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Photon-Pair Sources Based on Intermodal Four-Wave Mixing in Few-Mode Fibers

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Abstract: Four-wave mixing in optical fibers has been proven to have many applications within processing of classical optical signals. In addition, recent developments in multimode fibers have made it possible to achieve the necessary phase-matching for efficient four-wave mixing over a very wide bandwidth. Thus, the combination of multimode fiber optics and four-wave mixing is very attractive for various applications. This is especially the case for applications in quantum communication, for example in photon-pair generation. This is the subject of this work, where we discuss the impact of fluctuations in core radius on the quality of the heralded single-photon states and demonstrate experimental results of intermodal spontaneous four-wave mixing for photon-pair generation.

Keywords: quantum communication; photon-pair generation; nonlinear fiber optics; four-wave mixing

1. Introduction

Four-wave mixing (FWM) in optical fibers has been considered for many years in various applications within processing of classical signals, including wavelength conversion [1,2], phase-sensitive amplification [3], low noise amplification [4], and waveform sampling [5]. Until now, most of these applications have been based on the use of single-mode fiber optics. However, recent interest in application of spatial mode division multiplexing in optical communication has resulted in the development of new types of fibers, including few-mode fibers [6,7], which are very interesting for nonlinear fiber photonics and especially FWM. The reason for this is that the existence of multiple modes offers novel phase-matching schemes and phase matching over bandwidths not otherwise obtainable. Until now, most research has been focused on the processing of classical signals. However, in this work we focus on the FWM between multiple spatial modes, also referred to as intermodal FWM, with applications in quantum communication.

Within quantum communication science, the most promising sources for the generation and processing of single-photon states (including detection), rely on devices based on encoding information into atoms, ions, or solid state devices [8]. On the other hand, it is without question that the best carrier of photons over longer distances is the optical fiber. Therefore, within quantum communication there is a vital need for quantum-state sources optimized for low-loss interfacing to optical fibers, approaches for performing quantum-state-preserving frequency conversion, devices that can provide necessary interfacing between solid-state quantum systems (typically operating in the visible spectrum), and infrared photons suitable for fiber propagation.

FWM in single-mode fibers has already been researched for many different applications within the quantum communication sciences, including frequency conversion of quantum states [9], sorting and shaping of temporal modes [10], generation of temporally uncorrelated pure single-photon states [11], and two-temporal-mode photon states by vector FWM [12]. However, the application of single-mode

FWM poses significant challenges, such as spontaneous Raman scattering [13] and phase matching, which is constrained by group-velocity dispersion [14]. To circumvent this problem, photonic crystal fibers have been employed due to their flexible dispersion properties, allowing photon-pair generation at desirable wavelengths and without spectral correlations [15,16]. However, these fibers come with their own challenges, the main one being the difficulty of fabrication with homogeneous dispersion properties, currently limiting fiber lengths to around 1 meter [17,18]. Another possible method that has the potential to alleviate both the Raman scattering problem and the fabrication problem involves few-mode fibers using intermodal four-wave mixing. This process can be phase matched far away from the pump to avoid Raman contamination [19], potentially even spanning from the visible to telecom wavelength ranges [20]. In addition, the fiber design can be very simple (for example a step-index design), making it easier to control dispersion and allowing easy integration into the existing fiber infrastructure.

In this work, we report results on a heralded single-photon source and show the generation of single-photon states with single-photon generation at 1187 nm and a heralding photon at 965 nm. In addition, we show that a simple step-index fiber may be a suitable candidate for intermodal FWM since it provides phase matching between appropriate higher-order modes over a very large bandwidth. By careful fiber design, the quality of the generated single-photon states is very high, i.e., it has a purity of nearly unity, and is robust toward fluctuations in the core radius. Finally, such a fiber also has the advantage of being relatively simple and with a negligible splice loss when spliced to many other fiber types, including low-loss transmission fibers.

