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RESEARCH ARTICLE

Simulation of subnanosecond radio pulse electro-optical repeater

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Abstract

Objectives. The study aimed to construct and analyze a computational model of an electro-optical repeater of radio pulses, capable of reconstructing a pulsed radio image with subnanosecond resolution in a single reception under conditions of additive noise.

Methods. Numerical methods of network analysis were used, which are the basis of specialized computer-aided design systems, numerical methods of statistical radio engineering.

Results. A radiophotonic radio pulse repeater scheme was constructed, which is implemented based on the principle of fractional multiplexing with delayed feedback. Software simulation of infrared repeaters in the *Simulink* environment (Trial Version Soft) was developed, which allows for analyzing and investigating the efficiency of the optical reconstruction method of radio pulses using a fractional multiplexing with delayed feedback. It is shown that repeaters schemes, implemented on the principles of fractional multiplexing with delayed feedback, are able to effectively solve the scientific and practical problems of multiple probing of objects with ultrashort pulses (USP) for obtaining a radio image of a target with reliable reproducibility. In the course of numerical simulations, it was found that the two- and four-cascade schemes of delay lines with feedback do not provide reliable reproducibility in the case of reconstruction of an ultrashort pulse with a complex time profile. At the same time, the scheme with a cascade of 8 delay lines showed good results, providing a correlation reproducibility of more than 0.9. In this case, the scheme of an electro-optical repeater with a cascade of 16 delay lines did not make a significant contribution to increasing the accuracy of the USP reconstruction if compared to the scheme with a cascade of 8 lines; therefore, the latter can be determined as an optimal solution. An electro-optical method was proposed for solving the radio engineering problem of stroboscopic registration and reconstruction of subnanosecond radio pulses, which represent the signature of the radio image of dynamic objects for active radio imaging systems.

Conclusions. It was found that an electro-optical repeater with 8 delay lines is able to recover a complex pulse reflected from a target in 30 iterations with a correlation coefficient greater than 0.9 between the reference and reconstructed pulses at a signal-to-noise ratio of at least 9 dB.

Keywords: strobe-frame sampler, ultrashort radio pulse, radio image, electro-optical repeater, feedback delayed communication with fractional multiplexing

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НАУЧНАЯ СТАТЬЯ

Моделирование электрооптического повторителя субнаносекундных радиоимпульсов

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Резюме
Цели. Целью данной работы является построение и анализ программно-численной модели электрооптического повторителя радиоимпульсов, обеспечивающего восстановление импульсного радиоизображения за однократный прием в условиях воздействия аддитивных шумов с достижением субнаносекундного разрешения.
Методы. Использованы численные методы схемотехнического анализа, лежащие в основе специализированных систем автоматизированного проектирования, численные методы статистической радиотехники.
Результаты. Построена радиофотонная схема повторителя радиоимпульсов, реализуемая на принципе дробного мультиплексирования с обратной задержанной связью. Разработаны программные модели инфраоптических повторителей в среде *Simulink* (Trial Version Soft), позволяющие анализировать и исследовать эффективность метода оптической регенерации радиоимпульсов при помощи схемы дробного мультиплексирования с задержанной обратной связью. Показано, что схемы повторителей, реализуемые на принципах дробного мультиплексирования с задержанной обратной связью, способны эффективно решить научно-практическую задачу многократного зондирования объектов сверхкороткими импульсами для получения радиоизображения цели с достоверной воспроизводимостью. В ходе численного моделирования установлено, что двух- и четырехкаскадные схемы линий обратной задержки не обеспечивают надежной воспроизводимости в случае восстановления сверхкороткого импульса (СКИ) со сложным временным профилем. В то же время схема с каскадом из 8 линий задержки справляется с поставленной задачей, обеспечивая корреляционную воспроизводимость более 0.9. При этом схема электрооптического повторителя с каскадом из 16 линий задержки не дает весомого вклада в повышение точности восстановления СКИ относительно схемы с каскадом из 8 линий, поэтому последнюю можно определить в качестве оптимального решения. Предложен электрооптический метод решения радиотехнической задачи стробоскопической регистрации и восстановления сверхкоротких радиоимпульсов субнаносекундной длительности, составляющих сигнатуру радиоизображения динамических объектов для систем активного радиовидения.
Выводы. Установлено, что электрооптический повторитель с 8 линиями задержки за 30 итераций способен восстановить сложный импульс, отраженный от цели с коэффициентом корреляции больше 0.9 между эталонным и восстановленным импульсом при отношении сигнал/шум не менее 9 дБ.

