Spatial Mode Conversion of Single Photons

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With the fast development of quantum computers that could potentially break current cryptographic systems, significant research efforts have been focused on developing quantum-secure cryptography protocols. Quantum Key Distribution (QKD) is a widely used technique for securely distributing encryption keys. In QKD, keys are encoded in single photons, due to the no-cloning theorem [1], any eavesdropping attempt inevitably disturbs the quantum state, leaving detectable traces that can be observed by the sender and receiver.

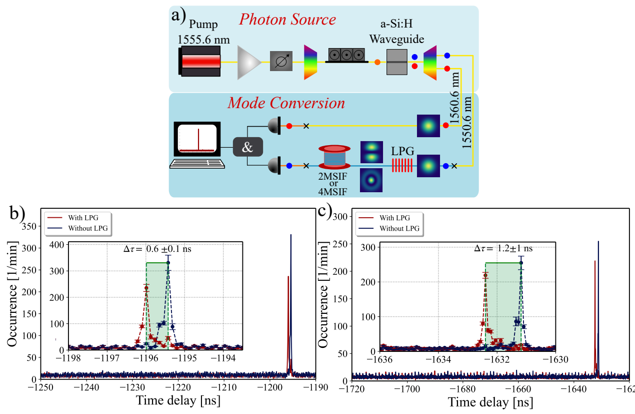

Figure 1: a) Setup used to generate a heralded single photon and show spatial mode conversion. b) and c) Show the coincidence histograms with and without the LPG designed to convert to the LP_{11} and LP_{11} modes, respectively

Typically, information is encoded in the polarization degree of freedom of single photons [2]. However, polarization encoding allows at most one bit of information per photon. One promising solution to scaling up QKD systems is to exploit alternative degrees of freedom (DoFs), such as the spatial mode of the photon [3]. Spatial modes can be used either as independent quantum channels (multiplexing communication lines) or be used in superposition to increase the information capacity per photon, thereby enhancing the overall capability of QKD protocols.

In this work, we demonstrate spatial mode conversion of single photons inside an optical fiber using a fiber-based long-period grating (LPG) [4]. A more complete analysis and demonstration of the mode conversion can be seen in our recent publication on *Scientific Report* [5]. Single photons from a heralded single-photon source were coupled into two few-mode fibers in the fundamental LP_{01} mode and subsequently converted into the higher-order modes LP_{11} and LP_{02} via the LPG, achieving conversion efficiencies exceeding 87 and 96%, respectively.

The experimental setup used to generate and convert the spatial mode of single photons is shown in Fig. 1a. A continuous-wave (CW) laser emitting at 1555.5 nm pumps a hydrogenated amorphous silicon (a-Si:H) waveguide, generating photon pairs at 1550.6 nm (signal) and 1560.6 nm (idler) via spontaneous four-wave mixing (SFWM) [6]. After appropriate filtering to suppress the pump and separate the signal and idler photons, the idler photons are sent directly to a single-photon detector (SPD), while the signal photons are directed to a long-period grating (LPG). Two different LPGs were used: one optimized for conversion to the LP_{11} mode and the other for conversion to the LP_{02} mode.

After mode conversion, the signal photons propagate through either a 260-meter two-mode fiber (TMF) or a 350-meter four-mode fiber (FMF), before being collected by another SPD. Both detectors are connected to a time tagger to record the arrival times of the photons. Figures 1b and 1c show the coincidence histograms obtained using the TMF and FMF configurations, respectively.

When the LPG is not inserted, the photons arrive at the two SPDs with delays of approximately 1195.4 ns (TMF) and 1631.1 ns (FMF). When the LPG is used, the arrival delay shifts by 0.6 ns (TMF) and 1.2 ns (FMF), respectively. This shift occurs because photons traveling in higher-order modes propagate more slowly than those in the fundamental mode. Simulations of the fibers yield differential mode delays between the LP_{01} and LP_{11} modes of 2.3 ps/m, and between the LP_{01} and LP_{02} modes of 3.17 ps/m, which agree well with the experimentally observed delays.

When using the LPG, a small residual peak appears at the position corresponding to unconverted photons. By measuring the ratio between the converted and unconverted peaks, we estimate mode conversion efficiencies of $87.5 \pm 1.4\%$ for the LP_{11} mode and $96.1 \pm 1.6\%$ for the LP_{02} mode.

We have experimentally demonstrated the spatial mode conversion of single photons using fiber-based long-period gratings. Spatial mode conversion up to $87.5 \pm 1.4\%$ and $96.1 \pm 1.6\%$ were obtained when converting photons in the fundamental LP_{01} mode this the high-order modes LP_{11} and LP_{02}, respectively. The advantage of using LPG over some free-space solutions such as spatial light modulaters are the low loss, affordability and it is free of alignment. Based on these results, we believe that fiber-based LPGs can be effectively employed in quantum communication protocols that utilize high-order spatial modes.

References

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