Heralded, pure-state single-photon source based on a KTP waveguide

Z. H. Levine[1], J. Fan[1,2], J. Chen[1,2], A. Ling[1,2], and A. Migdall[1,2]

[1]*Optical Technology Division, National Institute of Standards and Technology 100 Bureau Drive, Mail Stop 8441, Gaithersburg, MD 20899-8441*
[2]*Joint Quantum Institute, University of Maryland, College Park, MD 20742*
z.levine@nist.gov, jfan@nist.gov

Abstract: We present an analysis of the generation of single spatial mode, spectrally uncorrelated photon pairs via type II spontaneous parametric down-conversion in a Potassium Titanyl Phosphate (KTP) waveguide using real experimental parameters. We show that with spectral filtering to preserve nearly 90% of the photon pairs, this source can be used as an efficient, heralded, pure-state single-photon source.

OCIS codes: (190.4410) Nonlinear optics, parametric process; (270.5585) Quantum information and processing; (230.7370) Waveguide.

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1. Introduction

Photon pairs born as twins but without intra-pair correlation [1] are particularly useful to linear optical quantum computation [2] and many other quantum information applications [3]. The success of these applications is based on high visibility interference of single photons from independent sources on a beam splitter. The unit visibility can only be achieved if the independent single photons are pure and indistinguishable. This has never been an easy task. The primary single photon sources in use are heralded single photon sources based on parametric processes either in the form of spontaneous parametric down-conversion [4,5] or four-wave mixing [6,7], in which photon pairs are created in a large number of spectral and/or spatial modes. The detection of a single photon projects its twin in a mixture of these modes. Thus strong filtering is mandatory to approximate the heralded single photons in the pure state. This results in a low repetition rate which seriously hinders the two-photon quantum interference-based applications. This obstacle can be overcome with the proposal of Grice *et al* [1,8]. They showed that if photon pairs are produced such that the two-photon joint spectral amplitude is factorable, in other words, the heralding of one photon does not influence the state of the other photon. The advantage is obvious. Without post-selection, many replicas of this type of source ensure high visibility two-photon interference to occur at a high repetition rate which can significantly improves the performance of many applications in quantum information science.

The generation of a factorable two-photon state was proposed eight years ago by Grice *et al.* [1]. Only until very recently were there experimental demonstrations via parametric down-conversion in bulk crystals [9,10] or using four-wave mixing in optical fiber [11,12,13]. High visibility two-photon interference from independent, heralded, single-photon sources were observed at high rates.

To have a high purity heralded single photon source via spontaneous parametric down-conversion in a bulk crystal, one has to consider the impacts from many aspects of the experimental system, including the pump focusing, the phase-matching in the crystal, the collection of photon pairs, and possible inhomogeneities in the pump beam. All of these results in a significant amount of experimental work [10].

Recently, there has been a growing interest of realizing parametric down-conversion in a single-crystal waveguide, in which photon pairs were produced in only a few spatial modes [14,15,16,17,18,19,20,21]. The phase-matching in the waveguide is normally assisted by periodically inverting the material nonlinear coefficient to have efficient nonlinear conversion at the desired wavelengths [22]. However, it is difficult in practice to keep a perfect periodic poling structure along the entire length of the waveguide. The photon pairs produced in a periodically poled waveguide are still in a mixture of a few highly correlated modes.

In this paper, we present a realistic analysis of generating single spatial mode, spectrally uncorrelated photon pairs via parametric down-conversion in a Potassium Titanyl Phosphate ($KTiOPO_4$ or KTP) waveguide with both daughter photons in the telecom band. Being produced in the single spatial mode, the pair of photons is also spatially uncorrelated. We show that the factorization level, as characterized by the Schmidt number K, of the photon pairs equals to unity to within 0.2% with spectral filtering to preserve about 90% of produced photon pairs. This photon-pair source can be used as a heralded, single spatial mode, pure-state single-photon source for quantum information applications.

2. Theory of type II spontaneous parametric down-conversion in the waveguide

We briefly describe the theory of the generation of photon pairs via type II spontaneous parametric down-conversion in a waveguide. Interested readers can refer to previous publications for detailed descriptions [16,21].

