Quantum-Communication using Multicore Fibers

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Abstract *Quantum communication represents a key enabler for many applications from secure communications to advanced quantum simulations on the cloud. We here report our recent results on the generation, transmission and detection of high-dimensional quantum states exploiting multicore fibers.*

Introduction

A quantum network distributed all over the world, i.e. a network in which billions of users share information carried out by quantum systems, is the ultimate target of quantum communication i.e., a network in which billions of users share information carried out by quantum systems [1]. In order to accomplish this task, multiple actions and operations on the quantum systems are required, thus the performance of the network depends on the capacity of generating, transmitting, storing, and manipulating quantum states [2-4]. By exploiting two-dimensional quantum states (qubits), scientists have already proved extraordinary results in terms of reachable link distance and information rate. As an example is worth reporting the quantum network realized in China [5], and the entanglement distribution over 1200 km in a free-space link [6].

However, qubits have also shown their limitations in terms of noise robustness and photon information efficiency [7]. On the contrary, the possibility of exploiting qudits (quantum states defined in a Hilbert space larger than 2) offers multiple advantages in a wide area of applications, from quantum communications and quantum information to classical communications, from intrinsic randomness to fundamental research in quantum physics [8]. More specifically, qudits (high-dimensional quantum states) have peculiar properties which might be beneficial in the construction of future quantum networks, guaranteeing a larger information capacity and a higher tolerance to noise, exceeding the limitations imposed by qubits [8].

Here, we report a series of experiments, that we have recently completed, in which we exploit qudits encoded in the space domain (the cores of the multicore fibers) [9-10]. In particular, we have demonstrated the correct preparation, transmission, and detection of qudits over multicore fibers of different characteristics and in different environmental conditions, demonstrating that space encoded qudits are good candidates for future quantum networks.

Space encoding quantum states over fiber

Space division multiplexing (SDM) is considered as an important technology for classical optical communications, both in terms of bandwidth allocation but also in terms of sustainable optical networks [11]. More specifically, SDM in optical fiber exploits multicore (MCF) and higher-order modes fibers (HOM) in which different cores/modes, are used as distinct and parallel channels, see Figure 1 [12]. Likewise, these fibers have recently been used for quantum communications experiments both using discrete-variable and continuous variable technology [13-15]. Furthermore, these fibers have been used to transport high-dimensional (Hi-D) quantum states encoded in the modes/cores of these fibers [16-18].

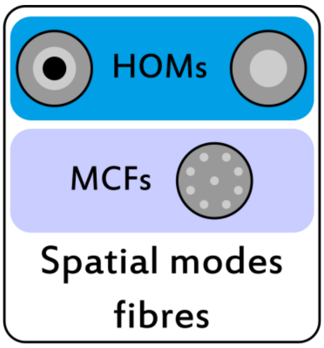

Figure 1. Different spatial modes fibers. Higher-order modes (HOM) and multicore fibers (MCF). Both fibers have been exploited for the propagation of Hi-D quantum states for quantum protocols.

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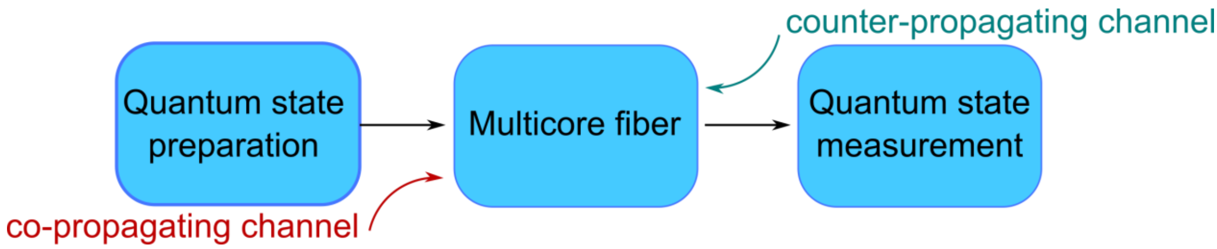

Figure 2. Overview scheme of quantum communication experiment using multicore fibers. The quantum states (single photons or weak coherent pulses) are prepared by using integrated or fiber optics and send through the multicore fiber. After the propagation, the quantum states are measured and analyzed. Since the quantum states are encoded in the cores of the multicore fiber, the phase drift between the different cores should be minimized. In order to stabilize the phase drift, we have exploited two different approaches, a co-propagating channel at a different wavelength (compared to the quantum signal), or a counter-propagating channel using the same wavelength as the quantum signal.

