Optimization of photon pair generation in dual-element PPKTP waveguide[1]

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ABSTRACT

A compact scheme for high-speed frequency doubling and down-conversion on a single dual-element PPKTP waveguide is investigated. Optimal temperature is achieved and photon pair coincidence is observed at over GHz repetition rate with pulsed pump input scheme.

Keywords: Dual-element PPKTP waveguide, Correlated photon pair generation, Up-conversion Detector

1. INTRODUCTION

The generation of entangled photon pairs at the wavelengths 1310 nm and 895 nm is desirable for the implementation of a quantum repeater. Light at 1310 nm has low loss transmission in standard optical fiber and is compatible with the existing fiber infrastructure. On the other hand, light at 895 nm is resonant with the 6s-6p transition line of Cesium atoms, and is therefore suitable for use in quantum memory. These characteristics of long distance transmission and quantum memory are basic elements in a quantum repeater, making correlated photon pairs at these wavelengths strategically important.

We previously developed a non-degenerated coincidence/entanglement photon pair source at over a GHz repetition rate using two separate periodically poled potassium titanyl phosphate (PPKTP) waveguides [1,2]. The first waveguide is for second harmonic generation (SHG) of 1064 nm to 532 nm while the second waveguide is for spontaneous parametric down conversion (SPDC) that converts pump photons at 532 nm to signal photons at 895 nm and idler photons at 1310 nm. Since there was no high speed modulator available for 532 nm, this arrangement allows us to modulate the pump into a 1 GHz pulsed beam using a high-speed lithium niobate electro-optical modulator (EOM) for 1064 nm. Following down-conversion, the 895 nm signal beam and the 1310 nm idler beam are separated and their coincidence counts are measured.

Although effective in the generation of correlated photon pairs at the desired wavelengths, this setup did not lend itself well to a compact implementation. The 532 nm output after the first waveguide must be coupled back into a single mode 532 nm fiber for mode and wavelength filtering and then aligned and coupled into the second waveguide in free space. Fiber coupling of the 532 nm light to the second waveguide is not ideal, since high energy 532 nm light may damage the epoxy used to attach the fiber to the waveguide. The coupling from the first waveguide to the 532 nm fiber and from the fiber to the second waveguide results in significant loss in the system. Additionally, since the 532 nm light must be coupled into the second waveguide from free space, it was very difficult to couple the fundamental mode of the 532 nm beam effectively into the second waveguide. Because the second waveguide must be large enough to hold at least single mode at 1310 nm, it is capable of accepting multiple 532 nm modes. The multimode 532 nm input to the second waveguide makes piezo tuning necessary in order to couple as much energy into the 532 nm fundamental mode as possible. Higher order modal down-converted photons at 1310 nm and 895 nm are not captured or counted and therefore results in a loss in the system.

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[1] The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology.

Recently, we used a single 2 cm dual-element PPKTP waveguide to implement both the SHG and the SPDC and successfully generated coincidence photon pairs at the desired wavelengths at over a GHz repetition rate. The key innovation is the compact dual-element crystal waveguide that performs both the SHG of the 1064 nm input and the SPDC of the 532 nm photons to 895 nm signal and 1310 nm idler photons. The 1064 nm modulated light can be safely fiber coupled to the SHG element of the waveguide. Once generated through SHG in the first element of the waveguide, almost all of the 532 nm light is in the ideal fundamental mode and can easily propagate into the second element without leaking energy into other modes, so that the overall conversion efficiency is greatly improved.

Although the use of a dual-element waveguide can simplify systems and reduce losses associated with multiple coupling of separate waveguides, placing both elements on a single structure required filtering and temperature optimization techniques that were not previously needed. For example, residual noise from the amplifier at wavelengths near 1310 nm and 895 nm can overwhelm the down converted photons at those same wavelengths. Therefore, this residual amplifier noise must be suppressed prior to entering the SPDC waveguide. Previously, with separated elements, this occurred when the output of the SHG waveguide is coupled to a single mode 532 nm fiber for transmission to the SPDC waveguide. This fiber will also remove the strong 1064 nm pump light. When using the dual-element waveguide, any residual light near the correlated photon pair wavelengths must be effectively removed prior to entering the dual element waveguide. This filtering of the 1064 nm pump can reduce the effective power of the pump and therefore result in loss in the system. Excess 1064 nm and 532 nm light after the waveguide is easily filtered away.

