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Pockels cell performance in N-photon demultiplexer

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Abstract. We investigate the efficiency of a loop scheme for the spatial demultiplexing of *N* successive photons using only one Pockels cell at the center of the loop scheme. The maximum operating frequency of the Pockels cell, due to technical limitations, is 13.5 MHz. We experimentally find the maximum achievable demultiplexing efficiency with a single Pockels cell using continuous-wave and pulsed lasers and analog fast photodetectors. The maximum efficiency achieved at the maximum switching frequency is 87%.

Keywords: photons demultiplexing, single-photon source, Pockels cell

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Эффективность ячейки Поккельса для N-фотонного демультиплексора

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Аннотация. Мы исследуем эффективность петлевой схемы пространственного демультиплексирования *N* последовательных фотонов с использованием только одной ячейки Поккельса в центре петлевой схемы. Максимальная частоты работы ячейки Поккельса, обусловленная техническими ограничениями, составляет 13.5 МГц. Мы экспериментально находим максимально достижимую эффективность демультиплексирования с помощью одной ячейки Поккельса с помощью непрерывного и импульсного лазеров и аналоговых быстрых фотодетекторов. Максимальная эффективность, достигнутая при максимальной частоте переключения, составляет 87%.

Ключевые слова: демультиплексирование фотонов, источник одиночных фотонов, ячейка Поккельса_

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Introduction

Applied tasks of quantum optics, such as boson sampling, require operations on several photons [1]. However, the most common sources of single indistinguishable photons, such as quantum dots, generate one photon per pump pulse [2–4]. This leads to the need to use demultiplexing, that is, the separation of photon sequence into channels for operations on them [5]. The most effective way of demultiplexing is the use of a Pockels Cells (PC). PC changes the polarization of photons to orthogonal, which makes it possible to separate them using Polarization Beam Splitters (PBS). The downside of this scheme is the need to use N-1 PC for demultiplexing N photons [6–7].

We are studying a scheme [8] where linear optics elements are used for the spatial separation of photons, and only one PC is required to demultiplex N photons. The principle of operation of the PC at its maximum switching frequency is considered. The maximum efficiency of the PC for demultiplexing N photons is experimentally determined using a pulsed laser and fast analog detectors.

Principal scheme

Photons from a single-photon source of indistinguishable photons fall into a spatial loop formed by two mirrors and a triangular prism. Photons pass between two mirrors, through an inactive PC, through a PBS and hit a triangular prism. The triangular prism makes it possible to reflect photons with a spatial shift so that during the return flight they are reflected from the mirrors. Each flight around the loop spatially shifts the photons, which ultimately allows them to be led into separate channels. The total number of photons in the loop depends on the geometric dimensions of the mirrors, the prism, and the aperture of the Pockels cell.

The length of the loop L_{loop} is chosen in such a way that the next photon from the source with the pumping frequency f_{pump} falls into it when the previous one has passed a full circle. When a sufficient number of photons are accumulated in the loop, the PC is activated, the photon polarization changes to orthogonal, and they are deflected by the PBS and exit the loop. The optical scheme on the example of 3 photons is shown in Fig. 1. The output channels of the multiplexer are numbered starting from the central one, the photons from which did not pass through the loop and immediately fell on the PBS.

The described scheme is easily scaled to a larger number of photons, provided that the geometric dimensions of the reflectors and PBS are increased. The assembly and measurement of the characteristics of the described demultiplexer working with single unresolvable photons from a quantum dot are described in detail in [8].

Pockels Cell operating mode

The Pockels Cell (Leysop) is controlled by four keys with high voltage driver (BME Bergmann). The change in the polarization of the transmitted radiation occurs only at the moments when A_{on} is on and B_{off} is off, or A_{off} is on and B_{off} is off. Fig. 2,*a* shows the smallest possible switching period of the Pockels cell, declared by the manufacturer.

