Quick single-photon detector with many avalanche photo diodes working on the time division

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Due to the limit of response speed of the present single-photon detector, the code rate is still too low to come into practical use for the present quantum key distribution (QKD) system. A new idea is put up to design a quick single-photon detector. This quick single-photon detector is composed of a multi-port optic-fiber splitter and many avalanche photo diodes (APDs). All of the ports with APDs work on the time division and cooperate with a logic discriminating and deciding unit driven by the clock signal. The operation frequency lies on the number N of ports, and can reach N times of the conventional single-photon detector. The single-photon prompt detection can come true for high repetition-rate pulses. The applying of this detector will largely raise the code rate of the QKD, and boost the commercial use.

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Quantum cryptography (quantum key distribution, QKD) is one of the core technologies in quantum communication. It is not based on the algorithm complexity but the basic principle of the quantum mechanics, and it can thoroughly settle the information leakage in the process of the key generation and the key distribution. Since the idea of QKD was firstly proposed by Bennett and Brassard in 1984, many QKD plans[1−6], aiming at all kinds of application environments, for solving the special problem, have been put forward, the amount of which reaches several dozens. The plug-and-play scheme was adopted mainly for the optical fiber communication which has been applied maturely in large scale[7−13]. However, the vital problem in the QKD at present lies in the low rate of the quantum key generation, and the representative value is only several thousand bits per second[12,13], which has greatly restricted its application. The most remarkable obstacle of the quantum key generation rate is the response speed of the single-photon detector. Now, for the telecommunication window, the best choice of the available single-photon detector is the avalanche photo diode (APD) which uses InGaAs/InP materials and works on the Geiger mode in low temperature (cooled by the Peltier effect). In order to decrease the impact of dark counts and the after-pulses, many gate-control circuits were developed to confine the time interval[14−18]. Concerning the existence of the dark count and the after-pulse, the work-time window of the detector is usually set as several nanoseconds and the silence window (the dead time) several microseconds to make it run in the best state, which decides that it is very difficult for the actual operation frequency of the detector to exceed megahertz[14−18]. Thus we propose a new idea designing a quick single-photon detector. It has a multi-port optic-fiber splitter and many APDs which work by time division.

For the representative configuration of the plug-and-play QKD system based on optical fiber communication, the raw bit rate can be expressed as[12]

$$R_{\mathrm{raw}} = q\nu\mu t_{\mathrm{AB}} t_{\mathrm{B}} \eta_{\mathrm{B}} \eta_{\mathrm{duty}} \eta_{\mathrm{T}}, \tag{1}$$

where q is the efficiency factor decided by the protocol type. For example, when BB84 protocol is adopted, q is 1/2. ν is the pulse repeating frequency of an optical source. μ is the average photon amount per pulse, for the sake of guaranteeing the safety of the QKD, we always take $\mu = 0.1$. $t_{\mathrm{AB}} < 1$ is the single photon transmission coefficient of the fiber from Alice to Bob, depending on the length and the loss coefficient of the fiber. $t_{\mathrm{B}} < 1$ is the photon transmission coefficient inside Bob. η_{B} is the detection efficiency of the single-photon detector, it can arrive at 20% for the high quality single-photon detector at present. η_{duty} is the coefficient decided by the structure of light path. η_{T} is the efficiency factor inducted by miscount which is caused by the after-pulse of the detector, correlated with the length of the dead time. As shown in Eq. (1), the most effective way to boost the QKD rate is increasing the repeating frequency of the single photon pulse. However, it is impossible to do so for the present work mode of the single-photon detection, which needs to shorten the dead time. The shorter the dead time is, the greater the miscount probability caused by the after-pulse will be, thus η_{T} reduces too sharply leading the detector worse until out of work.

Figure 1 shows the single-photon detector working on the gated Geiger mode, at the top right corner of which is the sequence relation of the reverse voltage put on APDs. The work time is usually set as $1 - 100$ ns and the dead time as $1 - 10$ μs in order to restrict the after-pulse, then the detector is in the silent state for the most of time. As a result, it fundamentally limits the code rate in the QKD system.

