Counterpropagating Twin Photons by Parametric Fluorescence

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An original geometry for parametric fluorescence is proposed and analyzed theoretically, in which counterpropagating twin photons are emitted in a thin waveguide. In this original down-conversion process, a dramatic decrease of the spectral signal bandwidth at degeneracy is expected, as compared to usual parametric fluorescence processes. The possibility of using the counterpropagating twin photons for quantum cryptography is emphasized. It is shown that the realization of a fibered semiconductor source of Einstein-Podolsky-Rosen photons is possible by this method.

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Pairs of photons generated by optical parametric down-conversion have appeared recently as excellent examples of entangled states, exhibiting quantum correlations between measurements on the two particles [1–5]. For this reason, twin photon sources obtained by parametric fluorescence (PF) are becoming fundamental tools in various quantum optics experiments, from quantum cryptography [1] and teleportation [4] to Bell experiments [2,5]. Some of these experiments, particularly in the field of quantum key distribution, use optical fibers for the transport of photons between the users. Twin photons are most of the time generated in a bulk nonlinear material, and the photons are coupled into optical fibers by a microscope objective, resulting in a quite complex setup. In this Letter, a new geometry of PF is proposed and theoretically analyzed. Down-converted photons are emitted into two counterpropagating guided modes in a thin waveguide. This original process provides key features for quantum optics because it leads to a very narrow spectral width, and it is naturally well suited for the generation of entangled pairs of photons, easily coupled into optical fibers by standard integrated optics technology.

Optical second harmonic generation (SHG) from two counterpropagating pump beams in a nonlinear waveguide has been demonstrated by several groups in the past [6,7]. In this scheme, the output beam at the SH frequency is emitted from the surface of the sample, and the conservation of the wave vector, or phase matching (PM), occurs only in the plane of the waveguide. This is related to the small waveguide thickness, whereas momentum conservation results from a translational invariance. A consequence of this in-plane PM is SH emission with an angle which depends on the birefringence of the waveguide [6,7], for $\chi^{(2)}$ tensors providing second order nonlinear polarization from the interaction of a TM and a TE polarized counterpropagating wave.

In this Letter, we propose to reverse this interaction, in order to generate pairs of twin photons by PF from a pump beam incident on top of the waveguide, signal and idler propagating in opposite directions (see Fig. 1). Signal and idler wavelengths are determined by the in-plane PM condition, depending on the angle of incidence θ of the pump.

Let us consider an ideal slab waveguide made of a nonlinear material with a zinc-blende crystalline symmetry, such as semiconductor materials which have been used previously for surface emitting SHG experiments. Let the air-semiconductor interface define the plane $x = 0$, and let the x-z plane be the plane of incidence for the p-polarized pump light (that is, with the magnetic field vector perpendicular to the plane of incidence). The $\chi^{(2)}_{xyz}$ tensor of the semiconductor couples the pump component on the z axis with a pair of TE (y-polarized) and TM (x-z polarized) parametric photons, counterpropagating along z. The three wave mixing process efficiency is generally governed by the vectorial PM condition $\mathbf{k}_p - \mathbf{k}_s - \mathbf{k}_i = 0$, the subscripts p, s, and i, of the wave vectors accounting for the pump, signal, and idler, respectively. If the waveguide thickness is small enough (i.e., within a half a pump wavelength), there is no phase mismatch in the direction perpendicular of the waveguide. Momentum conservation is then applied only in the plane of the waveguide. This is also true in the case of a thickness equal to an odd number of half pump wavelengths [6]. The projection gives $k_p \sin(\theta) - k_+ + k_- = 0$, where the positive (negative) subscript designates the down-converted photon which momentum gives a positive (negative) scalar product with the pump photon momentum. "+" and "−" waves are the TE and TM polarized waves in scheme (1a) in Fig. 1, respectively, and in opposite TM and TE in case (1b). In the former situation (1a), this leads to

$$\omega_p \sin(\theta) = \omega_+ \beta^{\mathrm{TE}}(\omega_+) - \omega_- \beta^{\mathrm{TM}}(\omega_-). \tag{1}$$

