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Xin-Yi Pan,[1] Christian Kurtsiefer,[1,2] Alexander Ling,[1,2,a)] and James A. Grieve[1,3,a)]

AFFILIATIONS

[1]Centre for Quantum Technologies, 3 Science Drive 2, National University of Singapore, Singapore 117543, Singapore
[2]Department of Physics, National University of Singapore, Blk S12, 2 Science Drive 3, Singapore 117551, Singapore
[3]Quantum Research Centre, Technology Innovation Institute, Abu Dhabi, United Arab Emirates

[a)]**Authors to whom correspondence should be addressed:** alexander.ling@nus.edu.sg and james.grieve@tii.ae

ABSTRACT

The temperature dependence of the refractive indices of potassium titanyl phosphate (KTP) is shown to enable quasi-phasematched type II spontaneous parametric downconversion (SPDC) with low temperature sensitivity. Calculations show the effect to be maximized for emission of photons at around 1165 nm, as well as producing similar plateaus for wavelengths throughout the telecommunications bands. We experimentally demonstrate the effect, observing temperature-insensitive degenerate emission between 20 °C and 100 °C at 1327 nm, within the telecommunications O band. This result has practical implications for the development of entangled photon sources for resource-constrained environments, and we demonstrate a simple polarization entangled source as a proof of concept.

Entangled photon sources form a core building block of a wide variety of quantum communication protocols.[1–4] For practical applications involving optical fiber, sources operating in the low-attenuation telecommunications bands are highly desirable,[5] with a number of mature and even commercial examples operating in the so-called C-band (centered at 1550 nm) where transmission losses are minimized. For short-haul distances and metropolitan networks, operation can also be viable in the O-band (centered at 1310 nm), where a relative increase in attenuation can trade off against the prospect of multiplexing quantum signals with classical traffic in the C-band.[6,7]

The workhorse technique for generating entangled photons is based on Spontaneous Parametric Down Conversion (SPDC) in bulk non-linear optical materials.[8–11] In addition to critically phasematched systems, such as Beta Barium Borate[10] (BBO), many sources make use of quasi phasematched processes in periodically poled crystals,[12] for example, Lithium Niobate[5] (PPLN) or Potassium Titanyl Phosphate[13] (PPKTP). In order to maintain the desired phasematching characteristics, these poled materials typically need to be temperature-regulated within 0.1 °C.

While this is readily accomplished under laboratory conditions, it may be desirable to relax these constraints for field deployment, to improve device stability or reduce mass or power requirements.[14] In this paper, we show by simulation how the thermo-optic properties of KTP give rise to reduced temperature sensitivity for quasi-phasematched downconversion into a range of wavelengths overlapping the popular telecommunications bands. This is experimentally demonstrated for emission at around 1327 nm. A source of O-band polarization entangled photons is also realized at a single (uncontrolled) temperature, within the wide 80 °C range over which the SPDC process has been shown to be stable. This suggests that it may be possible to generate entanglement over this range.

Spontaneous parametric downconversion (SPDC) is a process in which photons can split into pairs of lower energy "daughter" photons, obeying conservation of momentum and energy laws. These constraints define the spectral properties of the generated fields. In particular, conservation of momentum within the nonlinear crystal gives rise to phasematching conditions, in which the generated wavelengths depend strongly upon the refractive indices experienced by the downconverted photons.[17] Where the phasematching conditions cannot be satisfied directly by the properties of the medium, it may be possible to compensate the unbalanced phase by engineering a periodic inversion of the crystal symmetry. This technique is known as quasi-phasematching, with the relevant phase relationship given by

$$\Delta k = k_{pump} - k_{signal} - k_{idler} - \frac{2\pi}{\Lambda}, \quad (1)$$

where $k = 2\pi n/\lambda$ is the wavevector in the medium and Λ is the poling period, the domain length of the periodic inversion.[18] The process is considered as perfectly phasematched when the imbalance (Δk) is equal to zero. The intensity of the downconverted fields in a crystal of length L is then given by

$$I_{SPDC} = \mathrm{sinc}^2(\Delta k\, L/2). \quad (2)$$

The spectral characteristics of the SPDC photons are, in general, highly temperature sensitive, due to the temperature sensitivity of the refractive index and, to a lesser extent, the impact of thermal expansion upon the poling period.

