NONSTATIONARY REFLECTION OF A SUPERSHORT ELECTROMAGNETIC PULSES FROM THE LAYERED STRUCTURES

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Abstract. **Is carried out the theoretical and numerical study of non-stationary reflection of short and supershort electromagnetic pulses from a single-layer and multilayer interference structures, created test bench to measure of non-stationary reflection amplitude-modulated signal from the layered structure. It is shown that the envelope of the reflected signal substantially changes its appearance in the presence of even small losses in the non-reflection layers of the multilayer structure, the amplitude reflection coefficient depends linearly on the magnitude of the losses. At low loss in the layers of structure the envelope can be approximately described by the derivative of the N-incident signal envelope. Obtained the exact and approximate formulas that allow to calculate the characteristics of the multilayer interference structure, highly reflective matching the load to the waveguide, the waveguide due to a strong dispersion. It is shown that in multilayer interference structures with strong waveguide dispersion there is a significant increase in the amplitude and duration of the pulses of non-stationary reflection.**

Keywords: **electromagnetic ultrashort pulses of microwave, layered structure with strong losses and waveguide dispersion, transient reflectivity, the envelope of the reflected signal, highly reflective and load matching structure, multilayer interference filters**

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Content

1. INTRODUCTION

The main trend in the development of optical and microwave devices in the last decennary is a continuous decrease in the duration of their use in the electromagnetic pulses. Supershort electromagnetic pulses are increasingly used both for research and industry [1-3]. In connection with this generation are particularly relevant issues detection and control of such pulses. This tendency is observed in the literature devoted to research in the optical [4-14], in the millimeter and submillimeter ranges [15, 16].

Optical pulses having a duration of tens of femtoseconds to attoseconds units are used in the study of ultrafast processes in biology [1] and chemistry [2]. Large instantaneous pulse power is used in the study of nonlinear processes in semiconductor materials and devices [3]. In the millimeter wave band the electromagnetic pulses of short duration have been applied too, in the first place - in radiolocation [15, 16].

Marked trends in the development of microwave and optical engineering lead to the need to create the new and to improvement the already existing devices to control of ultrashort electromagnetic pulses.

To control the signals of long duration multilayer interference structures are widely used (MIS). Today, MIS is actively used in devices operating both in the millimeter, and in the optical wavelength range. Methods of their analysis and synthesis worked out quite well.

Attempts to use MIS to control ultrashort pulses revealed the presence of a number of new effects [11, 17-20], not observed in the interaction with MIS signals of long duration. In the interaction of an electromagnetic signal with a multilayer structure interference of waves reflected from its layers, forms the past and reflected signals. At high incident signal duration time for establishing a stationary process in a multilayer structure is negligible compared with the duration of the signal, so the influence on the formation process of unsteady reflected and transmitted signals is not considered. For short pulses, which are defined as pulses with a duration of up to 100 periods of the electromagnetic field oscillations of [21], the duration of the transition process can be comparable to the duration of the signal, so the influence of non-stationary process accounting for forming the reflected and transmitted signals becomes necessary.

To date, research on the interaction of ultrashort pulses with multilayer interference structures are actively conducted in various directions. Deep enough to study the interaction of ultrashort pulses with mirrors on the basis of the MIS. Created multilayer mirrors, capable of not only effectively reflect short electromagnetic pulses, and even reduce the duration of the reflected signal, as compared to the incident signal [4-7].

The interaction of ultrashort pulses with non-reflective type structures on the basis of the MIS, in particular - with multilayer interference filters covered less extensively, although in this area a large number of publications [8-14] appeared in the last ten years.

Despite the high intensity of research of interaction of ultrashort electromagnetic pulses from the MIS, there are a number of phenomena that are not well understood and covered both in the domestic and foreign literature. One of such phenomena include the phenomenon of non-stationary reflection of electromagnetic pulses of short duration of the MIS. Lack of research on this subject in the first place, due to the peculiarities of observation of the phenomenon. For example, in the study of the processes occurring in the interaction of short electromagnetic pulses with multilayer mirrors, analyze non-stationary reflection process is quite difficult, as the intensity of the reflected signal from the primary mirror is many times higher signal intensity, formed as a result of non-stationary reflection.

In the vast majority of publications devoted to the issue of the interaction of electromagnetic pulses of short duration with non-reflective-type multi-layered structures, the reflected signal is regarded as undesirable. Therefore, the synthesis MIS reflected signal (including pulses having a generated during unsteady reflection) to be suppressed, typically numerical optimization algorithms, without analyzing the mechanism of its occurrence.

One of the first studies on the effects of non-stationary reflection of ultrashort pulses from the MIS non-reflective type, have been [17, 18, 22-24]. They first introduced the concept of "non-stationary reflection" and analyzed the processes taking place in the reflection of the electromagnetic pulse of short duration of the multi-layer structure.

As is well known [25], when electromagnetic wave is incident on a layered structure as a result of interference in its layers after a certain time ts in the stationary structure established electromagnetic field distribution. The amplitude of the wave reflected from the structure will tend to zero as a result of the negative interference of waves in the antireflection multilayer structure. However, if for some time tp - less time to establish a stationary field distribution in ts layers - a change of parameters (amplitude or phase) of the incident ultrashort pulse is disturbed amplitude-phase balance of interfering in a multilayer structure waves varies stationary distribution of the wave field in the structure tp and it appears in the reflected signal over time. Thus, changes in the amplitude of the wave incident on the multilayer structure will change the amplitude of the signal reflected from the multilayer structure. In case, if no signal is stationary - for example, if the wave reflected from the antireflection structure or wave passed through the multilayer mirror - will be reflected (for antireflective structure) or past (for multilayer mirror) pulse signal of corresponding duration.

In [17] the analysis of non-stationary process of reflection was made on an example of a quarter of the film deposited on the substrate. An analytical solution for the amplitude envelope of the signal reflected from the structure with amplitude modulation in the following form

$$U(t) = \frac{r_0}{1-r_0^2}\left[\sum_{n-1}^{\infty}\frac{1}{n!}\frac{d^n A(t)}{dt^n}(2k+1)\frac{T}{2}\right]e^{i\omega t}, \qquad (1)$$

where U(t) - the envelope of the amplitude of the reflected wave, r_0 - Fresnel reflection coefficient of the film material, A(t) - the envelope of the amplitude of the incident signal, T - wave period in the pulse oscillation, k = 0, 1, 2. . . - the multiplicity of the film thickness of a quarter wavelength, ω - angular frequency. In [17, 24] have been calculated according to the amplitude of the reflected signals at the drop of the bleaching pulse structure with trapezoidal and Gaussian envelope (**Fig. 1**a, b). Obtained in this work for some types of antireflection of periodic structures analytical expression can be used to analyze the time course-limited pulse amplitude.

