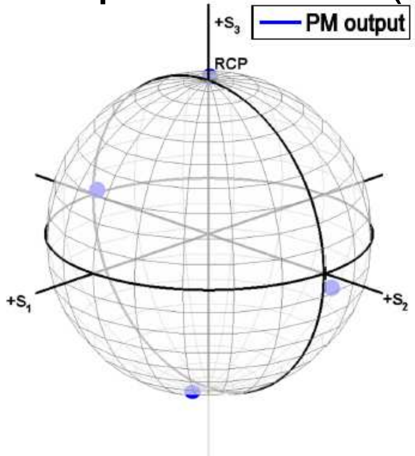
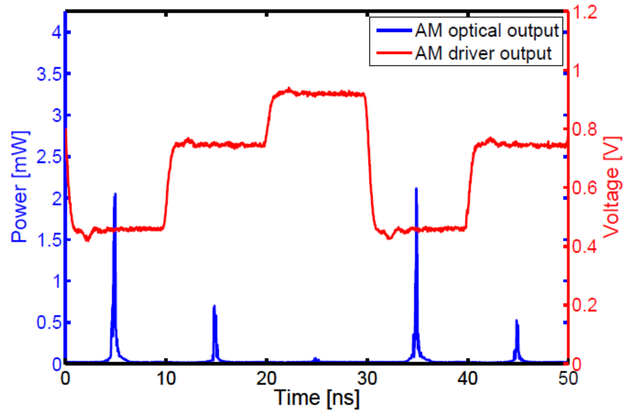
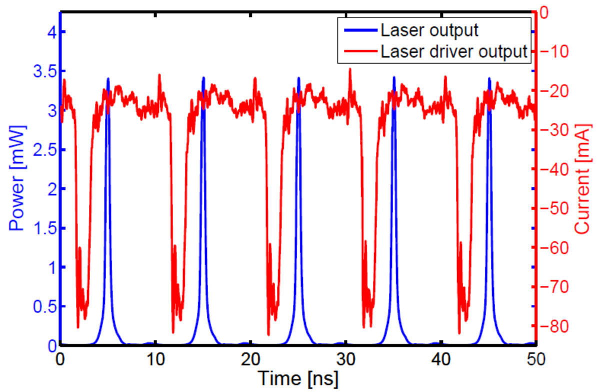
FPS generated states

- Dissociate pulse generation from polarization and intensity settings (external modulation).
- At least 4 polarization (BB84) with 3 intensities (decoy-state).





- No phase coherence between successive pulses (direct laser modulation).



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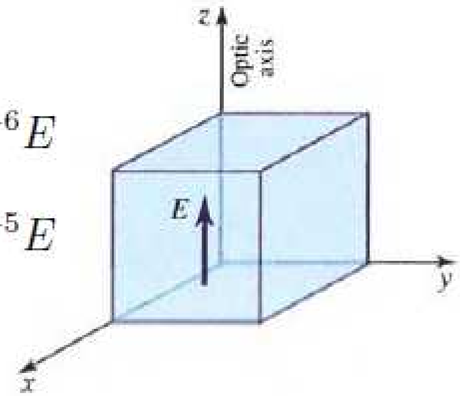
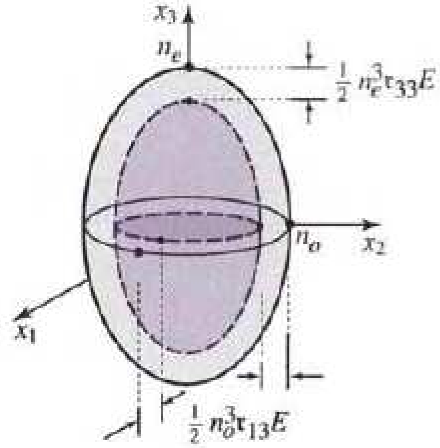
Electro-optics

$$n_0(E) \approx n_0 - \frac{1}{2} n_0^3 r_{13} E = 2.16 - 2.02 \cdot 10^{-6} E$$
$$n_e(E) \approx n_e - \frac{1}{2} n_e^3 r_{33} E = 2.24 - 1.69 \cdot 10^{-5} E$$

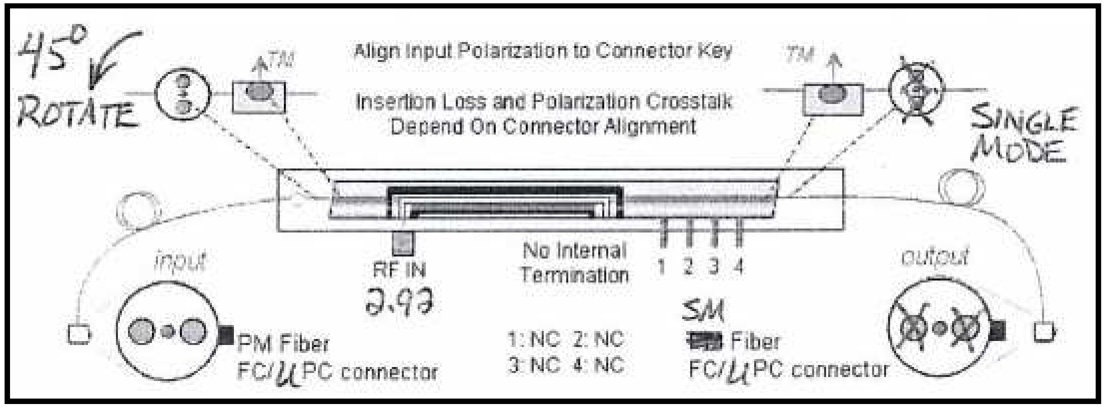




Specified LiNbO3 modulators:

No termination resistor:

- 500 MHz modulation bandwidth.
- < 2V driving voltage.



Polarization modulator (PM) connectorization.

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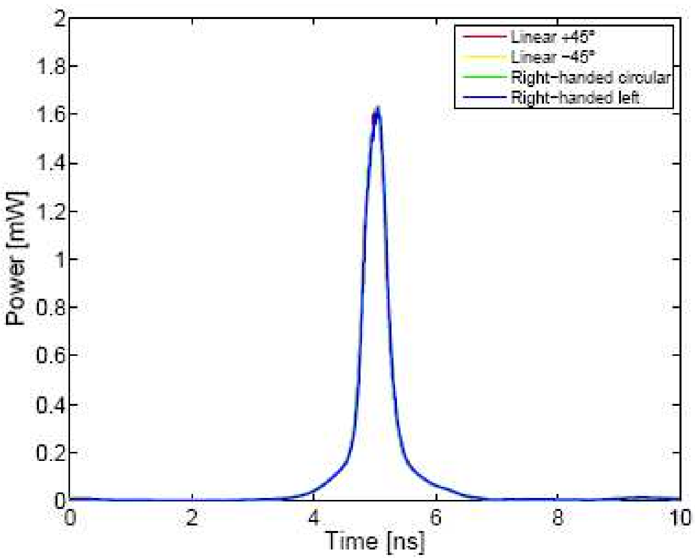
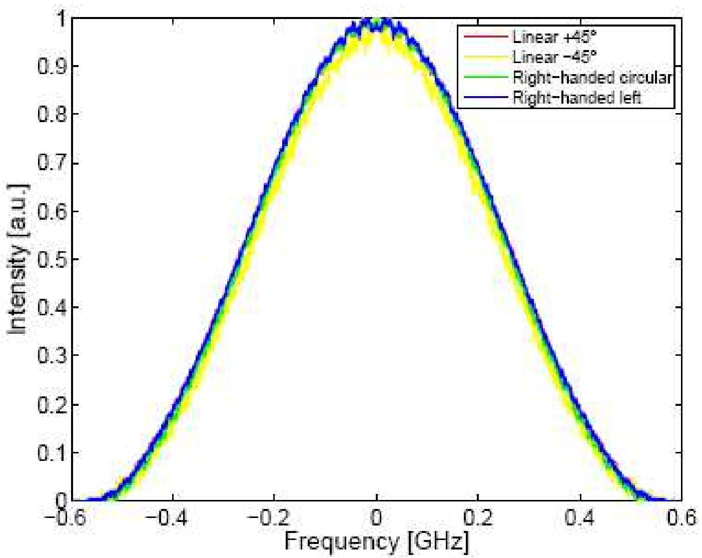
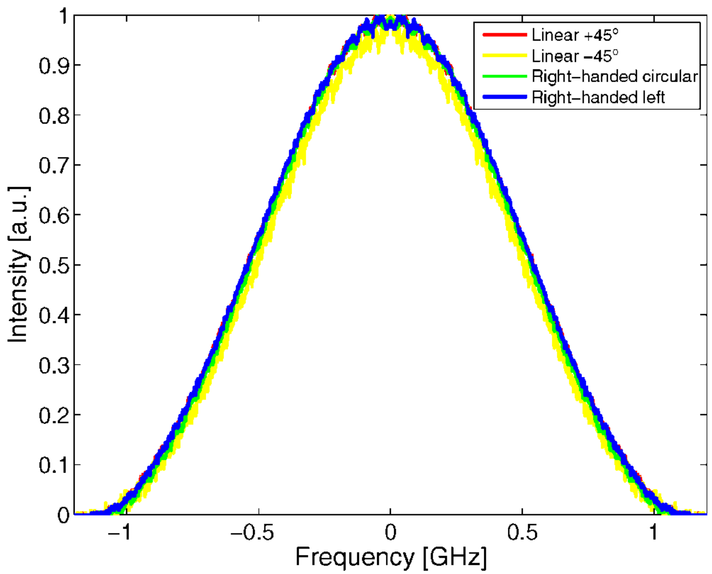
Indistinguishability in polarization

- Optical pulses in a BB84+decoy-state protocol should:
  - Differ in polarization and intensity.
  - Indistinguishable in other characteristics (temporal shape and frequency spectrum).







High degree of similarity.

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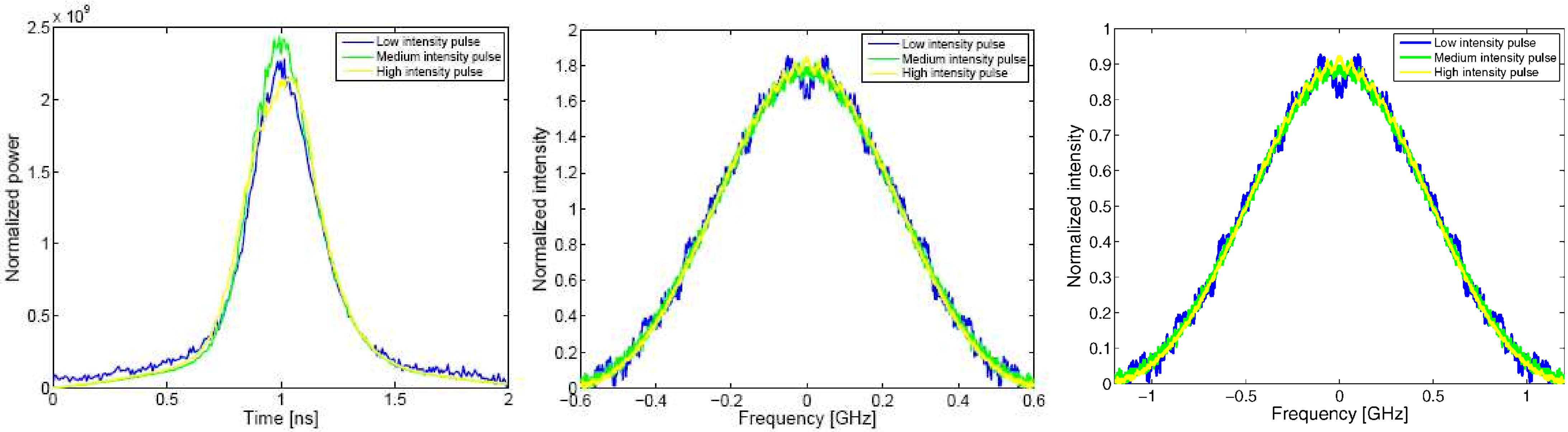
Indistinguishability in intensity

- Normalized to the total energy for comparison.
- Polarization statistical similarity is more important (than intensity).



High degree of similarity.

Minimal distortion.

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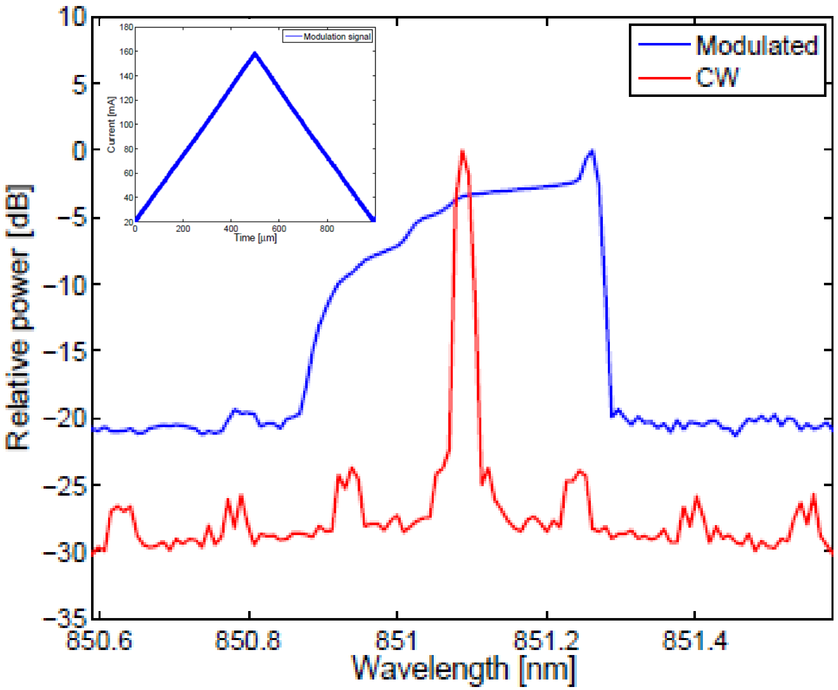
PMD compensation

Impairment in PM entering at 45° : $LiNbO_3$ birefringence causes PMD.

