10

Optimization of information transmission using a random flow of single gamma-ray photons

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Recently, we have proposed a method for transmitting information using a random photon flow. It is controlled by an absorber-piezoelectric-transducer assembly, to which rectangular voltage pulses are fed. Information is encoded in the pulse duration and time intervals between them. It turned out that such pulses excite mechanical vibrations in our assembly, which lead to the appearance of small radiation pulses at undesirable moments in time. Pulses of a different shape with a smooth change in fronts, which reduce the probability of excitation of mechanical vibrations, are proposed. The advantages of the proposed pulses are demonstrated experimentally.

Keywords: information transmission, piezoelectric transducers.

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The development of methods for information transmission with the use of single photons is made relevant by the need to create reliable cryptographic protocols [1]. It has been proposed to encode information in the polarization of photons [2], in the relative phase of components of a single-photon wave packet split in time into two pulses [3,4], and in various other ways (see review [1]). We have recently suggested a method for information transmission with the use of a random flow of single gamma-ray photons [5]. This flow is controlled by a resonant absorber that is subjected to rapid shifts of half the radiation wavelength. A gamma pulse is generated each time the absorber undergoes a shift. The effect is based on the interference of incident radiation from the source and radiation scattered coherently by the absorber. The interference of these fields becomes constructive as a result of a rapid shift of the absorber relative to the source, and a pulse is generated. These pulses may be observed if the absorber shift is synchronized with the recording unit for resonant gamma photon counting [6,7]. The proposed method has advantages over traditional communication techniques utilizing radio, microwave, and optical radiation in energy efficiency, compactness, and high penetrating power of gamma radiation, which propagates through various media that are opaque to traditional communication signals. In addition, the method provides a significantly higher rate of modulation of radiation intensity compared to known techniques of mechanical modulation of radiation of radioactive nuclei with shutters (see, e.g., [8]).

We use a ^{57}Co radioactive source that emits photons with an energy of 14.4 keV. Stainless steel (AISI 304) foil serves as a resonant absorber, which is glued to a polymer piezoelectric transducer (PVDF). Rectangular voltage pulses are applied to it. Figure 1, *a* shows the radiation phase variation under the influence of a rectangular voltage pulse and the time dependence of probability of detecting photons emitted from the absorber. The generator used in the discussed experiments has the capacity to shape rectangular voltage pulses with a duration of 1000 ns and edge duration on the order of 15 ns. The electrical capacitance of the piezoelectric element extends the duration of pulse edges to 30 ns. The theoretical dependence of probability $N(t)$ of detecting photons at the absorber output, which was obtained using the theory developed in [6,7], is shown in the same figure. The variation of radiation phase $\varphi_s(t) = kx(t)$, which is determined by the time dependence of absorber shift $x(t)$ under the influence of the piezoelectric transducer and radiation wave vector k, is written as

$$\varphi_s(t) = \alpha\Big[\phi(t - t_1) - \phi(t - t_2)\Big], \qquad (1)$$

where α is the maximum phase value, $\phi(t) = \big[1 - \exp(-t/\tau)\big]\theta(t)$, $\theta(t)$ is the Heaviside step function, τ is the phase rise/fall time, and $t_{1,2}$ are the time points at which voltage is switched on and off. Time τ is specified by the capacitance of the piezoelectric transducer. Gamma radiation bursts at the leading and trailing edges of a rectangular voltage pulse, which causes the shift, are seen clearly in Fig. 1, *a*. It should be noted that the maximum phase change value does not necessarily have to be equal to π to obtain the optimal signal value. It may be lower than π, and the radiation burst will then be less intense. It may also be greater than π and even exceed 2π. According to theory, two bursts should be observed in this case on crossing the values of π and 2π (i.e., each time the phase changes by π: from zero to π and from π to 2π).

However, the emergence of repeated gamma-ray bursts was observed in our experiments regardless of the maximum phase value, which is proportional to the applied voltage.

