Proposal for in-fiber generation of telecom-band polarization-entangled photon pairs using a periodically poled fiber

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Received April 15, 2009; revised May 22, 2009; accepted May 27, 2009; posted June 9, 2009 (Doc. ID 110084); published July 9, 2009

We treat spontaneous parametric downconversion in a periodically poled fiber, quasi-phase matched to allow for the generation of photon pairs at wavelengths within the low-loss telecommunications window. For an appropriate pump polarization, the unusual properties of such a fiber's effective $\chi^{(2)}$ result in a biphoton wave function that is symmetric upon simultaneous exchange of downconverted photon frequencies and polarizations and that is nonzero over a wide range of downconverted frequencies. This could lead to a significant technical simplification of sources of in-fiber telecom-band polarization-entangled photons. © 2009 Optical Society of America

OCIS codes: 190.4370, 190.4975, 270.0270.

Ongoing improvements in the generation and processing of single photons and entangled photon pairs in the low-loss telecommunications window are helping to make a high-speed, high-capacity, quantum communication network a reality [1–5]. Pairs of photons have been created via spontaneous parametric downconversion (SPDC) in two orthogonally oriented, periodically poled, KTP crystals, and then collected in single-mode fibers [6]. More recently, specially engineered waveguides have been used to generate polarization-entangled photons efficiently and compactly [7–9]. Yet, as is always the case when coupling light into fiber, such schemes incur undesirable photon losses. To avoid this, the in-fiber generation of photon pairs has also been proposed and demonstrated [10–13]. However, to date, the generation of polarization-entangled photons for telecommunication systems has relied on spontaneous four-wave mixing with dual pumps in a counterpropagating loop geometry. Although this can be done at room temperature in photonic crystal fibers [11], cryogenic cooling is typically required in conventional telecommunications fibers to suppress background noise from Raman scattered photons [10,13].

In this Letter we propose using a straight piece of periodically poled fiber [14,15] at room temperature to generate pairs of orthogonally polarized photons in a SPDC process. The poling allows the ordinarily isotropic material to possess an effective $\chi^{(2)}$ that is then selectively erased to enable quasi-phase matching (QPM). Two years ago it was shown experimentally that SPDC could be used in these types of structures to produce photon pairs [16]. However, it does not seem to have been realized that this process allows for the possibility of Type II QPM, i.e., orienting the polarization of the pump photons such that the downconverted photons are polarized orthogonally to each other. These pairs of orthogonally polarized photons can then be further processed to serve as either a source of single photons, if passed through a polarization beam splitter so that one photon can herald the other, or polarization-entangled photons, as described below.

Our proposed scheme offers many advantages. There are minimal photon losses when such fibers are spliced to a transmission fiber; orthogonally polarized photon pairs are generated naturally upon the pass of a single pump pulse through the poled fiber; and using a SPDC process ensures that the generated photons are far away in frequency from any Raman scattered photons. In addition, because we need only a short length of fiber, polarization mode dispersion does not limit our approach as it would if four-wave mixing, where long lengths of fiber are typically required, was used to generate orthogonally polarized photons [17].

We estimate the efficiency of this scheme by extending an earlier approach [18] to include polarization effects. The photon mode operators satisfy $[a_{m\sigma k}, a^{\dagger}_{m'\sigma' k'}] = \delta_{mm'}\delta_{\sigma\sigma'}\delta(k-k')$, with all other commutators zero. m restricts the range of frequencies involved in an expression to be near that of the fundamental field ($m=F$) or second harmonic ($m=S$), and σ labels the specific mode type in the range of frequencies labeled by m. Taking the z direction as the propagation direction, σ might indicate either the LP_{01}-like mode with the majority of its polarization in the x direction ($\sigma=x$) or the LP_{01}-like mode with the majority of its polarization in the y direction ($\sigma=y$); $\omega_{m\sigma k}$ are the eigenfrequencies of the modes. The coupling Hamiltonian is

$$\sum_{\alpha,\beta,\gamma} \int \mathrm{d}k_1 \mathrm{d}k_2 \mathrm{d}k S_{\alpha\beta\gamma}(k_1,k_2,k) c^{\dagger}_{\alpha k_1} c^{\dagger}_{\beta k_2} b_{\gamma k} + \mathrm{H.c.}, \tag{1}$$

