

# Generation of counterpropagating photon pairs in periodically poled Rb-KTiOPO<sub>4</sub>

Albert Peralta Amores , Andrius Zukauskas, Patrick Mutter , Fredrik Laurell ,  
Valdas Pasiskevicius , and Marcin Swillo 

*School of Engineering Sciences, Royal Institute of Technology (KTH), 114-21 Stockholm, Sweden*



(Received 3 February 2025; accepted 14 August 2025; published 11 September 2025)

We demonstrate the generation of counterpropagating, twin-photon pairs in the optical communication band, utilizing periodically poled Rb-doped KTiOPO<sub>4</sub>. The spectral and polarization indistinguishability of the photon pairs is confirmed through a Hong-Ou-Mandel interference measurement. At degeneracy, the photon-pair generation exhibits a broad angular distribution. Notably, the forward-propagating photon tunes with the pump frequency while the backward-propagating photon frequency remains nearly independent of the pump wavelength.

DOI: [10.1103/5b5f-x6nc](https://doi.org/10.1103/5b5f-x6nc)

## I. INTRODUCTION

Spontaneous parametric down-conversion (SPDC) in nonlinear crystals is an essential resource of quantum optics because of its ability to generate entangled photons [1] and squeezed states of light [2]. While traditional studies focus on copropagating SPDC schemes [3,4], where the signal, idler, and pump photons share the same propagation direction, we explore counterpropagating SPDC (CPSPDC), where the signal and idler photons propagate in opposite directions.

CPSPDC enables the generation of polarization- and spectral-indistinguishable photons that remain distinguishable by their propagation direction. Such characteristics are unattainable in traditional copropagating configurations, where polarization distinguishability is imperative for the separation of photons. CPSPDC configurations are preferable for the generation of two-mode squeezed vacuum states [5] and for a demonstration of the Einstein-Podolsky-Rosen paradox [6]. The intrinsic decrease of the spectral signal bandwidth at degeneracy by CPSPDC schemes [7], as compared to copropagating SPDC [8], is beneficial for applications relying on entanglement. Quantum optical applications, such as linear optical quantum computing (LOQC) [9], or quantum key distribution (QKD) techniques [10], benefit from long coherence times of the entangled photons.

Optical parametric oscillators (OPOs) represent the most efficient sources of quadrature-squeezed light [11] and their suppressed noise properties enable the detection of small phase shifts induced by weak forces. This has been experimentally exploited for the GEO600 gravitational wave detector [12]. To date, periodically poled KTiOPO<sub>4</sub> (PPKTP)

OPOs are used in the LIGO detector [13] due to their high efficiency [14] and negligible amount of green- and blue-induced infrared absorption [15,16]. The backward-wave OPO (BWPO) leverages CPSPDC in a self-resonating device, offering unique advantages in terms of spectral purity at the cost of reduced efficiency when compared to the standard OPOs [17]. Recent work has shown that the BWPO configuration can reach conversion efficiencies exceeding 70% and provides a good beam quality [18], while being naturally suitable for integration in a waveguide format due to the absence of a resonator [19]. Close to the oscillation threshold, CPSPDC geometries should allow for a high level of squeezing, comparable to conventional OPOs, despite the lack of filtering of the cavity [20]. Moreover, Chuu and Harris have theoretically shown that by placing the CPSPDC crystal in a cavity, entangled photons with subnatural linewidths and Glauber correlation times greater than 65 ns can be generated, allowing for multiphoton entanglement without the need for synchronization [21]. These distinct properties would allow photon entanglement storage in atomic ensemble memories [22], critically needed for multiphoton entanglement in LOQC [23,24] and quantum repeaters [25]. Furthermore, CPSPDC exhibits intriguing properties, distinct from those observed in traditional copropagating SPDC. For instance, compensation of the momentum mismatch between the excited modes by pump tilting, enabling tunable degenerated emission across the *S*, *C*, and *L* bands, has been recently demonstrated [26] in semiconductor waveguides. However, sub- $\mu\text{m}$  poling periods, which are extremely challenging to fabricate, are required to quasi-phase-match (QPM) the interaction, as the Bloch wave vector must compensate for a significantly larger momentum mismatch compared to a copropagating process [27]. These technological limitations have been circumvented by using third- and fifth-order QPM crystals [28,29], or introducing dielectric spacers [30], at the cost of a substantial efficiency decline. However, Liljestrand *et al.* [31] and Mutter *et al.* [32] have recently demonstrated that coercive field engineering can overcome the fabrication difficulties for Rb-doped KTP (RKTP) and obtain high-quality submicrometer periodic domain structures [33].

