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Single-photon devices in quantum cryptography

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Modern communication in absolute secrecy requires creation of new intrinsically secure quantum communication channels. It is particularly necessary during the first connection between two parties establishing then in assumed unconditional security the secret cryptographic key which is supposed to be used afterwards during normal information exchanging. This new emerging field of quantum information technology is based on a new type of light sources, in which numbers of emitted photons can be carefully controlled. Especially advantageous are sources of single photons emitted at strictly predetermined moments, so called single-photon devices. Then any possible eavesdropper activity will be followed by some unavoidable disturbance which alerts both communication parties to an event. In the present paper, the Purcell effect associated with enhancement of spontaneous emission coupled to a resonator is explained, methods used to produce streams of antibunched photons are given, mechanisms applied to control carrier injection into quantum dots are shown and some possible designs of single-photon devices are presented and described. These devices are based on taking advantage of both the Purcell effect and the atom-like energy spectrum of quantum dots.

Keywords: quantum cryptography, single-photon devices, communication systems, secrecy in communication.

1. Introduction

Every year modern communication systems offer communication networks of still higher speed and still higher capacity. Only security of those communication channels is still questioned. Two people exchanging pieces of information cannot be ever sure that the message has not been read by anyone else, by an unauthorised person.

The science which deals with methods used to increase secrecy of communication is called cryptography. Theoretically cryptography allows two parties, who have not agreed beforehand on a key, to communicate in absolute secrecy. In principle, it is mostly connected with producing the secret key which is first used by a sender to exchange a plain text of a sent message into its coded version, i.e., a stream of numbers, and then it is applied by a recipient to recover the secret text. An eavesdropper cannot understand the coded message without knowing the key. So, basically it is enough to have a secret key (unknown for anyone else) by both authorised parties to secure secrecy of their communication channel. But at the same time, it is also possible that the message may be read secretly (without even warning both the parties about the fact) by an eavesdropper when he was successful to capture the key.

The key may be sent earlier or delivered in a different way. But the most convenient way is to send it in a moment of establishing a communication exchange or even during it. The secrecy of this communication depends on the fact that the key is secret. So, the so-called "key distribution problem" is very crucial in cryptography. If the key may be sent secretly in any moment, it may be changed many times during the communication connection which makes key discovery very difficult (for a possible eavesdropper) during the message exchange.

This problem has just been solved using modern quantum physics. A new kind of cryptography, quantum cryptography [1], enables exchanging a cryptographic key with absolute security guaranteed by the laws of quantum physics, because it is impossible to intercept a key without introducing some perturbations into quantum objects. It is the case because according to quantum physics any measurement unavoidably modifies the state of a single quantum system, so an eavesdropper cannot gather information without being noticed provided that the pulses used in the transmission do not contain two or more photons, they should be single-photon pulses. Therefore a secure key distribution is possible when the message containing a secret key is sent in a form of light pulses, each containing only a single photon. Hence, an essential element of the secure key distribution in quantum cryptography is an optical source emitting a train of identical pulses that contain one and only one photon each.

Unavoidable multiphoton emission generated by hitherto existing conventional light sources render cryptography insecure from certain types of eavesdropper attack [2] In principle, any classical key distribution can always be passively monitored, without the legitimate users being even aware that any eavesdropping has taken place. For the

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first time, quantum cryptography using single-photon devices offers a method of secrete key distribution during which any eavesdropper attack will cause some disturbance which will alert both communication parties to an event. So, at present, modern communication in absolute secrecy, necessary especially during the first connection between two parties establishing then in assumed unconditional security the secret cryptographic key, which is supposed to be used afterwards during normal information exchange, definitely requires usage of devices emitting a train of identical single photons. Therefore this paper is devoted to such devices emitting one and only one photon in a given time interval, which are called single-photon devices. The paper is organised as follows. The Purcell effect is explained in Section 2. Streams of antibunched photons are described in Section 3. Methods used to control an injection of single electrons and single holes into quantum-well (quantum-dot) recombination region are explained in Section 4. Some designs of single-photon devices with atom-like quantum dots are presented in Section 5, which is followed by conclusions.

