Quantum frequency converter based on the sum frequency generation in a nonlinear crystal

2020.02.05

Abstract

Single photons, the basic information carrier for linking different nodes of a quantum network, provide fast and absolute safety by its quantum nature for communication. Facing the vast network built by various quantum devices operating at different optical frequencies, a device of quantum frequency converter (QFC) that coherently converts the wavelength of single photons from one to another and simultaneously maintains its quantum nature is needed. In this work, we systematically study the QFC for the conversion of the narrow-band single-photon states at 780 nm to 407 nm based on the sum-frequency generation (SFG) in a PPKTP nonlinear crystal within an optical cavity[1]. The single photon is generated by the cavity-enhanced spontaneous parametric down-conversion (CE-SPDC)[2] and is then sent into the QFC-device. By analyzing the normalized cross correlation function \( g^{(2)} \) between the converted photons and the heralding photons, we verified that the \( g^{(2)} \) values are significantly larger than the classical limit of 2 and thus the quantum nature of the single-photon is preserved. The conversion efficiency is ~40% at a pump power of 64 mW, which is relatively efficient compared to most of the QFC devices.

Experimental Setup

In our experiment, we generate single photon pairs (CE-SPDC) in first cavity, then send idler photons into second cavity for SFG. Its conversion efficiency \( \eta \) and \( G(2) \) become

\[
\eta = \frac{\int d\omega d\Omega |E_{id}^{\omega}(\omega)|^2}{\int d\omega d\Omega |E_{id}^{\omega}(\omega)|^2}
\]

and

\[
G(2)(\tau) = \left\langle |\langle E_{id}^{\omega}(\omega_1)E_{id}^{\omega}(\omega_2)\rangle|^{2} \right\rangle
\]

where \( |1; \Phi\rangle = \int d\omega d\Omega (\Phi^{\omega}(\omega)|0\rangle |0\rangle \) and \( \int d\omega d\Omega (\Phi^{\omega}(\omega)|0\rangle |0\rangle = 1 \).

Theory about CE-SPDC and SFG in cavity

Cavity-Enhanced Spontaneous Parametric Down-Conversion (CE-SPDC)

Hamiltonian for CE-SPDC (Double resonance for nondegenerate state):

\[
\hat{H}_t = \hbar \omega \left( \int d\Omega d\Omega' \hat{a}_t^{\dagger} \hat{a}_{\omega}^{\dagger} \hat{a}_{\omega'}^{\dagger} (\omega_{\omega} + \Omega_{\omega'}) + \text{H.c.} \right)
\]

where \( \hat{a}_t \): signal and idler mode; \( \gamma \): output coupling rate and \( \alpha \) is a value about pump power, frequency mode and properties of crystal.

For Heisenberg picture, its cross correlation \( G(2) \) for far below threshold becomes

\[
G^{(2)}(\tau) = \left\langle |\langle \hat{a}_t(t)\hat{a}_t(t+\tau)\hat{a}_t(t)\hat{a}_t(t+\tau) \rangle|^{2} \right\rangle \approx \frac{4\alpha^2}{(\gamma_{\omega}^{2}+\gamma_{\Omega}^{2})(\frac{\omega_{\omega}^{2}}{\gamma_{\omega}^{2}}+\frac{\Omega_{\omega}^{2}}{\gamma_{\Omega}^{2}})} e^{-\frac{2\tau}{\gamma_{\omega}^{2}+\gamma_{\Omega}^{2}}}, \quad \tau < \tau_{c}
\]

Sum Frequency Generation (SFG) in cavity

Hamiltonian for SFG in cavity (Single resonance):

\[
\hat{H}_2 = \hbar \omega \left( \int d\Omega d\Omega' (\hat{a}_t^{\dagger} \hat{a}_{\omega}^{\dagger} \hat{a}_{\omega'}^{\dagger} + \text{H.c.} \right)
\]

where \( \hbar \): lower and higher mode.

For Heisenberg picture, sending a single photon(resonant) in cavity, its conversion efficiency becomes

\[
\eta = \left\langle |\langle \hat{a}_t(1)\hat{a}_{\omega}^{\dagger}\hat{a}_{\omega'}(0)\hat{a}_{\omega}^{\dagger}\hat{a}_{\omega'}(0) \rangle|^{2} \right\rangle \approx \int d\Omega d\Omega' \left\langle |\langle \hat{a}_t(1)\hat{a}_{\omega}^{\dagger}(0)\hat{a}_{\omega}^{\dagger}(0)\hat{a}_{\omega}^{\dagger}(0) \rangle|^{2} \right\rangle
\]

Conclusions and Outlook

1. The conversion efficiency is ~40% at a pump power of 64 mW.
2. After SFG, its \( g^{(2)} \) is still significantly larger than 2, which is classical limit.
3. We optimize system then using the theory of SFG in cavity & phase-matching theory[3] to find the maximum conversion efficiency & \( g^{(2)} \) values.
4. Measure more parameter, like signal-to-noise ratio and Cauchy-Schwarz inequality etc.

References

2. Pin-Ju Tsai and Ying-Cheng Chen, Quantum Science and Technology, Volume 3, Number 3 (2018)