Multiple-Photons Resolving Detector using Fibre Ring

George André Pereira Thé and Rubens Viana Ramos

***Abstract* – Optical devices able to resolve the number of photons of an optical pulse are very important in quantum state preparation and quantum communication. However, these devices are very hard to implement and an alternative is the multiple-photons resolving detector. Basically, it is an optical device able to distinguish optical pulses with 0 photons, one photon and more than one photon. In this work we show how to implement a different multiple-photon resolving detector using a fibre ring, polarising beam splitter and single-photon detectors.**

***Keywords* – Single-photon detector, photon number resolution, multiple-photons resolving.**

I. INTRODUCTION

A new kind of optical communication arose in the past few years. In these systems, weak optical pulses are used, that is, pulses having low mean photon number. In this regime, one can take profit of the quantum aspects of light in order to carry, protect and distribute information. The most famous examples of these quantum optical communication systems are quantum key distribution (QKD) [1,2] and quantum teleportation [3]. In the first case, single-photon or two-photons pulses can be used while in the second case at least two-photon pulses are employed. Usually the information is carried in the pulse's phase or polarisation, but it is also possible to design a quantum optical communication system in which the information is carried in the parity of the number of photons of the pulses, being possible to run QKD and teleportation protocols in this scheme [4]. For QKD employing single-photon pulses, for example, the security is, among others issues, based on the fact that each optical pulse used has only one photon, otherwise an eavesdropper (Eve) could use the photon number splitting attack [5] and obtain complete information about the bit written in that optical pulse. However, single-photon sources are not yet readily available and single-photon pulses are just mimicked by weak coherent pulses in the present QKD set-ups. By its turn, weak coherent pulses can have, with low probability, more than one photon. A smart Eve can use this to obtain precious information. Thus, the sender in a QKD system must be sure about the photon number distribution of the pulses produced by its weak coherent state source. Using a photon number resolving detector (PNRD), the sender could measure the number of photons in each optical pulse produced and be sure that the probability of multiple-photons pulse produced by its source is low enough in order to keep the QKD system working in the unconditional secure region. Photon counting could also be important in the quantum teleportation using parity of the number of photons in a pulse, since we can determine the parity counting the number of photons. Hence, a PNRD is very important in quantum optical communication. In despite of its importance, it is very hard to construct, with current technology, such equipment. A less complicated task is to determine if the optical pulse has zero photons, one photon or more than one photon. This kind of PNRD, that is called multiple-photons resolving detector (MPRD), has been proposed and implemented using common optical devices [6-8]. Even not being able to determine the exact number of photons in an optical pulse, a MPRD still has applications in QKD. In this direction, we propose a different implementation of a MPRD from the one proposed in [6-8] and we give some examples of its use in QKD. This work is outlined as follows: In Section II presents a brief review of single-photon detector. In Section III the MPRD proposed is presented and compared to other proposed in the literature. At last, in Section IV the conclusions are presented.

II. SINGLE-PHOTON DETECTOR

Single-photon detectors (SPD) are crucial devices in optical quantum information technology. Basically, the SPD must provide a TTL output pulse for each incoming photon. The main device of a SPD is the avalanche photodiode (APD). When a single-photon pulse impinges on the APD window, if this is correctly biased, it can, through an avalanche process, produce a detectable voltage pulse across a resistor. Such pulse is amplified by a fast operational amplifier and formatted by a digital logic, resulting in a TTL pulse at the detector's output [9,10]. The important parameters of a SPD are the quantum efficiency, η, and dark count probability, P_d. The quantum efficiency is the probability of an incoming photon to produce a TTL pulse at detector output whereas dark count probability is the probability of the TTL pulse appears at the detector output when none light pulse impinges on the APD. Both of them depend on the voltage across APD terminals, V_{apd}, and the APD temperature, T. The larger (lower) V_{apd} (T) the larger (lower) η and P_d. An important parameter of APD is the breakdown voltage, V_B. If V_{apd} is lower than V_B an avalanche cannot occurs and, hence, a photon cannot be detected. Once the avalanche has been fired, it must be quenched in order to do not damage the APD. There are three types of quenching circuits: passive, active and gated mode. In this work only the gated mode will be discussed since it permits lower dark count. In the gated mode the APD is reverse biased below V_B. A pulse generator producing (ideally) square pulses, hereafter named gate pulses, having amplitude V_g, is used to increase V_{apd} only during short time windows, T_w. During T_w we have $V_{apd}=V+V_g>V_B$ and a photon can be detected. The difference $V_{apd}-V_B$ is named excess voltage, V_e. The larger (lower) V_e the larger (lower) η and P_d. In Fig. 1 it is shown the basic circuit for single-photon detection and the gate pulses sequence.

