A Simple and Inexpensive Single-Photon Source by Means of Four-Wave-Mixing and Attenuation

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Abstract — We developed a simple and inexpensive single-photon source based on four-wave-mixing in a dispersion shifted optical fiber. The four-wave mixing process is conjugated with optical attenuation to reduce the number of photons generated per pulse. This type of source can be useful to study optical pulses with an average number of photons near or less than one.

I. INTRODUCTION

Single photon sources and detectors are key enabling technologies in the growing field of quantum information. When the concept of photon was first introduced, the generation of single photons was not considered. But recently, progresses in the quantum optics field have made the single-photon regime accessible and increasingly important. Strongly attenuated laser beams, to ensure that the probability of having more than one photon in a given time interval became negligible, had been used as traditional photon sources for quantum optics experiments. However, such attenuated beams differ from 'true' single photons sources because they operate predominantly in a 'non-photon' regime with occasional generation of a photon and because the probability of getting two photons per pulse is different than zero, but essentially follows a Poisson distribution. Although this weak beam has been useful in quantum optics, the advent of quantum information science has placed extra demands on optical sources, sources that are able to produce single photons on demand. In particular, secure quantum cryptography and optical quantum computing depend on the availability of such single-photon sources. The combination of strict requirements for single photons sources, plus new technologies, is driving an exciting research effort into single-photon generation [1].

An efficient and reliable photon source that delivers a train of pulses containing one, and only one, photon per pulse is a challenge. In quantum information systems it is desirable to deal with single photons synchronized to an external clock, namely, *triggerable* single photons sources, furthermore *polarization states* of single photons are also important since they enable polarization-qubit encoding of information. A single photon source should present the following properties**:** one and only one generated photon, wavelength stability, high efficiency, generation on demand, and polarization should be controllable.

Four-wave mixing is a process in which optical waves at two or more frequencies interact via the non-linear response of a medium. Providing a condition known as phase matching is satisfied, light at a new frequencies is generated using optical power from the original frequencies. The small core diameters of single mode optical fibers (typically ~ 5 to 10 μm) permit high optical intensities and therefore fibers offer conditions for non-linear effects to occur.

As a means to generate correlated photons pairs, optical fibers have some advantages over other $\chi^{(3)}$ nonlinear optical mediums. Signal and idler photons can be generated far apart from the pump beam with good efficiencies which facilitate the detection of the signal even in the presence of a strong pump beam. Correlated photon pairs generated in this way allow an easy separation and combination using standard optical fiber technologies. Also, the correlated photons can be easily generated at optical communication wavelengths, making them readily compatible with fiber optics communication technologies and applications. These factors work to bring down costs, implying an inexpensive optical fiber source of correlated photons that can be a contribution to the achievement of a realistic quantum cryptographic communication system [2]. In this work we implemented a photon source using the four-wave-mixing effect, we choose two wavelengths, λ_1 and λ_2, in order to generate by means of FWM approximately one photon per pulse in other wavelength. To reduce the average number of photons per pulse we increase the optical attenuation.

II. EXPERIMENT

The photon source developed in this work has the advantage of generate correlated photons pairs at two different wavelengths, which can be separated by standard optical communications technologies. The photon counting was measured with a Single Photon Detector Module (SPDM) *id200,* from "Id Quantique". The detected average number of photons per pulse can be obtained by [4]:

$$n = \frac{1}{\eta} \ln\left[\frac{P_{dc}-1}{P_{dc}+P_s-1}\right] \tag{1}$$

where, n is the average number of detected photons per pulse, η is the detection efficiency, P_{dc} the dark count probability and P_s the signal count probability. The dark count probability and the signal count probability are directly

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measured from the *id200* SPDM, the detection efficiency is evaluated by the numerical method proposed in [3]. In this method is assumed that the photon counting fluctuations follow a Poisson probability distribution law that is given by:

$$P_r(n,T) = \frac{(\lambda T)^n e^{-\lambda T}}{n!} \tag{2}$$

where P_r is the probability of detecting an average number of photons, n, in the interval T. The interval T is the period during which the detector gate will be open. In this way, the probability of detecting any number of photons in that time interval is:

$$P_r(n \neq 0,T) = 1 - P_r(n = 0,T) = 1 - e^{-\lambda T} \tag{3}$$

Assuming that:

$$n = \lambda T = \frac{P}{h\nu}T \tag{4}$$

then

$$P_r(n \neq 0,T) = 1 - e^{-\frac{P}{h\nu}T} \tag{5}$$

where h is the Planck's constant and ν is the photons frequency. Considering that, due to several effects inside the detector, there are dark counts, the total optical power, P, will be given by:

$$P = \eta \times P_{in} + P_N \tag{6}$$

where η is the detector efficiency, P_{in} the optical power at the detector entrance and P_N is an optical power due to dark counts. In this way, adjusting this model with the experimental data of P_r, obtained directly from the detector, as a function of P_{in}, measured recurring to an OSA (Advantest Q8384 Optical Spectrum Analyser) and a previous calibrated optical variable attenuator (JSD Fitel), it is possible to obtain η and P_N, for the detection system by a simple linear regression. Replacing expression (6) in expression (5):

$$-\frac{h\nu}{T}\ln[1 - P_r(n \neq 0,T)] = \eta \times P_{in} + P_N \tag{7}$$

With this model it was possible to obtain the detection efficiency for several gates available in the SPDM. We made measurements for the five different time duration gates available; 2.5ns, 5ns, 20ns, 50ns and 100ns.

