Advances in quantum communication using integrated optics

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Abstract - *In this paper, we investigate the possibility of increasing the maximal achievable transmission distance of a one-way quantum key distribution link using integrated optical technology on $LiNbO_3$. Based on our experience on guided-wave quantum communication, we studied numerically and fabricated a telecom oriented chip that merges all the necessary optical functions at the heart of a quantum relay based on the quantum teleportation scheme. We report here on experimental characterizations in both classical and single photon counting regimes of this first "quantum relay chip" that allow predicting an improvement of the maximal achievable distance by a factor of 1.8.*

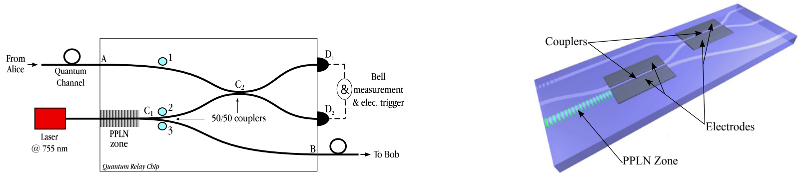
Introduction on quantum communication

In our everyday world, almost all the information exchanged, stored, and processed is encoded using elementary entities called bits, conventionally represented by the discrete values 0 or 1. In today's fiber-based telecommunications systems, these classical bits are carried by light pulses, corresponding to macroscopic packets of photons, allowing a classical description of their behaviour and propagation. To draw a simple picture, each light pulse consists of at least hundreds of photons to encode the bit value 1, or of no photons to encode the bit value 0.
In the past twenty years, physicists have realized that individual quantum objects, for instance photons, could also be employed to deal with another kind of information. Here information is no longer encoded on the number of involved photons, but individual photons merely serve as carriers and quantum information is encoded on their quantum properties, like polarization or time-bins of arrival [1]. Indeed, by selecting two orthogonal states spanning the Hilbert space, $|0\rangle$ and $|1\rangle$ now encode the 0 and 1 values of the quantum bit (qubit), and quantum superposition makes it possible to create states of the form $|\psi\rangle = \alpha|0\rangle + e^{i\phi}\beta|1\rangle$, provided α and β follow the normalization rule $|\alpha|^2 + |\beta|^2 = 1$.
A profound way in which quantum information differs from classical information lies in the properties, implications, and uses of quantum entanglement when two or more particles are involved in the considered quantum system. Here, the information contained in such a system is stored in the form of quantum correlations between the subsystems and have no classical analog. Entanglement is a generalization of the superposition principle to multi-particle systems but in this case the entangled state describing the whole system cannot be factorized, i.e. written as a tensor product of the properties associated with each subsystem. For instance, entangled pairs of qubits implying two particles can be described by a state of the form $|\Phi\rangle_{A,B} = \alpha|0\rangle_A|0\rangle_B + e^{i\phi}\beta|1\rangle_A|1\rangle_B$, with $|\alpha|^2 + |\beta|^2 = 1$, where indices A and B label the two qubits. Then, measuring for instance qubit A provides a random result, but if we find it to be $|0\rangle$ (with probability $|\alpha|^2$), we learn from the

entangled state that qubit B will be found in the same state for a similar measurement, and conversely for $|1\rangle$. These are the correlations exploited in quantum communication.
Let us emphasize that $\{|0\rangle, |1\rangle\}$ can represent any observable related to the considered quantum system. Moreover, from an abstract point of view, the nature of the carrier is irrelevant because only amplitudes and relative phases are exploited in the above states to encode the qubits. It is clear however that photons are the natural "flying qubit carriers" for quantum communication, and the existence of telecommunication optical fibres makes the wavelengths of 1310 and 1550 nm particularly suitable for distribution over long distances.
Quantum communication protocols, such as quantum key distribution (QKD), quantum teleportation [3] and entanglement swapping [4], mainly deal with single qubit and entangled qubit resources. Particularly, QKD offers a provably secure way to establish a confidential key between distant partners commonly called Alice and Bob [2] and is already commercially available [2]. In spite of progress in photonics and telecommunications technologies, losses in optical fibres, and especially dark-counts in the detectors, limit the maximum achievable distance for QKD to about $\sim 100\,km$. A quantum relay, based on quantum teleportation, allows increasing the communication signal-to-noise ratio (SNR) and thus extending this maximum achievable distance [4].
In this context, we show that integrated optics offers the possibility of compact and stable components suitable for enabling quantum communication experiments. More specifically, we will describe in the following preliminary results obtained with a "relay-chip" for fiber-based quantum communication systems.

