

PPLN-based photon-pair source compatible with solid state quantum memories and telecom optical fibers

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Abstract. We report on the realization of a tunable source of correlated photon pairs compatible with telecommunication networks and quantum memories involving dielectric crystals doped by Nd^{3+} ions. The source is based on spontaneous parametric down-conversion in a 25 mm periodically poled lithium niobate crystal pumped by 532 nm cw laser. Spectral and correlation characteristics of the corresponding heralded single-photon source compatible with quantum memories are presented.

1. Introduction

Sources of correlated photon pairs is a commonly used tool in experimental quantum optics and necessary ingredient for important quantum information protocols like quantum key distribution [1] and long-distance quantum communication via quantum repeaters [2]. In particular, for applications in long-distance quantum communication networks, it is required that quantum memories are connected to optical fibers. Therefore, nondegenerate photon-pair sources producing one photon in each pair corresponding to a telecommunication band, while another to a quantum memory absorption line, are demanded [3]. To date the most common method of creating such photon pairs is spontaneous parametric down-conversion (SPDC) [4]. Using periodically-poled crystals or waveguides makes it possible to tailor the phase matching [5] thereby allowing the creation of photons at very different wavelengths. In this work, we report on a widely nondegenerate photon-pair source compatible with Nd^{3+} doped quantum memories and with telecom optical fibers. The photon pairs are obtained by SPDC and have a wavelength near 867 nm (the resonant wavelength of Nd^{3+} ions in YLiF_4 crystals) and 1377 nm (the telecom E-band). The crystal $\text{YLiF}_4:\text{Nd}^{3+}$ is a promising material for solid-state implementation of quantum memory protocols based on off-resonant Raman interaction [6, 7]. Recently, it was used for implementing the atomic frequency comb protocol of quantum storage [8-10]. We study the present source as a heralded single-photon source compatible with this material.

2. Basic results

In SPDC, a pump laser illuminates a material with a $\chi^{(2)}$ optical nonlinearity, creating two photons (usually called signal and idler) under the constraints of momentum and energy conservation: $k_p = k_s + k_i$ and $\omega_p = \omega_s + \omega_i$, where indexes s, i, p stand for the signal, idler and pump photons, respectively. In periodically poled crystals, the effective nonlinearity of the medium is periodically inverted by the application of an electric field with alternating directions during the crystal fabrication process. In



contrast to birefringent phase-matching in bulk crystals, the quasi phase-matching conditions now involve an additional term that depends on the crystal-poling period Λ :

$$\vec{k}_p(\lambda_p, n_p(\lambda_p, T)) = \vec{k}_s(\lambda_s, n_s(\lambda_s, T)) + \vec{k}_i(\lambda_i, n_i(\lambda_i, T)) + \frac{2\pi}{\Lambda(T)}, \quad (1)$$

where $\vec{k}_{p,s,i}$ and $n_{p,s,i}$ are the wavevectors and the wavelength- and temperature-dependent refractive indices of the crystal for the corresponding wave fields. Assuming a fixed pump wavelength, equation (1) shows that the wavevectors of the signal and idler photons are temperature dependent, in particular, for a fixed emission angle. Quasi-phase-matching in periodically poled crystals allows for almost arbitrary phase-matching angles and wavelengths in comparison to the nontrivial conditions in bulk nonlinear crystals, where only birefringent and angle phase-matching is possible. In particular, periodically poled crystals can be tailored such that $\vec{k}_{p,s,i}$ are parallel to one of the crystallographic axes X, Y or Z , which allows one to avoid birefringence and utilize maximum nonlinear coefficients.