In [18] analyzed the interaction of electromagnetic pulses with the phase and frequency modulation of a broad class of antireflective structures - thin-film interference aligner (TIS). Amplitudnospektralnyh theory, structural and invariant properties TIS was developed in [26, 27]. The paper deals with super-Gaussian pulse with an envelope type:

$$E_0 = A(t)e^{-i\varphi(t)} \qquad (2)$$

$$A(t) = e^{\left(\frac{t}{\tau}\right)^{2p}}, \qquad (3)$$

φ (t) - a real time-varying phase. Assuming the quadratic phase modulation $\varphi(t) = \alpha t^2/2$ [28, 29] (the most interesting from the point of view of applications) for the complex amplitude of the reflected wave was obtained by the following expression:

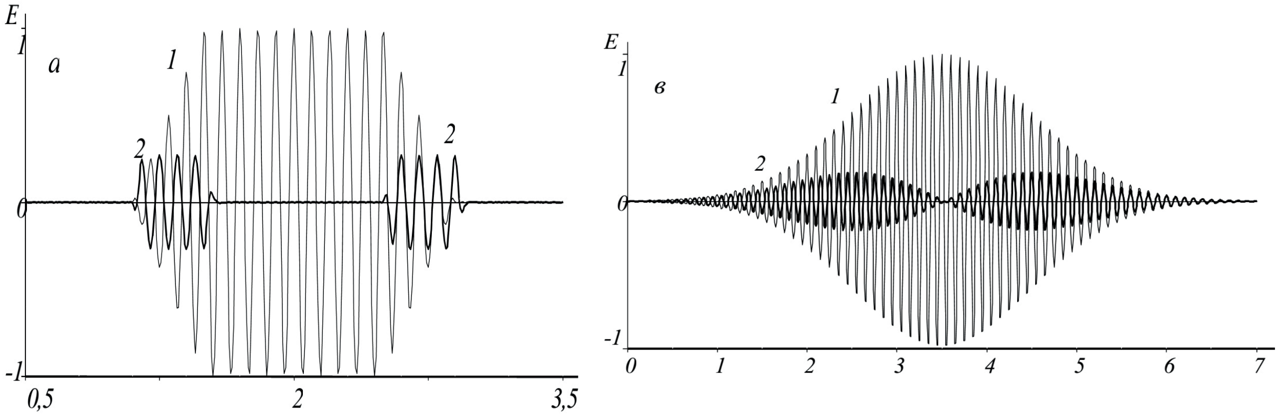

Рис. 1. *Напряженности электрического поля отраженного сигнала для падающего импульса с трапецеидальной огибающей (а) и с (b) супергауссовой огибающей 1) падающего сигнала; 2) отраженного сигнала* [24].

$$E_r(t) = r_0 \frac{A(t)e^{-i\varphi(t)} - A(t-\Delta t)e^{[-i\varphi(t-\Delta t)]}}{1 - r_0 e^{i[\varphi(t)-\varphi(t-\Delta t)]}}, \quad (4)$$

here Δt - transit time wave twice the film thickness. The expression for the envelope of the reflected wave of the FM pulse has the form [18]:

$$E_{0r}(t) = |r_0| \frac{A(t)^2 - 2A(t)A(t-\Delta t)\cos(\phi(t)) + A^2(t-\Delta t)}{1 - 2r_0^2\cos(\phi(t)) + r_0^4} \quad (5)$$

The results obtained in [18] analytical expressions allow you to select the time evolution of the phase modulation (FM) pulse. This follows from the fact that the analytical expression (4) is retained for the amplitude modulation of the phase information as a function of φ (t). If using direct methods of correlation or received envelopes of the incident pulse A (t) and E0 is reflected, then, using (4), it is possible to determine the phase function φ (t).

Fig. 2 shows the results of calculation of the spectral method forms the reflected pulses from the FM film deposited on a substrate with ns = 3.42. In both cases, the pulse duration τ was 7 ns, the carrier wavelength λ = 1.5 microns; Gaussian pulse ατ2 = 1, for a super-Gaussian pulse ατ4 = 4, in the expression (3) the parameter p = 3. The envelope of the reflected pulses E0r built according to the formula (5). The results obtained with the Fourier transform of the incident pulse taken as:

$$E(t) = A(t)e^{[-i(\omega_0 t + \varphi(t))]}. \quad (6)$$

In practice, often there are situations when the FM pulses acquire a flat or almost flat top. For this case, [18] the following ratio

$$E_r = \frac{r_0}{1 - r_0^2}\varphi(t). \quad (7)$$

This result (7) points to the prospects of the use of non-stationary reflection phenomenon to convert electromagnetic pulses.

In [18] it is noted that the TIS can be used to analyze the time dependence of the FM phase pulses and to produce ultrashort pulses with the above properties.

The phenomenon of non-stationary reflection effect causing his physical characteristics (absence of background reflection of the incident radiation, adequate dependence of its amplitude-time characteristics of the shape of the incident pulse and the physical properties of the framing structure of the media), not only relatively easy to obtain ultrashort electromagnetic pulses, but also to develop methods of analysis and the pulse parameters of transient processes in layered media.

It should be noted that the studies mentioned have not been given attention to a number of important details, such as - the influence of losses in the fibers of the structure and the process for the dispersion of a nonstationary reflection. Moreover, studies were analytical or numerical character -without experimental studies. All this causes concern and the need for further study of the phenomenon of non-stationary reflection, as well as the opportunities and conditions for its implementation.

The aim of this work is to conduct a detailed theoretical and experimental studies of the phenomenon of non-stationary reflection of

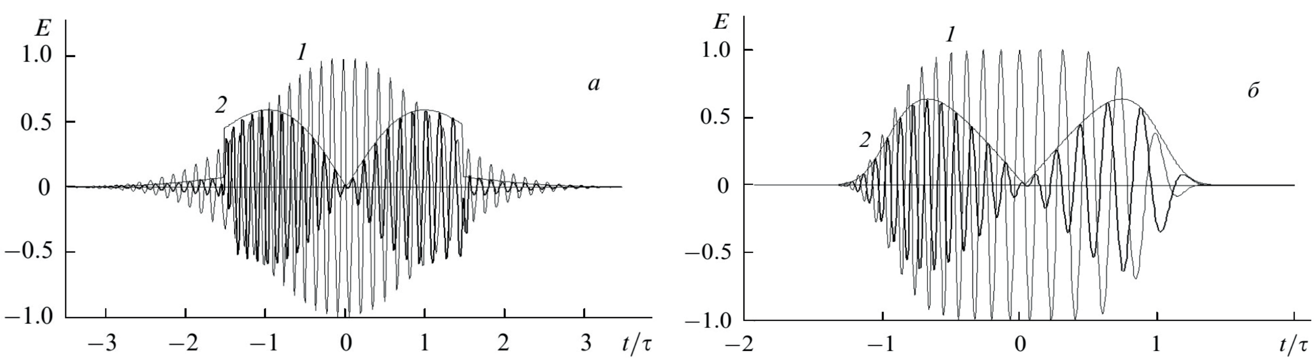

Рис. 2. *Фазомодулированные падающий (1) и отраженный (2) импульсы с гауссовой (a) и супергауссовой (b) огибающими; отраженные импульсы увеличены в 7 раз (a) и в 2 раза (b)* [24].

short and ultrashort pulses of electromagnetic interference multilayer structures, including an analysis of the impact of a strong waveguide dispersion, irregularities and losses in a multilayer structure on the formation of the reflected signal.

