

Demonstration of a polarization-entangled photon-pair source based on phase-modulated PPLN

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Abstract: We develop and demonstrate a source of polarization-entangled photon pairs using spontaneous parametric down-conversion (SPDC) in domain-engineered, periodically poled lithium niobate (PPLN) at telecom wavelengths. Pumped at 775 nm, this domain-engineered type-II SPDC source produces non-degenerate signal and idler pairs at 1530 nm and 1569 nm. Because of birefringence, the photon pair with horizontally polarized signal and vertically polarized idler has a different phasematching condition than the pair with vertically polarized signal and horizontally polarized idler. Using phase-modulation of the domain structure, we produced a crystal that can simultaneously generate both states in a distributed fashion throughout a single crystal. Performing SPDC using this aperiodically poled crystal, we observed polarization entanglement visibility above 93%. We compare the phase-modulated crystal to other aperiodic structures, including dual-periodically-poled and interlaced biperiodic structures.

Entangled photon pairs are important for quantum information networks, where they are used to connect quantum nodes [1] and for quantum communications [2], including teleportation of quantum states [3–5], and quantum key distribution [6,7]. Entangled photons have also been used for tests of Bell's theorem and local realism [8–10], as well as for generation of certified random numbers [11]. Spontaneous parametric down-conversion (SPDC) is often used to produce the entangled photon pairs in these applications [8]. In SPDC, a pump photon with frequency ω_p propagating in a nonlinear optical crystal spontaneous splits into a pair of lower energy photons, signal (ω_s) and idler (ω_i), whose frequencies are related by $\omega_p = \omega_s + \omega_i$. The signal and idler photons are correlated in polarization, energy, time and other degrees of freedom, which serves as the basis for photon entanglement.

Quasi-phasematching (QPM) [12] is a powerful technique that enables engineering of the down-conversion process to allow efficient pair production at the desired wavelengths. Aperiodic QPM or domain-engineered structures are additional tools that can enable further control of SPDC such as simultaneous multi-wavelength conversion [13–16] and apodization for side-lobe suppression [17,18] to shape the joint-spectral intensity and produce factorable photon states [19].

To produce polarization entanglement by SPDC, two consecutive crystals rotated by 90° relative to each other are often used [20,21]. The collinear configuration of these sources allows efficient collection into single-mode fibers. A similar scheme uses a single crystal with two sections in series having different QPM periods [22,23]. In these schemes, the first section produces $|H_s\rangle|V_i\rangle$ while the second section produces $|V_s\rangle|H_i\rangle$ (where the $|H\rangle$ and $|V\rangle$ refer to horizontally and vertically polarized states, respectively). When the signal and idler wavelengths are different, the two down-conversion processes are associated with two different phase-mismatches, $\Delta k = k_p - k_s - k_i$ and hence, two different QPM periods. In our work, we use an aperiodic QPM crystal to generate both sets of signal and idler pairs simultaneously in a distributed fashion throughout the crystal.

The concept of using domain-engineering to phasematch multiple SPDC processes has been previously explored. References [24,25] theoretically describe the dual-periodically-poled crystal structure, which is a special case of the phase-modulation procedure described in [14] and applied here. Reference [26] fabricated a phase-modulated crystal and observed interference during SPDC related to high indistinguishability between the two down-conversion paths. Recently, [27] produced a dual-periodically-poled waveguide crystal and observed excellent polarization entanglement. A closely related method of multi-process SPDC is the use of an interlaced biperiodic structure [28], where two different QPM periods alternate along the length of a QPM crystal. Here, we compare phase-modulation to other domain-engineering techniques. We also follow-up on studies presented in [26] to show that such a phase-modulated crystal can indeed be used to generate high-visibility polarization entanglement.

