A nonlinear waveguide source of spatially pure photon pairs

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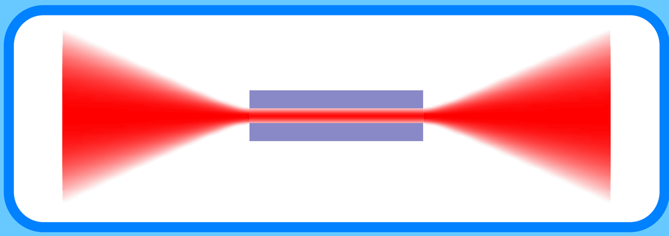
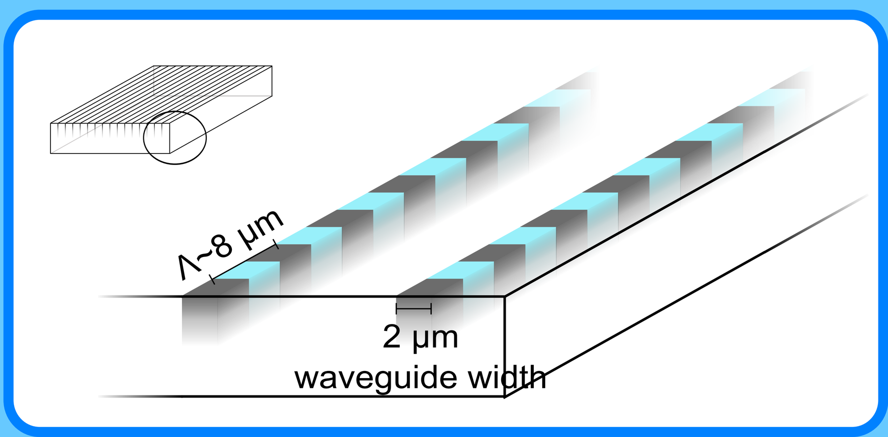
Motivation

Spontaneous parametric downconversion (SPDC) sources are capable of delivering pure heralded single photons in a well controlled way. In bulk crystal sources relatively high pump power is needed to give reasonable rates of photon pair generation. Using a non-linear $\chi^{(2)}$ waveguide enables more efficient photon pair generation with lower pump powers, thanks to the combination of long interaction length and tight transverse light confinement offered by the waveguide. The possibility to periodically pole the waveguide enables engineering of the phase matching characteristics of the waveguided nonlinear process. Additionally nonlinear waveguides offer a possibility of integration into hybrid integrated optical systems.



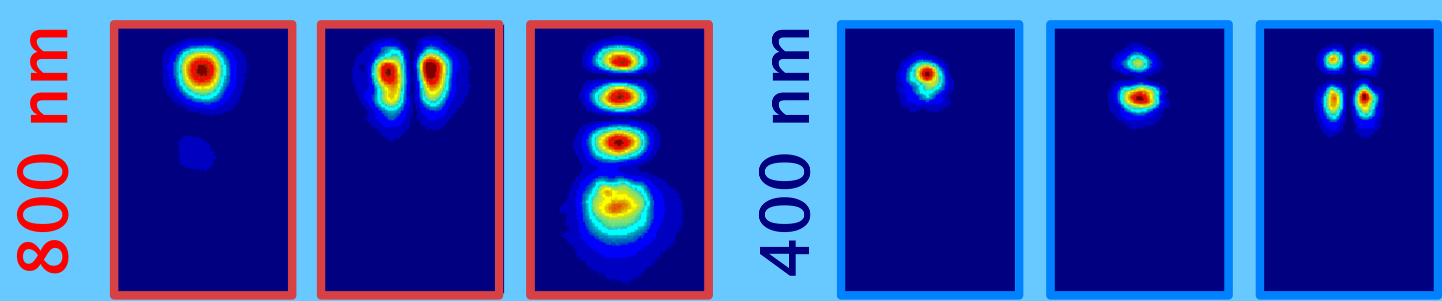
In the VIS-NIR spectral region spectral region periodically poled KTiOPO4 (PP-KTP) waveguides offer high SPDC efficiencies. In this work we experimetnally study the possibility of obtaining photon pairs in a pure state from PP-KTP waveguide downconversion source, especially focusing on the transverse spatial purity of the downcoverted photons.

