Dual-Pump Design Enables Novel Photon-Pair Characterization and Engineering

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Abstract: We experimentally demonstrate a dual-pump spontaneous four-wave mixing photon-pair source for which we quantify the noise to determine the generation probability and collection efficiency directly, and that generates photons in pure quantum states.

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Optical quantum information processing applications such as quantum computation, metrology, and communication are based on single photons as the qubit. Spontaneous parametric down-conversion and spontaneous four-wave mixing (SFWM) are common ways to generate heralded single photons, and there has been much research on tailoring these nonlinear interactions to optimize sources for quantum applications. Here we show that by utilizing two pumps in SFWM, a new method is opened up to directly characterize the contributions of noise and thus the photon-pair generation probability and collection efficiency, critical figures of merit in quantum applications. This ability is lacking in traditional photon-pair sources due to the mode overlap of the generated photon pairs and inherent noise. In addition, we show this technique allows the generation of heralded single photons in pure quantum states, which is critical for applications that rely on high-visibility interference of photons from separate sources. Specifically, as predicted in our previous theoretical work [1], in the regime of complete temporal walk-off between the pumps, the phase-matching function for the nonlinear interaction exhibits a Gaussian spectral-temporal profile; this profile is often assumed when simulating quantum state purities, but in practice has only been experimentally achieved through spectral filtering, complex material engineering or choosing specific wavelengths based on phase-matching conditions.

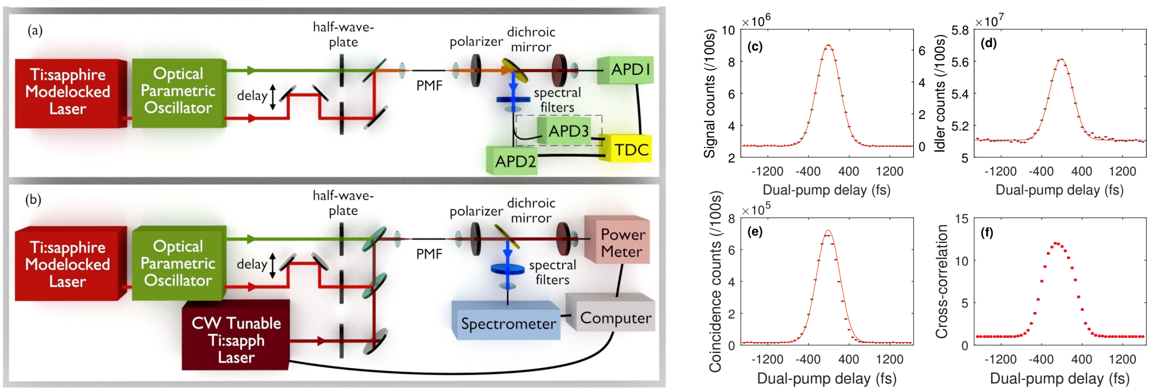

Fig. 1: (a) Experimental setup for statistical measurements of photon pairs generated via dual-pump SFWM. (b) Experimental setup for stimulated-emission-based joint spectral intensity measurements. A tunable continuous wavelength (CW) laser stimulates photon-pairs; signal spectra are saved for each seed wavelength as the laser is tuned across the bandwidth of the idler. (c-e) Raw counts (squares) and multi-curve fits (solid lines) vs. dual-pump delay for (c) signal singles, (d) idler singles, and (e) coincidences. (f) Raw $g^{(2)}$ cross-correlation vs. dual-pump delay.

The experimental setup for statistical measurements of the generated photon-pair state is shown in Fig. 1(a). A Ti:sapphire modelocked laser with 80 MHz repetition rate, 772 nm center wavelength, and 5 nm bandwidth is used as one pump, and a second pump is generated via an optical parametric oscillator that is tuned between 530-660 nm. The time delay between the pumps is controlled using an automated translation stage. The pumps are coupled into a 1.6-cm long polarization-maintaining fiber (PM630-HP, birefringence 3.5×10^{-4}). Second-order coherence cross-correlation, auto-correlation and conditional auto-correlation measurements are performed by measuring coincidence counts between APDs 1 & 2; 2 & 3; and 1, 2, & 3; respectively.