2. NONSTATIONARY REFLECTION OF ELECTROMAGNETIC PULSE FROM THE SINGLE-WALLED STRUCTURES

2.1. The impact of losses in the layer on the non-stationary reflection

As used struktrury monolayer non-reflecting in a stationary mode dielectric layer whose thickness is a multiple of half wave optical thickness, placed between two identical characteristics in wave environments. This structure is the simplest implementation of a half-wave interference filter.

For the analysis of wave propagation through the layered structure of the losses the method of impedance characteristics [30-32]. At the same time the concept of impedance is introduced as the ratio of the tangential components of the electric and magnetic fields in this section of the layered structure.

Let some environments, which is a plane-parallel layer to the complex relative permittivity ε = ε'+ iε" and thickness d, completely fills the cross section of a waveguide with a characteristic impedance of the Z0, a regular on both sides. For further consideration, we introduce the index j, indicating the number of the layer. In this indexing will produce so that closest to the emission layer the source will have a maximum index. **Fig. 3** shows the direction of propagation of electromagnetic waves from the source and designated impedance layers Zj, and input impedances at the boundary layers jZin. The expressions for the propagation constant wave γj and Zj impedance look like:

$$\gamma_j = \alpha_j + i\beta_j, \qquad (8)$$

$$\alpha_j = \frac{2\pi}{\lambda}\sqrt{\frac{\sqrt{\varepsilon_j''^2 + \Lambda_j^2} - \Lambda_j}{2}}; \beta_j = \frac{2\pi}{\lambda}\sqrt{\frac{\sqrt{\varepsilon_j''^2 + \Lambda_j^2} + \Lambda_j}{2}}; \qquad (9)$$

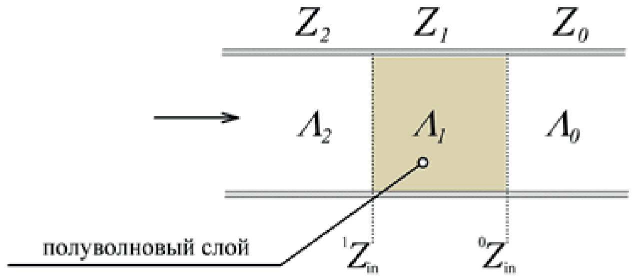

Рис. 3. *Диэлектрический слой в волноводе.*

$$Z_j = C_j + iD_j, \qquad (10)$$

$$C_j = \sqrt{\frac{\sqrt{\varepsilon_j''^2 + \Lambda_j^2} + \Lambda_j}{2(\varepsilon_j''^2 + \Lambda_j^2)}}; D_j = \sqrt{\frac{\sqrt{\varepsilon_j''^2 + \Lambda_j^2} - \Lambda_j}{2(\varepsilon_j''^2 + \Lambda_j^2)}}; \qquad (11)$$

For the analysis of multilayer structures installed in the waveguide must also take into account the effect of the waveguide dispersion. In this case:

$$\Lambda_j = \varepsilon_j' - \left(\frac{\lambda}{\lambda_c}\right)^2, \qquad (12)$$

λc - critical wavelength in the waveguide mode for H10, λc = 2a, a - the size of the wide wall of the waveguide, λ - the wavelength in free space.

The expression for the reflection coefficient at the interface between the waveguide and the portion of the free portion of the dielectric layer with the set can be written as:

$$r = \frac{{}^1Z_{in} - Z_0}{{}^1Z_{in} + Z_0}, \qquad (13)$$

$$Z_0 = \frac{1}{\sqrt{1 - \frac{\lambda}{\lambda_c}}}. \qquad (14)$$

The value 1Zin, in the expression for the reflection coefficient, which can be calculated using the following recurrence relation:

$${}^1Z_{in} = \frac{{}^0Z_{in} + Z_1 th(\gamma_1 d)}{Z_1 + {}^0Z_{in} th(\gamma_1 d)} Z_1. \qquad (15)$$

In this case, an isolated layer set in regular waveguide:

$${}^0Z_{in} = Z_0. \qquad (16)$$

We estimate the impact of losses in a secluded dielectric half-wavelength layer on a range of non-stationary reflection amplitude-modulated signal. The imaginary part of the relative permittivity ε", is responsible for the loss included in the expression for the layer of the impedance (10, 11) and the expression for the propagation constant (8, 9). To simplify the problem, take into account that the vast majority of materials used in the synthesis of multilayer structures exhibit low loss ε"/ε'<< 1. Considering the loss of a plate with small, we introduce a small amount $\xi_1 = \frac{\varepsilon_1''}{\Lambda_1} \ll 1$. Then, after simple transformations for the input impedance and the propagation constant , up to the first order, we obtain the following expressions:

$$Z_1 \approx \frac{1}{\sqrt{\Lambda_1}} + i\frac{\xi_1}{2\sqrt{\Lambda_1}}; \tag{17}$$

$$\gamma_1 \approx \frac{2\pi}{\lambda}\sqrt{\Lambda_1}\left(\frac{\xi_1}{2} + i\right). \tag{18}$$

For the reflection coefficient of the dielectric plate by substituting (17) and (18) into (15) and then into (13) we have:

$$r \approx \xi_1 \frac{\pi}{\sqrt{\Lambda_1}} \frac{\left(1 - Z_0^2\Lambda_1\right)}{4Z_0}. \tag{19}$$

From the relation (19) shows that the losses in the case of small amplitude reflection coefficient depends linearly on the magnitude of losses in the layer. In addition, the reflection coefficient is purely real value and therefore, small losses in the fiber will not influence the phase relation between multipath waves, i.e. phase of the reflected signal pattern will be formed in the same manner as in the case of no loss.

The numerical calculation of the dependence of the reflection coefficient of a half-wave layer, mounted in a rectangular waveguide, provided ν0/νs ≈ 1.3, where νs - critical frequency. Accounting waveguide dispersion leads to the fact that at the same offset from the center frequency ν0 reflection coefficient has different values. The calculation showed that the minimum reflectance remains on the same frequency for different values of the imaginary part of the relative permittivity of the dielectric layer (ε = 2 + 0.0i, ε = 2 + 0.01i and ε = 2 + 0.05i), which indicates the constancy phase balance in the layer of the interfering waves. The negative value of r in the expression (19) shows that reflection from the layer occurs in antiphase with respect to the incident wave and the phase of the reflection coefficient φr = π. Thus, in the case of small losses in the half-wavelength layer violation occurs only balance the amplitude of the interfering wave, which in turn gives rise to a reflected signal.