In type II collinear processes in PPKTP, serendipitous correlations between the thermo-optic effect in the Y and Z refractive indices for certain values of $\lambda_{pump,signal,idler}$ can give rise to low sensitivity to temperature. While this has been previously noted for the critical phasematched second harmonic generation,[19] these correlations may also be leveraged in quasi-phasematched processes, greatly extending their utility. Our calculations are based on the KTP characterizations performed by Kato and Takaoka[15] and Emanuelli and Ady,[16] with the latter including a model for the thermal dependence of the refractive index. The effect appears to be most dramatic for degenerate emission at 1165 nm, where it is almost invariant over a 100 °C region. It is also visible in operationally useful wavelengths spanning the Telecom O and C bands.

The calculated temperature dependence of the refractive index experienced by pump, signal and idler fields in a type II collinear SPDC process in an x-cut KTP crystal is plotted in Figs. 1(a) and 1(b) for degenerate emission at 1165 and 1310 nm, respectively, taking 60 °C as a reference. It is clear that variation in the Y index at the pump wavelength lies between the variation of the Y and Z indices at the signal/idler wavelengths, leading to a degree of compensatory behavior in the resulting wavevectors. This is shown for the same wavelengths in Figs. 1(c) and 1(d), where the sum of changes in the signal and idler wavevectors approximately matches that of the change in pump wavevector over a wide temperature range.

Quasi-phasematched, type II SPDC spectra are calculated for a range of interesting wavelengths, with poling periods calculated to produce degenerate collinear emission at 60 °C and the effects of thermal expansion included.[16] The results are plotted in Fig. 2 and include 1064 (a), 1165 (b), 1310 (c), and 1550 nm (d). While the temperature insensitive behavior is most dramatically observed at 1165 nm, the wide plateau also observed at 1310 nm may be of more practical interest as it lies at the center of the telecommunications O band.

In order to observe temperature-insensitive emission, we select a PPKTP crystal with 54.05 μm poling period, which is specified by the manufacturer for the type II second harmonic generation at 1310 nm. While this is similar to the 54.6 μm predicted by our calculations [see Fig. 2(c)], small discrepancies of this sort are commonly attributed to the manufacturer using proprietary dispersion relationships measured for their own materials, which may differ slightly from those available in the literature.

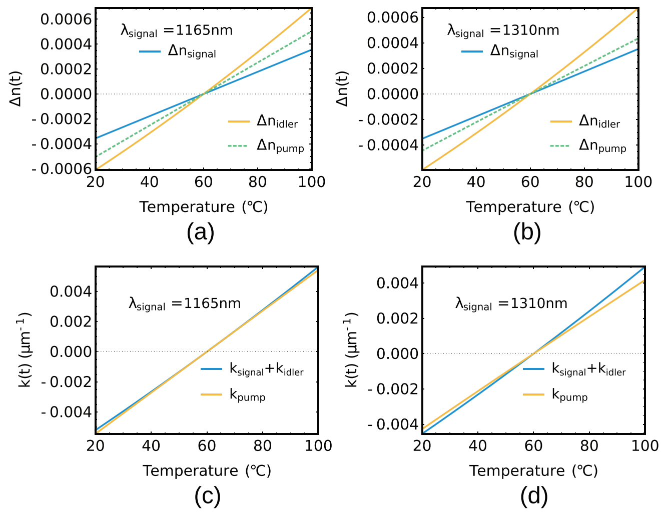

FIG. 1. (a) and (b) Calculated thermally induced changes in the refractive index for pump, signal and idler photons in a type II quasi-phasematched SPDC process in x-cut PPKTP, using published thermo-optic coefficients for Y and Z axes from.[15,16] Curves are plotted taking 60 °C as a reference, for emission at (a) 1165 nm, poling period 102.2 μm and (b) 1310 nm, poling period 54.6 nm. Poling periods calculated to produce degenerate emission at 60 °C. Corresponding changes in wavevector [$k(t)$] for pump and (summed) signal and idler photons are shown in (c) and (d).

We assemble a correlated photon pair source following the schematic in Fig. 3. The PPKTP crystal is pumped from a fiber-coupled laser diode, with downconverted photons emitted in a collinear direction collected into a single mode fiber using appropriate collection optics.[20] Residual pump light is removed using a long pass filter.