Ключевые слова. строб-фрейм дискретизатор, сверхкороткий радиоимпульс, радиоизображение, электрооптический повторитель, обратная задержанная связь с дробным мультиплексированием

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INTRODUCTION

The wide bandwidth of subnanosecond pulses makes it possible to extensively study the parameters of the irradiated media and surfaces of objects by pulse characteristics [1, 2]. Mastering the subnanosecond range opens up new possibilities in the study of radiophysical properties of materials in the area of laser optics and electrodynamics. The scientific interest in the radio wave features of the change in shape of ultrashort optical pulses in infrared range or subnanosecond radio pulses reflected from irradiated surfaces or transmitted through various media makes the search for high-speed methods of receiving ultrashort pulse (USP) signals relevant for their reconstruction [3] and further digital processing. Since a laser pulse can be easily converted into a radio-frequency one, the work is devoted to the development of new methods for the shape-time recuperation of USP in the problems of high-speed digitization of these pulses by adding an electro-optical repeater to such systems, which provides fractional cloning of USP.

The technology of strobe-frame-sampling (SFS) used in this work eliminates the disadvantages of analog reception, including high-frequency clocking of the USP signal for taking digital samples [4, 5].

THE STROBE-FRAME DISCRETIZER MODEL

The proposed SDF model was previously implemented in the *Simulink* software environment [6]. The model consists of a generator to produce pulses of a given shape, an array of elementary signal time delay lines, an array of counters, a comparator, and an output system for displaying the results.

The main disadvantage of this model is the need for stroboscopic reception to reconstruct the USP signal scattered by the signature of a dynamic object. In this case, the pulse is emitted as many times as the number of the comparator levels we need to reconstruct the USP signal [7].

An arbitrary 1 ns pulse (Fig. 1), consisting of the superposition of several bipolar Gaussian pulses (1) with different amplitudes, phases and time delays, was chosen as the probing USP signal.

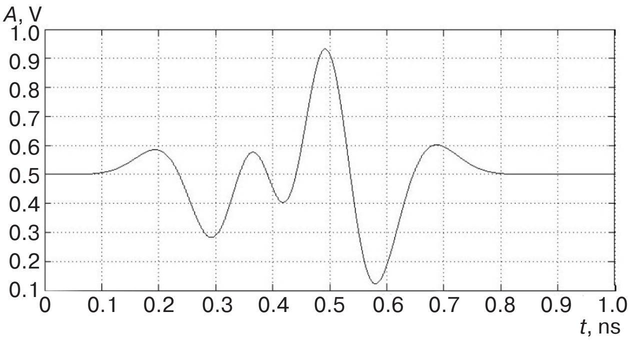

Fig. 1. Probing pulse; *A*, V, is the signal amplitude in volts, *t* is time in ns

$$\begin{aligned} A(t) = &-0.33\alpha t e^{-\beta t^2} - 0.63\alpha(t-0.5\tau)e^{-\beta(t-0.5\tau)^2} + \\ &+ 0.33\alpha(t-0.25\tau)e^{-\beta(t-0.25\tau)^2} + \\ &+ 0.63\alpha(t-0.75\tau)e^{-\beta(t-0.75\tau)^2} + \\ &+ 0.25\alpha(t-\tau)e^{-\beta(t-\tau)^2} - \\ &- 0.23\alpha(t-1.25\tau)e^{-\beta(t-1.25\tau)^2} - \\ &- 0.13\alpha(t-1.5\tau)e^{-\beta(t-1.5\tau)^2} - \\ &- 0.13\alpha(t-1.75\tau)e^{-\beta(t-1.75\tau)^2} + \\ &+ 0.33\alpha(t-2\tau)e^{-\beta(t-2\tau)^2} + \\ &+ 0.63\alpha(t-2.25\tau)e^{-\beta(t-2.25\tau)^2} - \\ &- 0.33\alpha(t-2.5\tau)e^{-\beta(t-2.5\tau)^2} - \\ &- 0.63\alpha(t-2.75\tau)e^{-\beta(t-2.75\tau)^2} - \\ &- 0.25\alpha(t-3\tau)e^{-\beta(t-3\tau)^2} + \\ &+ 0.13\alpha(t-3.25\tau)e^{-\beta(t-3.25\tau)^2} + \\ &+ 0.13\alpha(t-3.75\tau)e^{-\beta(t-3.75\tau)^2} + \\ &+ 0.13\alpha(t-4\tau)e^{-\beta(t-4\tau)^2}, \end{aligned} \tag{1}$$

where, $A(t)$ is the signal amplitude as a function of time, t; $\alpha = 5 \cdot 10^{10}$; $\beta = 10^{20}$; $\tau = 10^{-10}$; $e \approx 2.718$.

