Space-division multiplexing for quantum communication networks (MuRin)

Exploratory Action

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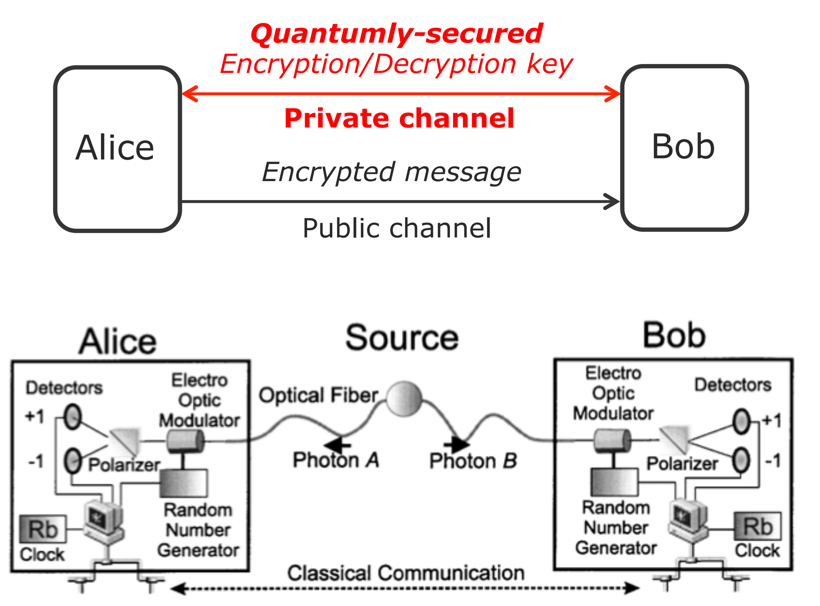
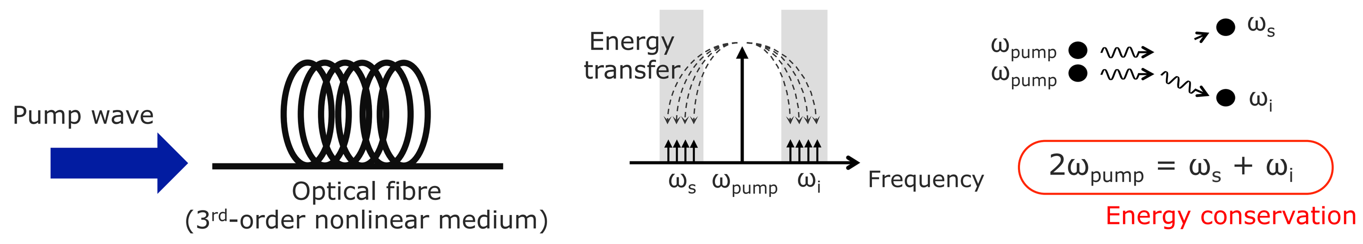
Introduction

Quantum cryptography



Setup for the E91 protocol (using entangled photon pairs)
[Jennewein *et al.*, *Phys. Rev. Lett.* **84**, 4729 (2000)]

Generation of photon pairs by spontaneous four-wave mixing in optical fibres



$2\omega_{pump} = \omega_s + \omega_i$ — Energy conservation

+ Phase-matching condition: $2\,\beta(\omega_{pump}) = \beta(\omega_s) + \beta(\omega_i)$

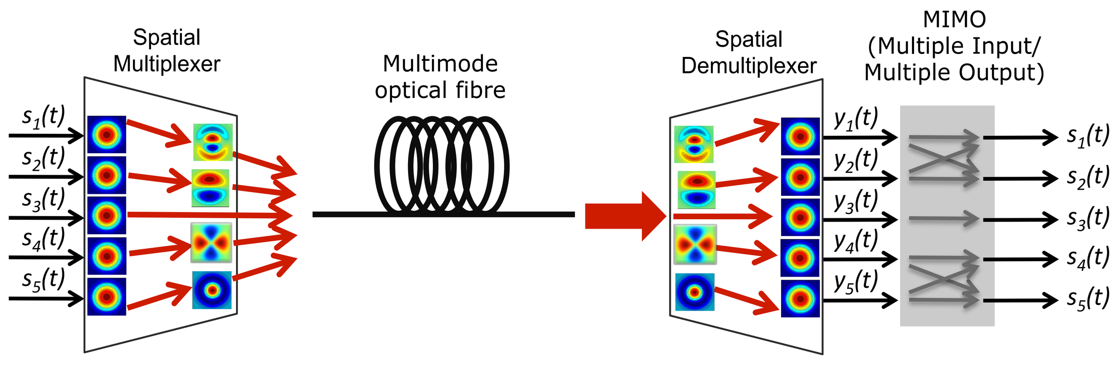
Propagation constant of the wave at frequency ω_{pump} (resp. ω_s and ω_i) in the medium

