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# Near-perfect two-photon interference at a telecom wavelength using picosecond regime separated sources

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We report on a two-photon interference experiment in a quantum relay configuration for long distance quantum communication at a telecom wavelength. In contrast to already reported regimes, namely femtosecond and CW, we propose for the first time to employ the picosecond regime which allows achieving a near-perfect visibility two-photon interference using only standard telecom components and detectors. Our experiment is based on two photons at 1550 nm emitted by two separate PPLN waveguides. We show a net interference visibility of 99% which clearly proves the very high potential of our experimental scheme to achieve quantum networking applications in real conditions.

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Keywords: Quantum Communication, Two-photon interference, Guided-wave Optics

In this paper, we demonstrate that the picosecond regime of operation associated with a guided-wave scheme should have important repercussions for quantum relay implementations, essential for improving both the working distances and the efficiency of quantum cryptography and networking systems [1, 2].

At the end of the 70's, physicists started to develop entanglement based quantum experiments for testing the completeness of quantum theory [3]. They soon realized that quantum physics could be strongly related to information theory, and introduced the notion of quantum bits (qubits) as superpositions of  $|0\rangle$  and  $|1\rangle$  states associated with any two dimensional quantum system observable. Currently, single and pairs of entangled qubits are seen as resources for quantum information and communication protocols, among which quantum key distribution is seen as a major application [1]. The experimental potential of quantum communication, i.e. dealing with qubits encoded on photons, relies on the ability to generate, distribute, and manipulate qubits. In this context, teleportation of single qubits [4] and entanglement swapping between pairs of qubits [5–8] are practical examples.

Photon coalescence lies at the very heart of these quantum operations and is seen as a first step towards achieving both teleportation and entanglement swapping. This effect has been extensively studied both theoretically [9, 10] and experimentally, initially based on two photons coming from a single downconversion source and therefore sharing both a common past and clock [11]. However, experiments involving truly independent photons represent an important challenge in quantum communication since this is the key to achieving longer quantum links by means of quantum relays based on teleportation or entanglement swapping schemes [2, 6–8, 12]. Such achievements appear to be much more difficult since a perfect synchronization between the related sources is necessary to prevent from any kind of distinguishability. Unfortunately, beyond the fundamental interest of

these previous demonstrations, the reported interference visibilities remain far from the near 100% needed for practical implementations [13]. For these experiments, the reduced visibilities are always associated with partial distinguishability due to the operating regimes, namely femtosecond or CW, placing highly stringent constraints on both the employed material and components.

Here, we demonstrate for the first time why the picosecond regime provides an efficient trade-off permitting the attainment of a near-perfect two-photon interference visibility, while using standard components available from the telecommunications industry. We realized a guided-wave optics experiment based on two periodically poled lithium niobate (PPLN) waveguides emitting photons around 1550 nm and report the highest two-photon interference visibility, i.e. of 99%, ever demonstrated in a quantum relay configuration. This emphasizes why guided-wave technology and the use of the picosecond regime should lead to realistic quantum relay schemes. In the following, we shall first introduce the quantum relay principle and discuss why the picosecond regime is a valuable trade-off. We then focus on our picosecond regime demonstration. Finally, we detail a comparative study of performance with similar reported experiments.

When considering long distance quantum communications, the preferred qubit carriers are photons at 1550 nm allowing the users, namely Alice and Bob, to use optical fibers for distribution purpose. However, even if telecom fibers show propagation losses as low as 0.2 dB/km at 1550 nm, ultimately, dark counts in the detectors limit both the signal-to-noise ratio (SNR) and the maximum achievable distance. The quantum relay function, based on quantum state teleportation, allows partially overcoming this problem [2]. Teleportation success is indeed validated by the emission of an electrical signal which is eventually used as a trigger for Alice and Bob's detectors. It therefore reduces the overall channel noise by turning on the detectors only when the probability of having a pair

of qubits available at Alice and Bob locations is high.

A basic scheme of a quantum communication link in the entanglement swapping relay configuration is shown in FIG.1. In this figure, two properly synchronized sources (EPR) produce two photon pairs, one at each source. Sending the two inner photons that share no common past to the BS projects them onto an entangled state thanks to a Bell state measurement stage (BSM). Using a dedicated detection, entanglement can be swapped from these photons to the outer ones making Alice and Bob connected by entanglement, as if they had received each one photon from an entangled pair directly. In terms of SNR, we see in FIG.1 that Alice and Bob photons have actually travelled only one half of the total distance, the other half being covered by the two inner photons which give rise to a heralding signal when entanglement swapping is successful. Thus, two-photon interference is a means to entangle independent photons and to connect two remote locations by such a quantum operation. Note that for quantum networking applications, it has been demonstrated theoretically in Ref. [13] that a two-photon interference net visibility of at least 95% is required for practical implementations using currently available photon pair sources and multimode quantum memories.

