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Generating transverse-mode entanglement in optical fiber

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ABSTRACT

We report our recent progress in the generation and verification of a transverse-mode Bell state using spontaneous four-wave mixing in a few-mode polarization-maintaining fiber. Utilizing spatial light modulators, we show control over individual four-wave mixing processes through precise beam shaping of the pump transverse mode and verify entanglement via quantum state tomography. We discuss challenges in temporal and frequency distinguishability and illustrate how they can be resolved. This work represents a first step towards creating a versatile fiber-based transverse mode-entangled photon-pair source matched to fiber infrastructure.

Keywords: Transverse spatial mode, entanglement, optical fiber, spontaneous four-wave mixing, spatial light modulator

1. INTRODUCTION

The innate high-dimensionality of the transverse mode degree of freedom of photon pairs can be used to enhance quantum information capacity and for diverse quantum applications such as quantum computation[1] and quantum key distribution.[2] Optical fibers[3] are appealing for building such spatial mode-entangled sources due to their capability for smooth integration with existing fiber technology, the existence of well-developed multiplexing techniques,[4,5] and the potential for hybrid entanglement.[6,7] Despite these benefits, the fiber platform[8–10] has seen less progress compared to free-space[1] and waveguide[11] implementations.

In this work, we report our recent progress in generation and verification of a transverse-mode Bell state, $|\psi_{si}\rangle = 1/\sqrt{2}(|ee\rangle + |oo\rangle)$ (see Fig. 1(a)), using spontaneous four-wave mixing in a few-mode polarization-maintaining fiber (PMF). Here, e and o represent linearly polarized (LP) even (LP_{11e}) and odd (LP_{11o}) modes that are supported in our PMF along with the fundamental Gaussian mode (LP_{01}). Compared to typical schemes where transverse-mode shaping is implemented *post*-photon-pair creation, our scheme *pre*-shapes the pump transverse mode to control the creation of a transverse-mode-entangled photon-pair state.

2. METHODS AND RESULTS

As shown in Fig. 1(b), the experimental setup involves preparing the pump photons in a specific quantum state and measuring the created signal and idler quantum states. Pump photons emitted from a laser (central wavelength at 620 nm, 80 MHz repetition rate, and $\approx$ 200 fs pulse duration) are first precisely tailored in polarization and transverse spatial mode using a spatial light modulator (SLM) and employing multiplexing techniques developed for classical communication.[4,5] These pump photons are then coupled into our polarization-maintaining fiber where signal ($\sim$ 570 nm) and idler ($\sim$ 680 nm) photons corresponding to desired spontaneous four-wave mixing (SFWM) processes are created. Out-coupled from the fiber, the photon-pairs are filtered based on both polarization and wavelength. To reconstruct the quantum state, we perform quantum state tomography (QST), which utilizes an SLM and two single-mode fibers to perform 36 projective coincidence measurements on the photon pairs. Finally, the resulting quantum state represented in a density matrix form is analyzed for quantities such as concurrence, state fidelity to target state, and purity.

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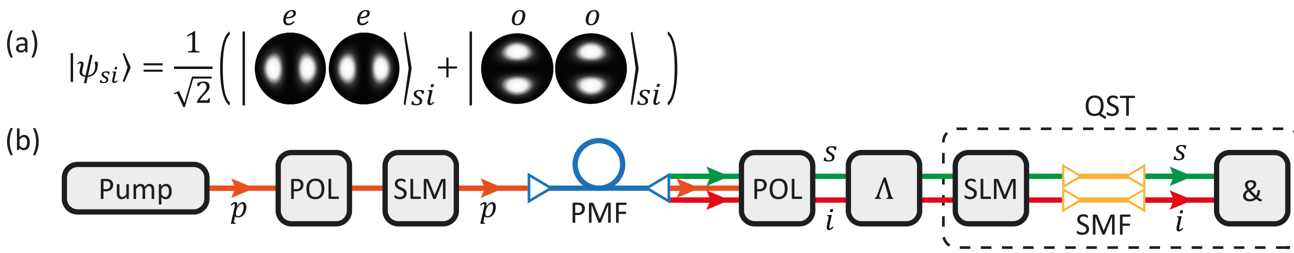

Figure 1. (a) Target transverse-mode Bell state for signal and idler photon pair. (b) Simplified experimental setup for p: pump, s: signal, and i: idler photons. PMF: polarization-maintaining optical fiber used as a SFWM medium, SLM: spatial light modulator for transverse-mode control, POL: polarization control optics including linear polarizers, half-wave plates, and quarter-wave plates, Λ: spectral control optics consisting of spectral filters and dichroic mirrors, SMF: single-mode optical fibers used in-series with an SLM to filter out undesired transverse modes, &: coincidence counter comprised of single photon detectors and a time-tagger, QST: quantum state tomography.

To quantify the performance of our source of photon pairs whose transverse mode is controlled by the pump transverse mode, we measure a maximum quantum state purity of ≈ 0.99 (derived from QST measurements) for both for $|ee\rangle$ and $|oo\rangle$ states, using independent control of pump transverse modes in e and o, both with a maximum intensity fidelity of ≈ 0.97 (measured with a camera).

Expanding on our previous work,[8] we further investigate the temporal and spectral distinguishability between modes $|ee\rangle$ and $|oo\rangle$ caused by modal dispersion within the fiber. One possible solution requires using two PMFs in series, where the latter, 90-degree-rotated PMF compensates for the dispersion caused by the former. Using this method, we measure a preliminary concurrence of ≈ 0.36 for the targeted Bell state, which indicates partial entanglement. This may be improved through choosing the optimal length of PMF to maximize the spectral overlap between the two SFWM processes.

In summary, we have generated and verified a transverse-mode Bell state in few-mode fiber controlled solely by pump transverse mode. With further improvements related to indistinguishability, we envision our fiber-based photon-pair source may allow for generation of high-fidelity transverse-mode-entangled states, providing pathways to diverse quantum applications, including quantum random walks[12] and entanglement distillation.[13]

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