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Fast and highly resolved capture of the joint spectral density of photon pairs

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Controlling the spatial and spectral–temporal properties of photon pairs produced in artificially structured materials is fundamental to the realization of numerous photonic quantum information applications. Tailoring the joint spectral properties of photon pairs is of particular importance for applications relying on time–energy entanglement, high-visibility interference, and heralding. Yet measuring the joint spectral properties is a time-consuming task requiring coincidence counting, typically resulting in low-resolution spectra with a poor signal-to-noise ratio. In this work we capture the joint spectral correlations of photon pairs that would be produced in optical fibers with unprecedented speed, resolution, and signal-to-noise ratio, using a scheme based on stimulated four-wave mixing. We also illustrate that this technique can be used in engineering joint spectral correlations, making it a powerful tool for studying quantum states. © 2014 Optical Society of America

Some of the most promising strategies for enabling quantum information applications rely on photonic quantum states produced in artificially structured materials. These strategies take advantage of the wide tunability of the spontaneous four-wave mixing (SFWM) interaction and the single-mode nature and compactness of the structures to generate photons with specific spatial and spectral–temporal properties [1–11]. The design of the joint spectral properties of photon pairs [12–14] is of particular importance, as many protocols rely on specific types of spectral correlations, such as strongly correlated photons for time–energy entanglement [15] and uncorrelated photons for high-visibility interference and heralding [16].

Quantum correlated photon pairs [9] are typically described using a biphoton wave function, or equivalently a joint spectral amplitude. With knowledge of the joint spectral amplitude, we can extract information about the different degrees of freedom of the photon pairs and their quantum correlations. To date, measurement of the properties of the joint spectral amplitude and its magnitude [12,17–20] has been nontrivial, typically relying on single-photon detection, which results in slow characterization and low resolution. Recently, a simple relation between spontaneous and stimulated emission of photon pairs in second-order nonlinear materials was demonstrated theoretically [21], implying that the joint spectral amplitude of photon pairs that would be generated in the spontaneous process can be measured through the corresponding stimulated process. This was recently confirmed for photon pairs generated by spontaneous parametric downconversion in AlGaAs waveguides [22].

In this work, we experimentally demonstrate that the protocol in [21] is more general, and it can be applied to photon-pair generation based on higher-order nonlinear processes. We use stimulated four-wave mixing to capture, with unprecedented speed and resolution, the joint spectral density (JSD) of photon pairs that would be generated by SFWM in an optical fiber. The generation of photon pairs in this system has been studied for more than a decade, and yet our experimental results reveal details of the JSD that have never been observed before. We also illustrate how this technique can serve as a tool in the engineering of joint spectral properties.

In the silica fiber used in our experiments, the photon pairs are generated with the same linear polarization, and their state can be written as [12]

$$|\Psi\rangle = \iint d\omega_s d\omega_i f(\omega_s, \omega_i)|\omega_s, \omega_i\rangle, \qquad (1)$$

where $|\omega_s, \omega_i\rangle$ is the quantum state with the signal (idler) at angular frequency ω_s (ω_i) and $f(\omega_s, \omega_i)$ is the joint spectral amplitude. Thus the measurement of $|f(\omega_s, \omega_i)|^2$, called the JSD, allows one to obtain some information about the quantum correlations. Traditionally, its determination follows a statistical approach, based on spectrally resolved coincidence experiments [12,18,19]. This approach is time consuming and has low resolution, due to the low generation rate of photon pairs. An example of a state-of-the-art JSD measurement performed using coincidence counting for a 10 cm long polarization-maintaining fiber (PMF; Fibercore HB800G) is used for comparison, kindly provided by Smith *et al.* [12]. Here we apply a stimulated-emission-based measurement, in which the detected signal is much larger than that measured in the coincidence experiment, and thus the speed and signal-to-noise ratio are greatly improved. Indeed, the number of photon pairs emitted in the stimulated process is proportional to the number that would be emitted in the spontaneous process, with a proportionality constant approximately equal to the average number of photons in the stimulating seed [21]:

$$\frac{\langle n_{\omega_s}\rangle_{A_{\omega_i}}}{\langle n_{\omega_s} n_{\omega_i}\rangle} \approx |A_{\omega_i}|^2, \qquad (2)$$

where $\langle n_{\omega_s}\rangle_{A_{\omega_i}}$ is the average number of signal photons with frequency ω_s stimulated by an idler seed with frequency ω_i, $\langle n_{\omega_s} n_{\omega_i}\rangle$ is the average number of photon pairs that would be generated in the spontaneous process, and $|A_{\omega_i}|^2$ is the average photon number within the coherence time of the seed. Thus, one can extract the information to reconstruct the JSD by measuring the output signal. The captured JSD has a high fidelity with theoretical predictions.