Multicore fiber and quantum applications

MCFs have recently been explored for high-dimensional quantum communication. More specifically, the quantum states are encoded in the superposition of multiple cores of the fiber. As an example, a four cores fiber can encode a four-dimensional quantum state [19]. The principle of the quantum protocol is reported in Figure 2. Once the quantum states have been prepared, both using integrated photonics or fiber optics, the single photons (or weak coherent states) are coupled to the fiber. After the propagation through the MCF, the quantum states are projected and measured on different bases. It is worth noting that photonic integration has played an important role in recent quantum information by integrating different functionalities of traditional discrete bulky components into ultra-compact chips [20-21]. In addition, integrated photonic circuits provide excellent performances (compactness, good optical phase stability, access to new degrees of freedom), and are particularly suitable for the manipulation of quantum states. In fact, in 2017 we have demonstrated the correct generation, propagation, and measurement of a 4-dimensional quantum state prepared using compact silicon photonic integrated circuits [9]. The ququarts were matched to four cores of a multi-core fiber, through a highly efficient MCF grating coupler. However, although the high precision of the optical actuators included in the photonic circuits, the transmission distance was limited to 5 meters mainly due to phase instability of the MCF.

Stabilization signal: co- and counter-propagating signals

Although the stability of the multicore fiber is intrinsically higher compared to a bundle of single-mode fibers (we have experimentally measured the relative phase drift in a 2 km long multicore fiber and 2 single-mode fibers of 2 km), a stabilization loop is needed for a longer and more stable transmission of the quantum states. Recently, we have investigated two main strategies: the first one employs a weak classical laser as stabilization signal counter-propagating respect to the quantum states, while in the second one the stabilization light is co-propagating with it [22-23]. The latter uses the same wavelength employed for the transmission of the quantum states. In particular, by monitoring the phase fluctuations using a photo-detector, and by using an active fiber-based phase shifter (controlled by an ad-hoc custom software) we are able to stabilize the multicore fiber. As a concrete example, we report in Figure 3 the quantum bit error rate (QBER) as a function of time, in which we have used a counter-propagating technique for stabilizing the multicore channel. In this

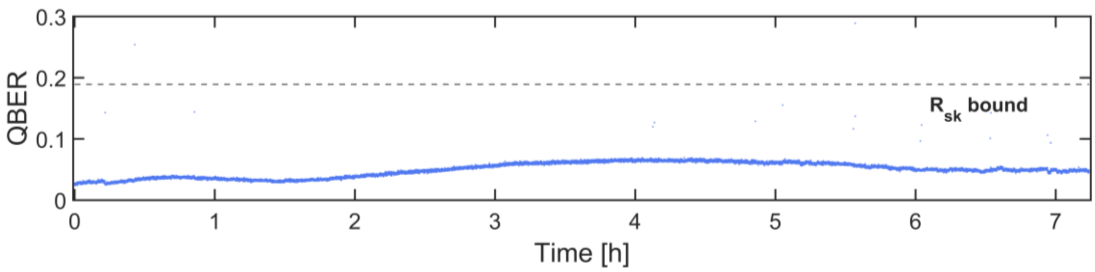

Figure 3. Experimental quantum bit error rate (QBER) as a function of time. The blue line represents the measured QBER in a 2 km long multicore fiber in which we have used a counter-propagated stabilization laser at the same wavelength of the quantum signal. The dashed grey line is the fundamental threshold of collective attack security.