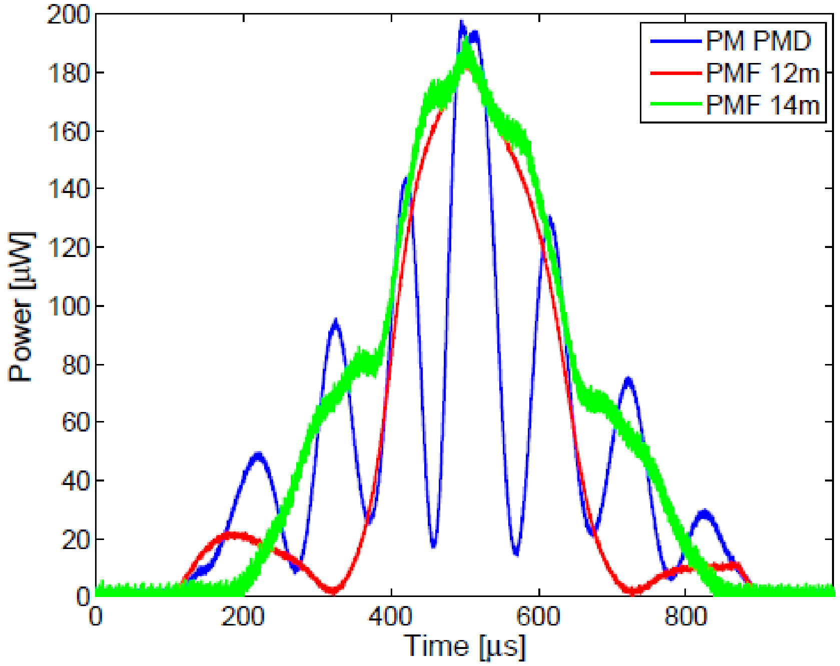
$$\Delta\theta = \Delta\tau 2\pi\Delta\nu$$



Intensity scan produces

0.45nm sweep.

$\Delta\lambda \sim \Delta I$



9.7% QBER due to PMD.

1.4% QBER with compensated PMD.

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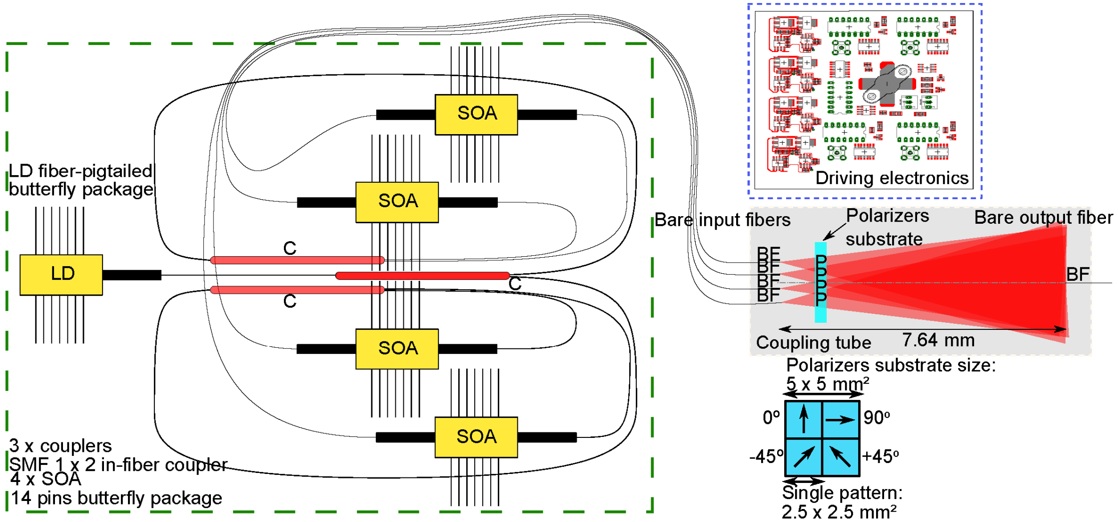
Compact FPS

FPS-4SOA: based on integrated semiconductor optical amplifiers (SOAs).



- Single laser diode followed by integrated SOAs (having):
  - Indistinguishability.
  - High PER (>20 dB).
  - High bit rates (100Mb/s).
  - 850nm (free space).
  - Space-qualified.
  - Low power consumption (5W).
  - High integration.

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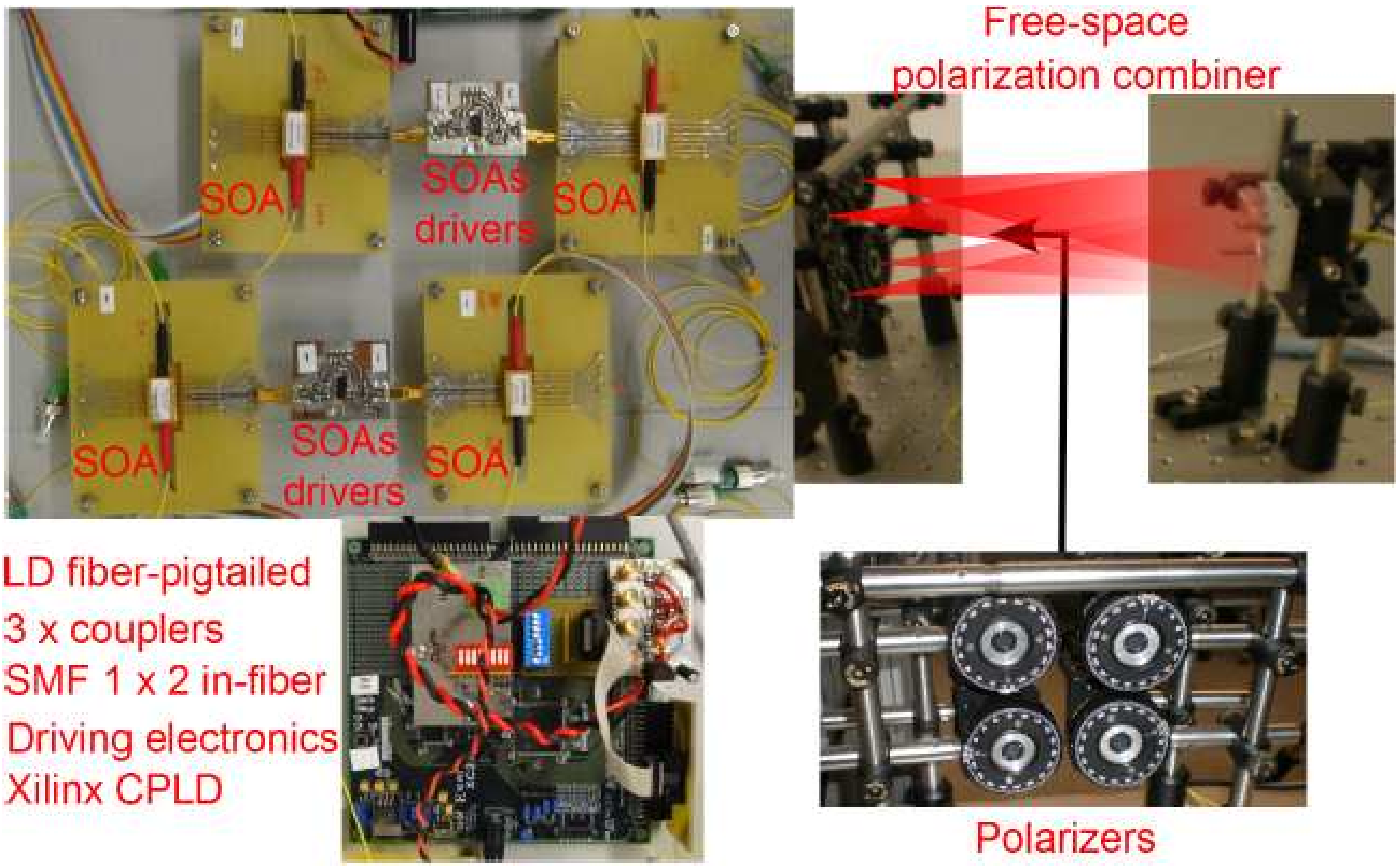
SOA based FPS



M. Jofre, et al., “Fast optical source for quantum key distribution based on semiconductor optical amplifiers” Opt. Exp., **19**, 3825-3834 (2011).

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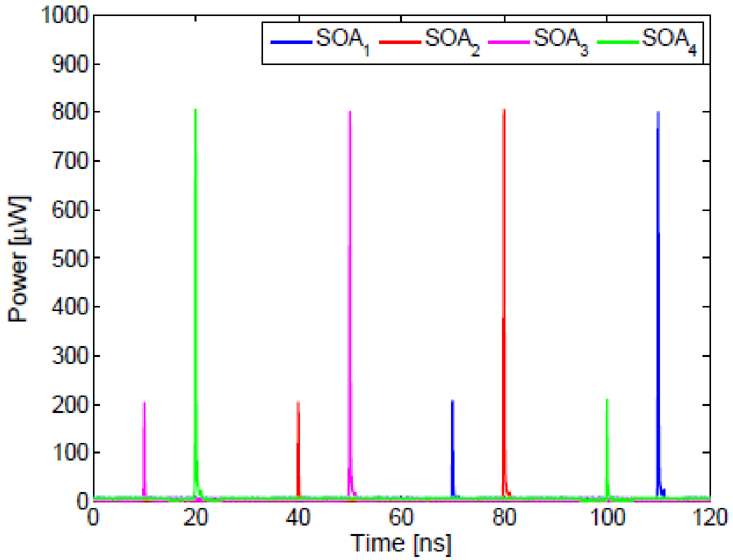
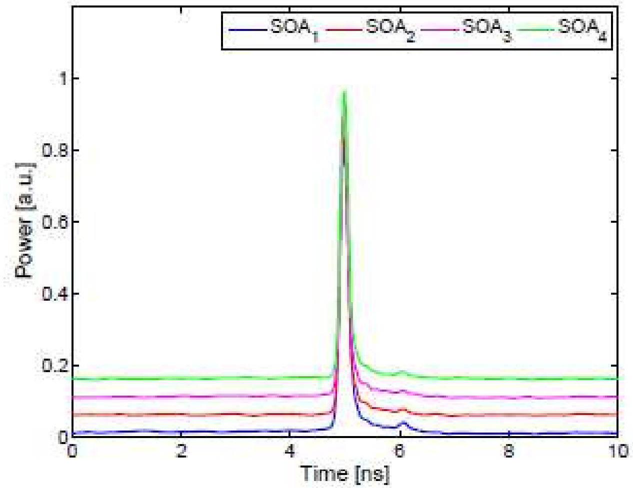
Generated states

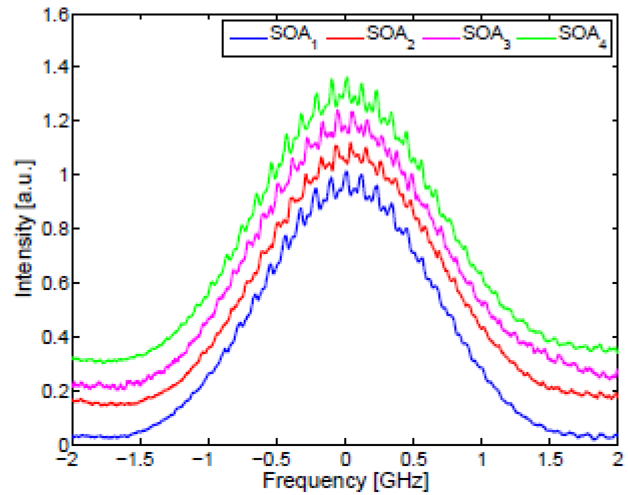
Continuous periodic sequence



	1	2	3	4	5	6	7	8	9	10	11	12
SOA/Polarization	1	2	3	4	1	2	3	4	1	2	3	4
Intensity	3	2	1	3	2	1	3	2	1	3	2	1

Facilitates QKD performance evaluation.





High degree of similarity.

