Engineering Joint Spectral Densities with Orbital Angular Momentum States in Optical Fibers

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Abstract: We exploit the large modal space available in ring-core fibers supporting orbital angular momentum modes to demonstrate a versatile means to control the shape of photon-pair joint-spectral densities generated by spontaneous four-wave mixing.

Spontaneous four-wave mixing (SFWM) in optical fibers is a promising method for photon pair generation [1]. For various quantum applications, such as those that require indistinguishable photons from different sources or use time-energy entanglement, control of the shape of the photons' joint spectral density (JSD) is necessary. The shape of the JSD is intimately linked to phase matching conditions, and past attempts at engineering it in a single-mode optical fiber include utilizing birefringent phase matching in polarization-maintaining fibers [2] or exploiting dispersion-engineering, either by tailoring the index profile of fibers [3] or by controlling gas pressure in hollow-core fibers [4]. Photon pairs can also be generated in multimode fibers [5], where transverse spatial modes can offer an additional degree of freedom with which to control phase matching. Here we show, to the best of our knowledge, the first demonstration of JSD engineering with orbital angular momentum (OAM) modes in specially designed, ring-core optical fibers that can transmit large ensembles of modes over km-length scales [6]. We show, using stimulated emission tomography [7,8], that spectrally correlated, anti-correlated, as well as uncorrelated photon pairs may be engineered with different OAM mode combinations.

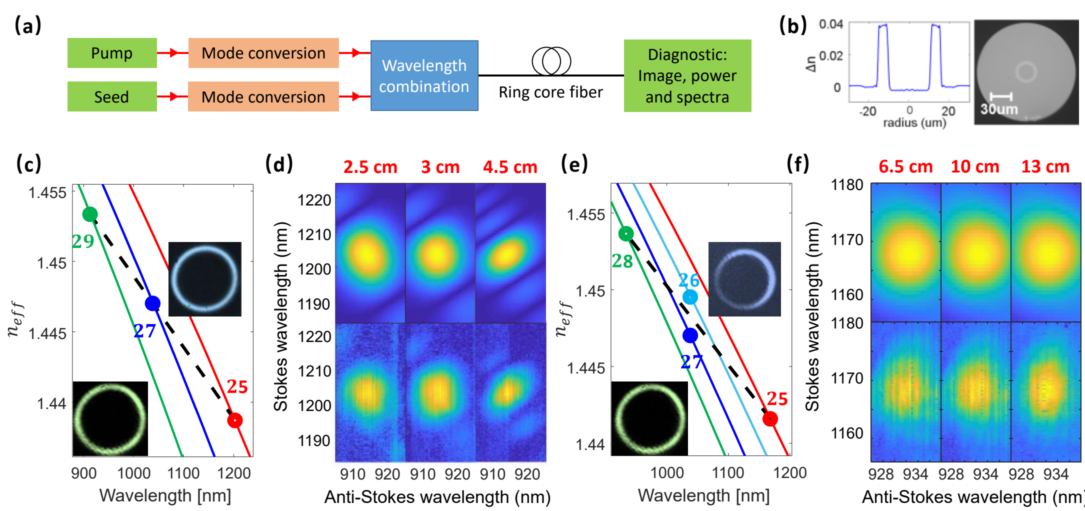

Fig. 1 (a) Experiment setup. (b) Refractive index profile and facet image of the ring core fiber. (c), (e) n_{eff} plots as a function of wavelength for the modally-degenerate (c) and modally non-degenerate (e) pumps used in the experiments. Colored markers on the n_{eff} curves denote the wavelength, and corresponding numbers denote the OAM values (L) for the anti-Stokes seed (left), pump (center) and Stokes (right) emissions. Blue and green ring-shaped images show measured output modes for the pump and seed, respectively. (d), (f) Simulated (top rows) and measured (bottom rows) square root of JSDs for the two pump configurations depicted in (c) and (e), respectively, as a function of fiber length.

