Optimized Entangled Photon Pair Generation via Intermodal Four-Wave Mixing in a Telecommunication-length Few-Mode Fiber

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ABSTRACT

We report our recent progress in generating and verifying entangled photon pairs in a telecommunication-length few-mode fiber using spontaneous four-wave mixing in a non-degenerate pump configuration. We demonstrate through seeding the desired four-wave mixing effect for pair production in the presence of a strong mode-coupling when using integrated mode multiplexers known as photonic lanterns. The mode content and phase-matching requirements were validated through computations and experiments. We discuss the challenges and requirements for phase matching and photon visibility without modifying the fiber structure. This work represents our first steps toward an efficient tunable source of entangled photons for space division multiplexing applications.

Keywords: Few-mode fiber, Intermodal four-wave mixing, Entangled photon pairs.

1. INTRODUCTION

Entangled photon pairs (EPPs) generated in various spatial modes of few-mode and multimode fibers have many degrees of freedom, which allows for quantum state manipulation and enhancement for hybrid communication systems, quantum information science, and quantum spectroscopy. The process through which these highly dimensional photon pairs get generated in few-mode and multimode fiber is known as four-wave mixing (SFWM), first discovered by Stolen et al. [1]. Since then, nonlinear fiber optics, particularly the FWM effect, have been of great interest for various applications, from telecommunication to medical imaging. While many studies have been performed in this realm [2-5], many issues remain to be addressed for efficient EPP generation and its practical utilization.

In this, we report our recent progress in designing and demonstrating spatially diverse and high-efficiency room-temperature sources of EPPs in few-mode fibers (FMFs) [6]. We study a non-degenerate pump configuration scheme where two different pumps at two different wavelengths and modes are coupled into the fiber, and EPPs through SFWM are expected to be observed due to the phase-matched condition of carefully chosen pumps' wavelengths. Due to the use of continuous wave (CW) lasers and fiber amplifiers, a seed laser is coupled at the Stokes or anti-Stokes photon wavelength, and the spectral content of the fiber is further analyzed in the presence of storing mode coupling.

2. EXPERIMENTS AND RESULTS

The spontaneous four-wave mixing (SFWM) effect requires the phase-matching condition in (1) to be satisfied for a specific mode combination of the involved frequencies. Here $\Delta\omega_k = \omega_0 - \omega_k$ with k$\in \{p_1, p_2, i, s\}$ where ω_0 is an arbitrary frequency around which the propagation constant, $\beta(\omega)$, is expanded using a Taylor series. ω_{p1}, ω_{p2}, ω_i, and ω_s are the pump 1, pump 2, idler, and signal frequencies. In this context, β_1^m represents the inverse of the group velocity and β_2^m represents the group velocity dispersion for modes $m = \{01\ or\ 11\}$. In (1), the assumption is that ω_{p1} and ω_s are in the LP_{01} mode and ω_{p2} and ω_i are in the LP_{11} mode.

$$\beta_1^{11} + \frac{\beta_2^{11}}{2}\left(\Delta\omega_i + \Delta\omega_{p2}\right) = \beta_1^{01} + \frac{\beta_2^{01}}{2}\left(\Delta\omega_{p1} + \Delta\omega_s\right) \quad (1)$$

Figure 1 outlines the experimental setup for investigating the spontaneous FWM in a 25.121-kilometer graded-index few-mode fiber (FMF) supporting three spatial modes, including LP_{01}, LP_{11a}, and LP_{11b}. These modes each have two orthogonal polarization states, which result in a total of 6 polarization modes. The LP_{11a} and LP_{11b} modes are degenerate; therefore, we couple them together using a 50:50 coupler in the mode multiplexer and refer to them as LP_{11}. The setup utilizes two

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external cavity lasers, amplified using high-power erbium-doped fiber amplifiers and broadened with a phase modulator that is used to suppress the Brillouin scattering effect. Two programmable fiber-coupled optical filters are used to reduce the background noise generated by the EDFAs. Integrated spatial mode multiplexers are used to couple the signals into the fiber and de-couple them at the output. Finally, the spectrum was taken using an optical spectrum analyzer with a 0.05 nm resolution. A seed is also coupled with one of the pumps to stimulate the process and increase the signal-to-noise ratio of the experiment.