2. Spontaneous Four-Wave Mixing for Photon-Pair Generation

Several FWM configurations exist depending on whether the goal is frequency conversion or photon-pair generation. In the case of frequency conversion, the pumps may be at different wavelengths and thus nondegenerate. In the case of photon-pair generation, the pumps can be either completely degenerate or nondegenerate in some degree of freedom, such as polarization, spatial mode, or wavelength. For photon-pair generation, the preferred configuration has traditionally been degenerate FWM where a pump at frequency ω_p is launched into a fiber and during the FWM process two pump photons are spontaneously annihilated to simultaneously create two new photons, one at a lower frequency ω_s and one at a higher frequency ω_i, respecting energy conservation $2\omega_p = \omega_s + \omega_i$. Due to the probabilistic nature of the FWM process, this approach is incapable of delivering single photons on demand. However, detecting one of the two photons implies the existence of the other. This process, whereby one can know exactly when a photon has been created by measuring its partner, is called heralding. It is noted that the probability of generating a photon within a given time slot, as for example determined by the presence of a pump pulse, can be made very close to unity by multiplexing a number of such heralded single-photon sources [21].

Phase Matching

The two-photon states produced by weakly-driven spontaneous FWM are often described by a joint wavefunction of the signal and idler photon frequencies $\mathcal{A}(\omega_s, \omega_i)$, called the joint spectral amplitude [22]. If this amplitude is normalized, then $|\mathcal{A}(\omega_s, \omega_i)|^2$ is the joint probability density of detecting photons with frequency ω_s and ω_i. As with any FWM process, the central frequencies of the produced signal and idler are determined by energy and momentum conservation. In the case of intermodal FWM with a frequency-degenerate pump divided between multiple modes (here the linearly polarized modes denoted as the LP_{01} and LP_{11} modes [23] and guided by the few-mode fiber), the phase matching requires [24]

$$\Delta\beta = \beta^{(01)}(\omega_{p0}) + \beta^{(11)}(\omega_{p0}) - \beta^{(01)}(\omega_{i0}) - \beta^{(11)}(\omega_{s0}) = 0, \tag{1}$$

where $\beta^{(\mu)}(\omega_{j0})$ denotes the propagation constant in mode μ at the frequency ω_{j0}. This configuration generates photons with central frequencies ω_{s0} and $\omega_{i0} > \omega_{s0}$ in the LP_{11} mode and the LP_{01} mode, respectively. Expanding all propagation constants in Equation (1) to the second order around the frequency ω_{p0} in terms of the pump-idler frequency separation $\Omega = \omega_{i0} - \omega_{p0}$ gives the following approximation for the phase mismatch:

$$\Delta\beta = \left(\beta_1^{(01)} - \beta_1^{(11)} + \frac{\beta_2^{(01)} + \beta_2^{(11)}}{2}\Omega\right)\Omega. \tag{2}$$

This equation is obtained by expanding each propagation constant in a Taylor series around ω_{p0} to the second order and exploiting the energy conservation $2\omega_{p0} = \omega_{i0} + \omega_{s0}$, where β_n^{μ} is the nth order derivative of the propagation constant of mode μ at ω_{p0}. Since β_1^{μ} is the inverse group velocity of mode μ at ω_{p0} and β_2^{μ} is related to the group-velocity dispersion of mode μ at ω_{p0}, Equation (2) provides the phase matching as a function of inverse group velocities, the group velocity dispersion of the fiber modes at the pump wavelength, and the pump signal frequency separation (identical to the pump idler frequency separation).

3. Single-Photon Quantum Purity

A vital property of a single-photon state is its quantum purity of the heralded single-photon state. This determines the visibility of Hong-Ou-Mandel interference [25], which is crucial in many quantum-optics applications such as linear optical quantum computing [26]. There are two main mechanisms that degrade the purity. The first is noise photons from other processes e.g., spontaneous processes, pump leakage, detector dark counts etc., leading to a reduction in the number purity of the heralded photon. The second important property is the spectral purity, determined by the spectral correlation between the two photons in the pair before heralding.

