Highly Efficient Integrated Generator of Tripartite Entanglement from Whispering Gallery Microresonator

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Abstract: We propose an integrated generator to produce pump-signal-idler tripartite entanglement through a high-Q whispering gallery microresonator filled with lithium niobate which would be the key to future quantum computation on chip.

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Introduction

Quantum computation (QC) is expected to provide exponential speedup for particular mathematical problems such as integer factoring and quantum system simulation. Quantum cryptographic communication, on the other hand, provides an absolutely safe way to pass information without the risk of eardropping. In the center of both quantum computation and quantum communication lies the concept of quantum entanglement, therefore the generation of multipartite entanglement always draws wide attention. Conventionally, entangled photon pairs are generated in $\chi^{(2)}$ bulky crystals that are usually difficult to operate and susceptible to environmental perturbations. It is recently proposed that entangled photon pairs can also be generated from monolithic microresonators of whispering-gallery type [1] via spontaneous parametric down conversion (SPDC) in $\chi^{(2)}$ materials or four-wave mixing (FWM) processes in $\chi^{(3)}$ materials [2]. In a whispering-gallery resonator, whispering-gallery modes (WGMs) of discrete propagation constant are guided by continuous total internal reflection along a curved surface. WGM resonators have the strengths of high confinement to the optical field, exceptionally high quality factor, and compatibility to compact, chip-scale integration, so they have been replacing $\chi^{(2)}$ bulky crystals in many other application of laser optics recently.

The $\chi^{(2)}$ parameter is usually about three orders higher than $\chi^{(3)}$, so the former paradigm enjoys a much more significant nonlinear effect, and therefore, achieve entanglement more easily. In this paper, we propose a theoretical model for generation of a tripartite quantum entanglement from a whispering gallery mode, and exhibit the design parameters over $\chi^{(2)}$ medium, paving the way for future optical quantum computation on chip.

Result

The resonator is a spherical cavity of radius $R = 1.5$mm, thickness $d = 0.5$mm, filled with lithium niobate. The coupling coefficient of our system is $g = 2\pi\omega_s \frac{\chi^{(2)}}{\varepsilon_s}\frac{V_{sip}}{V_s}\sqrt{\frac{2\pi\hbar\omega_p}{\varepsilon_p V_p}}$ [3] , in which $\omega_s = 1.937\times10^{14}s^{-1}$, $\omega_p = 4\times10^{14}s^{-1}$, $V_p \approx 2\pi R\times 2R\sqrt{(\frac{2\pi}{\upsilon_p})}\times\frac{R}{\upsilon_p^{2/3}} = 10^{-6}\ cm^3$, and $\chi^{(2)} = 7\times10^{-10}$cgs, $V_{sip}/V_s = 0.3$. Besides that, loaded Q factors are: $Q_p \simeq 8\times10^6$, $Q_s \simeq 1.2\times10^7$. The wavelength of the pump beam is $\lambda_p = 775$nm in the vacuum and wavelength of signal beam is $\lambda_s = 1548$nm, idler beam is $\lambda_i = 1552$nm.

The generator scheme is shown in Fig. 1 . A narrow linewidth laser is continuously pumped into the microresonator to intrigue nonlinear effect in the whispering gallery mode cavity and then we utilize AWG to separate different frequency beams generated in the microresonator. Once the different frequency components generated in the microresonator is separated by AWG, we will be able to analyse each component in Fabry-Pérot(FP) analysis cavities. The whole procedure above is governed with the rotating-wave approximation [4] by following master equation:

$$\frac{\partial\rho}{\partial t} = \frac{1}{i\hbar}[H_i + H_{pump}, \rho] + \sum_{i=1}^{3} L_i\rho, \tag{1}$$

where $H_{pump} = i\hbar_p^\dagger \varepsilon_p + H.C.$, $H_i = i\hbar(g a_p a_{s1}^\dagger a_{i1}^\dagger) + H.C.$ and $L_i\rho = \gamma_i(2a_i\rho a_i^\dagger - a_i^\dagger a_i \rho - \rho a_i^\dagger a_i)$, where γ_i represents the damping rate. The entanglement between pump, signal and idler waves could be analysed by solving above master equation.

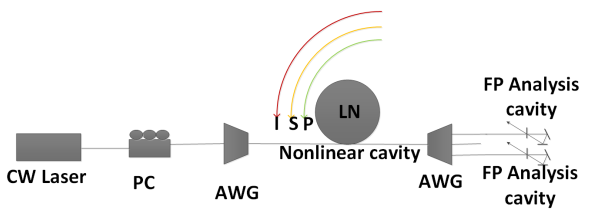

Fig. 1. Tripartite entanglement generator with LN WGM and angle-polished fiber coupling. CW,continuous-wave;PC,polarization controller; AWG,arrayed waveguide grating

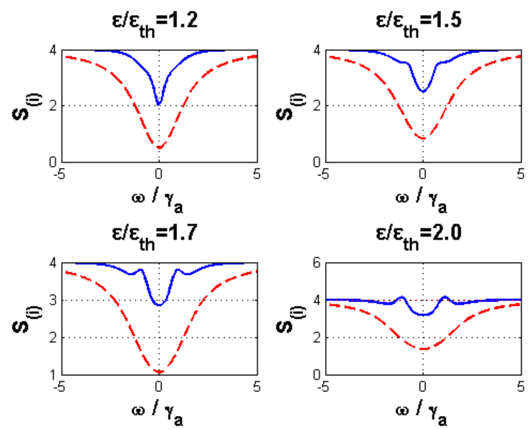

Fig. 2. Extracavity variance vs. pump frequency

When it comes to the tripartite entanglement, we consider Fokker-Planck equation in P representation and then analyse the entanglement condition that van Lock and Furusawa criteria [5] are violated simultaneously. We plot the minimum of the variance versus frequency when $\frac{\varepsilon}{\varepsilon_{th}} = 1.2, 1.5, 1.7, 2.0$ in Fig. 2. And the blue solid one relates with $V(X_p + X_s) + V(Y_p - Y_s - gY_i)$ and red dashed curve stands for $V(X_s - X_i) + V(Y_s + Y_i - gY_p)$. When we change pump power, we could easily see the corresponding change of entanglement. And our coupling coefficient for $\chi^{(2)}$ is 0.0136 around, much larger than $\chi^{(3)}$ coupling coefficient, proving its highly efficiency.

Conclusions

In conclusion, we propose the theoretical model for the pump-signal-idler entanglement based on the high Q microresonator filled with $\chi^{(2)}$ medium. By solving Fokker-Planck equation in P representation, we analysed the entanglement case where Van Lock and Furusawa criteria are violated at same time. We provide with specific design details and find that the intensity of entanglement was largely influenced by the $\frac{\varepsilon}{\varepsilon_{th}}$. The results would offer a new path for the future study for entanglement over integrated microrresonator filled with $\chi^{(2)}$ nonlinear medium.

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