The setup [Fig. 1(a)] comprises an ultrashort pulse pump (λ_{center}~1038 nm; $\Delta\tau$~156 fs; $\Delta\lambda$~10 nm; repetition rate ~10 MHz) and a CW Ti:Sapphire laser seed, tunable from 850-1000 nm. Both beams are shaped by a spatial light modulator (SLM) to achieve desired OAM modes, and multiplexed into the fiber [index profile and facet image shown in Fig. 1(b)] with a dichroic filter. The solid lines of Fig. 1(c) and 1(e) illustrate the spectral evolution of the effective indices (n_{eff}) in our fiber, with corresponding numerals denoting the mode's OAM value L. The dashed lines represent the combinations of modes at specific wavelengths that, ignoring small self/cross-phase modulation corrections, yield phase matching [9], i.e. $c \cdot \Delta k = n_{eff}^{j}(\omega_p)\omega_p + n_{eff}^{k}(\omega_p)\omega_p - n_{eff}^{l}(\omega_s)\omega_s - n_{eff}^{m}(\omega_{as})\omega_{as} = 0$, where the superscripts j,k,l and m denote mode orders for the two pumps, Stokes and anti-Stokes lines, respectively. This calculation is specific to the case where both pump modes j, k are degenerate in frequency ω_p (but may not be modally degenerate), as is the case for all experiments described below. The resultant JSD is given by $|f(\omega_{as},\omega_s)|^2 = \left|\int d\omega_p \alpha(\omega_p)\alpha(\,\omega_{as}+\omega_s-\omega_p)\,\phi(\omega_{as},\omega_s)\right|^2$, where $\alpha(\omega_p)$ is the pump envelope function, and $\phi(\omega_{as},\omega_s) = sinc(\Delta kz/2)exp(i\Delta kz/2)$ with z being the propagation length (i.e. fiber length) [8].

We consider two distinct regimes of operation. When the pump resides only in the $L = 27$ OAM mode, corresponding to the case where the SFWM pump fields are modally as well as spectrally degenerate, phase matching is obtained with the $L = 29$ mode around ~915nm, and the $L = 25$ mode around ~1205nm [see Fig. 1(c)]. The theoretically calculated JSDs for different fiber lengths are shown in the top row of Fig. 1(d), and the corresponding experimentally measured JSDs with a pump peak power of 43 kW and seed power (in the anti-Stokes L=29 mode) of 42 mW, are shown in the bottom row of Fig. 1(d). As is evident, the experimentally measured JSDs match well with theoretical predictions and point to the ability of engineering photon-pair distributions from correlated, to uncorrelated to anti-correlated by choice of fiber length. Also note the existence of sidebands, arising from the abrupt rise and drop of nonlinear interactions as the pump pulses enter and exit the fiber, in all cases – a feature that could potentially be deleterious in several applications. All features shown here provide the proof-of-concept for engineering JSDs of OAM carrying photons as has been achieved for Gaussian beams with single-mode fibers in the past.

The second regime we explore involves pumps at the same frequency but in distinct modes. As shown in Fig. 1(e), when the pump is equipartitioned into the $L = 26$ and 27 OAM modes at 1038nm, the JSDs are devoid of sidebands across the fiber lengths we tested. Since the pump mode now occupies two modes with distinct group velocities, the nonlinear interaction is effectively length-wise apodized, hence yielding sideband-free spectral features that are desirable for many applications. The pump walk-off length is estimated to be only 4 cm for this mode combination, which explains the length-independent, stable, uncorrelated JSDs we observe. Such an effect can also be obtained in single-mode fibers, but primarily by using pump lasers at two distinct wavelengths [10]. Here, the availability of many modes enables achieving pump non-degeneracy (and hence smooth walk-off) with only a single pump laser. Another benefit of this multimode system arises from the fact that the pump modes not only have different group velocities, but also distinct group-velocity dispersions [11]. Hence, the amount of walk-off between the pumps can also be tailored. This capability is shown in Fig. 2(b), which illustrates the ability to switch between correlated and uncorrelated JSDs via input pump laser chirp control alone.

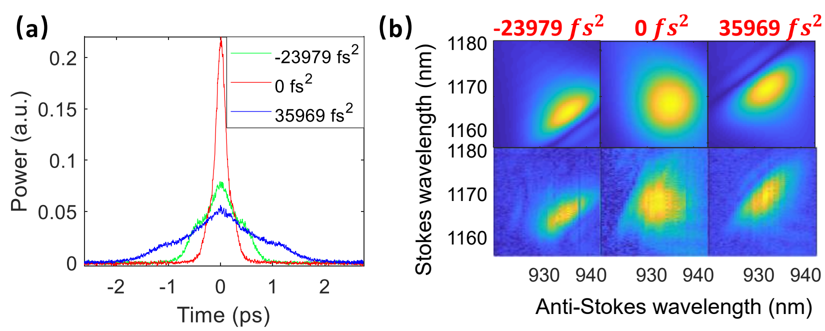

Fig. 2 (a) Auto-correlator measurement of pump pulses with different pre-chirp values. (b) Simulated (Top) and measured (bottom) square root of JSDs for different pre-chirp values.

In summary, we demonstrate the ability to engineer JSDs of photon pairs by utilizing OAM modes in optical fibers. The large ensemble of available stable modes allows a plethora of phase-matching possibilities, which allows for the generation of photon pairs at a variety of wavelengths. Since group velocity and dispersion are intimately tied to the OAM a fiber mode carries, this toolbox also allows engineering JSDs in ways that would have required multiple pump lasers in single-mode systems. Finally, the output of these fibers yields spatially diverse OAM modes, potentially with much higher brightness than that feasible with bulk generation techniques.

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