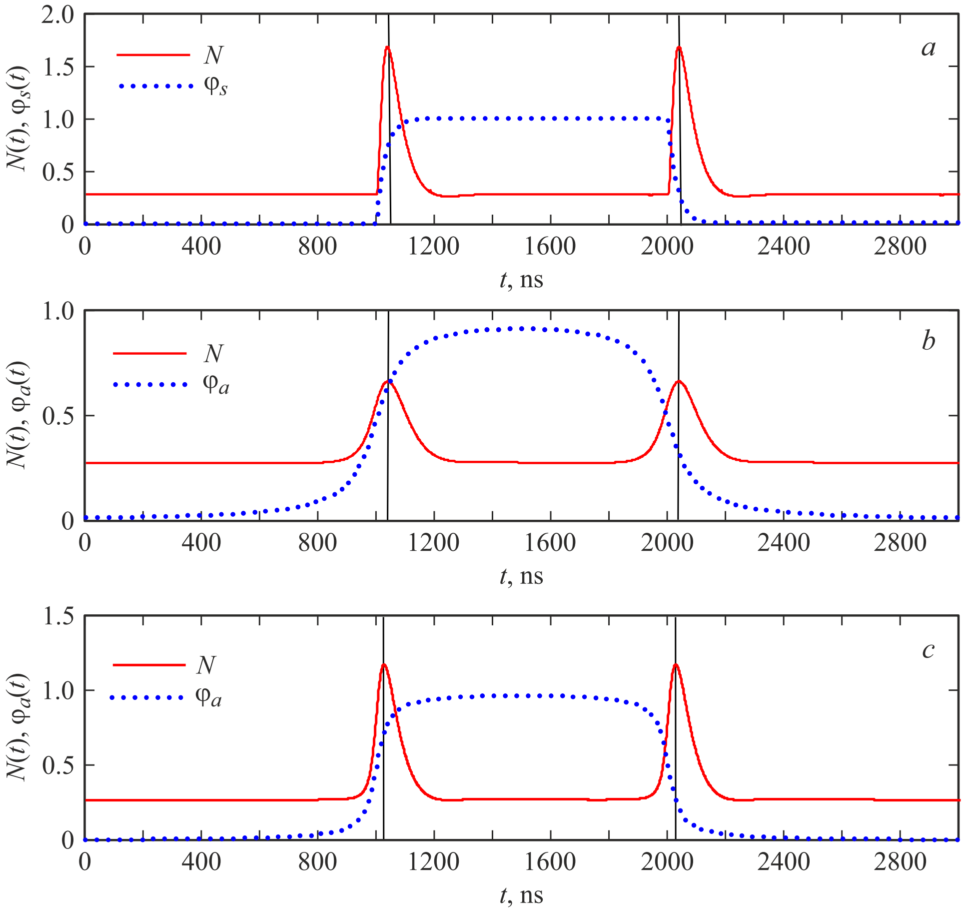

Figure 1. Dependence of probability $N(t)$ of detecting a photon at the absorber output (solid curve) and radiation phase variation $\varphi(t)$ under the influence of a piezoelectric transducer shift (dashed curve). Subscripts s and a correspond to step shift $\varphi_s(t) = kx(t)$ and shift $\varphi_a(t) = kx(t)$ that follows the arctangent law. Parameter τ of these shifts assumes a value of 30 (a), 70 (b), and 30 ns (c). The radiation phase is normalized to π. Vertical lines denote the positions of radiation maxima.

