Towards Photon Pair Generation in ppLN & ppKTP with High Purity using Pulsed Lasers

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Introduction

No matter whether the setup relies on quantum entanglement, single-photon heralding or quantum interference – the generation of indistinguishable photons in pure quantum states is a crucial task in any quantum lab.

Pair creation by *spontaneous parametric down-conversion* (SPDC) has become a reliable source for single photon states, used in many kinds of quantum-related experiments. In order to be spectrally pure, two photons from different sources should be as frequency-uncorrelated as possible. For this purpose most experiments use narrow bandpass filters, having to put up with a drastic decrease in count rates. In our research we investigate (theoretically and by numerical evaluation) how to engineer a setup such that the SPDC-generated quantum states are *intrinsically pure*. By mutual matching of pulsed pump lasers (centre wavelength and spectral width) and periodically poled crystals (material, crystal type, poling periodicity, temperature) this approach makes bandpass filtering obsolete and allows for significantly higher output intensities and therefore count rates in the detectors. The aim of this presentation is to find configurations best suited for experimental realisation.

Pure Photon States via SPDC

In a typical SPDC setup a non-linear crystal is impinged by a pump laser whereupon a certain portion of pump photons (usually between 10^{-10} to 10^{-6}) decays into two daughter photons, usually referred to as *signal* and *idler*. The three photons, pump, signal and idler, obey energy conservation and can, depending on the type of down-conversion, be polarisation-degenerate or polarised orthogonally to each other. In order to allow for a positive energy transfer from pump to daughter fields throughout the crystal, thus to prevent the three waves to interfere destructively, pump, signal and idler are phase-matched by the *quasi-phase-matching* (QPM) technique. This approach makes use of a change of the crystal's non-linearity coefficient in multiples of a certain longitudinal constant Λ in order to reset the phase mismatch periodically and permit the output intensity to increase together with the crystal length. For any kind of collinear three-wave mixing it is possible to manufacture a periodically poled non-linear crystal to meet the quasi-phase-matching condition.

The process of SPDC is in principle determined by two functions: the pump envelope amplitude $\mu(\omega_p)$ and the phase-matching amplitude $\psi(\omega_s, \omega_i)$. While μ describes the spectrum of the pump laser, ψ determines which wavelength configurations are supported for a given SPDC type, non-

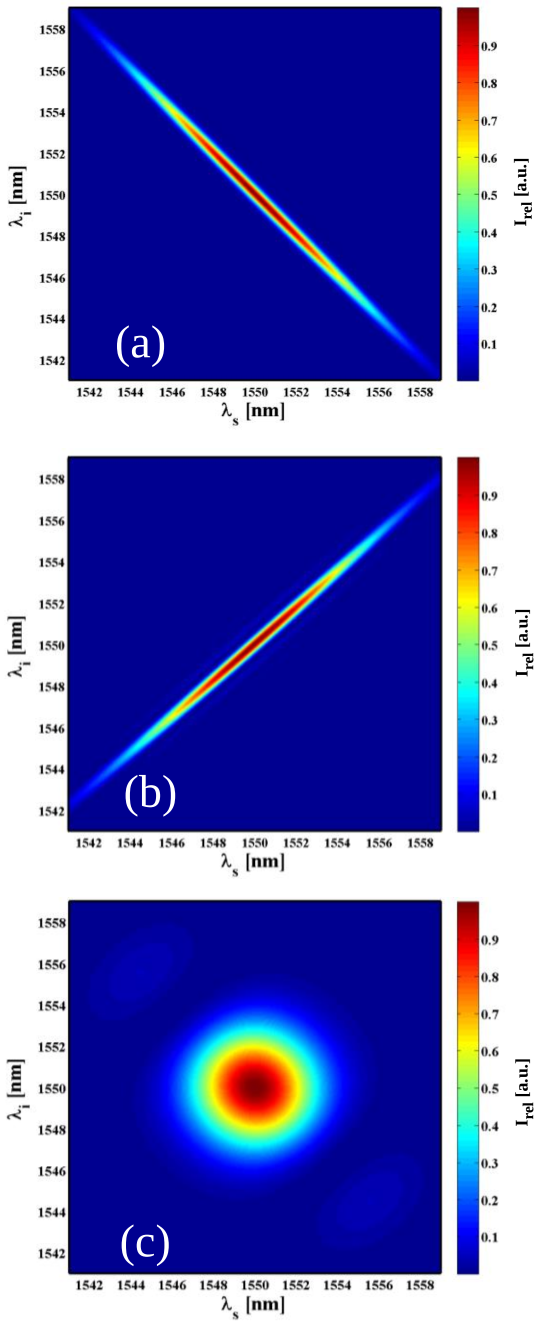

Figure 1: Graphical representation of the joint spectral intensity in three examples. Figures (a) and (b) show cases where signal and idler wavelengths (x- and y-axis) are highly (anti-) correlated, resulting in a purity of P~0; Figure (c) illustrates a frequency-uncorrelated down-conversion, represented by a circular JSI with P~1.