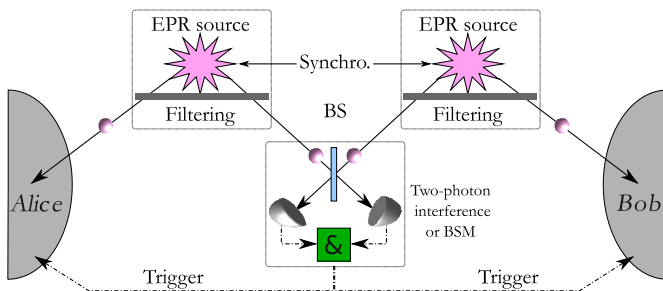


FIG. 1: Schematics of a quantum relay involving two pairs of entangled photons emitted synchronously. After separation of the pairs, the two inner photons are sent onto a BS where a joint-measurement, or Bell state measurement (BSM) which is based on two-photon interference, is performed. This results in projecting these two photons onto an entangled state, and, accordingly, the outer ones onto the same state. The two inner photons detection is used as a heralding signal of a successful entanglement swapping. The filtering stages in each sources is necessary to prevent any distinguishability.

Theoretically, the photons can come from any type of source, provided they are identical before the BS (pre-selection) or before the detectors (post-selection). In any case, synchronizing the two EPR sources is of great importance to prevent any kind of distinguishability.

Synchronization essentially depends on the pump laser regime employed in the EPR sources and is also strongly related to the filtering stages placed on the path of the emitted paired photons. From the experimental side, this two-fold issue amounts to the need of erasing any temporal distinguishability between the two interfering

photons. Here, we have to compare the coherence time,  $\tau_{\text{coh}}$ , of these two photons to the time uncertainty,  $t_{\text{uncert}}$  within which they are created (i.e. the pulse duration of the pump laser(s)) or are detected (detector's timing jitters), which can be written as:

$$\tau_{\text{coh}} \geq t_{\text{uncert}} \quad (1)$$

Suitable bandpass filters are therefore employed to achieve optimal interference visibilities. Up to now, this issue has been addressed using different approaches based on pulsed or CW lasers (see also Table I for comparison).

On the one hand, the first experiments reported two independent crystals pumped by a single laser operating in the femtosecond regime [5]. The reason for this lies in the fact that this regime allows operating with broadband filters, i.e. on the order of a few nm. However, the large photon bandwidths makes them more prone to chromatic or polarisation dispersions and leads to reported visibilities below 85% when the photons travel in optical fibers. When two independent lasers are used, one has to take into account the synchronization difficulty since the two related laser cavities have to be driven so as to be identical within the pump pulse duration, which is usually on the order of 100 fs [6, 7]. Additional efforts have therefore to be provided to actively drive the two laser cavities together using phase-locked loops or atomic clocks and dedicated electronics [14, 15]. Any remaining jitter between the two lasers will have to be compensated by narrowing the filters which implies a substantial reduction of the pair production rate for equivalent powers.

On the other hand, the development of narrow-bandwidth fiber Bragg grating (FBG) filters allows using two independent CW lasers stabilized against an atomic transition. Since the CW regime does not provide any reference clock, the timing function is transferred to the coincidence detection after the BS. To ensure a high quality interference, the photons have to show a coherence time longer than the jitter of the employed detectors. Experimentally, entanglement swapping is made possible using a suitable combination of low-jitter detectors (based on superconducting or up-conversion technologies), on the order of 70 ps, associated with ultra-narrow FBG filter bandwidths, on the order of 10 pm [8, 16]. In such a situation, one gets rid of the synchronisation but the price to pay is rather high in terms of sensitive fluctuations of the filters central wavelengths, low experimental rates due to the narrow filters coupled to the randomness of entangling photons coincidence detection, and rather high statistical fluctuations due to low count rates. All these features prevent reaching high visibilities.

Between these two extremes, the picosecond regime appears to be an efficient compromise. First, the timing condition (1) is easily met by using FBG filters showing much larger bandwidths than in CW, i.e. on the order of 100 pm [12]. In addition to the FBGs, this also

allows taking advantage of off-the-shelf telecommunications components, such as standard InGaAs avalanche photodiodes (APD), optical circulators, and 50/50 couplers. Eventually, synchronizing two picosecond lasers is a much easier task compared to synchronizing two femtosecond lasers. Note that synchronization up to 1 ps can be achieved by simply distributing a common clock by means of a standard telecom pulsed laser between Alice and Bob. All these features should permit the implementation of realistic quantum relays.

