Multiphoton entangled states generation on silicon

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Optical quantum states with entanglement shared among several photons are critical resources for studies in quantum science. Therefore, the controllable and scalable realization of multiphoton quantum states would enable a practical and powerful implementation of quantum technologies. Nonlinear interactions in integrated circuits show great promise as excellent platforms for photon pair generation with its high brightness, stability and scalability [1]. Recently, optical integrated kerr frequency combs were used to generate time-bin bi- and four-photon entangled qubits [2], which started a new time to manipulating multiphoton entangled states with quantum photonic integrated circuits. The silicon-on-insulator (SOI) photonic circuit is a promising platform for realizing complex quantum states for its strong third-order optical nonlinearity, low nonlinear noise, small footprint, mature fabrication techniques and compatibility with complementary metal oxide semiconductor (CMOS) electronics, as well as telecom techniques. Nevertheless, multiphoton entanglement was not realized in silicon photonic circuits yet.

In our study, a single silicon nanowire waveguide, which has a length of $1\ cm$ and transverse dimension of $\sim\ 450\ nm\ \times\ 220\ nm$, is employed with a Sagnac-ring interferometer to generate polarization encoding state:

$$|\Phi^{2n}\rangle = \frac{1}{\sqrt{2^n}}(|H_{s1}H_{i1}\rangle + |V_{s1}V_{i1}\rangle)\otimes\cdots\otimes(|H_{sn}H_{in}\rangle + |V_{sn}V_{in}\rangle). \qquad (1)$$

Firstly, non-degenerate multi-photon entangled states were generated with a pulsed pump laser at 1550 nm. We performed the four-photon quantum state tomography for the selected frequency channels. The measured density matrix of the non-degenerate four-photon states agrees well with the ideal case and the measured density matrix of the four-photon stated reaches a fidelity of 0.75 ± 0.02, which is applicable to quantum information processing. We estimated the two-photon generation rate of $270\ kHz$ per channel with $120\ \mu W$ pump power and four-photon generation rate of $340\ kHz$ by setting the pump power of $600\ \mu W$ [3].

Then, we also realized the generation of degenerate four-photon quantum Fock states and entangled states at telecom wavelength (1550 nm) by using the dual-pulsed-pump spontaneous four wave mixing process (SFWM) in the silicon waveguide. The generated quantum states include $|11\rangle_{HV}$, two-photon NOON state $\frac{1}{\sqrt{2}}\left(|20\rangle_{HV} + |02\rangle_{HV}\right)$, four-photon Fock state $|04\rangle_{HV}$ and four-photon entangled state $\sqrt{\frac{3}{8}}\left(|40\rangle_{HV} + |04\rangle_{HV}\right) + \sqrt{\frac{1}{4}}|22\rangle_{HV}$. Here, $|mn\rangle_{HV}$ means *m* photon in horizontal polarization and *n* photon in vertical polarization. Quantum interference and state tomography methods were used to analyze the generated states for each case, and the density matrix constructed from the coherence measurement agrees well with the ideal case [4].

In conclusion, we experimentally showed that a single silicon nanowire can be used for multiphoton source generation. Because of the strong third-order nonlinearity, we achieved a high brightness with a very low pump power. The fidelity of the four-photon entangled state is high enough for most practical applications. The multiphoton entangled source is directly compatible with the dense wave division multiplexing communication system and frequency based post-processing system, thus providing a scalable and practical platform for optical quantum information processing.

References

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