3.1. Coincidence-to-Accidental Ratio in Spontaneous FWM

A common measure for the noise performance of a single-photon source is the so-called coincidence-to-accidental ratio (CAR), which is the ratio between generated photon-pairs to accidental counts. An accidental event could, for example, be caused by spontaneous Raman scattering, detector dark counts, or multipair emissions. Detector dark counts are typically negligible, while the multi-pair emissions can be kept low by only generating pairs in less than 10% of the pump pulse bins. In conventional dispersion-shifted silica-based fibers, the CAR has been limited to around 10 [27], but up to more than 100 when cooling the fiber with liquid helium [13] For practical applications, a CAR of 10 is often cited as the lower bound [27].

For a frequency separation $\Omega > 0$ between a frequency-degenerate pump and the quantum sidebands, the spontaneous Raman scattering is proportional to $n(\Omega) + 1$ on the Stokes (signal) side, and $n(\Omega)$ on the anti-Stokes (idler) side [28], respectively, where $n(\Omega)$ is the phonon population number. In addition, it is proportional to a Raman-scattering cross-section specific to the material i.e., here silica [29]. The way to avoid spontaneous Raman scattering is therefore either to choose a material free of Raman scattering such as a noble gas or liquid-filled hollow-core fiber [30], to cool the material, or to obtain phase matching far from the pump frequency. Here, we pursue the latter option, which allows very high CARs, even at room temperature with both continuous [28] and pulsed [31] pumps. The recent development of few mode fibers has made the last option even more relevant since it is now realistic to consider fibers where phase matching may be achieved between multiple modes separated in a wavelength beyond the bandwidth of Raman scattering, and methods have been developed that allow control of the excitation of individual modes [32].

3.2. Spectral Purity

A high spectral purity of photons heralded from a parametric source is the second requirement for a very high-purity single-photon source. The heralded spectral purity can be calculated from a Schmidt decomposition of the joint spectral amplitude [33]

$$\mathcal{A}(\omega_s, \omega_i) = \sum_n \lambda_n f_n(t_s) g_n(t_i), \tag{3}$$

where λ_n are Schmidt coefficients and f_n, g_n are Schmidt functions. If the state is normalized, the spectral purity is then

$$P = \sum_n |\lambda_n|^4. \tag{4}$$

without careful dispersion engineering, the spontaneously created two-photon state is generally spectrally entangled and the heralding process projects the heralded photon into a classical mixture of spectral modes making it impure. In fibers, various schemes exist to generate pure photons without extensive spectral filtering with both degenerate pumps [34,35] and nondegenerate pumps [11,24,36].

4. Few-Mode Fiber Design for Photon-Pair Sources

In nonlinear signal processing, much effort has been put into design of fibers to maximize the nonlinear strength and to minimize the Brillouin scattering [37] while maintaining a specific group-velocity dispersion. As a consequence, specific fibers, for example microstructured fibers or aluminum co-doped fibers, have been developed for this purpose. However, when choosing or optimizing a fiber for photon-pair generation based on spontaneous FWM, the phase matching as discussed above is the most critical parameter. In addition, it is important to obtain phase matching at wavelengths well separated from the pump to minimize the noise photons from spontaneous Raman scattering. For the purpose of intermodal FWM, a few-mode step index fiber that guides the fundamental mode and the LP_{11} mode-group enables the use of a pump wavelength at 1064 nm, where pump sources are readily available, while at the same time minimizing the impact of Raman scattering.