In the regime of spontaneous radiation and considering that only the first order non-vacuum mode is significant, the quantum state for photon pairs produced via parametric down-conversion in a waveguide is expressed as

$$\left|\psi\right\rangle = \left|0_s, 0_i\right\rangle + \chi \iint d\omega_s d\omega_i\, f(\omega_s, \omega_i) a_s^+(\omega_s) a_i^+(\omega_i) \left|0_s, 0_i\right\rangle, \qquad (1)$$

where χ is a constant and it is proportional to the nonlinear coupling of the three-wave mixing as

$$\chi \sim \iint_A dydz\, d_{24} [U_s^z(y,z) U_i^y(y,z)]^* U_p^y(y,z), \qquad (2)$$

where d_{24} is the nonlinear optical coefficient and it relates to the 2nd order optical susceptibility as $d_{24} = \frac{1}{2}\chi^{(2)}_{yzy}$. $U_\mu^j(y,z)$ is the transverse spatial profile of the electric field in the waveguide with $j = y, z$ (crystal axes) and $\mu = s$ (signal), i (idler), and p (pump). The polarizations of the signal, idler, and pump photons are along the crystal axes accordingly (see Fig. 1(a) for the definitions of crystal axes)).

The two-photon joint spectral amplitude $f(\omega_s,\omega_i)$ is a product of the pump spectrum $p(\omega_s,\omega_i)$ and the phase-matching function $\mathrm{sinc}(\Delta\kappa L/2)$ for parametric down-conversion in the waveguide,

$$f(\omega_s,\omega_i)=p(\omega_s,\omega_i)\mathrm{sinc}(\Delta\kappa L/2). \tag{3}$$

In the one dimensional waveguide, the perfect phase-matching condition is reduced as the wave-number difference between the signal, idler, and pump photons,

$$\Delta\kappa = k_s^z + k_i^y - k_p^y + 2m\pi/\Lambda = 0, \tag{4}$$

where the harmonic frequency $2m\pi/\Lambda$ (m is an integer) is introduced to take into account the periodically inverted nonlinear optical coefficient d_{24} (with spatial period Λ) of the waveguide. For example, in a period, the nonlinear coefficient is d_{24} for $x\in[0, \Lambda/2)$ and $-d_{24}$ for $x\in[\Lambda/2, \Lambda)$. Such a periodically modulated material nonlinear response can be expressed as the superposition of a set of spatial harmonic frequencies, $\{e^{i2m\pi/\Lambda}\}$ [22]. The perfect phase-matching condition of $\Delta\kappa=0$ may be satisfied for multiple groups of signal, idler and pump photons that are offset in wavelength, for a given poling period Λ. Denoting the frequency detuning from the center frequencies for the signal and idler photons, respectively, as $\xi_s=\omega_s-\omega_{s0}$, $\xi_i=\omega_i-\omega_{i0}$, with $\omega_{s0}+\omega_{i0}=\omega_{p0}$ which is the center frequency of the pump photon, the phase-mismatch in the waveguide is written as,

$$\begin{aligned}\Delta\kappa L &= (k_s^z + k_i^y - k_p^y + 2m\pi/\Lambda)L \\ &= (k_{s0}^z + k_{i0}^y - k_{p0}^y + 2m\pi/\Lambda)L + [k_s'\xi_s + k_i'\xi_i - k_p'(\xi_s+\xi_i)]L \\ &= (k_s'-k_p')L\xi_s + (k_i'-k_p')L\xi_i \\ &= \tau_s\xi_s + \tau_i\xi_i\end{aligned}, \tag{5}$$

where $k_\mu' = 1/(d\omega_\mu/dk_\mu^i) = 1/\upsilon_\mu$ is the inverse of the group velocity, $\tau_s=(k_s'-k_p')L$ is the group delay between the signal photon and the pump photon after propagation in the waveguide. A similar relation holds for the idler and pump photons, $\tau_i=(k_i'-k_p')L$. We have used the phase-matching condition $k_{s0}^z + k_{i0}^y - k_{p0}^y + 2m\pi/\Lambda = 0$ at the center frequencies in the derivation of Eq. (5).

