COINCIDENCE DETECTION WITH FREE-RUNNING ID220 DETECTORS

APPLICATION NOTE

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Recent progress in near-IR avalanche-photodiode (APD)-based single-photon detectors (SPD) have allowed for free-running operation [1]. The previous generation of telecom-band APD-SPDs needed to be gated to suppress the dark count of the detectors, resulting in low duty cycles. In gated single-photon detection, an external trigger is used as the gating signal and the light source detected must be pulsed to allow for effective (synchronous) detection.

The issues with gated SPDs are compounded when coincidence measurement (the detection of two or more time-correlated photons) is required. In the case of detecting a photon pair with two gated SPDs, not only must both SPDs be synchronously triggered, but one must also be able to vary the time-delay between the two trigger signals at a resolution that is smaller than the gate width of the SPDs. This is so that the light pulse from the source under observation can be temporally aligned with the gates of the SPDs.

However, with free-running SPDs, the triggering electronics are obviated. Coincidence detection then only requires that we have the ability to measure the time interval between each detector's avalanche events. This can be done by interfacing the electrical output of the SPD (which adheres to an voltage standard such as TTL or NIM) with a time-interval analyzer (TIA). For the experiments described below, we use a low-cost home-made TIA with 500 ps resolution based entirely within FPGA fabric (an Altera Cyclone IV E was used).

Free-running detectors have an additional benefit; the light source monitored can be either continuous-wave (CW) or pulsed. Since, in some experimental conditions it may be advantageous to use CW light compared to pulsed light while in other cases the opposite is true, free-running detectors provide added flexibility. In what follows, we describe two coincidence measurement experiments with a Ti:Sapphire laser-pumped parametric downconversion (PDC) source. In the first experiment, we observe how the detection characteristics vary when the PDC source is pumped with CW light versus a mode-locked pulse-train. In the second experiment, we exploit the free-running nature of the id220 detectors [1] to time-multiplex two coincidence events, and demonstrate that our PDC source is also a source of polarization-entangled photon pairs.

Our PDC source is a fiber-based device with a non-zero second-order nonlinearity produced by the thermal poling [2] process. We utilize its type-II phase-matching [3] to generate polarization-entangled photon pairs [4]. Pumping the device with a Ti:Sapphire laser at a wavelength of around 775 nm, we can generate broadband polarization-entangled photon pairs in the 1.5-μm band. The Ti:Sapphire pump light is removed by pump suppression filters (Fig. 1), and the downconverted photon pairs are deterministically separated into frequency-conjugate pairs centred at 1530 nm and 1570 nm with a coarse wavelength division multiplexer (CWDM) that has a 3 dB bandwidth of 16 nm. The coincidence detection is performed with a pair of id220 detectors (labeled 'SPD' in Fig. 1) and the home-made TIA mentioned above.

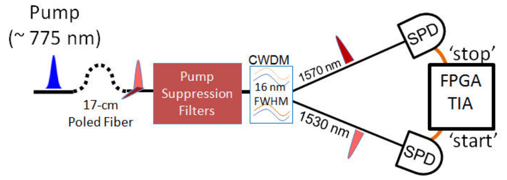

Fig. 1 Experimental setup for coincidence measurement of PDC photon pairs.

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The TIA measures the difference in arrival time (to within 500 ps) of the two SPDs' electrical outputs, and creates a histogram (Fig. 2) of all events within a 1μs window (although only the first 65 ns is shown in the figure). Because the two photons of a downconverted photon-pair are generated simultaneously within the PDC source, there is only a small window in which these coincidences can occur. Therefore, the difference in arrival time is dictated by the path-length difference ($t_{stop} - t_{start} = \frac{\Delta L}{v_g}$) of the two photons.

For pulsed excitation (Fig. 2a), accidental coincidences resulting from multi-photon pair generation are observed only when the pulse is 'on'. For our mode-locked Ti:Sapphire pulsetrain at 81.6 MHz, this means that accidentals peaks are spaced every $\frac{1}{81.6\ \mathrm{MHz}} \sim$ 12 ns apart. For CW excitation, accidentals counts are spread out over the entire histogram.

Fig. 2 shows the results of two coincidence-detection measurements performed at similar average powers, when the Ti:Sapphire pump is pulsed (Fig. 2a) and when it is CW (Fig. 2b).

