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COUNTERPROPAGATING ENTANGLED PHOTONS IN A WAVEGUIDE WITH PERIODIC NONLINEARITY

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The conditions required for spontaneous parametric downconversion in a waveguide with periodic nonlinearity in the presence of an unguided pump field are established. We find that counterpropagating beams exhibit narrow bandwidth permitting the generation of quantum states that possess discrete-frequency entanglement. Such states may be useful for experiments in quantum optics and technologies that benefit from frequency entanglement.

1 Introduction

Entangled photons, which may be generated through the process of spontaneous parametric downconversion (SPDC) in a crystal with $\chi^{(2)}$ nonlinearity, have long been in the spotlight for quantum-optics experiments.[1,2] SPDC suffers from low conversion efficiency, on the order of 10^{-9} entangled-photon pairs per mode per pump photon, which ultimately limits their use for many practical applications. Quasi-phase matching in crystals with periodic nonlinearity, however, offers the promise of increased photon-pair production.[3] Furthermore, with the integration of a waveguide structure, it is possible to control the spatial characteristics of the downconverted photons while still maintaining a substantial increase in conversion efficiency.[4] It turns out that the waveguide structure imparts yet another critically important feature: the possibility of generating counterpropagating signal and idler photons. We compare the crystal tuning characteristics and spectral properties of counterpropagating beams to those for copropagating beams under typical experimental conditions.

2 Conditions for counterpropagating SPDC

We consider the specific example of a PPLN waveguide, with a $\chi^{(2)}$ nonlinearity that is modulated as a square wave in the z-direction. Because in a series expansion of this nonlinearity, the dominant Fourier components are of order $m = \pm 1$, the PPLN waveguide tuning characteristics result primarily from the $m = \pm 1$ curves, as shown in Fig. 1.

If we consider an example in which the pump-beam angle is 80°, there are signal-idler wavelength combinations of approximately 880 nm/1350 nm ($m = -1$, dashed curve, open circles) and 930 nm/1240 nm ($m = +1$, solid

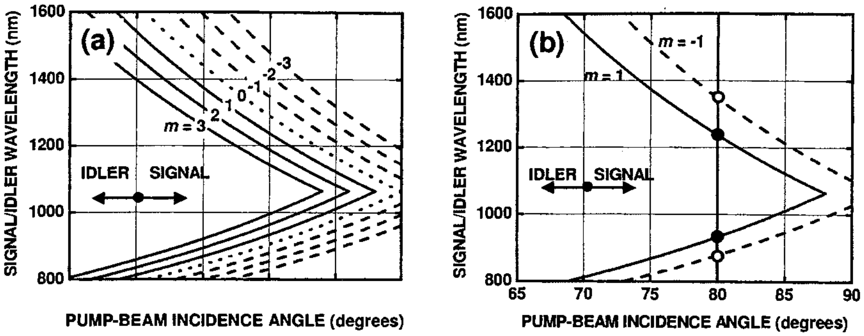

Figure 1. Tuning curves for perfect QPM with various values m: (a) Signal and idler wavelengths versus pump-beam incidence angle θ for grating vector orders $m = 0, \pm1, \pm2$, and ±3 with a poling period $\Lambda = 6.8$ μm. (b) Subset of tuning curves in (a) for $m = \pm1$ with the poling period $\Lambda = 6.8$ μm. The signal photon propagates in the positive z-direction and the idler photon counterpropagates in the negative z-direction as shown by the inset. The pump wavelength is $\lambda_p = 532$ nm in both (a) and (b). Circles in (b) indicate the two signal-idler combinations possible for a pump-beam incidence angle of 80°: 880 nm/1350 nm ($m = -1$, dashed curve, open circles) and 930 nm/1240 nm ($m = +1$, solid curve, solid circles).

curve, solid circles). This quantum state can be represented by

$$|\Psi^{(2)}\rangle \sim c_1|880, 1350\rangle + c_2|930, 1240\rangle, \tag{1}$$

where the constants c_1 and c_2 are determined mainly by the pump properties. By simply selecting the pump-beam incidence angle to be 74.6°, for example, the two-photon quantum state given above can be readily tuned to new signal-idler wavelength combinations of 810 nm/1550 nm and 860 nm/1380 nm.

3 Spectral properties of counterpropagating SPDC

We also consider effects on the spatio-temporal distribution of downconverted light imparted by the finite crystal length and the modal structure of the waveguide. In a comparison of the tuning curves and spectral properties of counterpropagating beams to those for copropagating beams under typical experimental conditions, we find that the counterpropagating beams retain a narrow bandwidth across many signal-idler wavelength combinations, unlike the results shown in Fig. 2(a) for copropagating beams. This finding supports the claim that a superposition of two counterpropagating nondegenerate photons pairs occurs naturally within the PPLN waveguide structure.

