Grating-Enhanced Narrow-Band Spontaneous Parametric Down Conversion

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Abstract: We propose a new method to narrow the linewidth of entangled photons from spontaneous parametric down conversion incorporated with an internal Bragg grating. We study and show that it is a promising way to generate narrow-line entangled photons.
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OCIS codes: (270.5565) Quantum optics, quantum communications; (190.4410) Nonlinear optics, parametric processes

I. Introduction

Quantum communication is one of the most important and practical applications of quantum information science and technology. For highly efficient long distance quantum communication, quantum repeater is a necessary component to recover the fidelity of the quantum information encoded on single photons after long transmission [1]. To store the quantum information into and retrieve it from the quantum memory, the linewidth of the entangled photons should be comparable to the atomic transition linewidth of a few MHz.

One method to generate entangled photons is by the spontaneous parametric down conversion [2]. However, the entangled photons from periodically poled nonlinear crystal waveguide have relatively broad linewidth, typically several nanometers. Passive filtering and below-threshold optical parametric oscillator have been used to narrow the parametric down conversion bandwidth [3,4], but, they either suffer additional loss for the desired signal and idler waves, or contain multiple spectral modes and have bulky and complex configuration. In this paper, we propose and study a new method to narrow the linewidth of entangled photons by spontaneous parametric down conversion using an internal Bragg grating. This approach, if implemented, has only a single longitudinal mode, and its configuration will be much compact. We show that it is a promising way to generate narrow-line entangled photons.

II. Results

The schematic of the proposed device of SPDC with internal Bragg grating is shown in Fig. 1. A Bragg grating is written onto a periodically poled nonlinear crystal waveguide. We consider two Bragg grating structures. One has a continuous grating. Another has a half grating period of flat spacer in the middle of the full Bragg grating, which is commonly used in semiconductor distributed feed-backed lasers.

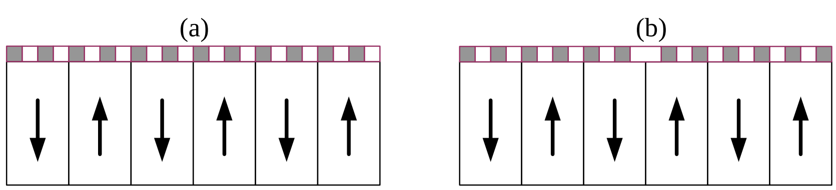

Fig. 1. Periodically poled nonlinear crystal waveguide with a Bragg grating. (a) Continuous grating; (b) grating with midway π-phase shift.

We proceed with the calculation of optical parametric down conversion with an internal Bragg grating by the semi-classical method, with equivalent input noise fields. We assume a non-degenerate parametric optical down conversion, and the Bragg grating is coupled strongly only with the signal wave. For simplicity, we assume the perturbation of dielectric constant and the periodically poled nonlinearity have sinusoidal variations. Under the SVEA, the grating-coupled parametric down conversion process is governed by the coupled differential equations:

$$\frac{dA_s}{dz} = -j\kappa_d A_i^* e^{-j\Delta\beta_Q z} - j\kappa_g B_s e^{j\Delta\beta_G z}$$

$$\frac{dA_i^*}{dz} = j\kappa_d^* A_s e^{-j\Delta\beta_Q z}$$
$$\frac{dB_s}{dz} = j\kappa_g A_s e^{-j\Delta\beta_G z}$$

In the above equations, A_s is the forward signal field, A_i is the forward idler field, and B_s is the backward signal field, $\Delta\beta_G$ is the frequency detuning from the Bragg grating line-center, and $\Delta\beta_Q$ is the phase mismatch away from the signal/idler line-center. The field amplitudes are normalized such that the modular square of the amplitude gives the photon flux density in a particular wave. For the second Bragg grating structure, it is equivalently to have a π-phase shift at the midpoint of the full Bragg grating, corresponding to κ_g changing a sign in the second half region. We take the equivalent noise input ($z = 0$) signal and idler waves with random phases and zero backward signal wave at $z = L$, and the physical SPDC response is ensemble-averaged over random noise inputs. Note that the calculation here is different from the previous study of distributed-feedback optical parametric amplifiers [5].