In a phase-modulated QPM crystal, the device can be designed to phasematch multiple simultaneous processes, each with associated phase-mismatch Δk_m , such that [14,29,30]

$$\Delta k_m = 2\pi \left(\frac{1}{\Lambda_0} + \frac{m}{\Lambda_{\rm pm}} \right) = 0. \tag{1}$$

m is an integer, Λ_0 is the fundamental grating period and Λ_{pm} is the phase-modulation period (see Fig. 1a). To simultaneously phasematch two processes, we assign the processes to m = 1 and -1. Solving for Λ_0 and Λ_{pm} , we find

$$\Lambda_0 = \frac{4\pi}{\Delta k_1 + \Delta k_{-1}}$$

$$\Lambda_{\rm pm} = \frac{4\pi}{\Delta k_1 - \Delta k_{-1}}.$$
(2)

In a nearly degenerate process where $\lambda_p \longrightarrow (2\lambda_p - \Delta\lambda/2) + (2\lambda_p + \Delta\lambda/2)$ and $\Delta\lambda$ is small, the average phase-mismatch $((\Delta k_1 + \Delta k_{-1})/2)$ scales as λ_p while the difference $(\Delta k_1 - \Delta k_{-1})$ scales as the detuning between the signal and idler, $\Delta\lambda$. It follows from Eq. 2 that Λ_0 should vary as λ_p while Λ_{pm} depends on $\Delta\lambda$, which we confirmed in numerical calculations. If we choose the down-conversion wavelengths to be 776 nm \longrightarrow 1535 nm + 1570 nm and use the temperature-dependent dispersion relation for MgO:PPLN [31] at 47 °C, we find $\Lambda_0 = 9.2 \ \mu m$ and $\Lambda_{pm} = 1.684$ mm. By increasing the signal-idler separation to 38 nm while keeping the same pump wavelength, we find that Λ_0 is unchanged and Λ_{pm} becomes 1.534 mm. We use the d_{31} coefficient in MgO:PPLN for type-II down-conversion so that the $|V\rangle$ ($|H\rangle$) state corresponds to the extraordinary (ordinary) polarization.

The dual-periodically-poled structure discussed in [24,25,27] corresponds to the structure sketched in Fig. 1a, which we call the 50:50 phase-modulation structure where the phase function switches from π to 0 with 50% duty cycle. By allowing more complicated phase functions $\phi(z/\Lambda_{\rm pm})$, we can adjust the relative amplitudes of the two downconversion processes. To calculate the down-converted spectra for different $\phi(z/\Lambda_{\rm pm})$, we use [13,14]

$$I_{\text{out}} \propto \left| \int_0^L d(z) \exp\left(-i\Delta kz\right) dz \right|^2,$$
 (3)

where d(z) is the spatially modulated nonlinear coefficient (which includes effects of $\phi(z/\Lambda_{pm})$) and Δk is the phase-mismatch between the pump, signal and idler. Figure 1b shows four example phase-modulation functions. To adjust the relative amplitudes of $|H_s\rangle|V_i\rangle$ and $|V_s\rangle|H_i\rangle$, we inserted a short section with phase offset close to but not equal to π (see Fig. 1b). Our calculations using Eq. 3 predicted that designs #1, #2, #3 and 50:50 shown in Fig. 1b would produce relative intensity ratios, $I(|H_s\rangle|V_i\rangle)/I(|V_s\rangle|H_i\rangle)$, of 1.00, 1.06, 0.94 and 1.02, respectively. We note that these phase-modulation functions are not unique and that other functions may also produce the



Fig. 1. (a) Section of a phase-modulated grating with phase shifts π and 0. (b) Example phase-modulation functions, $\phi(z/\Lambda_{\rm pm})$, that produce different relative amplitudes. The functions differ from each other in a short section around $z/\Lambda_{\rm pm} = 0.5$ where the phase shift deviates from π . The domain-engineered grating associated with the 50:50 phase-modulation function is sketched in (a).

desired intensity ratios. The calculations also showed that the bandwidths of the $|H_s\rangle|V_i\rangle$ and $|V_s\rangle|H_i\rangle$ processes match to within 3%.

To better understand the difference between the domain-engineering techniques, we numerically modeled different domain structures for the same combination of wavelengths and polarizations. We looked at type-II downconversion in MgO:PPLN of 776 nm \rightarrow 1533.5 nm + 1571.5 nm in a crystal with 25 mm total length. In the simulations, we numerically integrated Eq. 3 and recorded intensity snapshots at different lengths to produce a map of SPDC growth as a function of position inside the crystal. Plots of these maps are shown in Fig. 2. We have normalized the maximum intensity to 1 at each crystal position. We examined six cases: (a) two consecutive periods, (b) 50:50 phase modulation, (c) phase modulation function #2 from Fig. 1b, and interlaced bi-periodic structures [28] with domain repeat lengths of (d) 10, (e) 22 and (f) 175. The domain repeat length, *N*, is the number of QPM periods in each one of the interlaced sections [28]. We also compared the output intensities and full-width half-maxima (FHWM) calculated from these simulations to that of a single, uniform QPM period for degenerate downconversion of the same pump wavelength (see Table 1).

