A high heralding efficiency source of polarization entangled photon pairs

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Abstract:

OCIS codes: (270.0270) Quantum Optics; (190.4410) Nonlinear Optics, parametric processes

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1. Introduction

Sources of polarization entangled photon pairs or heralded photons are a fundamental resource for a wide range of fields like quantum communication[1], computation[2] and metrology[3]. The underlying protocols behind these applications often require a complete detection of all photons to outperform their classical counterparts. While photodetectors have come close to unit detection efficiency[4], photon pair sources seem to be the current bottleneck in applications requiring a high efficiency. Likewise, the efficient transfer of information from photons to microscopic systems like single atoms or molecules requires an optical bandwidth that is much smaller than what most current photon pair sources can provide. In this paper, we present a photon pair source which addresses these issues. A pump laser beam (λ= 405 nm) is focused into a type II PPKTP crystal, where it undergoes spontaneous parametric down-conversion into signal and idler modes which are collinear with the pump mode, maximizing the mode overlap between the target modes.

2. The source

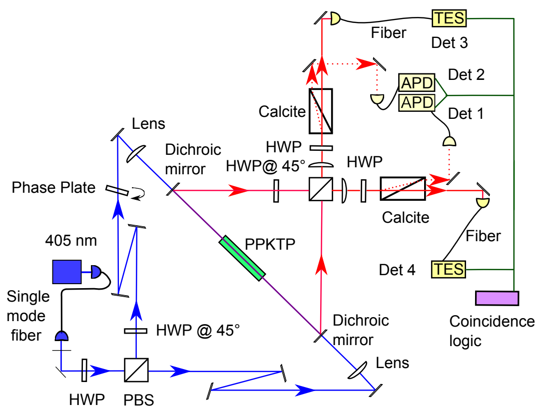

Fig. 1. Experimental setup, showing independent alignment degrees of freedom for the pump and downconvertedmodes). **This figure needs to be edited. The pump lenses are now a telescope before the the pump pbs and the tes detectors need to be changed into apds**

2.1. Source components

2.1.1. Crystal description name and length

A 25 mm Periodically Polled potassium Titanyl Phosphate ($KTiOPO_4$, PPKTP) crystal

2.1.2. Pump description

is pumped from both directions by 405nm light. This pump light is generated by an Ondax 405nm laser diode (with a bandwidth of 160 MHz (datasheet)) which is mode filtered by using a singlemode fiber. A blue glass filter is used to eliminate any IR fluorescence from the pump fiber. The correct polarization is maintained by using a glan taylor polarizer. After passing through a beam splitter and reflecting off several mirrors the two pump modes are focused into the crystal. The waist of the pump modes can be varied by changing a pair of lenses (see Fig. 1.).

2.1.3. Downconv style

The crystal its self is a type *II* donconversion crystal which means that the pair of photons produced will consist of a horizontally and a vertically polarized photon. The geometry used in our setup is a collinear one. The downconverted modes are then coupled into single mode fibers after reflection off of one more dichroic mirror and passing through an interference filter; both of which serve to remove any residual pump light.

2.1.4. waists

The downconverted modes from the crystal are focused into singlemode 780-HP fibers by a lens in each arm placed just after the PBS and aspheric lenses in the fiber couplers. We experimentally optimized the focusing of the pump and collection modes for the maximum efficiency (pairs to singles ratio). We use a pump waist of 265 μm and collection waists of 160 μm all of which are centered in the crystal.