Compared to other proposed fibers, the few-mode step-index fiber has a very simple fiber design, is easy to splice to most other fibers (including transmission fibers), and it can provide the necessary phase matching. Figure 1a shows predicted inverse group velocity curves for the LP_{01} mode and the LP_{11} mode in a step-index fiber with a core radius of 4 micrometers and a germanium co-doping concentration of 6.7 % to raise the refractive index of the core, corresponding to a core-cladding contrast in a refractive index of $\Delta n = 9.9 \times 10^{-3}$ at 1064 nm. The inverse group velocities directly determine the phase matching as in Equation (2) with the pump at 1064 nm and signal and idler at 1216 nm and 946 nm, respectively, all marked by black dots. The gray shaded zone marks a frequency range of 32 THz on both sides of the pump wavelength, indicating the region where spontaneous Raman scattering is the strongest. Thus, with a simple step-index fiber, phase matching can be achieved outside the Raman active zone using only two modes, and the mode-nondegenerate pumps are very useful for generating pure photons as we discuss later [24].

From FWM in single-mode fibers it is well known that fluctuations in the group-velocity dispersion are a critical issue [38]. Such fluctuations may be caused by very small fluctuations in the core radius. This has lead to the development of fibers where the group velocity dispersion properties have been made robust toward fluctuations in core radius [39]. Such dispersion fluctuations caused by geometric fluctuations (mainly core radius fluctuations in the case of step-index fibers) are equally critical in the case of all-fiber photon-pair sources. This represents a major challenge in fabricating fibers for pure photon generation, especially for schemes where long fiber lengths are advantageous. Fiber inhomogeneities change the dispersion and the phase matching along the fiber length, introducing undesired spectral correlations to the two-photon state, leading to reduced purity of heralded single-photon states. This is currently a limiting factor in photonic crystal fibers, which represent the preferred platform for pure photon generation in fibers [17,18].

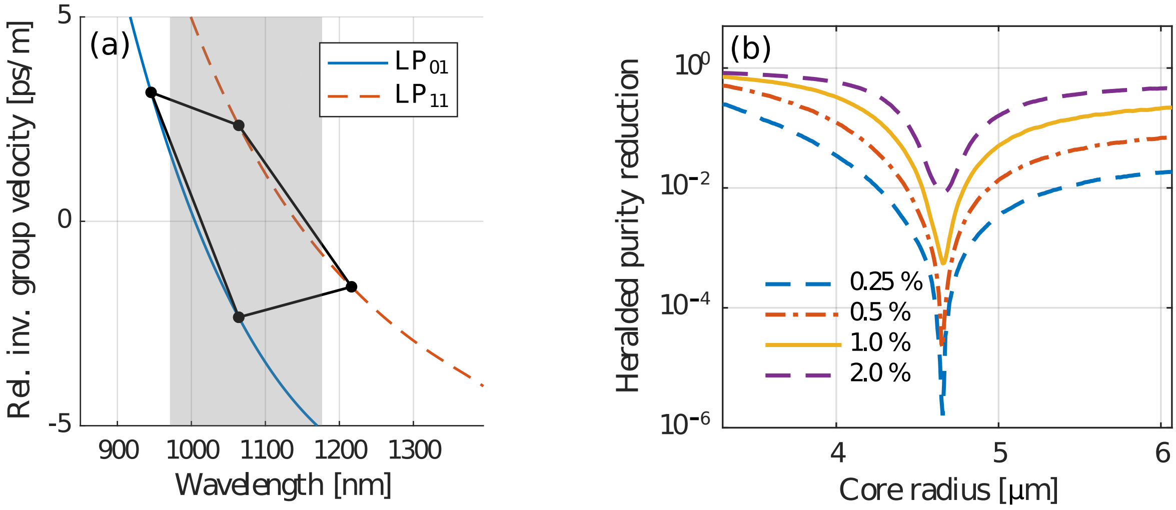

Figure 1. (**a**) Visualization of phase matching for two fiber modes. The inverse group velocities are relative to the average of the inverse group velocities of the two modes at the pump wavelength of 1064 nm. (**b**) The reduction in purity (i.e., the purity without fluctuations minus the purity with fluctuations) from a near-unit value depending on fiber-core radius using the specific scheme in [24] for varying degrees of relative core radius fluctuations in a step-index fiber with a doping concentration of 6.7%.