Secondly, since two distinct non-linear waveguides or elements with different phase-matching condition are used in these systems, the optimal temperature for phase-matching for each waveguide or element section may be different. In our previous work, each waveguide may be optimized for the phase-matching condition by tuning its temperature independently. Although designed to achieve phase matching at the same temperature, a dual element waveguide may also have slightly different optimal phase-matching temperatures for each waveguide element. In the dual-element waveguide, therefore, a single compromise temperature must be found in which the phase-matching condition for both elements are reasonably, if not absolutely, satisfied.

Finally, the spectral line widths of the correlated photons generated in a SPDC waveguide are related to the length of the waveguide [3,4]. The longer the waveguide is, the narrower the spectral width will be. The current fabrication limit on the length of PPKTP waveguides is about 2 cm. In our previous work the down-conversion waveguide was 2 cm. In the dual-element waveguide the down-conversion section is approximately 1 cm. Therefore, a widening of the output line width of the correlated photons is expected.

In this paper, we characterize the dual-element waveguide in terms of filtering techniques, temperature and input wavelength optimization and the down-conversion output line width and investigate the differences between this configuration and our previous configuration. We also outline some of the tools used in this experimental process, including the NIST developed up-conversion detector for detecting the 1310 nm idler photons and the up-conversion spectrometer used to measure the low-light 1310 nm linewidth.

2. SYSTEM CONFIGURATION

The 2 cm long dual-element waveguide was fabricated using a technique called ‘segmented submount micro-electrode poling’ (AdvR Inc.) whereby the periodic poling of the waveguide is segmented into smaller poling areas. By poling smaller areas, local variations in the crystal waveguide can be accounted for and this, it is claimed, leads to a more homogenous poling throughout the waveguide. More importantly for our application, each section may be poled with distinct poling periods allowing more than one element on the waveguide. In our case, the first element of the waveguide was poled for SHG and the second element for SPDC. The poling can be configured such that optimal quasi-phase matching occurs at about the same temperature in each of the waveguides. The waveguide was fiber pigtailed at the input side and free space at the output. Figure 1 shows the conversion for each element in the waveguide. The manufacturers measured performance before pigtailing for the SHG element was 89 %/W/cm^2 and 354 %/W/cm^2 for the SPDC element of the waveguide.

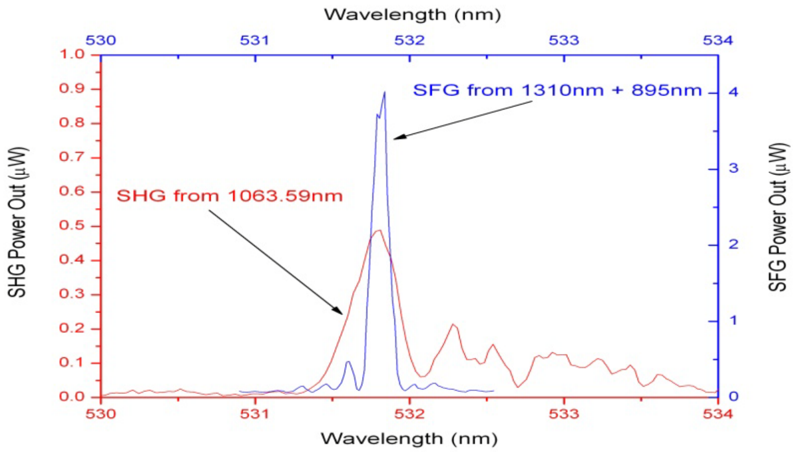


Fig. 1: The conversion efficiency for each element in the dual-element waveguide. The manufacturers measured performance before pigtailing for the SHG portion of the waveguide was 89 %/W/cm^2 and 354 %/W/cm^2 for the SPDC portion of the waveguide. Graph provided by AdvR. Inc.

