Characterization of a fiber based heralded single photon source at telecom wavelength

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ABSTRACT

Single photon sources are fundamental elements for quantum information science, mainly for quantum key distribution (QKD) applications. Nevertheless, on-demand single photon sources are difficult to obtain, and their implementation in a practical application, such as QKD, demands further developments. A different approach to a single photon source is based on the generation of quantum correlated photon-pairs. In that case, the detection of one photon of the pair heralds the presence of the second photon. In this work, we present a heralded single photon source based on the spontaneous four-wave mixing (FWM) process in optical fibers. We characterize theoretically the heralded photon source by means of the conditional second-order coherence function, $g_c^{(2)}$, with $g_c^{(2)} = 0$ for a perfect single photon source. We observe the nonclassical nature of the source, with $g_c^{(2)} \ll 1$ far below the classical limit. Our results also show that the Raman scattering in general degrades the quality of the source, due to the generation of uncorrelated photons. However, our findings show that in some frequency regimes we are able to observe a $g_c^{(2)} \approx 10^{-3}$. Moreover, our analysis shows that the propagation of the photons in a standard single mode fiber (SSMF) does not change significantly the value of $g_c^{(2)}$, for distances of $L < 25/\alpha$, with α the loss coefficient of the SSMF. This results can help to guide the development of single photon sources for quantum information applications.

Keywords: Quantum Communications, Four-Wave Mixing, Raman Scattering, Single Photon Source, Photon Statistics

1. INTRODUCTION

The continuous increase of Internet traffic over optical fibers has made the security one of the most important issues on the modern optical communication systems. In that scenario, quantum key distribution (QKD) can provide an alternative to the nowadays mathematical unproved cryptographic schemes[1]. In this context, the generation and transmission of single photons over optical fibers appears as an important topic for QKD applications. However, ideal or on-demand single photon sources are very difficult to realize experimentally[1, 2]. Due to that, most of the nowadays implemented QKD systems uses faint laser pulses as an approximation to a true single photon source[1]. A different approach to obtain a single photon source is based on the generation of quantum correlated photon-pairs in a nonlinear material[3]. In this kind of sources, the detection of one photon of the pair is used to heralded the presence of its twin photon[3, 4]. In this case, the spontaneous four-wave mixing (FWM) process in optical fibers can be used to obtain quantum correlated photon-pairs at telecom band[5].

The spontaneous FWM process as a source of heralded single photons was investigated experimentally in Refs. 6–10. Subsequent studies, Ref. 11, characterize the photon statistics of the heralded single photon source based on FWM considering the spectral shape of pump pulses. In this work, we present a theoretical characterization of a heralded single photon source based on spontaneous FWM in optical fibers.

This paper contains four sections. In section 2, we discuss the conditioned second-order coherence function for the heralded single photon source, and we present the theoretical model that describes the generation of quantum-correlated photon pairs through the FWM, considering the Raman scattering process. Section 3 reports the theoretical results. The main conclusions of this paper are summarized in section 4.

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2. THEORY

The photon statistics of a heralded photon source can be obtained through the measurement of conditional second-order coherence function, $g_c^{(2)}(t_1,t_2|t_i)$[12]. This can be achieved through the implementation of a Hanbury-Brown and Twiss interferometer[12] for the signal photons, conditioned to a detection of an idler event. In this work, we admit that an unique pump field at frequency ω_p is sent to a dispersion shifted fiber (DSF) in order to induce the FWM process. The DSF has a length of $L_1 = 300$ m, nonlinear parameter of $\gamma = 2$ W^{-1}km^{-1}, zero dispersion-wavelength of $\lambda_0 = 1550$ nm, third- and fourth-order dispersion coefficients at λ_0 of $\beta_3 = 0.1$ ps^3/km and $\beta_4 = 10^{-4}$ ps^4/km, respectively. The DSF input pump power is $P_0 = 30$ mW. At DSF output a filter blocks the pump photons, and the signal and idler photons generated through FWM at frequencies ω_s and ω_i, respectively, are sent to a single mode fiber (SMF) with length L, and loss coefficient, $\alpha(\omega) = 0.25$ dB/km. The idler photons are detected by a single photon detector module, Det$_i$, whereas the signal photons are collected by two single photon detectors, Det$_1$ and Det$_2$. A detection of an idler photon in Det$_i$ heralds the presence of a signal photon in Det$_1$ and Det$_2$.