2. The Purcell effect

Spontaneous emission of an atom is usually considered to be its inherent property. It has been, however, revealed using principles of the quantum electrodynamics, that this emission is in fact a result of the interaction between the atom dipole and the zeroth fluctuations of the vacuum electrodynamic field [3]. Hence the emission may be dramatically modified when the field is, for example, disturbed by a cavity [4], whose size is comparable to the radiation wavelength . Such behaviour is governed by the cavity quantum electrodynamics [3,5]. In this case, the number of allowed modes is reduced, but the vacuum field intensity in the cavity modes may be considerably increased, assuming some of them (so-called resonant modes) are in resonance with some of level-to-level atom transitions [6]. As a result, the spontaneous emission within the cavity resonance is enhanced at the expense of the spontaneous emission outside the cavity resonance, which is called the Purcell effect. Then, the very large fraction β (exceeding even 0.9, Ref. 7) of photons spontaneously emitted into a single mode of the cavity is reported. Consequently, for an ideal atom (with a negligible linewidth) placed exactly at the antinode of the mode standing wave, the Purcell enhancement factor F_P (describing the amount by which the spontaneous emission rate is enhanced for an emitter on resonance with a cavity mode) is given by the following equation [4]

$$F_P = \frac{3Q(\lambda/n_r)^3}{4\pi^2 V}, \quad (1)$$

where λ is the atomic level-to-level transition wavelength, n_r stands for the refractive index of the cavity medium, Q is the cavity quality factor and V is the cavity effective mode volume. This effect becomes very strong in photonic-crystal devices, where electromagnetic waves can be confined in all three directions leading to very small mode volumes V [8,9], close even to its minimal possible value [10] of $(\lambda/n_r)^3$.

This revolutionary concept suggested by Purcell [4] for microwaves more than 50 years ago, i.e., an ability to enhance the spontaneous-emission rate, may be used for example to fabricate high-efficiency light-emitting diodes [11,12]. To observe a strong Purcell effect, low-dimensional photonic nanostructures are necessary. Their energy structures are characterised by well-separated discrete electronic states. Some designs of such devices will be presented in Section 5.

It is interesting to note that theoretically the Purcell effect enables designing a thresholdless laser [13,14]. In a conventional laser, only a small portion of the spontaneous emission couples into a single laser mode. The rest is lost to free-space modes, which radiate out the side of the laser. If we design a wavelength-size laser cavity in which only one optical mode exists, all spontaneous and stimulated emission couples to this mode [15]. So, clear distinction between the spontaneous and the stimulated regimes known in conventional lasers is not observed in such microcavity lasers. In practice, one can imagine a device, in which an internal quantum efficiency is nearly perfect and only the fundamental mode can exist (all other modes are effectively suppressed). Such a hypothetical device would really have a very low lasing threshold. But also it would have a very low power output because single-mode microcavities should have sizes comparable with the wavelength of emitted radiation. Some calculations [16] carried out for an ultimate microscopic limit of a semiconductor laser [17], i.e., for one electron-hole pair confined by a single InAs/GaAs quantum dot located at the antinode position of the mode standing wave inside a microsphere cavity, lead to the threshold current of about 9 pA, i.e., about six orders of magnitude lower than the current record of 8.7 μA for a microcavity semiconductor laser [18].

3. Streams of antibunched photons

Light generation in standard diode lasers and light-emitting diodes can be described with classical Maxwell's equations. Then photons emitted by such classical light sources follow Poisson statistics [19], which means that their emission events are not correlated with one another. Secure quantum communication channels require, however, weak optical sources with strong quantum correlations between single photons, which may be realised with the aid of the fundamental principles of quantum mechanics. Then, a regulated photon stream pulses containing one and only one identical photon each in a given time interval is emitted. Such an antibunched source of identical photons is useful in the new field of quantum cryptography [1], because, using it in the quantum communication channel, information exchanged by both authorised parties cannot be gathered unnoticeably by an eavesdropper [2].