It can figure out the problem of the low code rate in the process of the QKD radically, if making full use of the time interval when “one APD” is at silent state. So we put forward a new idea which adopts the multiplex detector with a multi-port optic-fiber splitter and many APDs working on the time-division mode for all ports,

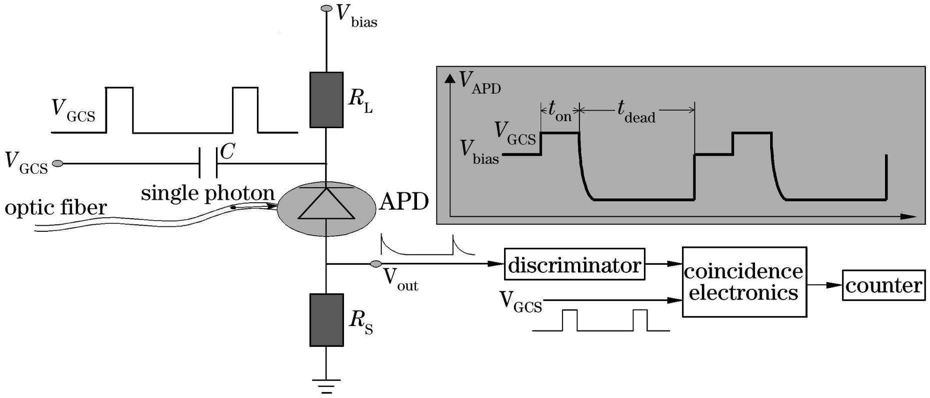

Fig. 1. Single-photon detector and input/output signal.

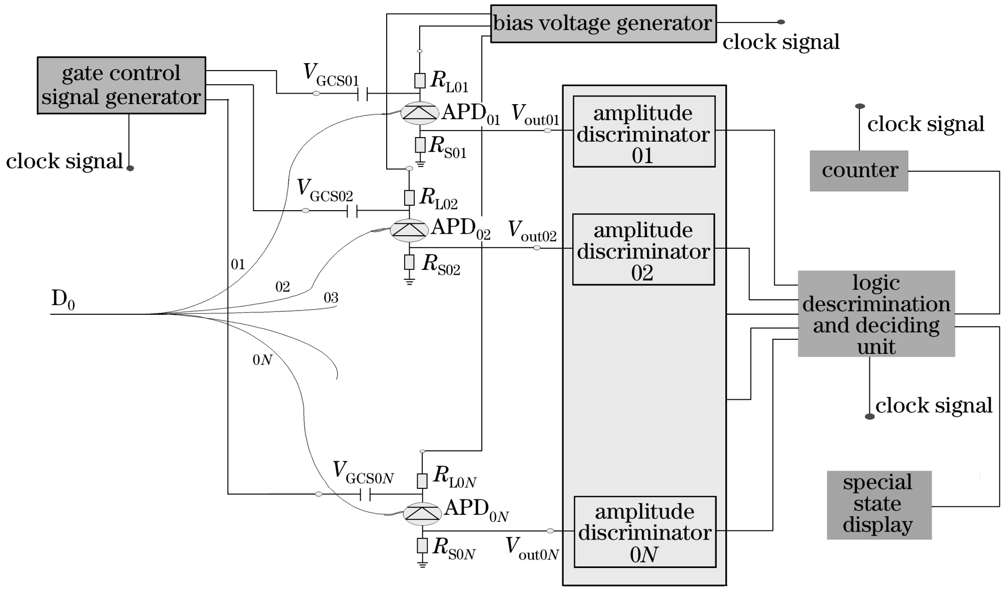

Fig. 2. Quick single-photon detector with multi-port splitter and many APDs working on time division.

instead of the usual single-photon detector. The structure is shown in Fig. 2. It connects the optical fiber through a symmetric optical splitter with N ports, and every port deploys a reverse biased APD.

The APD of every port works on the Geiger mode, the bias voltage of which is supported by a bias voltage generator, and the gate signal is also supported by a gate signal generator. Thus it can decrease the complexity of the circuit and the cost of the detector, and increase the reliability. The bias voltage generator and the gate signal generator can be controlled by the clock signal extracted from the source of the single photon. The avalanche signal exported from each port is firstly discriminated by the amplitude, then input into a logic judging unit, where it coincides with the clock signal, so as to judge whether it is the miscount induced by the dark count or the after-pulse. It can also be judged whether the multi-photon pulse arrives at the multiplex detector. Suchlike special events will be recorded. Finally, the avalanche signal which represents the entering of a single photon is counted for posing bit “0” or “1”.