Removal of 10^{-3} bits per pulse

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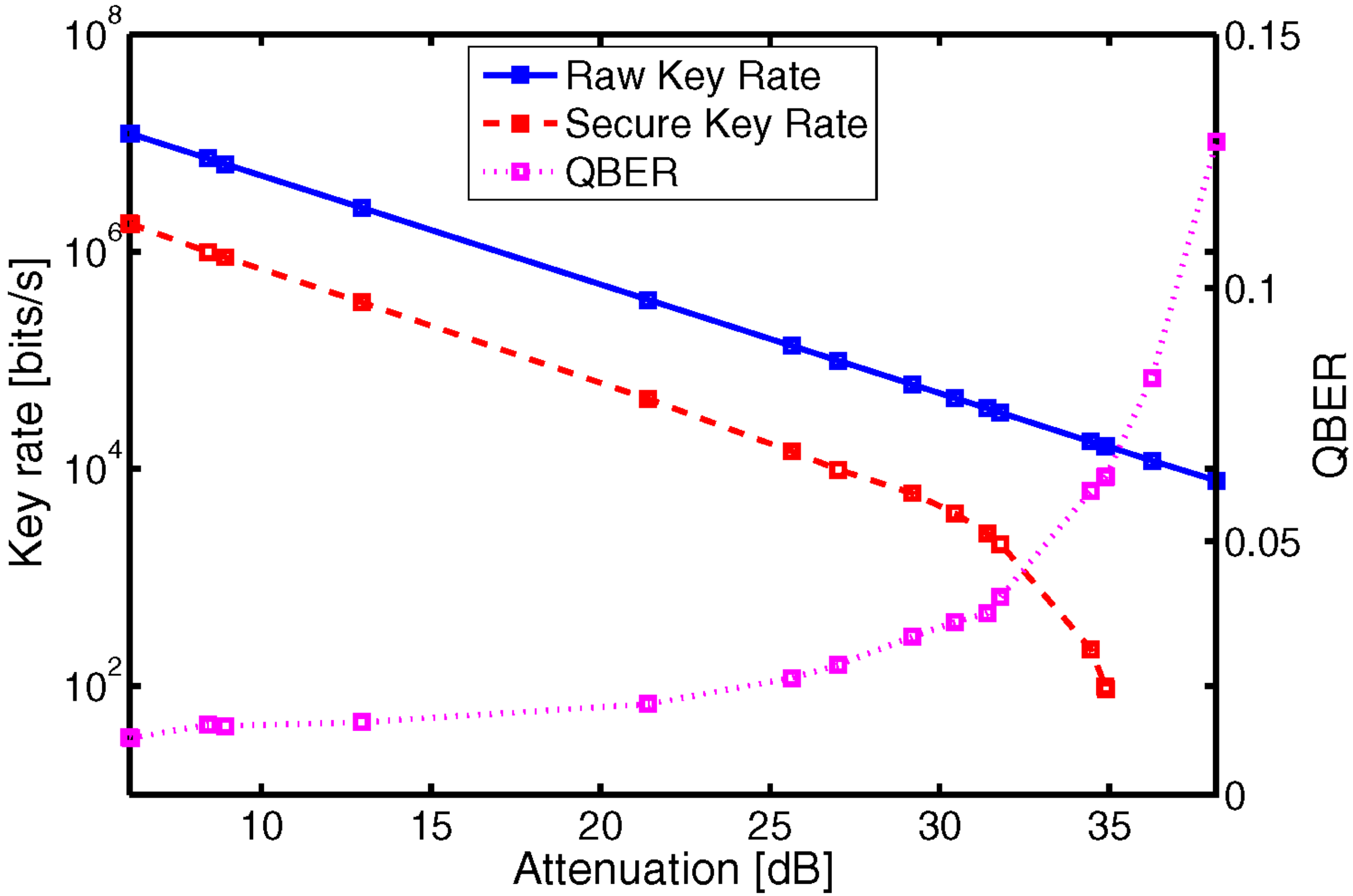
FPS QKD results



- 3.64 Mbps with 1.14% QBER for 6dB attenuation.
- 187 bps for 35 dB attenuation.

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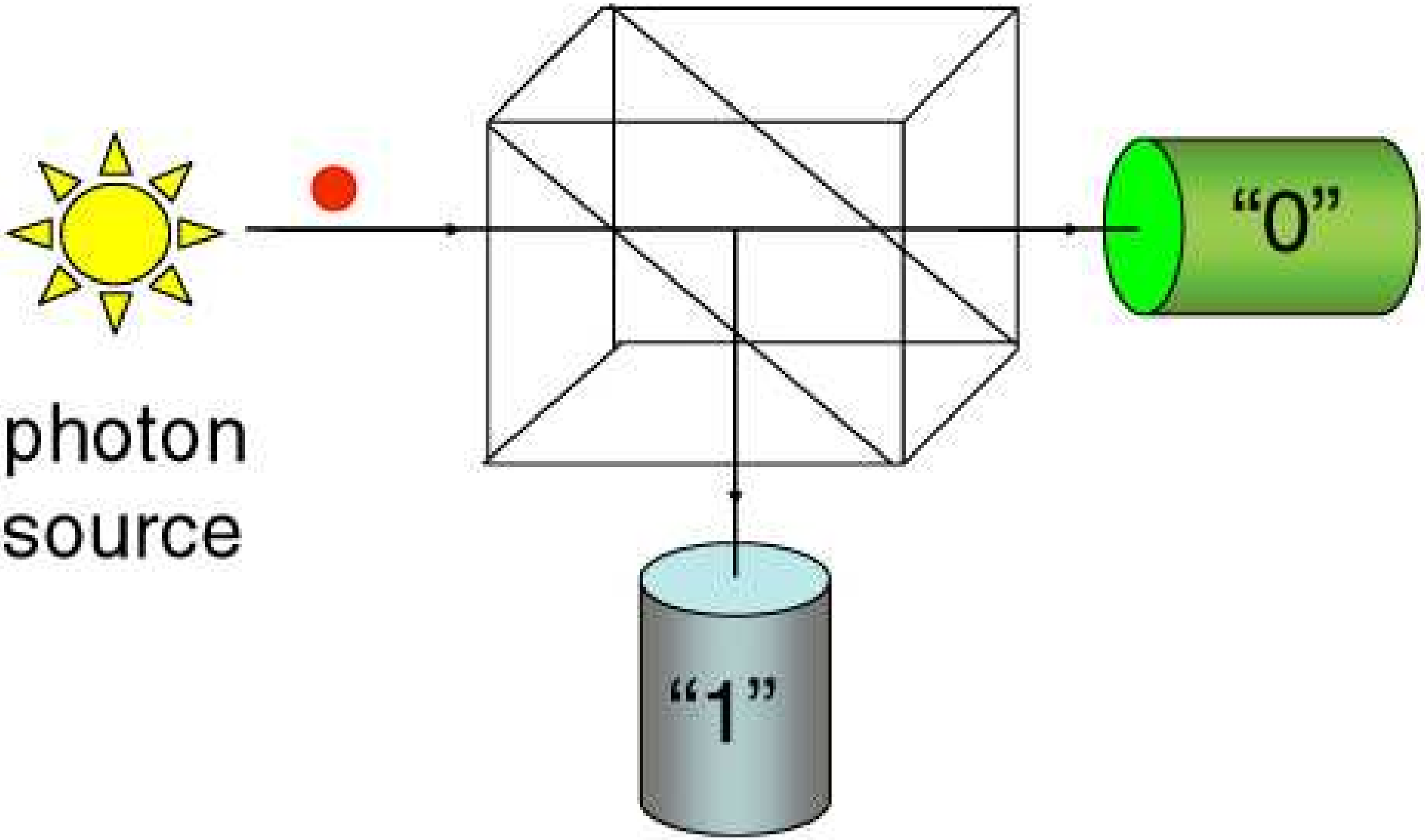
QRNG

Randomness is the absence of pattern or regularity



Example: single photon quantum indeterminacy in 50/50 beam splitter.

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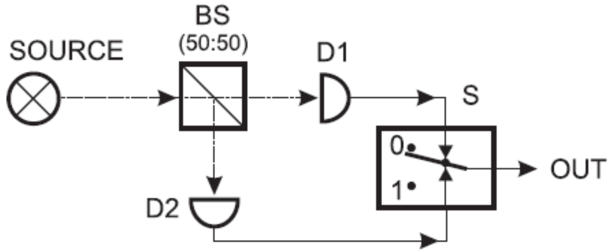
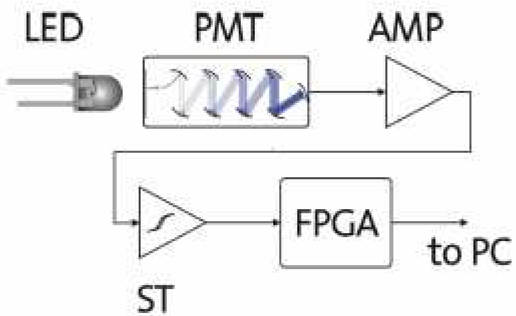
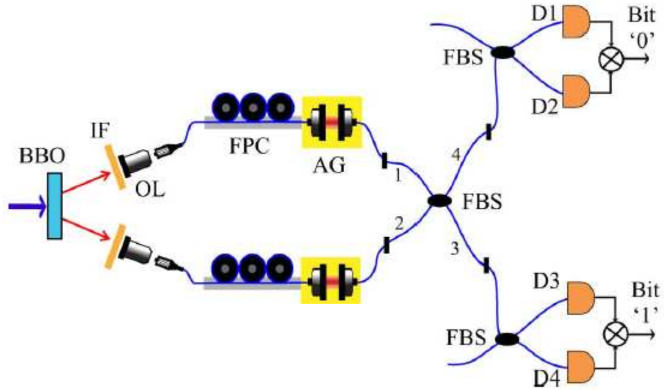
State-of-the-art: QRNG



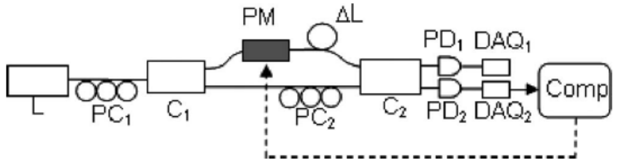
T. Jennewein, et al.,
Re. Sc. Inst. 71, 1675 (2000).



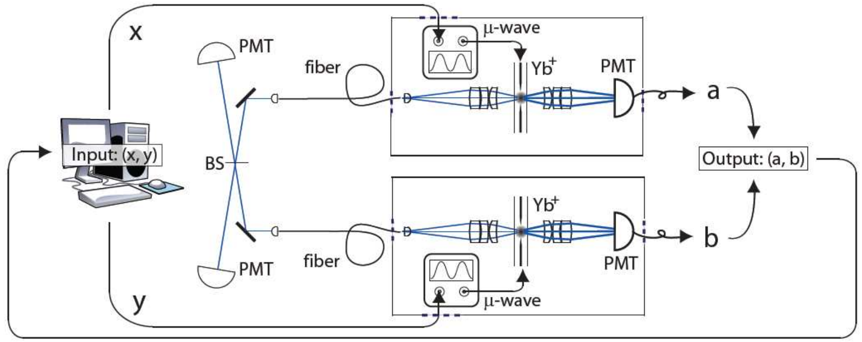
M. Fürst, et al.,
Opt. Exp. 18, 1302913037 (2010).



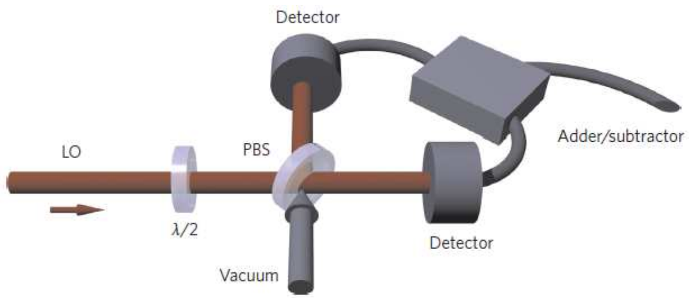
O. Kwon, et al.,
App. Opt. 48, 1774-1778 (2009).



B. Qi, et al.,
Opt. Lett. 35, 312-314 (2010).



S. Pironio, et al.,
Nature 464, 1021-1024 (2010).



C. Gabriel, et al.,
Nat. Photonics 4, 711-715 (2010).

Low bit rate
High complexity

Future demands for secure communications >100 Gbps

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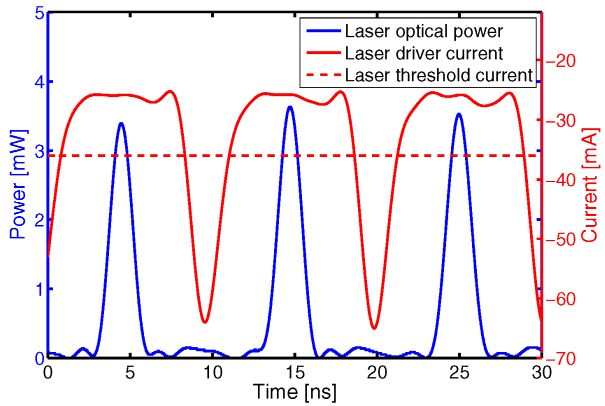
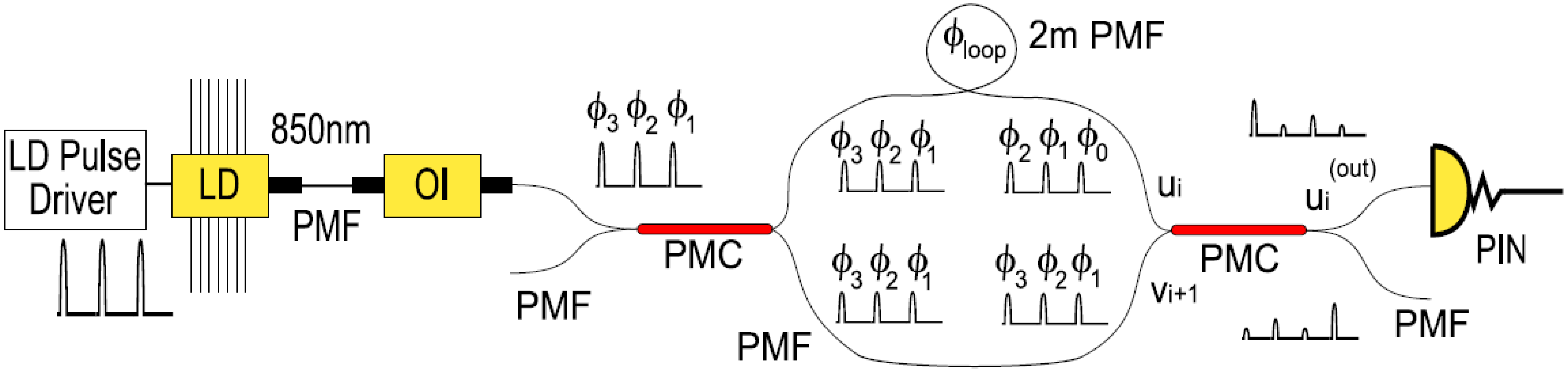
QRNG device

- Highly integrated.
- Practical and robust.
- Long operational life time.





- True random numbers from amplified quantum vacuum (having):
  - Vacuum fluctuations.
  - Electrical amplification.
  - Macroscopic signal level (mW).
  - High bit rates (>1 Gbps).
  - 100 MHz pulse rate.
  - 11 bits per pulse.