When operating the system with all components at room temperature, the source emits non-degenerate photon pairs centered at 1316 nm (the pump wavelength of 658 nm). While most quasi-phasematched sources in the literature employ temperature tuning

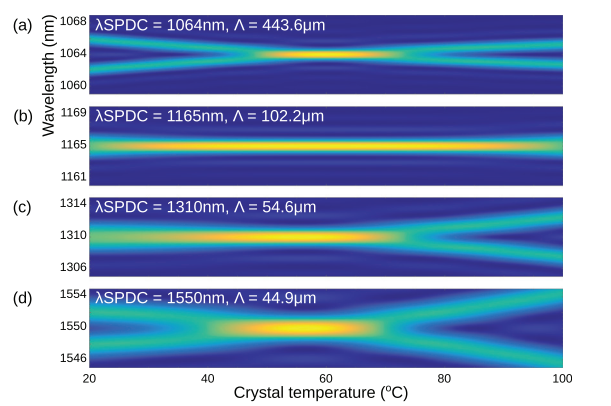

FIG. 2. Calculated SPDC spectra as a function of crystal temperature for a variety of commonly used wavelengths. The spectrum is simulated for 10 mm PPKTP crystals with poling periods (Λ) calculated to produce degenerate type II SPDC at 60 °C (see plot labels). We observe near-degenerate regions in which signal and idler photon spectra overlap for a wide range of temperatures. While the effect is most pronounced for downconversion to 1165 nm (b), it is seen in all calculations with target wavelengths above ~1000 nm.

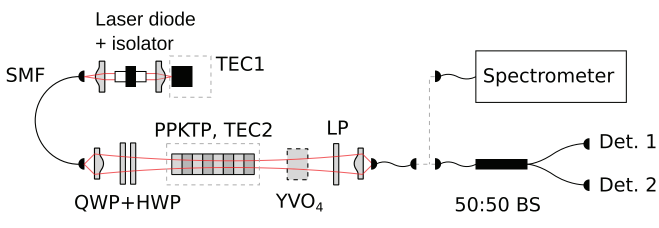

FIG. 3. Experimental schematic. We use a single longitudinal mode laser diode to pump a PPKTP crystal, with downconverted photons collected into a single mode fiber (SMF28, Corning) using appropriate focusing and collection lenses. Residual pump light is removed prior to the collection optics by a long-pass filter (LP). In order to investigate temperature-insensitive quasi-phasematching, the laser diode and PPKTP crystal are mounted on independent temperature controlled stages (TEC1, TEC2). The output fiber may be routed to a home-built spectrometer, or to a fiber beam splitter and avalanche photodiodes (ID220, ID Quantique). When operated as a polarization entangled photon source, a single YVO_4 crystal is placed in the path of the downconverted beam to compensate for signal and idler phase differences.

of the downconversion crystal to achieve degenerate emission, this is obviously not practical in our system (see Fig. 2). Instead, we tune the SPDC spectrum via the pump wavelength. This is achieved by varying the temperature of our pump laser, a free running laser diode designed to produce a single longitudinal mode (HL6501MG, Hitachi).

We measure the spectrum of downconverted photons using a home-built grating spectrometer (resolution ∼1.5 nm) coupled to an InGaAs avalanche photodiode (ID220, ID Quantique), with the measurement as a function of pump laser temperature plotted in Fig. 4. Our results are consistent with a continuously varying pump wavelength, and we infer a tuning rate of 0.18 nm $^\circ$C^{-1}. The production of degenerate photons is observed at a laser temperature of approximately 60.2 °C, corresponding to a pump laser wavelength of 664 nm.

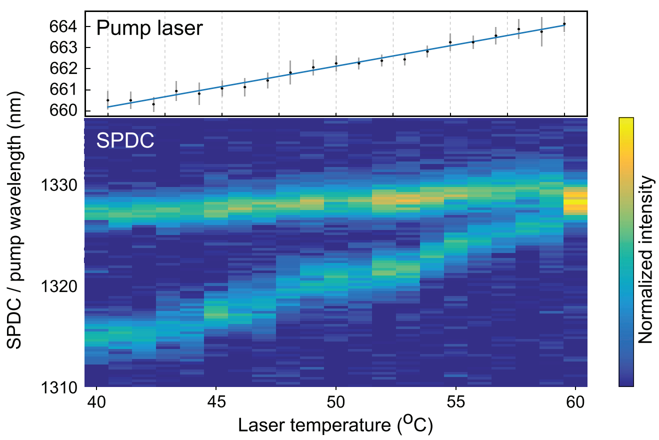

FIG. 4. Measured SPDC spectrum as a function of pump laser temperature. The spectrum is obtained at a crystal temperature of 22.0 °C, at input power 7.3(2)mW. We observe the convergence of signal and idler wavelength with increasing pump laser temperature (wavelength), with a degenerate condition reached at a laser temperature of approximately 60.2 °C. The upper panel shows the pump laser wavelength extrapolated from the SPDC data, exhibiting a linear relationship between laser temperature and wavelength, with a trend of 0.18 nm $^\circ$C^{-1}.

