Spectral characteristics of an integrated Type-I parametric down-conversion source in Ti:PPLN waveguides

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Application Note

Introduction

In recent research on quantum communication parametric down-conversion (PDC) in $\chi^{(2)}$-nonlinear crystals plays a major role for the generation of photon pairs (see e.g. [1], [2], [3]). In particular, the addressing of atomic transitions for quantum memory applications [4], [5] requires a precise knowledge about the spectral emission characteristics of PDC sources.

With their integrability of different functionalities on one chip, promising pair sources rely on sophisticated wave guiding structures providing nonlinear conversion efficiencies, which are several orders of magnitude higher than those of any bulk crystal [6]. The Z-cut Lithium Niobate (LN) is a well-understood material with a high nonlinearity and the possibility to fabricate high-quality guides, which can confine wave propagation over several centimeters, whereas in bulk crystals high pump intensity is only achieved over much shorter lengths.

In this work, we spectrally characterized a non-degenerate Type-I PDC source in Titanium-indiffused periodically poled Lithium Niobate (Ti:PPLN), where a pump photon at 532 nm, which is polarized along the extraordinary crystal axis, decays into two photons of the same polarization at around 800 nm and 1575 nm, respectively.

In Figure 1 the schematic of our source is shown. It consists of a Ti:PPLN waveguide, which was periodically poled with a periodicity of around 6.8 µm to achieve so-called quasi-phasematching. This process is explained in more detail later in this report.

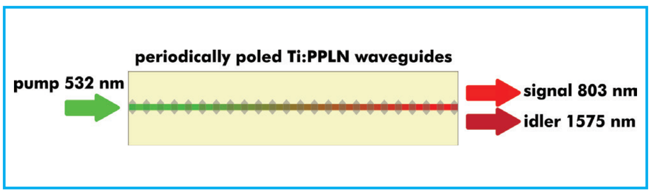

Figure 1: Schematic of the Ti:PPLN photon-pair source

Parametric down-conversion

Parametric down-conversion is a three-wave-mixing process, where pump photons of a specific energy, represented by their wavelength λ_p, can couple to a vacuum quantum state and decay into two daughter photons, commonly labeled signal (s) and idler (i). For this process, energy conservation has to be fulfilled:

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \qquad [1]$$

Furthermore the conservation of momentum must hold:

$$\overrightarrow{k_p} = \overrightarrow{k_s} + \overrightarrow{k_\iota} \qquad [2]$$

where the different $\vec{k}$ represent the wave vectors of the respective photons. This equation is usually called phasematching condition. In bulk $\chi^{(2)}$-nonlinear and birefringent optical materials an angular degree of freedom is given with respect to the phasematching condition, so that by angle tuning the choice of a specific combination of signal and idler wavelengths can be made.

In contrast to that, waveguides in nonlinear materials are assigned to allow for the confinement of light over longer distances due to total reflection of light at the waveguide boundaries. However this also implies that we are limited to only one translatory degree of freedom, namely the propagation direction of the interacting photons. The wave vectors can be replaced by scalars of effective wave numbers for the individual guided mode

$$k = \frac{2\pi}{\lambda} n_{eff}\,, \qquad [3]$$

where λ is the wavelength and n_{eff} is the effective refractive index. Due to chromatic dispersion, usually a phase-mismatch occurs in waveguided PDC processes:

$$k_p - k_s - k_i = \Delta k\,. \qquad [4]$$

Here the additional term Δk expresses the phase mismatch in terms of an additional wave number. To compensate for this, a common technique, called periodically poling is typically employed. The defined inversion of the spontaneous polarization of the crystallographic domains introduces an additional grating vector, which modifies the phase-matching condition of Equation (2). The required poling period Λ_G is given by

$$\Delta k = \frac{2\pi \cdot m}{\Lambda_G}, \qquad [5]$$

with m being an odd integer value, which denotes the order of the achieved quasi-phasematching. Together with the conservation of energy in Equation (1) the conservation of momentum therefore defines the possible wavelength combinations for a given poling period in waveguide-based PDC processes.

For a fixed poling period and pump wavelength we are able, in turn, to determine the wavelength combination of signal and idler. Tuning those wavelengths can be accomplished by temperature tuning of the device. This is due to the temperature dependence of the effective refractive indices. For stable applications of PDC sources it is therefore important to know about the spectral shift with the device temperature.