George André Pereira Thé and Rubens Viana Ramos are with Department of Teleinformatic Engineering, Federal University of Ceara, Fortaleza, Ceará, Brazil, e-mails: geothe@deti.ufc.br, rubens@deti.ufc.br.
This work was supported by the Brazilian agency CNPq.

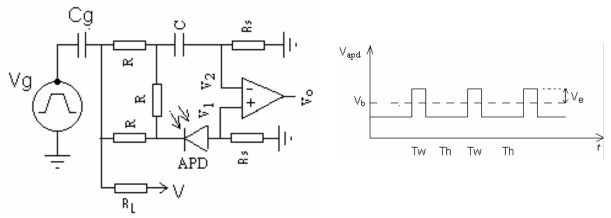

Fig. 1. APD in the gated mode and the gate pulses train.

The time slot T_w in which the V_{apd} is larger than V_B is also an important parameter for the performance of the detector. The shorter the slot time the lower the number of dark counts. Since the APD will be turned on only in defined time slots, the gate pulse and the light pulse must arrive in the APD at the same time. On the other hand, when an avalanche occurs and it is quenched by the gate pulse end the APD needs some time for recovering. This means that once a photon was detected, the APD needs some time relaxing before to be able to detect another photon. Thus, there is a hold-off time in which the device is unable to detect photons. This hold-off time limits the bit transmission rate of QKD systems and defines the length of the fibre loop in MPRDs. If the recovery time is not respected dark counts increases due to an effect known as afterpulsing [9,10]. Based on the above explained, for complete characterisation of a SPD, one must determine η, P_d, T_w and T_h. The optimal operation point of SPD is the one that minimises the noise equivalent power (NEP), given by:

$$NEP = \frac{h\upsilon}{\eta}\sqrt{P_d T_w} \tag{1}$$

where $h\nu$ is the photon energy. In order to find the optimal operation point, once T_w and T_h were chosen, T_w as minimal as possible (values between 2ns-10ns are common) and T_h large enough to make afterpulsing negligible, one has to vary both V_e and the APD temperature, and calculate the NEP for each possible value of both. In Fig. 2, the TTL output pulse (1) and the avalanche pulse (2), due to a dark count, are shown.

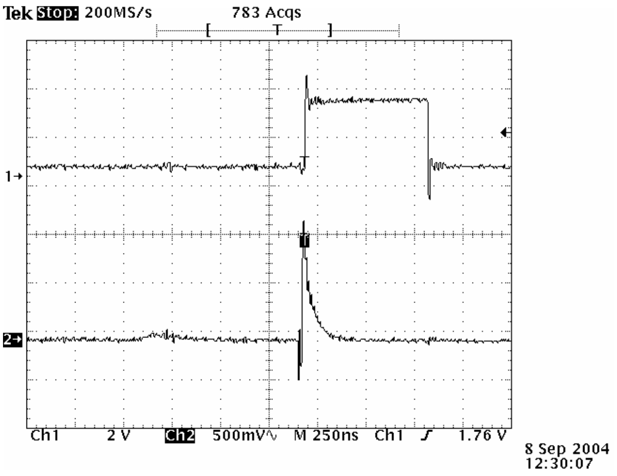

Fig. 2. Avalanche pulse (2) and TTL output pulse (1).