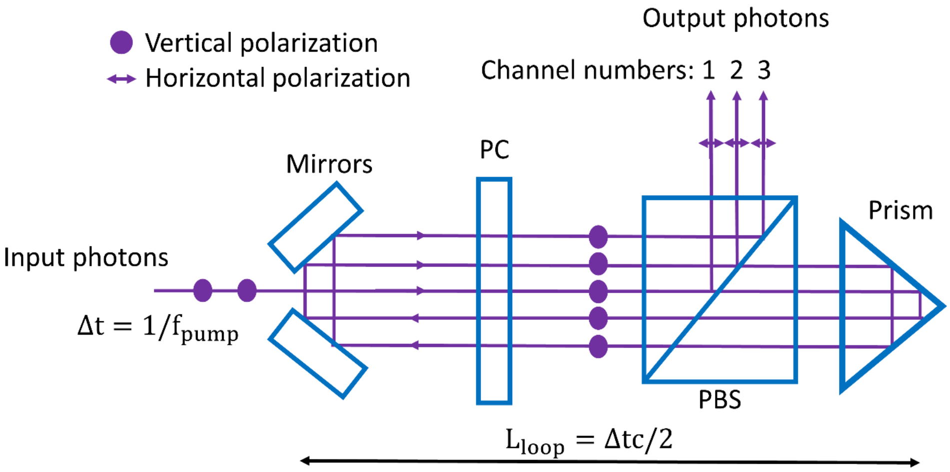

Fig. 1. Principal scheme of the spatial demultiplexer for 3 photons

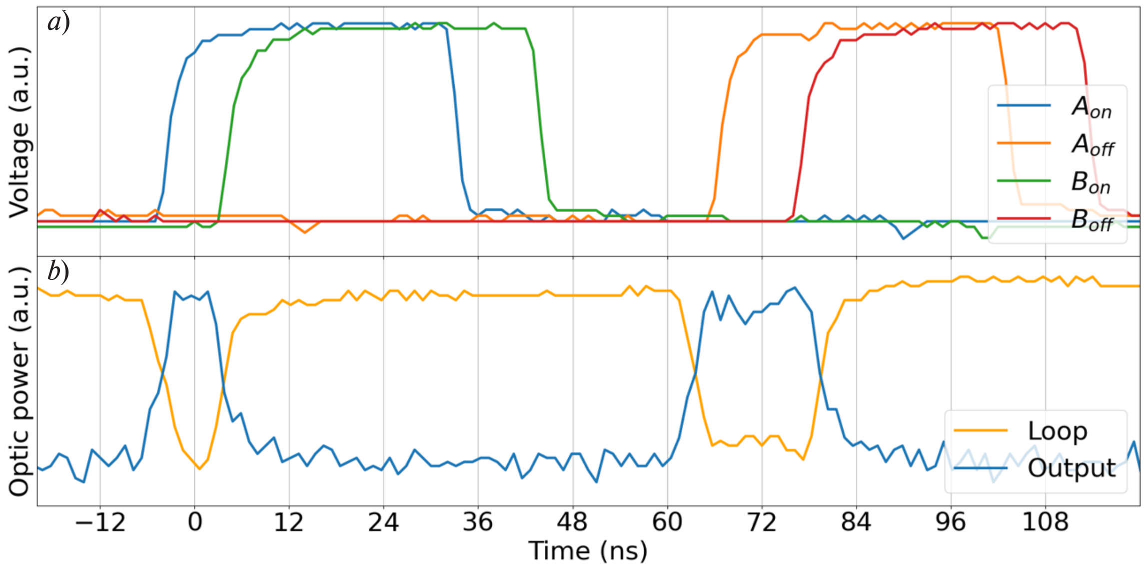

Fig. 2. Voltage on the keys of the PC(*a*) and CW-laser radiation in and out of the optical loop (*b*) per time

It can be seen that at the limiting switching frequency, the time windows of the polarization rotation change periodically – each second switching is bit longer in time. When using a continuous-wave laser, the detected difference is more clearly visible as shown in Fig. 2,*b*. The output power of the CW laser varied from 350 μW to 0.3 μW, which was at the sensitivity limit of the analog detector. No effect of the radiation power on the width of the exit time windows from the optical loop was found. This can be explained by the fact that for the manifestation of negative nonlinear effects of the Pockels cell crystal, the radiation power must be much higher.

The difference in the duration of the time windows means that in the case of single photons, the probability of losing every second photon increases. The observed effect can be explained by the maximum possible frequency of operation of the PC. By carefully selecting the delay between the switching period of the Pockels cell and the laser synchronization pulse, it is possible to reduce this effect.