According with our measurements, the 5ns gate is the one which best balance the need of a high efficiency and the requirements of low noise generated inside the detector. For that reason we use the 5ns gate in our experiments. The detection efficiency for de 5ns gate is 3.89%±0.02%.

Measuring the counts, in the single photon detector module, with the modulated signal and without the modulated signal, we can obtain the signal count probability and the dark count probability, and using expression (1) the average number of photons per pulse can be calculated. Increasing the attenuation we can decrease the average number of photons at the detector input.

An outline of the experimental setup is presented in figure 1. We use two tunable lasers (NetTest Tunics Source) at wavelengths λ_1=1549.72nm and λ_2=1550.72nm with a constant average optical power of 5dBm and 12.92dBm, respectively. The signal at wavelength λ_1 was externally modulated with a Mach-Zehnder modulator and the signal at wavelength λ_2 was kept in continuous mode. Through external modulation we were able to produce an optical signal at wavelength λ_1, with optical pulses with a temporal full-width at half maximum of 3ns, and a repetition rate of 607kHz.

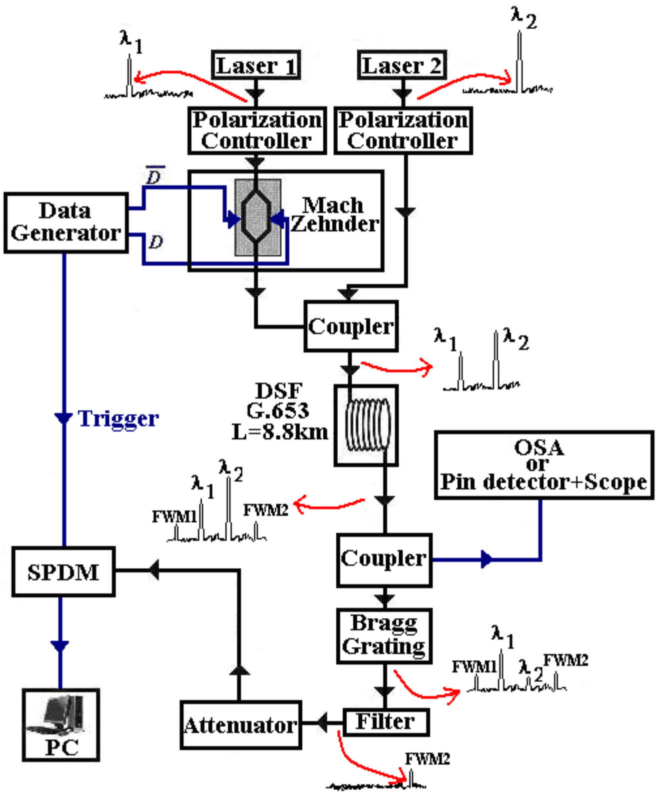

Fig. 1. Experimental setup.

The photon generation occurs inside a dispersion-shifted optical fiber with length of 8.8km and zero dispersion wavelength at 1547nm. The four-wave-mixing signals are generated at wavelengths $FWM_1=2\lambda_1-\lambda_2$ and $FWM_2=2\lambda_2-\lambda_1$. The generated signal may be switched on and off by switching off one of the interacting light sources.

The two signals, at wavelengths λ_1 and λ_2, and the generated signal at FWM_1 were filtered at the fiber output, leaving only the FWM_2 signal. We use, as optical filters, a Bragg fiber grating to remove the signal at wavelength λ_2, with λ_{Bragg}=1550.7nm, and a tunable optical filter (XTract from NetTest) to select the signal at wavelength FWM_2. The Bragg fiber grating was used because the signal at wavelength λ_2, could not be completely removed by the tunable optical filter only. The filtered signal passes through a tunable optical attenuator and finally is injected in a single photon detector module.

III. RESULTS

As we can see from figure 2, with the proposed experimental setup of figure 1, we can built a simple and inexpensive photon source, which has the advantage of generate a variable average number of photons per pulse according to the induced attenuation.

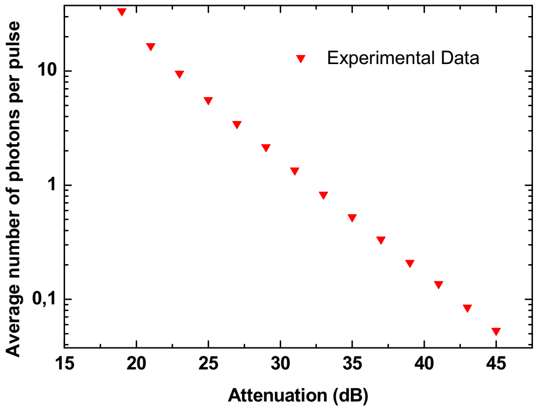

Fig. 2. Detected average number of photons as a function of the induced attenuation.

IV. CONCLUSION

We built a simple and inexpensive single-photon source based on four-wave-mixing inside a dispersion shifted optical fiber, which has the advantage of producing a reduced and adjustable average number of photons per pulse. The generated signal may be switched on and off by switching off one of the interacting light sources, because two or more frequencies of light are required for FWM.

We were able to generate pulses with an average number of photons lower than one. This type of source could be useful to study optical pulsed signals with an average number of photons near or less than one per pulse.

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