To evaluate the value of correlation coupling between the reference and reconstructed pulses, we use the Chaddock scale [8].

The correlation coefficient between the reference and the reconstructed pulses is calculated by the formula

$$r_{x,y} = \frac{\sum_{i-1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i-1}^{n}(x_i - \bar{x})^2 \sum_{i-1}^{n}(y_i - \bar{y})^2}}, \tag{2}$$

where $r_{x,y}$ is the correlation coefficient between the original and the reconstructed pulse, x_i is the ith value of the initial pulse, $\bar{x}$ is the average value of the sample of the original pulse, y_i is the ith value of the reconstructed pulse, and $\bar{y}$ is the average value of the sample of the reconstructed pulse.

THE MODEL OF ELECTRO-OPTICAL USP REPEATER WITH FRACTIONAL MULTIPLEXING AND DELAYED FEEDBACK

As one of the solutions of the radio engineering problem of registration and reconstruction of ultrashort radio pulses of subnanosecond duration, which represent the signature of the radio image of dynamic objects for active radio imaging systems, the authors propose a model of an electro-optical repeater (Fig. 2). This model combines the advantages of fractional multiplexing and delayed feedback schemes [9–11]. This makes it possible to more effectively solve the problem of spectral-temporal iterative degradation of the received USP signal due to the accumulation of amplifier noise as the number of reconstruction iterations increases [12, 13]. In addition, the proposed scheme architecture eliminates the main disadvantages of fractional multiplexing associated with the overall bulkiness of the scheme [8].

The model shown in Fig. 2, consists of an optical signal forming unit, an optical amplifier, a delayed feedback scheme, an optical beam divider, a cascade of optical delay lines, an optical multiplexer, and a photodetector.

The USP signal is delivered to the optical signal forming unit (OSFU), where it is amplified to the values required for its detection, and modulates the optical carrier. After that, the optical pulse is sent to the optical beam divider. Part of the pulse is split off the divider and sent to the cascade of delay lines, while the other part of the pulse is sent to the feedback loop. The chain of units consists of an amplifier that amplifies the input signal to the value required for digitizing the USP signal, and a delay line. The delay time is equal to the duration of the pulse reconstruction iteration in the scheme. In the cascade of delay lines, each copy of the pulse is delayed for a time from T_d to NT_d, where T_d is the delay time, which is equal to the duration of the frame; N is the number of delay lines. Further, all optical beams/pulses are combined by an optical multiplexer and sent to a photodiode, where the signal is demodulated and sent to a strobe-frame-discretizer.

The transfer functions $W(p)$ of the USP electro-optical repeater schemes with different delay lines cascades can be described by formulas (3.1–3.5).

$$W_{\text{wod}}(p) = \frac{1}{1 - K_{\text{amp}} e^{-\tau_{\text{gld}} p}} \quad (3.1)$$

$$W_{2\text{d}}(p) = \frac{1 + e^{-\tau_1 p}}{1 - K_{\text{amp}} e^{-\tau_{\text{gld}} p}}, \quad (3.2)$$

$$W_{4\text{d}}(p) = \frac{1 + e^{-\tau_1 p} + e^{-\tau_2 p} + e^{-\tau_3 p}}{1 - K_{\text{amp}} e^{-\tau_{\text{gld}} p}}, \quad (3.3)$$

$$W_{8\text{d}}(p) = \frac{1 + \sum_{i=1}^{7} e^{-\tau_i p}}{1 - K_{\text{amp}} e^{-\tau_{\text{gld}} p}}, \quad (3.4)$$

$$W_{16\text{d}}(p) = \frac{1 + \sum_{i=1}^{15} e^{-\tau_i p}}{1 - K_{\text{amp}} e^{-\tau_{\text{gld}} p}}, \quad (3.5)$$

where $W(p)$ is the ratio of the Laplace image of the output signal to the Laplace image of the input signal at zero initial conditions; $W_{\text{wod}}(p)$ is the transfer function without delay lines; $W_{2\text{d}}(p)$, …, $W_{16\text{d}}(p)$ are the transfer functions with a particular number of delay lines; K_{amp} is the gain (for how many times the input signal was amplified); τ_i is the length of the ith delay line; τ_{gld} is the length of the global delay line.