1. Phase matching can be **spectrally broad**
2. Phase matching depends on the **dispersive properties** of the medium

Space-division multiplexing for classical telecoms

- ✓ **Time-division multiplexing**
- ✓ **Wavelength-division multiplexing** (about 100 channels)
- ✓ **Polarization-division multiplexing** (x2)

➡ **Spatial dimension** was the last unexploited degree of freedom of light propagating in optical fibres for increasing the data transmission capacity



The challenge

How to distribute, from a single source, entangled photon pairs in a multi-user network?

A critical issue in the framework of industrial deployment of large-scale quantum-secured communication networks

Project structure

① **Modelling** of nonlinear light propagation and generation of photon pairs by spontaneous four-wave mixing (FWM) in few-mode optical fibres (FMFs)

- **Numerical modelling** of inter-modal FWM in classical (amplification) regime — *Exploratory Action*
- **Semi-classical analytical modelling** of inter-modal FWM in spontaneous regime

② **Experimental development** of the fibred multimode photon pair source

- **Design, fabrication and characterization** (linear and nonlinear properties) of the device
- **Generation of photons pairs** by inter-modal FWM and **characterization of the pairs** (spectral and modal properties, generation efficiency, quantum purity)

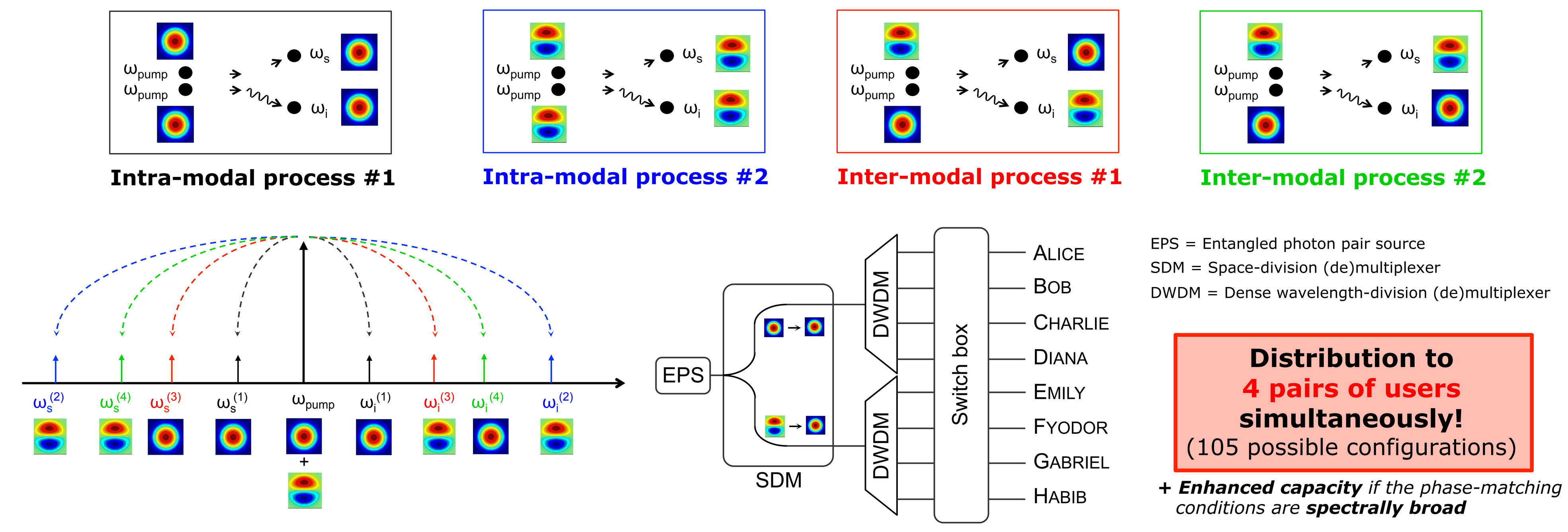
③ **Entanglement of the pairs** and **distribution by wavelength- and space-division multiplexing**