Figure 2 outlines the setup for this experiment. A 1064 nm continuous wave beam is emitted from a tunable laser (New Focus: TLB 6321) and is modulated to a 1 GHz pulsed beam using an electo-optic modulator and pulse generator (Tektronix: DTG5274). The pulse width is 330 ps at FWHM. The beam is then amplified using a fiber amplifier (IPG: YAR-1K-LP). Following polarization control of the pulsed 1064 nm beam, it is filtered (using narrow bandpass filters centered at 1064 nm) to remove any residual amplifier noise that may extend to the low-light SPDC regions. This narrowed 1064 nm source is fiber coupled to the waveguide at the SHG portion of the dual-element PPKTP, where it is converted into a pulsed 532 nm pump beam. The 532 nm pump beam continues through the waveguide, with it modal integrity maintained, into the SPDC element where it is down-converted into non-degenerate correlated photon pairs at 895 nm and 1310 nm. The emerging beam is filtered to remove any non-converted 532 nm and 1064 nm light, leaving only the SPDC generated signal and idler beams at 895 nm and 1310 nm respectively. These beams are then separated using a dichotic beam splitter and each is fiber coupled with a suitable collimator. The 895 nm signal beam is sent to a silicon based avalanche photodiode (Si-APD) (PerkinElmer: SPCM-AQR-14) for single photon counting. The 1310 nm idler beam is sent to an up-conversion detector system with very low noise, previously developed by this group [5,6]. Finally, the coincidence is measured when the electrical detection events from the detectors are fed into a time correlated single photon counter (PicoQuant: PicoHarp 300).

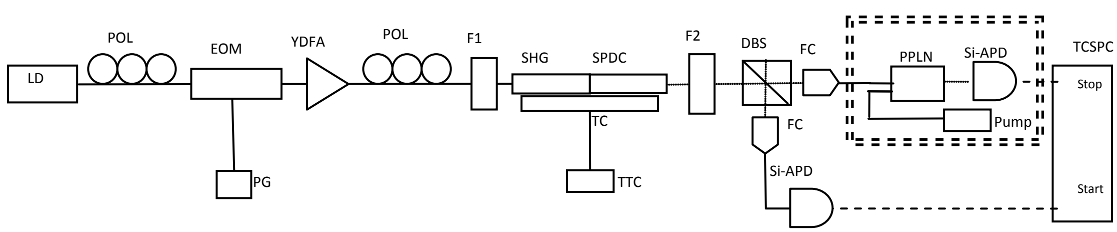


Fig. 2: LD: 1064 nm laser diode; POL: Polarization controller; EOM: Electro-optic modulator; PG: Pulse generator; YDFA: Ytterbium doped fiber amplifier; F1: 1064 nm bandpass filter; SHG: Second harmonic generation frequency doubler; SPDC: Spontaneous parametric down converter; TC: Temperature control; TTC: Thermoelectric temperature controller; F2: 532 nm and 1664 nm blocker; DBS: Dichotic 1310 nm/895 nm beam splitter; FC: Fiber collimator; PPLN: Periodically poled lithium niobate ($LiNbO_3$) waveguide for frequency up-conversion; Pump: 1550 nm pump for up-conversion detector; Si-APD: Silicon avalanche photo diode; TCSPC: Time correlated single photon counting module; Solid line: Fiber optical path; Squared line: Free-space optical path; Dashed line: Electrical connection; Double dashed line: Protective box surrounding the up-conversion detector.

The up-conversion detector, shown in figure 3, uses a 5 cm long periodically poled lithium niobate (PPLN) waveguide to frequency up-convert the idler photons at 1310 nm, using a 1550 nm bright pump beam, to 710 nm after which they are efficiently detected by a Si-APD. The waveguide is a reverse-proton-exchange PPLN waveguide with magnesium oxide doping. The waveguide is 52.3 mm long (50 mm uniform grating) and both ends have anti-reflection (AR) coatings for

1310 nm, 1550 nm and 710 nm. A 1550 nm beam is modulated by a synchronization pulse from the high-speed modulator used to modulate the 1064 nm beam earlier in the system. It is then amplified by an erbium-doped fiber amplifier (EDFA) (IPG: EAR-0.5K-C). Two 1550/1310 nm wavelength-division-multiplexer (WDM) couplers, each with an extinction ratio of 25 dB, are used to remove the 1310 nm noise from the pump, and another 1550/1310 nm WDM coupler is used to combine the 1310 nm idler photon and the 1550 nm pump into one fiber. Two polarization controllers are used to align the polarization state of the idler beam and up-conversion pump beam respectively. The combined idler and pump beams are then coupled into the PPLN waveguide with coupling efficiencies of 64% for 1310 nm and 71 % for 1550 nm. A single 1310 nm photon and one of the 1550 nm photons are then converted by a sum-frequency-generation (SFG) process into a 710 nm photon for the optimal detection. In this configuration, the output of the PPLN waveguide is coated with a 710 nm anti-reflection coating and the output is not coupled into a fiber, but rather left in free space. By using two dispersive prisms, the SFG photons at 710 nm are separated from both the pump beam at 1550 nm and its weak SHG noise at 775 nm. Because the 775 nm beam is close to the 710 nm being detected, the second dispersive prism is used to further separate them, and we use an adjustable iris to block the 775 nm photons. Because all the light beams are linearly polarized and their polarization is aligned with the p-polarization direction of the prisms, there is no intrinsic loss when the incident angle of the 710 nm light is close to the Brewster's angle. A 20 nm band-pass filter (Omega Optical, Inc.: 3RD700-720) is used to reduce other noise, such as photons leaked from the environment. The 710 nm photons are then detected by a Si-APD. The total detection efficiency of the up-conversion detector for a certain wavelength near 1310 nm is about 32 %. By using a pulsed pump at a wavelength longer than the quantum photons the up-conversion detector has a dark count rate as low as 2500 Hz [5]. The up-conversion detector is selective of the input wavelength and acts as a narrow band filter with an acceptance bandwidth of about 0.25 nm. In other words, only 0.25 nm of the input idlers' line width will be up-converted and counted.