The scheme of our experimental setup is presented in figure 1. A cw neodymium laser (ALPHALAS MONOPOWER, 532 nm) pumps a 25 mm MgO:PPLN bulk crystal, provided by Labfer Ltd., with a 5% MgO-doping concentration and a poling period of 7.47 μm , which gives the phasematching condition necessary to produce photon pairs at 867 nm and 1377 nm via Type 0 (e, e, e) SPDC process at the temperature of 85 C. This crystal has a clear aperture of 1 mm $\times$ 2 mm and is anti-reflection coated on both sides for the pump, signal and idler wavelengths (see figure 1). The pump laser beam is focused with a lens of focal length 200 mm, which yields a 70 μm waist within the crystal. The generated signal (867 nm) and idler (1377 nm) photons are separated by a dichroic mirror DM1. The pump radiation is suppressed by the dichroic mirror DM2 in the idler channel and by the diffraction grating DG in the signal channel. The photons are then coupled into fibers using an aspheric lens (for the idler channel, $f=11$ mm) and micro objectives (for the signal channel, $f=14$ mm). The signal photons at 867 nm are detected by a free running Si-APD (SPCM-AQRH) with the efficiency of $\eta_{850}=40\%$, dark count rate of 2 kHz and dead time of 150 ns. The idler photons are detected by an InGaAs APD (ID201, ID Quantique) in free-running mode with the efficiency of $\eta_{1550}=10\%$ and dead time of 12 μs . Under such conditions, the dark count rate proves to be of 2.1 kHz. To reduce broadband fluorescence background and for scanning wavelength in the signal channel, the reflecting diffraction grating mounted on a rotation servo stage is used. The spectral width of the fiber coupler input aperture is equal to 2.5 ± 0.15 nm.

The second-order autocorrelation function of the signal field (867 nm) is measured using Braun-Twiss interferometer scheme. Signal-photon channel splits into two ones and coincidence rate between the detectors 1, 2 (R_{12}), 1, 3 (R_{13}), and 2, 3 (R_{23}) is measured simultaneously (figure 1). The coincidence rates R_{13} , R_{23} describe photon-pair generation rate. The coincidence rate R_{12} at zero time-delay between the photons propagating to detectors 1 and 2 describes the value of the second-order zero-time autocorrelation function:

$$g_2(0) = \frac{P_{12}}{P_1 * P_2}, \quad P_{1,2} = \frac{N_{1,2}}{N_t}, \quad P_{12} = \frac{N_{12}}{N_t}, \quad (2)$$

where P_{12} is the probability of joint detection on the detectors 1 and 2; P_1 , P_2 is the probability of detection on the detectors 1 and 2, respectively; $N_{12} = R_{12}$; $N_1 = R_1$; $N_2 = R_2$; N_t is the total normalized number of pulses coming to the channels 1 and 2. Normalization of N_t is carried out on total losses in the optical tract (optical elements, fiber coupling) and quantum efficiency of detectors. Figure 2 illustrates a linear dependence of $g_2(0)$ on the pump power. After optimization, we obtained the following parameters of the photon-pair production: the photon-pair generation rate, considering the general losses in the experimental setup, is equal to 160 kHz*mW/sec, and $g_2(0)=0.004 \pm 0.001$ for the pump power of 2 mW. Spectral width of the signal photons, which was measured using the diffraction

grating DG, proves to be of 0.15 ± 0.3 nm. The width of the correlation function measured via time-to-digital converter ID800 is of 330 ± 81 ps. Figure 3 illustrates the possibility of the temperature tuning of the single-photon wavelength. To simulate the experimental results, we used modified Sellmeier equations for the temperature-dependent refractive indices $n(\lambda, T)$ from [11].

