Tailored photon-pair generation in optical fiber through dual-pump spontaneous four-wave mixing

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Abstract: We experimentally tailor the joint spectra of photon pairs produced via dual-pump spontaneous four-wave mixing, achieving a joint spectral intensity without side-lobes. This work presents a new route towards generating spectrally uncorrelated photon pairs.

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Optical quantum information processing such as quantum computation, quantum metrology, and quantum communication are based on single photons as the physical realization of the qubit. Spontaneous parametric down-conversion and spontaneous four-wave mixing (SFWM) are common ways to generate heralded single photons. However, to fulfill the requirement that the photons be in pure quantum states, in general the joint correlations of the emitted photon pairs must be tailored to remove unwanted correlations. For untailored photon-pair source, due to the sudden onset and ending of the nonlinear interaction in the medium, sidelobes in the joint spectral intensity (JSI) degrade the purity (see Fig. 1(a)) [1] [2]. To address this without spectral filtering, which decreases heralding efficiency, researchers have used material engineering [4] to get rid of the sidelobes and thus realize factorable photon-pair generation.

In this paper, we employ dual-pump SFWM in polarization-maintaining fiber (PMF) to directly generate heralded single photons in spectrally pure states without using spectral filtering or material engineering. As shown in our earlier theoretical work [5], by using two distinct pumps with different group velocities such that the pumps experience complete temporal walk-off as they propagate through the fiber, spectrally factorable photon pairs can be generated, and as a consequence, heralded single photons in pure wavepackets.

In SFWM, two pump photons annihilate in a $\chi^{(3)}$ nonlinear medium and signal (s) and idler (i) photons are simultaneously created. The joint spectral state of the photon pair is determined by energy and momentum conservation and can be expressed as [5]: $|\Psi\rangle = \iint d\omega_s d\omega_i f(\omega_s,\omega_i)\,|\omega_s,\omega_i\rangle$, where $f(\omega_s,\omega_i)$ is the joint spectral amplitude (JSA). Under linear approximation the JSA can be expressed as $f(\nu_s,\nu_i) = \alpha(\nu_s,\nu_i)\phi(\nu_s,\nu_i)$, where ν_μ is the detuning defined by $\nu_\mu = \omega_\mu - {\omega_\mu}^0$, where $\mu \in \{s,i\}$ and ${\omega_\mu}^0$ is the central angular frequency, $\alpha(\nu_s,\nu_i)$ is the pump envelope function, which is typically set to be Gaussian, and $\phi(\nu_s,\nu_i)$ is the phase-matching function.

For degenerate pump photons, the phase-matching function is given by [3]

$$\phi(\nu_s,\nu_i) = \mathrm{sinc}\left(\frac{L\Delta k_{lin}}{2}\right)\exp\left(i\frac{L\Delta k_{lin}}{2}\right), \quad (1)$$

where L is the length of the fiber and Δk_{lin} is the approximate phase mismatch [5]. In the degenerate case, the sinc function result in sidelobes in the JSI, as seen in the experimental data shown in Fig. 1(a); the sidelobes degrade the state purity of the generated photons.

For non-degenerate pump photons from two distinct pumps, the pump center wavelengths can be tuned to achieve temporal walk-off [5], leading to a Gaussian phase-matching function:

$$\phi(\nu_s,\nu_i) = \exp\left[-\left(\frac{T_s\nu_s + T_i\nu_i}{\sigma\tau_p}\right)^2\right], \quad (2)$$

where σ represents an effective bandwidth of the pumps, τ_p denotes the group delay between the pumps, and $T_\mu, \mu \in \{s,i\}$, represent the effective group delays of the signal and idler photons. In the complete walk-off case, both the pump envelope function and phase-matching function are Gaussian and hence no sidelobes are present.