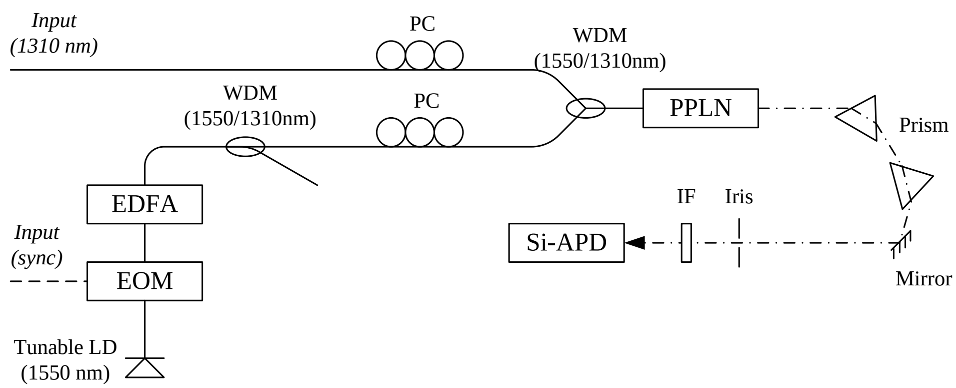
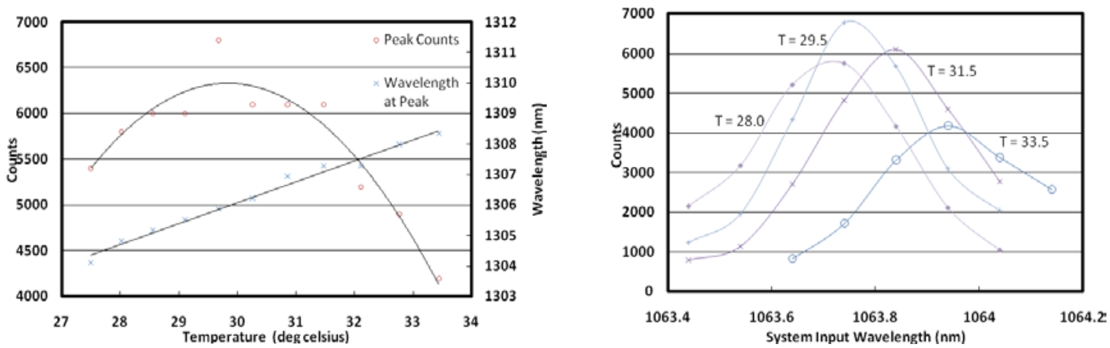


Fig. 3: Schematic diagram of the up-conversion detector. EOM: Electric-optic modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: Periodically-poled LiNbO3 waveguides; IF: Interference filter. Solid line: Optical fiber; Dash line: Free space optical transmission.

3. RESULTS AND DISCUSSION

The conversion efficiency of the non-linear crystal waveguide is maximized when optimal quasi-phase matching occurs for a particular input wavelength. For any waveguide, there is an input wavelength band in which the desired quasi-phase matching and non-linear effects occur, with one particular wavelength achieving optimal quasi-phase matching and conversion. Since the quasi-phase matching is a non-linear effect, a change in the temperature will alter the refractive index of the waveguide and also the condition for quasi-phase matching. In this way, changing the temperature of the waveguide will shift the optimal quasi-phase matching input wavelength. The temperature of the non-linear crystal therefore may be tuned to achieve optimal quasi-phase matching for any particular input wavelength.

