Fiber-Optical Communication System Using Polarization-encoding Photons

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We present a single-photon source based on the stimulated four-wave mixing process with adjustable linear state of polarization. This source allowed us to generate non-orthogonal states of polarization, that can be used for quantum key distribution experiments. The average number of photon counts as a function of the angle of the analyzer was obtained for two non-orthogonal linear states of polarization. The results show an accurate detection after propagation through a standard single-mode optical fiber with a length equal to 20 km. We also employed a master/slave configuration between two avalanche photodiodes, in order to check the probability of our single-photon source to emit pulses with more than one photon, for an average number of photons per pulse, $\mu \sim 0.2$, and consequently the probability of a photon to choose one of the paths. Results show that our experimental scheme is suitable for polarization-encoding experiments.

1. Introduction

In order to transmit information between two parties, most quantum protocols require single-photon sources [1]. These can be obtained from a variety of devices, like color centers in diamond, quantum dots, or from single atoms and molecules. There are, however, some practical problems with these sources. Low collection efficiency, technical complexity or molecule stability issues are some of them [2]. Recently, the stimulated four-wave mixing (FWM) process has been used to generate single-photons in optical fibers [3–6]. The stimulated FWM process 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 frequency known as idler [7]. Using the stimulated FWM process, we took advantage of generating the photons already inside the optical fiber [3–7]. This avoids the losses introduced by the coupling components used in another techniques [8]. This paper contains five sections. In section 2 we describe our single-photon source, which was used for generating single photons in two non-orthogonal linear states of polarization (SOPs). In section 3 we present a theoretical model to describe the photon counts obtained in two detectors, in two different configurations. First, using two detectors working as master, and second using a master/slave configuration between them. In section 4 we present and discuss the experimental results obtained in the two different configurations. Finally, in section 5 we present our conclusions.

2. Single-Photon Source Based on Stimulated Four-Wave Mixing Process

A schematic of the experimental setup used to generate, transmit and detect single photons, is shown at Fig. 1. A pump at λ_1, from an external cavity laser (ECL), passes through a polarization controller (PC1) before being coupled to another optical signal, λ_2, from a tunable laser source (TLS). This second optical signal passes through a polarization controller (PC2), and is then externally modulated to produce optical pulses with a width at half maximum of 1.6 ns and a repetition rate, $r = 550530$ Hz. After the modulation, λ_2 passes through another polarization controller (PC3), in order to assure that it will be co-polarized with λ_1. After the coupling, the two optical fields are launched into a dispersion-shifted fiber (DSF) with a length equal to 8400 m. Due to the stimulated FWM process, the new optical field is generated inside the DSF at $\lambda_3 = \lambda_1\lambda_2/(2\lambda_2 - \lambda_1)$ [7]. Next, a filter blocks the pump and signal waves, while the idler photon's polarization can be aligned with the rotating linear polarizer (RLP) using a new polarization controller (PC4). After transmission through the quantum channel (optical fiber), the idler photons pass through a 50/50 polarization beam splitter (PBS). Adjusting the PCs, PC5 and PC6, the photons with the input SOPs, $\theta = 0°$ or 45°, that can be chosen with the polarization analyzer (PA), can be redirected to detectors D1 or D2, respectively, and polarization changes inside the optical fiber be compensated [9]. The linear polarizers, P1 or P2, work as analyzers, and their transmission axes angle, θ, can be tuned with the PA. The detectors D1 and D2 are two InGaAs/InP avalanche photodiodes (APDs) from IdQuantique, operating in the so-called Geiger mode [10]. Detector D1 (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, $\eta_D \sim 10\%$ [11]. Detector D2 (id201) has a dark count probability per time gate, $t_g = 2.5$ ns, of $P_{dc} \sim 1 \times 10^{-6}$ ns^{-1}, and a quantum detection efficiency, $\eta_D \sim 10\%$ [12]. The average number of photons per pulse at the single-photon source output was $\mu \sim 0.2$, and the measurements were performed during a period time of 10 s.