Stream of antibunched photons was first observed from single atoms and ions in traps [6,20–24] excited by a laser. The most promising realisation of such a generation is, however, connected with an atom-like structure of quantum dots (QDs) and their strong confinement of electrons and holes [25–31]. Most importantly, quantum dots can be conveniently integrated in high-Q microcavities that improve the collection efficiency of the single photon train emitted by the dot. Moreover, QD may also emit two correlated (entangled) photons when two electron-hole pairs are injected into it and the biexciton state is created. For a large-scale implementation of secure telecommunication systems based on quantum cryptography, it is crucial to produce room-temperature operating electrically driven compact sources of single photons. It may be realised, for example, by an integration of a single QD in a light-emitting diode with a distributed-Bragg-reflector microcavity [10,32,33], whose fundamental mode should be on resonance with the QD photons. Thus, QD light-emitting diodes may provide attractive sources of single photons for secure quantum communication channels. The most crucial problem is associated with an efficient injection of single carriers into a single quantum dot, which will be analysed in Section 4.

Possible photon antibunching can be experimentally detected with the aid of measuring the joint probability of an arrival of one photon at the time t and another one at the time $t + \tau$. It is described by the normalised second order intensity correlation function $g^{(2)}(\tau)$ [27,28,32]

$$g^{(2)}(t) = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1(t)\rangle\langle I_2(t+\tau)\rangle} \tag{2}$$

where I_1 and I_2 are the emission intensities detected by two single-photon counting detectors, so in this experimental setup the time interval between two successive photons is measured. For perfectly single-photon devices, $g^{(2)}$ $(\tau = 0)$ $= 0$. In fact, in real devices, measurements of $g^{(2)}(\tau)$ indicate a distinct dip at zero time delay [28], which means that after an emission of the first photon a single-photon device needs some time to be excited again which is necessary to emit a next photon.

4. Control of the carrier injection

In order to obtain emission of single photons, single electron-hole pairs should be carefully injected into their recombination regions. It is possible, for example, in a heterostructure proposed by Imamoðlu and Yamamoto [34]. Its band model is shown in Fig. 1. Assuming the junction voltage V_j well below the built-in potential V_b

$$V_b - V_j(t) >> k_B T \tag{3}$$

where k_B is the Boltzmann constant and T stands for temperature, the carrier injection into the recombination quan-

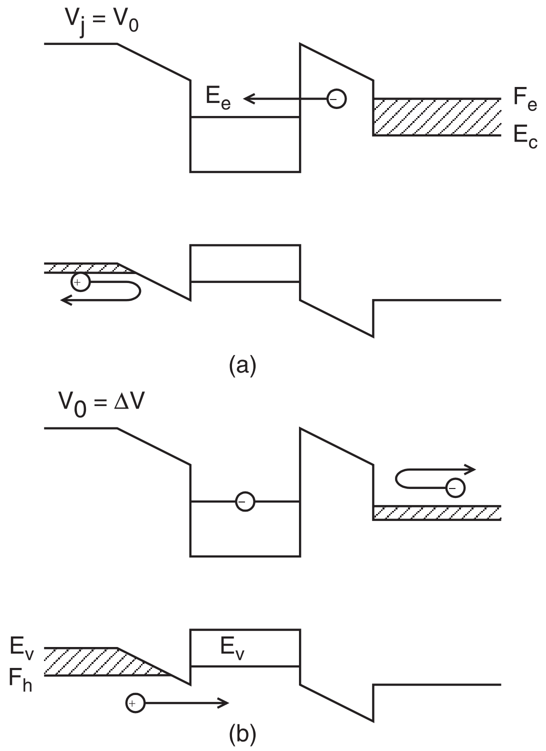

Fig. 1. Band structure of the first single-photon device proposed by Imamoðlu and Yamamoto [34]. Notation used is explained in the text.

tum well (or quantum dot) takes place by successive resonant tunnelling of electrons and holes into the QW (QD) which is followed by their radiative recombination. The electron resonant tunnelling is allowed [see Fig. 1(a)] when its quasi-Fermi energy F_e is higher than the first electron energy level E_e in the quantum well (QD)

$$F_e - W_e \geq E_e \geq E_c - W_e \tag{4}$$

whereas analogous hole resonant tunnelling may take place where its quasi-Fermi energy F_h is lower than the first hole energy level E_h [Fig. 1(b)]

$$F_h - W_h \geq E_h \geq E_v - W_h \tag{5}$$

where E_c and E_v stand for the conduction-band and the valence-band edges, respectively. In the analysis, electrostatic interactions connected with a presence of the electron W_e or the hole W_h are taken into account

