Time coincidence of entangled photon pairs using spontaneous four-wave mixing in a fiber loop

A. J. Almeida, S. R. Carneiro, N. A. Silva, N. J. Muga and A. N. Pinto

***Abstract*—We obtained a source of entangled photon pairs in the 1550-nm wavelength band using spontaneous four-wave mixing (SpFWM) in a Sagnac fiber loop. Time coincidence of entangled photon pairs was verified for a 300-m dispersion-shifted fiber (DSF), using an avalanche photodiode (APD).**

***Index Terms*—Spontaneous four-wave mixing, Quantum entanglement, Sagnac fiber loop, Coincidence.**

I. INTRODUCTION

THE generation of entangled photon pairs is one of the most important technologies for realizing quantum communications [1]. Li *et al.* demonstrated the generation of polarization entangled photon pairs using SpFWM in a Sagnac fiber loop [2], and later, Takesue and Inoue used the SpFWM processe in a Sagnac fiber loop formed by a polarization beam splitter (PBS) and a DSF, with only fiber connections [3]. Following that work, we implemented a similar experimental setup in order to verify the time coincidence of entangled photon pairs generated by SpFWM in a Sagnac fiber loop, using a 300-m DSF, in the 1550-nm wavelength band. This experiment confirmed the feasibility of generating entangled photon pairs that can be used to verify the violation of Bell's inequality.

II. ENTANGLED PHOTON PAIRS GENERATION

A. Experimental Setup

In the experimental setup, presented in Fig. 1, a pump at $\lambda_p = 1550.918$ nm from a tunable laser source (TLS), passes through a polarization controller (PC1), and is externally modulated to produce optical pulses with a width at half maximum of ~1 ns and a repetition rate of 1 MHz. The pump pulse sidebands were removed using an optical circulator and a fiber bragg grating (FBG). The pulses were amplified using an erbium-doped fiber amplifier (EDFA), and the correspondent noise introduced was removed by the fixed optical filter (F_{p1}). Next, the state of polarization of the pulses was adjusted to 45° using a polarization controller (PC2) and a linear polarizer (LP1). Then the pulses were launched into a Sagnac fiber loop, which consisted of a 4-port PBS, a DSF and two PCs (PC3 and PC4). The peak power of the pump pulse was 22 mW at the input of the Sagnac fiber loop. We adjusted PC3 and PC4 so that the generated photon pairs were properly output from the loop (on port 4 of PBS). The output photons from the loop were input into a fixed optical filter (F_{p2}) to suppress the pump photons, and were then launched into an arrayed waveguide grating (AWG) with a 100 GHz channel spacing to separate the idler and signal photons. AWG output channels with peak wavelengths of $\lambda_i = 1554.134$ nm and $\lambda_s = 1547.715$ nm were used for the idler and signal, respectively. The pump, idler and signal photons, with frequencies w_p, w_i and w_s, respectively, satisfy the relationship [3]:

$$2w_p = w_i + w_s\,. \tag{1}$$

The output photons from the AWG were filtered using a cascade of fixed optical filters (F_i and F_s) to further suppress the pump photons. With the F_{p2}, the AWG, the F_i and the F_s, the pump photons were suppressed by $>$ 140 dB relative to the idler and signal photons.

Each photon was detected with an InGaAs/InP avalanche photodiode (APD1 and APD2) from IdQuantique, operating in a gated Geiger mode [4]. APD1 (id201) has a dark count probability per time gate, $t_g = 2.5$ ns, of $P_{dc} < 5\times10^{-6}$ ns^{-1}, and a quantum detection efficiency, $\eta_D \sim 10\%$ [5]. APD2

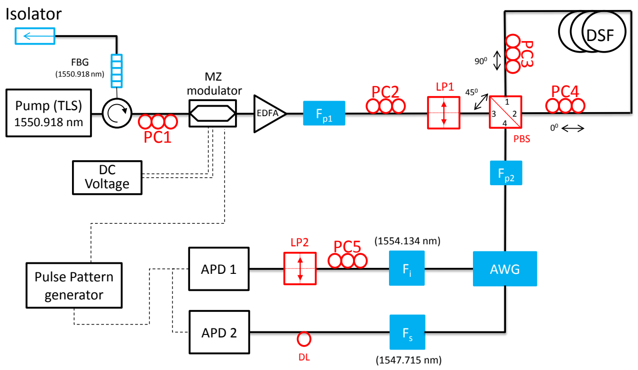

Fig. 1. Experimental setup used to generate entangled photon pairs using spontaneous four-wave mixing in a Sagnac fiber loop.