Our experimental setup is shown in Fig. 1. A Ti:sapphire laser generates pump pulses centered at 710 nm with an ∼3 nm full width at half-maximum (FWHM) bandwidth. The pump is coupled into an ∼10 cm long PMF (Nufern PM630-HP with a birefringence of 3.3×10^{-4}). A half-wave plate (HWP) is placed in front of the fiber to rotate the polarization of the pump such that it propagates along the slow axis of the fiber. When used for SFWM, two sideband photons, the signal at 626 nm and the idler at 820 nm, are spontaneously emitted with polarization orthogonal to the pump [12]. In the
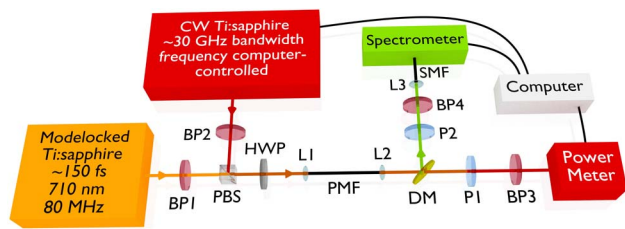
stimulated experiment, a tunable continuous-wave (CW) Ti:sapphire laser within the idler bandwidth is used as a seed to stimulate the emission of signal photons. A polarizing beam splitter (PBS) is used to combine the pump and seed before they enter the fiber. A dichroic mirror (DM) (Semrock FF685-Di02) separates the signal and idler photons. The signal is collected by a single-mode fiber (SMF) and sent to a spectrometer (Andor SR-303i-A). The power of the seed is detected by a power meter. The power for each slice (i.e., the measured signal spectrum for each idler seed wavelength) is used to normalize the corresponding spectrum taken by the spectrometer. We obtain slices of the JSD along the wavelength of the signal as we scan the seed across the idler bandwidth. The wavelength of the seed for each slice is also recorded. All the data are sent to a computer to directly generate the final joint spectrum.

A total pump power of 10 mW is coupled into the fiber. The stimulated process strongly enhances the signal, such that only 10 mW average seed power is used in our measurements to avoid saturation of the spectrometer when set to its shortest acquisition time, which is 10 ms per scan. We measure the dependence of the stimulated signal power on the seed power at fixed idler central wavelength. The result, shown in Fig. 2, confirms that the stimulated signal power varies linearly with the seed power, in agreement with Eq. (2).

The measured JSD is shown in Fig. 3(b). The sidelobes on either side of the central lobe are due to the sudden onset and end of the nonlinear interaction in the fiber [12,23]. The sidelobes are much less intense than the central lobe, and thus they are difficult to observe using the traditional JSD measurements in the spontaneous regime, such as that shown in Fig. 3(a). The stimulated-emission-based measurement gives a resolution of approximately 60 pm × 100 pm (signal × idler) per pixel. The resolution of the signal wavelength axis is determined by the resolution of the spectrometer, while the resolution of the idler wavelength axis can be controlled by the step size of the frequency scan.

To compare with the theory, we calculate the JSD numerically, using a standard approach in quantum optics that consists of finding the Hamiltonian of the FWM interaction
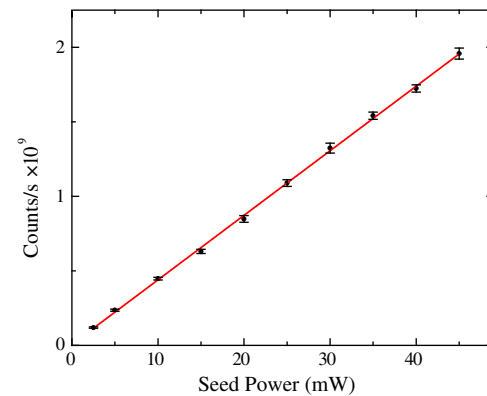

Fig. 1. Schematic of the experimental setup. BP1–4, bandpass filter; PBS, polarizing beam splitter; HWP, half-wave plate; L1–3, lens; PMF, polarization-maintaining fiber; DM, dichroic mirror; P1–2, polarizer; SMF, single-mode fiber.

Fig. 2. Power dependence of the stimulated photon counts. The black squares are the measured counts, with error bars indicating the standard deviation across 20 measurements. The red line is a linear least-squares fit.
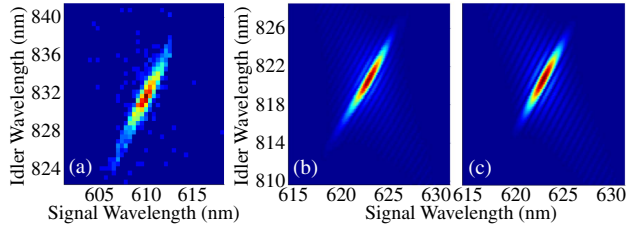
Fig. 3. (a) JSD measured by coincidence counting, provided by Smith *et al.* [12], (b) JSD measured by stimulated four-wave mixing, (c) numerical calculation of the JSD. Note the high resolution and low noise in (b) compared with (a). Also note that the measurements in (a) are taken for a fiber different from the one in (b), resulting in a generally different JSD.