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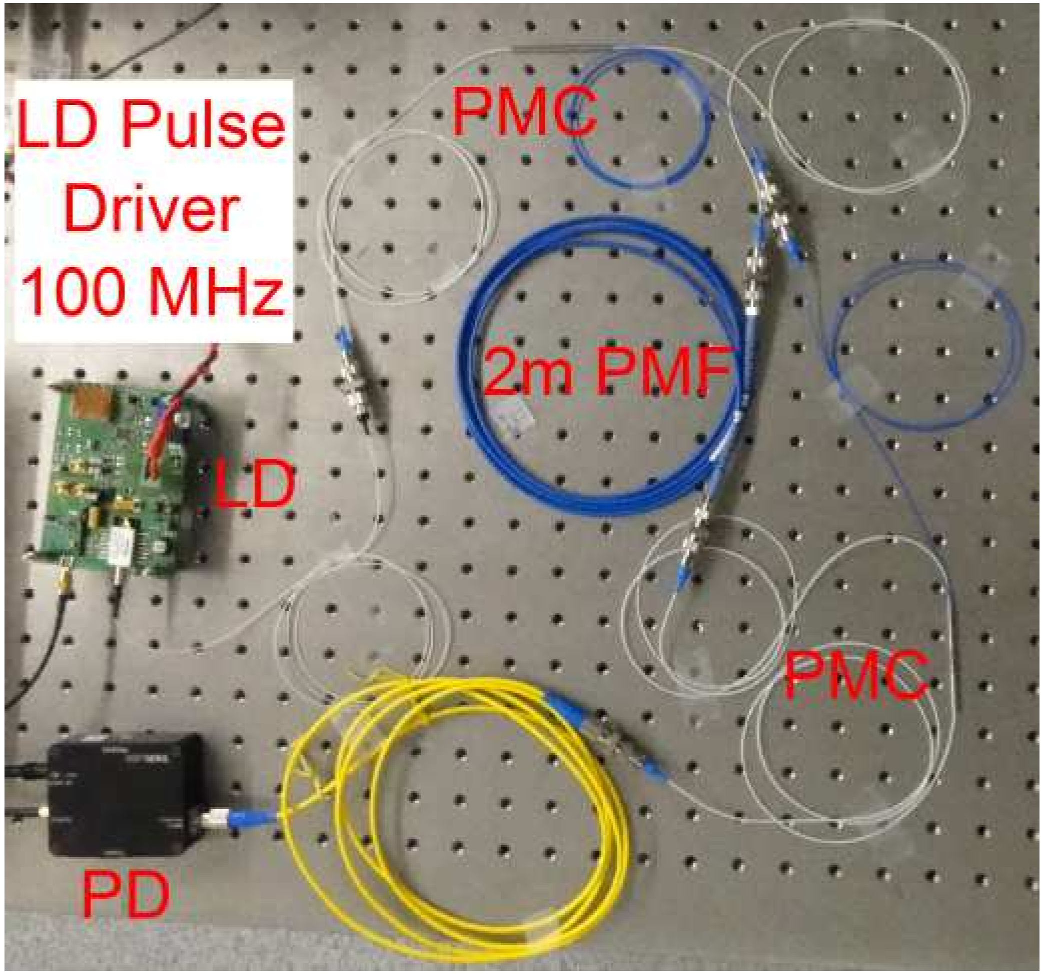
Pulsed LD based QRNG



M. Jofre, et al. “True random numbers from amplified quantum vacuum”, Opt. Exp., **19**, 20665-20672 (2011).

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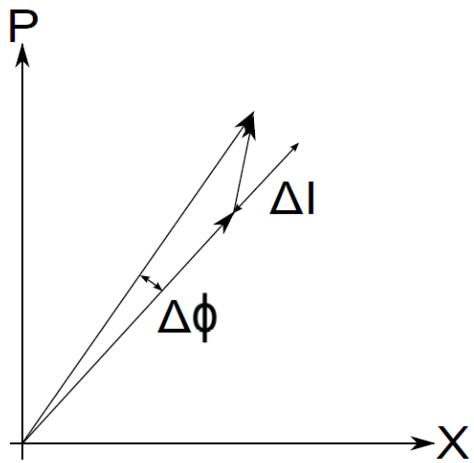
Laser physics

LD is a cavity.

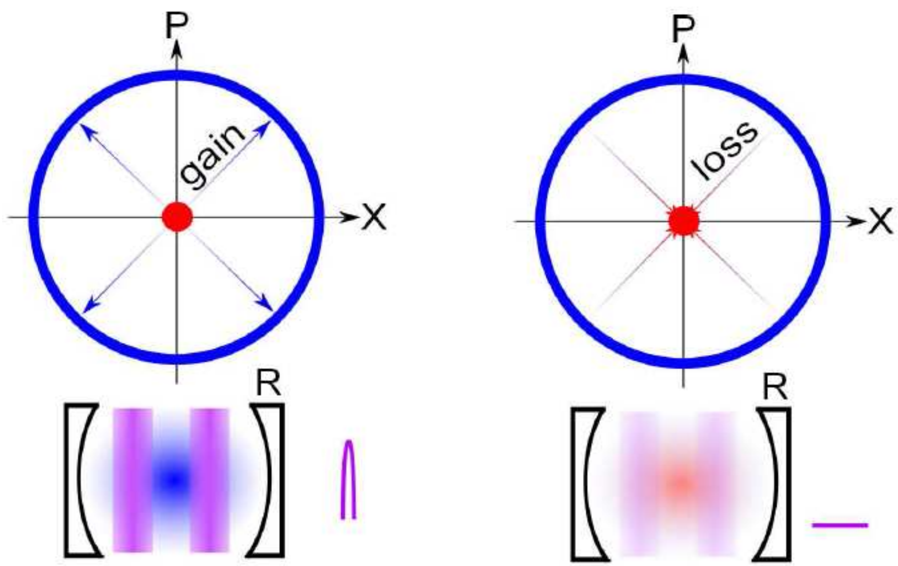
Direct LD modulation

Change due to a single spontaneous emission.



Intensity the same.

Random phase.



Trade off. The lower the DC current bias:

- The more phase variance.
- Time-scale dynamics slower.

The physics of the process can support >100 Gbps.

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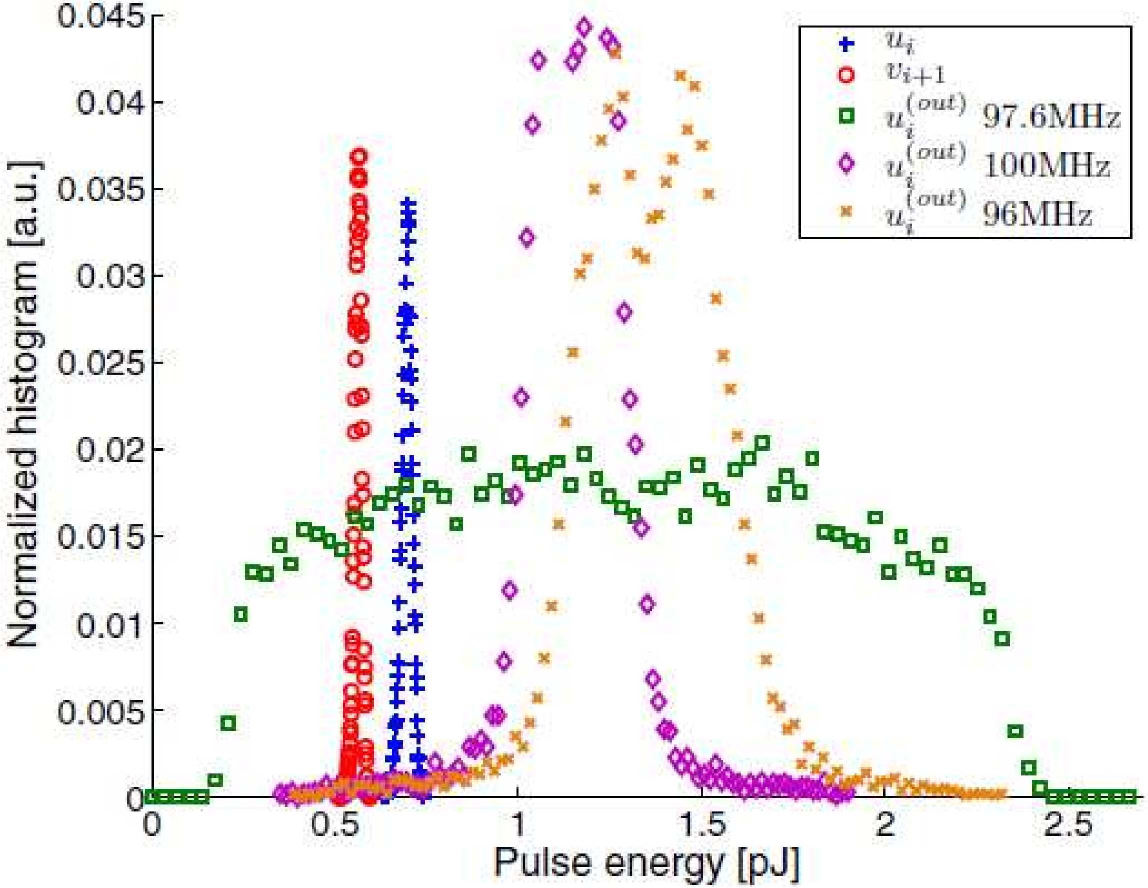
Interference distribution



90.22% interference visibility.

Broadening due to random phase.

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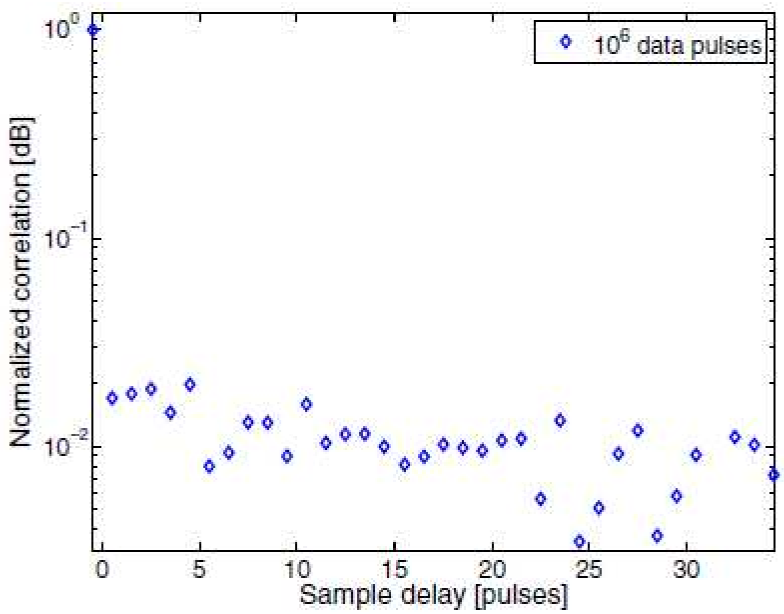
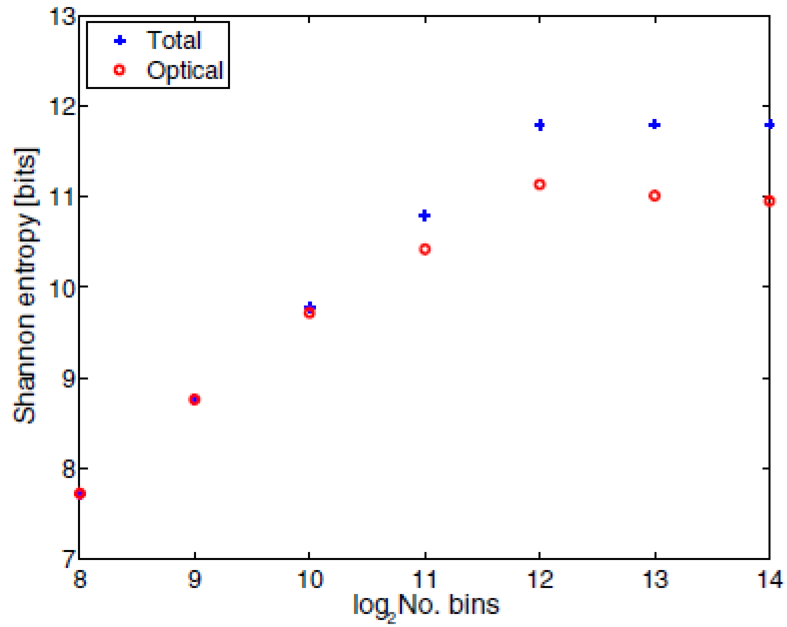
Statistical testing

Autocorrelation evaluates periodicity.



No periodicity
(Delta-function behaviour).

Entropy evaluates uncertainty.



11.1 bits per pulse
(classical noise removed).