Typically, a coherent pump laser beam may be assumed to have a Gaussian spectral profile, $p(\omega_s,\omega_i)=e^{-(\omega_s+\omega_i-\omega_{p0})^2/\sigma^2}$. The central lobe of the sinc-function can be approximated also by a Gaussian function, $\mathrm{sinc}(\Delta\kappa L/2)\approx e^{-\gamma(\Delta\kappa L/2)^2}$ with $\gamma\approx 0.193$. Neglecting the small contributions from side-lobes of the sinc-function, with Eq. (5), the two-photon joint spectral amplitude is written as

$$\begin{aligned}f(\omega_s,\omega_i) &= e^{-(\xi_s+\xi_i)^2/\sigma^2-\gamma(\tau_s\xi_s+\tau_i\xi_i)^2/4} \\ &= e^{-(1/\sigma^2+\gamma\tau_s^2)\xi_s^2-(1/\sigma^2+\gamma\tau_i^2)\xi_i^2-(2/\sigma^2+\gamma\tau_s\tau_i/2)\xi_s\xi_i}\end{aligned}, \tag{6}$$

which becomes a product of the individual spectral functions for the signal and idler photons as

$$f(\omega_s,\omega_i)=f_s(\omega_s)f_i(\omega_i)=e^{-(1/\sigma^2+\gamma\tau_s^2)\xi_s^2}e^{-(1/\sigma^2+\gamma\tau_i^2)\xi_i^2}, \tag{7}$$

if the cross term vanishes, i.e., if

$$4/\sigma^2 + \gamma\tau_s\tau_i = 4/\sigma^2 + \gamma(k_s' - k_p')(k_i' - k_p')L^2 = 0\,. \qquad (8)$$

Eq. (8) is the condition for a photon pair to be spectrally factorable. For a Gaussian-like laser pulse, Eq. (8) can be reinterpreted in terms of the coherence time of the pump laser pulse as

$$|\tau_s\tau_i| \approx \tau_{coherence}^2\,. \qquad (9)$$

To meet the requirement in Eq. (8), the group delays of the pump, signal and idler photons after propagating through the nonlinear medium need to satisfy $\tau_s\tau_i \leq 0$, or equivalently, their group velocities satisfy the relation

$$\upsilon_s \geq \upsilon_p \geq \upsilon_i\text{, or } \upsilon_s \leq \upsilon_p \leq \upsilon_i \qquad (10)$$

We show in Sect. 3 that this condition can be satisfied in a type II parametric down-conversion process in a KTP waveguide.

To characterize the degree-of-factorization of produced photon pairs, the Schmidt decomposition is applied to write the normalized two-photon joint spectrum as a superposition of a number of orthonormal modes [10,23,24],

$$f(\omega_s, \omega_i) = \sqrt{\eta_j}\,|u_j(\omega_{si})\;|v_j(\omega_i)\,, \qquad (11)$$

where $|u_j(\omega_s) >$ and $|v_j(\omega_i) >$ are the orthonormal modes, η_j is the weight of the two-photon intensity in mode *j* and $\sum_j \eta_j = 1$. The two-photon spectral function is factorable if there is only one mode, with $\eta_0 = 1$. The photon pairs are in the mixed states when there are more than one mode, with $\eta_j < 1$. Accordingly the Schmidt number is defined to characterize the degree-of-factorization,

$$K = \sum_j 1/\eta_j^2\,. \qquad (12)$$

When $K = 1$, the two-photon spectral function can be expressed as a product state as given in Eq. (7).

3. Optical modes in the KTP waveguide

KTP waveguides have been widely used in the generation of photon pairs. It can be fabricated by applying the diffusion exchange of 100% Rb^+ ions for K^+ ions and by masking the surface of the KTP crystal. The refractive index of the KTP crystal can be obtained from the Sellmeier equation. The area with Rb-diffusion (RTP) has bigger refractive index than the KTP substrate. Along the +z-direction, the refractive index difference of RTP relative to KTP is described as Δn erfc($z/z0$) according to the experimental analysis (dashed lines in Fig. 3), with $\Delta n = 0.02$ at the surface $z = 0$ [25]. Here we choose $z_0 = 3$ μm. The width of the mask is set to be 3 μm. The schema for the KTP crystal containing a fabricated waveguide and the crystal axes are shown in Fig. 1(a).