In this equation, β designs the effective index of the waveguide for the TM or TE polarization. Given a pump frequency ω_p and an angle of incidence θ, Eq. (1), associated with the energy conservation $\omega_p = \omega_+ + \omega_-$, gives only one solution for the pair of signal and idler frequencies ω_+ and ω_-. Note that another solution exists considering a TE polarization for $-$ and a TM polarization

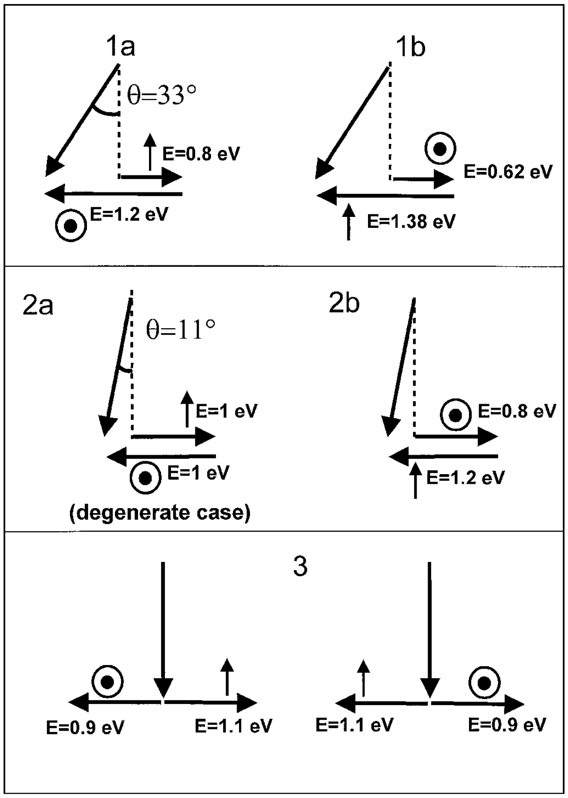

FIG. 1. Wave vectors of the three interacting beams, for different in-plane phase-matched counterpropagating PF processes, for a pump incidence of 33° [cases (1a) and (1b)], 11° [cases (2a) and (2b)], and 0° [case (3)]. The two horizontal arrows represent the wave vectors of the counterpropagating signal and idler waveguided modes; the small vertical arrow and dotted circle mean a TM and a TE polarization, respectively. For a given angle of incidence, two distinct parametric processes are phase matched: ($\uparrow +; \odot -$) and ($\uparrow -; \odot +$). (2a) describes a degenerate PF process, for an angle of incidence of 11°, related to the birefringence of the waveguide. Case (3): At normal incidence, the two processes reflect simply the symmetry of the system, and the two photon state generated by PF is an entangled state $1/\sqrt{2}[(1.1\ \text{eV}\uparrow \rightarrow; 0.9\ \text{eV}\odot \leftarrow) + (1.1\ \text{eV}\uparrow \leftarrow; 0.9\ \text{eV}\odot \rightarrow)]$.

for the + wave, so that for a given ω_p and a given θ, two different pairs of twin photons can be generated. This is summarized in Fig. 1 [pairs (1a) and (1b) for $\theta = 33°$; pairs (2a) and (2b) for $\theta = 11°$].

Let us analyze the typical tuning curve given by this system of two equations. If we neglect dispersion and birefringence, at degeneracy (i.e., $\omega_+ = \omega_- = \omega_p/2$) we simply find $\theta = 0$, as expected. Waveguide dispersion has, however, to be considered as a fundamental issue in this problem. Modal dispersion appears even in the absence of material dispersion, as a consequence of wave confinement [8]. To understand the concept of counterpropagating PF, a very simple example is studied: the case of a 250 nm layer of refractive index equal to 2 (and independent of frequency) in air ($n = 1$). The material dispersion or thickness does not change the fundamental characteristics derived in this analysis of counterpropagating PF but affects only the numerical results (PM wavelengths and angles, conversion efficiency, ...).

