ECIO 2010, Cambridge, 7 - 9 April 2010, paper ThC4

Novel Source of Polarization Entangled Photon Pairs Using a PPLN Waveguide with Interlaced Domains

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Abstract: **A novel source of polarization entangled photon pairs has been developed based on spontaneous parametric down conversion (SPDC) in a periodically poled Ti:$LiNbO_3$ waveguide. The domain structure consists of interlaced domains with two periodicities designed for type II quasi-phase-matching. Design issues as well as experimental results on second harmonic and SPDC characterization and entanglement measurements are reported.**

Keywords-SPDC; PPLN; entanglement; interlaced

I. Introduction

Entangled photon pair sources are essential devices for quantum key distribution. Different approaches have been demonstrated to generate entangled photon pairs. The most promising devices rely on spontaneous parametric down conversion (SPDC) especially in integrated optical structures. High efficiency and brightness can be achieved using nonlinear optical waveguides in periodically poled $LiNbO_3$ (PPLN). To generate in such waveguides polarization-entangled photon pairs, either both photons must have the same wavelength (operation at degeneracy) [1] or a hybrid – and thus less robust and compact - Sagnac scheme [2] has to be used.

In this contribution we present a novel scheme to generate non-degenerated polarization-entangled photon pairs in a PPLN waveguide with a specifically designed poling structure consisting of interlaced domains.

II. Design and Fabrication

A. Principle of Operation

Via nonlinear optical SPDC a pump photon can decay into a signal and an idler photon. In LN waveguides this process can be exploited taking advantage of the strong d_{33} nonlinear coefficient (type I) or via the d_{31} nonlinearity (type II). In the latter case the generated photons are orthogonally polarized. An efficient pair generation requires quasi-phase-matching, achievable by choosing the proper poling period. For type II phase-matching the signal- and idler wavelengths are shown in Fig. 1 as function of the pump wavelength for two different poling periods Λ_1 and Λ_2. Using a sample with one fixed poling period, polarization entangled photon pairs can be generated, if the device is operated at degeneracy and the pairs are subsequently spatially separated via a beam splitter [1]. However, half of the created photon pairs get lost if they are routed to a common output port of the splitter. To overcome this drawback, we apply a new scheme – which has recently been proposed in [3] - to create polarization-entangled pairs at non-degeneracy.

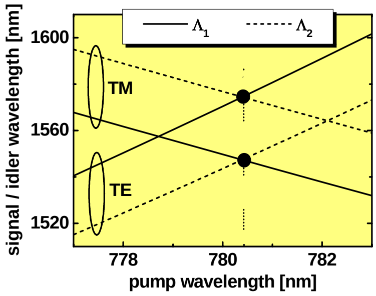

Figure 1: Phase-matching characteristics of type II SPDC for two different poling periodicities. The operating points of the novel entangled source are indicated by the black dots.

If the Ti:PPLN waveguide is poled with two periodicities Λ_1 and Λ_2, two different photon pairs, one corresponding to Λ_1 and the other to Λ_2 can be created. Non-degenerated orthogonally polarized entangled pairs can be generated if the device is operated at a pump wavelength where the TE emission of Λ_1 coincides with the TM emission of Λ_2 and vice versa (see Fig. 1).

B. Waveguide Design and Fabrication

To investigate this new scheme PPLN waveguides with different poling patterns have been designed. Segments with N domains of Λ_1 and N domains of Λ_2 are interlaced as shown in Fig. 2. The spacing δ_i between the segments was adjusted to maintain the proper phase relation between adjacent segments of the same period. Interlacing the two periods instead of a sequential arrangement should enhance the photon indistinguishability. To prove this, different structures with N=10, 100, 500 and 3000 have been designed and fabricated.

57 mm long single mode waveguides were fabricated by in-diffusion of photolithographically defined 7μm wide, 80 nm

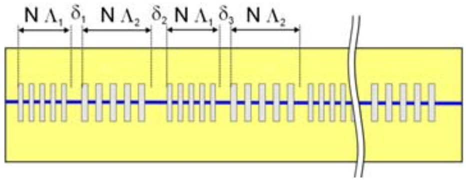

Figure 2: PPLN waveguide with interlaced domains.

thick Titanium stripes for 9 hours at 1060°C. Afterwards the waveguide is periodically poled. The poling periods (Λ_1=9.30 µm and Λ_2=9.37 µm) were chosen to obtain SPDC in the 1550 nm range with the wavelengths of the operating point separated by around 25 nm.