Figure 2 shows the spectral characteristics optical parametric down conversion with two types of Bragg grating in resonance with the signal wave. As a comparison, the broadband spectral response of parametric down conversion $(\kappa_d L = 1.1,\ \Delta\beta_Q = 0.1\Delta\beta_G)$ is also shown. With a straight Bragg grating $(\kappa_g L = 3, \kappa_d L = 1.1)$, within the stop-band of the Bragg grating, most of the signal wave is in the backward direction, while the idler wave's flux is also reduced. However, the signal and idler photons are generally still broadband. In contrast, with the Bragg grating structure that has a midway π-phase shift $(\kappa_g L = 3, \kappa_d L = 0.7)$, the forward signal and idler waves peark sharply, with comparable high fluxes, at zero detuning. The bandwidth is about one order of magnitude narrower than the stop-band of the Bragg grating.

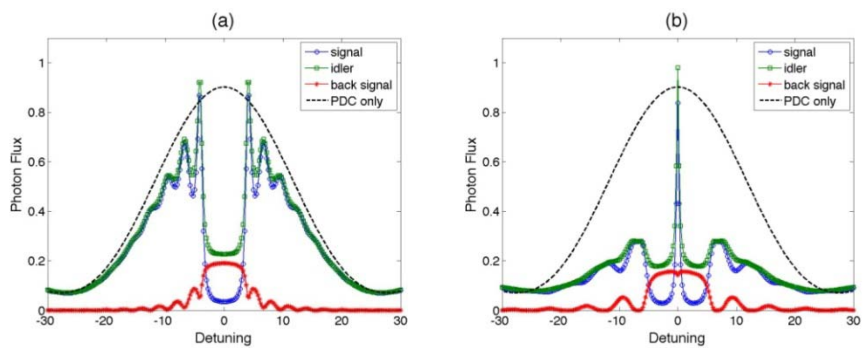

Fig. 2. Signal and idler photon flux densities with and without a Bragg grating. (a) Continuous grating; (b) grating with π-phase shift.

III. Discussion

The narrow-band peak of PDC is reminascent of a spectral resonant characteristics. In the context of quantum nature of SPDC, the resonant characteristics should be understood as a result of the imposition of a constraint on the nonlinear system by the π-phase-shifted Bragg grating and consequently forcing the spontaneous parametric down conversion into only a narrow band, as we note the fact that the spectral peak can reach a given flux level under a lower pump level compared to the necessary pump level for PDC without the Bragg grating. The device structure can be viewed physically as a mircro cavity of quarter-λ long and bounded by two Bragg reflectors. We conclude that incorporating a Bragg grating structur with a midway π-phase shift onto a nonlinear optical crystal waveguide, it is promising to generate very narrow linewidth signal and idler waves via the spontaneous parametric down conversion, an entangled photon source very usefull for quantum information and communication applications.

References:

[1] L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, " Long-distance quantum communication with atomic ensembles and linear optics," Nat. 414, 413-418,(2001)
[2] P.G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, "New high-intensity source of polarization-entangled photon pairs, " Phys. Rev. Lett. 75, 4337-4341 (1995)
[3] O. Kuzucu and F. N. C. Wong, "Pulsed Sagnac source of narrow-band polarization-entangled photons," Phys. Rve. A 77, 032314 (2008)
[4] C. Kuklewicz, F. N. C. Wong, and J. H. Shapiro, "Time-bin-modulated biphotons from cavity-enhanced down-conversion," Phys. Rev. Lett. 97, 223601 (2006)
[5] Y.-C. Huang and Y.-Y. Lin, "Coupled-wave theory for distributed-feedback optical parametric amplifiers and oscillators", J. Opt. Soc. Am. B, 21, 777-790 (2004)