The inset in Fig. 2 shows the two effective indices of fundamental modes guided by the 250 nm thick layer, increasing with the energy from the refractive index of the embedding medium (air, $n = 1$) to the refractive index of the slab ($n = 2$). The difference of effective index between TE and TM waves is the so-called form birefringence and comes from the lower confinement of the TM wave in the slab, arising from the electric displacement continuity in the TM case [9]. The birefringence $\beta^{\text{TE}} - \beta^{\text{TM}}$ has a maximum for an energy around 1 eV in our example. Figure 2 shows also the angle of incidence for degenerate PF, that is, the particular case (2a) of Fig. 1. This angle is the one measured in a surface emitting SHG experiment, which is nothing but the reverse of our degenerate PF process under study. This angle is directly related to the birefringence of the waveguide through $\sin(\theta) = (\beta^{\text{TE}} - \beta^{\text{TM}})/2$. θ is maximum for a pump energy of 2 eV, twice the frequency of maximum waveguide birefringence. The complete tuning curve of the counterpropagating PF process is shown in Fig. 3, for a given pump energy of 2 eV. For each angle of incidence of the pump, two in-plane phase-matched processes are found, as explained above: one is ($\uparrow +; \odot -$) and corresponds to a TM parametric wave (noted $\uparrow$, as in Fig. 1) collinear with the pump wave-vector in-plane projection and a counterpropagating TE wave (noted $\odot$). This case corresponds to the curves containing (1b) and (2b) processes. The symmetric situation ($\uparrow -; \odot +$) is the generation of a TE wave counterpropagating with the projection of the pump and a TM counterpropagating and corresponds to cases (1a) and (2a). The figure is symmetric with respect to the horizontal line $E = 1$ eV (half of the pump wavelength), because of energy conservation, and also symmetric with respect to the vertical line $\theta = 0$, due to the simple spatial symmetry

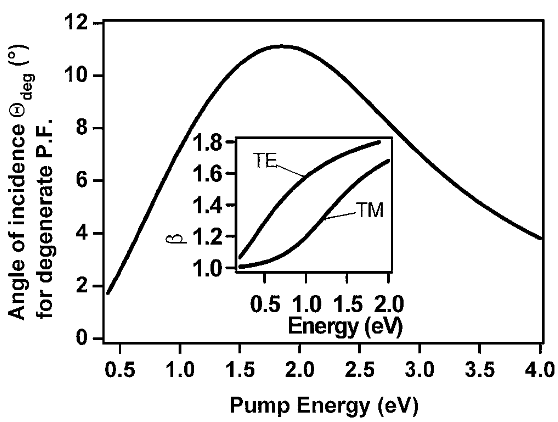

FIG. 2. For a large interval of pump energies, an angle of incidence exists for which degenerate PF is possible. This angle reflects the birefringence of the waveguide, which is maximum for signal and idler photons around 1 eV in our example (see the effective indices of the waveguide in the inset), and thus for a pump at 2 eV.

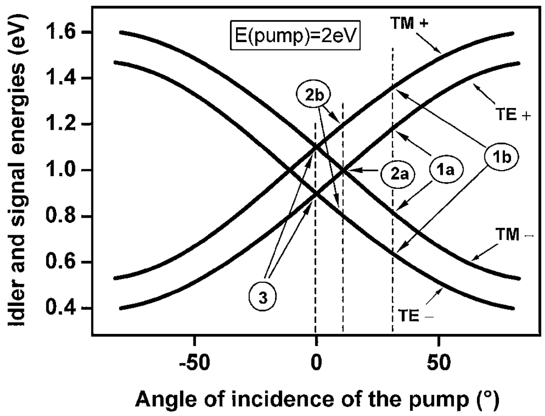

FIG. 3. Tuning curves of counterpropagating PF as a function of the angle of incidence, for an example of pump power of 2 eV. For a given angle of incidence, four photons can be down-converted, since two distinct processes are possible. The positions of processes which are represented in Fig. 1 are indicated.

of the system. Particular processes are the degenerate process (2a), where two photons of energy 1 eV are emitted, and the normal incidence ($\theta = 0$) process (3), where counterpropagating pairs of TM 1.1 eV and TE 0.9 eV are emitted, with equal amplitudes for the left and right versions of the process. In-plane momentum conservation for these different processes is pictured in Fig. 1. Tuning curves as a function of the pump energy are also shown in Fig. 4, for three angles of incidence. A striking characteristic of these tuning curves is the very large parameter space for phase-matched down-conversion, as a function of pump energy or angle of incidence. PF is obtained for angles from 0° to 90° and also with pump energies varying by a factor of 3. This contrasts with usual PF processes, where phase matching occurs for a pretty small interval of angles and a limited pump spectral range [10].