2.1 Theory of the spontaneous FWM process

The FWM process considered here consists of a single cw-pump field at frequency ω_p producing signal (ω_s) and idler (ω_i) photons, such that $2\omega_p = \omega_s + \omega_i$. Moreover, we assume that simultaneously with the FWM in the DSF occurs the Raman scattering process that generate uncorrelated (noise) photons. In that case the signal and idler annihilation operators in frequency domain at DSF output are given by[13–15]

$$\hat{A}(\mathrm{L}_1,\omega_u) = \Big(\Lambda_u(\mathrm{L}_1)\hat{A}(0,\omega_u) + \Gamma_u(\mathrm{L}_1)\hat{A}^\dagger(0,\omega_v) + \hat{N}(\mathrm{L}_1,\omega_u)\Big)\Phi(\mathrm{L}_1), \tag{1}$$

where $\Lambda_u(\mathrm{L}_1)$, $\Gamma_u(\mathrm{L}_1)$, and $\Phi(\mathrm{L}_1)$ functions were taken from Ref. 13. In (1), $u = s$ denotes the signal wave, and $u = i$ denotes the idler field, with $u \neq v = s\,\mathrm{or}\,i$, and

$$\hat{N}(\mathrm{L}_1,\omega_u) = i\int_0^{\mathrm{L}_1} \hat{m}(z,\Omega_{up})\Big(A_p\Lambda_u(\mathrm{L}_1 - z) - A_p^*\Gamma_u(\mathrm{L}_1 - z)\Big)dz, \tag{2}$$

where A_p is the pump field envelop such that $P_0 = |A_p|^2$, $\Omega_{up} = \omega_u - \omega_p$, $\hat{m}(z,\Omega_{up})$ is the Hermitian phase noise operator which accounts for the spontaneous Raman scattering, defined as in Ref. 16.

2.2 Conditional second-order coherence function

The conditional second-order coherence function $g_c^{(2)}(t_1,t_2|t_i)$ for the signal photons is given by[12,17,18]

$$g_c^{(2)}(t_1,t_2|t_i) = \frac{\langle \hat{E}_s^\dagger(t_1)\hat{E}_s^\dagger(t_2)\hat{E}_s(t_2)\hat{E}_s(t_1)\rangle_{\mathrm{pm}}}{\langle \hat{E}_s^\dagger(t_1)\hat{E}_s(t_1)\rangle_{\mathrm{pm}}\langle \hat{E}_s^\dagger(t_2)\hat{E}_s(t_2)\rangle_{\mathrm{pm}}}. \tag{3}$$

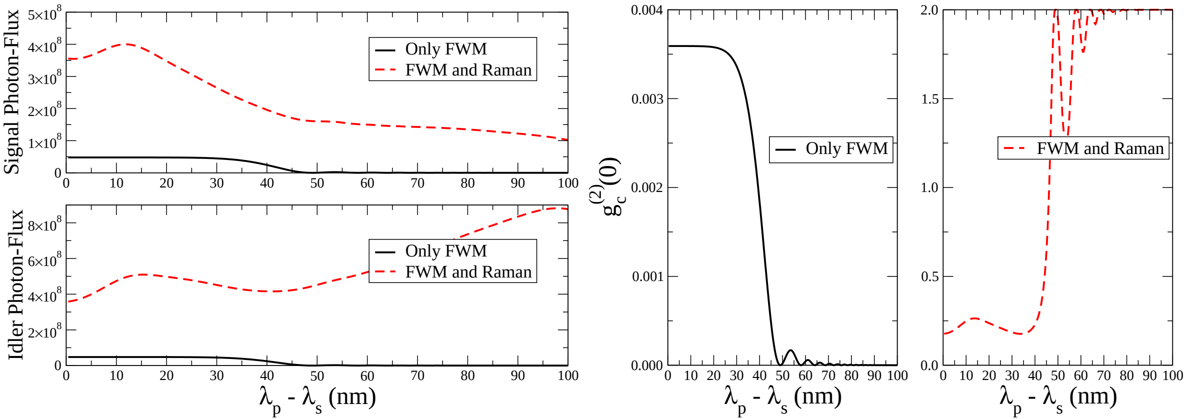
where $\langle \hat{X}\rangle_{\mathrm{pm}}$ for any operator $\hat{X}$, is the average over the post-measurement state (after detection of an idler event), given by[12,17,18]

$$\langle \hat{X}\rangle_{\mathrm{pm}} = \frac{\langle \hat{E}_i^\dagger(t_i)\hat{X}\hat{E}_i(t_i)\rangle}{\langle \hat{E}_i^\dagger(t_i)\hat{E}_i(t_i)\rangle}, \tag{4}$$

and $\hat{E}_u(t)$ is the positive-frequency field operator. The numerator and denominator in the conditional second-order coherence function (3) can be reduced to the sum of products of second-order moments using the Gaussian moment-factoring theorem[19].

3. RESULTS

In this section we present the results for the statistical characterization of the heralded single photon source, through the analysis of the $g_c^{(2)}(t_1,t_2|t_i)$ function. A $g_c^{(2)}(t_1,t_2|t_i) = 0$ represents an ideal conditional single photon source, $g_c^{(2)}(t_1,t_2|t_i) = 1$ denotes a source with a Poissonian distribution, and a $g_c^{(2)}(t_1,t_2|t_i) = 2$ corresponds to a thermal statistics[6,15,20].