The process of forming a reflected signal at falling amplitude modulated signal on a half-wave layer is lossy. considered as an example of a symmetric trapezoidal pulse with linear edges. Let the wave is incident on the half wave layer having a relative dielectric constant ε = 2 + 0.05i. We assume that the length of the trapezoidal pulse τ a lot more time passes wave double layer thickness. At the same time as a result of non-stationary reflection of electromagnetic pulse propagating toward the incident wave will be formed. We define a thickness equal to d = 30 mm layer and the carrier frequency are chosen so that the layer will be a half-wave. **Fig. 4** shows the result of calculating the finite-difference time-domain method (Finite Difference Time Domain, FDTD, or Yee algorithm) [33, 34] the field strength of the reflected pulse Er(t). For clarity, the reflected signal amplitude is increased by 10 times.

Note that, when calculating the finite-difference time-domain method, and during the actual experiment, no ability to capture the reflected signal directly at the interface of the dielectric layer. From the moment the signal generation prior to fixation of the reflected pulse will take some time. There is always, however small, the distance of space between the generator and the dielectric layer, which is to overcome the wave before impact. In the case of the finite difference method is - the distance between the plane on which the initial value of the field E(t), and the dielectric layer. As a rule, it is not less than 10 spatial grid cells, which are calculated. The presence of free space described by the site leads to an additional phase incursion between incident and reflected signals.

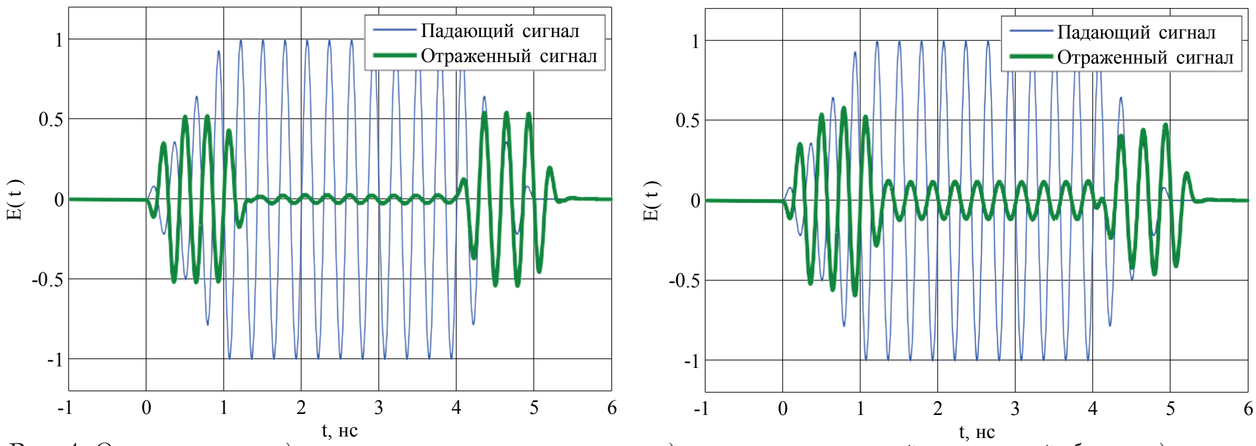

Рис. 4. *Отраженные и падающие сигналы, рассчитанные методом конечных разностей во временной области, для случаев: a) отсутствия потерь в полуволновом слое, (ε = 2+0.0i); b) наличия потерь в полуволновом слое, (ε = 2 + 0.05i).*

This phase shift complicates the analysis of the results, so for clarity in Fig. 4, it is compensated in such a way that the beginning of the reflected signal is combined with the beginning of the incident pulse.

For the analysis of the loss of influence on the process of unsteady reflection calculation Er (t) of the field was conducted both in view of the losses in the half-wavelength layer, and excluding these losses. In the second case it was assumed that ε " = 0. In the absence of loss (Fig. 4a), according to the relation (19) layer is non-reflective structure. Therefore, in the area of the incident pulse of constant amplitude of the reflected signal is negligible. Thus pulses reflected in the falling signal edges, have a rectangular envelope (Fig. 4a).

The presence of even small losses in the layer leads to disruption of the amplitude balance of the interfering waves, whereby there is the appearance of the reflected signal in the incident pulse of constant amplitude, as shown in Fig. 4b. When taking into account losses, the pulses generated in the non-stationary reflection in the area of the incident signal fronts, changing its shape as compared to the pulses in the case of absence of loss (Fig. 4b). Impulse formed in the leading edge is different from the pulse trailing edge region, which is not observed in Fig. 4a. The reflected signal in the case of losses in the fiber, and in the case of the dielectric layer without the loss consists of two pulses which are in antiphase.

We draw attention to a feature in the incident signal trailing edge in Fig. 4b. Despite the existence of loss at the time of the trailing edge of the reflection, there is a time when the amplitude of the reflected signal to zero, and the reflected signal phase changes by π. This shows that is currently running the amplitude balance condition interfering in the wave structure.

Impulse trapezoidal envelope is a convenient mathematical model for the analysis of non-stationary process of reflection, but in practice, these signals are used very rarely. This is due to the fact that the preparation of linear front in ultrashort pulse is quite a challenge. On the other hand trapezoidal pulse is a piecewise continuous function, which imposes additional restrictions when trying to pilot implementation.

For practical applications much more frequently used pulses with a Gaussian or super-Gaussian envelope. Therefore, on a par with trapezoidal pulses give the results of numerical modeling for Gaussian pulses.

In modeling the amplitude of the incident signal $E_i(t)$ was set according to the following formula:

$$E_i(t) = e^{-\left(\frac{t_0 - t}{\tau_1}\right)^{2p}} \cdot \sin(\omega t), \qquad (20)$$

here p - an integer, τ1 - scale factor, which determines the pulse duration, t0 - sets the position of the pulse center of the timeline, ω - normalized angular frequency. **Fig. 5** shows the results of numerical simulation of transient reflectivity of the dielectric layer c losses for a pulse with super-Gaussian envelope. The results were obtained for the values of p = 1 (Gaussian pulse) and p = 6 (supergaussov pulse); t0 = 6.5, τ1 = 5. The amplitude of the reflected signal on all charts increased fivefold.

From Fig. 5 shows that all the features of the formation of the reflected signal in the presence of losses in the layer are observed for pulses with Gaussian and super-Gaussian envelope. Numerical calculation of finite-difference time-domain method allowed to obtain the amplitude of the time pulse generated in the non-stationary reflection on the dielectric plate with losses. The analysis of the results of numerical experiments revealed a number of new features in the formation of the reflected pulse, which was not observed in the absence of losses.

For a more detailed analysis of non-stationary reflection process in the event of loss, we obtain an analytical expression for the reflected amplitude modulated signal.