$$W_e = \frac{e^2}{2C_n} \qquad W_h = \frac{e^2}{2C_p} \tag{6}$$

where C_n and C_p are the capacitances of the n-part and the p-part, respectively, of the QW (QD) surrounding. Successive electron and hole resonant tunnelling events into the recombination QW (or QD) may be carefully controlled with the proper applied junction voltage $V_j(t) = V_0 + v(t),$

where *v(t)* is in a form of square pulses: *v(t)* = 0 for the electron injection and *v(t)* = ΔV for the hole injection. V_0 and ΔV should be properly chosen to enable fulfilling the conditions of Eqs. (4) and (5), respectively. Then, during the first part of the cycle, when *v(t)* = 0, the single electron resonant tunnelling is enhanced. Next the hole injection takes place, when *v(t)* = ΔV. A possible second tunnelling event of a carrier of the same kind is blocked by the Coulomb blockade. Therefore within one cycle, a single electron and a single hole are injected into the QW (QD) which is followed by their recombination. If this heterostructure is properly coupled with a resonator, then single photons generated in its QW (QD) are spontaneously emitted into a resonator mode. This idea has been used in a first experimental demonstration [35] of a single photon turnstile device using a micropost QW heterostructure. Unfortunately, until now this approach has been limited to extremely low temperatures (< 0.1 K, [36–38]) because of relatively small Coulomb splitting and broadening with temperature of energy distributions of electrons and holes in layers from which a careful carrier injection into the QW (QD) is supposed to take place.

The above temperature limit may be considerably increased when, to control the carrier injection, the Pauli exclusion principle is used instead of the previous Coulomb blockade. In a QD device proposed by Benson *et al.* [25], first two electrons are injected into QD, which is followed by an analogous injection of two holes. Because of the Pauli exclusion principle, next electron or hole tunnelling events are suppressed since both electron and hole ground states are already filled with a pair of carriers of opposite spins. At first, they will occupy ordinary single-particle states, but because of strong electrostatic interactions between the carriers, they finally create a biexciton state. During one modulation cycle, a biexciton is created, so an entangled pair of photons may be emitted [31]. To receive only one photon, two methods may be applied. One of them is associated with different circular polarisations of both photons [25]. The second one is associated with an additional biexciton binding energy. Hence, during a recombination of the first electron-hole pair, a photon of slightly lower energy is emitted than during the second ‘exciton’ recombination. So, both photons may be spectrally separated [19]. It may be done with the aid of a precise adjustment of the ‘exciton’ photon to the energy of the resonant high-Q cavity mode. Then the spontaneous emission of these photons is enhanced thank to the Purcell effect [39] whereas the ‘biexciton’ photons cannot be efficiently coupled to this mode. As a result, only the last photon [19], the ‘exciton’ photon of well defined frequency, is emitted by the device during each excitation cycle. Permissible operation temperature of the device taking advantage of the Pauli exclusion principle is much higher than that of the previous one because the small Coulomb splitting is now replaced by much larger splitting between ground and excited states of the carriers in both allowed bands. This difference depends on the QD size and, in devices with smaller QDs, their operation at temperatures up to 50 K is possible [25]. Small enough QDs may even have only one electron and one-hole states. So, there is still a room for improvement.

5. Possible designs of single-photon devices

A complete QD single-photon device is composed of the single QD active region properly coupled with a microresonator. Strictly speaking, the QD should be placed exactly in the antinode position of the selected resonant-mode standing wave to optimise the coupling. Only such a QD, which is both well matched spectrally with the resonant cavity mode and located close to its antinode, experiences a strong enhancement of its spontaneous emission rate.

There are various resonator structures used in QD single-photon devices. Its simplest version is probably the micropost (or micropillar) cavity [7,10,11,25,32,40,41] shown schematically in Fig. 2(a). The Purcell enhancement factor F_P, Eq. (1), is inversely proportional to the mode volume, therefore diameters of resonator pillars are rather small (even < 0.5 μm) and additionally their tapering shape is sometimes produced by etching with a minimal cross-section close to the active region [10]. The cross-sectional areas of the active region as low as only 0.04 μm^2 were achieved [10]. The spontaneous emission lifetime has been found to be decreased from 1.3 ns to 250–280 ps by coupling to a micropillar cavity [10,11]. For a typical 1-m micropillar, quality factor Q as high as 2250 has been reported, which corresponds to the Purcell enhancement factor F^P as large as 32 [11]. Robert *et al.* [27,32] have proposed elliptical cross-section micropillars to obtain single photons of exactly the same polarisation.