Intensity in the channels of the demultiplexer

A pulsed laser with a pulse frequency of 82.6 MHz was used to obtain the dependences of the intensity on time in the output channels of the demultiplexer. The laser wavelength of 918.83 nm coincides with the wavelength of single photons from the quantum dot intended for use, the output power of the pulsed laser was 1 μW. The Pockels cell rotated the polarization of pulses with a period of 72.5 ns, due to technical limitations. Fast analog semiconductor detectors were used to measure the signal.

The obtained radiation intensities for 3 output channels of the demultiplexer are shown in Fig. 3, *a*–*c*). It should be noted that despite the alignment of the period of operation of the cell with the laser synchronization pulse, each second peak has a lower amplitude. This means that even when using 6 channels (for period of PC 72 ns and period photons 12 ns used in described scheme), when all photons from the loop are spatially separated into channels, the maximum efficiency will be less than 100%.

The amplitudes of the voltage peak from the analog detector is directly proportional to the radiation power in the optical pulse and depends linearly on it. Assuming that if all the peaks were the same size, then the demultiplexing efficiency would be 100%, was the demultiplexing efficiency obtained as the ratio of the sum of the average amplitudes of the large and small peaks to the two average amplitudes of the large peak. The resulting demultiplexing efficiency with a single PC is 87±3%.

It is also worth noting the increase in the amplitude of side peaks, especially noticeable for channel 3 in Fig. 3,*c*, which is farthest from the main optical axis. They are associated with the spatial distance of the photon trajectory from the center of the nonlinear crystal inside the PC. This leads to a rotation of the polarization through small angles when the PC is turned off. This problem can be overcome by using a Pockels cell with a larger entrance aperture or by using lenses with a longer focal length to form a 1:1 telescope.

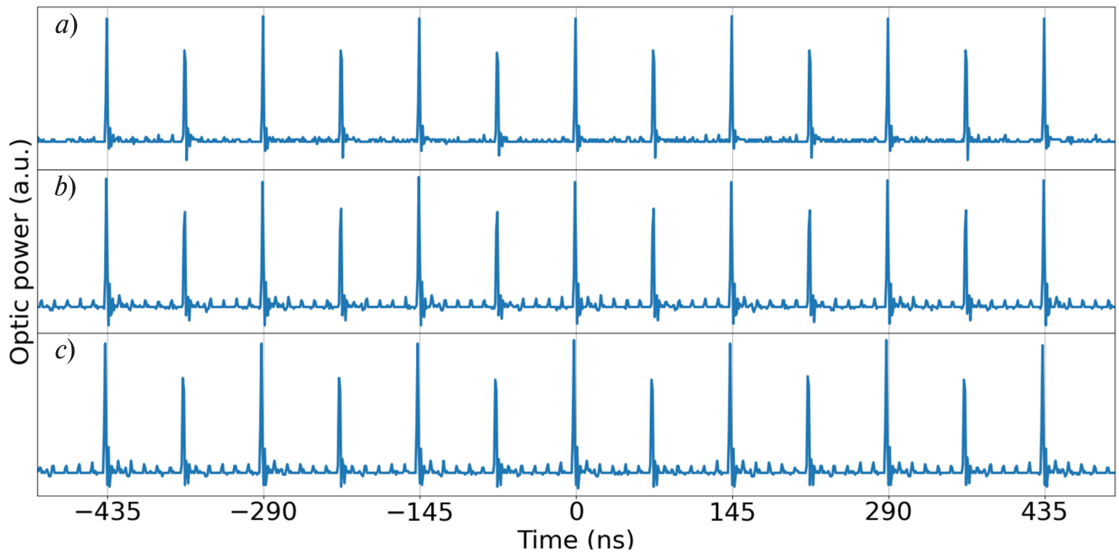

Fig. 3. Intensity at the output of the loop in the 1st (*a*), 2nd (*b*) and 3rd (*c*) channel of the demultiplexer

Conclusion

For the described spatial demultiplexing scheme with only one Pockels cell, the operation of the PC at the limiting switching frequency leads to optical losses. The maximum efficiency achieved by an accurate selection of the time delay between the switching period of the cell and the laser synchronization pulse is 87%. When increasing the number of channels of the demultiplexer, it is necessary, in addition to the geometric dimensions, to consider parasitic polarization rotations that occur when the photon trajectory in the loop moves away from the geometric center of the nonlinear crystal.

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