Optics Communications 327 (2014) 31–38

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Comprehensive characterization of a heralded single photon source based on four-wave mixing in optical fibers

Nuno A. Silva [a,b,*], Armando N. Pinto [a,b]

[a] *Department of Electronics, Telecommunications and Informatics, University of Aveiro, 3810-193 Aveiro, Portugal*
[b] *Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*

ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form
31 January 2014
Accepted 3 February 2014
Available online 13 February 2014

Keywords:
Fiber absorption
Four-wave mixing
Heralded single photon source
Nonlinear fiber optics
Raman scattering

ABSTRACT

A detailed statistical characterization of an optical signal obtained from a heralded single photon source is performed. The source is based on the spontaneous four-wave mixing process, and a dispersion shifted fiber is used to achieve phase matching. At source output, the derivation of the second-order coherence function shows the importance of choosing carefully the frequency detuning between the optical fields in order to avoid the uncorrelated photons generated through Raman scattering. Results indicate that with an accurate adjustment of the source parameters, it is possible to obtain an almost perfect conditional single photon source using spontaneous four-wave mixing. When a transmission fiber is considered, the losses change the source statistics due to the coupling with the noise absorption reservoir. Nevertheless, even at room temperature the impact of the absorption reservoir tends to be quite small, and the change is only observable for very long transmission lengths.

1. Introduction

Single photon sources at telecom band are basic elements for quantum key distribution (QKD) systems [1]. However, perfect single photon sources are very complex to implement, since in general they demand cryogenic temperatures or must be operated in vacuum [1,2]. Due to that, practical implementations of QKD protocols tend to rely on faint laser pulses, as an approximation to a source of single photons [1]. Nevertheless, a faint laser pulses obeys to a Poissonian statistics, which could lead to a loss of security [1]. An alternative approach for single photon generation relies on sources of quantum correlated photon-pairs [3]. In this kind of sources, typically known as heralded single photon sources, the detection of one photon of the pair heralds the presence of its twin photon [3,4]. In this context, the spontaneous four-wave mixing (FWM) process appears as a natural solution to obtain time correlated photon-pairs in $\chi^{(3)}$ materials [5–16]. Moreover, when implemented in dispersion shifted fibers (DSFs) the spontaneous FWM process can efficiently produce photon-pairs at the 1550 nm telecom window [6]. Nevertheless, inside the DSF and simultaneously with the FWM occurs the Raman scattering process, which generates uncorrelated (noise) photons. The detailed statistical characterization of the heralded single photon source remains an open issue, to the best of our knowledge. Besides that, the theoretical characterization of the statistics after propagation in a lossy standard single mode fiber (SSMF) has not been done yet.

The generation of quantum correlated photon-pairs through spontaneous FWM in optical fibers was investigated in [5,6,17], and their work was latter extended to account for the spectral shape of pump pulses [18–20]. Subsequent studies have include the spontaneous Raman scattering that occurs inside the optical fiber, and inevitably accompanies the FWM process [21–25]. Recently, in [26,27] was investigated the impact of fiber loss on the generation of quantum correlated photon-pairs through FWM. The FWM process as a source of heralded single photons was investigated experimentally in [28–32], through the measurement of the second-order correlation function. Subsequent studies [33] characterize the photon statistics of that source through the analysis of the Wigner function, and its performance in a QKD system. In [34] was investigated a synchronous heralded single photon source based on FWM in a liquid nitrogen cooled optical fiber. Recently, in [35] was shown that for a heralded single photon source based on FWM narrow band filters are not mandatory to obtain a high heralding efficiency. In [36] were investigated different schemes that best mitigate the trade-off between high purity and high photon generation rate. Recently, in [37] was

---

* Corresponding author at: Instituto de Telecomunicações, Campus Universitário de Santiago, 3810–193 Aveiro, Portugal. Tel.: +351 234 377 900; fax: +351 234 377 901.
E-mail address: nasilva@av.it.pt (N.A. Silva).

http://dx.doi.org/10.1016/j.optcom.2014.02.002
0030-4018

presented a quantum theory for the heralded single photon source based on FWM that takes into account the spectral shape of pump pulses. Moreover, in [37] were also reported experimental results for the conditioned second-order coherence function and heralding efficiency.

In this work, we focus on the theoretical evaluation of the conditioned second-order coherence function, $g_c^{(2)}$. Our goal is to quantify the impact of the Raman scattering and the propagation loss effects on the statistics of a heralded single photon source. We identify regimes for the pump power and frequency detuning that minimizes the $g_c^{(2)}$ function. We verify the nonclassical nature of the photon source over a high frequency bandwidth. We consider the presence of noise photons from the Raman scattering process and from a room temperature absorption reservoir.

This paper contains five sections. In Section 2, we present the theoretical model that describes the generation of quantum-correlated photon pairs through the FWM process, considering the Raman scattering process and the propagation loss effects. In Section 3, we discuss the conditioned second-order coherence function for the heralded single photon source. Section 4 reports the main results. The main conclusions of this paper are summarized in Section 5.

2. Theory

In this section, we present a quantum model for the generation of the signal and idler photon-pairs through spontaneous FWM inside a dispersion shifted fiber (DSF) [6], and for the propagation of the signal photons in a standard single mode fiber (SSMF). We consider the Raman scattering that inevitably accompanies the FWM process during the generation of the signal and idler photons inside the DSF. We also take into account the loss mechanism that affect the propagation of the signal photons in the SSMF.