linear crystal and temperature. The product of the two is known as the *joint spectral amplitude* (JSA) $f(\omega_s, \omega_i) = \mu(\omega_s + \omega_i)\,\psi(\omega_s, \omega_i)$ which uniquely determines the intensity, frequency spectrum and spectral purity of the output radiation. It can be shown by basic quantum mechanics that signal and idler single photon states can be considered pure if the joint spectral amplitude is separable, thus $f(\omega_s, \omega_i) = f_s(\omega_s) f_i(\omega_i)$. Our approach is therefore to design the experimental setup such that the JSA is *a priori* separable. For this purpose we are matching the pulse duration and the crystal length appropriately. Figure 1 (a) depicts the case of a narrow-band CW laser impinging a short crystal, resulting in anti-correlated signal and idler spectra. Conversely a broadband femtosecond laser impinging a long crystal would result in correlated daughter photons as shown in Figure 1 (b). When pulse duration and crystal length are mutually matched we can achieve frequency-uncorrelated signal and idler spectra as illustrated in Figure 1 (c).

While the postulates of quantum mechanics, combined with numerical mathematics, show how to evaluate the degree of purity of down-converted photons [1,2,3], first experimental tests of this approach yielded promising results [4,5,6,7,8]. In our research we investigate phase-matching conditions and quantum state purity of all types of down-conversion in all common wavelength regimes and in two kinds of periodically poled crystals, *lithium niobate* (ppLN) and *potassium titanyl phosphate* (ppKTP).

Unfortunately the generation of intrinsically pure quantum states is only possible for a limited amount of setups; as pointed out above, the JSA depends on the mutual relation of pump envelope intensity and phase-matching envelope intensity. The latter depends ultimately on the material's Sellmeier equations which provide the refractive index for a given polarisation and wavelength. As it turns out, each crystal allows for generation of intrinsically pure down-converted photons only in the case of very specific polarisation- and wavelength configurations.

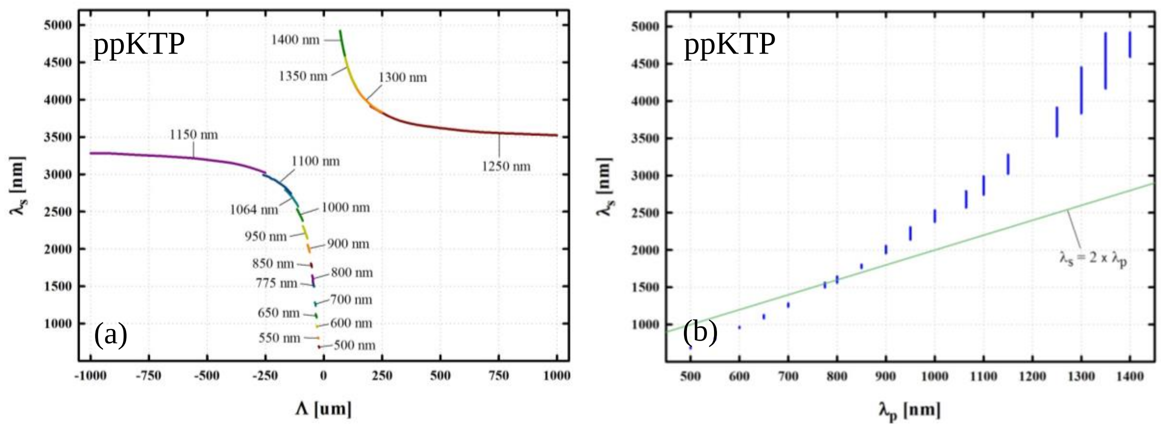

Figure 2: Signal wavelength versus (a) crystal periodicity Λ and (b) pump wavelength λ_p for type II SPDC ($e \longrightarrow o + e$) in ppKTP. Both plots exclusively display configurations which allow for an uncorrelated JSA (provided matched pump spectrum and crystal length). Each coloured line in Figure (a) corresponds to a certain λ_p as denoted in the graph. The green line in Figure (b) represents frequency-degenerate SPDC; its intersection with the blue lines illustrates that KTP allows for pure output states in the telecom regime which is well confirmed by recent experiments.