where we have set $a_{F\sigma k} \to c_{\sigma k}$, $a_{S\sigma k} \to b_{\sigma k}$, have labeled the mode types with Greek letters as above, have kept only terms associated with the downconversion of photons, and the coupling coefficient $S_{\alpha\beta\gamma}(k_1,k_2,k)$ is given by a straightforward extension of an earlier expression [18]. We consider a pump pulse polarized mainly in the y direction ($m=S$, $\sigma=y$), orthogonal to the poled DC (static) field in the fiber [see Fig. 1(a)], and write it as a coherent state with an expectation value $|\mu|^2$ of the number of pump photons and a pulse profile described by a normalized function $\phi_P(k)$; the asymptotic-in state [18] for such a pulse is $|\phi_{\text{in}}\rangle = \exp(\mu\int dk\,\phi_P(k)b_{yk}^{\dagger} - \text{H.c.})|vac\rangle$. Following Yang *et al.* [18], in the undepleted pump approximation, the asymptotic-out state is then

$$|\phi_{\text{out}}\rangle = \exp(\nu C_{\text{II}}^{\dagger} - \text{H.c.})|\phi_{\text{in}}\rangle, \tag{2}$$

where

$$C_{\text{II}}^{\dagger} = \frac{1}{\sqrt{2}}\sum_{\alpha,\beta}\int_0^{\infty} dk_1\int_0^{\infty} dk_2\,\phi_{\alpha\beta}(k_1,k_2)c_{\alpha k_1}^{\dagger}c_{\beta k_2}^{\dagger}, \tag{3}$$

and

$$\phi_{\alpha\beta}(k_1,k_2) = \frac{i\mu}{\nu}\int dk\,\phi_P(k)S_{\alpha\beta y}(k_1,k_2,k) \times \delta(\omega_{Syk} - \omega_{F\alpha k_1} - \omega_{F\beta k_2}) \tag{4}$$

is the biphoton wave function associated with photons with wavenumbers k_1,k_2 in modes α,β, respectively; it is naturally symmetric, $\phi_{\alpha\beta}(k_1,k_2) = \phi_{\beta\alpha}(k_2,k_1)$. The quantity $\nu=\mu\Gamma$, where Γ is set so that the biphoton wave function is normalized. If we switch to a frequency representation, where $\tilde{\phi}_{\alpha\beta}(\omega_1,\omega_2)$ is associated with photons with frequencies ω_1,ω_2 in modes α,β, respectively, the normalization condition takes the form

$$\sum_{\alpha,\beta}\int_0^{\infty} d\omega_1\int_0^{\infty} d\omega_2|\tilde{\phi}_{\alpha\beta}(\omega_1,\omega_2)|^2 = 1. \tag{5}$$

In Eq. (2) we see that in the limit of a low probability of pair production ($|\nu|\ll 1$, characteristic of a pulse rather than a cw pump), we have $|\phi_{\text{out}}\rangle \simeq |\phi_{\text{in}}\rangle + \nu C_{\text{II}}^{\dagger}|\phi_{\text{in}}\rangle + \cdots$, and so $|\nu|^2$ gives the probability of pair production.

