Energy-entangled W-state in optical fiber

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Abstract: We demonstrate progress towards the generation of an energy-entangled three-photon W-state via spontaneous four-wave mixing in a polarization-maintaining fiber and characterize it by reduced density matrix tomography, without involving frequency conversion.

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Tripartite entangled photonic quantum states are useful for fundamental tests of quantum mechanics and to enhance the robustness of quantum communication protocols. As one of the classes of tripartite entanglement, the so-called W-state has a form:

$$|W\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle), \tag{1}$$

which cannot be transformed into a tripartite Greenberger-Horne-Zeilinger (GHZ) state through local operations and classical communication. Compared to a GHZ state, which is fully separable after loss of one particle, the entanglement of the W-state is robust against loss, as the state of the remaining bipartite system still retains entanglement even if one of the particles is lost. Typically, these states are demonstrated experimentally using the polarization degree of freedom of photon-pairs generated through spontaneous parametric down-conversion (SPDC) or spontaneous four-wave mixing (SFWM). Entanglement in polarization is not always optimal for long-distance communication through optical fibers; it was recently proposed [1] that a W-state could be generated using the energy degree of freedom: a possibility which to our knowledge has not yet been implemented. As the energy of a photon can not be easily altered without a strong nonlinear interaction, an energy-entangled W-state is inherently robust against noise. In addition, the scheme for generating an energy-entangled W-state can be based on multi-pair generation in a single nonlinear material, which makes it relatively easy to implement in bulk optics, while also potentially realizable in an integrated optics platform for enhanced scalability and efficiency.

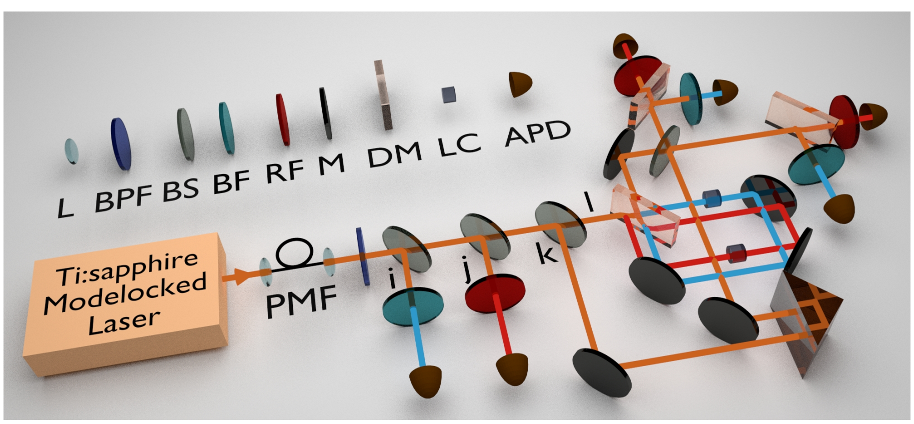

Fig. 1. Simplified schematic of the experimental setup. L, lens; BPF, bandpass filter; BS, beamsplitter; BF, blue filter; RF, red filter; M, mirror; DM, dichroic mirror; LC, liquid crystal; APD, avalanche photodiode; PMF, polarization-maintaining fiber.

In this abstract, we present our progress toward experimentally demonstrating the generation of an energy-entangled W-state in a polarization-maintaining fiber (PMF) via spontaneous four-wave mixing. As shown in the simplified schematic of the experimental setup (Fig. 1), a 1 m PMF (PM780-HP) is pumped by a femtosecond pulse at 810 nm from a Ti:sapphire laser. Pairs of sideband photons are created through SFWM: signal photons at 694 nm and idler photons at 975 nm. In contrast to traditional single-pair generation, here we focus on the simultaneous generation of two pairs; namely, the higher-order process that generates two blue (signal) and two red (idler) photons, which can be obtained by increasing the pump powers. The two pairs of photons travel through a series of beamsplitters with different splitting ratios (25/75, 33/67, 50/50), resulting in each photon having a probability of $\frac{1}{4}$ arriving at each channel. Upon detection of a blue photon at channel i, the remaining three photons will be in an energy-entangled W-state upon post-selection:

$$|W\rangle = \frac{1}{\sqrt{3}}(|BRR\rangle + |RBR\rangle + |RRB\rangle). \quad (2)$$

To characterize the W state, we perform reduced density matrix tomography [2]. In the case of a W state, its density matrix can be reconstructed by performing quantum state tomography on a pair of photons exiting from channels k and l (see Fig. 1), post-selected upon the detection of blue and red photons in channels i and j. In this case, the remaining photons should be in a maximally entangled state. To reconstruct this reduced density matrix, we use two nested interferometers, shown in Fig 1. In channel k, blue and red photons travel through an offset Sagnac interferometer. They are separated by a dichroic mirror and experience different phases imposed by liquid crystals placed in each path. They are recombined on the same dichroic mirror. The output from the Sagnac loop is combined with photons coming from channel l by a 50/50 beamsplitter. The two outputs from this beamsplitter and the outputs from channels i and j are coupled into single-mode fibers and sent to avalanche photodiodes (APDs) for coincidence measurement. This interferometric setup allows us to determine the off-diagonal terms in the reduced density matrix without using frequency conversion. The diagonal terms can simply be measured by excluding the last 50/50 beamsplitter. The reconstructed reduced density matrix, shown in Fig. 2(a), agrees well with expected reduced density matrix. A logarithmic plot of the power dependence of the four-fold coincidences, shown in Fig 2(b), indicates the counts are to fourth order with the pump power, which is as expected for two-pair generation. A full tomography of the W-state can be obtained by permutation of the interferometric measurement on channels i&l and channels j&k.

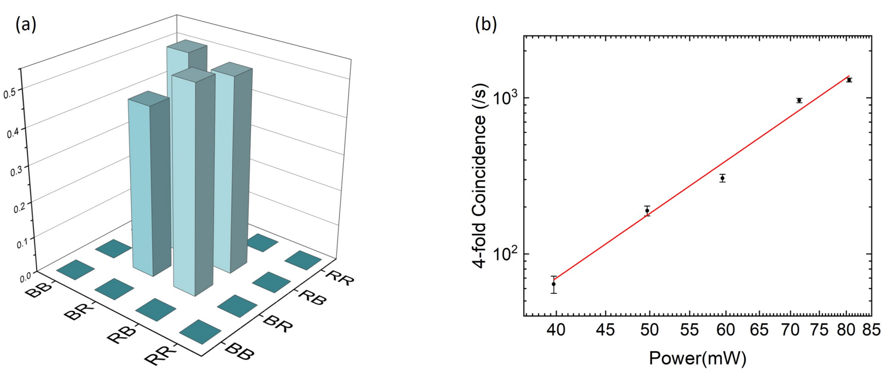

Fig. 2. (a) Estimated reduced density matrix based on raw counts. It is assumed there is no path difference between the k and l arms. The elements that are zero arise due to post-selection. (b) Four-fold coincidence as a function of pump power.

In summary, we have demonstrated the key steps towards the generation and characterization of an energy-entangled W state produced in polarization-maintaining fiber via SFWM. We characterized the state without involving any frequency conversion, taking advantage of the reduced density matrix formalism. The reconstructed reduced density matrix shows good fidelity to the expected state. With robustness against noise and loss, we anticipate the energy-entangled W state and this characterization method may find useful applications in future quantum information protocols. This work is supported in part by NSF Grant Nos. 1521110 and 1640968.

References

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