Figure 2 shows the results of experiments on generation of gamma pulses induced by a rectangular voltage pulse. The maximum voltage was 10 V (Fig. 2, a). It can be seen that the first peak of gamma radiation caused by the leading edge of a voltage pulse is followed by a second peak that forms approximately 100 ns later. The same pattern is repeated at the trailing edge of a voltage pulse. No qualitative changes are observed as the maximum voltage decreases from 10 to 2.5 V in 2.5 V steps. This suggests that the emergence of secondary radiation bursts does not depend on the maximum phase shift. It is likely to be caused by mechanical vibrations of the piezoelectric transducer, which are excited by the leading and trailing edges of a voltage pulse. We assume that these edges excite oscillations of the piezoelectric element with a frequency of ~ 10 MHz. Similar secondary bursts were observed in [9], where a quartz piezoelectric transducer exciting shifts of an ^{57}Co(Pd) radiation source was used. In addition, radiation bursts of a much lower intensity occur with a delay of ~ 400 ns relative to the leading and trailing edges of a rectangular voltage pulse. It may be assumed that the observation of secondary and delayed bursts of radiation is attributable the fact that our assembly has two frequencies of natural oscillations close to 10 MHz. The difference between these frequencies is ~ 2.5 MHz. A steep edge of a voltage pulse excites these frequencies, which induce a change in the phase of radiation. The secondary burst is caused by these mechanical vibrations. The delayed burst is caused by the interference of two high-frequency oscillations, which produces beats with a period of ~ 400 ns.

In light of the above arguments, we decided to apply voltage pulses with such edges that should help avoid the excitation of natural frequencies of the assembly, thereby suppressing the generation of unwanted radiation pulses. Two factors in the nature of phase change (shift), which is characterized by formula (1), may lead to the excitation of oscillations. The first one is the edge steepness, which is set by parameter τ. The second factor is shift derivative dx/dt. In expression (1), the derivative at the leading edge undergoes a jump from zero to the maximum possible value. To avoid such a jump, we set a voltage pulse shape that produces the following temporal variation of the radiation

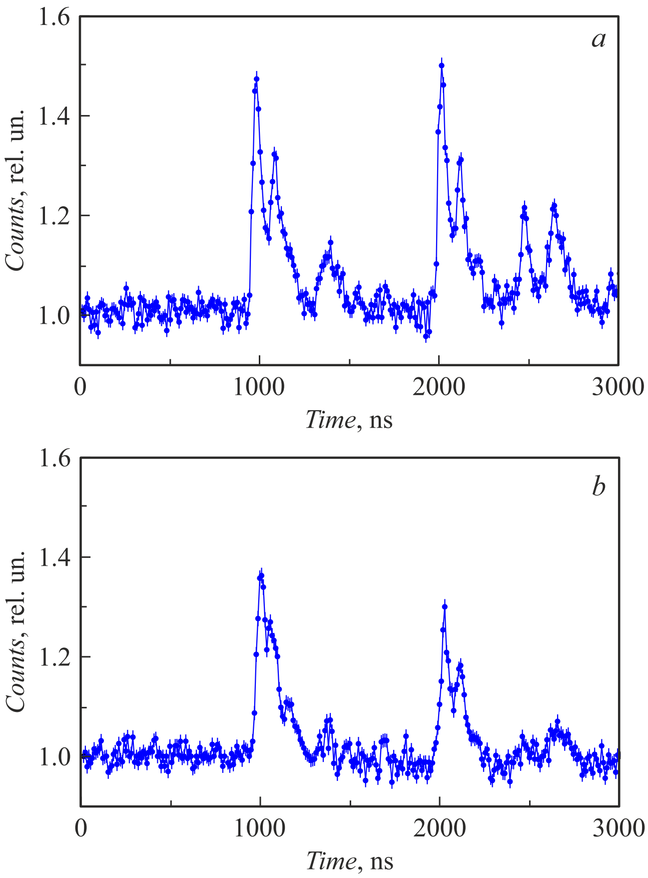

Figure 2. Bursts of gamma radiation at the absorber output observed when a rectangular voltage pulse, which induces phase change (1), with an amplitude of 10 (*a*) and 5 V (*b*) is applied to the piezoelectric transducer.

phase:

$$\varphi_a(t) = \frac{\alpha}{\pi}\left[\arctan\left(\frac{t-t_1}{\tau}\right) - \arctan\left(\frac{t-t_2}{\tau}\right)\right]. \quad (2)$$

Examples of such a dependence with two different values of parameter τ are shown in Fig. 1, *b* and *c* (dotted curve).