When modeling this scheme, we will consider the frequency distortions introduced by the Mach–Zehnder modulator, optical amplifier, and photodetector to

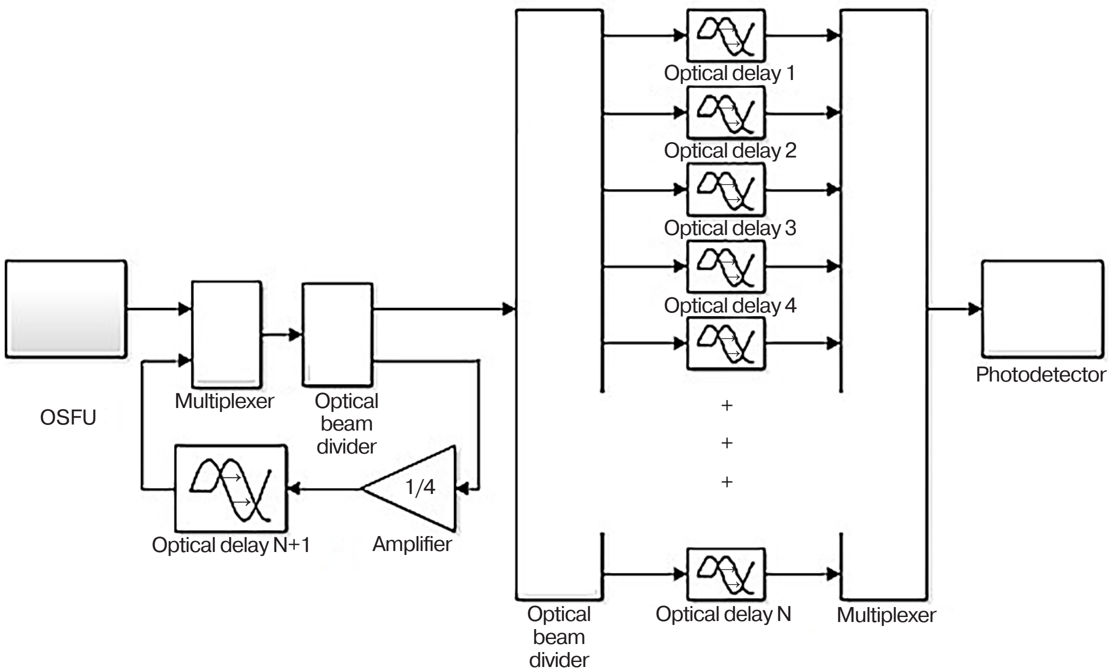

Fig. 2. The model of the USP electro-optical repeater with delayed feedback and fractional multiplexing