In our previous setup [1,2], the optimal phase matching condition could be achieved for each waveguide by tuning its temperature independently. Although the dual-element waveguide is designed such that the optimal quasi-phase matching condition is achieved at the same temperature for both the SHG and SPDC non-linear elements, the dual element waveguide used in this experiment achieved optimal quasi-phase matching for each of the two elements at slightly different temperatures. It was necessary to find a single compromise temperature and wavelength which achieves the best conversion efficiency for the entire dual-element waveguide. Several temperature values were chosen and for each temperature the input wavelength was adjusted to achieve the maximum output counts. Alignment and polarization control of the system was maintained while the wavelength was adjusted for each temperature. Figure 4(a) shows the temperature optimization (in terms of the peak idler count rate at 1310 nm) of the dual-element waveguide and the corresponding shifting output wavelength near 1310 nm at which the peak counts were recorded . The same data is presented in figure 4(b), but shows the output count as the input wavelength is adjusted for some sample temperatures.



(a) (b)

Fig. 4: (a) Maximum 1310 nm output counts (per 0.5 second) at various temperatures of the waveguide and corresponding optimal 1310 nm wavelength. (b) The measured count rate (per 0.5 seconds) as the input wavelength is adjusted for a sample of temperatures. The actual count rate are limited by the 0.2 nm spectral width of the up-conversion detector and by the input wavelength pump power.

The optimal temperature and input wavelength for the dual-element waveguide investigated in this experiment is therefore fount to be 29.5 °C and 1063.75 nm respectively. The corresponding output wavelength is 1306 nm. It can be seen that the conversion efficiency is reduced significantly as the input wavelength and temperature are adjusted to achieve a peak output at precisely 1310 nm. It should be noted though that this was an experimental dual-element fabrication and with further optimization of the fabrication and poling, it will be possible to get quasi-phase matching to occur at exactly the same temperature and the output to be exactly 1310 nm. The actual count rate is limited by the 0.25 nm narrow band selection of the up-conversion detector and by the input pump power. By increasing the pump power, the actual count rate can be increased significantly. For this initial study, we did not investigate the relationship between the input pump power and count rate.

As described earlier, the length of the waveguide influences the linewidth of the output spectrum [3,4]. In our previous work [1], a 2 cm waveguide is used for SPDC. In this dual-element waveguide, slightly less than half the length is used for SHG and the other half is used for SPDC. Due to the reduced length of the SPDC element of the waveguide, the linewidth of output from SPDC is broadened. We use a novel near infra-red (IR) up-conversion spectrometer [7] to measure the linewidth of the output near 1310 nm. The configuration of the up-conversion spectrometer is shown in figure 6 and uses the up-conversion detector described earlier. A tunable CW laser near 1550 nm controlled using a computer via a GPIB port provides the seed light for the up-converter pump. The seed light is modulated into a pulse train for noise reduction or performing time-resolution measurements. The light is then amplified by an erbium-doped fiber amplifier and combined with the 1310 nm idler beam being measured and they are coupled into the PPLN waveguide for up-conversion as described earlier. The 710 nm photons are then detected by a Si-APD. The output count of the Si-APD is then sent back to the computer. The computer controls the 1550 nm tunable laser to scan the pump light wavelength and also collects and processes the corresponding counts from Si-APD. The quasi-phase-matching (QPM) condition in the periodically poled structure of the PPLN limits the acceptance bandwidth of the input beam for a particular pump wavelength and therefore acts as a filter in the frequency domain. In theory, the longer the QPM structure (waveguide), the narrower the acceptance bandwidth. In our case (a 5 cm PPLN waveguide), the measured acceptance bandwidth is 0.2 nm. Because the line-width of the 1550 nm tunable laser is just 150 kHz, the up-conversion spectrometer resolution is determined by the QPM acceptance bandwidth of the waveguide. According to the QPM condition, we can get the spectrum of the idler beam by scanning the pump wavelength. The detection efficiency of the up-conversion spectrometer is about 32% and its sensitivity is -126 dBm. Its working dynamic range is from -126 dBm to -80 dBm.