Challenge



Waveguide sample characteristics. A commercially available sample: z-cut KTP crystal containing several waveguides fabricated on its surface by ion exchange. Waveguide width was 2 μm, effective depth approx. 5 μm. Length of the sample: 1 mm. Quasi phase matching was provided by periodic poling.

Available waveguide fabrication techniques do not enable production of single mode waveguides in the spectral region of high single photon detection efficiency by Si avalanche photodiodes. The studied sample supported >7 modes at 800 nm and approx. 30 modes at 400 nm, for each polarization. See below for exemplary instensity distributions. Note the mode assymetry in the vertical direction resulting from assymetry of the waveguide.



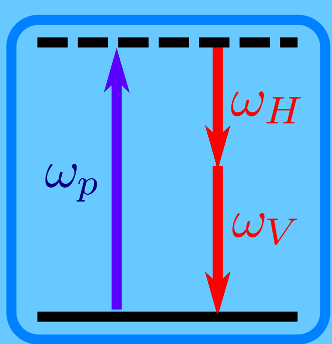
The multimode nature of the waveguide in general causes mixedness in the transverse spatial degree of freedom of downconverted photons. Whereas this can be suppressed by spatial filtering using single mode fibers, it comes at the cost of additional losses and thus significant reduction of the source efficiency. Thus arises the question of possibility to provide single mode operation of a PP-KTP waveguide based downconversion source without resorting to spatial filtering, namely:

Can we control the spatial degree of freedom?

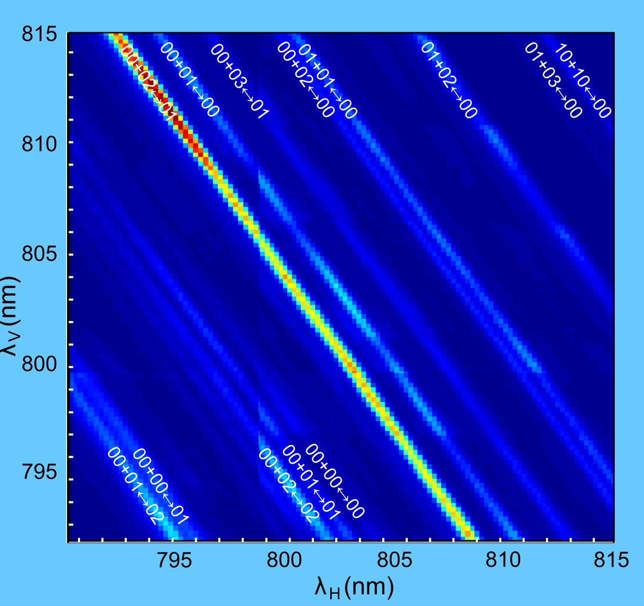
Solution: spatio-spectral coupling

Downconversion is efficient only when the phase matching condition for wave vectors of the interacting waves is satisfied. In a waveguide, the wave vector is modified by the geometrical (spatial mode dependent) contribution:

$$k(\lambda) = k_{\text{bulk KTP}}(\lambda) + \Delta k_{\text{geom.}}$$

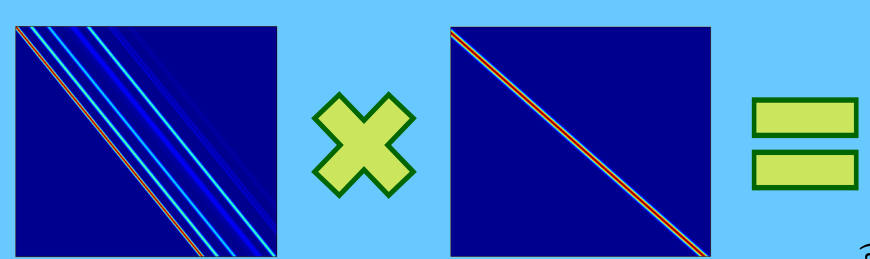


This introduces spatial mode dependence of the phase matching, leading to multiple spectrally separated bands of the phase matching function, each corresponding to a distinct mode triplet of interacting fields.