In this experiment, the APD was cooled at -40°C, V_e=4V and T_w=40ns. It is important to stress that SPD is not able to resolve the number of photons.

III. MUTIPLE-PHOTONS RESOLVING DETECTOR

The multiple-photons resolving detector proposed in [6-8] was composed by a fibre loop, a variable optical coupler and a single-photon detector, as shown in Fig. 3.

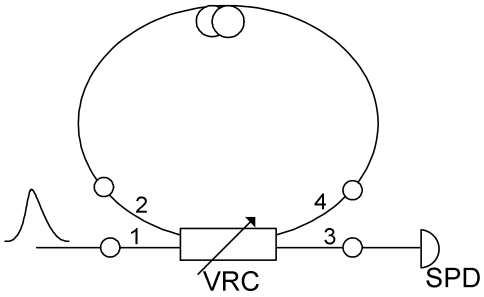

Fig. 3. Multiple-photons resolving detector employing fibre loop, variable ratio optical coupler (VRC) and single-photon detector.

Basically, when an optical pulse impinges on the variable coupler, a small part of its power is transmitted to the SPD while the rest of the pulse is reflected to the fibre loop. After the APD relaxing time (equal to the time wasted by the pulse to go from point 4 to point 2), the pulse reaches the coupler again and once more a small part of it will be guided to the SPD. Hence, the input pulse is split, in time, in several small pulses and each one should contain no more than one photon. It is very easy to note why the MPRD shown in Fig. 3 cannot work as PNRD: 1) There are losses in the connections, fibre loop and variable coupler that take photons from the pulse. 2) The dark count and low quantum efficiency of the SPD can, respectively, increase or decrease the number of counts. Considering ideal devices (lossless and noiseless), the mean photon number of the pulses reaching the SPD is given by:

$$\begin{aligned} \langle n\rangle_1 &= |\alpha|^2 r, \\ \langle n\rangle_k &= |\alpha|^2 (1-r)^2 r^{k-2}, k \geq 2 \end{aligned} \tag{2}$$

where r is the coupler reflection coefficient and $|\alpha|^2$ is the mean photon number of the input coherent pulse. The probability of detection is related to the mean photon number $\langle n\rangle$ of the pulse at the input of the (ideal) SPD by:

$$p = 1 - e^{-\langle n\rangle} \tag{3}$$

In order to have optimal distinguishability between input pulses having zero, one or more than one photon, the probability of detection in each time slot should be equal, that is, $\langle n\rangle_i = \langle n\rangle_j$ $\forall$ i and j. This condition is impossible to be achieved with a fixed optical coupler. Let us now consider, from the best of our knowledge, the new MPRD set-up shown in Fig. 4.

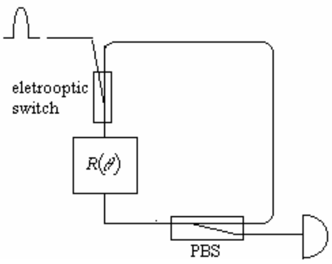

Fig. 4. Multiple-photons resolving detector employing polarisation controller.

The MPRD in Fig. 4 is composed by an electro-optic switch, a rotator $R(\theta)$, a polarisation beam splitter (PBS), a fibre loop and a SPD. Initially, let us assume that the PBS resolves the incident light polarisation in horizontal and vertical linearly polarised beams. When the optical pulse, initially linearly polarised in the horizontal direction, having mean photon number $\langle n\rangle$, enters in the fibre loop via electro-optic switch, it suffers a rotation in its polarisation of θ. After passing through the PBS the light going to the SPD will have mean photon number given by $\langle n\rangle\sin(\theta)$ while the light reinsert in the fibre loop has mean photon number given by $\langle n\rangle\cos(\theta)$ and it is once more linearly polarised in the horizontal direction. This pulse will suffer polarisation rotation of θ and pass through PBS several times, such that the mean photon number of the pulse going to SPD in any time slot is given by:

$$\langle n\rangle_k = |\alpha|^2 \sin(\theta)^2 \cos(\theta)^{2(k-1)} \tag{4}$$

In order to compare which set-up provides the best discrimination between light pulses having zero, one and more than one photon, we consider $r=\cos^2(\theta)$ and compare the variances of (2) and (4) for each value of r.