As a specific example, we consider a fiber similar to those fabricated by Myrén *et al.* [15]. We use the Sellmeier equation to model the refractive index of the fused silica cladding [19] and take the core to have a refractive index shifted 0.023 higher than the cladding, independent of frequency. We find that the core, with a radius of 2.3 μm, is, to a very good approximation, modeled as residing in an infinite background of cladding material; thus we set $k_{Fx}(\omega)\cong k_{Fy}(\omega) \to k_F(\omega)$, $k_{Sy}(\omega)\to k_S(\omega)$. Around the center frequencies we model these dispersion relations as $k_{F,S}(\omega)\simeq k_{F_0,S_0} + (\omega-\omega_{F_0,S_0})/v_{F,S} + \Delta_{F,S}(\omega-\omega_{F_0,S_0})^2$, with $k_{F_0,S_0}=k_{F,S}(\omega_{F_0,S_0})$, $\omega_{S_0}=2\omega_{F_0}$, $(v_{F,S})^{-1} = (dk_{F,S}(\omega)/d\omega)_{\omega=\omega_{F_0,S_0}}$, and $\Delta_{F,S}=(d^2k_{F,S}(\omega)/d\omega^2)_{\omega=\omega_{F_0,S_0}}/2$. In a simple model where $\chi^{(2)}$ results from the $\chi^{(3)}$ effect of a frozen DC field, for a DC field in the x direction, we have $\chi_{xxx}^{(2)}=3\chi_{xyy}^{(2)}=3\chi_{yxy}^{(2)}=3\chi_{yyx}^{(2)}$, which we take to be 0.04 pm/V [20,21], with all other components vanishing. This makes the relevant tensor elements for our proposed Type II QPM process $\chi_{xyy}^{(2)}=\chi_{yxy}^{(2)}=0.013$ pm/V. We note that in this model light polarized in the y direction cannot generate copolarized photon pairs; i.e., there is no Type I QPM process for y-polarized photons. We assume that $\chi^{(2)}$ exists solely within the fiber core, and to achieve QPM for a pump centered at 1.6 eV (775 nm), we take its profile along the fiber as a square wave with a 50% duty cycle and a period of $\Lambda=46.5$ μm [see Fig. 1(b)]. Keeping only the fundamental period in the square wave, which will serve as a good approximation here, the usual phase integral in $S_{\alpha\beta y}(k_F(\omega_1),k_F(\omega_2),k_S(\omega_1+\omega_2))$ [18] takes the form $L\sin\gamma/(\pi\gamma)$, with $\gamma=(k_S(\omega_1+\omega_2)-k_F(\omega_1)-k_F(\omega_2)-2\pi/\Lambda)L/2$, where L is the length of the poled fiber.

At the QPM condition, $\hbar\omega_{S_0}=1.6$ eV, we calculate $v_F=201.4$ μm/ps, $v_S=200.7$ μm/ps, $\Delta_F=-8.4\times10^{-9}$ ps^2/μm, and $\Delta_S=1.7\times10^{-8}$ ps^2/μm. We take a Gaussian pump pulse $\tilde{\phi}_P(\omega_P)$, centered at $\omega_P=\omega_{S_0}$, and an intensity FWHM of 5 ps. For a pulse with an energy of 1.61 pJ, containing $|\mu|^2=6.27\times10^6$ photons, we calculate that on average there would be $|\nu|^2 = 4.3\times10^{-3}$ orthogonally polarized downconverted photon pairs generated in a 1-m-long fiber. We note that this conversion rate is comparable to that of Liang *et al.* [10], where 5 ps duration pulses containing the same number of photons yielded $\approx 4.4\times10^{-3}$ entangled pairs per pulse in a 300-m-long dispersion-shifted fiber.