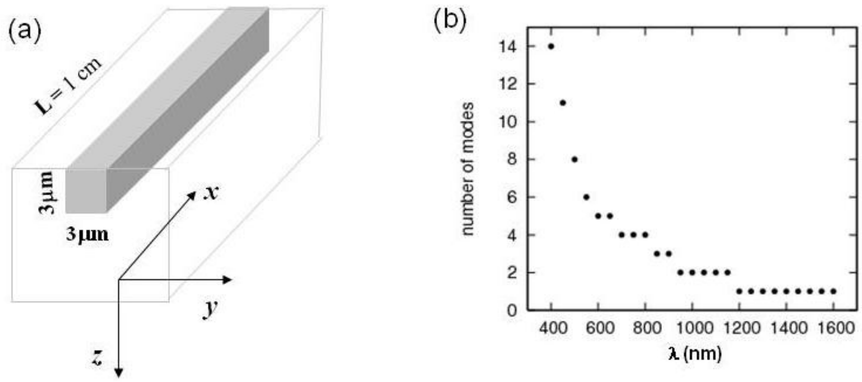

Fig. 1. (a) Schema for a KTP crystal containing a waveguide. The waveguide dimensions and crystal axes are labeled. (b) Number of bound modes in the waveguide with polarization along *z*-axis.

We numerically compute the bound optical modes polarized along the crystal *z*-axis (with the commercial software COMSOL [26,27]). As shown in Fig. 1(b), the number of bound optical modes in the waveguide decreases with increasing wavelength. For this waveguide, we find that there are 14 bound optical modes at the wavelength of $\lambda = 400$ nm. The number of bound modes drops to 4 at around $\lambda = 700$ nm. The waveguide becomes a single spatial mode optical waveguide for $\lambda \geq 1200$ nm.

We are interested in down-converting a pump photon into two daughter photons with wavelengths in the telecom band, for example, to down-convert a pump photon with λ_p=764 nm into a signal photon at $\lambda_s = 1550$ nm and an idler photon at $\lambda_i = 1506$ nm. The mode profiles (transverse electric field distributions) for the pump and daughter photons are significantly different but all three mode fields are well confined as shown in Fig. 2, where Figs. 2(d) and 2(e) are contour plots at the full width at half maximum (FWHM) of the amplitudes. (We only consider the fundamental modes in this paper. The pump may not be in a single spatial mode since its wavelength is necessarily no more than half of the maximum of the signal and idler wavelengths.) The effective mode-overlapping area is determined by the spatial distribution of the pump beam and it is about the size of the transverse cross-section of the waveguide, which can be seen in Figs. 2(d) and 2(e). The spatial distributions are symmetric with respect to the crystal-*z* axis but asymmetric with respect to the crystal-*y* axis: the mode field quickly becomes negligible after crossing the crystal-air interface into the air ($z < 0$) by a couple hundred nanometers which is due to the large refractive index contrast between the crystal ($n \approx 1.8$) and air ($n = 1$); in the +*z* direction, because of the smooth transition from the Rb-diffused area to the pure KTP substrate, the mode field extends into the crystal substrate for a few micrometers. Also we note that the two daughter photons in the telecom band have similar spatial distributions (see Figs. 2(d) and 2(e)), which will yield similar photon collection efficiencies.

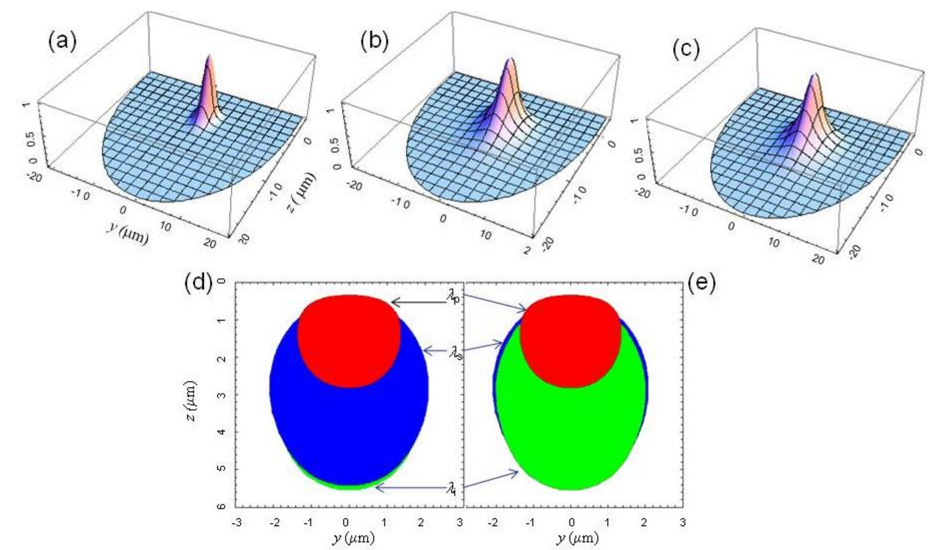

Fig. 2.Normalized transverse electric field amplitude profile for fundamental modes, (a) λ_p=764 nm, y-polarization; (b) λ_i=1506 nm, y-polarization; (c) λ_s=1550 nm, z-polarization. (d)(e) Contour plots at FWHM of (a)(b)(c).

