Quantum communications with space encoding technique

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Abstract: Quantum communications are a key enabler for multiple applications, from information theoretic communications to advanced remote quantum simulations. We here report our recent results on generation, transmission and detection of space encoded quantum states multicore.

1. Introduction

A full network deployed all over the world, i.e., an interconnection of billions of users sharing quantum information, is the holy grail of quantum communication [1]. To accomplish this long-term dream, a vast number of actions and operations on quantum systems are required. In other words, the performance of this network in terms of distance, speed, and security depends on the capacity of generating, transmitting, storing, and manipulating quantum states [2-4]. By using the so-called qubits systems, i.e., two-dimensional quantum states, scientists have yet proved impressive results in terms of reachable link distance and information rate. For example, it is worth reporting the metropolitan scale quantum network realized in China [5], and the entanglement distribution over 1200 km in a free-space communication link [6]. However, the two-dimensional encoding scheme has also shown their intrinsic limitations in terms of noise robustness and photon information efficiency [7]. Luckily, the possibility of exploiting qudits, quantum states defined in a Hilbert space with dimension larger than 2, offers concrete advantages in a wide area of applications, for example both in quantum communications and quantum information, and also in classical communications links. In addition, these special quantum states offer an advantage with intrinsic randomness and in fundamental quantum physics research [8]. More specifically, high-dimensional quantum states (qudits) own important properties which could be exploited in the design and realization of future quantum networks. As a concrete example, qudits present a higher photon information efficiency (more than 1 classical bit encoded in a quantum state) and a higher tolerance to noise, exceeding the limitations imposed by qubits [8].

Here, we report a series of experiments in which we exploit both qubit and qudits encoded in the space domain (the cores of the multicore fibers or the mode of an air-core fiber) [9-14]. We have thus proved the correct preparation, transmission, and detection of qubit and qudits over different multimode and multicore fibers (also deployed fiber) demonstrating that space encoded quantum states are an excellent candidate for future quantum networks.

2. Space encoding for quantum communications

Space division multiplexing (SDM) is one of the most important technology for classical optical communications, both in terms of bandwidth allocation but also in terms of sustainable optical networks [15]. In details, SDM in optical fiber exploits multicore (MCF) and higher-order modes fibers (HOM) in which different cores or modes are exploited as distinct and parallel channels, see Figure 1. Likewise, these fibers have recently been used for quantum communications experiments both using discrete-variable and continuous variable technology [16-17]. In addition, these fibers have been used to transport qudits encoded in the modes or cores of these fibers [18].

3. Multicore fiber

MCFs have been used both for high-dimensional quantum communication and space division multiplexing of quantum and classical light [12, 19]. More specifically, the quantum states are encoded in the superposition of multiple cores of the fibre. An example of the experimental setup is reported in Figure 1, in which a four cores fibre has been used for demonstrating a fast QKD setup over 2 km long MCF. 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 as we have demonstrated back in 2017 [9, 20].