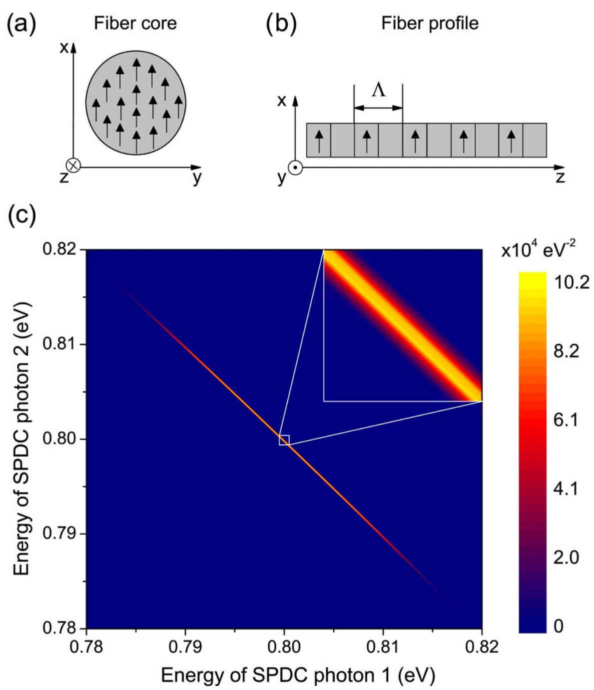

Fig. 1. (Color online) DC Poling and biphoton probability density. (a) Fiber core, with arrows representing direction of DC field. (b) Fiber profile, with arrows representing direction of DC field and Λ the QPM period. (c) Biphoton probability density $|\hat{\phi}_{xy}(\hbar\omega_1,\hbar\omega_2)|^2=|\hat{\phi}_{yx}(\hbar\omega_1,\hbar\omega_2)|^2$, where $\hat{\phi}_{\alpha\beta}(\hbar\omega_1,\hbar\omega_2)=\hbar^{-1}\tilde{\phi}_{\alpha\beta}(\omega_1,\omega_2)$.

We sketch the biphoton probability distribution function in Fig. 1(c). Note that as $\hbar\omega_1-\hbar\omega_2$ and $\hbar\omega_1+\hbar\omega_2-\hbar\omega_P$ range over their allowed values, the range of $\hbar|\omega_1-\omega_2|$ over which $|\hat{\phi}_{xy}(\hbar\omega_1,\hbar\omega_2)|^2$ is significantly nonzero is much larger than the range of $\hbar|\omega_1+\omega_2-\omega_P|$ over which it is significantly nonzero. The first of these ranges is set by fiber length and the dispersion factor Δ_F and is given approximately by $4\hbar\sqrt{\pi/(|\Delta_F|L)}$ at the QPM condition; the second of these is largely determined by the group velocities v_F and v_S and the FWHM τ of the pulse and is given approximately by $\min(2\hbar\sqrt{2\ln(2)}/\tau, 2\pi\hbar(|(1/v_S-1/v_F)|^{-1})/L)$ at the QPM condition. The large separation of these ranges means that while there is a small region in the center of Fig. 1(c) in which the photons are energy degenerate, this represents only a small fraction of the total downconverted photons, and to good approximation we can restrict ourselves to the region $(\omega_1>\omega_P/2,\ \omega_2<\omega_P/2)$ and to the region $(\omega_2>\omega_P/2,\ \omega_1<\omega_P/2)$ in the integrals in Eq. (3) once the variables are changed to ω_1 and ω_2. Then using the symmetry properties of $\tilde{\phi}_{\alpha\beta}(\omega_1,\omega_2)$ we can write $C^\dagger_{II}|vac\rangle$ as, to good approximation,

$$\sqrt{2}\int_{\omega_P/2}^{\infty} \mathrm{d}\omega_1 \int_0^{\omega_P/2} \mathrm{d}\omega_2 \tilde{\phi}_{xy}(\omega_1,\omega_2)[|x\omega_1;y\omega_2\rangle + |y\omega_1;x\omega_2\rangle], \tag{6}$$

where $|x\omega_1;y\omega_2\rangle \equiv \tilde{c}^\dagger_{x\omega_1}\tilde{c}^\dagger_{y\omega_2}|vac\rangle$, etc., with $\tilde{c}^\dagger_{\alpha\omega}$ as the frequency representation analog of $c^\dagger_{\alpha k}$. By routing the frequency components $\omega>\omega_P/2$ and $\omega<\omega_P/2$ in different directions, states that are polarization entangled over large distances would result.

Our approach is robust against a uniform effective birefringence in the fiber even if it were large enough to alter phase-matching conditions such that the pump frequency required for Type II QPM would be effectively shifted away from that required for other types of QPM. Indeed, from a practical point of view, this would ensure that all downconverted photon pairs would be orthogonally polarized when the fiber was pumped in the neighborhood of a particular frequency, even if the polarization of the pump photons was not well aligned.

In conclusion, we have proposed a scheme for the in-fiber production of telecom-band polarization-entangled photons that reduces the need for complicated interferometric setups and cooling to mitigate Raman background noise. The result is made possible by the presence of tensor elements in the effective $\chi^{(2)}$ within a periodically poled fiber that, with an appropriately polarized pump pulse, lead to the production of pairs of SPDC photons in which the downconverted photons are naturally orthogonally polarized.

References and Notes

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