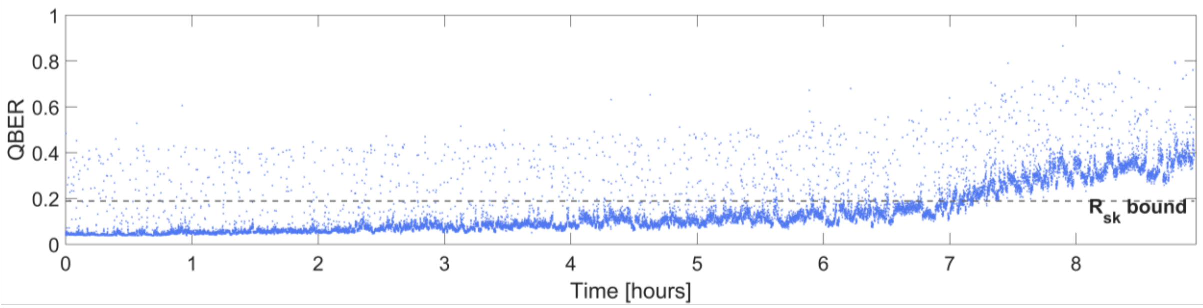

Figure 4. Experimental quantum bit error rate (QBER) as a function of time in a real-time QKD experiment. The blue line represents the measured QBER in a 2 km long multicore fiber in which we have co-propagated a stabilization laser at a different wavelength of the quantum signal. Dashed grey line is the fundamental threshold of the collective attack security.

specific experiment, we have used weak coherent states prepared in a superposition of two different cores of a 2 km long multicore fiber. The results clearly show that our stabilization method is able to correct the intrinsic phase drifts of the multicore fiber for more than 7 hours of measurement. However, the counter-propagating method presents some technical limitations like the time-of-flight problem (light traveling from left to right could be affected differently from light traveling from right to left in a longer fiber) and the impossibility of preparing the quantum states with a real-time system. To overcome these limitations, we have employed a co-propagating scheme. In particular, the attenuated classical laser, at a different wavelength, is combined with the quantum states in the same fiber. After the propagation through the fiber, the two wavelengths are divided and the stabilization laser is analyzed by a photo-detector, similarly to the counter-propagated method. This solution allows the preparation of Hi-D quantum states at high repetition rate (596 MHz) and the applicability of this method to a quantum key distribution protocol. We report in Figure 4, the QBER measured in our system in which we have employed a co-propagating stabilization technique. Also in this case the MCF was 2 km long. The measured QBER is collected over 9 hours of measurement and our system show good stability (below the error correction threshold) for more than 7 hours of measurement. The fluctuations (vertical burst dot) are the instants in which the locking system was not able to correct the phase drift. However, our system was able to automatically relock to the previous point with a similar QBER value.

Towards long-distance quantum communication using

MCFs have been explored for Hi-D quantum communication, but still many challenges are present and not solved. In particular, scalability is one of the most interesting ones, both in terms of distance and dimensionality [24-25]. Regarding the dimensionality of the quantum system, it is worth noticing that the combination of different degrees of freedom could be used for enlarging the Hilbert space. As an example, time and space can be combined together for increasing the overall dimensionality [26-27]. Regarding the overall link distance which could be achieved, we have recently accomplished a stabilization test on 4 uncoupled cores deployed fiber, 26-km long, available in the city of L'Aquila (IT) [25,28]. The results show the possibility of employing our method to longer fibers without changing the overall setup, suggesting a limited phase drift of the signals.

Conclusions

In conclusion, we have demonstrated the successful generation, propagation and measurement of high-dimensional quantum states encoded in the spatial domain exploiting MCFs. We have proved that MCFs are compatible with integrated photonics and more important our method can be employed for stabilizing long distance quantum link (including deployed fiber). Multicore fibers, thus, could become a new tool for increasing the performance of the future quantum networks [29, 30].

Acknowledgements

The authors would like to thank B. Da Lio and Y. Ding, K. Rottwitt, T. Napoleon Arge, E. Larsen.

Funding

This work is supported by the Center of ExcellenceSPOC - Silicon Photonics for Optical Communications (ref DNRF123), by the EraNET Cofund Initiatives QuantERA within the European Union's Horizon2020 research and innovation program grant agreement No.731473 (project SQUARE) and by the NATO Science for Peace and Security program under Grant No. G5485

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