For the two consecutive periods in Fig. 2a, the shorter wavelength is generated first followed by the longer wavelength. In the two phase-modulated structures (Fig. 2b and c), in addition to the two main SPDC peaks, we also see lower-intensity peaks at wavelengths corresponding to $m = \pm 3$ in Eq. 1 due to higher-order Fourier components present in the phase-modulated structure. These side peaks can be discarded by spectral filtering. The periodicity associated with the "zig-zag" features seen between 0 mm and 5 mm position in Figs. 2b and c are the phase-modulation period discussed above. For the interlaced biperiodic structures (Fig. 2d – f), having larger *N* causes the side peaks to move closer to the desired SPDC peaks, which was also



Fig. 2. Normalized SPDC intensity at different positions inside a crystal for different domain-engineered structures for (a) two consecutive periods, (b) 50:50 phase modulation or dual-periodic-poling, (c) phase-modulation function #2 from Fig. 1b, and interlaced biperiodic structures with (d) N = 10, (e) N = 22, and (f) N = 175.

seen by [28]. The interlaced biperiodic structures alternate between generating one wavelength and then the other, which is most clearly seen in the N = 175 example. For the crystal simulated here, N = 175 corresponds to 8 sets of the two-period pairs occupying the 25 mm long crystal. In Fig. 2f, one can make out 8 spots in the upper half of the figure where the longer wavelengths are generated. One interesting takeaway of these studies is that both phase-modulated and interlaced biperiodic structures lead to SPDC peaks with the same spectral widths as a single-period, 25 mm long device while the structure having two consecutive periods have twice wider peaks (corresponding to each period occupying half the crystal length).

It is interesting to note that the interlaced biperiodic structure is not a type of phase-modulation structure. The QPM period alternates in an interlaced biperiodic structure, from which one

| Description | 1533.5 nm Peak | | 1571.5 nm Peak | |
|----------------------------|----------------|-----------|----------------|-----------|
| | Height (a. u.) | FWHM (nm) | Height (a. u.) | FWHM (nm) |
| Single period ^a | 1.000 | 1.03 | | |
| Two consecutive periods | 0.255 | 1.95 | 0.254 | 2.10 |
| 50:50 phase modulation | 0.383 | 1.00 | 0.374 | 1.07 |
| Phase-mod. function #2 | 0.393 | 0.99 | 0.372 | 1.06 |
| Interlaced, $N = 10$ | 0.229 | 1.00 | 0.232 | 1.07 |
| Interlaced, $N = 22$ | 0.243 | 0.99 | 0.246 | 1.06 |
| Interlaced, $N = 175$ | 0.267 | 0.97 | 0.263 | 1.04 |

| Table 1. Calculated SPDC peak intensities and peak FWHM for different domain-engineered |
|---|
| structures |

^aSingle period has one peak at 1552 nm

might be able to identify a phase-modulation period. However, the spacing between periods is variable from section to section. The design of an interlaced biperiodic structure involves varying the gap between grating sections such that the overall spacing between identical gratings is an integer multiple of that periodicity [28]. To produce this spacing, the gap between sections changes across the crystal, which means the structure is not strictly periodic. In contrast for a phase-modulated grating, the phase-modulation period is strictly fixed over the length of the crystal.

We experimentally investigated the phase-modulated, domain-engineered structures. We designed a set of 25 mm long gratings, which were fabricated by a commercial vendor. We took care to keep the gratings designs as simple as possible, such as setting Λ_{pm} to an integer multiple of Λ_0 and limiting the dimensional resolution to 0.1 μ m. We aimed for 50% QPM duty cycle, but this was difficult to control as the actual poled domains tend to spread wider than the mask-defined domains. We estimated 2 μ m increase in poled domain widths compared to the designed widths and compensated the designs accordingly. We fabricated a set of gratings designed to phasematch at 47 °C pumped at 776 nm with signal and idler separations of $\Delta \lambda = 32$ nm, 35 nm, and 38 nm. We tested several different phase-modulation functions to achieve different amplitude ratios, including the first three shown in Fig. 1b.