Such geometric fluctuations can be modeled by expressing the phase factor on the joint amplitude as $\int dz\Delta\beta(z)$ instead of $\Delta\beta z$. By letting the core radius of a step-index fiber randomly fluctuate throughout the length of the fiber, with varying relative fluctuation strengths, $\Delta\beta(z)$ can be simulated many times. Figure 1b shows the reduction in purity of this fluctuating case, with relative core radius fluctuations of 0.25% to 2.0%, compared to the case of constant $\Delta\beta$, as a function of (average) core radius. This is for a specific scheme based on intermodal nondegenerate four-wave mixing where the non-fluctuating purity is very close to unity (>0.98 for all core radii) [24]. We see that for this doping concentration the purity reduction depends strongly on the core radius. Importantly, in a range around 4.65 µm the scheme is very robust to fluctuations in core radius and even a very large degree of fluctuation of 2% in core radius results in only 1% reduction in purity, which is acceptable for practical applications. This shows that it is sometimes possible to design a fiber with a very high robustness to this kind of fluctuation.

From the figure, the required precision in the manufacturing process can be easily estimated. Consider a high-purity source with the chosen design. Then if, for example, a less than 1% purity reduction is required with 1% core radius fluctuations, this requires that the core radius be between 4.53 µm and 4.80 µm.

5. Experimental Intermodal Photon-Pair Generation

To demonstrate the concept of intermodal FWM for photon-pair generation, we use a commercial few-mode step-index fiber (which is not optimized to reduce the impact fluctuations) to generate photon pairs beyond the Raman response in silica by using the setup in Figure 2.

A 1065-nm pulsed 10 ps laser is used to pump the few-mode fiber. To achieve phase matching beyond the main Raman peak, we perform non-degenerate intermodal FWM by exciting the pump in a combination of the LP_{01} and LP_{02} modes. The phase-matching condition is equivalent to Equation (2), but with LP_{11} substituted by LP_{02}. This in turn generates idler and signal in the LP_{01} (965 nm) and LP_{02} (1187 nm) modes, respectively. The mode excitation is done by a tapered splice from a single-mode fiber to a few-mode fiber. After generating the photon pairs, they are spectrally filtered by Gaussian filters with a full-width half maximum of 0.5 nm to reduce noise, and then detected using avalanche photodiode (APD) single-photon detectors.

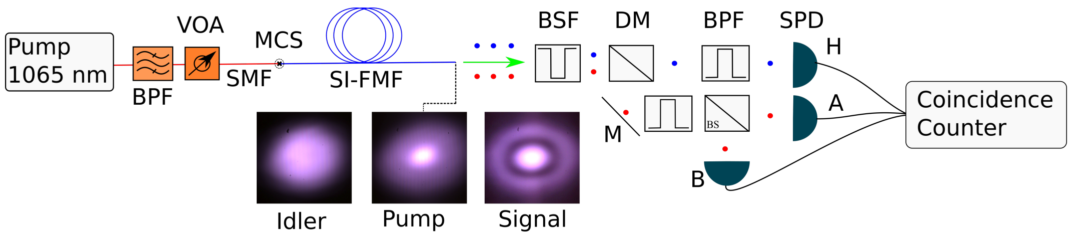

Figure 2. Experimental setup: BPF: bandpass filter, SMF: single-mode fiber SI-FMF step-index few-mode fiber, BSF: bandstop filter, DM dichroic mirror, M: mirror, SPDs: single-photon detector. Inserted images show the idler in the LP_{01} mode, the signal in the LP_{02} mode, and the pump in a combination of the LP_{01} and LP_{02} modes.

First, the desired intermodal process is investigated classically by pumping with high-power pulses in 100 m of the few-mode fiber. This generates intermodal modulation instability, as shown in Figure 3a. Peaks A and D are imaged and are shown to be from the desired LP_{01}–LP_{02} nonlinear process. Peak C is the first-order Raman peak. The peaks marked by a circle are spurious peaks from residual pump in other higher-order modes, and cascaded FWM. The most prominent peak at 1018 nm is from the LP_{11}–LP_{02} interaction, and its relatively large prominence is due to the signal being Raman-amplified in the first-order Raman peak, which does not happen in a lower power photon-pair experiment.