We calculate the effective refractive indices of the fundamental optical modes propagating in the waveguide for both y– and z– polarizations. The indices are smaller than that of the RTP as shown in Fig. 3(a) but above that of KTP. The difference becomes bigger for longer wavelength. Since at longer wavelength more of the mode field is distributed out of the waveguide to propagate in the substrate which has smaller refractive index, this makes the effective modal refractive index smaller.

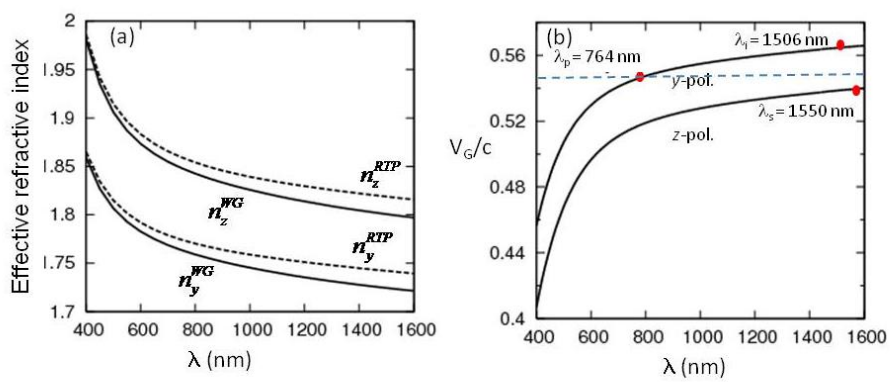

Fig. 3. (a) Effective refractive index of y- or z- polarized light beam propagating in bulk RTP and waveguide (WG). (b) Group velocity of y- or z- polarized optical modes in the waveguide. A selected group of wavelengths with group velocities satisfying Eq. (10) is shown as the red dots.

We then calculate the group velocity of the signal and idler photons in the waveguide along both crystal–y and –z axes. They increase monotonically with increasing wavelength (Fig. 3b)). Since type II down-conversion process has pump and idler photons polarized along crystal–y axis and signal photon polarized along crystal–z axis, many groups of pump, signal and idler wavelengths satisfy the group velocity condition in Eq. (10) for the signal-idler photon pairs to be spectrally factorable. A selected group of wavelengths with λ_p = 764 nm, λ_s = 1550 nm and λ_i = 1506 are shown as an example in Fig. 3(b).

4. Phase-matching of parametric down-conversion in the KTP

In the spontaneous parametric down-conversion process, the pump photons are down-converted into pairs of photons if energy conservation, $\omega_s + \omega_i = \omega_p$, is satisfied. However, the conversion efficiency is significant only when the process is phase-matched. The periodic poling method can be applied to the crystal waveguide to phase-match the down-conversion process at the desired group of wavelengths for the pump and daughter photons. They are shown by the contour plots in Fig. 4(a). Each contour plot represents that the perfect phase-matched down-conversion process occurs with the assistance of a certain spatial harmonic frequency, $2m\pi/\Lambda = -(k_s^z + k_i^y - k_p^y)$. The contour profiles curve back showing that for a certain spatial harmonic frequency, there are two groups of wavelengths that can be perfectly phase-matched for efficient down-conversion.

To have photon pairs produced from the down-conversion process spectrally uncorrelated, the group velocity relationship between the pump and daughter photons given by Eq. (10) needs to be satisfied. Furthermore, the wavelengths of photons used in many quantum information applications are either in the telecom band (~1550 nm) or in the visible, thus we require the wavelength of the produced photon pairs to be shorter than 1600 nm. These two conditions plus the energy conservation condition enclose a spectral region of interest for the parametric down-conversion process in the waveguide as shown by the shaded area in Fig. 4(b).