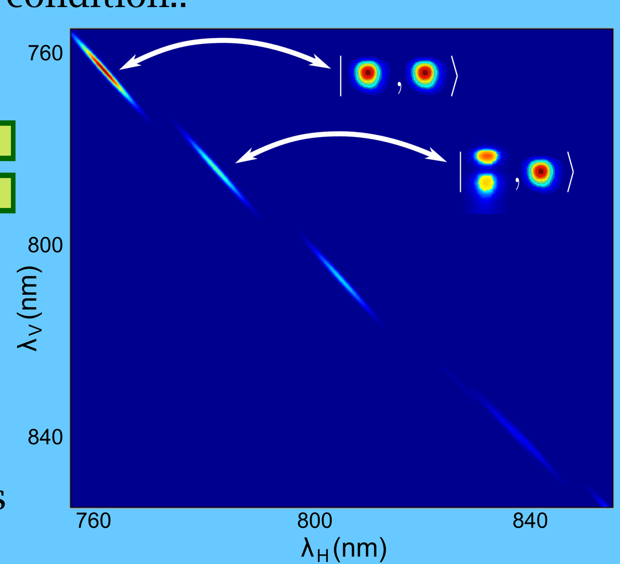
<Phase matching function for three wave mixing in a 6 mm long PP-KTP waveguide, experimentally determined by spatial mode resolved spectroscopy of sum frequency generation [1]. Bands are labeled by corresponding triplets of spatial mode triplets, the symbol *ij* denotes number of nodes in horizontal/vertical direction. Providing the downconversion pump field in a well defined mode supresses the bands not involving that particular mode, greatly simplifying the effective phase matching function.

Final joint spectrum of the downconverted fields is (approximately) described by the product of phase matching function and the energy conservation condition:.



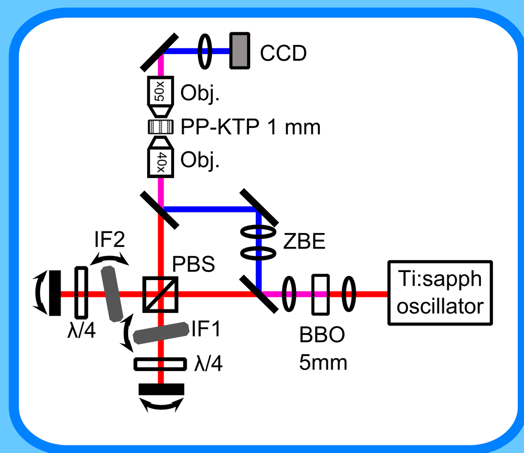
Phase matching for pump in fundamental mode

Energy conservation for narrowband pump

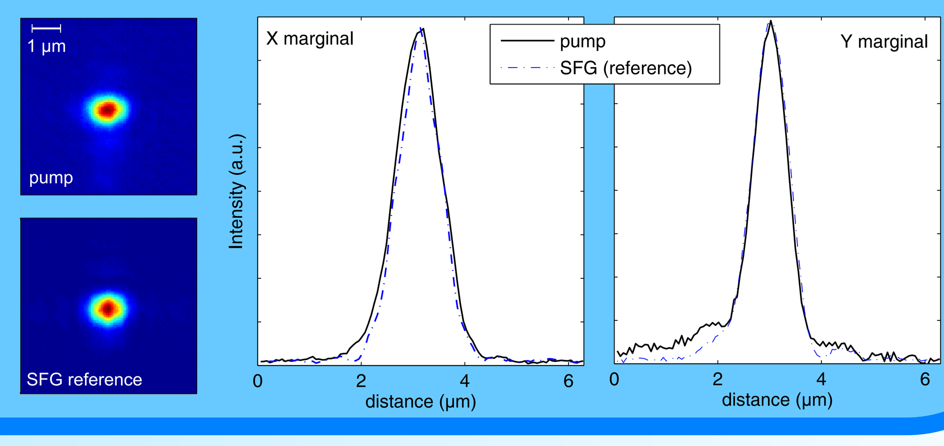


The resulting joint spectrum demonstrates distinct spectral contributions ("islands"), with the down-conversion process involving 3 fundamental modes being well separated spectrally. This happens provided that the pump field is appropriately narrowband and **prepared in a pure fundamental mode**. If this is not the case, the "islands" contain multiple contributions from different modes and may spectrally overlap.