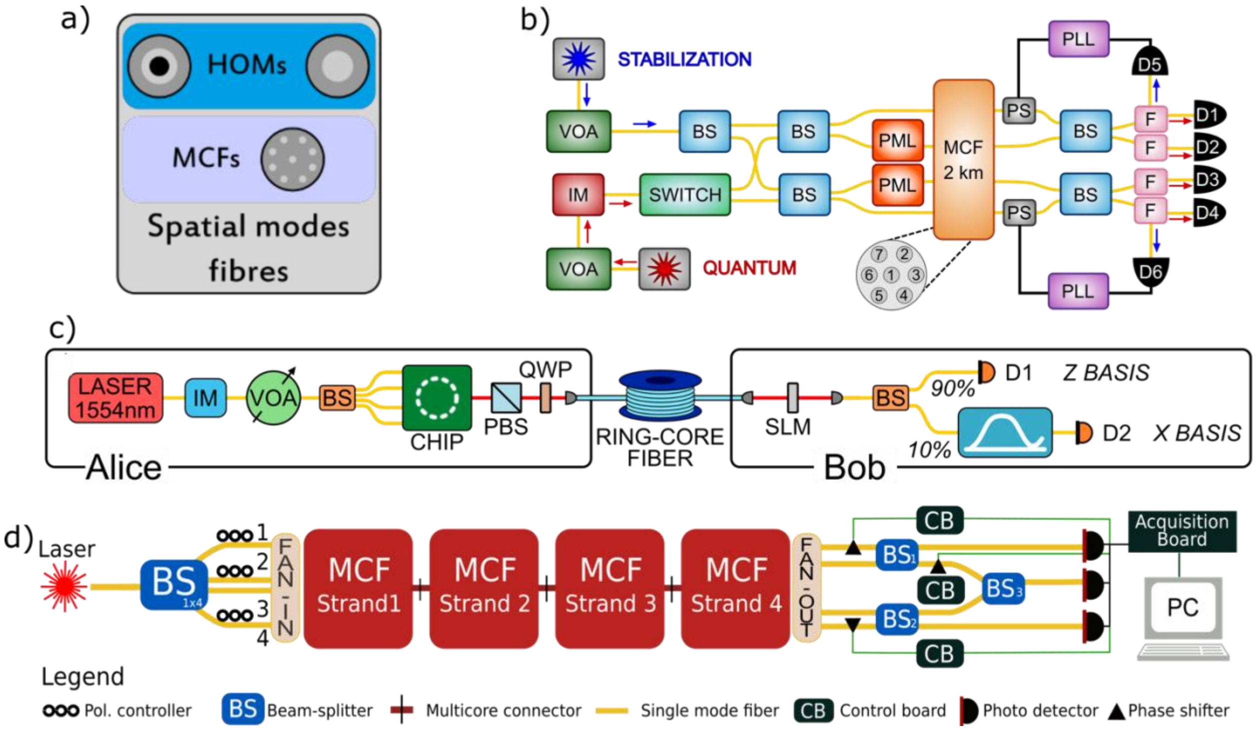

Figure 1. a) Different spatial modes fibers. Higher-order modes (HOM) and multicore fibers (MCF). Both fibers have been exploited for the propagation of Hi-D quantum states for quantum protocols. b) **High-dimensional quantum key distribution.** Experimental setup of the fiber base quantum communication setup over 2 km long multicore fiber. **c) Multiplexing quantum keys.** Experimental setup of the OAM multiplexing experiment, in which multiple quantum keys encoded in different OAM modes are multiplexed into the same OAM carrying fiber. **d) field trial high-dimensional setup**. A 4-core 26 km long deployed multicore fiber has been phase stabilized in the city of L'Aquila.

4. Multimode fiber

MMFs represent another approach for achieving the same scope. In particular, we have demonstrated how orbital angular momentum of light (OAM) carrying fiber can transport high-dimensional quantum states encoded in the superposition of multiple OAM modes (+6, -6, +7, -7) [10]. In addition, we have recently used an 800 m long OAM fiber for transporting parallel keys generated by a photonic integrated circuit. The experimental setup is reported in Figure 1 c [14]. The quantum keys were encoded using time-bin encoding and thanks to the orthogonality of the OAM modes it was possible to demonstrate the full multiplexing of quantum signals into the fiber [20-22].

5. Towards long-distance quantum communication using space encoding

Space encoding techniques have been explored both for qubit and qudit encoding, however, there are key challenges that are not solved yet. More specifically the space encoded fibers present a limitation in terms of scalability, i.e., in terms of link distance and dimensionality of the Hilbert space [23-25]. In terms of the dimensionality of the quantum system, it is worth noticing that by combining different degrees of freedom it is possible to increase the dimensionality of the Hilbert space [26]. In terms of overall link distance, 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.

6. Conclusion

Summarizing, we have presented the correct generation, transmission, and detection of qubit and qudit encoded in the space dimension using fiber-based and integrated photonic circuits. We also proved that our techniques are clearly scalable, and they work in field deployed link. More in general, space-encoding technique could become a new way for increasing the current state-of-the-art performance of the future quantum networks [29, 30].

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7. References

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