The above micropost cavity may be modified in a way shown in Fig. 2(b) to produce the microdisk cavity [11,29,39,42,43]. It supports a series of whispering gallery modes [42]. The modes are tightly confined by total internal reflections at the lateral edge of the disk, so resonators of very high quality factors Q are available. Routinely Q values as high as over 10 000 are obtained [11,44] which corresponds to the Purcell factor of the order of 125. Therefore microdisks appear excellent candidates for possible single-photon devices which are expected to operate at temperature range easily extended to 77 K [29,39]. Room-temperature operation is believed to be achieved by using QDs with higher confinement potential to avoid non-radiative recombination in barriers.

Still another single-photon device has been proposed by Yuan *et al.* [33]. It is a p-i-n diode [Fig. 2(c)] with a layer containing QDs. To confine the emission area to just one QD, special opaque metal layer is formed on the device surface with a small aperture just over the chosen QD.

All the above QD designs of single-photon sources are compact semiconductor devices. But emission of single photons may be also achieved in more complex structures, e.g., in a sample containing an isolated QD coupled with a glass microsphere cavity [Fig. 2(d)] [16,17,45–47]. Such a sphere may be produced by melting the tip of an optical fi-

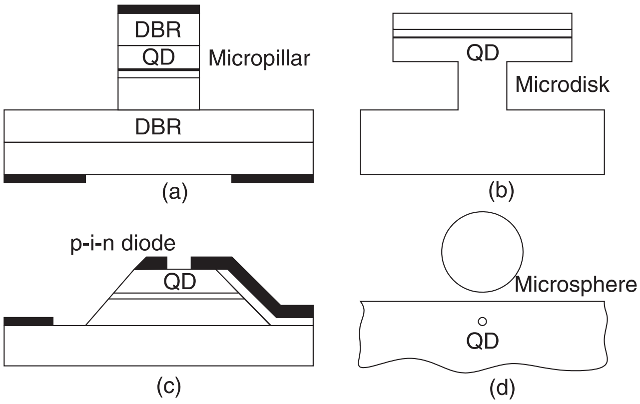

Fig. 2. Schematic structures of QD single-photon devices: (a) with a micropost (micropillar) cavity, (b) with a microdisk cavity, (c) with a DBR cavity of a p-i-n diode, (d) with a microsphere cavity.

bre with a CO^2 laser. Its quality factor Q may be extremely high (even as high as 3×10^9, [45]). Extremely-low threshold semiconductor laser based on this structure was proposed by Pelton and Yamamoto [16].

6. Conclusions

An optical device emitting a train of pulses that contain one and only one photon (i.e. a single-photon device) is an essential element of secure key distribution in quantum cryptography. Then an eavesdropper cannot capture information about the secret key without being noticed because such an event unavoidably modifies the state of a single quantum system. In this way, the quantum cryptography exploits the fundamental principles of quantum mechanics to provide unconditional security for communication.

According to Gerard and Gayral [11], three conditions should be fulfilled in order to get an efficient single-photon device. First of all, the carrier transport and recombination phenomena should ensure generation of single photons. They should be on resonance (high β, close to one) with a single high-Q mode of a coupled cavity. Besides, to avoid nonradiative emission, the photon emission should be characterised by a quantum efficiency very close to one.

Thus an ideal compact single-photon device is composed of a single quantum-dot active region coupled with a single resonant mode of a microresonator in such a way that the QD is placed exactly in the antinode position of the resonant-mode standing wave. To enable its operation at relatively high temperatures, energy splitting between ground and excited carrier states should be large for both electrons and holes so, QDs should be as small as possible. Microresonator, on the other hand, should ensure high photon storage time (high cavity quality factor Q). Until now, various cavity structures are considered. Not meaningless is also compactness of the whole device.

The history of single-photon devices designed for quantum cryptography is still rather short. Secure communication channels are important in many applications, practically for all of us. It may be expected that many new more compact, high-performance, room-temperature, easy to use quantum cryptography single-photon devices will be invented and designed in the closest future. A market demand is very strong.

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