This work was partially supported by the Fundação para a Ciência e Tecnologia, FCT, through the Laboratório Associado (IT/LA) program, project "QuantTel - Quantum Secure Telecommunications" and "Quant-PrivTel - Quantum Private Telecommunications" project (PTDC/EEA-TEL/103402/2008), FEDER and PTDC programs.

A. J. Almeida is with the Instituto de Telecomunicações, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, Tel: +351 234 377 900, Fax: +351 234 377 901 (e-mail: aalmeida@av.it.pt).

S. R. Carneiro and N. J. Muga are with the Departamento de Física, Universidade de Aveiro, and the Instituto de Telecomunicações, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, Tel: +351 234 377 900, Fax: +351 234 377 901 (e-mails: src@av.it.pt; muga@av.it.pt).

N. A. Silva and A. N. Pinto are with the Departamento de Electrónica, Telecomunicações e Informática, Universidade de Aveiro, and the Instituto de Telecomunicações, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, Tel: +351 234 377 900, Fax: +351 234 377 901 (e-mails: nasilva@av.it.pt; anp@ua.pt).

(id200) has a dark count probability per time gate, $t_g = 2.5$ ns, of $P_{dc} < 5 \times 10^{-5}$ ns^{-1}, and a quantum detection efficiency, $\eta_D \sim 10\%$ [6]. The delay line (DL) in APD2's arm is a 13 m optical fiber, which compensates the electronic delay between the two detectors.

B. *Experimental Results*

Using the experimental setup presented in Fig. 1, we obtained a source of entangled photon pairs in a Sagnac fiber loop. APD1 was used as the master detector, and was directly connected to the pulse pattern generator. APD2 worked as the slave detector and was only able to detect photons when APD1 counted at least one photon [7].

In Fig. 2 we present the coincidence counts over 20 s, as the gate delay in APD2 is varied, while keeping the gate delay in APD1 fixed. Time coincidence was found for a gate delay of 5.5 ns, using a 300-m DSF for the generation of entangled photon pairs. As can be seen in Fig. 2, there is a non-zero background. The reason for this background can be due to several factors: photons from the pump, from the EDFA, from dark counts and from spontaneous Raman scattering (SpRS). The contribution from pump, EDFA and dark counts is negligible (about 1 count). To estimate the contribution of SpRS we measured coincidence and single counts as a function of pump power.

In Fig. 3 we present the coincidence counts as a function of the idler counts, obtained for different pump powers. The coincidence counts, N_c, were fitted using the following equation [8]:

$$N_c = N_{dc} + s_1 N_i + s_2 N_i^2 , \tag{2}$$

where N_{dc} is the number of dark counts during a gate interval, $s_1 = 0.00108$ and $s_2 = 6.9562 \times 10^{-8}$ are the linear and quadratic scattering coefficients, respectively, and N_i is the number of idler photons. From Fig. 3 we can see that the experimental data follows a quadratic growth, which indicates that the major contribution for coincident counts came from SpFWM, as SpRS is the main contributor for background counts [9].

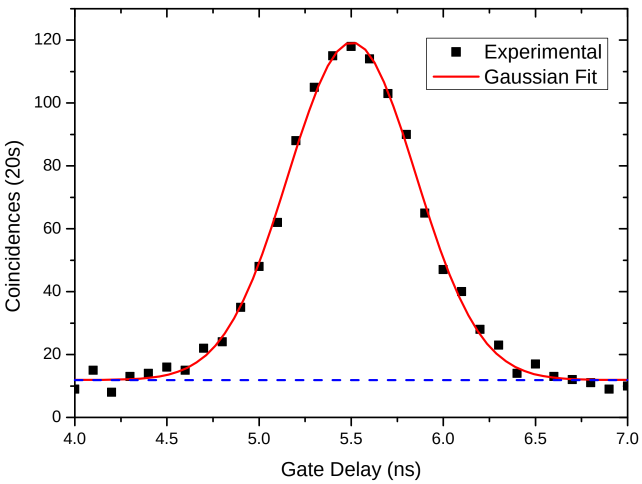

Fig. 2. Coincidence counts detected over 20 s as the gate delay in APD2 is varied, while keeping the gate delay in APD1 fixed, using a 300-m DSF.