For the convenience of further calculations proceed to dimensionless units. Let us introduce dimensionless time:

$$t = t'/\tau_0, \tag{21}$$

Here T0 - sets the scale of the timeline, t '- the time in seconds. For the amplitude of the reflected signal, without taking into account possible losses, in [35, 36] proposed an analytical solution of the form:

$$U(t) = \frac{r_0}{1-r_0^2}[A(t) - A(t-\Delta t)]e^{i\omega t}, \tag{22}$$

here ω - circular frequency of the signal in dimensionless units, r0 - Fresnel reflection

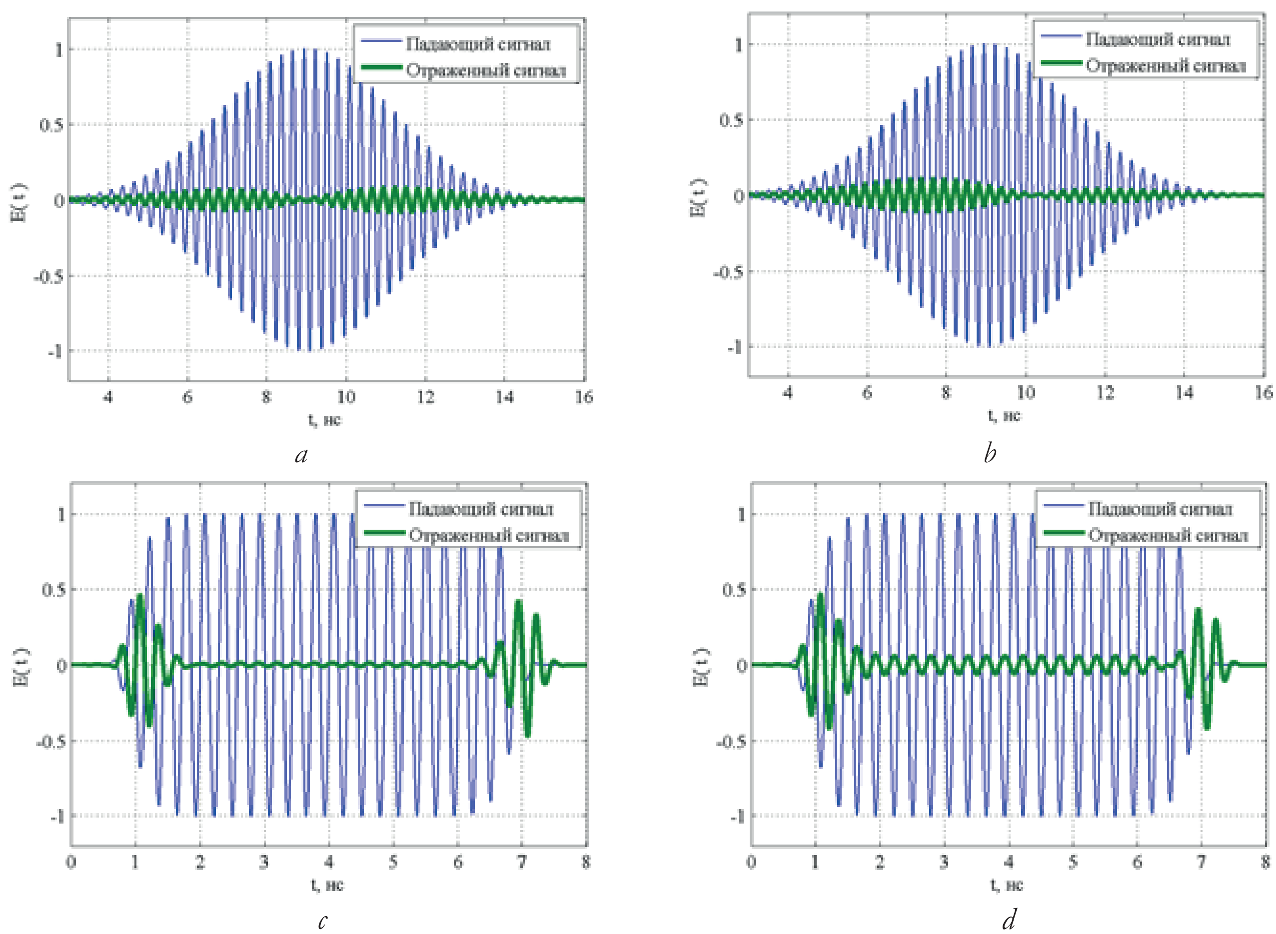

Рис. 5. *Отраженные и падающие сигналы, рассчитанные методом конечных разностей для случая: a) отсутствия потерь в полуволновом слое ε = 2, гауссовой формы импульс; b) наличия потерь в полуволновом слое ε = 2 + 0.05i, импульс гауссовой формы; c) отсутствия потерь в полуволновом слое ε = 2, импульс супергауссовой формы; d) наличия потерь в полуволновом слое ε = 2 + 0.05i, импульс супергауссовой формы.*

coefficient, by A (t) - is the dependence of the normalized incident signal amplitude versus time, Δt - twice the time of the film wave.

This result was obtained for an amplitude modulated signal reflected from the antireflection quarterwave film excluding possible losses therein. Equation (22) also holds for films fold thickness. In the derivation of the method of direct summation of interfering in a film of the waves and the approximation of slowly varying amplitudes. From the formula (22) shows that the reflected signal is the sum of two opposite signals. This representation is very convenient for the analysis of the formation of the reflected signal.

Accounting for small losses, as mentioned above, it leads to a change only the amplitude characteristics of interfering in the layer of waves. Applying the same approach as in [17], after simple calculations, you can get to a half-wave layer of lossy decision the following:

$$U(t) = \frac{r_0}{1-r_0^2}[A(t) - A(t-\Delta t)K]e^{i\omega t}, \tag{23}$$

Here, the coefficient K characterizes the energy loss in the propagation of the waves within the layer.

$$K = e^{-2\alpha d}. \tag{24}$$

Recall that α - the real part of the propagation constant (9), d - plate thickness.

Analyze the formation of the reflected signal using the obtained expression (22) for example a trapezoidal signal envelope. Let trapezoidal signal has a duration τ, and the slope angle of its edges equal to the absolute number of k = 1/s, s - length fronts (**Figure 6**). Let the duration of the signal rise time τ and s is much larger than the period of the carrier frequency. We denote the amplitude of the envelope of the signal as:

$$A(t) = \begin{cases} kt, & t_1 \le t < t_3 \\ 1, & t_3 \le t < t_5 \\ k(\tau - t), & t_5 \le t < t_8 \end{cases}. \tag{25}$$

In what follows we shall simply call the amplitude of the envelope amplitude, omitting the word "envelope" for short.