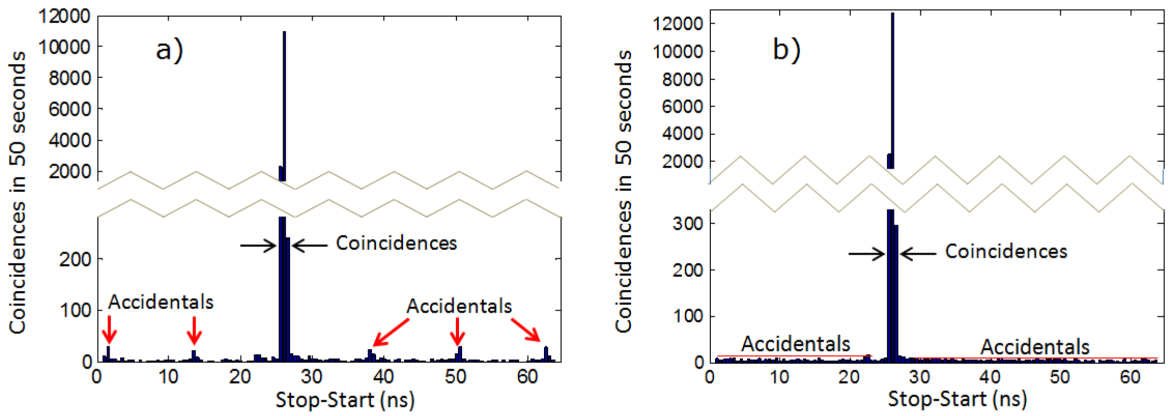

Fig. 2 Histogram showing PDC photon-pair generation with a Ti:Sapphire laser that is (a) mode-locked (average power in fiber is 11.1 mW), and (b) in the CW regime (pump power in fiber is 13.2 mW). The large width of the coincidence window (which occupies three 500-ps bins) is due to the jitter of the detection system; this system consists of the SPDs and the TIA, with each device contributing approximately 200 ps of RMS jitter.

Measuring the coincidences as a function of power, one can gauge the efficiency of the PDC source (Fig. 3a). However, due to the deadtime used in the free-running detectors to suppress afterpulsing, one must take care to account for the lowered duty cycle of the detectors at high count rates. Fig. 3a shows the raw coincidence counts as a function of power, and Fig. 3b plots the coincidences corrected for dead time, revealing a linear dependence with the pump power (as expected). The equation for correcting the raw coincidences (C_{raw}) for dead time is given by:

$$C_{correct} = \frac{C_{raw}}{(1 - N_1\tau_1)(1 - N_2\tau_2)} \qquad (1)$$

where N_i and τ_i are the singles counts per second and deadtime (respectively) for detector *i*. Here, the value of τ was set to 20 μs for both detectors.

A common measure of how good a correlated-photon pair source is to look at the coincidence-to-accidental ratio (CAR). For our source, we find that for high powers (Fig. 3c), a higher CAR can be achieved by CW pumping while also yielding higher counts (Figs. 3a, 3b).

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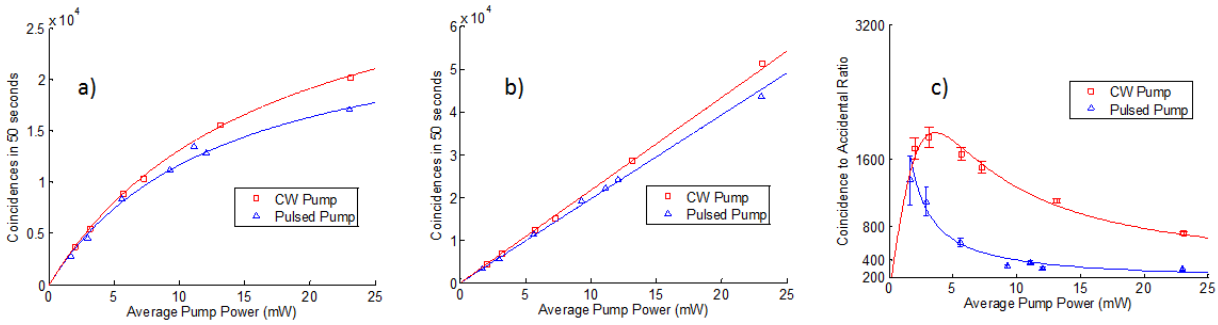

Fig. 3a) The raw coincidence rate is measured as a function of the pump power. Pumping in the CW regime results in higher coincidence rates at the same power. b) This figure shows that the coincidence rates, when corrected for detector deadtime using Eq. (1), scale linearly with the pump power. c) Plot of CAR vs pump power for CW and pulsed pumps. In all plots, solid-line curves are used to guide the eye only.