A quantum relay chip based on the teleportation scheme

As already mentioned, the channel SNR severely limit the quantum communication distance. Basically, for increasing the maximal achievable distance of a quantum communication channel, one could think that photon amplifiers like those used for telecommunications could be useful. However in quantum communication, only states matter and the no-cloning theorem forbids replicating unknown quantum states with a perfect fidelity [5].
A viable possibility for extending the distance is based on the quantum relay. Here we take advantage of another quantum communication protocol, quantum teleportation. In this scheme, the qubits encoded on photons by Alice are teleported onto other photons at some points along their propagation, for instance in the middle of the channel, without destroying their quantum properties. At the same time, when teleportation succeeds, the final user, here Bob, receives the relayed qubit-photon together with an electrical signal which makes it possible to synchronize his detectors and to increase the SNR of the communication channel and therefore the maximum achievable distance [4, 6]. In the case of long-distance quantum communication, integrated optics on lithium niobate permits realizing a telecom-like quantum relay chip that could provide the relay function, in a compact, stable, efficient, and user-friendly fashion. Figure 1(a) presents the structure's description where all the necessary optical functions are merged on the same chip. We will now discuss how this chip works.
Let's suppose there's an unknown qubit 1, encoded on a photon at 1550 nm and travelling along a fiber quantum channel connected at port A to the relay chip. At the same time, a photon from a laser pulse at 775 nm, synchronized with the arrival time of qubit 1, enters



(a) (b)

Figure 1: (a) – Quantum relay chip, see description in the text. (b) – 3D representation of the quantum relay chip with its two electro-optically controllable couplers C_1 et C_2.

a non-linear zone of the chip which consists of a waveguide integrated on periodically poled lithium niobate (*PPLN*). Thanks to the appropriate choice of the periodic poling grating period (here around $16\,\mu m$), this pump photon can be converted by spontaneous parametric downconversion (SPDC) into an entangled pair of photons (2 and 3) whose wavelengths are also centred at $1550\,nm$ [7]. Then, the first 50/50 directional coupler (C_1) is used to separate the created entangled photons in such a way that photons 1 (sent by Alice) and 2 arrive at the same time at the second 50/50 coupler (C_2). If conditions on the polarization states, central wavelengths, and coherence times are met, photons 1 and 2 can be projected onto one of the four entangled "Bell states". The resulting state is identified by detectors D_1 and D_2 placed at the output of the chip. This measurement signals that the qubit initially carried by photon 1 has been teleported to photon 3 that exits the chip at port B, in theory without any loss in its quantum properties. This has been possible since photon 3 was initially entangled with photon 2 providing quantum correlations that cannot be described classically. In other words, entanglement has to be seen as a quantum resource that is consumed during the teleportation process. Note that the initial quantum state has not been cloned since photon 1, together with photon 2, have disappeared in the measurement. As a consequence the resulting electrical trigger is not only the signature of the presence of the initial carrier photon at the relay chip location but also of the departure of a new carrier photon encoded with the same qubit state, which remains unknown.

From a practical point of view, when this teleportation process is repeated on all the qubits travelling along the quantum channel, we obtain, at the output of the chip, qubits still encoded on photons at $1550\,nm$ but now synchronized with an electrical signal given by the Bell state measurement at detectors D_1 and D_2. This allows triggering Bob's detectors only when the initial qubits have traveled half the distance, leading to an increase of both the SNR and the communication distance. Of course, the price to pay is a reduction of the quantum bit rate since such a chip introduces propagation and interconnection losses.

From a technological point of view (see figure 1(b)), the chip features a photon-pair creation zone, two $50/50$ couplers, and tapered waveguides at all input/output ports to maximize the mode overlap between the fibers and the waveguides at the particular wavelength of $1550\,nm$. PPLN waveguide-based photon-pair sources have already been developed in our group [7]. As usual, the SPDC non-linear interaction is ruled by the energy and momentum conservation laws. In this waveguide configuration, the latter is achieved using the so-called quasi-phase matching technique which compensates periodically for the dispersion between the three interacting photons (pump, 2 and 3). This technique allows phase-matching any desired wavelengths. Moreover, the waveguiding structures, obtained by soft proton exchange, enables light propagation with low losses ($\simeq 0.3\,dB/cm$) and very high conversion efficiencies thanks to strong light confinement over long distances ($\delta n \simeq 2.2 \cdot 10^{-2}$). The directional couplers C_1 and C_2 consist of two waveguides integrated close to each other over a certain distance. If the spacing is sufficiently small, energy is exchanged between the two guides. An electro-optical control of the coupling ratio can be made using deposited electrodes. To correctly separate photons 2 and 3 and entangle 1 and 2, we have worked with 50/50 couplers, for both C_1 and C_2.