The number N of ports should satisfy the following condition to make the quick single-photon detector achieve the best efficiency:

$$N > \mathrm{Int}\,[\mu * (t_{\mathrm{dead}}/t_{\mathrm{on}})] + 1, \qquad (2)$$

where μ is the average photon number per pulse, and Int means to adopt the bigger integer. t_{dead} and t_{on} represent the dead time and the work time of the single-APD detector respectively.

Which port to arrive at is random for the photon to induce an APD avalanche, decided by the route of the splitter with N ports which the photon gets through. It is ideal that the single photon of every pulse comes into a different port, and the response speed can reach the maximum, which is N times of the conventional single-APD detector. Figure 3 shows the time sequence relationship among ports of the quick detector. In this figure, we set $N = 5$, and assume that every pulse includes one photon which arrives at the port $1, 2, \cdots, N$ in turn. By the ports' working on time division, the electrical signal is output from the logic judging unit corresponding to the optical signal.

In the real lab environment, photons actually do not arrive at ports in turn but follow the discipline of probability and statistics. There exists the extreme status that

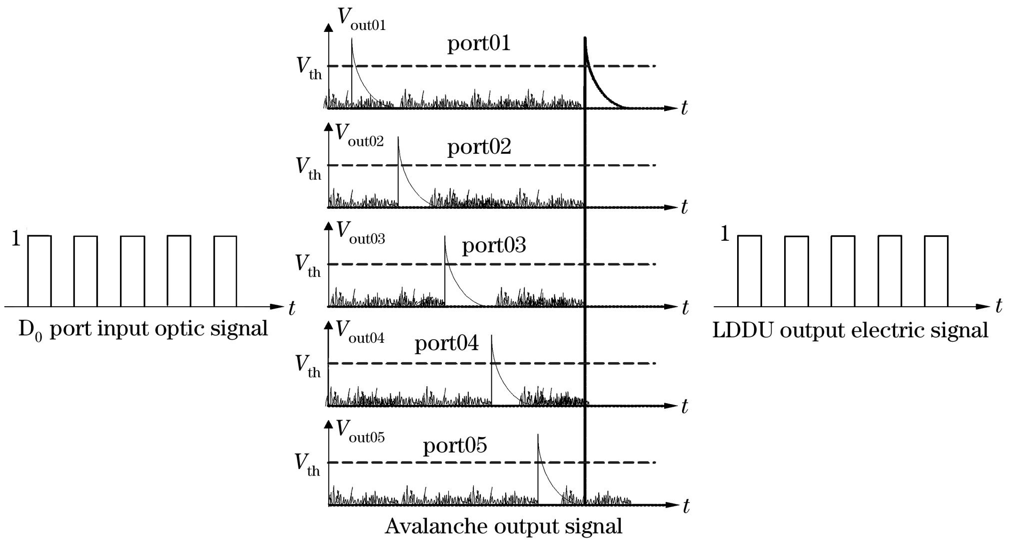

Fig. 3. Time sequence relationship among ports of the quick detector.

all photons from the first to the Nth pulse reach the same port in succession, so that only the first photon can be detected. For this circumstance, we can calculate the probability as

$$P(N) = 1/N^N. \tag{3}$$

From Eq. (3) we can see that it is efficient to reduce the probability of this worst status by increasing the port number N and keep advisable redundancy of ports. There also exists the likelihood that two photons between which the time interval is not so suitable reach the same port, but the probability is smaller. It can also be decreased by increasing the port number N. Furthermore, if adopting the optical switch or the time division multiplexing to control the route where photons arrive at all ports, the problem can be surmounted thoroughly.

In summary, it is feasible in principle to constitute a quick single-photon detector by engaging the multi-port optic-fiber splitter and many APDs. With optical switch controlling photons' route towards different ports, the problem that photons congest the same port will be solved. The code rate of QKD may raise N (the number of ports) times by utilizing this quick detector. To lower the cost, increase the reliability of this multiplex detector, and achieve miniaturization, the multi-port optic-fiber splitter and the control circuit, even APDs may be proposed to implementing optoelectronic integration. The silicon-based single-photon avalanche-diode array by the integration of 5 × 5 pixels had been fabricated successfully so as to detect photons in free space for the visible region[19]. We believe that this quick detection module for QKD in optic fiber communication will be applied in the near future. Thus the QKD will be truly reliable for information safety and can be commercially used.

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