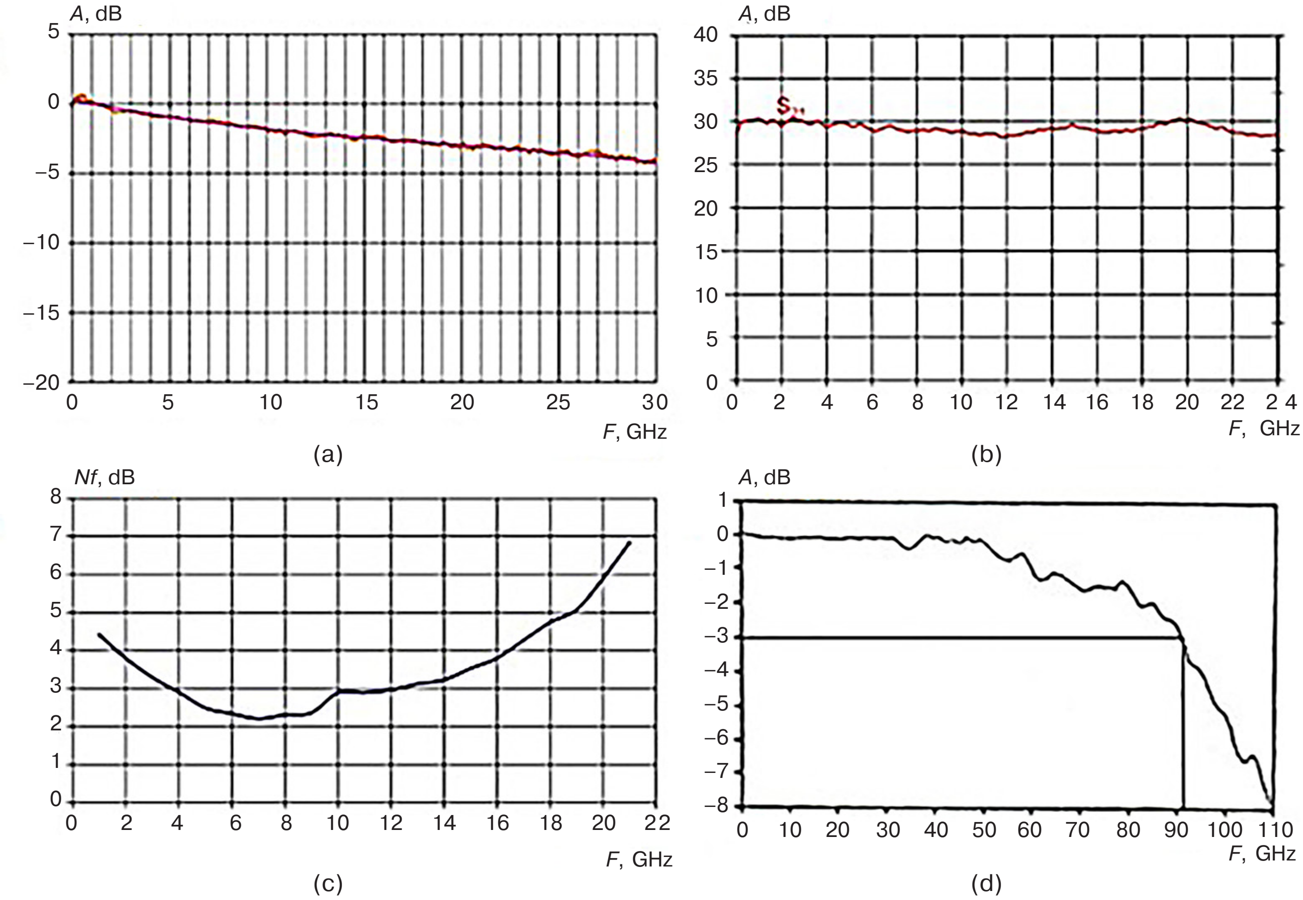

Fig. 3. Characteristics of the devices used in the model of the electro-optical repeater: (a) frequency response of the electro-optical Mach–Zehnder modulator, (b) frequency response of the optical amplifier, (c) *Nf* is the noise figure of the amplifier, and (d) frequency response of the photodetector

be insignificant, since they do not exceed 1 dB in the selected range. The noise figure of the amplifier is assumed to be 4 dB (Fig. 3).

MODELING AN ELECTRO-OPTICAL USP REPEATER WITH FRACTIONAL MULTIPLEXING AND DELAYED FEEDBACK OF DIFFERENT CONFIGURATIONS

In the course of modeling, different configurations of electro-optical repeaters with 2, 4, 8, and 16 delay lines were investigated, as well as a scheme with only delayed feedback as a reference (Fig. 4). Electro-optical repeaters were investigated with a different number of reconstruction cycles, which strongly affected the correlation coefficient between the original and the reconstructed pulse. The modeling was carried out with a signal-to-noise ratio (SNR) in the range from 3 to 18 dB. The graphs below show the mathematical expectations of 100 measurements for each point (Fig. 5 and Fig. 6).

The scheme, in which only the feedback was used, performed the worst as compared to other schemes. This is due to the accumulation of amplifier noise during pulse reconstruction and a complex pulse shape, which requires a large number of quantization levels to achieve the required correlation coefficient, and, accordingly, the reconstruction cycles.

The schemes with 2 and 4 delay lines (Fig. 5) demonstrated the best results relatively to the reference scheme, however, they did not provide the required threshold value of 0.9 for the correlation coefficient. Also observed in these schemes, was a negative interrelation between the correlation coefficient and the number of reconstruction cycles, therefore their use with an increase in the number of comparator levels is impossible.

Schemes with cascades of 8 and 16 delay lines (Fig. 6) showed better results in comparison with other configurations of USP electro-optical repeaters. The correlation coefficient between the reconstructed and reference USP signals was more than 0.9 at SNR of 9 dB. The best configuration was a scheme with 8 delay lines and 30 pulse reconstruction cycles. A further increase in the number of reconstruction cycles does not lead to a significant increase in the correlation coefficient between the original and restored pulses. The 16-line delay scheme also does not offer significant advantages over the 8-line delay scheme. At the same time, it has disadvantages associated with greater complexity and the pulse attenuation.

