Single-Photon Source With Adjustable Linear SOP

Álvaro J. Almeida, Gil G. Fernandes and Armando N. Pinto

***Abstract*—In this work we generate and detect single photons in optical fibers using the stimulated four-wave mixing (FWM) process. The results show an accurate generation of single photons at four different linear states of polarization (SOPs), with angles 0, 45, 90 and -45 degrees.**

***Index Terms*—Optical polarization, optical mixing.**

I. INTRODUCTION

In order to achieve quantum secure telecommunications with enhanced security, single-photon sources are an emerging key technology [1]. A single-photon source should present properties such as wavelength stability, high efficiency, generation of a low number of photons, and it also should allow the polarization control of the photons [1], [2].

Stimulated Four-Wave Mixing (FWM) is a third-order nonlinear process that occurs when light of two or more frequencies (known as pump and signal fields) are launched into an optical fiber given rise to a new wave, known as idler field [3].

Most of the quantum protocols require single-photon sources in order to transmit information between two different locations [4]. Recently, polarization encoded photons have been proposed in some quantum experiments to implement these quantum protocols in optical fibers [4]. Typically, single-photon sources with different linear states of polarization (SOPs) are obtained using several highly attenuated lasers [5]. In this paper we use the FWM process to obtain a source of single photons with adjustable linear SOP.

In section II, we present a description of the experimental setup, used to generate and detect single photons in four different linear SOPs. In this section we also present the obtained experimental results. The main results of this work are summarized in section III.

II. SINGLE-PHOTON SOURCE

Is this section we describe the proposed single-photon source with adjustable linear SOP, and present the obtained experimental results.

A. Experimental Setup

In the experimental setup, see Fig. 1, a pump at λ_1 from a tunable laser source (TLS), passes through a polarization controller (PC1), before being coupled to another optical signal, at λ_2, from a external cavity laser (ECL). This optical signal, λ_2, is externally modulated to produce optical pulses with a width at half maximum of 1.6 ns and a repetition rate of 555.6 kHz. The two optical fields, λ_1 and λ_2, pass through a linear polarizer (P1) and are launched into a dispersion-shifted fiber (DSF), with a length equal to 305 m. Due to the FWM process, a new signal, the idler, is generated inside the DSF at $\lambda_3 = \lambda_1\lambda_2/(2\lambda_2 - \lambda_1)$. At the fiber output, the three optical fields pass through the PC4 in order to align the SOP of the idler photons with the linear polarizer P2. A filter F1 blocks the pump and signal waves. At the exit of P2 the angle of the linear SOP is controlled using a rotatable key connector (RKC), θ_1. The SOP of the idler photons is analyzed using another linear polarizer (P3), whose orientation is tuned using a second RKC, θ_2.

The idler photons from P3 are detected with a Single-Photon Detector Module (SPDM) operating in Geiger mode. The dark count probability of the SPDM for a time gate, $t_g = 2.5$ ns, is $P_{dc} < 5 \cdot 10^{-5}$. The quantum detection efficiency is $\eta = 10$ % [6]. The average number of idler photons per pulse, $\bar{n}$, was measured during a period of time of 10 s [1].

B. Results

In Fig. 2 we plot the average number of idler photons per pulse as a function of the linear polarizer angle, $\Delta\theta_2$, for the four different linear SOPs generated by our single-photon source. From Fig. 2 we can see that exists a maximum and a minimum for each linear SOP, and the phase difference

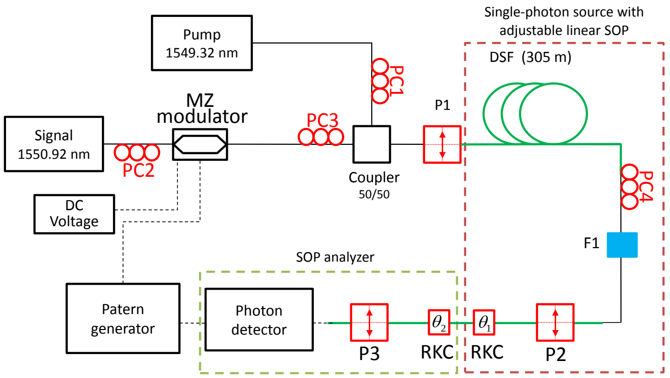

Fig. 1: Experimental setup used to generate and detect single photons at the linear SOPs with angles 0, 45, 90 and -45 degrees. Details of the setup are presented in the text.