2.1.5. Degenaracy/temp tuning

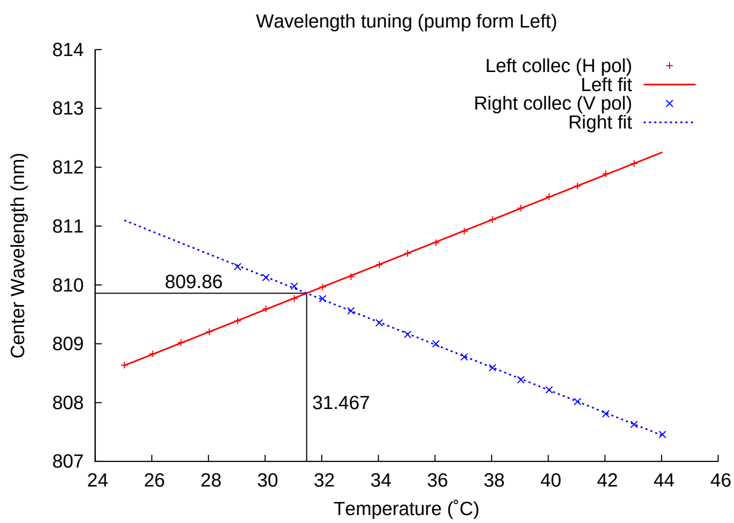

Fig. 2. Degeneracy of the down converted wavelengths is obtained at a 31.5 °C

The PPKTP crystal is placed in an oven and temperature stabilized to 10mK. By tuning the temperature of the crystal we can change the wavelength of the signal and idler. We measure the wavelength using an home built grating spectrometer connected to a single photon detector (Silicon Avalanche Photo Diode (Si APD)). We find the degeneracy temperature to be 31.5 °C (Fig. 2.).

2.1.6. Bandwidth

We also measure the bandwidth of the downconverted light by temperature tuning a 0.1mm thick etalon. The bandwidth of the signal and idler is 128 ± 4 GHz. Using a michelson interferometer we can measure the bandwidth of the downconverted light see Fig. 3 **This is by rotating an etalon, yet to take the temp tuning data**

2.2. Entanglement

2.2.1. , how to get

To obtain polarization entangled photons, we pump the crystal from both directions and interferometrically combine the two downconverted paths in a Sagnac interferometer[5].

2.2.2. Phase stability

The original implementation[6] used the same mirrors and PBS for both the pump and target modes, hence auto compensating for path length differences between pump and downconverted

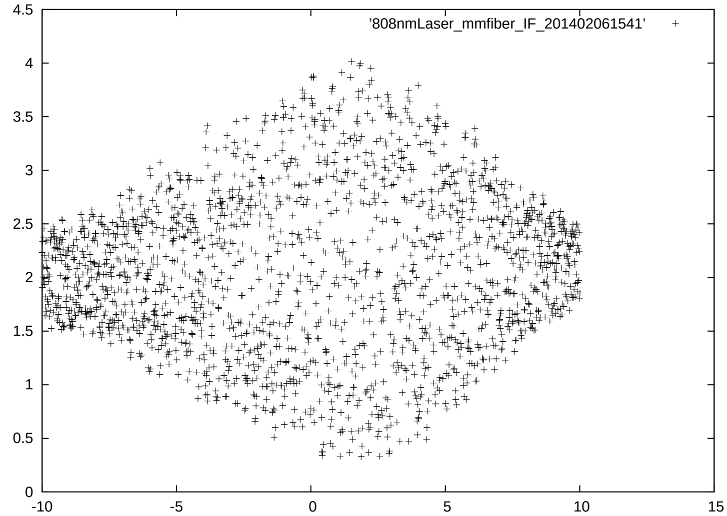

Fig. 3. **this is a place holder only. the proper data is on its way**

modes. Our modified geometry (see Fig. 1.) allows for a decoupling of alignment degrees of freedom and also for independent optimization of optical components. However, this design now requires interferometric stability since the auto compensation feature of the Sagnac geometry is lost. We introduce a thin glass plate into one of the pump arms which we can rotate to periodically correct the phase of one pump direction with respect to the other[6]**not sure about this citation need to check**.

2.2.3. Alignment

We optimize the mode overlap by alignment. To this end we first fix the alignment of the inner sagnac loop (the red path in Fig. 1.) to see the zeroth fringe of this sagnac interferometer. This also fixes the alignment of the collection optics. We then align the pump using our specially folded sagnac geometry, which introduces an extra mirror, such that the downconverted light is collected with optimal efficiency.

2.3. Focus optimization

For the mode overlap optimization we must also adjust the focusing of the aspheric lenses used to couple light to the singlemode fibers. It is important to center the waists in the crystal to preserve the symmetry of the pump and collection modes form either direction.