Given that relatively little time Δt the duration τ of the signal, we expand the second term in formula (23) in a row:

$$A(t-\Delta t) = A(t) - \frac{dA}{dt}\Delta t. \tag{26}$$

The envelope of the reflected signal takes the following form:

$$U(t) = \frac{r_0}{1-r_0^2}\left[A(t) - A(t)K + \frac{dA}{dt}\Delta t\right]. \tag{27}$$

For ease of analysis conditionally divide the duration of the incident signal at several intervals. **Fig. 6** shows the A (t) and A (t - Δt), and their difference. In the time interval from t1 to t2 Fresnel reflection signal occurs. The time interval from t1 to t2 is equal to twice the transit time in the dielectric layer:

$$|t_1 - t_2| = \frac{2d\sqrt{\Lambda_1}}{c}. \tag{28}$$

In the time interval from t2 to t3 for the echo envelope obtain

$$U(t) = \frac{r_0}{1-r_0^2}[kt(1-K) + kK\Delta t]. \tag{29}$$

Then the slope of the envelope of the echo - k ', at the interval, we get:

$$k' = \frac{r_0}{1-r_0^2}(1-K)k. \tag{30}$$

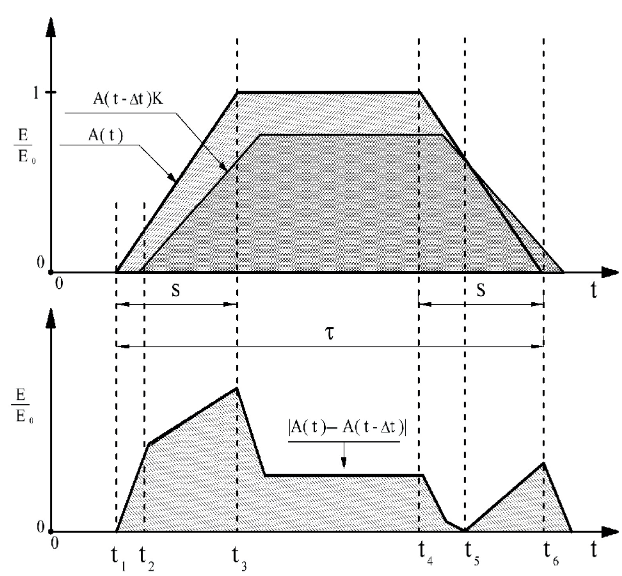

Рис. 6. *Обозначения для расчета амплитуды отраженного сигнала.*

Note that the tangent of the angle of inclination of the fronts of the reflected signal is not dependent on the duration of the falling edge of the signal. In the time interval from t3 to t4 we have: dA/dt = 0, therefore:

$$U(t) = \frac{r_0}{1-r_0^2}[A(t)(1-K)], \tag{31}$$

considering that A (t) = E0, we obtain:

$$U(t) = \frac{r_0}{1-r_0^2}(1-K)E_0. \tag{32}$$

In the particular case, there are no losses in the layer, the expression (32) gives the well-known result: U (t) = 0.

In the time interval from t4 to t6, the condition:

dA/dt <0. (33)

From Fig. 6 shows that there is always a time tmin, when

A(tmin) = A(tmin - Δt), (34)

a reflected signal amplitude (23) has a local minimum. It is important to note that the function A(t) is not continuous, and depending on the time A(t) and A(t - Δt) can be different. For example, in the considered time interval from t4 to t6 are two possibilities:

$$A(t) = \frac{\tau - t}{s}, A(t-\Delta t) = 1; \tag{35}$$

$$A(t) = \frac{\tau - t}{s}, A(t-\Delta t) = \frac{\tau - t + \Delta t}{s}; \tag{36}$$

second embodiment is illustrated in Fig. 6.

Let us find out the minimum of reflection for any value tmin time for these two cases. Recall that the minimum amplitude of the reflected signal was observed by us in the numerical simulation of finite difference method (see. Fig. 4). In the first case we have:

$$\frac{\tau - t_{\min}}{s} - K = 0, t_{\min} = \tau - Ks. \tag{37}$$

This relation is valid only for the time τ - s <t5 <τ - Ks. For the second case, substituting the explicit expression for the rear edge of the incident signal amplitude (36), we obtain:

$$A(t) = \frac{\tau - t}{s}, \frac{dA}{dt} = -k. \tag{38}$$

Then:

$$t_{\min} = \tau - \frac{sKk\Delta t}{1-K}. \tag{39}$$

From the analysis it is clear that the resulting analytical expression (23) allows you to accurately calculate the amplitude of the reflected signal without resorting to numerical methods. Also, the analysis shows the possibility of determining the dielectric properties of the layer by measuring the parameters of the reflected pulse.

2.2. The reflection from the layers Nλ / 2

Numerical simulation of non-stationary reflection amplitude modulated signal showed that the intensity of the reflected signal is only a few percent of the intensity of the incident. In the practice of the reflection phenomena of unsteady desirable that the amplitude of the formed pulses resulting in unsteady reflection was maximum, provided that the structure of the reflection coefficient at the carrier frequency of the pulse is close to zero.

In the formula (23) includes two parameters: the reflection coefficient r0 and twice the time Δt wave propagation through the layer. Changes in each of these parameters leads to a change in the amplitude of the reflected signal. We analyze the possibility of strengthening the non-stationary phenomenon reflected by changes in these parameters.

From the formula (23) shows that the increase in r0 will exacerbate the phenomenon of non-stationary reflection. Fresnel reflection coefficient r0 is given by the dielectric properties of the material of construction of the plate. It follows that the use dielectrics with high relative dielectric constant and low loss for the manufacture of the half-wave layer enables to enhance the effect of unsteady reflection. Unfortunately, materials with low loss and a high refractive index is extremely small. Task gain effective indicator on the border between the half-wave plate and the free space or waveguide line can be solved by installing a plate between the multilayer mirrors [38].

We turn now to the analysis of the possibility of strengthening the phenomenon of transient reflectivity due to changes in the propagation time wave in the dielectric layer.

From the expression (23) shows that the reflected signal amplitude can be increased by increasing the time of signal propagation in the structure. Indeed, the passage of the wave through the layer included in the expression for the envelope, and the amplitude of the reflected pulse is directly dependent on that time.

If we consider the process of non-stationary reflection from the layer thickness of a multiple of λ / 2, ie, d = Nλ / 2, for example, when N> 3 the contribution due to the propagation time may become significant. This is easily explained by the fact that the difference between A (t) - A (t + Δt), a member of the formula (23) increases.

(22) for linearly rising edge should be that an increase in thickness of the plate twice will result in the same increase in the echo amplitude. For a plate thickness of λ Formula (23) takes the form:

$$U(t) = \frac{2r_0}{1-r_0^2}[A(t) - A(t-\Delta t)K_2]e^{i\omega t}, \tag{40}$$

here K_2 is characterized by loss factor in the layer.