To confirm the relative insensitivity of our source to the PPKTP crystal temperature, we measure the SPDC spectrum as the crystal is heated over a range of 20 °C–100 °C. The results are shown in Fig. 5 and confirm a low variation, with the signal and idler photons spectrally indistinguishable across this interval. We measure the center wavelength by fitting a sinc^2 distribution to the data [per Eq. (2)], which reveals a variation of 0.11 nm (standard deviation) with no clear trend (Fig. 5 top panel). Limitations in our experimental apparatus prevented us from increasing the temperature further.

Type II degenerate SPDC systems are natural candidates for the construction of polarization entangled photon sources. After collection into a single mode fiber, downconverted photon pairs may be split into two fibers in a probabilistic manner. Since the type II SPDC process produces orthogonally polarized photons, interference between the two possible polarization/mode pairings results in the creation of the state

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle + |V_1H_2\rangle), \tag{3}$$

where $|H_1\rangle$ denotes a horizontally polarized photon in fiber 1 and $|V_2\rangle$ a vertically polarized photon in fiber 2, and vice versa. This mechanism is similar to that described in Refs. 21 and 22, in that both components of the state arise from the same SPDC process. Consequently, there is no phase introduced between the $|HV\rangle$ and $|VH\rangle$ components (though some may later be introduced within the optical fibers).

The birefringent, dispersive nature of the PPKTP crystal causes each photon pair traveling through the crystal to incur a relative phase. Unless compensated, this phase difference will result in the creation of a mixed state over the downconverted photons' spectrum, effectively obscuring the polarization entanglement. We make use of a second birefringent crystal (Yttrium orthovanadate, YVO_4) to compensate for this phase difference, placing it in the beam after the PPKTP crystal with its extraordinary axis oriented perpendicular to that of the PPKTP (for more detailed discussion of "longitudinal phase" and this compensation technique, see for example Refs. 23 and 24).

To estimate the acquired phase, we take the center of the PPKTP crystal to be the point at which most of the collected SPDC photon pairs originate. While photon pairs are produced throughout the crystal, this choice minimizes the mean distance to these points of origin,

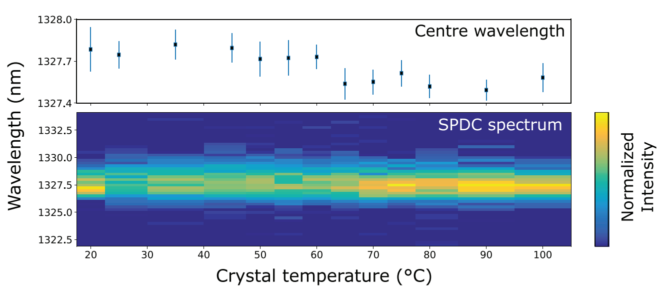

FIG. 5. Measured SPDC Spectrum as a function of crystal temperature. The spectrum is obtained at a constant pump laser temperature of 59.6 °C, for temperatures in the range 20.0 °C–100.0 °C. The center wavelength is obtained by fitting the data for each temperature, and plotted in the top panel. We observe relatively little sensitivity to crystal temperature, with the center wavelength varying by 0.11 nm (standard deviation), no clear trend, and signal and idler photons indistinguishable across this range.

with pairs produced before or after this point under- or over-compensated, respectively. The phase difference between signal and idler photons as a function of their wavelength is shown in Fig. 6(a), assuming co-propagation through 5 mm of PPKTP and taking the degenerate wavelength of 1328 nm as a zero reference. Solving for the minimum phase difference, we obtain an optimum YVO_4 length of 4.34 mm, with the resulting compensated phase reduced below $\pm 0.06°$ over the SPDC spectrum as shown in Fig. 6(b).

Our photon pair source is again assembled as described in Fig. 3, with the addition of the YVO_4 crystal for phase compensation. Generated photon pairs are split probabilistically using a fused fiber beam splitter and detected using InGaAs avalanche photodiodes. Events are recorded using a home-built timestamping system with a 0.125 ns resolution, and we configure the system to identify coincident detection events within a 8 ns window, effectively post-selecting only the outcomes in which the photons are found in separate fibers.

In order to evaluate the polarization entanglement of the source, we route the two output fibers to a polarization tomography system, with fiber birefringence mitigated using manual polarization controllers. By fixing the idler polarizer to the H, V, +45 and –45 bases and scanning the signal polarizer, we are able to reconstruct the polarization correlations as shown in Fig. 7. For this measurement, the pump laser was emitting 5.8(2) mW, with pairwise events detected using InGaAs APDs with nominal efficiency ~24% (ID220, ID Quantique). The observed rates are limited by the reduced efficiency induced by propagation through free-space polarizers and subsequent coupling back into fiber-coupled detectors. Our timestamp-based signal processing electronics enable the direct measurement of background (or "accidental") correlations. By fitting Malus curves to these data, we infer a visibility of approximately 100.0% in the H and V (production) bases. The visibility in the +45 and –45 bases is 95.4% and 97.4%, respectively, giving us a fidelity of 98.2% to the Ψ^+ state.