\*Contact author: marcin@kth.se

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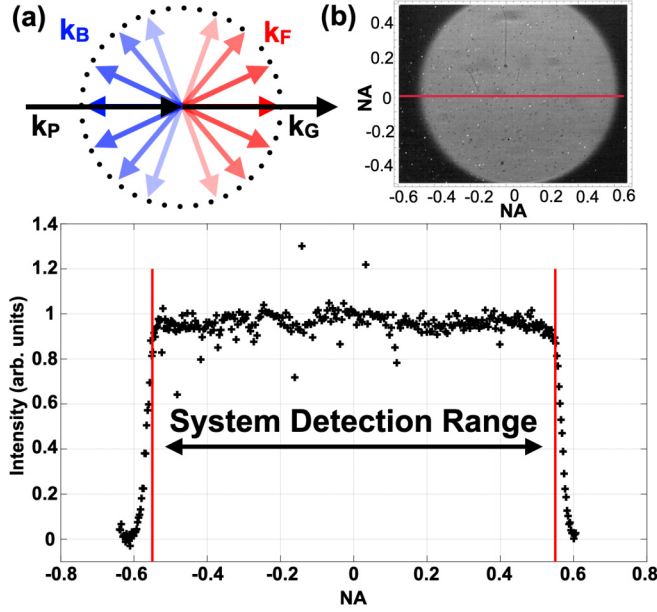


FIG. 1. (a) Phase-matching scheme. (b) Angular distribution of the CPSPDC photons at the crystal output.

In this work, we demonstrate the generation of counter-propagating twin-photon pairs at 1.6  $\mu\text{m}$  using a first-order QPM RKTTP crystal. We experimentally verify the photon-pair spectral and polarization indistinguishability through a Hong-Ou-Mandel interference measurement and study the angular and spectral properties of the interaction. This contributes to the advancement of quantum optics and holds significant promise for future developments in quantum communication and related fields.

## II. PHASE MATCHING THE INTERACTION

The phase-matching condition for photon-pair generation via CPSPDC, shown in Fig. 1(a), is expressed by the equation

$$k_p = k_f - k_b + k_G. \quad (1)$$

Here,  $k_j = (2\pi n_j)/\lambda_j$  are the wave vectors of the pump ( $p$ ), forward ( $f$ ), and backward ( $b$ ) generated photons while  $k_G = 2\pi m/\Lambda$  is the Bloch wave vector for the grating with QPM order  $m$  and period  $\Lambda$  [34]. In this work, we have fabricated a periodically poled Rb-doped KTiOPO<sub>4</sub> periodically poled Rb-doped KTiOPO<sub>4</sub> (PPKTP) sample with a period of 433 nm in a 1-mm-thick and 7-mm-long RKTTP crystal. The fabrication method is extensively described in Ref. [32]. The grating period was chosen for a degenerate parametric interaction when pumped at 798 nm.

First, we investigated the nature of degenerate CPSPDC by studying the phase-matching condition in Eq. (1). As the momentum associated with the Bloch wave vector compensates for the momentum of the pump photon, the phase matching is fulfilled when the signal and idler momenta cancel out each other. Thus, photon pairs can be generated at any angle relative to the pump as long as the two photons propagate in opposite directions, as depicted in Fig. 1(a).

