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# High-dimensional quantum communication with twisted photons propagating in a fiber link

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**Abstract.** Quantum communication (QC) represents a key enabler for many quantum applications. However, low information rates and short propagation distances, limit the development of this field and its practical applications. High-dimensional (Hi-D) QC can address these challenges enhancing the information rate and the systems error tolerance. We transmit, for the first time ever, Hi-D quantum states prepared in four orbital angular momentum (OAM) modes in a 1.2 km long OAM-carrying fiber. Furthermore, we successfully implement a real-time decoy-state Hi-D QKD protocol, and demonstrate the highest secret key rate and longest transmission distance of OAM-QKD presented to date.

**Keywords:** Quantum Communications, Orbital Angular Momentum, Quantum Key Distribution, High-Dimensional quantum states

## 1 Introduction

Quantum communication (QC) is the backbone of the quantum technologies. Indeed, for quantum computation, simulation and sensing, the exchange of secure and reliably information between two or more users is essential [1, 2]. Hence, the ability to faithfully transmit, manipulate and detect genuine quantum states- either on microscopic or kilometric channels- is fundamental and paves the way for a quantum network. Low information rates and short propagation distances are the main challenges of most of the QC systems, which are restricting the application space and the fast deployment of novel quantum technologies. A fundamental way to surmount these obstacles is represented by high-dimensional (Hi-D) quantum states, which allow increased information capacity and higher robustness against channel noise [3–5]. The generation, transmission and detection of high-dimensional quantum states is very challenging and only a few experimental realizations have been achieved for Hi-D QC protocols [6, 7]. The orbital angular momentum (OAM) of light is a promising feature of light to generate and manipulate Hi-D quantum states. Indeed, it provides a natural discrete Hi-D basis for quantum states [8]. However, fiber based quantum communication with OAM states was considered, so far, impossible [8]. We leverage recent advances in specially designed optical fibers supporting orbital angular momentum (OAM) modes, to design and implement a Hi-D QC system [9]. We experimentally demonstrate the first Hi-D QC system using OAM states of light propagating through an optical fiber. Generation, transmission over 1.2 km long fiber and detection of 4 OAM quantum states (and their superpositions) is experimented and characterized. As a practical application, we demonstrate a Hi-D quantum key distribution (QKD) protocol, achieving the highest secret key rate and longest transmission distance of OAM based QKD protocols to date [10].

## 2 Generation, transmission and detection of the OAM quantum states

High-dimensional quantum states are suitable for longer transmission distance and higher secret key rate transmission, being more robust to noise level and allowing a higher channel capacity [3]. In Figure 1(a) we report the setup of the Hi-D QC system based on the OAM degree of freedom. Weak coherent pulses are polarization modulated through a phase modulator (PM) and subsequently vortex plates allow for the spin-orbit coupling. The quantum states are coupled to the fiber that enables conservation of orbital angular momentum modes (about 1dB/km losses). Due to different mode group velocities in the air-core fiber, a free-space delay (about 4.5 m) is implemented before coupling the weak pulses to the fiber. This delay is required in order to pre-compensate the different time-of-arrivals of the modes with $\ell = |6|$ and $\ell = |7|$. To detect the OAM quantum states the receiver (Bob) implements projective measurements to recover the encoded information. An OAM mode sorter is used to separate even and odd modes, in our case $\ell = |6|$ and $\ell = |7|$. The implemented mode sorter is a free-space MZI with two Dove prisms with a relative angle of 90° [11]. After the sorting process, the photons are converted back to the fundamental Gaussian mode with two other vortex plates and then conveniently separated according to their polarization. In particular, to measure the basis $\mathcal{M}_0$, half-waveplates (HWPs), quarter-waveplates (QWPs) and two polarization beam-splitters (PBS) are adopted in the two arms of the sorter. In the case of $\mathcal{M}_1$, a free-space MZI is required to measure the relative phase difference between the OAM modes. The photons