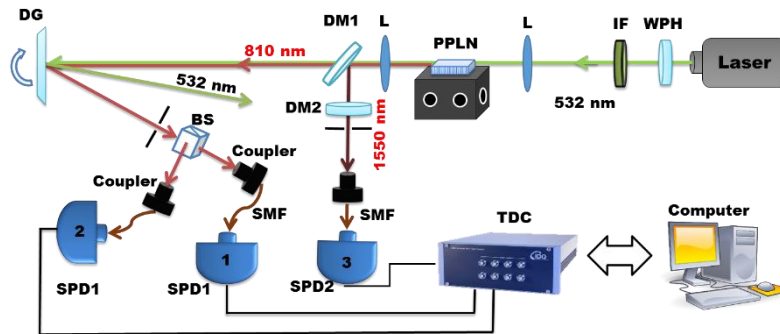


Figure 1. Schematic of the experimental setup. Laser is the cw neodymium laser ALPHALAS MONOPOWER-532-100-SM; L is a coated lens; DM1 is a dichroic mirror with 98% transmission at 850 nm and 94% reflection at 1550 nm; IF is an interference filter for the pump field at 532 nm; WHP is a half-wave plate at 532 nm; DM2 is a dichroic mirror with 95% transmission at 1550 nm and 91% reflection at 532 nm; PPLN is the periodically poled lithium niobate placed in a thermostat for crystal temperature stabilization; DG is a reflective diffraction grating with the angular dispersion of 3.2 nm/mrad placed on a rotation stage; BS is a nonpolarizing 50/50 beam splitter; Coupler is a cage fiber coupler system; SMF is a single-mode fiber; SPD1, SPD2 are Perkin Elmer single-photon detectors; SPD3 is the single photon detector ID210; ID800 is the eight-channel time-to-digital converter with the time resolution of 81 ps.

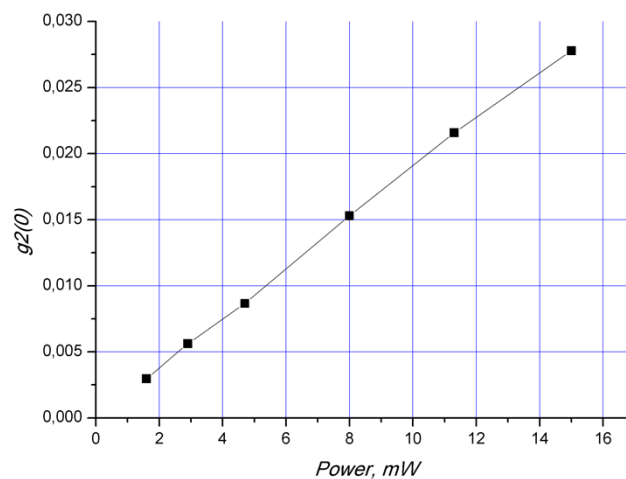


Figure 2. The dependence of the second-order zero-time autocorrelation function $g^{(2)}(0)$ on the pump power.

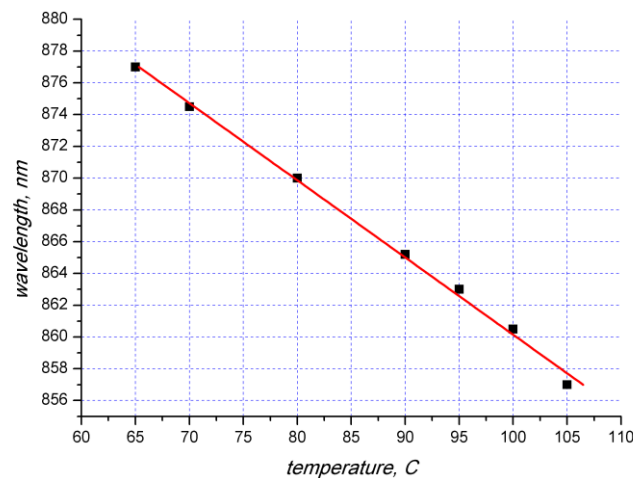


Figure 3. Wavelength of the signal photons vs temperature of the PPLN crystal. Solid line is the result of theoretical calculation using equation (1).

3. Conclusion

We have studied spontaneous parametric down-conversion in a periodically poled lithium niobate crystal wherein correlated photon pairs compatible with telecommunication networks (wavelength 1377 nm) and Nd³⁺ doped quantum memories (wavelength 867 nm) are produced. The basic features of the corresponding heralded single-photon source compatible with such quantum memories are studied. In particular, the second-order zero-time autocorrelation function for the field generated at 867 nm is measured as a function of the pump power, and possibilities of wavelength tuning are demonstrated. The present source may be used as a basis for developing a narrowband variant based on the cavity-enhanced spontaneous parametric down-conversion, which can produce photons interacting effectively with the YLiF₄:Nd³⁺ crystal.

Acknowledgments

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