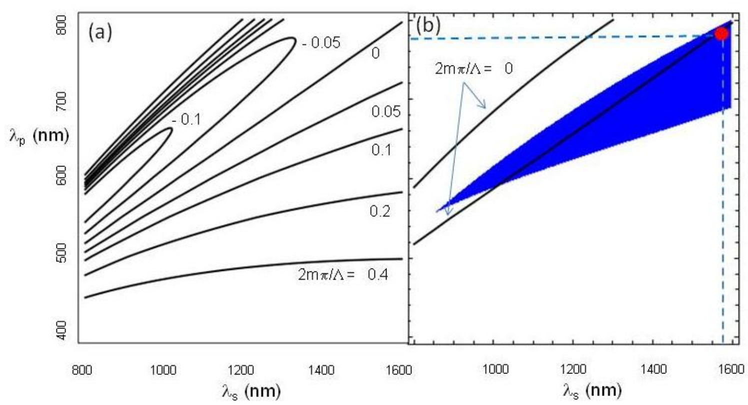

Fig. 4. (a) Sample contours for phase-matched down-conversions with different groups of pump and signal wavelengths, each group has a certain spatial harmonic frequency. (b)Shaded spectral region of interest. The red dot corresponds to the phase-matched down-conversion at λ_p = 764 nm, λ_s = 1550 nm and λ_i = 1506 nm. See text for detail.

Although high order spatial modes may introduce additional degrees-of-freedom which are useful in encoding information [20], it is hard to harness the photons in these modes in practice; photons created in a single-spatial mode simplify the operations. As discussed in Sect. 3, the waveguide becomes a single-spatial mode optical waveguide for $\lambda \geq 1200$ nm. We also wish to generate photon pairs with wavelengths in the telecom band where the instrumentation and the infrastructure for information exchange are sophisticated. With two daughter photons in the telecom band, this puts the pump wavelength at around 780 nm which is a standard output wavelength of the titaniumsapphire laser (with typical output wavelength between 700 nm and 1100 nm). With these additional requirements, there are still a range of wavelengths that satisfy the phase-matched down-conversion in this specific waveguide as shown in Fig. 4(b).

The contour (solid line in Fig. 4(b)) for the perfect phase-matching with zero-spatial harmonic frequency crosses the enclosed spectral region. Considering the imperfection of the periodic poling structure in the waveguide, (which causes the photon pairs produced in mixed states and may produce small reflections at the interfaces of the regions,) it is preferable to have a phase-matched down-conversion process without poling the crystal. We arbitrarily choose λ_p = 764 nm, λ_s = 1550 nm and λ_i = 1506 nm along the zero-spatial harmonic frequency contour line for our discussion. However, other allowed choices would be qualitatively similar. It is worth noting that λ_p = 788 nm and $\lambda_s = \lambda_i$ = 1575 nm is an allowed choice with the signal and idler differing only in their polarizations.

5. Single-spatial mode, spectrally uncorrelated photon pairs

The spectral intensity profiles of the pump, sinc-function, and the two-photon joint spectrum (with peak intensity normalized to one) for down-converting the pump photons at λ_p = 764 nm into pairs of daughter photons at λ_s = 1550 nm and λ_i = 1506 nm in a 1 cm KTP waveguide are plotted in Fig. 5(a)-(c), where the pump bandwidth is optimized to have the highest degree-of-factorization for the produced photon pairs.