Experimental characterizations

We therefore studied numerically, and then fabricated, a $4.9\,cm$ long quantum relay chip merging all the necessary functions. To implement an actual quantum relay based on such a chip, as depicted in figure 1, we first test separately all the optical functions in the classical regime, i.e. using standard lasers.
The photon-pair source is designed to ensure the conversion of $775\,nm$ pump photons into two photons at $1550\,nm$. This can be achieved thanks to lithium niobate periodic polings between $16.4\,\mu m$ and $16.7\,\mu m$. In previous work we have already shown that photon-pair sources based on PPLN waveguides lead to the highest conversion efficiency reported to date and to very high quality of entanglement [7]. Here, the PPLN zone used in our new chip is $10\,mm$ long. The SPDC response of this non-linear waveguide zone when pumped by a CW laser at $765\,nm$ is represented in figure 2(a).

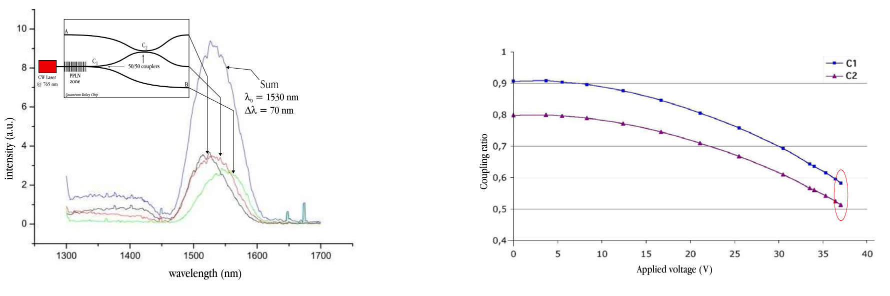


Figure 2: (a) – SPDC from the non-linear waveguide zone, see the text for explanations. (b) – Characterization of the coupling ratios obtained with couplers C_1 and C_2 in both classical (lines) and single photon counting (dots) regimes.

We see in this figure that the SPDC signal is distributed at the three output ports of the chip due to the presence of the two couplers. To characterize significantly the response of the non-linear zone, the sum of these three contributions have been added in figure 2(a). We get here a degenerate signal around $1530\,nm$ for a poling period of $16.6\,\mu m$ and at a temperature of $80°C$. Both the spectral width and SPDC efficiency are in excellent agreement with theoretical calculations and with previously obtained results for the same poling period (see [7] for more details).
Regarding the couplers, numerical simulations have been carried out using the beam propagation method in order to choose and optimize their size parameters so as to get the 50/50 required ratios. Here the radius of the bends have to be carefully chosen since too small radii would introduce important losses while the opposite would lead to too long a chip. We selected $10\,mm$ long bends, corresponding to losses lower than $1\,dB$

for the propagation over the entire component. Note that the waveguides input/output spacing was imposed by external consideration since standard V-Grooves with 250 μm separated fibers were used at both end facets to couple photons into and out of the chip. The interaction length required to transfer half of the energy to the opposite arm is of a few *mm*, and strongly depends on the separation between the two waveguides forming the couplers. Taking into account all these constraints we selected couplers made with 6 μm width waveguides and having a set of parameters going from 5.0 to 5.3 μm for the waveguides separation.

Figure 2(b) presents the characterization of the two couplers in both classical and single photon counting regimes at 1550 *nm*. To carry out the measurements, we launched successively a standard laser and single photons coming from a source previously built in our lab [8]. The results reported here are in good agreement with theoretical calculations. We see moreover that the electro-optical control permits obtaining our necessary 50/50 coupling ratios for a voltage of around 40 V. This is higher than expected but still shows we can correct the coupling length despite fabrication errors. These results show that we obtained couplers fulfilling the requirements for a quantum relay chip. Note that the repeatability of the fabrication was demonstrated to be good since couplers coming from different runs showed the same coupling lengths within a few percent.

Moreover, loss measurements at 1550 *nm* over the entire chip have been performed and shown to be 5.5 *dB* between any couple of input/output ports. This has been made possible using tapered-waveguides at all the input and output ports [9]. This result is in good agreement with the simulations when coupling, propagation as well as separation losses at the couplers are taken into account.

Conclusion and outlook

We have seen that all the elements of the integrated quantum relay have been tested separately: the photon-pair source, the taper-waveguides and the couplers. Taking into account all the above mentioned characterization results, we expect an increase of the maximum achievable distance for a one-way QKD link by a factor of 1.8. Current work now consists of testing this quantum relay chip in the quantum regime, i.e. when actual qubits are first encoded and then teleported through the chip. We believe this is a significant demonstration of the applicability of integrated optical technology to photonic quantum information treatment.

References

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