In this proof-of-concept source, the overall pairwise brightness was relatively low (approximately 300 pairs/s/mW, as detected with InGaAs APDs, nominal detection efficiency ~24%) as the photon pairs were separated by chance using a fused 50:50 beam splitter. For an approximately twofold performance improvement, the separation could be conducted instead using momentum correlations.[25] One limitation of this geometry is that a pump laser with the correct wavelength must be used. We have achieved this by temperature tuning the laser and then maintaining its temperature stability to within 0.5 °C.

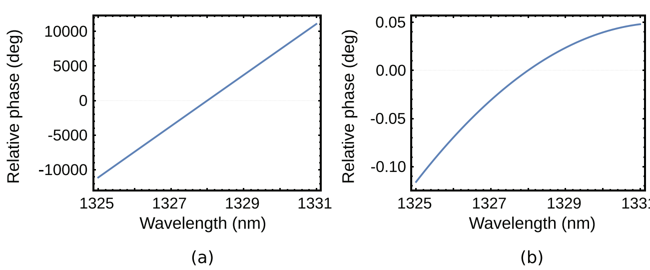

FIG. 6. Calculated phase differences between signal and idler photons as a function of wavelength, for both uncompensated (a) and compensated (b) scenarios. Calculations were performed for orthogonally polarized photons produced at the center of a 10 mm PPKTP crystal. For the compensated phase illustrated in (b), photons are further propagated through a 4.34 mm YVO_4 crystal, oriented with its extraordinary axis perpendicular to that of the PPKTP.

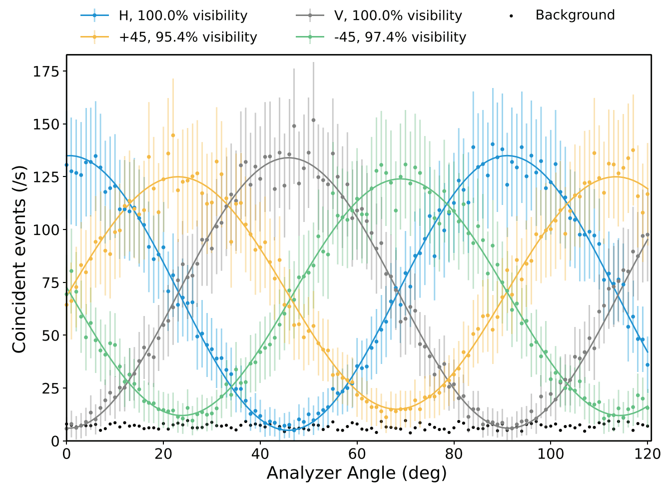

FIG. 7. Characterization of source polarization enatanglement. We plot the coincident event rate obtained as a function of analyzer angle (signal arm) with the idler polarizer set to H, V, +45, and −45 states. Error bars indicate shot noise, at one standard deviation. As the data are obtained using a timestamp-based cross correlation system with 8 ns coincidence window, we are able to make an independent assessment of the background (or "accidental") event rate at each point.

In the future, power requirements could be further optimized by using optical feedback methods (e.g., with a grating[26]) so that the laser could maintain the correct wavelength passively.

While our work has concentrated on degenerate emission, the same principles should also hold for non-degenerate SPDC. For these configurations, efficient separation of signal and idler photons can be achieved by using appropriate dichroic mirrors. It may also be possible to harness the reduced sensitivity to temperature when operating in a non-collinear collection scheme, where an alternative approach to temperature stability has been demonstrated previously in a type 0 SPDC experiment.[27] In contrast to this work, our technique does not show a significant influence of crystal temperature upon source brightness.

In conclusion, we have described and demonstrated a regime in which quasi-phasematched SPDC can be observed without stringent temperature control. We further construct and validate a source of polarization entangled photons, and while no deliberate temperature detuning was attempted, we did not employ temperature stabilization of the SPDC crystals. We focused our experimental efforts primarily on a source of photon pairs in the telecommunication O-band. However, a region of relaxed temperature requirements is also predicted in the commonly used C-band [see Fig. 2(d)] and, to a much lesser extent, the L-band. This finding can be used to increase the utility and reliability of entangled photon systems for field deployment and may open up a new class of entangled photon sources for applications.

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DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.4663932, Ref. 28.

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