Pump beam preparation: mode matching

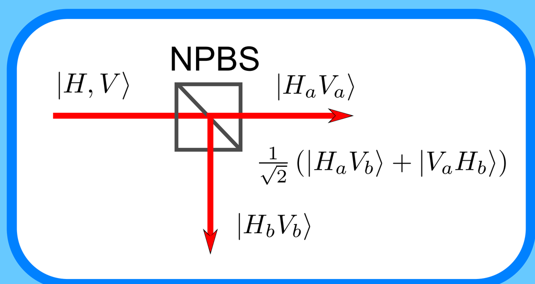


A pair of orthogonally polarized auxiliary 800 nm beams was frequency tuned with interference filters (IF1,2) to produce sum frequency (400 nm) beam in the fundamental mode of the waveguide, which served as a reference. The pump beam mode was matched to the reference using a zoomable beam expander (ZBE) placed before the focusing objective.

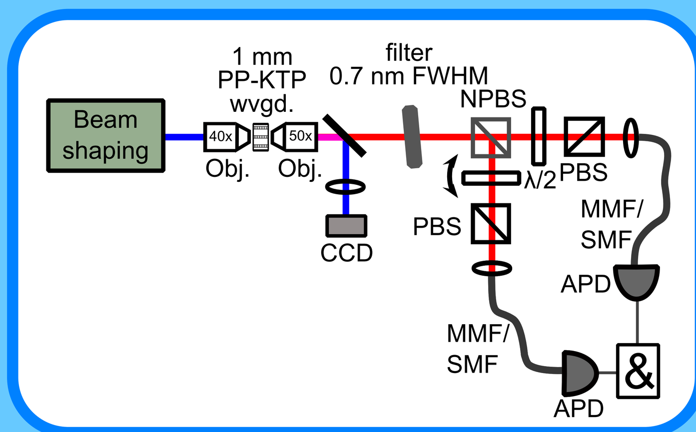


Comparison of the intensity profiles of reference and pump beams at the output face of the waveguide: 2-D and marginal intensity profiles.

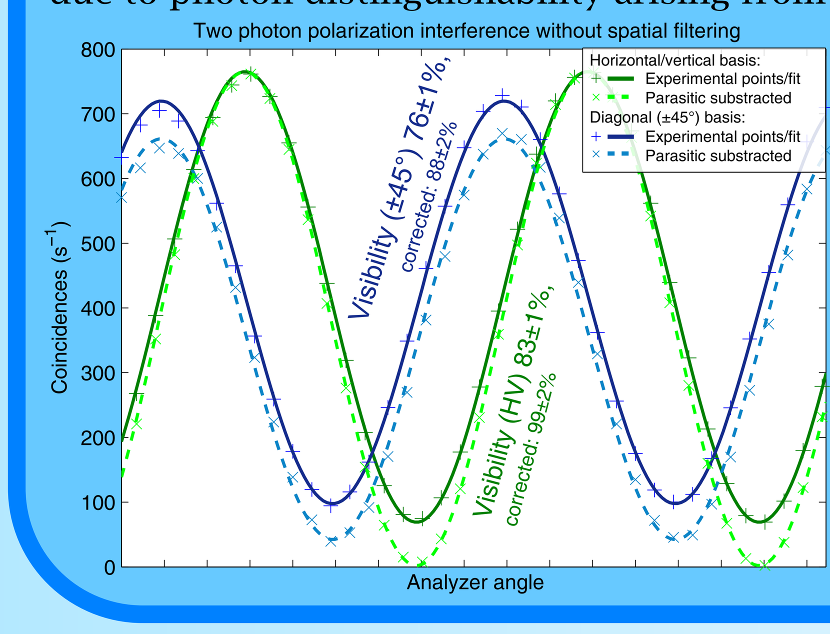
Purity verification: Shih-Alley entanglement



Purity of the downconverted photons can be verified by creating an entangled state conditional on detection of a photon in both output modes of a non-polarizing beamsplitter [2] (see left).



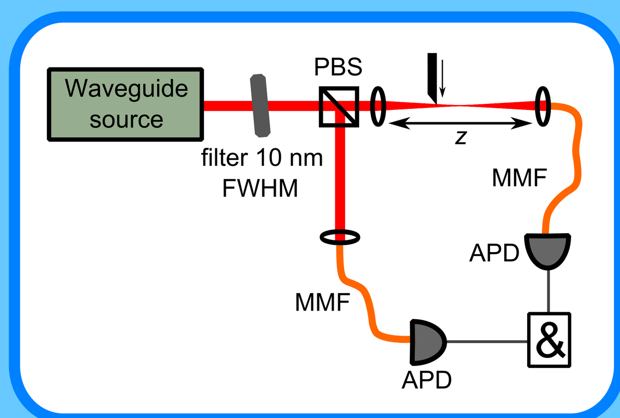
Photon purity was verified by comparing the visibility of polarization correlations in horizontal-vertical and diagonal bases, for detection without spatial filtering (using multimode fibers) and for spatially filtered detection by employing single mode fibers. Narrowband (0.7 nm FWHM) spectral filtering was used to suppress visibility reduction due to photon distinguishability arising from spectral correlations.