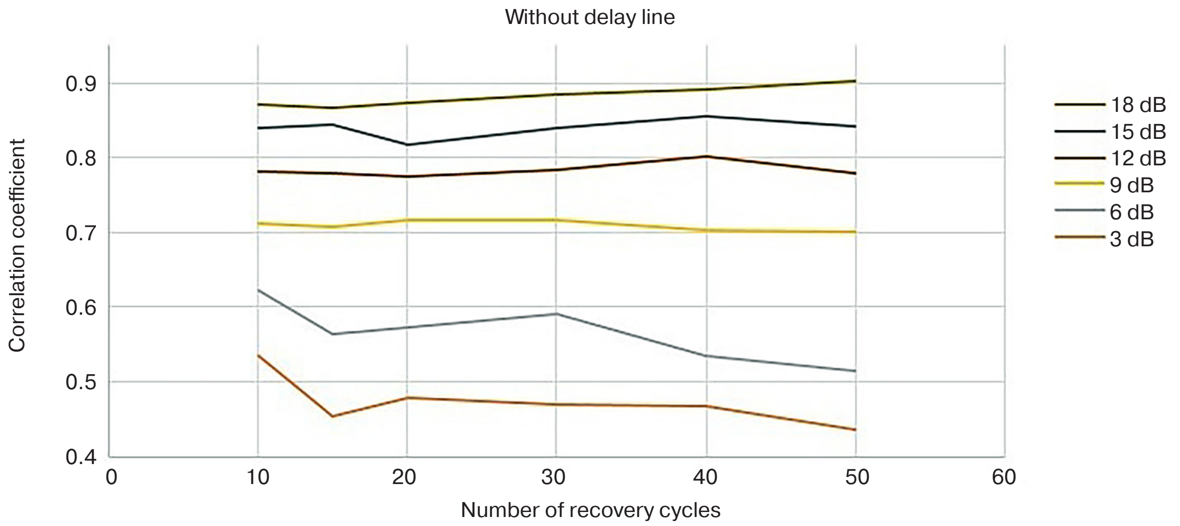

Fig. 4. Correlation coefficient between the original and reconstructed USP signals obtained for a scheme without a cascade of delay lines