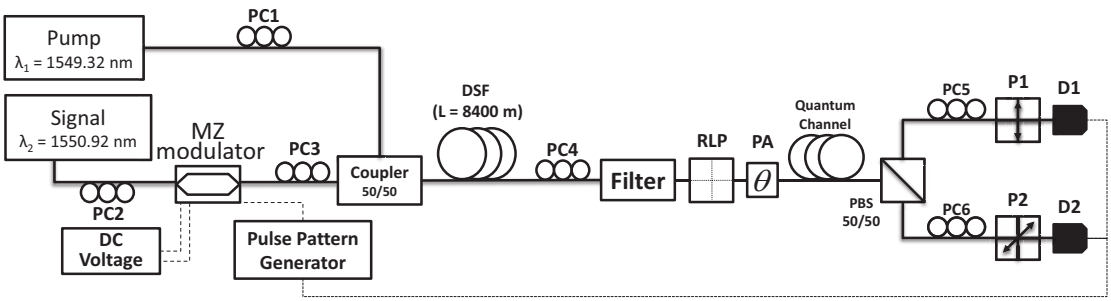

Figure 1: Experimental setup used to generate, transmit and detect single photons with quantum information, encoded into polarization. Using this setup we were able to analyze two non-orthogonal linear SOPs ($\theta = 0°$ and 45°).

3. Theoretical Model

In this section we present a theoretical model to describe the photon counts that can be registered in the APDs (D1 and D2), as a function of the PA angle, θ, as presented in Fig. 1.

Assuming that the photon distribution of our single-photon source follows a Poissonian statistics, the probability of a pulse carries n photons is given by,

$$P(n, \mu) = \frac{\mu^n}{n!} e^{-\mu}, \tag{1}$$

where μ is the average number of photons per pulse [8]. After the photons pass through a single-mode fiber (SMF), the quantum channel, the probability that the pulse carries at least one photon can be written as,

$$P = 1 - e^{-\eta_F \mu}\,, \tag{2}$$

with $\eta_F = 10^{-\alpha L/10}$, where α and L are the fiber losses and the fiber length, respectively [13]. When the beam passes through a 50/50 beam splitter, it will generate two beams with independent Poissonian statistics. Then, we will have in each arm [14],

$$P = 1 - e^{-\eta_F \mu/2}\,. \tag{3}$$

Next, the beam will pass through a PA, which transmits photons in the state, $|T_\theta\rangle$, given by,

$$|T_\theta\rangle = \cos(\theta)|H\rangle + \sin(\theta)|V\rangle\,, \tag{4}$$

where $|H\rangle$ and $|V\rangle$ represents the horizontally and vertically polarized SOPs, respectively, and the transmission axis forms and angle θ with the horizontal [15]. The probability of transmission of a photon in a state $|\psi_\phi\rangle$ is given by,

$$P_t = |\langle T_\theta|\psi_\phi\rangle|^2\,, \tag{5}$$

where the general input photon state can be written as,

$$|\psi_\phi\rangle = \cos(\phi)|H\rangle + \sin(\phi)e^{i\xi}|V\rangle\,, \tag{6}$$

being $\xi = \xi_y - \xi_x$ the phase between the quantum states [16]. Substituting (4) and (6) in (5), we obtain that,

$$P_t = \cos(\theta)^2\cos(\phi)^2 + \sin(\theta)^2\sin(\phi)^2 + 2\cos(\theta)\cos(\phi)\sin(\theta)\sin(\phi)\cos(\xi)\,. \tag{7}$$

From (3) and (7) we can write the probability of detection in an APD as,

$$P_d = (1 - e^{-\eta_F \eta_B \eta_D \mu/2})P_t\,, \tag{8}$$

where $\eta_B = 10^{-L_B/10}$, and L_B represents the total losses in each arm, between the beam splitter and the APD, and η_D is the quantum efficiency of the APD.

The probability of a detector to click can be denoted by,

$$P_{click} = P_d + P_{dc} - P_d P_{dc}\,, \tag{9}$$

where P_{dc} is the probability of a click due to detector's dark counts [13]. In terms of a detector count, (9) results in,

$$C = rP_{click}\,, \tag{10}$$

where r is the pulse repetition frequency per second [13].

In case of employing a master/slave configuration between two APDs, (10) can be written as,

$$\begin{cases} C_M = rP^M_{click} & (11) \\ C_S = C_M P^S_{click}\,, & (12) \end{cases}$$

where C_M and C_S are the average number of photon counts in master and slave detectors, respectively, and P^M_{click} and P^S_{click} are the probabilities of having a click in master and slave detectors, respectively.