Time-Multiplexing

To demonstrate the polarization-entangled nature of our type-II downconverted photons (the downconverted photon pairs are in the triplet state $|HV\rangle + |VH\rangle$), we perform a two-photon interference experiment. This is achieved by performing projective measurements in the polarization degree-of-freedom. Fig. 4 shows the experimental setup. In the bottom (1570 nm) leg an automated polarization analyzer, composed of (half- and quarter-) waveplates and a polarizer, performs projective measurements on linearly-polarized light. In the top (1530 nm) leg, a free-space setup performs measurements either in the H/V (horizontal/vertically polarized) or D/A (diagonal/anti-diagonal) bases, depending on how the waveplates are adjusted.

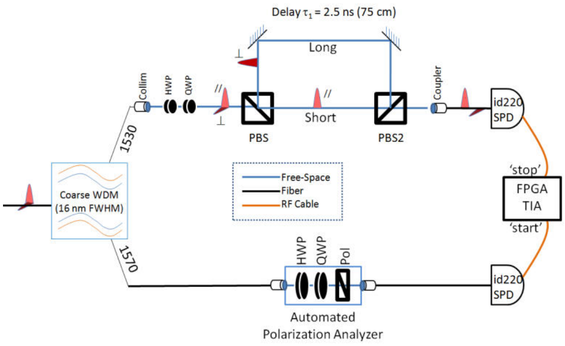

Fig. 4
Experimental setup for time-multiplexed two-photon interference. An unbalanced Mach-Zehnder interferometer composed of two polarizing beam splitters (PBS) allows for the time-multiplexing of two orthogonally-polarizing signals (either H/V or D/A, depending upon the waveplate settings).

Through the use of two polarizing beam splitters, it is possible to time-multiplex both the H- and V-polarized (or D- and A- polarized) photons into one detector. The two time-multiplexed signals are separated by a time delay of 2.5 ns; this time difference is readily observed by our TIA (Fig. 5a). The long path is taken by the *H* (*D*) photon, while the short path is taken by the *V (A)*-polarized photon. From Fig. 5a, we observe that when the bottom leg's polarization is set to *D*, measurements in the H/V basis for the top leg are uncorrelated, while in the D/A basis, the measurements are positively correlated. Scanning over the entire range of the 1570-nm polarizer, we observe the interference fringes shown in Fig. 5b. Because the fringe visibilities in both bases exceed 98.3%, this demonstrates that our source is a high-visibility entangled source.

We can time-multiplex these two signals, because the likelihood of both 'short' and 'long' arms each having a photon are extremely rare (in fact, according to Fig. 3b, the likelihood is more than two orders of magnitude lower than having a photon in just one time slot). The ease with which time-multiplexing can be achieved with free-running detectors like the id220 allows us to use one detector to replace multiple gated detectors.

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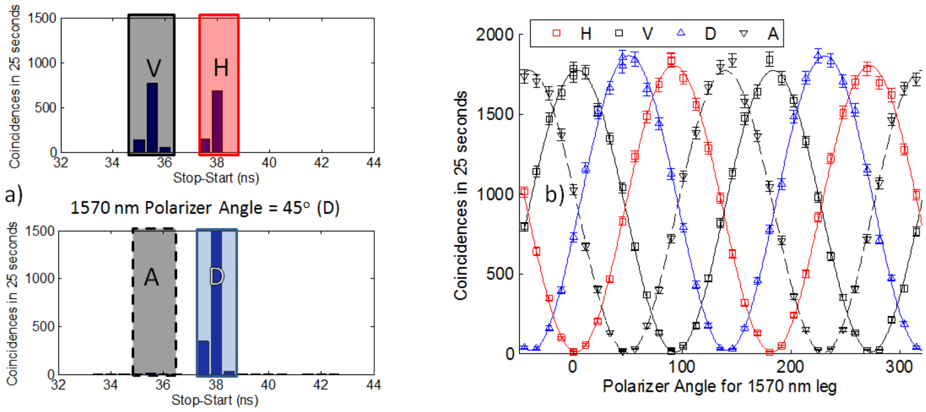

Fig. 5a) The polarization in the bottom leg of the setup (Fig. 4) is projected onto *D*. TIA histograms are shown when H/V basis (upper plot) or D/A basis (lower plot) is measured. b) As the bottom polarizer is swept for when the top leg is set to various polarizations (H/V, D/A), we observe high-visibility fringes, demonstrating polarization entanglement.

Conclusions

The id220 free-running near-IR single-photon detectors give us the flexibility to run our PDC experiments using either CW or pulsed pumps. We have also demonstrated that time-multiplexed coincidence events can be observed, allowing for more economical use of the detectors.

References

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