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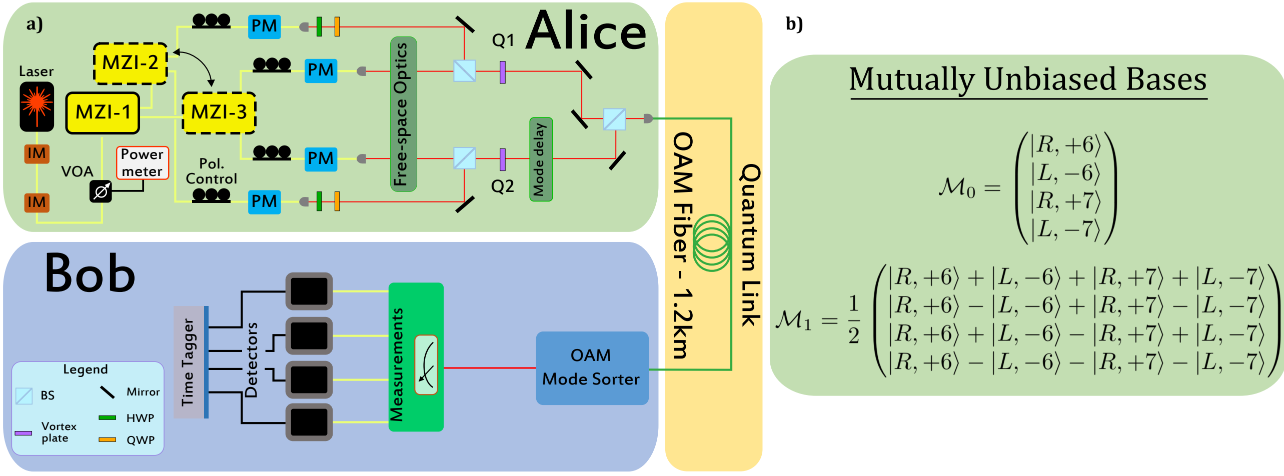


Figure 1: **a) Setup of the experiment.** Fast Mach-Zehnder Interferometer (MZI) switches, controlled by a field programmable gate array (FPGA), allow the real-time preparation of the MUBs $\mathcal{M}_0$ and $\mathcal{M}_1$. Only a single MZI is required to separately generate the two bases (dashed edges MZI). Note that, within each basis, the states are prepared in real-time mode. At the input of the MZI, we inject attenuated pulses, carved out of a continuous wave (CW) laser beam at 1550 nm by an intensity modulator (IM) driven by the same FPGA. A second IM is used to implement a three-intensities decoy-state technique for the QKD protocols. A variable optical attenuator (VOA) allows for reaching the quantum regime. The polarization of the quantum states is prepared by a phase modulator (PM). Two different voltages are chosen to yield diagonal and anti-diagonal polarizations at the output of the PM. Vortex plates with topological charge $L = +6$ and $L = +7$ (Q1, Q2) assign different OAM orders to the quantum states. The quantum states are then coupled into the air-core fiber. After the fiber transmission, an OAM mode sorter is implemented to separate even from odd modes ($L = |6|$ and $L = |7|$). Two other vortex plates are used to convert from OAM to Gaussian modes. After the OAM sorter, the quantum states are separated using their polarization. Four single photon detectors collect the events, which are registered by a time-tagger unit. **b) Mutually unbiased bases description.** The two MUBs used for the Hi-D QKD protocol are shown. The quantum states in $\mathcal{M}_0$ are called $|\psi_i\rangle$, whereas those in $\mathcal{M}_1$ are called $|\phi_j\rangle$.

are then detected by four InGaAs single photon detectors and registered by a time-tagger unit [10].