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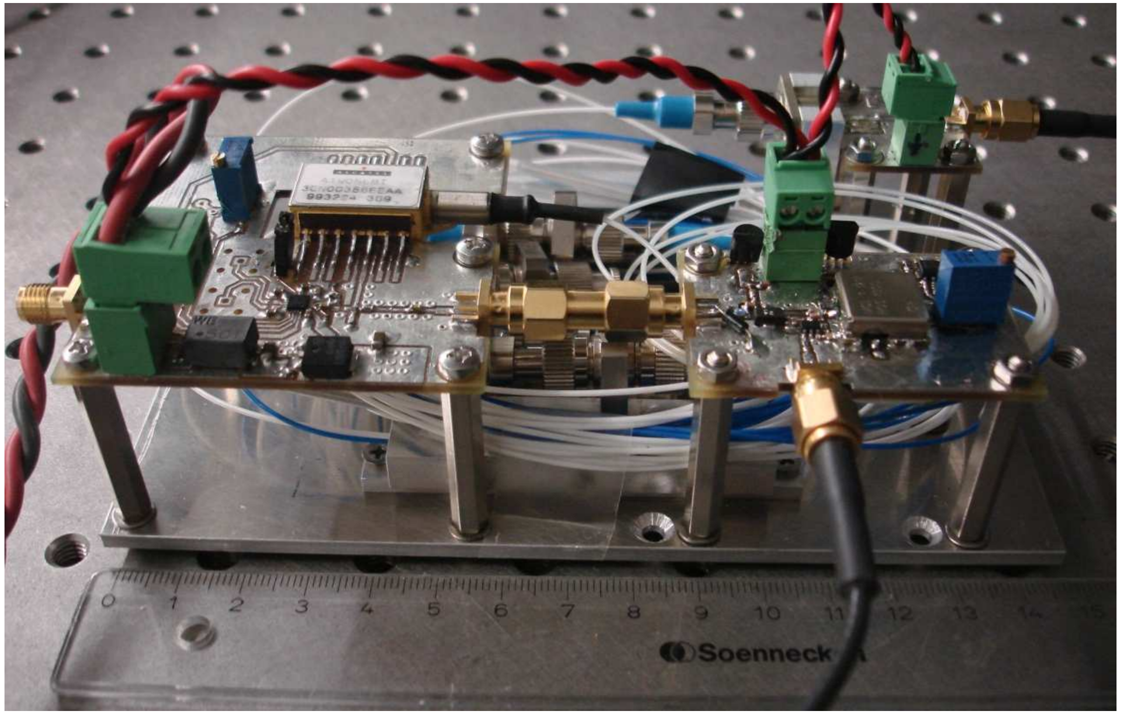
Improved, integrated QRNG

5.825 GHz pulsed LD

X 10 random bits per pulse = 58 Gbits/s



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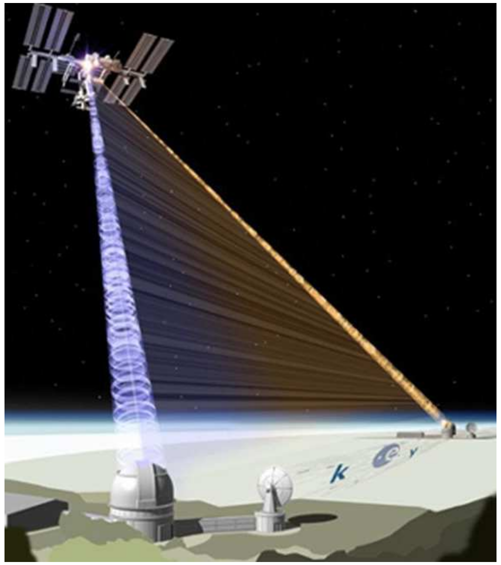
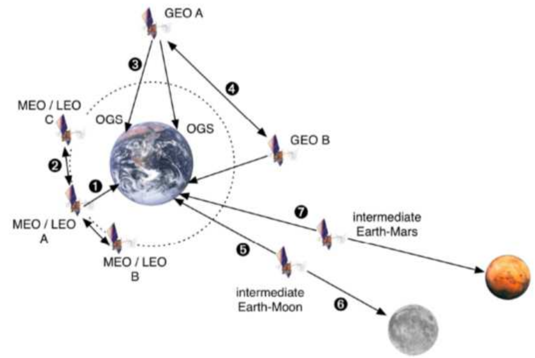
Entangled photons for Quantum Cryptography and ….

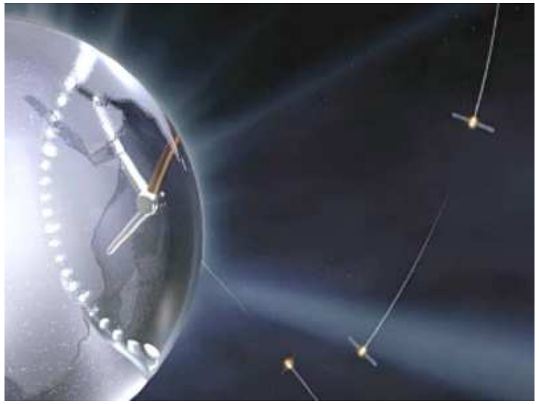


QKD allows **global unconditionally secure** information transfer



…… Quantum enhanced metrology

…push limits of **clock synchronization** and **ranging**



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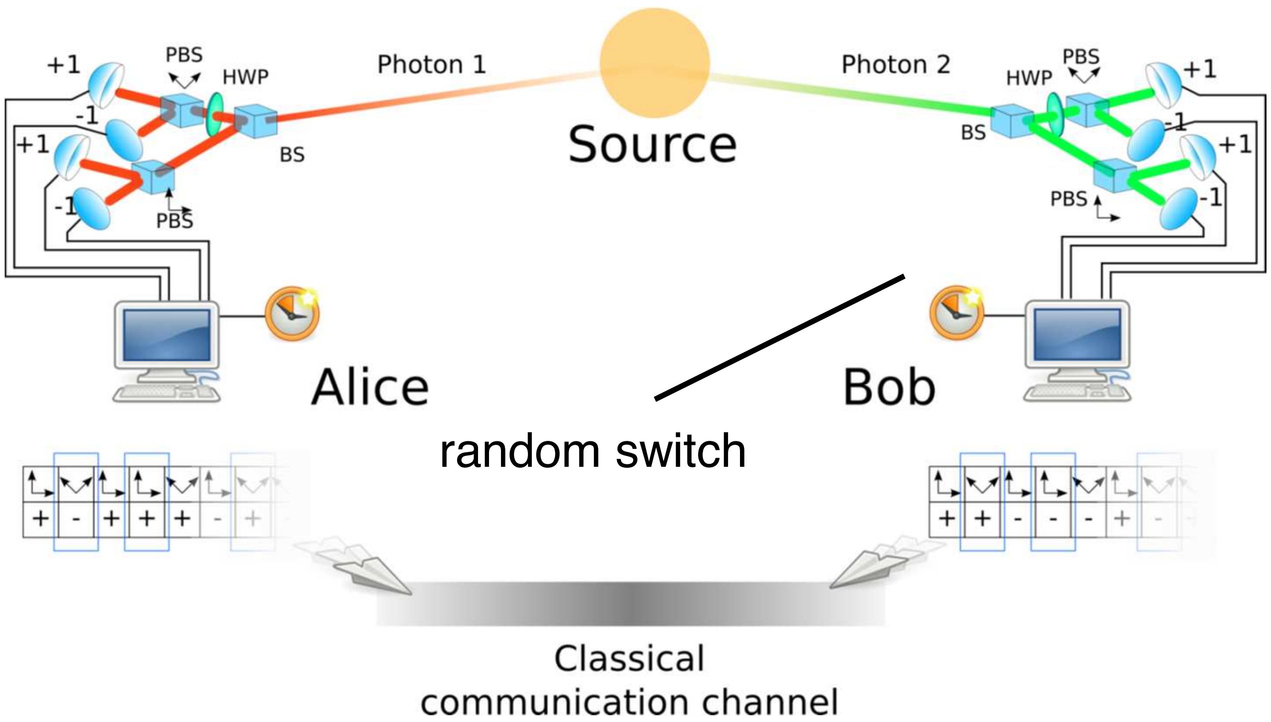
Quantum cryptography with entangled photons

Entanglement: Distribute random but perfectly correlated sequence → cryptographic key



Eavesdropper detectable due to errors when wrong basis is chosen

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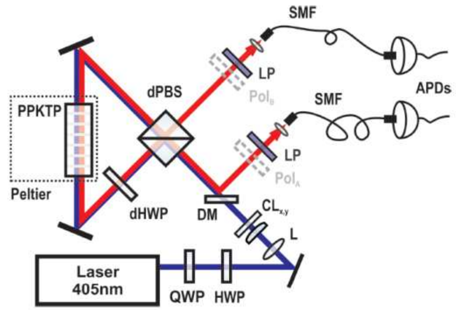
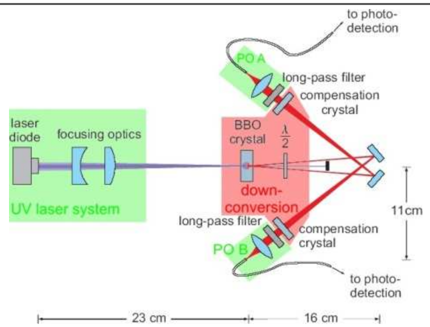
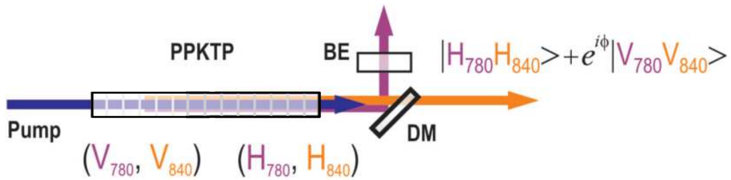
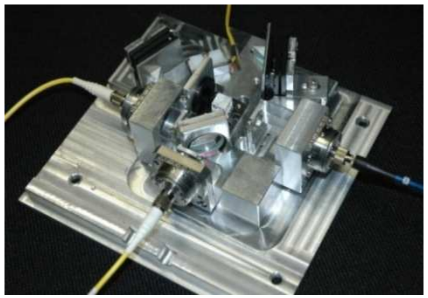
State-of-the-art: EPS

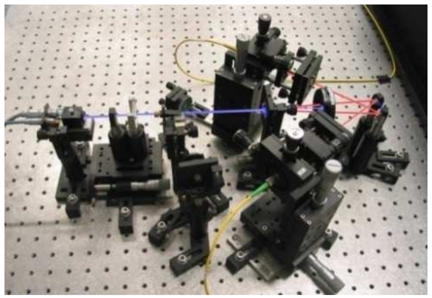
Material	Geometry	Visibility	Spectral brightness (detected pairs/s/mW/nm)	Bandwidth
25 mm ppKTP (deff=2.5pm/V)	Type II-Sagnac micro-optical (bulk)	Exp-99.5%	Exp-2.7x10^{6}	Exp-0.3nm
Two 15.8mm BBO crystals @ 90º (deff=2pm/V)	Type I-Linear micro-optical (bulk) cavity	Exp-98.4%	Exp-2x10^{3}	Exp-15nm
10mm ppKTP waveguide (deff=2.5pm/V)	Type II-Linear waveguide	Exp-79%	Exp-3x10^{6}	Exp-1nm
Exp=Experimental.				











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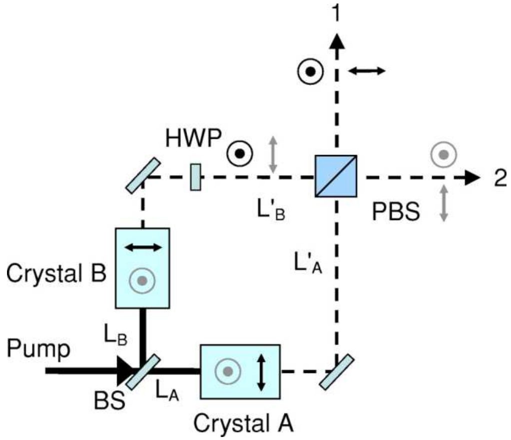
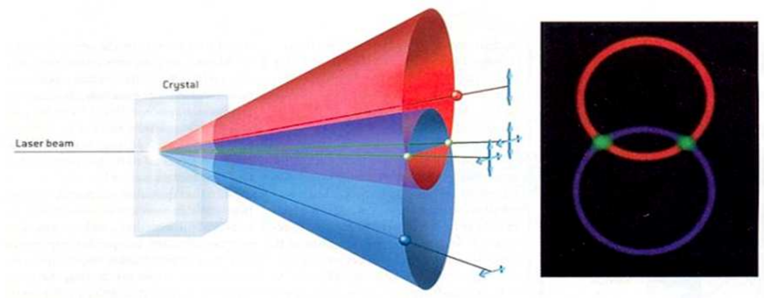
State-of-the-art pair sources not well-suited for harsh environments

(-) interferometric stabilization



(-) bulky lasers

(-) low efficiency



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EQUO : Entangled photon source for QC

equ0

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LMU

qutools

IQI

University of BRISTOL

Thomas Jennewein
(IQC)

Main requirements :

-high brightness (pairs/s)

-high entanglement quality (visibility)

-suitable for space transmission

-robust, compact design

European Space Agency
Contract #:22542/09/NL/SFe

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Optical requirements

	Requirement	Goal
Wavelength	750 – 850 nm	
Type of entanglement	Polarization	
Pumping scheme	405 nm LD	
Optical bandwidth	≤10 nm	≤3 nm
(Back-to-back) detected coincidence rate	> 10^7 pairs/s	> 10^9 pairs/s
Visibility	> 90 % in 0º/90º and +45º/-45º basis	> 95 % in 0º/90º and +45º/-45º basis
Spectral brigthness	> 40 000 pairs/s/mW/nm	>10^7 pairs/s/mW/nm