Waveguide technology

For our experiments we manufactured samples carrying waveguides with a fixed width of 7 µm. We varied the poling periods between 6.71 µm and 6.91 µm across the device width. The waveguides were fabricated by Titanium-indiffusion at 1060 °C for 8.5 hours. To achieve the best possible coupling of light into and out of the waveguides, the end-facets were polished perpendicularly to the propagation direction. To improve the overall conversion efficiency of the device, we developed and deposited dielectric coatings (EFC) for an optimum incoupling of the pump wavelength. The best possible outcoupling of signal and idler wavelengths including the reflection of the pump was achieved by a 16-layer coating at the waveguide output, which shows more than of reflection for the pump, while it allows for the idler wavelength to be transmitted with more than .

Experimental Setup

For the nonlinear optical characterization we used a simple setup, depicted in Figure 2. It can be separated into three divisions: incoupling part, sample adjustment and analysis part.

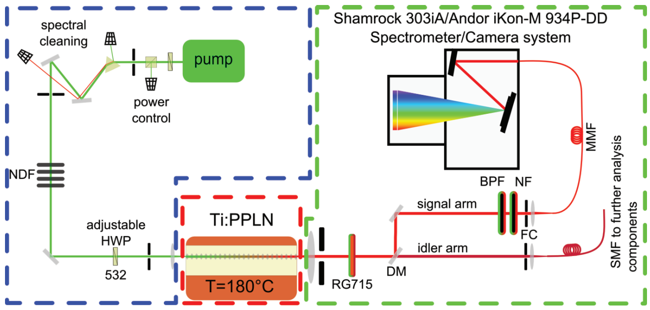

Figure 2: Experimental setup for spectral PDC measurements; NDF: neutral density filters, BL: beam blocker, HWP: half-wave plate, RG715: customized absorptive filter, DM: dichroic mirror, NF: needle filter, BPF: band-pass filter, FC: fiber coupling stages, MMF: multi-mode fiber. SMF: single-mode fiber

A prism-based cleaning ensures that only the pump wavelength is launched into our device and variable attenuators in combination with neutral density filters are used to control the optical pump power. The TM polarization is set with an additional half-waveplate prior to the AR-coated coupling lens.

The sample alignment setup consists of a home-assembled high-precision 5-axis stage, while the temperature can be changed or stabilized at sufficiently high levels to prevent so called photorefractive damage (T>140 °C), which is the light-induced, highly dynamic change of refractive indices, mediated by the nonlinear electro-optic effect.

Experimental flexibility in the analysis is achieved by using a free-space configuration as far as possible. Several – partially home-made – spectral filters and absorbers provide good transmission of the signal and idler beam.

A dichroic mirror splits up the PDC output into signal and idler arm, whereof the signal arm is coupled to a multimode fiber. For the spectral characterization it is connected to an Andor spectrometer system (spectrograph Shamrock SR-303i-A-SIL and CCD detector iKon-M DU934P-BR-DD) with x-y-adjustable fiber coupler for spectral PDC characterization. This spectrometer device can be driven with three different dispersive gratings mounted on a software-controlled turret for comfortably changing them online. In addition to that we also applied an included and electronically addressed entrance slit. For the highest possible resolution of less than 0.2 nm we used a grating with 1200 lines per mm, blazed at 500 nm and chose a slit of 10 µm width. The Andor SOLIS software also offers the option that we can measure-and-glue spectra over the whole sensitive range of the CCD detector, which is read out in full vertical binning mode and has a dynamic range of 16 bit in the kinetic acquisition mode. The readout rate of 50 kHz together with a 4-fold pre-amplifier gain allows for an excellent signal to noise ratio still at low electronic noise and within the acquisition time window of less than 0.025 s.

Results and Discussion

The nonlinear characteristics of the PDC source have been determined by measuring the spectral behavior, when changing either the device's temperature or its poling period. Both dependencies are shown in Figure 3, respectively, and indicate coarse (poling period) and fine (temperature) wavelength tunability. We can identify a strong dependence of the PDC signal emission on the poling period and the position on the device. The higher central peaks indicate stronger nonlinear interaction efficiency in the central parts of the PDC device. We identified this to be caused by a more homogeneous periodic poling pattern in this section, while in the edge regions the poling slightly suffers from so called over- or underpoling. This reduces the effective interaction length of the PDC process.

In Figure 3 (below) we can clearly see, that temperature tuning provides us with the precise control of the generated wavelengths. Within these measurements, the Andor spectrometer system not only is sensitive at the single photon level but suppresses etaloning due to the deep depletion design of the CCD sensor. The graphs in Figure 3 and 4 show no significant disturbances of our spectra due to Fabry-Pérot effects. For the high pre-amplifier gain chosen, the base level is around 300 counts.