The experimental setup consisted of a continuous-wave Ti:sapphire laser pumping the PPRKTP sample, with the elec-

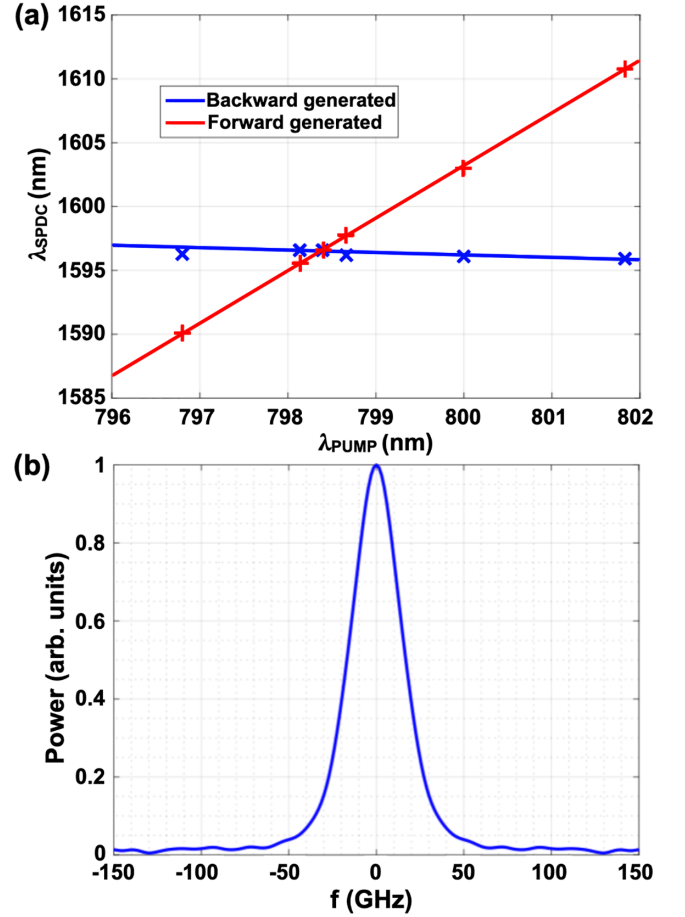


FIG. 2. (a) Wavelength dependence of forward (red) and backward (blue) photon generation in PPRKTP via CPSPDC: data (crosses) vs theory (solid line). (b) Frequency spectra at degeneracy showing 40 GHz bandwidth for both directions at 250 mW pump power at 1597.2 nm.

tric field vertically polarized to address the  $\chi_{33}^{(2)}$  nonlinearity. The pump wavelength was tuned to the degeneracy point at 798.4 nm and the beam was confocally focused to a field diameter of 55  $\mu\text{m}$  in the center of the crystal. We filtered out residual pump light after the crystal and measured the forward down-converted angular light distribution in the Fourier plane using an InGaAs camera. A broad spatial distribution, corroborated by the observations in Fig. 1(b), is exhibited by the signal and idler photons. However, a more efficient generation is expected within a limited angular distribution. It should be noted that the probability of photon-pair generation is dependent on the interaction time of the signal, idler, and pump photons within the nonlinear crystal. Figure 2(a) presents the simulated and measured wavelengths of the signal and idler photons as a function of the pump wavelength. A characteristic of the backward-generated parametric process is that the forward and backward frequencies tune with the pump as

$$\Delta\omega_b = \delta\Delta\omega_p, \quad \Delta\omega_f = (1 - \delta)\Delta\omega_p, \quad (2)$$

where  $\omega_p$ ,  $\omega_f$ , and  $\omega_s$  correspond to the frequency of the pump, forward- and backward-propagating photons, respectively and  $\delta$  is a parameter, related with the group velocities,