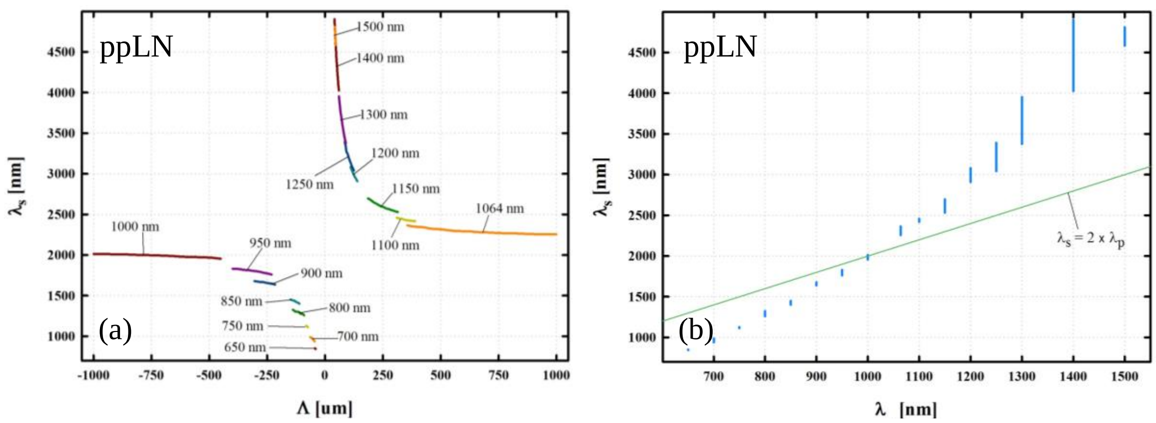

Figure 3: Signal wavelength versus (a) crystal periodicity Λ and (b) pump wavelength λ_p for type II SPDC ($e \longrightarrow o + e$) in ppLN. We see that for pump wavelengths between 1000 and 1064 nm the periodicity approaches infinity, thus enabling spectrally pure output generation without periodic poling. The green line in Figure (b) represents frequency-degenerate SPDC; its intersection with the blue line at $\lambda_p = 1000$ nm illustrates that LN allows for pure output states at $(1000 \longrightarrow 2 \times 2000)$ nm.

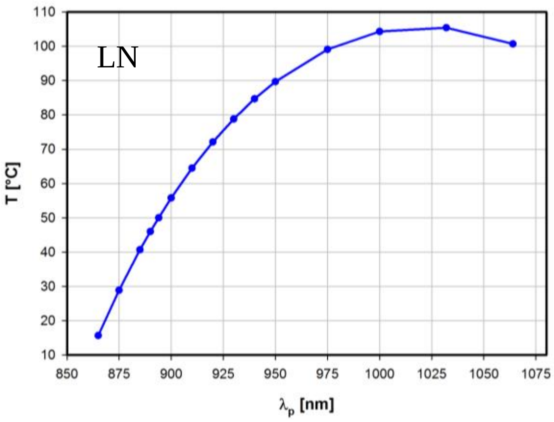

Figure 4: Temperature vs. pump wavelength for frequency-degenerate type II SPDC in LN. The blue line represents phase-matched and intrinsically pure processes for which no periodic poling is required.

The state purity of single photons that are generated by SPDC can be determined numerically by a singular value decomposition of the joint spectral intensity. Using this method we investigated the suitability of LN and KTP for various kinds of down-conversion processes. This systematic and extensive search for setups which allow for generation of intrinsically pure quantum states is – to our knowledge – unprecedented so far. This way we were able not only to confirm the choice of specific crystals in recent experiments but also to find many other promising (type I and type II) setups that were previously unknown (Figures 2 and 3).

In particular we found that in the case of frequency-degenerate type II SPDC with signal and idler in the telecom band KTP is clearly superior to LN in terms of single photon state purity. It turns out however that, according to our calculations, LN offers high spectral purity in frequency-degenerate type II down-conversions within the region $(870 \longrightarrow 2 \times 1740)$ nm to $(1100 \longrightarrow 2 \times 2200)$ nm (Figure 4). Moreover we found that using temperature tuning these intrinsically pure quantum states can be achieved *without periodic poling* of the crystal which allows not only for significant *cost savings* and larger crystals but also for even *higher SPDC efficiencies* and therefore bit rates.

Conclusion

Our calculations accurately confirm the results known from very recent experiments using ppKTP for down-conversions close to $(775 \longrightarrow 2 \times 1550)$ nm. Furthermore we found that ppLN allows for intrinsically pure SPDC around $(1000 \longrightarrow 2 \times 2000)$ nm with the promising benefit that under proper temperature tuning no periodic poling would be required. Temperature tuning can also be used to shift the daughter wavelengths close to the quantum efficiency peak of novel superconducting nanowire detectors.

Acknowledgement

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