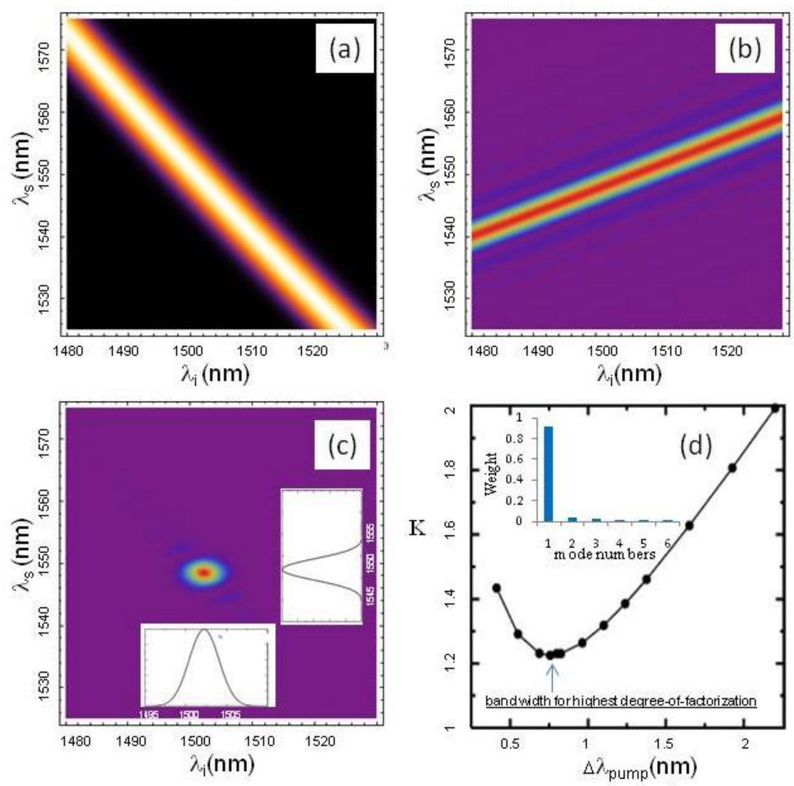

Fig. 5. Normalized spectral intensity profiles for the pump (a), phase-matching sinc-function (b), and two-photon joint spectrum (c), at the condition of the optimized pump bandwidth for the highest degree-of-factorization of two-photon joint spectrum. Insets in (c) are lineout across the center. (d) Degree-of-factorization of photon pairs as a function of the pump bandwidth. Inset in (d) is the mode distribution in the Schmidt decomposition with the optimized pump bandwidth.

By applying the Schmidt decomposition, we show that the best Schmidt number obtained is $K \approx 1.2$ with the optimized pump bandwidth (Fig. 5(d)). This means that the produced photon pairs are in mixed states of different modes. The histogram plot of the mode distribution is plotted in the inset of Fig. 5(d). About 91% of the photon pairs are in the first Schmidt mode.

This result is not surprising. Recall that we have approximated the phase-matching sinc-function by a Gaussian function in the derivation of two-photon factorization condition. However, in real case, the contribution from the side-lobes of the sinc-function is not negligible as shown in Fig. 5(c). These side-lobes are spectrally distinguishable from the central lobes, which allow us to apply hard-edge filters to strongly attenuate the contributions from them. As shown in Fig. 6(a), filtering either the signal or idler photons leads to a marked reduction in K, but filtering both is yet more effective. By applying hard edge filters of 5 nm bandwidth to both signal and idler photons, the Schmidt number K is ≈ 1.002 for the transmitted photon pairs and the pair transmittance is close to 90% (Fig. 6(b)). Comparing these numbers with the results presented in Fig. 5(d) where about 90% of photon pairs are in the first mode in the Schmidt decomposition, it suggests that the side-lobes in the phase-matching sinc function are the main cause of the residue intra-correlation in the photon pairs.

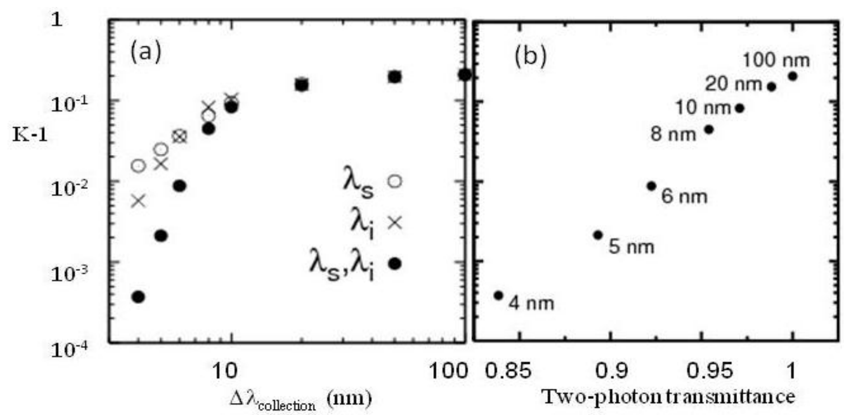

Fig. 6. (a) Degree-of-factorization of photon pairs as a function of spectral filter bandwidth, filtering only the signal, only the idler, or both. (b) Degree-of-factorization and two-photon transmittance as a function of collection bandwidth, filtering both the signal and the idler.

In conclusion, we have presented a realistic analysis of the generation of spectrally uncorrelated, single spatial mode photon pairs via type II spontaneous parametric down-conversion process in a KTP waveguide, with both daughter photons in the telecom band. Being produced in the single spatial mode, the pair of photons is also spatially uncorrelated. We show that the factorization level, as characterized by the Schmidt number K, of the photon pairs equals to unity to within 0.2% with spectral filtering which preserves about 90% of produced photon pairs. This configuration provides a simple solution to the requirement of a pure-state single-photon source in many quantum information applications.

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