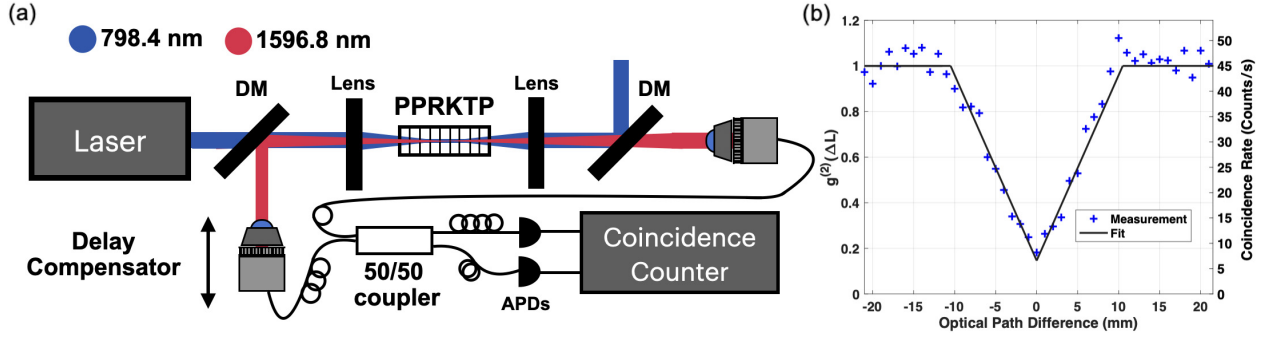


FIG. 3. (a) Experimental setup for measuring the Hong-Ou-Mandel interference: Dichroic mirrors (DM) are used to separate the pump from the CPSPDC photons for later coupling into single-mode polarization-maintaining fibers. One coupling stage is mounted on a translation stage, allowing adjustable delay between both optical paths. Subsequently, the photon pairs are superimposed on a 50/50 beam splitter and detected with InGaAs single-photon avalanche photodiodes (APDs). (b) Hong-Ou-Mandel interference as a function of optical path difference.

$v$ , of the interacting fields by

$$\delta = \frac{\partial \omega_b}{\partial \omega_p} = \frac{v_{g,b}(v_{g,p} - v_{g,b})}{v_{g,p}(v_{g,b} + v_{g,f})}. \quad (3)$$

Figure 2(b) shows the frequency spectra after combining the forward- and backward-propagating SPDC beams in a 50/50 single-mode polarization maintaining coupler. The presented spectra have been measured using a Fourier transform spectrometer technique.

### III. NONCLASSICAL PROPERTIES

The interaction Hamiltonian  $\mathcal{H}$ , describing SPDC processes, can be expressed as

$$\mathcal{H} = i\hbar\alpha(\hat{a}_f^\dagger \hat{a}_b^\dagger - \hat{a}_f \hat{a}_b), \quad (4)$$

where  $\hbar$  is the Planck's constant and the photon creation and annihilation operators are represented by  $\hat{a}^\dagger$  and  $\hat{a}$ , respectively. The parameter  $\alpha$  can be expressed as

$$\alpha = \frac{2dLS}{\pi} \sqrt{\frac{\hbar N_p \omega_p \omega_f \omega_b}{8V^3 \epsilon_0 n_p^2 n_f^2 n_b^2}}, \quad (5)$$

where  $d$  is the effective nonlinear coefficient,  $L$  is the crystal length,  $N_p$  is the photon density at the pump wavelength,  $V$  is the effective quantization volume,  $\epsilon_0$  the electric permittivity of free space, and  $n_{p,f,b}$  and  $\omega_{p,f,b}$  the refractive indices and frequencies for the pump, forward, and backward waves, respectively. The interacting fields' overlap [35]  $S$  can be computed as

$$S = \left| \iint E_p(r, z) E_s(r, z) E_s(r, z) dr dz \right|^2, \quad (6)$$

where  $E_p$  and  $E_s$  are the normalized electric field amplitudes of a Gaussian beam with an equal beam waist at the crystal center for the pump and signal wavelengths, respectively. The time evolution of  $\hat{a}^\dagger$  and  $\hat{a}$  governed by the Heisenberg equations of motion, yields the photon-pair generation rate  $\frac{\langle N \rangle}{t}$  in the interaction picture,

$$\frac{\langle N \rangle}{t} = \frac{2PLd^2}{S\lambda_f \lambda_b \epsilon_0 n_f^3 n_b^2 n_p^2}, \quad (7)$$

where  $\lambda_f$  and  $\lambda_b$  are the wavelengths of the forward- and backward-generated photons, respectively. Based on previous