To characterize the constructed heralded single-photon source, Figure 2 the CAR is determined by the time correlation between the signal and idler channel photons, which is given as $CAR = (CC - CC_{acc})/CC_{acc}$ where CC is the coincidence counts from the same pump pulse, and the accidental coincidences CC_{acc} are estimated by evaluating the signal idler coincidences from separate pump pulses. Thus, a high CAR means that the quantum state is very close to a two-photon state.

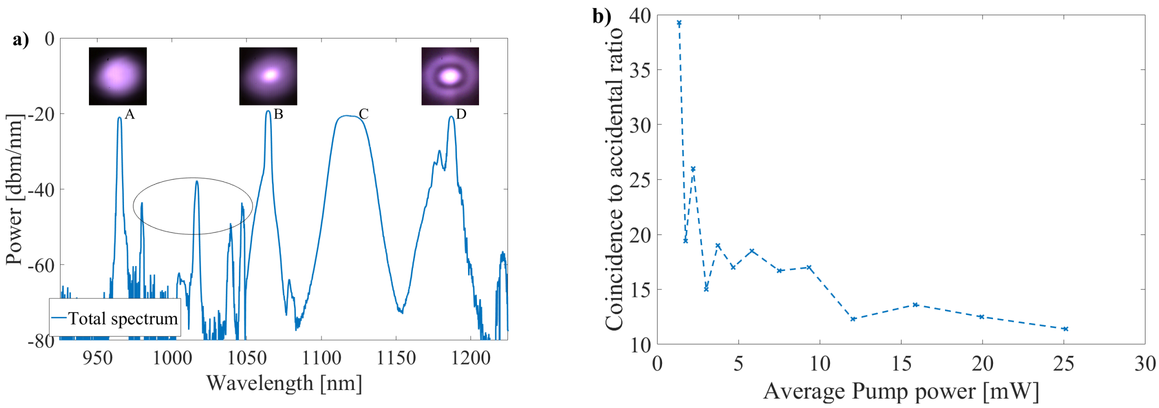

Figure 3. (**a**) Spectrum showing the intermodal four-wave mixing (FWM) between the LP_{01} and LP_{02} modes. Notice the narrowband phase-matching compared regular single mode FWM. This makes it suitable for generating pure heralded photons without excessive filtering. (**b**) Coincidence to accidental ratio (CAR) as a function of average pump power. The occurrence of accidental coincidence increases with rising pump power, lowering the CAR.

Figure 3b shows the CAR as a function of average pump power and for all powers the CAR is above 10, which makes the source useful for a range of quantum applications [27]. Lastly, the heralded second-order correlation is measured to be 0.13 at a pump power of 25 mW, which shows the source operates in the single-photon regime.

6. Conclusions

The combined use of four-wave mixing and higher-order modes in optical fibers has promising applications within quantum communication sciences. In this paper, we have demonstrated a heralded single-photon source based on these principles. One of the important characteristics for such a source is the purity of the generated single-photon states. We have shown how the purity of a heralded single-photon state is impacted by fluctuations in the radius of the core. From this, we have demonstrated that careful design of the fiber enables a design that is nearly independent of fluctuations of the core radius. Lastly, we reported experimental results of a photon-pair source based on intermodal four-wave mixing in a few-mode step-index fiber. The intermodal phase matching allows the photons to be generated outside the Raman-active zone close to the pump, resulting in high coincidence-to-accidental ratios without cooling.

Author Contributions: E.N.C. performed the experimental work; J.G.K. carried out the theoretical work. The results were reviewed by all authors and all authors contributed equally to writing the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FWM	Four-wave mixing
LP	Linearly polarized
CAR	Coincidence-to-accidental ratio
APD	Avalanche photodiode

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