The amplitude of the echo pulse dependent on the difference between the two signals. By increasing the delay time between the waves reflected from the front and rear faces of the plate, this difference increases. The maximum pulse amplitude is reached when the delay time equal to the rise time. A further increase in travel time will not lead to an increase in the amplitude of the reflected signal, since the amplitude of the first term in the expression (23) will not increase.

Fig. 7 shows the results of numerical modeling of the influence of the thickness of the dielectric layer on the amplitude of the reflected signal. For clarity, the amplitude of the reflected signal is increased 10 times. Thickness varied multiple of λ / 2. The simulation was performed by impedance characteristics and then applying the inverse Fourier transform. Results are given for a thickness of the dielectric layer 6 to λ λ. As material for the dielectric layer was taken with a relative dielectric constant ε = 2 equal to + 0.01i. The calculation was made without regard to the waveguide dispersion.

The initial calculation of the data was such that on the dielectric plate falling pulse with trapezoidal envelope. The carrier frequency corresponds to the frequency of the minimum reflection. With increasing layer thickness in a multiple number of times reflection zero frequency does not change.

As can be seen from the graphs in Fig. 7, by increasing the thickness increases the duration of the reflected pulse, as predicted. At a constant amplitude of the reflected signal amplitude should be minimized incident signal otherwise ceases to be non-reflective structure. As can be seen from Fig. 7, this requirement is fulfilled for the layers with a thickness of λ / 2 to 2λ, and partly for the layers 4λ and 8λ. For a layer thickness 8λ amplitude reflected signal time to reach its maximum just at the moment when the amplitude of the incident signal becomes constant. In this case, a change in shape of the reflected signal as well as its duration.

The analysis showed that for increasing the intensity of the pulses generated in the non-stationary reflection AM signal, there are several possibilities.

Firstly, it is possible to reduce the length of the front structure of the incident pulse; secondly, to increase the time of the pulse through the

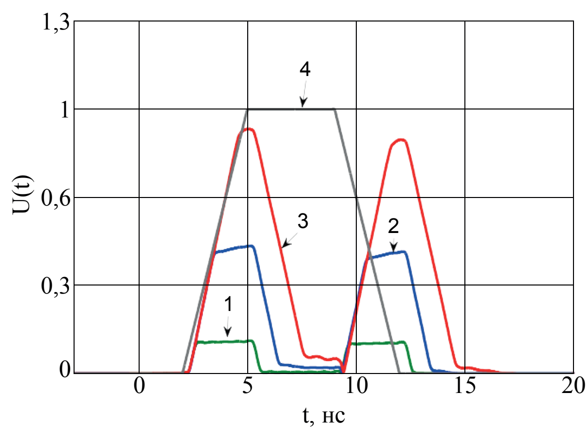

Рис. 7. *Огибающие отраженного сигнала при разной оптической толщине диэлектрического слоя: 1 – толщина слоя d = λ; 2 – толщина слоя d = 4λ; 3 – толщина слоя d = 8λ; 4 – падающий сигнал.*

layer. On the other hand, it is important to remember that the increase in thickness leads to a multiple increase in the energy losses therein. As shown above, an increase in loss adversely affects the unsteady reflection phenomenon due to suppression of the interfering waves in the layer.

2.3. Influence of waveguide dispersion

In the experimental study of non-stationary process of reflection is convenient to use multilayer structures collected in the waveguide path. This approach allows to fix the layers of the multilayer structure at a desired distance from each other with high accuracy. It is necessary to take into account the effect of the waveguide dispersion in the non-stationary process of reflection.

The theoretical analysis of the influence of the waveguide dispersion in the non-stationary process of reflection amplitude-modulated signals. For this, consider a half-wave layer is established in a regular rectangular waveguide. Let waveguide excited fundamental mode H10. Let us write the dispersion relation by the wavelength dependence of the waveguide in a free frequency. To get fashion H10:

$$\lambda = \frac{\frac{c}{\nu}}{\sqrt{1-\left(\frac{\nu_{c_0}}{\nu}\right)}} \text{ї ðè} \qquad (\nu \in;\ \nu_{c_0}), \nu_{c_1} \tag{41}$$

here - the speed of light, v - the frequency of the signal, $\nu s0$ - critical frequency for fashion H10, $\nu c1$ - critical frequency for the H01 mode. The relation shows that for $\nu \to \infty$ $\lambda = c / \nu$, and the influence of the dispersion can be neglected. As is known [38], in the waveguide can simultaneously exist a large number of events, and at a frequency $\nu > \nu c2$ happen excitation of the second mode. Excitation of the second mode have a significant impact on the dispersion characteristics of the waveguide, complicating the analysis. The optimum range of operating frequency is approximately in the range of 1.25 νc to $\nu c1$.

To analyze the effect of dispersion, we need the ability to change the carrier frequency of the signal from the region with weak dispersion to an area with strong. This requires that the reflectance of the layer had several minima in this frequency range as the carrier signal must coincide with a frequency of minimum reflectance.

Consider the process of transient reflectivity of the layer thickness in 6λ installed in rectangular waveguide section 23 × 10 mm 2. **Fig. 8** shows the reflection coefficient of the layer. The spectrum was calculated by the method of impedance characteristics.

Presented in Fig. 8 results show that in strong dispersion of the reflectance increases. It is also seen that in this range there are several frequencies, at which reflectance goes to zero.

For the frequencies corresponding to the zero reflection, calculated the reflected signal envelope. Let fall upon layer trapezoidal signal envelope. Let the carrier frequency of the signal as a v0. The carrier frequency ν0 express in terms of relative frequency νs critical for ease of analysis.

From the results presented in **Fig. 9** shows that the presence of the waveguide dispersion shape of the envelope of the signal changes. With

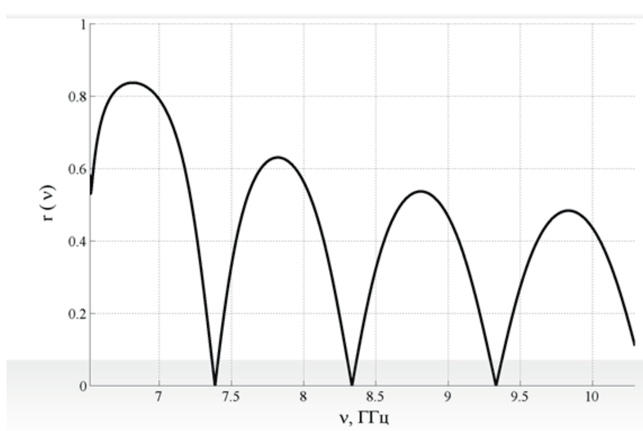

Рис. 8. *Спектр отражения от диэлектрической пластинки толщиной 6λ в волноводе.*

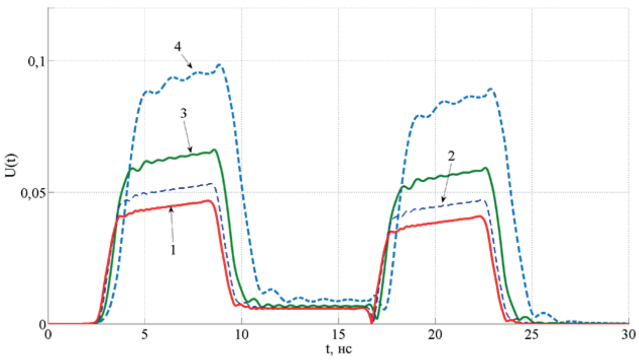

Рис. 9. *Огибающие отраженного сигналя при различных значениях несущих частот падающего импульса, для случаев: 1) частота падающего импульса* $\nu_0 = 1.135\nu$; *2) частота падающего импульса* $\nu_0 = 1.128\nu$; *3) частота падающего импульса* $\nu_0 = 1.143\nu$; *4) частота падающего импульса* $\nu_0 = 1.159\nu$.