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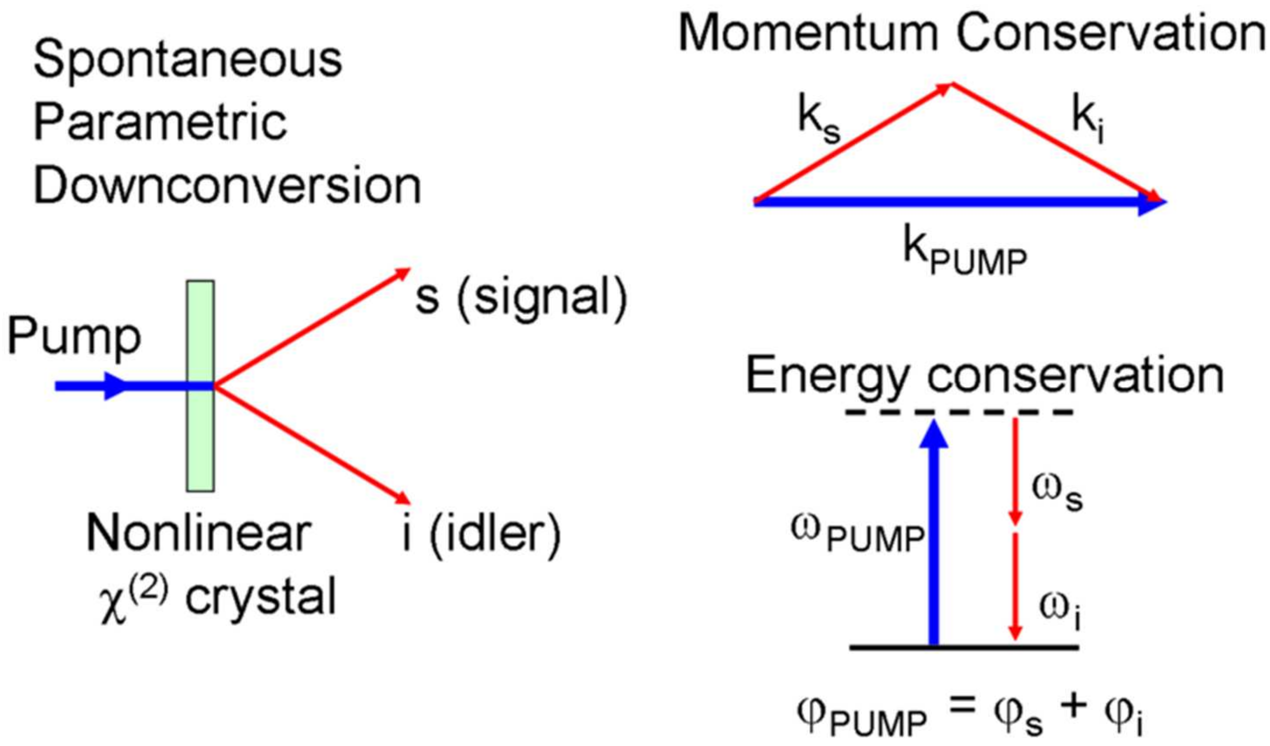
Spontaneous Parametric Down Conversion (SPDC)

$$P_i = \epsilon_0(\chi^{(1)}_{ij} E_j + \chi^{(2)}_{ijk} E_j E_k + \chi^{(3)}_{ijkl} E_j E_k E_l + \ldots)$$



750-850 nm (*Si detectors, link loss-budget, pump*)

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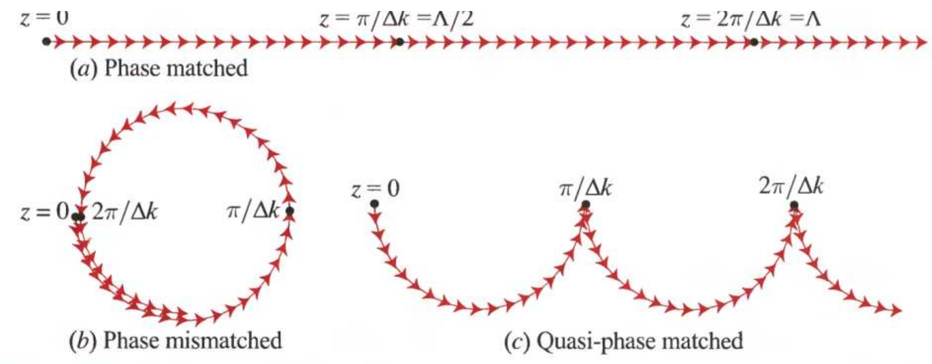
Periodic Poling: Efficient SPDC

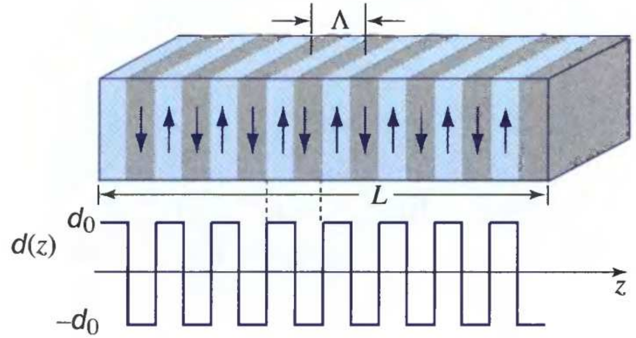
Long crystals + collinear interaction + Large nonlinear coefficient

+ 405-nm LD pump + 750–850 nm range + …

→quasi-phase matching (QPM) : **periodic poling**

$$\vec{k}_p(\omega_p, n_p(\omega_p, T)) = \vec{k}_s(\omega_s, n_s(\omega_s, T)) + \vec{k}_i(\omega_i, n_i(\omega_i, T)) + \frac{2\pi}{\Lambda(\vec{r}, T)}\vec{e}$$





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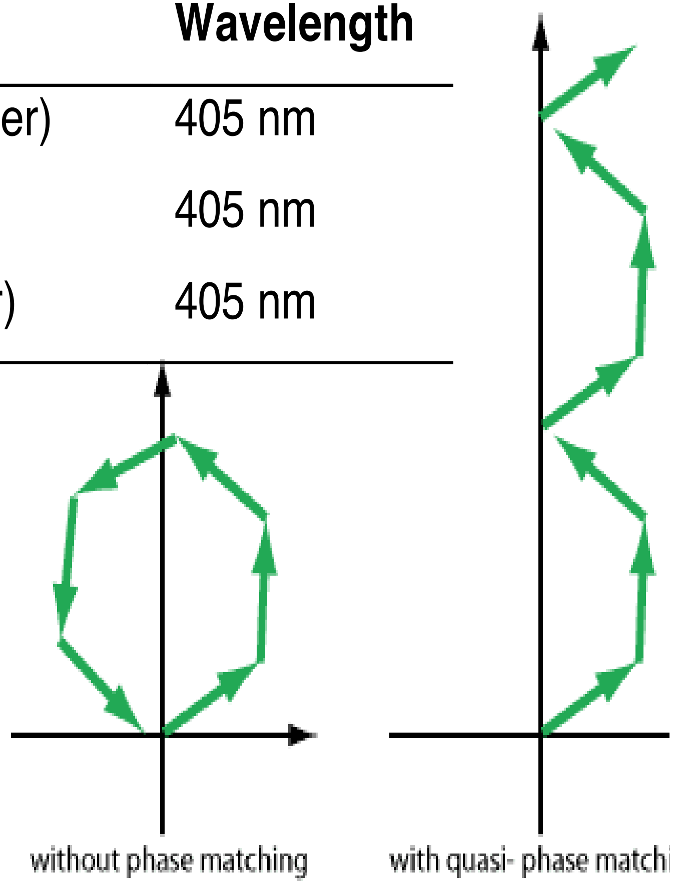
Periodic Poling: Efficient SPDC

type	Crystal	deff	Poling	Pump Wavelength
0	PPKTP	12 pm/V	3.35 µm (1st order)	405 nm
0	Mg:PPLN	20 pm/V	9 µm (9th order)	405 nm
II	PPKTP	2.5 pm/V	10 µm (1st order)	405 nm

ppKTP

+Photorefractive effect
+Gray-tracking
+Multiphoton absorption



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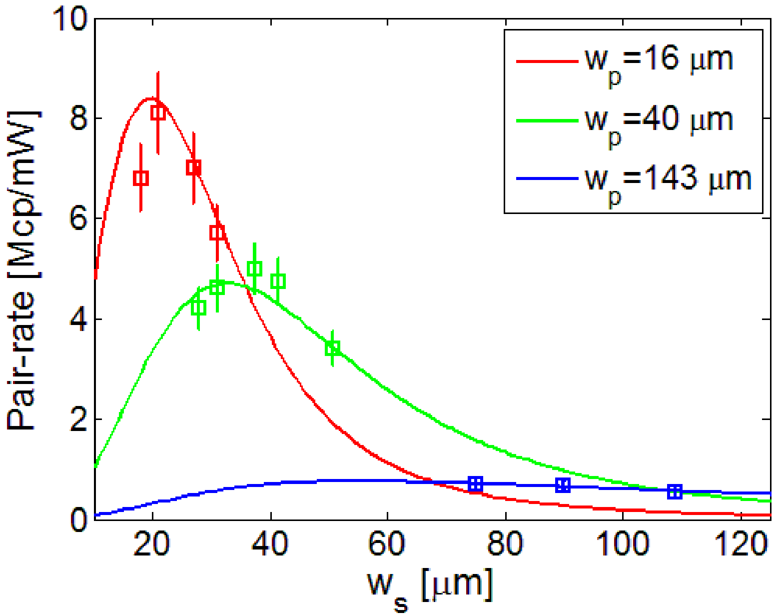
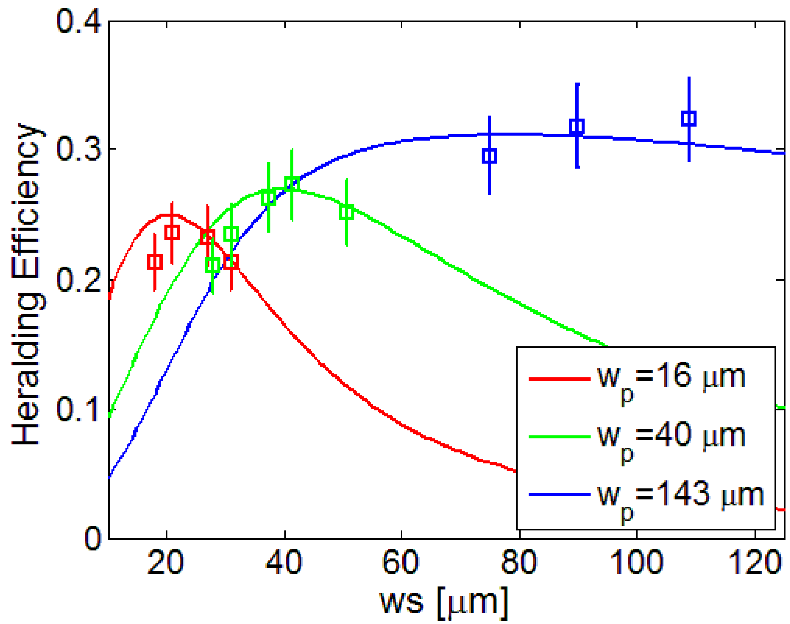
Optimized focus-conditions for 20-mm ppKTP

pair-rate favours small waists



pair-heraling favours larger waists



Trade-off between **pair-rate** and **heralding-efficiency**

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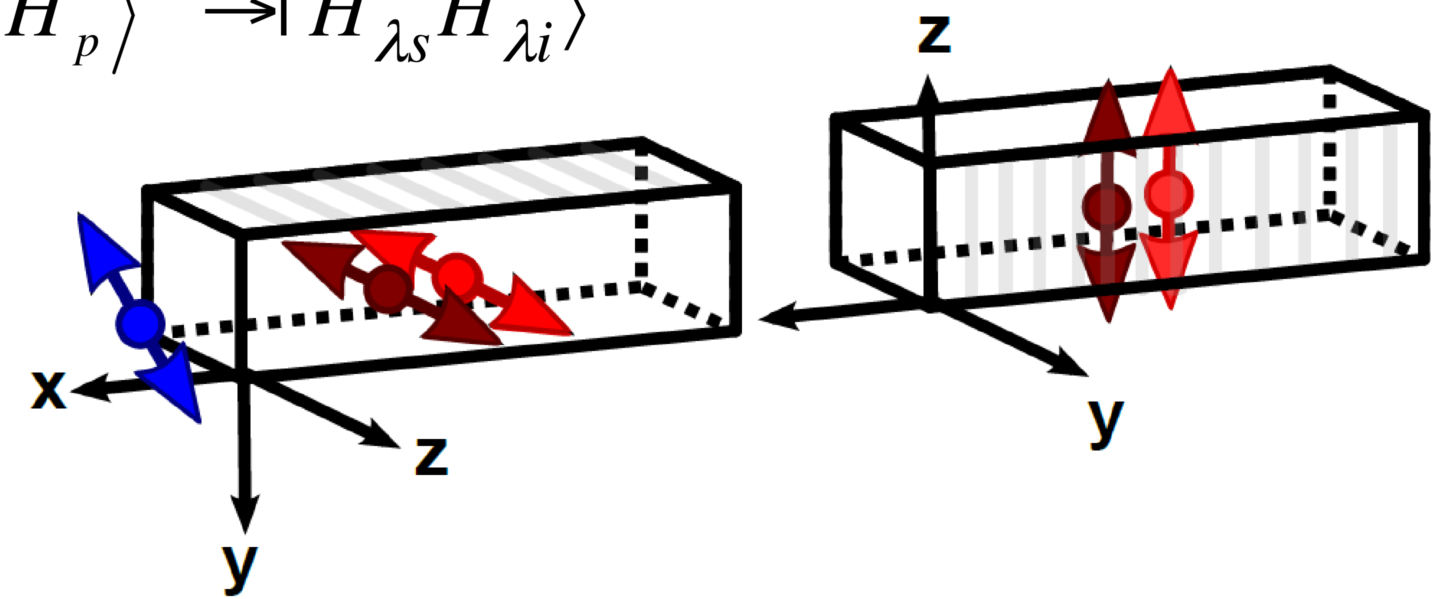
Approach: Spontaneous parametric down-conversion in crossed crystals

$$|V_p\rangle \rightarrow |V_{\lambda s}V_{\lambda i}\rangle$$

$$|H_p\rangle \rightarrow |H_{\lambda s}H_{\lambda i}\rangle$$

$$|H_p\rangle + |V_p\rangle$$



$$|\Phi(\varphi)\rangle = |H_{\lambda_s}H_{\lambda_i}\rangle + e^{i\varphi}|V_{\lambda_s}V_{\lambda_i}\rangle$$