An outstanding property of the counterpropagating geometry is the spectral linewidth of the down-converted signal. For a given angle of incidence, and assuming a monochromatic pump wavelength, the full width at half maximum of the PF is equal to

$$\Delta\lambda = \frac{0.886\lambda^2}{Lb'}, \tag{2}$$

where L is the sample length and

$$b' = \beta_0^{\mathrm{TM}} + \beta_0^{\mathrm{TE}} - \lambda_{s,0}\frac{\partial\beta^{\mathrm{TM}}}{\partial\lambda}\bigg|_{\lambda_{s,0}} - \lambda_{i,0}\frac{\partial\beta^{\mathrm{TE}}}{\partial\lambda}\bigg|_{\lambda_{i,0}}. \tag{3}$$

This expression of b' contrasts with the usual PF linewidth involving a term b expressed as b' except that the plus sign is a minus, and the second minus sign a plus [10]. This difference is characteristic from the counterpropagating geometry. As a consequence, b' is the sum of four positive terms. In our numerical example, for a counterpropagating degenerate PF process such as case (2b)

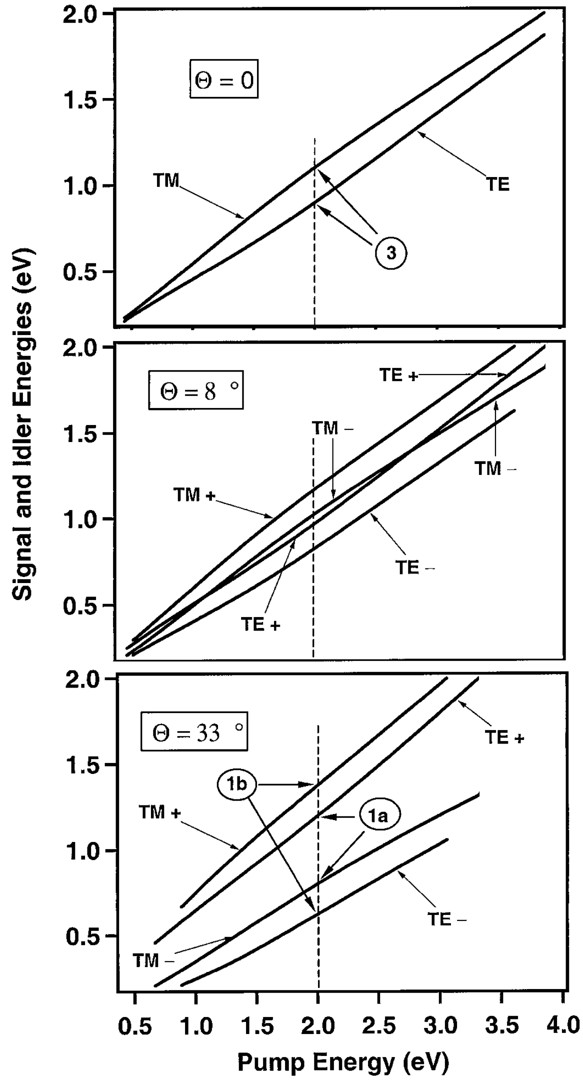

FIG. 4. Tuning curves for three different angles of incidence, as a function of the pump photon energy. The label "+" or "−" indicates if the propagation of the generated photon is parallel or antiparallel to the pump wave-vector projection.

(see Fig. 1), $b' = 3.68$. In a classical PF process, the different terms in the expression of b have different signs and cancel each other: taking the same waveguide we find $b = 0.28$ only. The down-conversion spectral linewidth is therefore more than 1 order of magnitude narrower in the counterpropagating case. We found in our example of counterpropagating PF $\Delta\lambda \times L = 0.037$ nm cm, which has to be compared to 0.486 nm cm in a type II collinear process in a waveguide with the same indices and derivatives, and to 50 nm cm for a type I process in a GaAs/Alox form birefringent waveguide [11].