Our approach

Multi-user distribution of photon pairs by space-division multiplexing

Reminder: Phase matching depends on the **dispersive properties** of the medium, thus **on the transverse propagation modes** that are involved in the process. ➡ *If several modes are possible, then several phase-matching conditions can be satisfied.*

Simplest case: In a 2-mode fibre, if the pump is injected into both of the modes, 4 distinct four-wave mixing processes can be expected:



Distribution to 4 pairs of users simultaneously! (105 possible configurations)

+ ***Enhanced capacity*** *if the phase-matching conditions are* ***spectrally broad***

Exploratory Action – *Numerical study of inter-modal four-wave mixing in few-mode optical fibres*

Numerical modelling of nonlinear light propagation in few-mode optical fibres

Numerical resolution (split-step Fourier method) of the **nonlinear Schrödinger equation in multimode regime** [1] (which describes the propagation of electromagnetic waves in few-mode optical fibres)

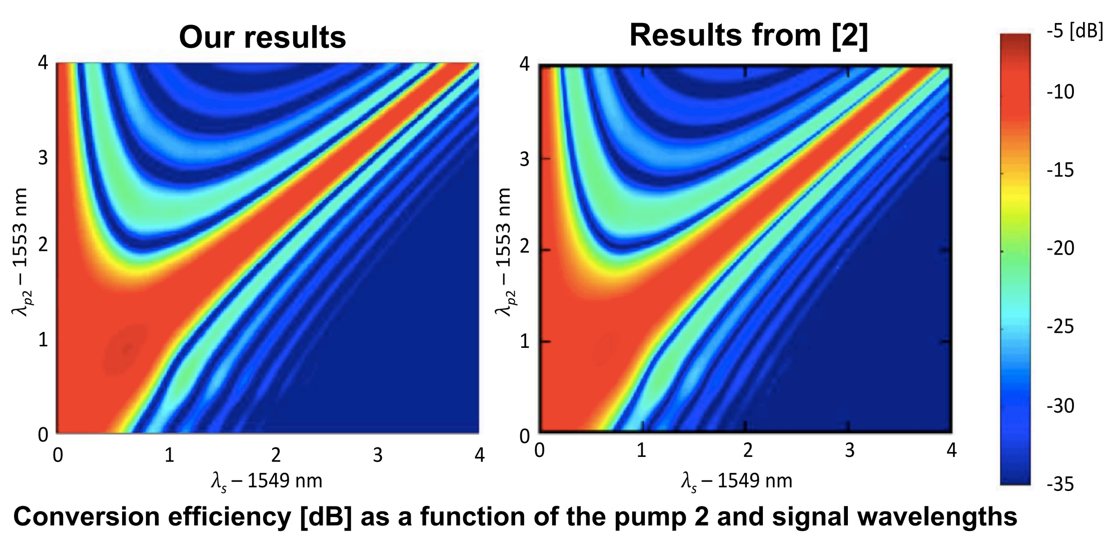
Validation by comparison with the numerical results reported in [2]

Comparison parameter:

$$\text{Conversion efficiency} = \frac{\text{Output power at } \omega_i\ (= \omega_{p1} + \omega_{p2} - \omega_s) \text{ in } LP_{11}}{\text{Output power at } \omega_s \text{ in } LP_{01}}$$

Simulated configuration:

	Pump 1	Pump 2	Signal
Wavelength	1549 nm	From 1553 to 1557 nm	From 1549 to 1553 nm
Input power	27,5 dBm	27,5 dBm	3,5 dBm
Transverse propagation mode	LP_{01}	LP_{11}	LP_{01}