The experimental setup is shown in Fig. 2. A Ti:sapphire modelocked laser with 80 MHz repetition rate and 772 nm center wavelength is used as one pump, and a second pump (tunable from 550-650 nm) is generated via an

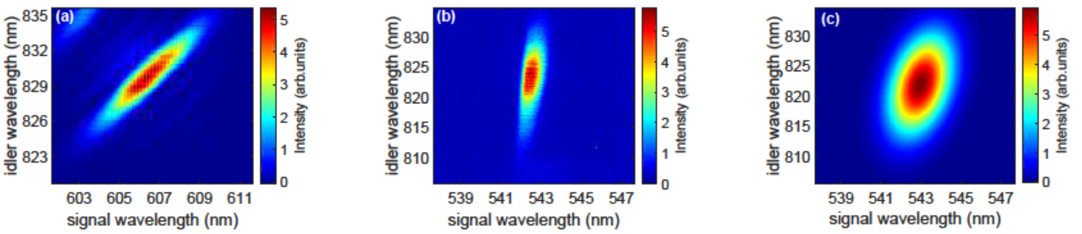

Fig. 1: (a) Joint spectral intensity (JSI) for degenerate pump at 700 nm; note the presence of sidelobes to either side of the main peak. (b) JSI for dual pumps at 772 nm and 570 nm with complete temporal walk-off; note there are no sidelobes, which leads to higher purity; (c) Theoretical JSI for the dual-pump case [5]. Note that the main peak in (a) is at an angle compared to (c) due to the longer interaction length for the degenerate pump case.

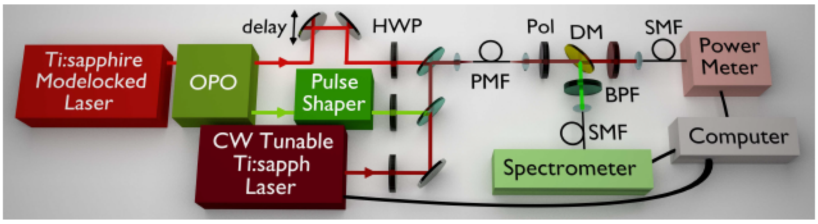

Fig. 2: Experimental setup for measurement of the JSI of the dual-pump SFWM photon-pair source via stimulated emission. PMF: polarization-maintaining fiber; SMF: single-mode fiber; DM: dichroic mirror.Pol: Polarizer; BPF: Band-pass filter

optical parametric oscillator. To measure the JSI, we perform a stimulated-emission based measurement using a tunable continuous wavelength (CW) Ti:sapphire ring laser [6]. The 772 nm pump is set to arrive a few pulse widths before the tunable pump using a translation stage. A 4f pulse shaper in the other arm is used to filter the wings of the spectrum in the regions of the generated signal photons. The three beam are coupled into a 9-cm long polarization-maintaining fiber. A computer controls the seed laser wavelength, and the stimulated signal is coupled to a spectrometer. Spectra are saved for each seed wavelength to generate the JSI.

As a first demonstration, we measure the JSI in the complete temporal walk-off regime. The pump generated by the OPO is set at 570 nm, corresponding to a $202nm$ detuning between the pumps. Based on our numerical simulation [5] (see Fig. 1(c)), the expected signal (idler) photon should be created around 550 nm (820 nm) with no significant sidelobes. The recorded JSI is shown in Fig. 1(b); the JSI does not exhibit sidelobes, as expected theoretically.

These results confirm the feasibility of the dual-pump approach to generating heralded single photons in pure wavepackets. Further work will focus on improving the factorability by adjusting pump powers, bandwidths and wavelengths, with close to unity purity anticipated [5]. By changing the pump wavelengths, the signal and idler photons can be generated across a wide range of different wavelengths and detunings. In addition, by changing the pump overlap position inside the fiber via the time delay, it is possible to investigate the longitudinal properties of the fiber without cutting the fiber [7] (the overlap region in our PMF is about 10 times the pulse length, meaning the longitudinal variation of the fiber nonlinearity can be probed with $\sim 300\ \mu$m resolution). With these capabilities we anticipate this dual-pump source may be quite useful in projects related to quantum information processing. This work is supported in part by NSF Grant Nos. 1521110 and 1640968.

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