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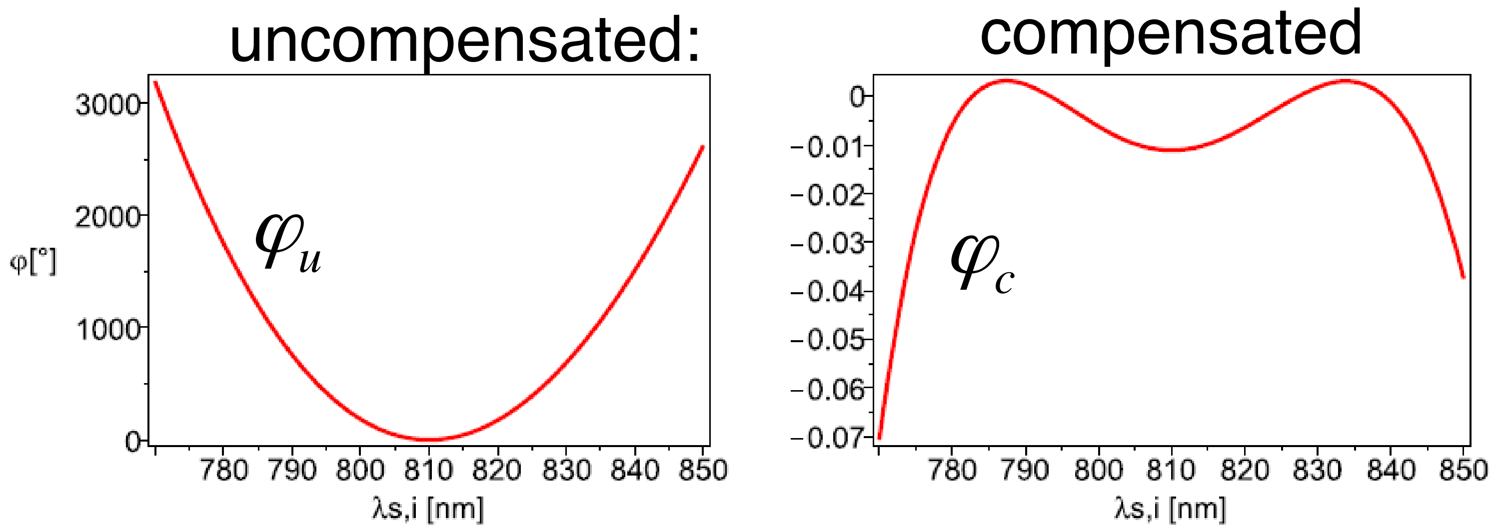
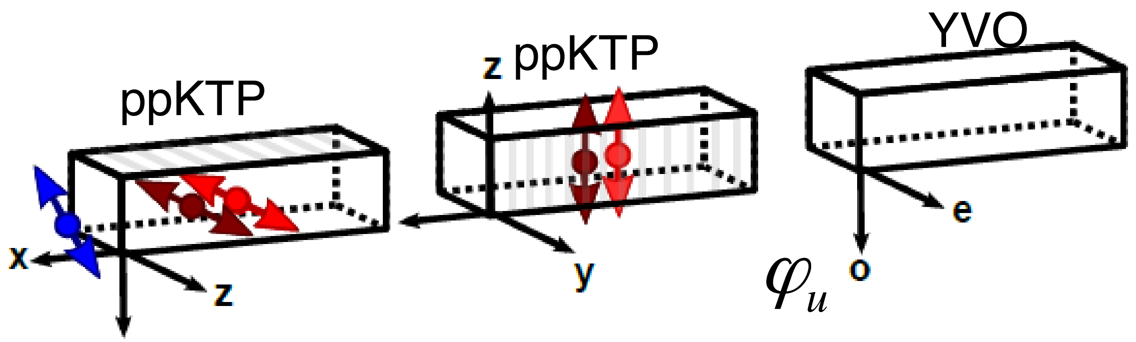
Kwiat et al. Phys. Rev. A 60, R773–R776 (1999)

YVO4 compensation-crystal flattens phase-map

$$|\Phi(\varphi)\rangle = |H_{\lambda_s} H_{\lambda_i}\rangle + e^{i\varphi(\lambda)} |V_{\lambda_s} V_{\lambda_i}\rangle$$





$$\varphi_c = \varphi_u + \varphi_{YVO}$$

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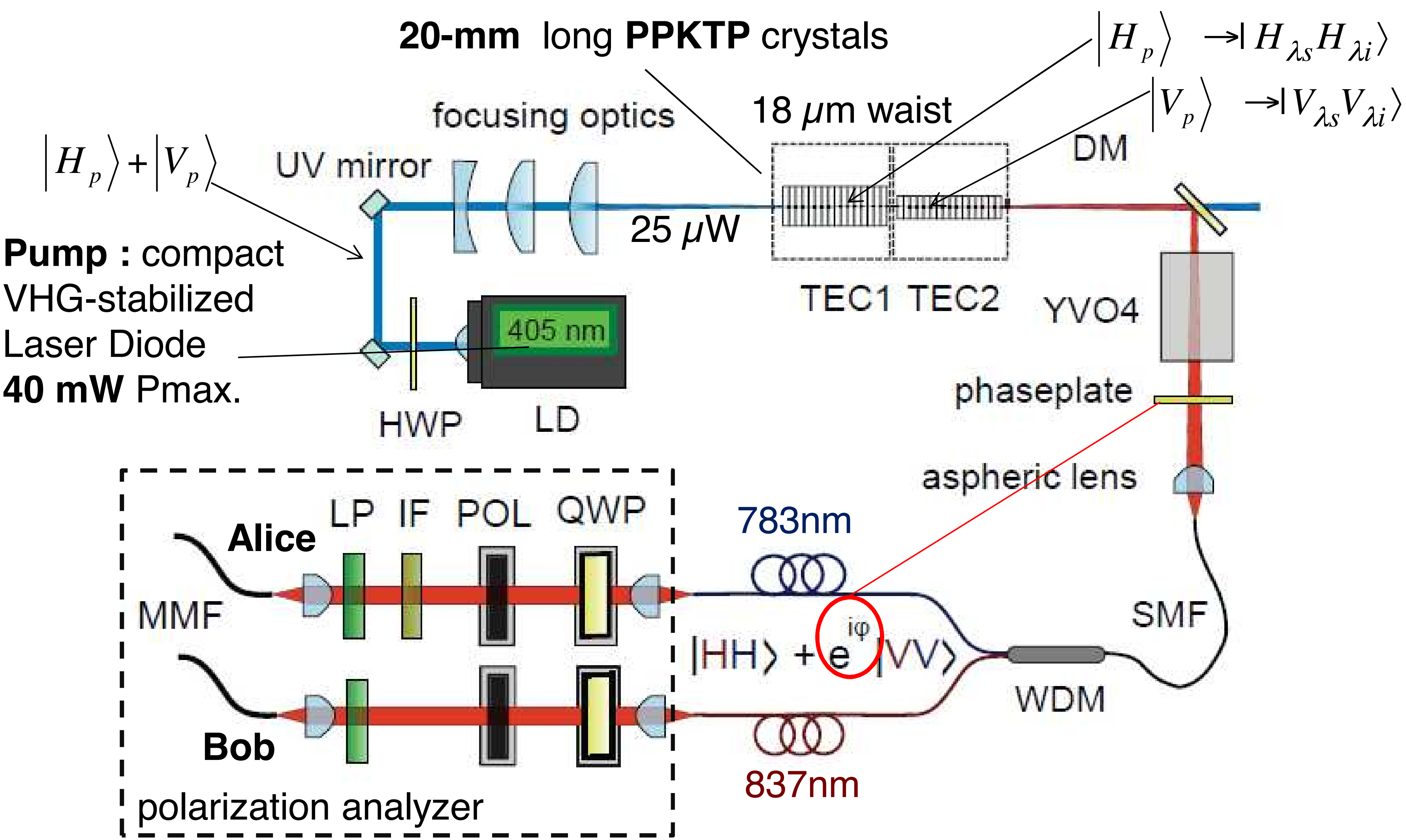
Trojek et al. Appl. Phys. Lett. ***92, 211103 (2008)***

Robust, compact EPS breadboard



Opt. Express ***20***, *9640-9649 (2012)*

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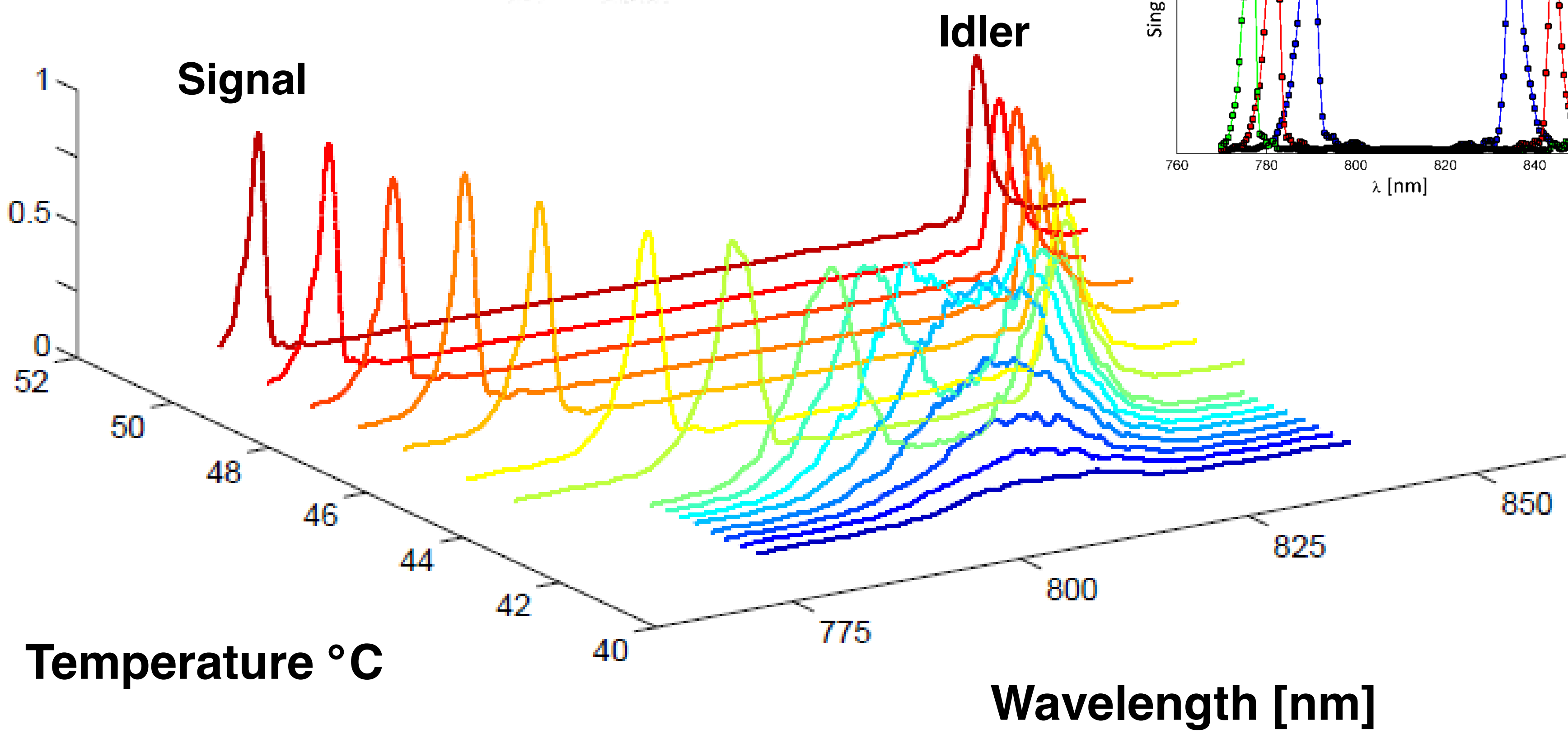
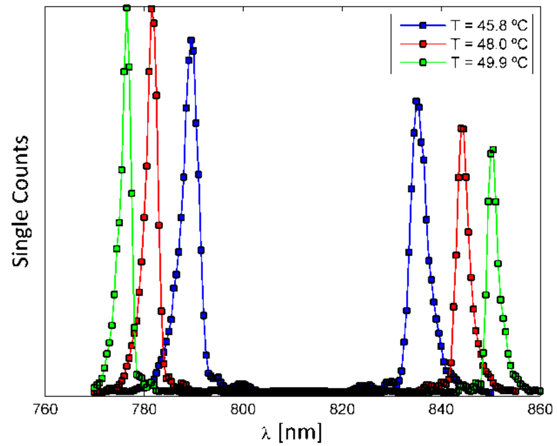
Spectral SPDC properties tailored to atmospheric transmission