(a) (b)

Figure 1. (a): Signal and idler photon fluxes at DSF output as a function of wavelength separation between pump and signal field; (b): Conditional second-order coherence function given by (3) as a function of wavelength separation between pump and signal field, for the case L=0, at trigger time. We have used $\lambda_p = \lambda_0$.

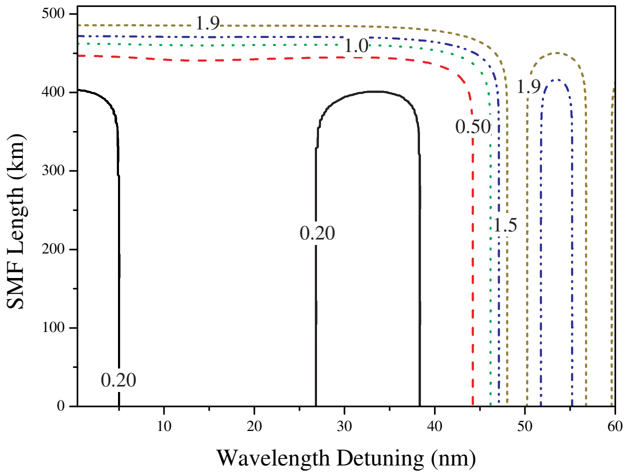


Figure 2. Conditional second-order coherence function given by (3), at trigger time, as a function of SMF length, L, and as a function wavelength detuning between pump and signal fields. We have used $\lambda_p = \lambda_0$.

In Fig. 1 we present results for the signal and idler photon-fluxes, Fig. 1(a), and for $g_c^{(2)}(0)$, Fig. 1(b), as a function of wavelength detuning between pump and signal field, $\lambda_p - \lambda_s$, for the case L=0. The $g_c^{(2)}(t_1, t_2|t_i)$ function is evaluated at trigger time, $g_c^{(2)}(t_1, t_2|t_i) = g_c^{(2)}(0)$. Results show that, when we consider only the FWM process, the $g_c^{(2)}(0)$ function in Fig. 1(b) is of the order of 3.5×10^{-3}, an almost perfect single photon source. Increasing the wavelength separation between pump and signal field, the value of the $g_c^{(2)}(0)$ function decreases. That decrease is mainly due to the fact that the signal and idler photon-fluxes represented in Fig. 1(a) decrease with the increase of $\lambda_p - \lambda_s$. When we consider both FWM and Raman scattering processes we obtain $g_c^{(2)}(0) \approx 0.2$, for small values of $\lambda_p - \lambda_s$, Fig. 1(b). This increase on $g_c^{(2)}(0)$, when compared with the case where we consider only the FWM process, is due to the uncorrelated (noise) photons generated by Raman scattering. Increasing the wavelength detuning between pump and signal field, the $g_c^{(2)}(0)$ function tends to 2, a thermal statistical. This is due to the fact that, most of the signal and idler photons are generated through Raman scattering process, as presented in Fig. 1(a). Since the Raman noise photons presents a thermal statistics[6], we observe a $g_c^{(2)}(0) \approx 2$ for our heralded single photon source.

In Fig. 2 it is presented the conditional second-order coherence function given by (3), at trigger time, as a function of SMF length, and as a function of wavelength detuning $\lambda_p - \lambda_s$. In Fig. 2 we have used $\lambda_p = \lambda_0$, and we consider the Raman scattering process. Results indicate that, for certain regimes of wavelength detuning it is possible to maintain a constant value of $g_c^{(2)}(0) \approx 0.2$ over distances of the order of L$\approx$ 400 km. However, for high values of SMF length, results show that the statistics of the source tends to thermal. This can be due to the SMF loss coefficient that absorbs must of the photons generated through FWM in the DSF. For high values of wavelength detuning, the statistics at SMF output is thermal, since at SMF input $g_c^{(2)}(0) \approx 2$, according with the results in Fig.1(b).

4. CONCLUSIONS

In summary, we investigate the statistics of a heralded single photon source based on spontaneous FWM process inside a DSF. We observe the nonclassical nature of the source over a high wavelength bandwidth. In the absence of Raman scattering process, we were able to obtain a $g_c^{(2)}(0) \approx 10^{-3}$. Our results also show that, the propagation of the photons in a SMF, does not change significantly the statistics of the source, for L< 400 km. After that, the statistics of the heralded photons changes to a thermal statistics with $g_c^{(2)}(0) = 2$. For high values of $\lambda_p - \lambda_s$ the statistics is the same at SMF input/output, with $g_c^{(2)}(0) \approx 2$.

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