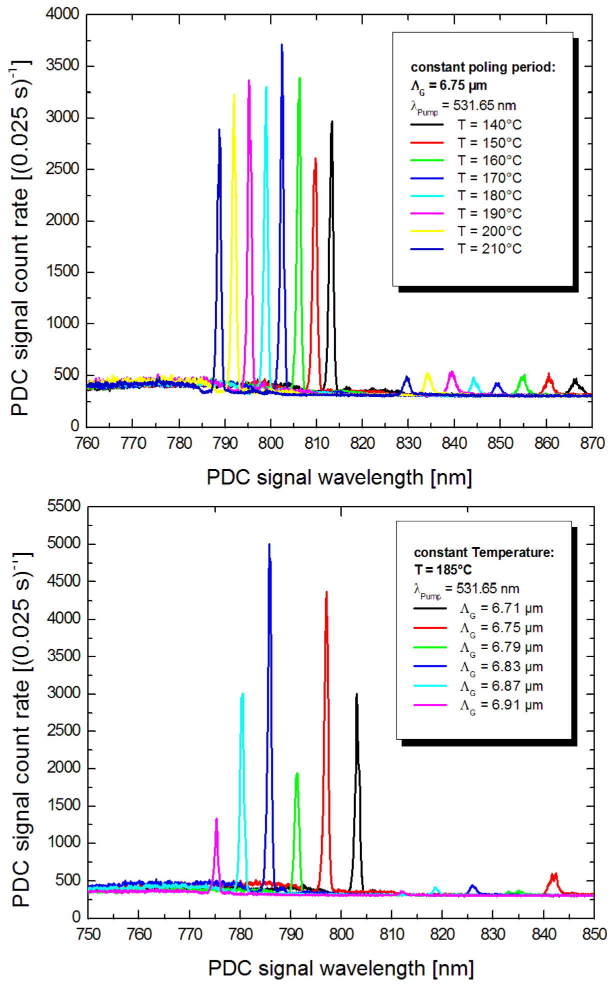

Figure 3: Tunability of the PDC signal wavelength with the crystal's poling period (top) and temperature (below)

Note that there is only one sidepeak per spectrum indicating a higher order spatial waveguide mode excitation around 45 nm shifted to longer wavelengths. This represents an excellent waveguide homogeneity and good coupling of the pump light to the fundamental spatial waveguide mode.

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In preparation of later experiments, we implemented a dielectric needle filter to the signal arm. With this, the spectral characteristics of the PDC source in the Silicon detection band exhibits no additional photons exceeding 0.6% of the maximum PDC signal level. The needle filter has a FWHM bandwidth of <0.5 nm and a maximum classical transmission of $T_{NF,s}$=0.78 as shown in figure 5 and its inset. The large wavelength range of the inset graph indicates the convenient measure-and-glue technique of the spectrometer system software measured at maximum resolution.

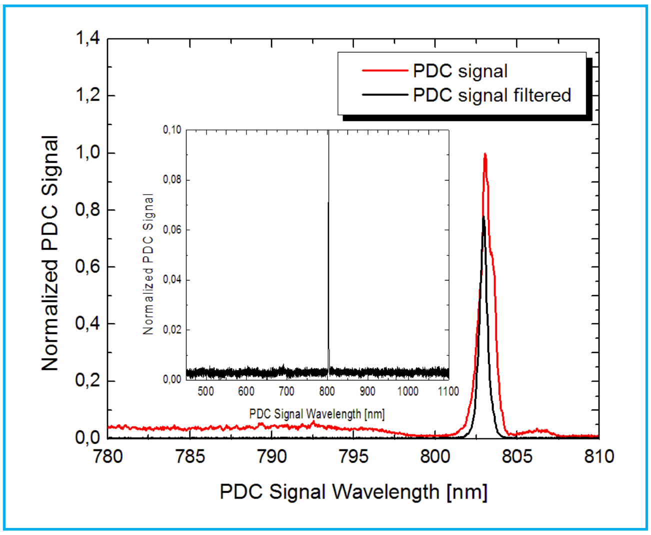

Figure 5: Unfiltered (red) and needle-filtered PDC signal (black), inset: background spectral characteristics

Conclusion

We spectrally characterized a waveguide-based type-I PDC source in Titanium-indiffused waveguides in periodically poled Lithium Niobate with a single-photon sensitive high-resolution spectrometer and were able to verify its excellent performance with respect to sample homogeneity and tunability.

Acknowledgments

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