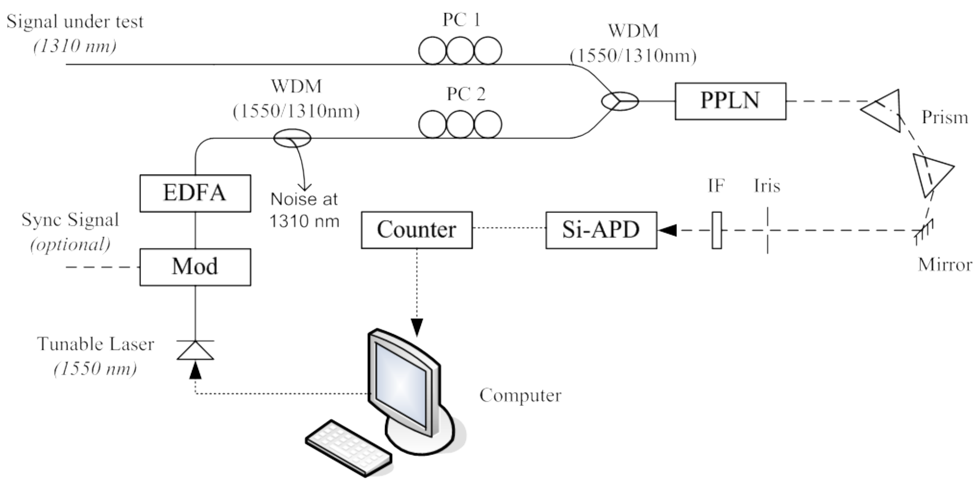


Fig. 5: Schematic diagram of the waveguide-based spectrometer. Mod: Wavelength insensitive modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: periodically-poled LiNbO3 waveguides; IF: Interference filter. Solid line: Optical fiber; Dash line: Free space optical transmission.

Figure 6 shows the broadening of the idler linewidth for the shorter SPDC portion in the dual-element waveguide when compared to the longer SPDC waveguide used in our earlier work. We are currently investigating alternative spectrum narrowing techniques.

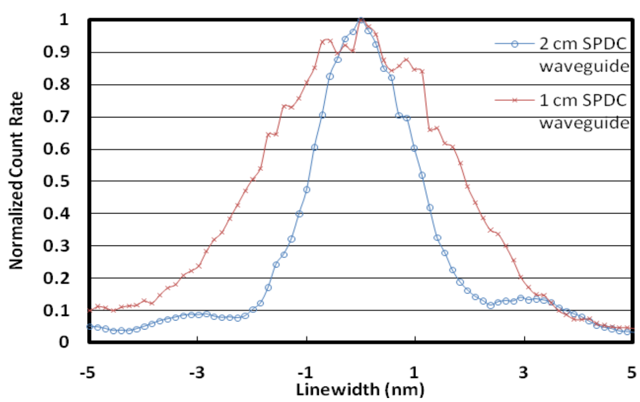


Fig. 6: Measured spectra of 1310 nm SPDC photons for a dual element waveguide (1 cm long SPDC) and an individual 2 cm SPDC waveguide.

Finally, we successfully demonstrate the generation of correlated photons from the dual element waveguide, as shown in figure 7 below. Significant noise analysis is not performed although the coincidence count rate shows a signal to noise ratio of greater than 20 dB. Again, is should be noted that the actual count rate is limited by the narrow band up-conversion detector and by the pump power. By increasing the pump power, the coincidence counts may be increased significantly, but it will also increase the probability of multi-photons and may reduce the visibility.

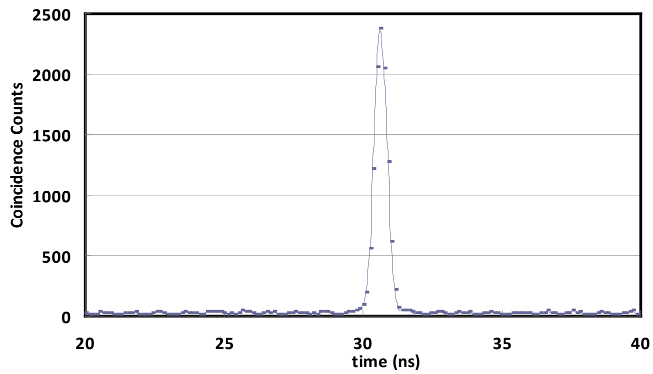


Fig. 7: Histogram of the coincidence counts of photon pairs per the setup described above.

4. CONCLUSION

In conclusion, we have successfully generated coincidence photons from a dual-element waveguide at GHz repetition rate. The compact format of the dual-element waveguide can simplify systems that require high-speed repetition rates and reduce the losses associated with multiple coupling of separate waveguides. The maximum count rate is achieved by optimizing the input wavelength and the waveguide temperature. Because the length for SPDC is shortened by half in the dual-element waveguide, the spectrum is broadened. We are investigating techniques to achieve narrower linewidths in short SPDC waveguides.

ACKNOWLEDGEMENT

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