The photon number distribution of the heralded single photon source can be obtained through the setup shown in Fig. 1. In the figure, a pump at ω_p is sent through a DSF with length L_1. Inside the DSF two pump photons are annihilated, and two new photons are created at frequencies ω_s (signal field) and ω_i (idler field), such that $2\omega_p = \omega_s + \omega_i$, with $\omega_s > \omega_i$. Inside the DSF are also generated Raman noise photons that inevitably accompanies the FWM process. At the DSF output, the three optical fields plus noise passes through an arrayed waveguide grating (AWG) to separate the pump from the signal and idler fields. The output idler photons are spectrally filtered (H_i) and collected by the photon detector module, Det_i. The signal photons pass through a SSMF with length L_2 and an optical filter H_s, before been launched into a non-polarizing beam splitter (BS). Note that, we consider two identical filters with central frequency $\overline{\omega}_i$ for H_i and $\overline{\omega}_s$ for H_s, such that $2\omega_p = \overline{\omega}_s + \overline{\omega}_i$. At the beam splitter output the signal photons are collected by the photon detector modules, Det_1 and Det_2. In Fig. 1, τ_{1i} and τ_{2i} represent an adjustable time delay in each arm of the beam splitter. The counting system in Fig. 1 measures the delays between a trigger click in Det_i and the clicks in Det_1 and Det_2, i.e. $t_1 - t_i + t_R$ and $t_2 - t_i + t_R$, with t_1, t_2, and t_i representing the time detection event in detector Det_1, Det_2, and Det_i, respectively, and t_R is a reference time. The reference time t_R is adjusted in order to compensate for the path delay difference between signal and idler photons. Single and coincidence measurements can be performed in order to obtain $g_c^{(2)}(t_1, t_2|t_i)$ [28,37].

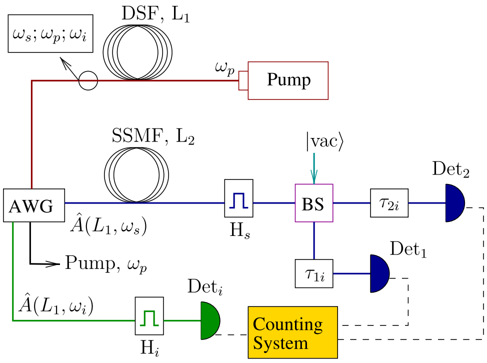

Fig. 1. Setup to obtain the photon counting statistics of the heralded single photon source based on spontaneous FWM in optical fibers. The dashed lines represent electrical signals and the solid lines the optical path. Details of the setup are presented in the text.

In this work, we develop a theoretical model for the heralded single photon source assuming a continuous wave pump field. However, in practice pump pulses of duration τ_p and repetition rate of f_p are used to implement time-correlated photon-pair sources. Neglecting the Raman scattering, the role of the pump shape spectrum on the generation of signal and idler photon pairs can be obtained using the Schrödinger picture [37,38]. In that case, we can describe the signal and idler waves by means of the two-photon quantum state, rather than using the expectation values [18,37]. To include the Raman scattering in a pulsed regime we can use the theoretical formalism developed in this work, if the fiber length L_1 is shorter than its walk-off length [39]. In that scenario, we must multiply the signal and idler photon fluxes, and the signal-idler correlation coefficients by the pump duty cycle ($\tau_p f_p$) [25].

2.1. Photon-pair generation inside the DSF

We focus on the single undepleted pump configuration, where a unique pump is used to induce the FWM process, see Fig. 1. In this configuration, the signal and idler annihilation operators in the frequency domain at DSF output are given by [25,40,41]

$$\hat{A}(L_1, \omega_u) = (\Lambda_u(L_1)\hat{A}(0, \omega_u) + \Gamma_u(L_1)\hat{A}^\dagger(0, \omega_v) + \hat{N}(L_1, \omega_u))\Phi(L_1), \tag{1}$$

with $\langle \hat{A}^\dagger(L_1, \omega_u)\hat{A}(L_1, \omega_u)\rangle$ representing the mean spectral photon-flux density, where $u \neq v = s$ or i denote the signal and idler field [42]. In (1), $\Phi(L_1) = \exp\{i(k_p + \gamma P_0)L_1\}$, where k_p is the pump propagation constant, γ is the DSF nonlinear parameter, L_1 is the DSF length, and P_0 is the input pump power for a continuous wave optical field. In (1), the field operator satisfies the commutation relation [25]

$$[\hat{A}(L_1, \omega), \hat{A}^\dagger(L_1, \omega')] = 2\pi\delta(\omega - \omega'), \tag{2}$$

where ω and ω' are two angular frequencies. The coefficients $\Lambda_u(L_1)$ and $\Gamma_u(L_1)$ appearing in (1) are given by [25]

$$\Lambda_u(L_1) = \left(\cosh(g_{up}L_1) + i\frac{\kappa_{up}}{2g_{up}}\sinh(g_{up}L_1)\right)e^{i((k_u - k_v)/2)L_1} \tag{3a}$$

$$\Gamma_u(L_1) = i\frac{\gamma\eta_{up}}{g_{up}}A_p^2\sinh(g_{up}L_1)e^{i((k_u - k_v)/2)L_1}, \tag{3b}$$

with

$$g_{up}^2 = ((\gamma\eta_{up}P_0)^2 - (\kappa_{up}/2)^2) \tag{4a}$$

$$\kappa_{up} = \Delta\beta + 2\gamma P_0\eta_{up} \tag{4b}$$

$$\eta_{up} = 1 - f_R + f_R\tilde{R}_a(\omega_u - \omega_p) + f_R\tilde{R}_b(\omega_u - \omega_p), \tag{4c}$$

with ω_p representing the pump frequency, A_p is the pump field amplitude such that $P_0 = |A_p|^2$, and $\Delta\beta$ is the linear phase-mismatch parameter [39,43]. In (4c), $f_R = 0.18$ is the fractional contribution of the Raman process to the nonlinear refractive