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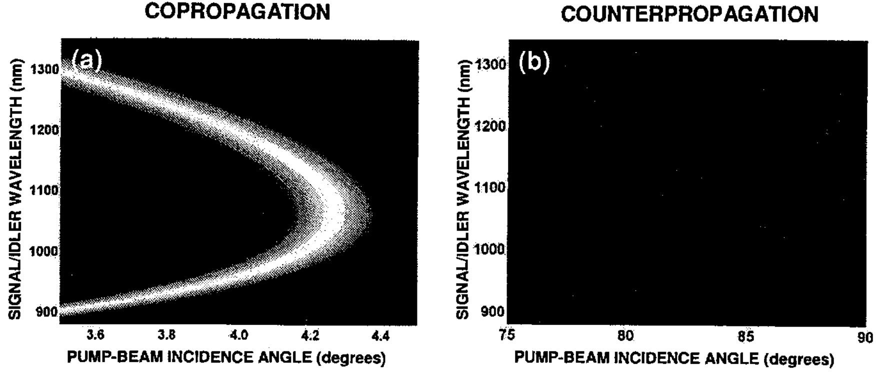

Figure 2. (a) Calculated signal and idler spectra versus pump-beam incidence angle for copropagating beams in a 1-mm PPLN waveguide with a poling period $\Lambda = 7.4$ μm and positive grating vector K_m ($m = 1$). The pump wavelength is $\lambda_p = 532$ nm. (b) Calculated signal and idler spectra versus pump-beam incidence angle for counterpropagating beams in a 1-mm PPLN waveguide with a poling period $\Lambda = 6.8$ μm and $m = \pm1$. The pump wavelength is $\lambda_p = 532$ nm. Although this plot includes all the information pertaining to the spectra of the downconverted light, it is visually indistinguishable from the plot presented in Fig. 1(b).

4 Application to quantum communication

Copropagating entangled photons generated by SPDC have previously been observed in periodically poled silica fibers (PPSFs) by directly coupling of the pump beam.^{5} If the pump beam is coupled to the core medium in a scheme analogous to that of a cladding-pumped fiber laser, it would be possible to generate counterpropagating signal and idler photons directly in the poled fiber. Due to the inherent narrow bandwidth of the counterpropagating beams, a dispersion-free quantum communication apparatus could be realized as illustrated in Fig. 3.

5 Conclusions

It is possible to control the superposition of two or more counterpropagating nondegenerate photon pairs by tuning the pump-beam incidence angle, by appropriately changing the pump field profile using, e.g., a superposition of pump angles, and by engineering the periodicity of the nonlinearity. Such a quantum state cannot be generated in bulk nonlinear media, nor in media with periodic structures, but they are generated naturally in media with both periodic nonlinearity and a waveguiding structure. Although we primarily discussed theoretical results for a PPLN waveguide, the results are general and will also apply, for example, to a periodically-poled cladding-pumped fiber with $\chi^{(2)}$ nonlinearity.

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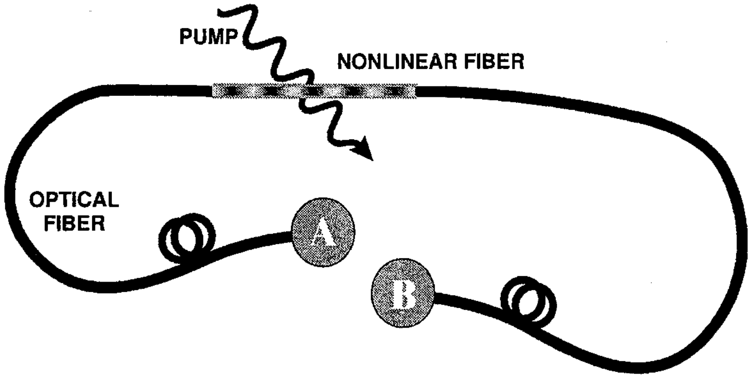

Figure 3. Application to quantum communication. The pump beam (which is guided in the fiber cladding) couples to the core medium as it propagates. Since the core medium has a modulated nonlinearity (illustrated as striations), counterpropagating entangled photons can be generated directly within the communication fiber to provide dispersion-free quantum communication between Alice (A) and Bob (B).

Acknowledgements

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