Fig. 4. Measured JSDs for fiber lengths of (a) 2.6 cm, (b) 1.6 cm, and (c) 1.1 cm. From (a)–(c), the spectral correlation changes from correlated to nearly uncorrelated to anticorrelated as the length of the fiber decreases.

and calculating the evolution of the pump state [24]. In our birefringent optical fibers, as in Smith *et al.* [12], the resulting JSD can be written as

$$|f(\omega_s, \omega_i)|^2 = \left| \int d\omega_p \alpha(\omega_p) \alpha(\omega_s + \omega_i - \omega_p) \phi(\omega_s, \omega_i) \right|^2,$$

(3)

where $\alpha(\omega_p)$ is the pump envelope function (assumed to be Gaussian) and $\phi(\omega_s, \omega_i) = \text{sinc}(\Delta k L/2) \exp(i\Delta k L/2)$ is the phase-matching function, where L is the length of the fiber and $\Delta k = 2n(\omega_p)\omega_p/c - n(\omega_s)\omega_s/c - n(\omega_i)\omega_i/c + \Delta n\omega_p/c$ is the phase mismatch, with $n(\omega)$ being the refractive index given by the Sellmeier equation of bulk silica, Δn the birefringence of the fiber, and c the speed of light in free space. As in earlier studies [12], we are working in a low-pump-power regime in which self- and cross-phase modulation can be safely neglected. The calculated JSD, plotted in Fig. 3(c), has ∼94% fidelity to the experimental JSD. The clear presence of the weak sidelobes in the stimulated measurement demonstrates that this approach provides access to properties of the JSD that cannot be detected using traditional coincidence-counting techniques. The signal photon count rate when the idler seed wavelength is at the peak of the JSD is ∼4.5 × 10⁸ photons/s. Compared to the traditional coincidence-counting method [18], which has a resolution of ∼0.5 nm and a count rate that requires hours to obtain a full JSD, the improvement is substantial. The whole measurement can be done within 10 min. Most of the time is spent by the computer-controlled mechanical turning of an actuator to control the seed wavelength. Many more investigations of photon-pair correlations can be pursued with the benefit of this efficient measurement technique.

Finally, we illustrate how this technique can be used as an aid in engineering joint spectral correlations of the photon pairs. In general, the photon pairs can range from correlated to uncorrelated; the latter has wide use in quantum schemes requiring pure heralded single-photon states. Although a full engineering study would require determination of the joint spectral amplitude, the JSD is the most important part for identifying when conditions have been achieved for the generation of uncorrelated photons, as the joint spectral phase typically varies little across the range in which the flux of
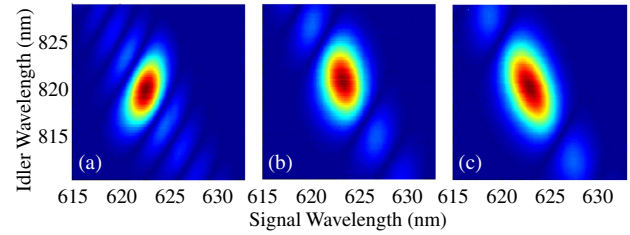
generated pairs is appreciable; thus, any improvement in determining the JSD will facilitate the design process. As an example, in this study we tailor the JSD by changing the length of the fiber; for fiber lengths of 2.6, 1.6, and 1.1 cm, we use the stimulated FWM technique to capture the JSDs. Figure 4 shows the results for the different fiber lengths, indicating that the photons change from correlated to anticorrelated as the fiber is shortened. The data suggest that a length close to 1.6 cm is the best candidate for producing nearly uncorrelated photons, a result that has been achieved much faster than previous techniques that rely on the spontaneous generation of the photon pairs would allow.

In summary, we have successfully demonstrated that the JSD of photon pairs that would be produced by SFWM can be obtained from the results of a stimulated four-wave mixing experiment. The stimulated emission allows us to capture the full JSD in a few minutes, with a resolution as fine as 60 pm, and using a standard spectrometer. This represents an improvement of about an order of magnitude in resolution per axis (two orders of magnitude per unit area) with respect to a typical coincidence experiment, which would take several hours and require single-photon detectors. This measurement has required only a few minutes, less than a tenth the time reported in Ref. [22], demonstrating that the full potential of this technique has yet to be completely exploited. The ability to quickly determine JSDs with high resolution is essential for the efficient design of systems to produce quantum correlated photons with desired properties, and so we can expect that the technique demonstrated here will become central in engineering systems to produce pairs of photons by SFWM. We expect it will also become the preferred technique in future studies of the physics of various states of photon pairs that can be produced by parametric fluorescence in fibers as well as integrated devices.

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