$$S(\lambda_{s,i}) \propto sinc^2\left(\Delta k \frac{L}{2}\right)$$





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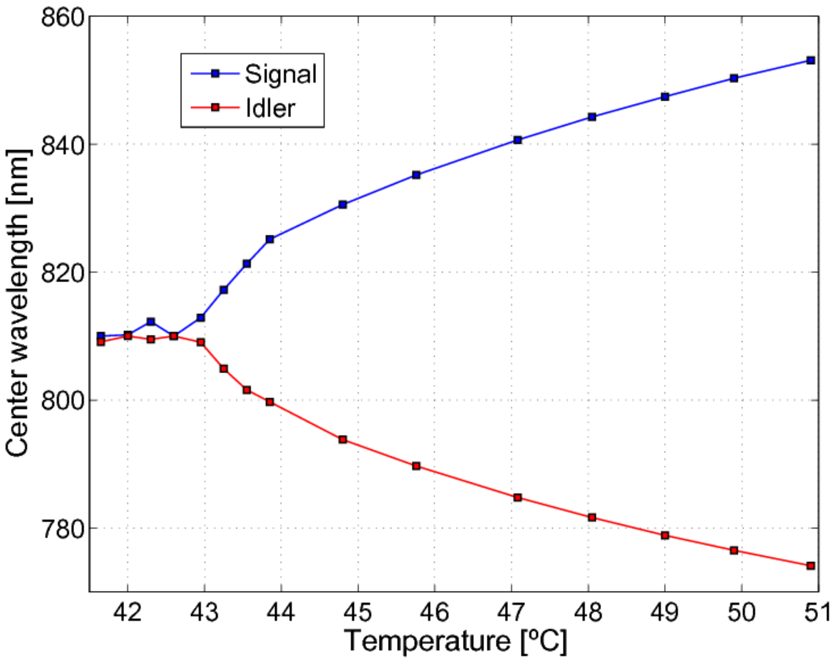
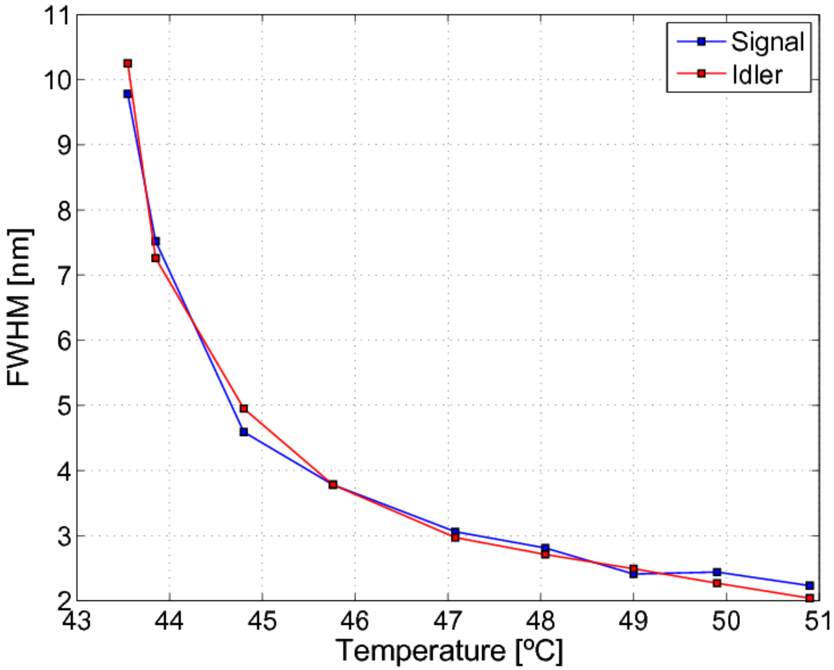
CWL & FWHM SPDC

Pump : 405.4 nm CW, ppKTP : 3.425 μm pp , Length: 20 mm





degeneracy increases with temperature

bandwidth decreases with temperature

Tunable around optimized wavelenght: **810 nm**

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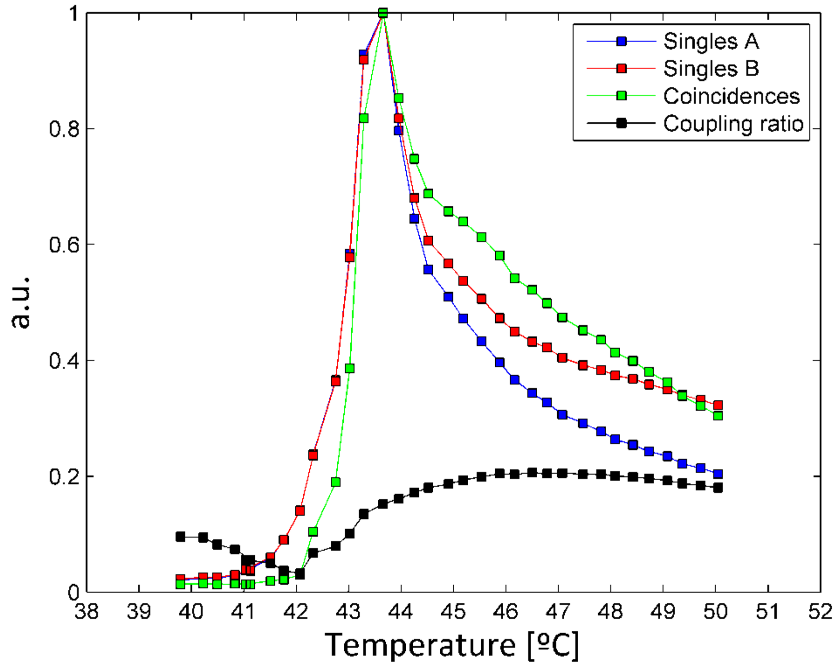
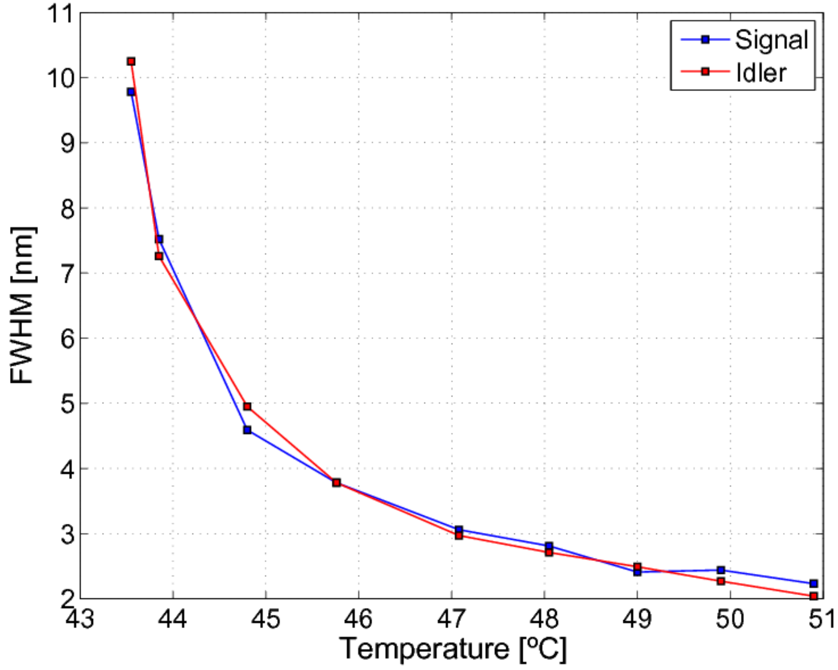
Brightness SPDC





Brightness peaks at degeneracy

~20 Mcp/mW

Spectral Brightness remains constant

~2 Mcp/nm/mW

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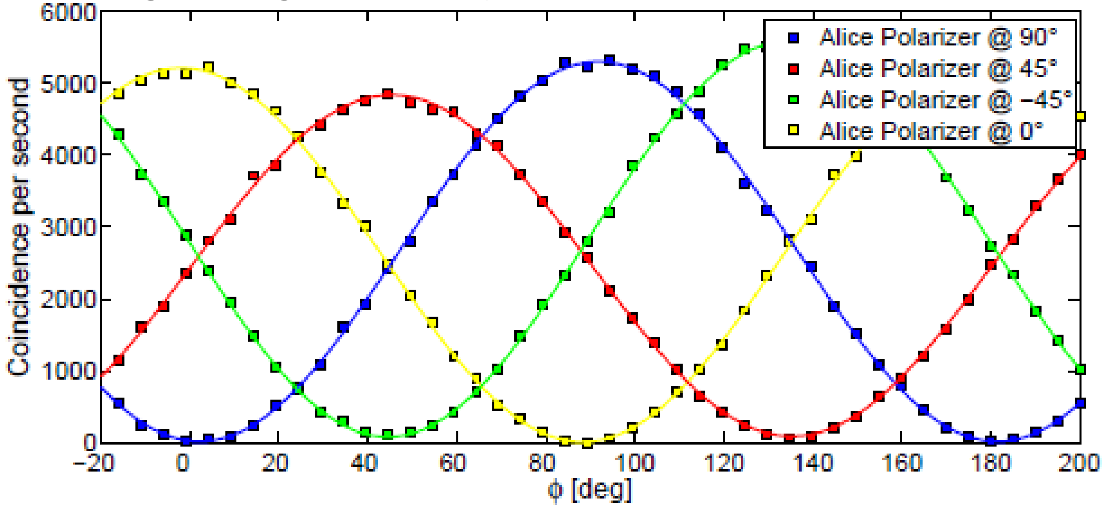
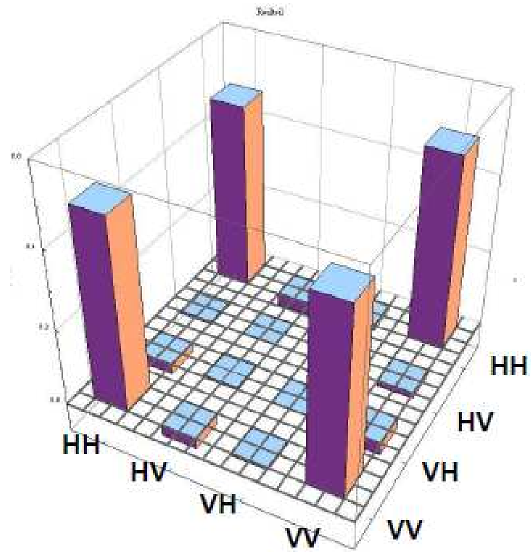
EQUO source exhibits unprecedented performance:

High fringe-visibility polarization correlations





High state-fidelity : **98%**

Optical bandwidth	**2.3 nm**
Visibility	**99.5 / 99.5 % H/V** **95.7 / 97.6 % D/A**
Detected spectral brightness	**278 kcps/mW/nm**
Normalized detection rate	**640 kcps/mW**
Heralding efficiency	**18 %**

pump power:
25 μW

no correction for losses!

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Flux generated exceeds saturation level of commercial SPADs

full pump power **40mW**

coincidences: R_c > 20 Mcps

$2 \times \frac{R_c}{0.18} \approx$ total singles: $R_s + R_i$ > 200 Mcps

SPAD saturation: ~10 Mcps

60 SPADs

(at 33% saturation level)

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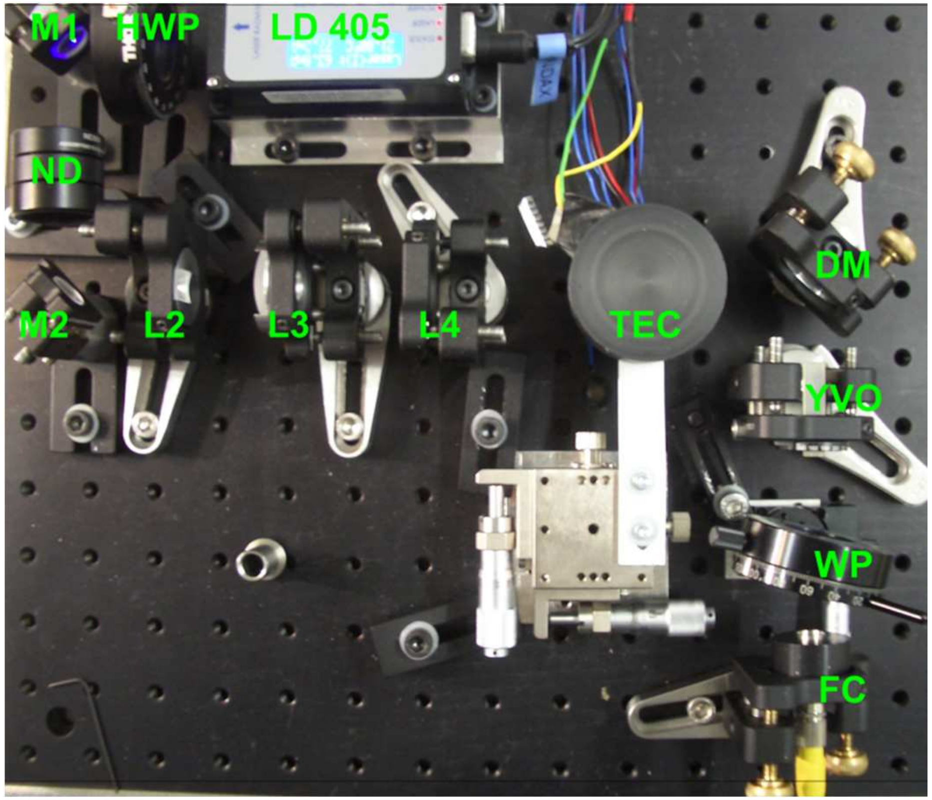
EQUO:robust, compact EPS breadboard based on space-proofable components



Main features EPS:

-high brightness (pairs/pump power). ✓
-high entanglement quality (visibility). ✓
-suitable for space transmission ✓
-robust, compact design ✓

equ0 LMU qutools IQI University of BRISTOL

European Space Agency Contract #:22542/09/NL/SFe

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Related literature

Quantum Cryptography/Communication review articles:

N. Gisin et al., Quantum Cryptography http://arxiv.org/abs/quant-ph/0101098
N. Gisin et al., Quantum Communication http://arxiv.org/abs/quant-ph/0703255
P. Kumar et al., Photonic Technologies for Quantum Information
http://www.stanford.edu/group/nqp/jv_files/papers/qucomp-review.pdf

ICFO examples for sources for quantum optics in free-space

M. Jofre et al. *Opt. Express, Vol.* ***19*** *, 3825-3834 (2011)*
F. Steinlechner et al. *Opt. Express* ***20****, 9640-9649 (2012)*

Books:

Fundamentals of photonics,
Bahaa E. A. Saleh, Malvin Carl Teich
The physics of quantum information
Dirk Bouwmeester, Artur K. Ekert, Anton Zeilinger
A Guide to Experiments in Quantum Optics
Hans-A. Bachor, Timothy C. Ralph

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Thanks for your attention!
Contact:
valerio.pruneri@icfo.es