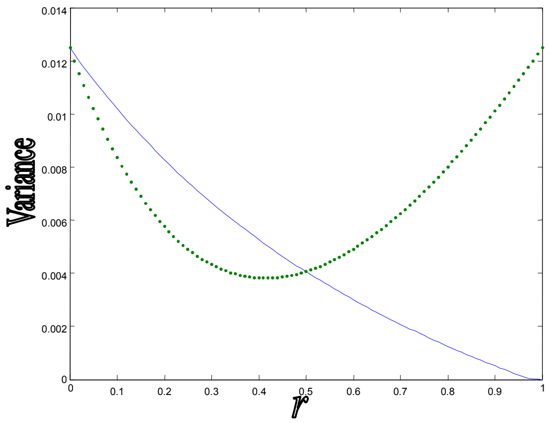

Fig. 5. Variances of the mean photon number of the pulses at the input of the SPD at MPRD using variable coupler (dotted line) and MPRD using polarisation controller (continuous line).

Observing Fig. 5 we can see that the MPRD proposed is the best for $r>0.5$ which implies $\theta=\pi/4$. For the MPRD implemented in [6,8] the optimal implementation required $r<0.5$, exactly as is seen in Fig. 5 (dotted line). Further, decreasing the value of θ the MPRD proposed we could obtain better performances. In fact, as can be seen in (4), if θ is low enough and k is not so large, (4) is not so dependent on k, and, hence, the mean photon number of the pulses at the SPD input does not vary so much, making the set-up presented in Fig. (4) very suitable as MPRD.

IV. CONCLUSIONS

Initially we described the functioning of a single-photon detector and a result of an implementation was presented. Following, the multiple-photons resolving detector using single-photon detector is described. Two possible configurations were shown and their performances were compared through the variances of the mean photon number of the pulses at the SPD input. From that, we conclude that the MPRD proposed can reach much better performance than that other discussed in the literature.

REFERENCES

[1] N. Gisin, G. Ribordy, W. Tittel and H. Zbinden, "Quantum cryptography", quant-ph/0101098, 2001.

[2] S. J. D. Phoenix and P. D. Townsend, "Quantum cryptography: how to beat the code breakers using quantum mechanics", *Contemp. Phys.*, 36 pp. 165-195, 1995.

[3] M. A. Nielsen and I. L. Chuang, *Quantum computation and quantum information*, Cambridge University Press 2000.

[4] R. V. Ramos, "Quantum teleportation with number states and beam splitters", *J. of Mod. Opt.*, 51, 4, pp. 525-536, 2004.

[5] N. Lutkenhaus, "Security against individual attacks for realistic quantum key distribution", *Phys. Rev. A*, 61, pp. 052304(1-10), 2000.

[6] O. Haderka, M. Hamar and J. Perina, "Experimental multi-photon-resolving detector using a single avalanche photodiode", quant-ph/0302154, 2003.

[7] J. Rehácek and Z. Hradil, "Multiple-photon resolving fiber-loop detector", quant-ph/0303032, 2003.

[8] K. Banaszek and I. A. Walmsley, "Photon counting with loop detector", quant-ph/0206162, 2002.

[9] G. Ribordy, J. D. Gautier, H. Zbinden, and N. Gisin, "Performance of InGaAs/InP avalanche photodiodes as gated-mode photon counters", *Applied Opt.*, 37, 12, pp. 2272-2277, 1998.

[10] M. Bourennane, D. Ljunggren, A. Karlsson, P. Jonsson, A. Hening and J. P. Ciscar, "Experimental long wavelength quantum cryptography: from single-photon transmission to key extraction protocols", *J. of Mod. Opt.*, 47, 2/3, pp. 563-579, 2000.