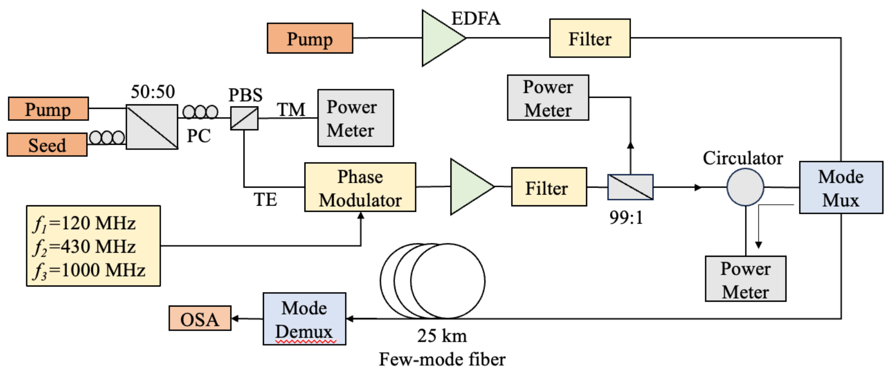

Figure 1. Experimental setup to demonstrate the intermodal spontaneous four-wave mixing, PC: polarization controller, WS: Wave Shaper (programmable optical filter), PBS: polarization beam splitter.

The spliced system consisting of the fiber spool and the mode-multiplexers is then analyzed using an optical time domain reflectometer measuring the total length of the FMF to be 25,121.53 meters, with a loss rate of 0.25 dBm/km. Preceding the lanterns, the lengths of the single-mode fibers are measured to be 171 cm and 145 cm at the LP_{01} and LP_{11} outputs, respectively. The relative inverse group velocity of the fiber is $\beta_1^{11} - \beta_1^{01} = -60.94$ ps/km, and each mode's inverse group velocity dispersions are 19.108 Ps/km-nm and 19.818 Ps/km-nm for LP_{01} and LP_{11}, respectively. Pumps 1 and 2 are calibrated at 1536 nm (in LP_{01}) and 1539.2 nm (in LP_{11}). The anticipated wavelengths for Stoke and anti-Stokes are calculated to be 1526.3 nm (in LP_{01}) and 1549.05 nm (in LP_{11}) from the phase matching equation (1) for the SFWM. Due to the low efficiency of entangled photon pairs in the FMF, we seeded the fiber at 1549.05 nm to observe the FWM effect in the corresponding mode of the 1526.3 nm signal. Figure 2 depicts the spectra of the LP_{01} and LP_{11} outputs of the mode-demultiplexer, where the expectant 1526.32 nm signal was observed in both outputs, demonstrating strong coupling between fiber modes. Simultaneously, other FWM effects are also generated, which, based on their corresponding phase mismatch values calculated from the phase mismatch of all the observed effects for various mode coupling configurations, are both intermodal and intramodal effects. Such intramodal FWM represents the processes of two pumps and the signal, where effects with the lowest phase mismatch are likely to be generated. Figure 2 (a and b) presents results from the OSA at 0.05 nm spectral resolution for both LP_{01} and LP_{11} output ports of the demultiplexer.

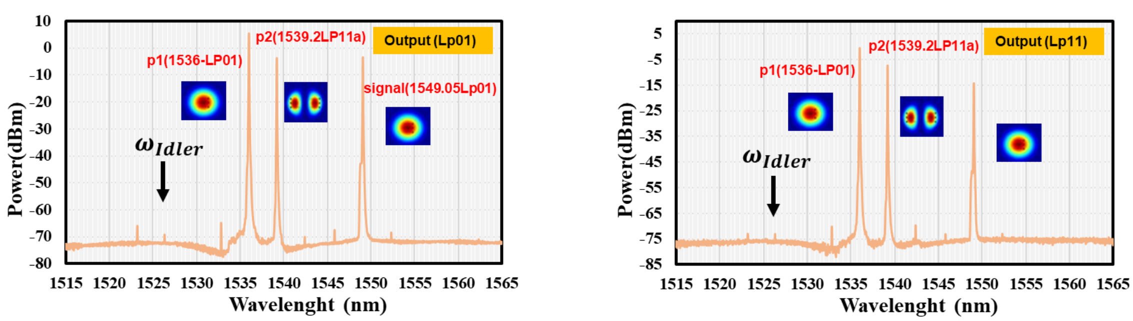

Figure 2. (a/b) The spectra measured when selecting the LP01/ LP11a output port of the MDMUX and two pumps are at 1536 nm, 1539.2 nm, and the signal is at 1549.05 nm.

In summary, we have improved our experimental design and setup to observe EPPs through seeding and identified all the observed FWM effects in the presence of strong mode coupling. We will perform quantum correlation measurements by adding filters at the fiber end and moving the EPPs wavelengths outside the EDFA gain. Our ultimate goal is to design and demonstrate spatial-mode-entanglement in an FMF and utilize it for hybrid communication systems as well as applications in quantum repeaters.

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