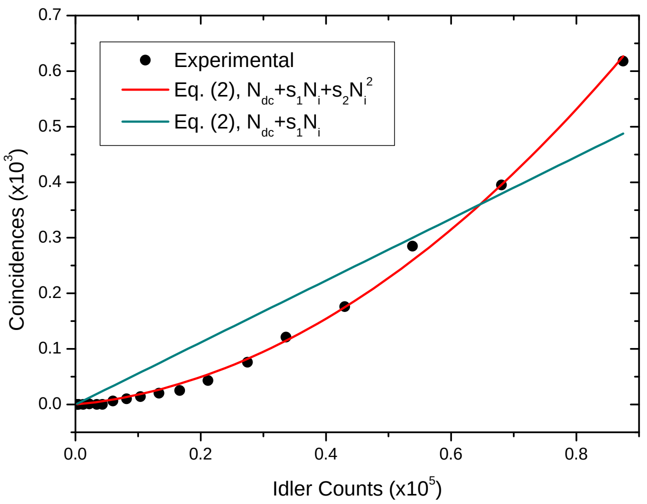

Fig. 3. Coincidence counts as a function of the idler counts detected over 20 s, using a 300-m DSF.

III. CONCLUSION

We successfully implemented a source of entangled photon pairs using the SpFWM process in a Sagnac fiber loop composed of a PBS, a DSF and two PCs. In order to verify the time coincidence of the entangled photon pairs we implemented a master/slave configuration between two APDs. This time coincidence was verified using a 300-m DSF for entangled photon pair generation. From the several contributions that can raise background counts, it was found that SpRS is the most important, as the SpFWM has the main contribution for the coincident ones.

According to the obtained experimental results, we were able to generate polarization-entangled photon pairs in order to verify the violation of Bell's inequality.

REFERENCES

[1] C. H. Bennett and G. Brassad, "Quantum cryptography and its application to provably secure key expansion, public-key distribution, and coin-tossing," *IEEE International Symposium on Information Theory*, p. 91, Sep. 1984.

[2] X. Li, P. L. Voss, J. E. Sharping, and P. Kumar, "Optical-Fiber Source of Polarization-Entangled Photons in the 1550 nm Telecom Band," *Physical Review Letters*, vol. 94, no. 5, pp. 053 601–+, Feb. 2005.

[3] H. Takesue and K. Inoue, "Generation of polarization-entangled photon pairs and violation of Bell's inequality using spontaneous four-wave mixing in a fiber loop," *pra*, vol. 70, no. 3, pp. 031 802–+, Sep. 2004.

[4] G. Ribordy, N. Gisin, O. Guinnard, D. Stucki, M. Wegmuller, and H. Zbinden, "Photon counting at telecom wavelengths with commercial InGaAs/InP avalanche photodiodes: current performance," *Journal of Modern Optics*, vol. 51, pp. 1381–1398, Sep. 2004.

[5] idQuantique, *id 201 Single-Photon Detector Module - Operating Guide, Version 4.0*, 2008.

[6] ——, *id 200 Single-Photon Detector Module - Operating Guide, Version 2.2*, 2005.

[7] A. J. Almeida, N. A. Silva, N. J. Muga, and A. N. Pinto, "Fiber-optical communication system using polarization-encoding photons," *15th European Conference on Networks and Optical Communications*, Jun. 2010.

[8] M. Fiorentino, P. L. Voss, J. E. Sharping, and P. Kumar, "All-fiber photon-pair source for quantum communications," *IEEE Photonics Technology Letters*, vol. 14, pp. 983–985, Jul. 2002.

[9] Q. Lin, F. Yaman, and G. P. Agrawal, "Photon-pair generation in optical fibers through four-wave mixing: Role of Raman scattering and pump polarization," *pra*, vol. 75, no. 2, pp. 023 803–+, Feb. 2007.