BWOPO experiments we estimate the effective nonlinear coefficient to be  $d = 4.6$  pm/V [36]. To mitigate any potential impact of parametric oscillation the crystal was pumped with a low power of 15 mW, which is more than five orders of magnitudes below the BWOPO threshold [37]. We estimate a photon-pair generation rate of 4.7 kc/s, corresponding to a quantum efficiency of  $\approx 7 \times 10^{-11}$  photon pairs per pump photon, which, accounting for the detection efficiency of the InGaAs detectors (20%) and the total system losses including coupling efficiency into the single-mode fibers, is in good agreement with the measured detection rate of  $\approx 0.4$  kc/s on each channel.

To demonstrate the indistinguishability of the generated photons at degeneracy, a Hong-Ou-Mandel (HOM) interference experiment [38] was conducted with counterdirectional photon pairs using the experimental setup shown in Fig. 3(a). The measured second-order correlation function  $g^{(2)}$  is presented in Fig. 3(b), with a triangular fit exhibiting a visibility  $V = 0.80 \pm 0.05$ . The path difference at full width at half maximum (FWHM) of the HOM is 10.37 mm, which corresponds to an interaction length of 5.71 mm inside the PPRKTP crystal [39]. This implies that almost the entire periodically poled section of the crystal contributed to the down-conversion. In an SPDC process, the photon-pair generation rate follows a Poissonian distribution. However, the random coincidence detection of two pairs at complementary ports is determined by the detector dark counts and the detection time window (6 ns). Consequently, the expected rate of coincidences due to the two photon-pair detection is 0.05 c/s, which is much lower than the observed 8 c/s at the minimum path difference. Therefore, we attribute the non-negligible value of  $g^{(2)}$  at the minimum path difference to the low, but inherent, wavelength fluctuation of the pump laser, resulting in a diminished spectral overlap between the signal and idler photons.

### IV. CONCLUSION

To conclude, we have demonstrated the generation of spectrally and polarization indistinguishable counterpropagating photon pairs at 1.6  $\mu\text{m}$  using a first-order QPM PPRKTP crystal. At degeneracy, the compensation of the Bloch wave vector by the pump wave vector facilitated effective phase

matching of the signal and idler over a broad angular range. Additionally, we show that tuning the pump wavelength results in a shift in wavelength for the forward-generated photons while the backward-generated photons remain almost unchanged. This unique spectral feature offers a pathway for generating high-purity and narrow-band heralded single photons [28]. The broad angular distribution (numerical aperture  $NA > 0.57$ ) obtained in the degenerate down-conversion could potentially be exploited for lateral high-resolution quantum imaging applications. Furthermore, the successful implementation of submicrometer periodic poling provides a crucial breakthrough in unlocking the potential of counter-propagation nonlinear optical schemes. It can pave the way for efficient photon-pair sources, but also serve as simple and robust generators of two-mode squeezed states, hence providing different resources for applications in optical quantum networks, quantum sensing, and related fields.

## ACKNOWLEDGMENTS

We acknowledge the financial support from the Knut and Alice Wallenberg Foundation through the Wallenberg Center for Quantum Technology (WACQT). Financial support from the Swedish Research Council (Grants No. 2018-03457 and No. 2023-04258) is also acknowledged.

A.P.A., P.M., and F.L. wrote the paper; A.P.A. and M.S. conceptualized the work, made the measurements, and analyzed the data; P.M., A.Z., F.L., and V.P. fabricated the crystals; all authors reviewed and edited the paper.

## DATA AVAILABILITY

The data are available upon reasonable request from the authors.

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