III. CHARACTERISATION

A. *Second Harmonic Generation (SHG) and SPDC*

At first, the sample was characterized by SHG. At 45° linear polarized light from a tunable extended cavity laser (ECL) was coupled into the waveguide to excite TE and TM modes simultaneously. The generated SH power was measured as function of the ECL wavelength as shown in figure 3. A structure with only two segments (N=3000) provides two distinct SH peaks (left diagram). The second diagram corresponds to the waveguide with multiple segments (N=500). Due to the segmentation satellite peaks appear in addition to the main peak. Similar satellite peaks can be expected for SPDC. The satellites can be pushed away from the wavelength range of interest by decreasing the number of domains per segment. With 10 domains per segment, the satellite peaks are outside the measurement window as shown in the right diagram.

The measured SH efficiency was about 5 % / W. The full width at half maximum (FWHM) of each peak is about 0.2 nm.

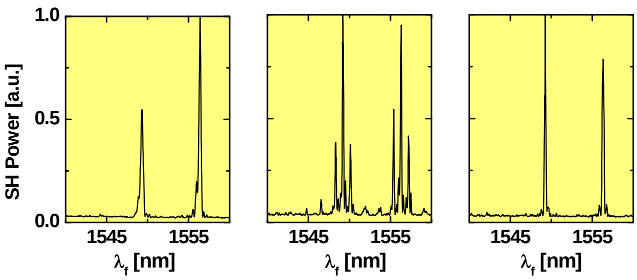

Figure 3. Measured SH phase-matching spectra with N=3000, 500 and 10 domains per segment, respectively.

SPDC spectra of a waveguide with 10 domains per segment were investigated. The pump radiation from an ECL (λ_p~775 nm) was coupled into the waveguide. The spectrum of the down-converted radiation was measured by an InGaAs PIN diode behind a monochromator. The residual pump radiation was blocked by a combination of absorption and dielectric filters. Measured SPDC spectra are shown in figure 4 for a pump wavelength slightly offset (left) and exactly at the operating point. The amplitude of the TM peaks is smaller compared to the TE peaks because of the higher losses in the waveguide and in the measurement setup. The measured SPDC

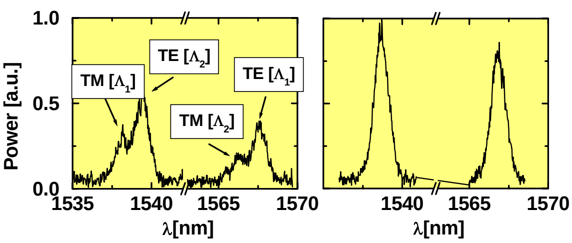

Figure 4: Measured SPDC spectra: Pump wavelength slightly offset from the correct point of operation (left) and at the correct value (right).

efficiency was ~ 4×10^{-9} % and the FWHM was 0.4 nm.

B. *Characterisation of Entanglement*

The experimental setup to study entanglement is shown in figure 5. The photons are butt-coupled into an optical fiber and spatially separated using a circulator and a fiber bragg grating (0.5 nm spectral width). The reflected photons enter the single photon detector (SPD) after passing through a half wave plate (HWP) and a polarization beam splitter (PBS). The transmitted photons are routed via a band pass filter (1 nm width) and a

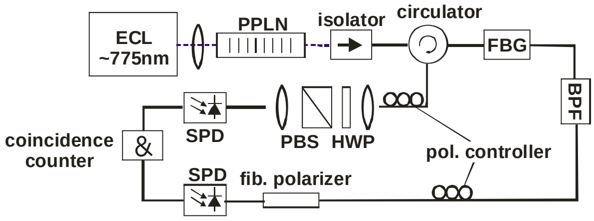

Figure 5: Experimental set-up to analyse polarization entanglement.

fiber PBS to a second SPD. Coincidence counts were measured for different orientations of the HWP as shown in Fig. 6. As predicted for entangled states the coincidence count rate oscillates with a period of 90° as we rotate the HWP. A quantitative analysis of the quality of entanglement is currently under progress.

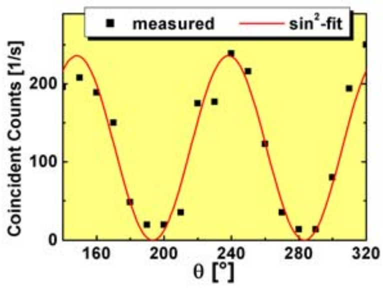

Figure 6: Coincident counts for different orientations of the HWP.

IV. CONCLUSIONS

We have demonstrated a novel type of polarization entangled photon pair source using interlaced domains in a Ti:PPLN waveguide. This novel scheme strongly simplifies the development of efficient, compact and robust sources of entangled photon pairs for applications especially in quantum key distribution.

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