As shown in FIG.2, our experiment is based on two of our PPLN waveguides, known for their high efficiency and easy handling [8, 18]. They are pumped by a picosecond laser at 768 nm and both designed to produce identical degenerate paired photons at 1536 nm within a bandwidth of 50 nm (spectrum not represented).

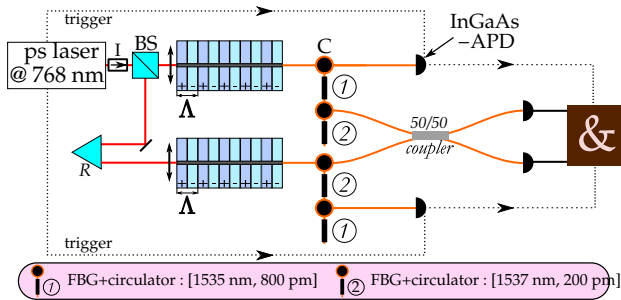


FIG. 2: Coalescence experiment based on two PPLN waveguides pumped by a single picosecond laser ( $\lambda_p = 768$  nm,  $\Delta\lambda_p = 0.25$  nm, Coherent MIRA 900-D) which provides 1.2 ps duration, Fourier-transform limited, pulses, at a repetition rate of 76 MHz. A very weak part of this beam is sent to a silicon APD (not represented) whose output serves as the laser clock to trigger four InGaAs-APDs (id-Quantique 201).  $\Lambda$ : poling period of the PPLN waveguides; I: isolator; R: retro-reflector; C: circulator; &: AND-gate.

The pump laser is first sent to a BS whose outputs are directed towards two PPLN guides. From each source, we select pairs of photons meeting the Fourier transform criterion using narrowband demultiplexers made of two optical circulators and a pair of FBG filters. These are set to reflect energy-matched pairs of wavelength at 1537 nm and 1535 nm, associated with bandwidths of 800 pm and 250 pm, respectively. A slightly wider (800 pm) filter is used on the long wavelength (1537 nm) photons mainly to minimise losses. This filtering solution based on standard telecom components provides a simple way to separate the photons at the output of the waveguides and makes them each available in a single mode fiber [8]. We have estimated the 250 pm filter bandwidths to accommodate the 1.2 ps-width of the laser pulses and any possible jitter due to laser synchronization up to 4 ps. However, as in Refs. [5, 12], we used a single laser which is sufficient for a proof-of-principle demonstration. Regarding this, the two lasers in Ref. [6] are not truly independent since they share the same Ti:Sapphire crystal Kerr medium for

precise synchronization. To observe the two-photon interference, the four-fold coincidences are detected thanks to four InGaAs-APDs triggered with the laser clock. The evolution of the effective five-fold coincidence rate is given in FIG.3 in which a remarkable dip is obtained when the delay between the two inner photons is zero.

Using 1 mW of pump power per source, we obtained  $4 \times 10^3$  coincidences per hour per source which corresponds in term of normalized rate to  $1.6 \times 10^3$  pairs·s<sup>-1</sup>·pm<sup>-1</sup>·mW<sup>-1</sup>. When the two photons are made indistinguishable in time ( $\delta t$ ) thanks to the adjustment of the retro-reflector (R) and spectral modes, a  $93\% \pm 3\%$  reduction in the raw five-fold coincidence count rate is obtained. Moreover, the net five-fold coincidence count rate, i.e. when the accidental coincidences are subtracted, reaches  $99\% \pm 3\%$ . The width at half the height of the dip is approximately  $\Delta\tau = 11$  ps, which is well in agreement with the coherence time of 14 ps associated to our filtering stages. This interference visibility is extremely close to the maximum value of 99.9% that can be obtained from theory taking into account our filtering bandwidths, as properly outlined in Refs. [10, 17, 19].