2.3.1. Measurement pol, aux dets

In each collection arm we introduced a PBS and a motorized half wave plate. Together they serve as the measurement polarizers. The other output port of both of these PBS cubes is coupled into an auxiliary set of collection fibers. We connect these fibers to a pair of auxiliary detectors. We use these detectors to periodically readjust the phase difference between the pump modes (ϕ). This leaves the primary collection fibers free to connect to high efficiency single photon detectors (TES).

2.3.2. State generation

To generate the state

$$|\,\psi\rangle = sin(\theta)\,|\,HV\rangle + e^{i\phi}cos(\theta)\,|\,VH\rangle \tag{1}$$

We introduce a motorized half wave plate before the pump PBS. This allows us to control the ratio of pump powers in each arm (θ) and a glass cover slip in one pump arm which we can tilt to change the phase of one pump arm with respect to the other. This phase plate allows us to control ϕ.

2.3.3. Visibility

For a maximally entangled state we can measure the polarization correlation in the 45° basis by rotating one of the half wave plates in the collection arm (Fig. 3.). The visibility obtained is $99.4 \pm 0.2\,\%$.

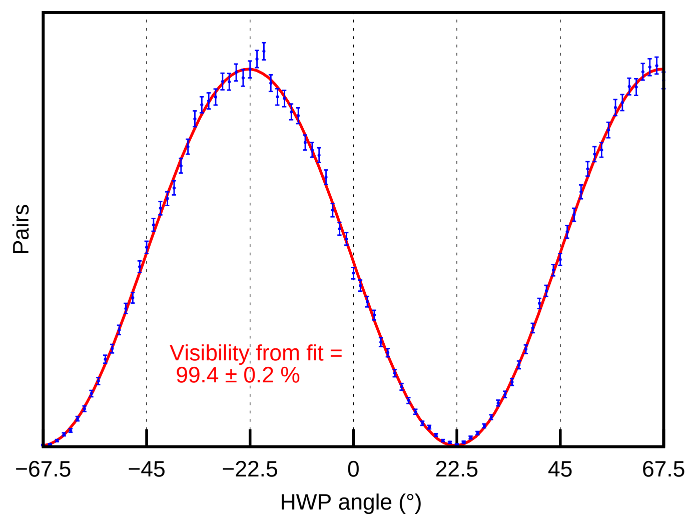

Fig. 4. Visibility in the 45 deg basis is $99.4 \pm 0.2\,\%$

2.3.4. Locking

Using the signal on the auxiliary detectors, the phase between the two pump modes and consequently the phase of the two downconverted modes (HV and VH) is periodically readjusted. This ensures that the source produces a constant state $|\,psi\rangle$.

2.3.5. Stability

Using a maximally entangled state we measure the polarization correlation visibility repeatedly for more than 6 hours and find it to be stable. The average visibility is $99.37 \pm 0.15\,\%$(Fig. 4,Fig. 5 .).

2.3.6. Non maximally

When set to produce a particular non maximally entangled state we can perform an in-plane tomography for linear polarization states. The reconstructed density matrices have a fidelity of $99.3 \pm 0.1\,\%$. This is of particular importance for experiments like device independent random number generation and loophole free violation of a Bell inequality with non maximally entangled states.