4. Experimental Polarization-encoding Photons

4.1 Two Non-orthogonal Linear SOPs Detection

Before transmission through a SMF with a length equal to 20 km we performed a back-to-back measurement, i.e., without using the quantum channel, in order to verify the feasibility of our experimental setup (see Fig. 1). In Fig. 2a) we plot the average number of photon counts registered by detectors D1 and D2 as a function of the PA angle, θ (degrees), in a back-to-back configuration, and the theoretical prediction given by (10). As described by (4), we have a maximum when the photon's polarization is aligned with the transmission axis of the linear polarizers, and a minimum when they are orthogonal. As can be seen in Fig. 2a), (10) describes correctly the experimental results that were obtained. In Fig. 2b) we plot the average number of photon counts registered in detectors D1 and D2, as a function of the PA angle, θ (degrees), after transmission through a standard SMF with a length equal to 20 km, and the theoretical prediction given by (10). As can be seen, there is a decrease in the number of counts registered in both detectors, which is due to fiber attenuation. The 45° separation between the two SOPs remain, since polarization rotations performed by the optical fiber could be compensated adjusting PC5 and PC6 in order to align the SOPs at the fiber link output with the linear polarizers P1 and P2, respectively. The theoretical equation given by (10) also describes correctly the obtained experimental results. According to Fig. 2, we can see that it is possible to code information in photons polarization, transmit it through an optical fiber with a length up to 20 km, and detect it correctly.

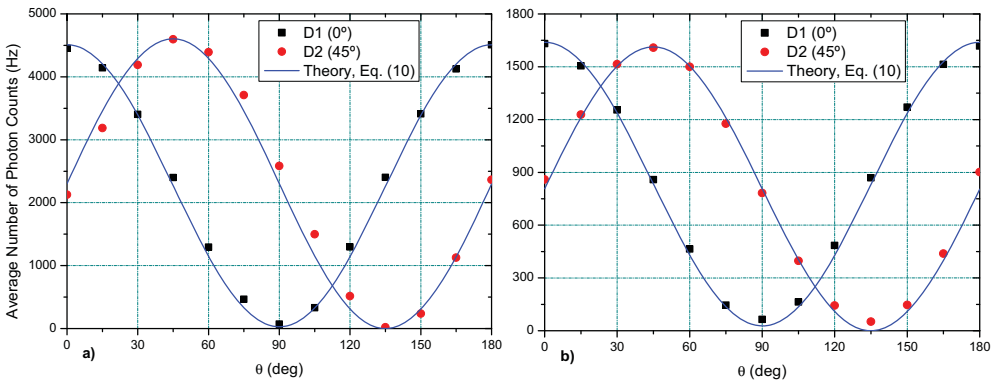

Figure 2: Average number of photon counts (Hz) as a function of the polarization analyzer angle, θ (degrees), for the linear SOPs with angles $\theta = 0^\circ$ and 45°, a) in a back-to-back configuration, and b) after propagation through a standard SMF with a length equal to 20 km. The pump and signal optical powers at the DSF input were $P_1 = 0.69$ mW, and $P_2 = 0.39$ mW, respectively.

4.2 Master/Slave Configuration

In order to check the probability of our single-photon source to emit pulses with more than one photon, for $\mu \sim 0.2$, we implemented a master/slave configuration between two APDs, where the slave detector only works when the master detector counts at least one photon. In this case only when the pulse carries at least two photons we will be able to have a count in slave's detector. In Fig. 3 we present the experimental setup used to obtain a master/slave configuration between two APDs, D1 and D2. The master detector trigger was directly connected to the pulse pattern generator. Slave detector trigger is connected to the master detector D1 through a NIM output. The delay line (DL) in slave detector arm is a 10 m optical fiber, which allows compensating

of the electronic delay between the two detectors. The quantum channel that was used to transmit the photons was a standard SMF with a length equal to 20 km.

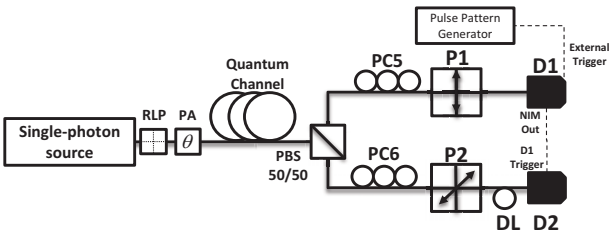

Figure 3: Experimental setup used to obtain a master/slave configuration between two APDs, using two non-orthogonal linear SOPs ($\theta = 0°$ and 45°).