We used single-photon time-of-flight spectroscopy [26,32–34] to characterize the SPDC spectra of our fabricated devices (see Fig. 3a). A fiber dispersion compensation module (DCM) is used to spread the photons in time, and the spectrum is calculated from the relative arrival times of the signal and idler at the superconducting nanowire single-photon detectors (SNSPDs). For details of the time-of-flight spectroscopy measurement, see [26,30]. We note that by performing type-II SPDC and using the d_{31} coefficient of PPLN instead of the d_{33} coefficient, the SPDC efficiency drops by a factor of 40 [35] and as a result, the higher sensitivity of SNSPDs compared to InGaAs avalanche photodiodes was extremely valuable for detecting the down-converted single photons. We found a larger than expected difference between the predicted phasematching temperature (47 °C) and the actual temperature (144 °C). This operating temperature is the point where the signal and idler wavelengths of $|H_s\rangle|V_i\rangle$ and $|V_s\rangle|H_i\rangle$ become matched; that is, where $\lambda(H_s) = \lambda(V_s)$ with the corresponding idler wavelengths also matched due to energy conservation.

We measured the SPDC spectra of several phase-modulated gratings at 144 °C. Table 2 presents results from three gratings all with total length 25 mm and $\Lambda_0 = 9.2 \ \mu m$. Λ_{pm} was equal to $198\Lambda_0$ for grating #1 and $167\Lambda_0$ for gratings #2 and #3. The phase-modulation functions for these three gratings are shown in Fig. 1b. We compare several designed and measured properties for these gratings. We found that even though the phasematching temperature was not well-predicted



Fig. 3. Experimental setup for characterizing (a) SPDC spectra using time-of-flight spectroscopy and (b) polarization entanglement. CW, continuous-wave; HWP, half-wave plate; PBS, polarizing beam splitter; DCM, dispersion compensation module; TC, temporal compensation crystal; Dic, dichroic mirror; F, filter; D1(2), superconducting nanowire single-photon detector 1(2).

Table 2. Comparison of designed and measured $\Delta\lambda$ and peak intensity ratios of several phase-modulated gratings

| Grating | $\Delta\lambda$ | $\Delta\lambda$ | Peak ratio | Peak ratio |
|---------|-----------------|-----------------|------------|-----------------|
| | (design) | (meas.) | (design) | (meas.) |
| #1 | 32 nm | 32.5 nm | 1.00 | 0.84 ± 0.04 |
| #2 | 38 nm | 38.7 nm | 1.06 | 1.06 ± 0.03 |
| #3 | 38 nm | 38.6 nm | 0.94 | 0.65 ± 0.01 |
| | | | | |

by the dispersion relation [31], the difference in wavelength between the signal and idler was well-predicted. For the peak intensity ratios, there was agreement in the trend of ratios between the designed and measured values but not in the values. In the measurements, we found the peak intensity ratio varied with sample position, which is reflected in the 1σ uncertainties given in the table. Grating #2 had the measured peak ratio closest to 1 with value 1.06 ± 0.03 . Figure 4 shows the measured downconversion spectra for this grating at 144 °C. We used this grating for demonstrating polarization entanglement.

To observe polarization entanglement, we modified the setup to use a dichroic filter rather than a polarizing beam splitter (PBS) to split the down-converted photons (see Fig. 3b). After the temporal compensation crystal, we placed a dichroic mirror (Semrock NIR01-1570/3) that reflected the signal and transmitted the idler. However, this optic reflected about 1.5% of the idler photons into the signal mode, so we placed another filter (Semrock NIR01-1535/3) before the signal collection fiber. Both filters were placed near normal incidence to avoid polarization selectivity. Tilting the filters away from normal incidence also causes slight blue-shifting of the spectra, which we used to fine tune the filtering to match the down-converted photon wavelengths. The beam transmitted through the first dichroic filter was directed to the second, idler collection fiber. The spectra of the dichroic filter system are shown in Fig. 5. We rotated the polarization state coupled into each fiber using a PBS preceded by a half-wave plate (HWP). The fibers delivered the signal and idler photons to the SNSPDs, which have some polarization dependence. By fixing the PBS and using a fiber polarization controller before the SNSPD, we could ensure that the polarization in the fiber was aligned to the direction of maximum sensitivity of the SNSPD. Rotating the HWP before the PBS changed the detected polarization state while maintaining the same polarization at the SNSPD.