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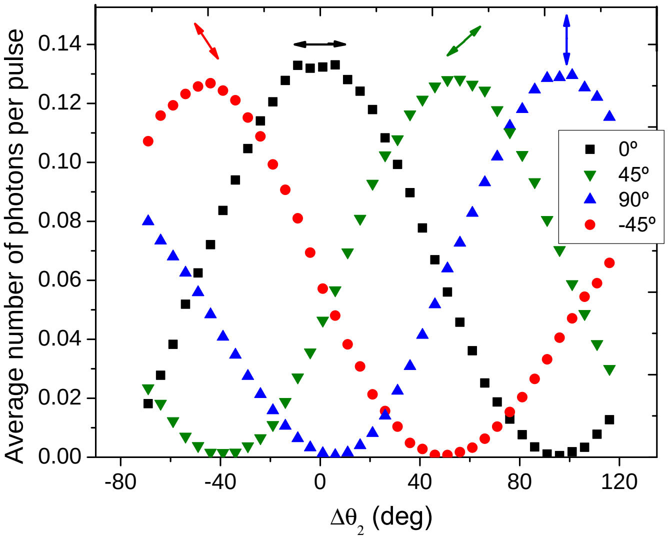

Fig. 2: Average number of idler photons per pulse as a function of the angle (degrees), for the linear SOPs with angles 0, 45, 90 and -45 degrees. The pump and signal optical powers at the fiber input were $P_1 = 3.39$ mW, and $P_2 = 0.54$ mW, respectively. The wavelengths for the pump and the signal were $\lambda_1 = 1549.32$ nm and $\lambda_2 = 1550.92$ nm, respectively.

between the maximum value for each linear SOP is 45 degrees. The maximum value, $\bar{n} \sim 0.14$, is obtained when the polarizer is aligned with the SOP of the single-photon source, while the minimum, $\bar{n} \sim 0$, is found when they are orthogonal.

In order to obtain a theoretical approximation for the experimental results, we can consider that the SOP at the polarizer output is given by,

$$\hat{s} = \mathcal{R}(\theta)\mathcal{M}_{\mathcal{P}}\mathcal{R}(-\theta)\hat{s}(0)\,, \tag{1}$$

where $\mathcal{R}(\theta)$ and $\mathcal{M}_{\mathcal{P}}$ are, respectively, the rotation and the linear polarizer Mueller matrices in Stokes space [7], and $\hat{s}(0)$ is the Stokes vector corresponding to the initial SOP. Assuming an initial SOP given by $\hat{s}(0) = [1,0,0]^T$, where T is the transpose, we obtain,

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} \cos^2(2\theta) \\ \sin(2\theta)\cos(2\theta) \\ 0 \end{bmatrix}\,. \tag{2}$$

As the total optical power is given by $P = |s_0|^2 = s_1^2 + s_2^2 + s_3^2$, where s_1, s_2 and s_3 are the Stokes parameters [8], we have,

$$P = [\cos^2(2\theta)]^2 + [\sin(2\theta)\cos(2\theta)]^2 = \cos^2(2\theta)\,. \tag{3}$$

From (3) we can obtain a theoretical fit for the experimental results of the form,

$$\bar{n} = A\cos^2[\Delta\theta_2 + \phi]\,, \tag{4}$$

where A is the amplitude, $\Delta\theta_2$ is the shift in the angle in relation to the linear SOP of 0°, and ϕ is the phase difference between the linear SOPs.

In Fig. 3 we plot the average number of idler photons per pulse as a function of the angle $\Delta\theta_2$, and the theoretical fit given by (4), for the linear SOPs with angles 0 and 45 degrees. From Fig. 3 we can see that the theoretical fit given by (4) is a good approximation to the experimental results.

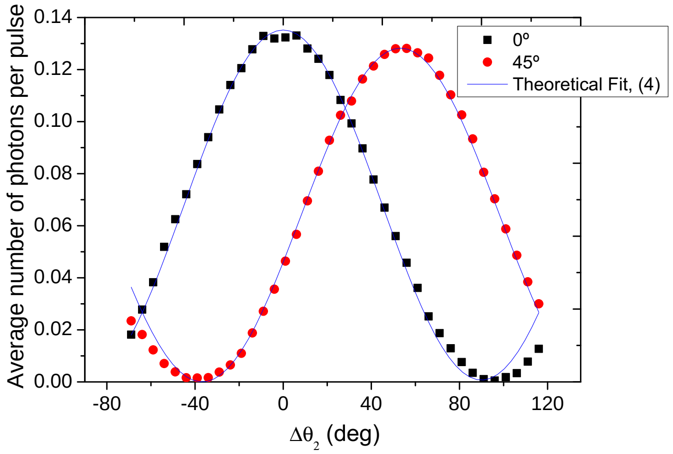

Fig. 3: Average number of idler photons per pulse as a function of the angle $\Delta\theta_2$, for the linear SOPs with angles 0 and 45 degrees. The circles and the squares represents the measured values, and the solid lines represents the theoretical fit given by (4). The optical powers and the wavelengths are the same used in Fig. 2.

III. CONCLUSION

We have shown that it is possible to generate and detect single photons in well defined four linear SOPs. This can be used to implement a quantum protocol to authenticate classical messages with enhanced security.

With our single-photon source we could select the linear SOP at the source using only one optical field.

To improve the results, a better alignment between the keys of the linear polarizers and the keys of the polarization maintaining fibers must be performed.

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