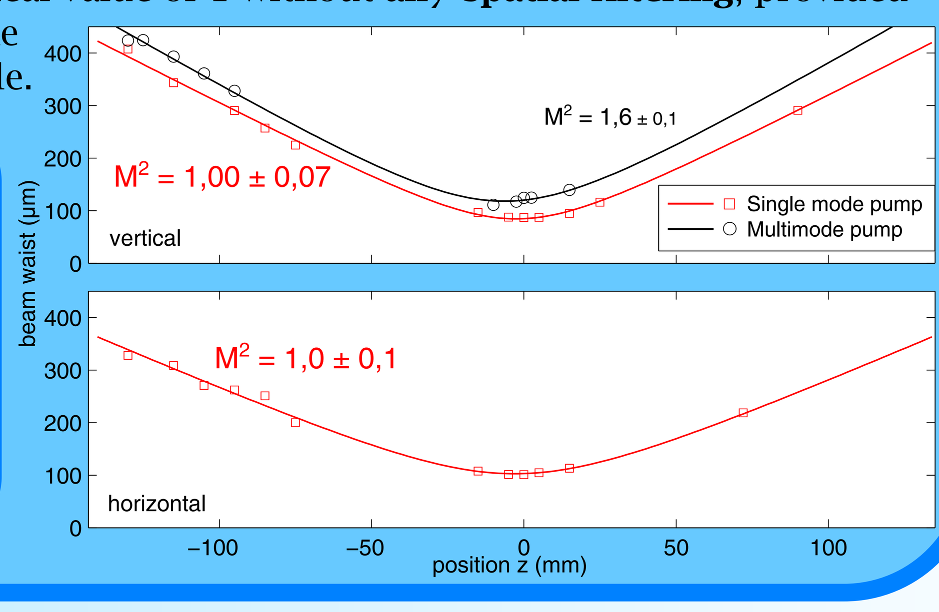


High two-photon polarization interference visibility (76% in ±45° basis) confirms photon purity obtained **without spatial filtering**. Employing single mode fiber spatial filtering yields a small visibility increase up to 84±1%. Deviation from perfect visibility comes mainly from parasitic process delivering pairs of identically polarized photons. After substracting the measured parasitic counts from the polarization interference data, corrected visibility of **88%** is obtained in the non-spatially filtered case [3].

Direct measurement of beam quality

Beam quality of the conditionally prepared single photons was characterized by measuring the M^2 factor using the razor blade method (following the ISO standard). The measured values are close to the ideal value of 1 without **any spatial filtering**, provided the pump beam is launched into the waveguide in the fundamental mode.





Summary and conclusions

Spontaneous parametric downconversion photon pair source based on a multimode PP-KTP waveguide was constructed. Spatio-spectral coupling and controlled pump beam launching were used to engineer the downconversion process to yield single spatial mode photon pairs. Photon spatial purity was confirmed by measuring high two photon polarization interference visibility in the Shih-Alley configuration (76%, 88% after correcting for parasitic processes) and by determining the M^2 beam quality value of less than 1,1 in horizontal and veritcal planes.

Our results show that employing the spatio spectral coupling enables precise control of the spatial properties of the downconverted field in a multimode nonlinear waveguiding medium. This leads to higher efficiency photon pair production, reduced losses due to spatial filtering, as well as opens a possibility to explore phenomena connected with the transverse spatial degree of freedom.

Acknowledgements

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References

[1] M. Karpinski, C. Radzewicz, K. Banaszek, Appl. Phys. Lett. 94, 181105 (2009).
[2] Y. H. Shih and C. O. Alley, Phys. Rev. Lett. 61, 2921-2924 (1988).
[3] M. Karpinski, C. Radzewicz, K. Banaszek, in preparation.