All-Fiber Source and Sorter for Multimode Correlated Photons

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Abstract: We use spontaneous four wave mixing to generate multimode photon pairs in a few mode fiber. We show the photons are correlated in the fiber mode basis using an all-fiber mode sorter. © 2021 The Author(s)

1. Introduction

High-dimensional quantum bits hold great potential for quantum communication owing to their robustness to noisy environments [1]. Implementations based on encoding information in the transverse spatial modes of photons are especially promising due to the large Hilbert space they span. In recent years, such implementations were successfully demonstrated in free space [2]. Meanwhile, efforts for multimode fiber-based technologies are expected to achieve high-dimensional quantum communication without line of sight, based on the existing multimode fiber component and infrastructures.

The leading approach for generating entangled photons in the transverse spatial modes is through spontaneous parametric down conversion in bulk crystal [3]. However, it is extremely challenging to couple transverse entangled photons to fibers since it requires a precise mapping between the free space transverse modes and the fiber guided modes. An alternative is to generate the photons inside the fiber by using spontaneous four wave mixing (SWM). Over the past two decades, generation of photon pairs by SFWM was studied using multiple types of single mode optical fibers [4]. SFWM in multimode fibers was recently utilized for generating photons occupying a high dimensional transverse mode [5]. Generating photon pairs in a superposition of multiple fibers modes, however, requires precise theoretical analysis of the phase matching conditions that will allow multiple SFWM processes in the same spectral band [6]. Experimentally, such phase matching conditions were recently studied for parametric amplification of a weak signal [7], but not in the spontaneous regime. Hence correlations between pairs of photons generated in multiple fiber modes were not measured to date.

In this work, we propose and demonstrate an all-fiber source of photon pairs which occupy multiple fiber modes. We show that the photons are correlated in the guided mode basis, by mapping the mode the photons occupy to their arrival time at the end of a 1 km long fiber. The 1 km fiber acts as an all-fiber in-line mode sorter, in contrast to bulk free-space mode sorters that are typically used for measuring correlations between transverse modes [8]. Using our in-line mode sorting method, we verify for the first time the spatial correlation of the photon pairs generated in a multimode fiber.

Fig. 1. All-fiber multimode source and mode sorter for photon pairs, correlated in the fiber modes. Ultrashort pulses of 140fs at \(\lambda_{\text{pump}} = 695\text{nm}\) are focused into a 1 km-long fiber. At the first few centimeters of the fiber, two pump photons are spontaneously annihilated and two photons called signal and idler are generated at two different spectral bands (\(\lambda_{\text{signal}}=542\text{nm}, \lambda_{\text{idler}}=970\text{nm}\)). At these wavelengths, the fiber (SMF-28) supports a few modes. The modal distribution of the photons is determined by the phase matching condition of the fiber. After the first centimeters, the temporal spread of the pump pulse prevents SFWM. In the next 1km of the fiber, the different modes are separated due to modal dispersion. Higher spatial modes arrive after lower spatial modes, and shorter wavelengths arrive after longer wavelengths. At the output of the fiber the signal and idler photons are spectrally separated by a dichroic mirror (DM), filtered by a bandpass filter (BPF) and their arrival times are registered using two single photon detectors and a time-to-digital converter (TDC). An electronic delay of 70ns is introduced to the idler detector to compensate for chromatic delay between the signal and idler photons.

2. Results

To experimentally test the feasibility of a fiber as a source for high dimensional photon pairs, we launch Ti:Sapphire 140 fs long pulses into a few mode fiber as shown in Figure 1(a). In SFWM, two pump photons are spontaneously annihilated, and two photons called signal and idler are generated in two spectral bands. Each spectral
band is composed of many different spatial modes. The photons occupy the guided modes of the fiber, which can be approximated by the linearly polarized (LP) modes of a weakly guiding optical fiber. The state of the photons governed by the phase matching conditions can be written as: \( |\Psi⟩ = \alpha |LP_{02}⟩_s |LP_{01}⟩_i + \beta |LP_{11}⟩_s |LP_{11}⟩_i \), where subscripts \( s \) (\( i \)) mark the mode of the signal (idler) photon and the coefficients \( \alpha, \beta \) are determined by the nonlinear overlap integrals. The photon pairs are generated mostly in the first few centimeters of the fiber, after which due to the temporal spread of the pump pulse the peak power is too weak for SFWM. The next 1km section of the fiber serves as a mode sorter of the fiber’s guided modes. Due to modal Group Delay Dispersion (GDD), the arrival times of the photons at the end of the fiber depend on their modal distribution and their spectral band, as depicted in Figure 1(b). We can therefore map the arrival times of the photons to their modal decomposition. Although this sorting scheme is quite common in classical optics, it was only recently demonstrated at the single photon regime for weak coherent pulses [9].

To investigate the modal distribution of the two-photon states, we use the mode-to-time mapping and study the temporal two-photon probability \( P(T_s, T_i) \) that describes the probability to detect a signal (idler) photon at time \( T_s \) (\( T_i \)).

To this end, we register the detection times of both detectors using a time-to-digital converter (TDC) and plot the two-dimensional histogram of the arrival times (Figure 2(a)). Two correlation peaks are observed, corresponding to the delay between either \( |LP_{02}⟩_s \) and \( |LP_{01}⟩_i \) (\( \Delta T_1 = 3\text{ns} \)), or between \( |LP_{11}⟩_s \) and \( |LP_{11}⟩_i \) (\( \Delta T_2 = 1.5\text{ns} \)). These delays match numerical calculations for the modal group delays of the fiber. Clearly, the two-photon probability is not-separable, indicating that photons are correlated in the modal basis.

Our demonstration is the first step towards realizations of high-dimensional quantum protocols using standard, commercially available, fibers in an all-fiber configuration. A source of photon pairs which are correlated in the fiber mode basis can be utilized for an efficient distribution of high dimensional heralded single photons. For protocols based on entanglement, a full tomography of the quantum state of the photons will have to be performed.

3. References

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