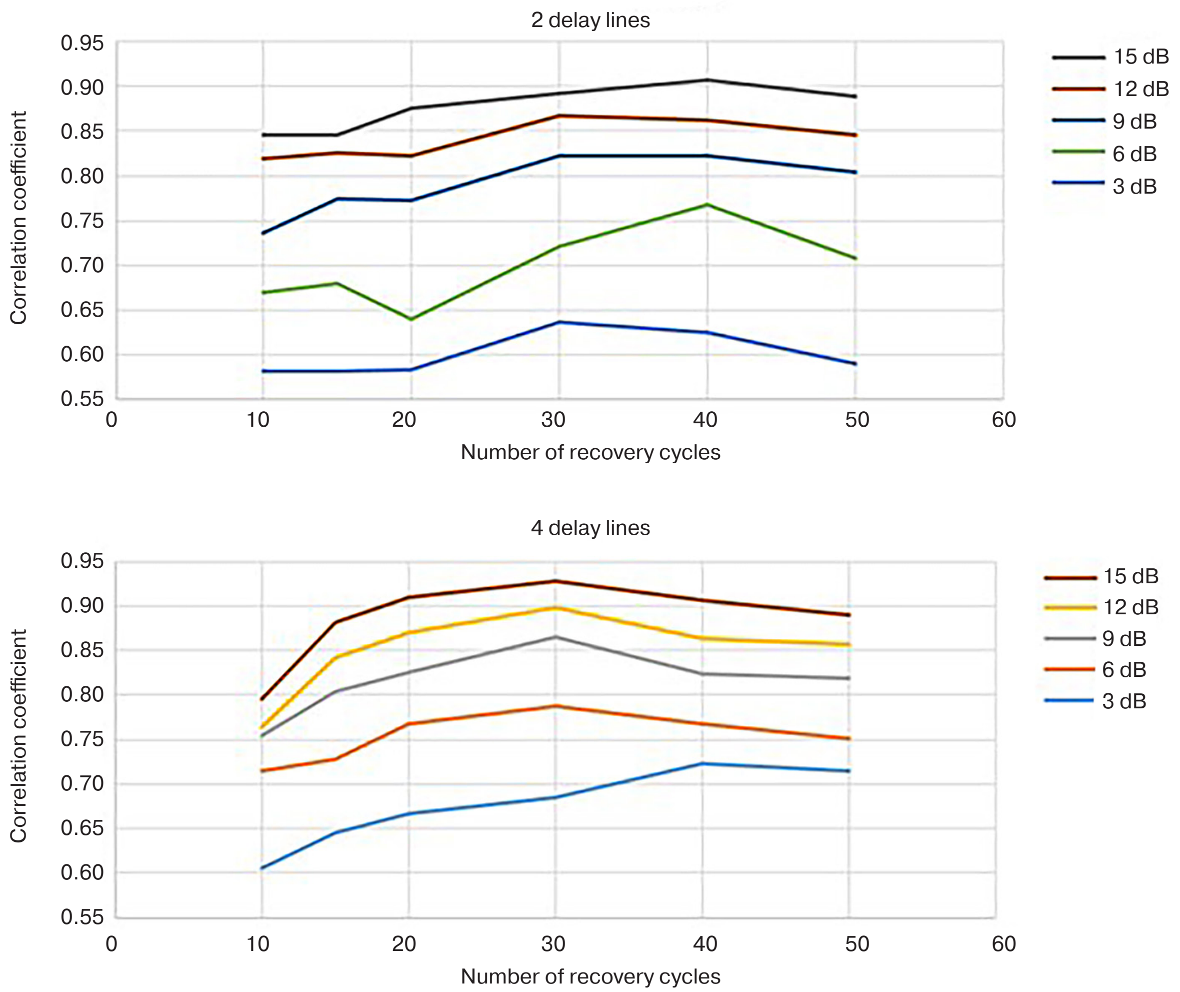

Fig. 5. Correlation coefficient between the original and reconstructed USP signals obtained for schemes with 2 and 4 delay lines as a function of the number of reconstruction cycles at different SNRs