## 3 Results

In order to characterize the system, a quantum state tomography technique is implemented for 2-dimension and 4-dimension quantum states. Figure 2 shows the two matrices for the two cases, measured with weak laser pulses and mean photon number $\mu = (9.9 \pm 0.2) \times 10^{-3}$ for 1.2 km. Using the definition of fidelity $F(p,q) = \sum_i (p_i q_i)^{1/2}$, where $p$ ($q$) is a discrete probability distribution with elements $p_i$ ($q_i$), we measure in average $F = 0.980 \pm 0.002$ for the qubit (D=2) and $F = 0.954 \pm 0.004$ in the ququart ($D = 4$) case. To demonstrate the usefulness of quantum communication through the air-core fiber using OAM states, we implement real-time 2D and 4D quantum key distribution protocols [2, 12]. Following the standard authentication process between Alice and Bob, Alice randomly switches between the two MUBs and modulates the secret key on the different states (two or four, depending on the dimension). Usually, one of the two bases provides the key and the other monitors the presence of an eavesdropper. After the transmission through the OAM-fiber, Bob decides in which of the two bases to project the quantum states. Photons measured in the wrong basis will be discarded during the sifting procedure. The protocol implemented can be considered as a BB84 with a three-intensities decoy-state method ($\mu$, $\nu$, $\omega$) with dimensions $D = 2$ and $D = 4$. In Figure 2 c) we show the experimental secret key rate for $D = 2$ and $D = 4$ as a function of the channel loss. The first blue and first red circles are the experimental data measured after the propagation through 1.2 km fiber for 4D and 2D respectively. The following red and blue circles are measured data obtained by adding further channel loss with a VOA. The experimental data fit the theoretical prediction (dashed lines), showing that the secret key extraction would be guaranteed by our protocol over a distance of $\sim 14$ km, with a secret key rate of 0.78 kbit/s and 0.40 kbit/s, for the 2D and 4D case respectively. We measure an average QBER of 6.7% for the states $|\psi_2\rangle$ and $|\psi_4\rangle$, and 7.9% for $|\xi_1\rangle$ and $|\xi_2\rangle$. Furthermore, in the case of high-dimensional encoding a QBER of 14.1% in the $\mathcal{M}_0$ basis and 18.1% in $\mathcal{M}_1$ is measured. The QBER values are obtained over $\sim$ 7 minutes of measurement time and these values are below the individual and collective attack thresholds [10]. Positive secret key rates of 21.81 kbit/s ($D = 2$) and 37.43 kbit/s ($D = 4$) are obtained after the 1.2 km fiber. An enhancement of 71% in the final key rate is achieved by using high-dimensional encoding.

## 4 Conclusions

In this work, we propose and demonstrate the first fiber based high-dimensional quantum communication with twisted photons. We successfully prove the principle by sending two- and four-dimensional MUBs through 1.2 km of a special air-core fiber. These groundbreaking

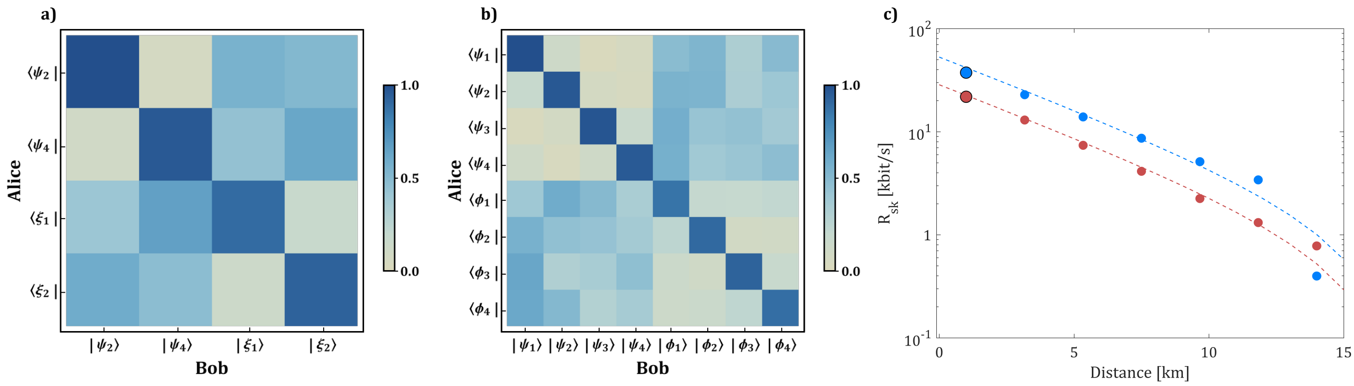


Figure 2: **a) Tomography measurement for 2 D.** Average fidelity measurement for 2 minutes is $0.980 \pm 0.002$. Here the quantum states are defined as $|\xi_1\rangle = |\psi_2\rangle + |\psi_4\rangle$ and $|\xi_2\rangle = |\psi_2\rangle - |\psi_4\rangle$. **b) Tomography measurement for 4 D.** The average fidelity measured over 5 minutes is $0.954 \pm 0.004$. The measurements were acquired with a mean photon number value of $\mu = (9.9 \pm 0.2) \times 10^{-3}$. **c) Secret key rate as a function of the channel losses.** The first blue circle represents the rate measured after transmission through the 1.2 km fiber (37.43 kbit/s for 4D and 21.81 kbit/s for 2D), while the others are obtained by adding further channel losses with a VOA.

results represent a key point for the development of distributed quantum applications, proving that fiber based spatial modes protocols can be used for quantum communications.

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