In Fig. 4a) we plot the average number of photon counts as a function of the PA angle, θ (degrees), when detector D1 worked as master and detector D2 as slave, and the theoretical predictions given by (11) and (12). As can be seen, detector D1 collects almost all the photons with SOP angle, $\theta = 0°$, and only a few goes to detector D2, that is prepared to receive the photons with SOP angle $\theta = 45°$. It can be seen in Fig. 4a) that the master detector shows the same behavior as in Fig. 2, while the counts registered by the slave detector shows some difference. Results show that the slave detector presents two minimums, one in 90° and other in 135°. Since the slave detector is only able to count when the master detector receives at least one photon, when its polarization is orthogonal to the transmission axis of the linear polarizer, the master detector will have a minimum number of counts, and consequently, the slave detector too, since it uses the master detector's counts as trigger. As the 45° SOP was maximized using PC6, in order to be detected in D2, it will be also a minimum at 135°, as the maximum will be at 22.5°. The theoretical predictions given by (11) and (12) describes with good accuracy the experimental results, being the slightly differences due to experimental constraints. In Fig. 4b) we plot the average number of photon counts as a function of the PA angle, θ (degrees), when detector D1 worked as slave and detector D2 as master, and the theoretical predictions given by (11) and (12). From comparison with Fig. 4a), we can see that the behavior do not depends on choosing D1 or D2 as master detector. This indicates that a photon has the same probability to go to each arm of the beam splitter, and consequently, the non empty pulses carries in average one photon, when we use $\mu \sim 0.2$.

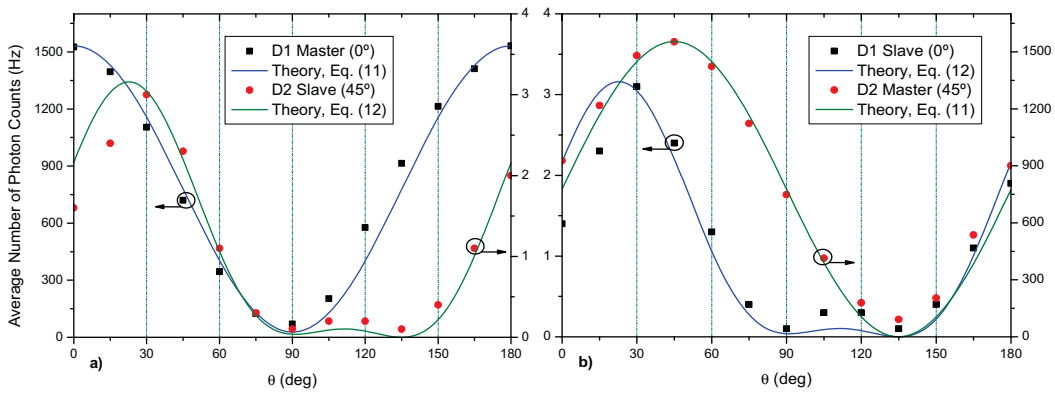

Figure 4: Average number of photon counts as a function of the polarization analyzer angle, θ (degrees), for the linear SOPs with angles $\theta = 0°$ and $45°$, with a) detector D1 working as master, and detector D2 as slave, and b) detector D1 working as slave, and detector D2 as master. Photons were transmitted through a SMF with a length equal to 20 km. The pump and signal optical powers at the DSF input were the same as presented in Fig. 2.

5. Conclusions

We successfully implemented a single-photon source based on the stimulated FWM process, with adjustable linear SOP. This allowed us to generate single photons linearly polarized, and transmit them through a standard SMF with a length equal to 20 km. Results showed that it is possible to code information into photons polarization, and decode it correctly after propagation through an optical fiber with a length of several kilometers. In order to verify the probability of our single-photon source to emit pulses with more than one photon, for an average number of photons per pulse, $\mu \sim 0.2$, we employed a master/slave configuration between two detectors. Results showed that a photon has the same probability to choose one of the arms of the beam splitter, and that non empty pulses carries in average one photon. The master/slave configuration can also be used on entanglement-based quantum experiments.

Acknowledgments

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 "QuantPrivTel - Quantum Private Telecommunications" project (PTDC/EEA-TEL/103402/2008), FEDER and PTDC programs.

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