In the counterpropagating PF scheme, the nonlinear interaction length is in the micrometer range (i.e., the waveguide thickness), whereas the interaction length can be of the order of several cm in a collinear process [11,12]. For a pump beam area of width W and length L (in the direction of propagation of down-converted photons), the efficiency of the down-conversion process (in W/W) is found to be

$$\eta = \frac{16\pi^3\hbar c}{\epsilon_0\beta_s\beta_i}\frac{\Delta\lambda_s}{\lambda_s^5}\frac{L}{W}\left[\int d_{\text{eff}}\psi_p\psi_s\psi_i\,dx\right]^2, \quad (4)$$

where d_{eff} is the nonlinear coefficient. This expression is obtained in a similar way as for copropagating three wave mixing, using the coupled mode analysis [13]. The slowly varying approximation is applied only to signal and idler normalized guided mode fields $\psi_{s,i}$. The pump field ψ_p is a plane wave propagating in a stratified medium and is equal to the sum of a progressive and a reflective wave. We have chosen the convention for the incoming part $\psi_p^+(0) = 1$ at the air-waveguide interface. For typical waveguide length and width equal to 1 mm and 3 μm, respectively, with a nonlinear integral of 100 pm/V, a typical efficiency of 10^{-11} is obtained. An improved structure, in which the pump field is resonant in a vertical microcavity, leads to an efficiency greater than 10^{-9}. This numerical optimization is beyond the scope of this Letter and will be detailed elsewhere. With a 1 mW pump power only, this gives a typical rate of a few 10^6 down-converted photons per second, suitable for quantum information purposes. Our waveguide geometry provides a highly compact source of twin photons, as compared to usual systems. Using the standard semiconductor pigtailing process [14], with a standard antireflection coating on each waveguide facet, it is easy to provide twin photons, one in its own fiber. This would be obtained without any beam splitter microscope objective, nor piezoelectric positioning technology. All these components are source of losses to avoid in quantum correlation based measurements.

One of the most interesting possibilities offered by this counterpropagating geometry of twin photons is the generation of entangled twin photon states. For instance, the $\Theta = 0$ process pictured in Fig. 1 (case 3) gives a pair of photons in an entangled state with the photon traveling to the left equally likely to have either of two energies but correlated with the right traveling photon in such a way that the sum of the two energies always equals the pump photon energy. Note that entanglement is obtained simultaneously for the three variables: energy, momentum, and polarization. More complex experimental setups open other perspectives: let us suppose that pump photons are coming with two angles of incidence $+\theta$ and $-\theta$, corresponding to the degenerate parametric process ($\theta = 11°$ in our case 2a). This can simply be obtained by splitting the pump beam into two equal parts by means of a beam splitter or of a simple diffraction grating just above the sample, diffracting pump photons into two first order $+\theta$ and $-\theta$. The two pump beams $+\theta$ and $-\theta$ create their own $(\updownarrow +; \odot -)$ pair, but the two pairs have opposite directions of propagation, $+$ and $-$ being defined with respect to the direction of each pump beam. As a consequence, one of the pump beams creates the degenerate pair $(\updownarrow \rightarrow; \odot \leftarrow)$, and the symmetric one generates the symmetric pair $(\updownarrow \leftarrow; \odot \rightarrow)$. In this notation, $\rightarrow$ and $\leftarrow$ indicate the right and the left direction of propagation of down-converted photons. The superposition is an entangled pair of photons, one of the so-called four Bell states:

$$|\psi\rangle = \frac{1}{\sqrt{2}}[(\updownarrow \rightarrow; \odot \leftarrow) + (\updownarrow \leftarrow; \odot \rightarrow)]. \quad (5)$$

Any of the other three Bell states can be obtained by using a dephasing element at one waveguide output.

Finally, the dramatic reduction of the spectral linewidth in the counterpropagating geometry is a critical issue in the context of quantum information measurements. The counterpropagating source of twin photons gives naturally a typical linewidth of less than 1 nm for a 1 mm waveguide only, without the need of any additional filtering.

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