Using an arbitrary-shape voltage pulse generator, we specified shifts that produce a phase change in accordance with formula (2). Figure 3 shows gamma radiation bursts that emerge under the influence of such a voltage pulse with the following parameters: $\tau = 70$ (*a*) and 30 ns (*b*). It is evident that unwanted radiation bursts were eliminated almost completely. It is interesting to note that, in line with theoretical predictions (Fig. 1, *b*), the radiation pulse acquires a symmetrical shape at $\tau = 70$ ns (*a*). As the value of this parameter decreases, the pulse shape becomes asymmetrical, which also agrees with theory (Fig. 1, *c*).

The word „Nature" in eight-bit ASCII encoding, which contained 48 bits of information, was used in our previous study [5] in information transmission tests. A sequence of 14 rectangular voltage pulses of different durations with different time intervals between them was produced for generation of gamma radiation pulses. The overall duration of this sequence was 17 μs. It was divided into 347-ns-long time slots. Bits 1 and 0 were assigned to time slots in which voltage was present and lacking, respectively. The observed gamma radiation pulses provided an opportunity to reconstruct unambiguously the sequence of voltage pulses and decode the transmitted text. The presence of parasitic bursts resulting from the elastic properties of our modulator necessitates the accumulation of data with a high signal-to-noise ratio for reliable information reception. In turn, this requires additional time to read the transmitted information accurately. Therefore, the proposed method of suppression of parasitic bursts allows one to speed up significantly the process of extraction of information from the observed signals.

It should be noted that the suppression of parasitic signals is due to the peculiarities of shape of the proposed pulses, which have vanishingly small components at the resonant modulator frequency of ~ 10 MHz in their Fourier spectrum. We have already demonstrated that the excitation of harmonic oscillations of the used assembly is most efficient exactly at this frequency [10].

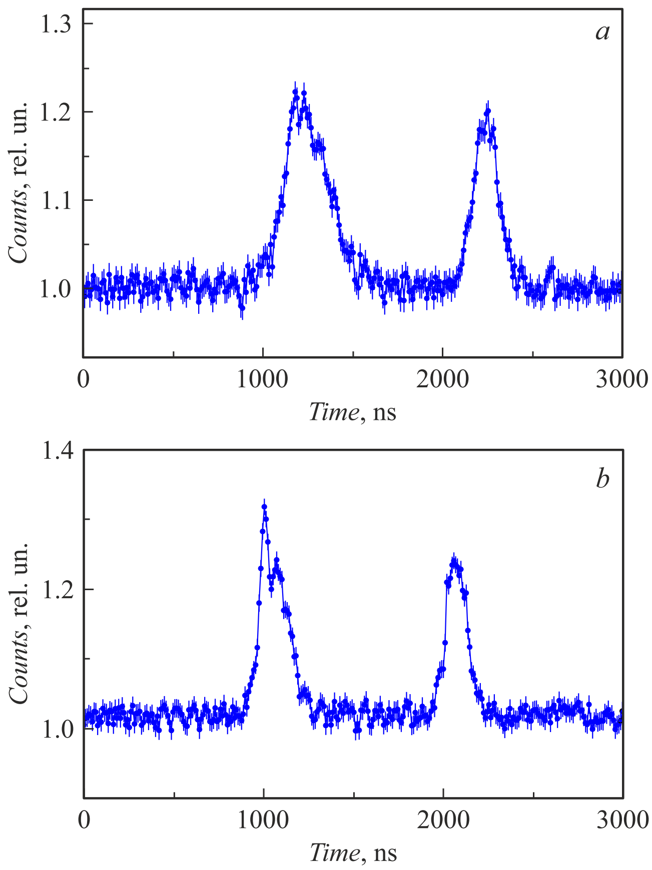

Figure 3. Generation of gamma pulses with the use of rectangular voltage pulses with their edges characterized by arctangent function (2). The parameter of this function is $\tau = 70$ (*a*) and 30 ns (*b*).

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Conflict of interest

The authors declare that they have no conflict of interest.

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