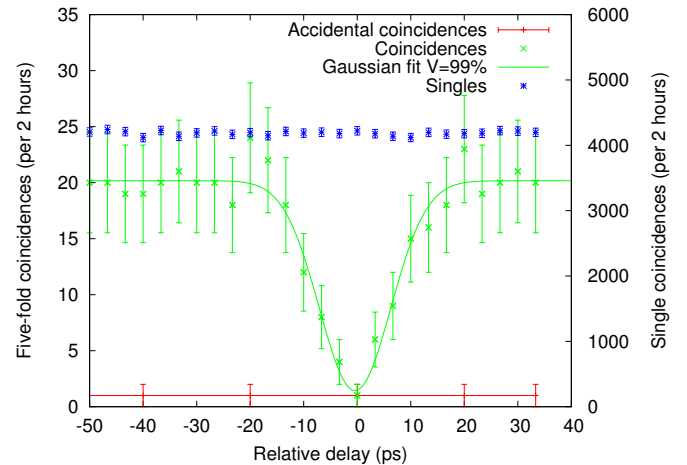


FIG. 3: Five-fold coincidence rate as a function of the relative delay,  $\delta t$ , between the interfering photons. We clearly observe a dip for  $\delta t = 0$  that reaches the noise level. The Gaussian fit of the interference pattern shows a net visibility of  $99\% \pm 3\%$ . We also plotted one of the average single count rates.

Table I presents the results reported in the literature. From the experimental point of view, all the different configurations can be summarized in four key points: (i) the type of nonlinear generators, (ii) the emitted photon wavelengths, (iii) the pumping regime and its associated time uncertainty, (iv) and, finally, the applied filtering bandwidths and their associated coherence times. From a comparison of all the reported configurations, it appears that the combination of the picosecond regime and the single mode properties of the employed telecom components is the most performant scheme. It allows matching efficiently the inequality (1) and obtain-

TABLE I: Compared two-photon interference visibilities, source's brightness, and whole experimental coincidence rates, between reported works in continuous wave (CW), picosecond (ps), and femtosecond (fs) regimes. Regarding time uncertainties, note that the first number is always associated with the pulse duration while the  $\pm$  sign corresponds to the synchronisation jitter if two pulsed lasers are involved. In contrast, the time uncertainty for the CW case is associated with the detector's timing jitters. The coherence time is calculated for Gaussian filters using the standard relation  $\tau_c = 0.44 \frac{\lambda^2}{c\Delta\lambda}$ . Here, the net visibility is given after subtraction of the accidentals originated by the detectors dark counts.

Reference	Source	Wavelength <i>nm</i>	Brightness <i>pair/s/pm/mW</i>	Regime <sup>a</sup> (time uncertainty)	Filter bandwidth (coherence time)	Rate <i>pair/s</i>	Raw visibility	Net <sup>b</sup> visibility
Geneva [8]	PPLN/w	1550	$0.9 \times 10^3$	2 × CW (70 ps)	0.01 nm (350 ps)	$3 \times 10^{-3}$	NA	77%
Nice	<b>PPLN/w</b>	<b>1550</b>	$1.6 \times 10^3$	1 × <b>ps (1.2 ps)</b>	<b>0.25 nm (14 ps)</b>	$3 \times 10^{-1}$	<b>93%</b>	<b>99%</b>
Bristol [12]	Fiber	600	NA	1 × ps (1.5 ps)	0.3 nm (1.8 ps)	$4 \times 10^{-1}$	88%	NA
Geneva [17]	Bulk LBO	1310	NA	1 × fs (200 fs)	5 nm (500 fs)	$7 \times 10^{-1}$	77%	84%
Beijing [6]	Bulk BBO	800	$1.2 \times 10^{-2}$	2 × fs(60 ± 2 fs)	2.8 nm (335 fs)	$3 \times 10^{-2}$	NA	82%
Vienna [7]	Bulk BBO	800	NA	2 × fs (50 ± 260 fs )	1 nm (940 fs)	$6 \times 10^{-1}$	NA	83%

<sup>a</sup>In this column, the figures associated with the pump regimes correspond to the number of employed lasers.

<sup>b</sup>The net visibility is given after subtraction of the accidentals initiated by the detectors noise.

ing near-perfect two-photon interference. For practical long distance quantum communication, it is also interesting to compare the rates in terms of effective number of created pairs per second Alice and Bob actually receive. This figure of merit is calculated by normalizing the four-fold coincidence rates with respect to Alice and Bob detectors efficiency. A comparison with similar entanglement swapping configurations at telecom wavelengths indicates that the picosecond regime allows maintaining a high effective pair production rate equivalent to the femtosecond regime but shows a much higher visibility. One should note the two orders of magnitude rate difference for equivalent source technologies and brightness between the CW and picosecond regimes.

The results demonstrated in this experiment are of broad interest since the obtained net visibility is the best value reported to date for competing configurations. According to reference [13], this allows considering for the first time the possibility to use quantum relays in actual quantum cryptography networks. In this context, where two synchronized lasers would be used, we expect results of the same order due to easy picosecond synchronization and well-fitted filter bandwidths.

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