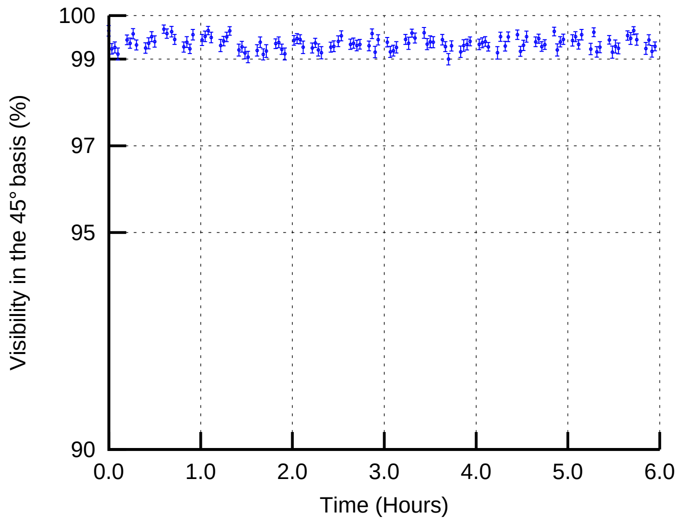

Fig. 5. Visibility Stability in the $\pm 45^\circ$ basis. By periodically readjusting the phase difference between the two pump modes we are able to maintain a stable visibility of $99.37 \pm 0.15\,\%$

2.4. *Efficiency*

2.4.1. fibers

The downconverted modes are collected into AR coated singlemode fibers. The AR coating was done in situ by transferring a coating from a glass substrate to the fiber tip using an optically transparent epoxy (353ND). Singlemode fibers also allow us to mode-filter the downconverted light and carefully mode-match the pump and downconvered modes. This reduces the amount of stray light collected from unwanted modes and background or fluorescent light.

2.4.2. detectors

We use Si APDs as single photon detectors. However their detection efficiency is low. To characterize the efficiency of our source we must account for the detector efficiency. This is of particular importance since there are now detectors with a near unit detection efficiency[4]. To measure the detection efficiency of our Si APDs we used a scheme similar to [13]. We compare the counts seen on the Si APDs to the expected number of photons from an attenuated 810nm laser. A bolometrically calibrated photodiode is used to calibrate a set of neutral density filters and a beamsplitter. We then use the calibrated photodiode to monitor the laser power while coupling the attenuated laser light to the Si APD. We measure a detection efficiency of $51.9 \pm 2.8\,\%$ and $46.7 \pm 2.5\,\%$ for the two primary detectors.
subsubsectionThe other large loss (splice) The source collection is optimized into singlemode 780-HP fibers. We then splice these fibers onto SMF28e fibers. The SMF28e fibers have a lower transmission and allow us to separate the entangled photon pairs by several meters with a negligible loss. However this splice between two different types of fibers with different core sizes and dopant concentrations has a few percent of loss.

2.4.3. Value uncorr

Inclusive of this splicing loss and all optical and coupling losses, we obtain efficiencies of $39.16 \pm 0.16\,\%$ and $39.27 \pm 0.21\,\%$ efficiencies $(pairs/\sqrt{Singles_1 Singles_2})$ in the two pump arms using Si APDs.

2.4.4. Apd correction

Correcting only for the dark counts and detection efficiencies of these detectors, the source has an efficiency of $79.5 \pm 3\,\%$ and $79.8 \pm 3\,\%$ in the two pump arms. When the source produces an entangled state, the mode overlap between the two downconverted modes is still good and we have an entangled efficiency of $78.6 \pm 3\,\%$ **I am still checking if i can improve this value**

3. Conclusion

For now this is just a list of the numbers i have

The efficiency of my detectors are $51.9 \pm 2.75\,\%$ and $46.7 \pm 2.5\,\%$ mentioned

Left arm efficiency $= 39.16 \pm 0.16\%$ When corrected for detector loss this is $79.54 \pm 3\,\%$ not mentioned together with R arm

Right arm efficiency $= 39.27 \pm 0.21\,\%$ When corrected for detector loss this is $79.77 \pm 3\,\%$

$\pm 45^\circ$ basis entangled efficiency $= 38.7\,\% \pm$???? When corrected for detector loss this is $78.61 \pm 3\,\%$ Said

For a final detection efficiency of $74\,\%$ optimal Bell violation will occur when $\theta = 0.22272$. If I choose this state then the fidelity between the chosen state and the tomographically reconstructed state is $99.3\,\% \pm 0.1$ The first bit is not mentioned

Pump bandwidth = ??????? 160MHz by data sheet mentioned

pairs/s/mW = 4069.5 **needs to go somewhere**

pump waist is 265±???? centered in the crystal both waists are mentioned

Collection waist is $160\,\mu m \pm$????

Bandwidth of downconverted by interferometer= ????

4. What others have