To show the capability of this dual-pump photon-pair source for determining photon-pair generation probability and collection efficiency directly, we measure single and coincidence counts as a function of pump delay (Fig. 1(c-e)). For these data the pump center wavelengths are 772 nm and 622 nm, at powers of 70 mW and 20 mW, respectively. The signal and idler singles counts and the coincidence counts as a function of time delay are shown in Fig. 1(c-f). Based on these counts statistics, the raw cross-correlation $g_{si}^{(2)}$ is calculated, shown in Fig. 1(f). The raw noise counts acquired in the region of no overlap make it possible to eliminate the noise contribution in the $g_{si}^{(2)}$ measurement. By multi-curve fitting based on the theory [1] (solid lines in Fig. 1(c-e)), these results give us a straight-forward way of retrieving the emission probability P of this photon-pair source directly, giving $P = 0.006$ per pulse for zero pump delay. The overall noise-corrected collection efficiencies for signal and idler are determined to be $\eta_s = 13.58 \pm 0.02\%$ and $\eta_i = 10.90 \pm 0.01\%$, respectively. We emphasize that these values were obtained from a fit to the raw data, with no additional measurements or assumptions. These values agree with estimates based on attenuation due to optics, fiber coupling efficiencies, and detector specifications.

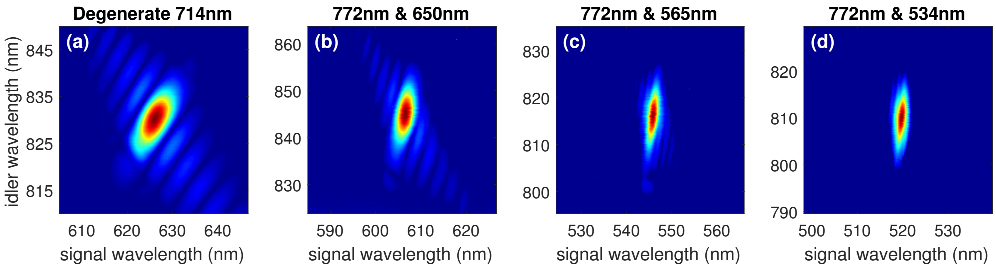

Fig. 2: Experimental JSIs from stimulated-emission-based measurement, with pump wavelengths shown above each JSI. From left to right, the detuning between the two pumps increases and the sidelobes clearly weaken, representing generation of heralded single photons of increasing purity.

To demonstrate how the dual-pump SFWM scheme enables the generation of heralded single photons in pure quantum states, we perform measurements of the joint spectral intensity (JSI) via stimulated four-wave mixing [2] (see Fig. 1(b) for experimental setup and Fig. 2 for results) for detunings from 0 nm (degenerate case) to 240 nm, corresponding to varying degrees of temporal walk-off in the fiber. For the degenerate pump case, the JSI contains spectral correlations from both the presence of sidelobes and an overall tilting (see Fig. 2(a)). The overall tilting can be mitigated by choosing specific fiber lengths [2]; however, the sidelobes arise from the sudden turning on and off of the nonlinear interaction as the pump enters and exits the fiber, which results in a sinc phase-matching function [3]. At large detunings in which the temporal walk-off is nearly complete (Fig. 2(d)), the phase-matching function becomes Gaussian [1] thanks to the spatial-temporal apodization of the interaction, resulting in higher purity compared to the degenerate case due to a lack of sidelobes. This purity improvement is further verified through unheralded signal $g^{(2)}$ autocorrelation measurements, using the setup of Fig. 1(a) with APDs 2 & 3, with powers of around 30 mW and 20 mW for the fixed and tunable pumps, respectively. Here again we find that the dual-pump scheme provides an advantage for quantifying the properties of the source, enabling noise-corrected purity measurements. The purity results are in agreement with numerical simulations [1], with measured purities for detunings of 0 nm (degenerate case), 122 nm, 153 nm, and 178 nm of 0.804 ± 0.012, 0.88 ± 0.04, 0.90 ± 0.04 and 0.97 ± 0.03, respectively. The trend of improving purity with detuning confirms the dual-pump approach for generation of heralded single photons in pure quantum states. We also note that, by changing the pump overlap position inside the fiber via time delay, it is possible to investigate the longitudinal properties of the fiber without cutting the fiber ($\sim$5 mm resolution at 150 nm detuning) [4].

In conclusion, we experimentally demonstrate a new approach for heralded single-photon generation that enables new direct measurements of source emission probability, collection efficency, and purity, and show its capability for generating heralded photons with high quantum state purity. We anticipate this source may be useful for future quantum information applications. This work was supported in part by NSF Grant Nos. 1205812, 1521110, 1640968 and 1806572.

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