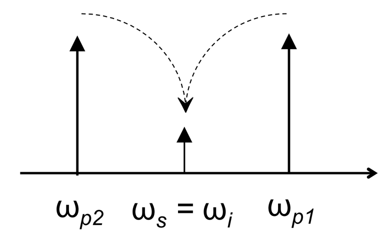
Conversion efficiency [dB] as a function of the pump 2 and signal wavelengths

[1] F. Poletti and P. Horak, *J. Opt. Soc. Am. B* **25**, 1645 (2008)
[2] S. Friis *et al.*, *Opt. Express* **24**, 30338 (2016)

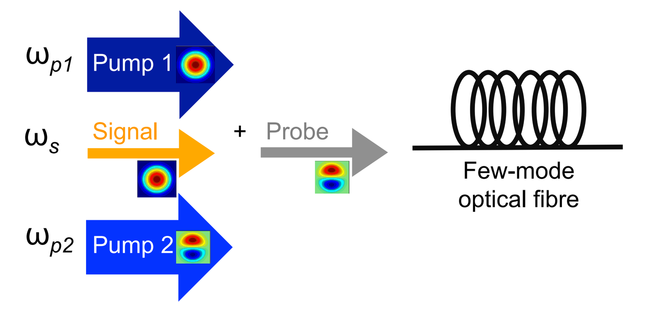
Application: Phase-sensitive amplification by inter-modal four-wave mixing

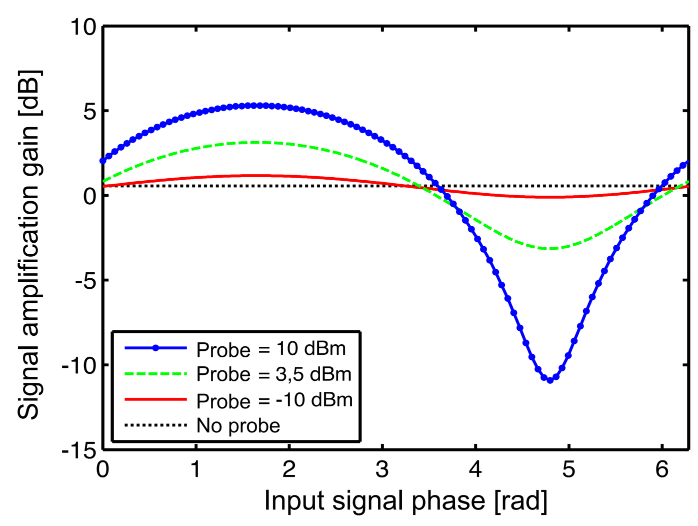
Particular case where signal and idler waves are *frequency degenerate*

$$\omega_s = \frac{\omega_{p1} + \omega_{p2}}{2}$$



Injection of a *probe wave* at the same frequency as the signal, but in the other transverse mode





Two distinct IM-FWM processes simultaneously occur, leading to interferences that can **inhibit or enhance the signal amplification** (depending on the phase of the input signal wave).

The extinction ratio (contrast between enhancement and inhibition) can be adjusted by tuning the input probe power.

Results of the Exploratory Action & Future prospects

Results of the Exploratory Action

1. Implementation and validation of a numerical model for the nonlinear propagation of light in few-mode optical fibres (FMFs) in classical regime
   ➡ **Essential tool for the entire project**
2. Numerical investigation of phase-sensitive amplification (PSA) by inter-modal four-wave mixing (IM-FWM) in FMFs
3. Initiation of discussions between the Optics, Networks, and Security communities to **instigate trans-disciplinary collaborations** for the development of **new technological resources and know-hows for the next generation of secured networks** (data transmission in multimode optical fibres, security of short-reach networks such as data centres, etc.)

Short-term Prospects

1. Experimental demonstration of PSA by IM-FWM in FMFs
2. Entry into the quantum regime (spontaneous IM-FWM) in order to generate photon pairs that could be exploited for e.g. quantum cryptography protocols

➡ **Towards the demonstration of generation, entanglement, and space-division multiplexing-based distribution of photon pairs by spontaneous IM-FWM in FMFs**