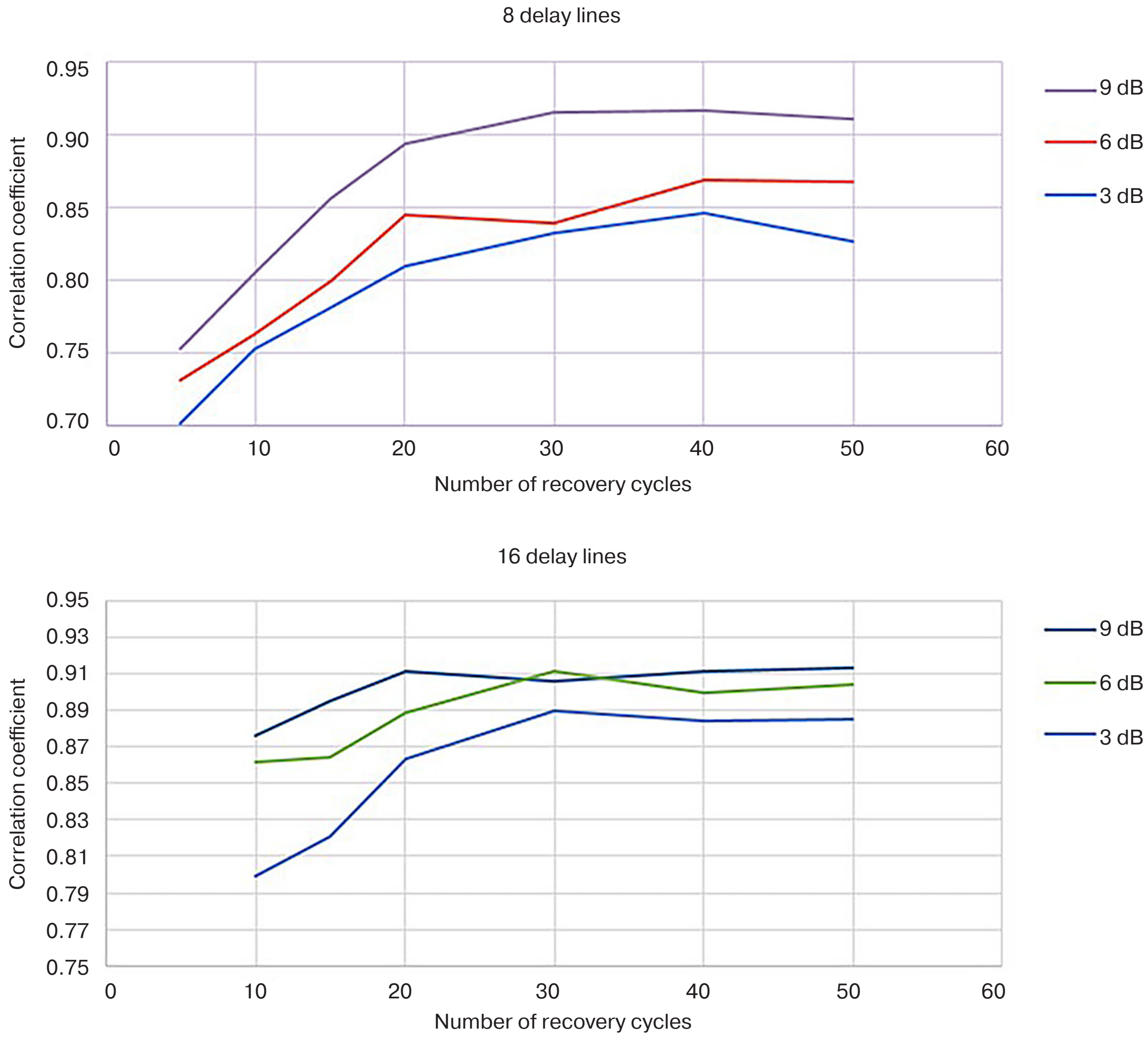

Fig. 6. Correlation coefficient between the original and reconstructed USP signals obtained for schemes with 8 and 16 delay lines as a function of the number of reconstruction cycles at different SNRs

Figure 7 shows the dependence of the correlation coefficient between the reconstructed and reference pulses on the SNR of the reconstructed pulse with confidence intervals for each point. The configuration includes a cascade of 8 delay lines and requires 30 iterations to reconstruct the pulse because of 30 comparator levels. We can see that at the point corresponding to the SNR of 9 dB, the mathematical expectation of the correlation coefficient exceeds 0.9, which meets the condition of strong correlation[1]. So, with a probability of 0.95, all values of the correlation coefficient lie in the confidence interval, the lower value of which is greater than 0.9. This configuration of an electro-optical repeater of subnanosecond pulses is the most advantageous in terms of the reliability of the reconstruction of a noisy pulse reflected from the target, if we take into account such parameters as the complexity of the scheme, its power consumption, and operating time.

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CONCLUSIONS

The schemes of electro-optical repeaters of subnanosecond pulses considered in this work make it possible to reconstruct an USP in a single reception. The analysis of the schemes of electro-optical repeaters including 2, 4, 8, and 16 delay lines showed the following results:

- the schemes with 2 and 4 delay lines do not provide reliable reproducibility in the reconstruction of an USP radio image with a complex time profile;
- the scheme with 8 delay lines was good in modeling, providing a correlation reproducibility of greater than 0.9;

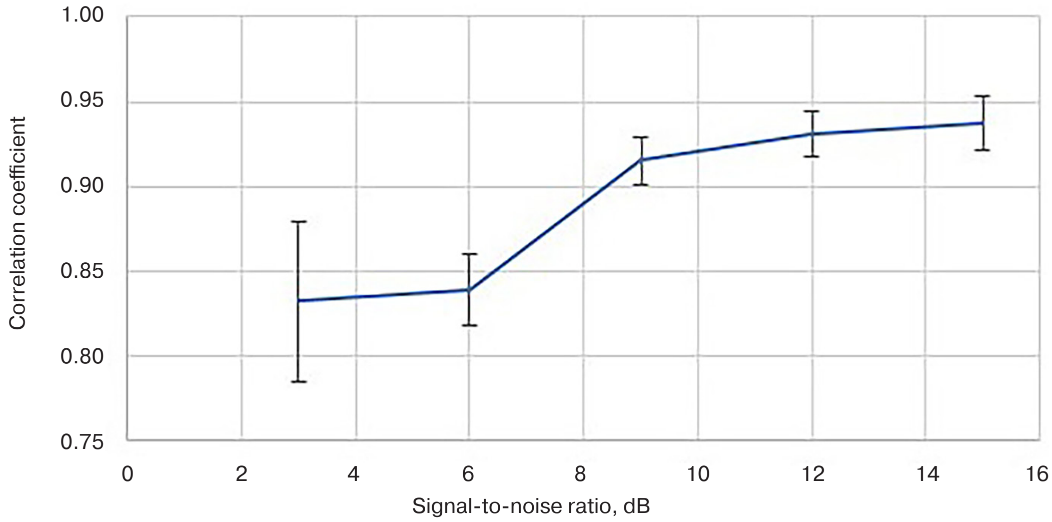

Fig. 7. Experimental dependence of correlation coefficient between the reference and reconstructed pulses on an SNR at the receiver input (with confidence intervals shown by brackets)

- the scheme with 16 delay lines does not offer significant advantages over the scheme with 8 delay lines, while it has disadvantages associated with the greater complexity and attenuation of the registered USP.

The results of modeling obtained in this work solve the problem associated with the necessity of multiple radiating an ultrashort pulse for the reconstruction of reflected by a target radio image by methods of stroboscopic registration.

Authors' contribution. All authors equally contributed to the research work.

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