The experimental setup included a temporal compensation (TC) crystal, which consisted of a 12.5 mm long unpoled MgO:LiNbO₃ crystal. The TC crystal is needed to erase temporal distinguishability between the $|H_s\rangle|V_i\rangle$ and $|V_s\rangle|H_i\rangle$ states [36]. The MgO:LiNbO₃ TC crystal is



Fig. 4. (a) SPDC spectrum for grating #2 at 144 °C with closely matched peaks at 1530.4 nm and 1569.1 nm. (b) Spectra of horizontally (H) and vertically (V) polarized signal.



Fig. 5. Reflection and transmission of the filter system.

rotated by 90° compared to the PPLN crystal so that the fast and slow birefringence axes are swapped. Other groups have used a Michelson interferometer to provide temporal compensation [23]. An ideal TC crystal should have exactly half the optical path length as the SPDC crystal, but since these two crystal were fabricated separately, it was hard to ensure the lengths were exactly correct so we placed the TC crystal in an oven to adjust its temperature and its optical path length. We adjusted the temperature of the TC crystal to maximize entanglement visibility.

Figure 6 shows results of the polarization entanglement measurement using our domainengineered SPDC source. The temperature of the temporal compensation crystal was set to 35 °C, which maximized the visibility. The continuous-wave pump power incident on the PPLN crystal was 2 mW with confocal focusing. We fixed the polarization of the signal (at detector 1) while rotating the polarization of the idler (at detector 2). We recorded the coincidence counts in a 2 ns window over a 30 s integration time. We observed visibilities of $(96.8 \pm 0.2)\%$ when the signal was horizontally polarized, and $(94.3 \pm 0.3)\%$ and $(93.0 \pm 0.5)\%$ when the signal was diagonally and anti-diagonally polarized, respectively (Fig. 6a). We believe the imperfect visibilities are due to imperfect matching of the spectra and amplitudes of the SPDC processes. We also examined the effect of temporal compensation by removing the TC crystal and repeating the measurement with diagonally polarized signal (Fig. 6b). Without temporal compensation, the visibility was only $(15.0 \pm 0.8)\%$. Uncertainties in the visibility analyses represent 2σ half widths.

We demonstrate that phase-modulated SPDC sources can be used to produce polarization entangled photons with excellent visibility. The phase-modulated structure has advantages



Fig. 6. (a) Coincidence counts as a function of idler polarization with the signal polarization set to horizontal (H), diagonal (D) or anti-diagonal (A). (b) Coincidence counts with the signal polarization in the diagonal direction with and without the TC crystal.

over other domain-engineered structures. In Table 1, calculations show that for fixed crystal length, the phase-modulated structure will have higher conversion efficiency than the interlaced biperiodic structure or the two consecutive periods. The phase-modulated structure will also have narrow SPDC peaks, with spectral widths that are equal to the spectral width generated by a single uniform grating. By using slightly more complicated phase-modulation functions, we can adjust the relative intensities between the $|H_s\rangle|V_i\rangle$ and $|V_s\rangle|H_i\rangle$ processes, which is important because this property is fixed during fabrication of the SPDC crystal. Many properties are fixed in fabrication, which means that domain-engineered sources are inherently robust to perturbations such as variations in alignment. We believe that these types of SPDC source are useful as stand-alone entangled photon sources or for quantum sources using lithium niobate integrated optics platforms [37,38]. We note that our bulk, phase-modulated SPDC source has relatively modest pair generation rate (about 1.2×10^3 pairs/s-mW), which can be increased by using waveguides [27,28].

In conclusion, we describe the design, fabrication and testing of phase-modulated, domainengineered PPLN gratings for generation of polarization-entangled photons with non-degenerate signal and idler wavelengths. We compare the phase-modulated structures to other structures including the interlaced biperiodic structure. We were able to closely match the wavelengths, bandwidths and amplitudes of two type-II down-conversion processes. Using this SPDC source with proper temporal compensation, we successfully observed polarization entanglement with greater than 93% visibility.

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Disclosures

The authors declare no conflicts of interest. The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology.

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