increasing dispersion (approaching the critical wavelength), the amplitude of the reflected signal increases and increases its durability. Also in the area there are additional strong dispersion of the oscillation amplitude of the reflected signal. It is easy to note that at a frequency v0> 1.25νs envelope shape of the reflected signal does not change its nature. Unlike discussed in paragraph 2.2 the case of increasing signal propagation time through the structure, the approach to the critical frequency does not increase the losses in the layer.

Summarizing, we can say that the use of the phenomenon of waveguide dispersion and increased multiplicity layer can increase the amplitude of the signal generated in the non-stationary reflection. Increasing the thickness increases the loss in multilayer structures, which adversely affects the appearance of reflection unsteady. Using a waveguide dispersion allows more efficient to increase the amplitude of the reflected signal.

2.4. Experimental study of the reflection signal from the half-wave filter

The phenomenon of non-stationary reflection of short electromagnetic pulses from the layered structure was measured on the stand (**Fig. 10**), which consists of a vector network analyzer Rohde & Schwarz ZVB-20 with an attached rectangular waveguide into which the layered structure, completely filling the cross-section. On the one hand excited waveguide coaxial-waveguide transition (OHR) with the whip antenna, on the other - enables consistent waveguide load. Stated dynamic range for ZVB-20 amounted to more than 125 dB [39]. When calibrating its input path used waveguide section with a loaded load. Spurious reflections arising waveguide system has been filtered in the time domain with a window function gated Hannah [40] using the inverse Fourier transform [41] The calibration signal.

The subject of the study was to analyze the envelope of the signal reflected from the plate. The experiment was conducted for plates made of dielectrics with different values of the relative permittivity. The materials were chosen: Teflon-4, polyamide-6 (caprolon), quartz brands KU and KB. Quartz and fluoroplastic-4 have low loss in the microwave wavelength range (tg (δ) <10-3). Kaprolon was chosen as the material having more losses than PTFE-4 and quartz.

The dependence of the complex reflection coefficient of frequency r (ν). Measurements were carried out in the frequency range from 6 GHz to 14 GHz, which covers the area H10 fashion the existence of frequencies for the connected waveguide section 23 × 10 mm 2.

The measured reflectance was used in the next calculation of the envelope of the reflected pulse of short duration. Let a multilayered structure falls trapezoidal envelope signal. The amplitude of the signal can be written as:

$$E(t) = A(t)\cos(2\pi\nu t), \quad (42)$$

where ν - the carrier frequency and A (t) is given by

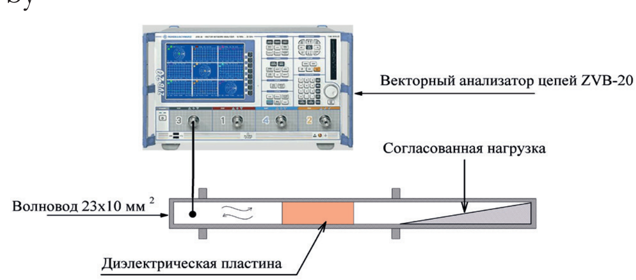

Рис. 10. *Схема установки с однослойным фильтром.*

$$A(t)=\begin{cases}\dfrac{t}{s}, & 0\le t<s,\\ 1, & s\le t<(\tau\text{-s}),\\ \dfrac{\tau-t}{s}, & (\tau\text{-s})\le t<\tau,\end{cases} \qquad (43)$$

here s - pulse rise time, τ -Duration pulse level of -10dB.

If you know the reflection coefficient of the investigated multilayer structure r(ν), then to calculate the spectrum of the reflected signal, you can use the ratio:

$$Hg(\nu) = r(\nu)\,F(\nu). \qquad (44)$$

Applying the inverse Fourier transform to the region Hgν positive frequencies obtain analytical signal:

$$h(t)=\frac{1}{\pi}\int_0^{\infty}H_g(\nu)e^{i2\pi\nu t}d(2\pi\nu). \qquad (45)$$

Analytical Signal Module |h(ν)| It is the desired envelope of the reflected pulse. Thus, by measuring the reflection coefficient r (ν) in the positive frequency, we can obtain the envelope of the reflected pulse, and varying the parameters ν, Δt, s possible to change the center frequency and duration of the incident signal and its fronts.

2.4.1. The impact of losses in the layer on the non-stationary reflection

With unsteady reflection of electromagnetic pulses of short duration of the non-reflective multilayer structures such as play an important role in the loss of the layers of structures. For the experimental study of loss of influence in the layers in the process of non-stationary reflection of several materials were chosen. As dielectrics with low losses was chosen quite frequently used in microwave engineering material - Teflon-4. A material with a relatively high loss of polyamide-6 was selected.

For measuring the half-wave layer was placed in the middle of the free cross section of the waveguide 23 × 10 mm2. As the incident signal used trapezoidal electromagnetic pulse duration of 20 ns, the duration of the front and rear edges of which was 7 ns. **Fig. 11** in dashed lines shows the experimentally obtained for the echo envelope half-wave layers made of polyamide and a fluoroplastic. For clarity, shows the envelope of the incident pulse, decreased in 10 times.

Also in Fig. 11 shows the results of a theoretical calculation. Theoretical curves were obtained by impedance characteristics then applying the inverse Fourier transform. In the calculation, the following values of the permittivity: polyamide-6, ε = 2.98 + 0.037i, Teflon-4 ε = 2.03 + 0.003i.

As can be seen from Fig. 11, the theoretical calculation results are in good agreement with the experimental data. Comparing the results obtained for polytetrafluorethylene and polyamide, we see that the echo envelopes in the two cases differ.

In the case of a material with low losses (PTFE) shows that the reflected signal at constant amplitude of the incident pulse is practically absent. The reflected signal consists of two solitary pulses. The presence of small losses leads to the fact that the amplitude of these pulses is different and the shape of the envelopes of these pulses is different from the rectangular. This result shows that even with small losses in the structure layers, they must be taken into account.

With an increase in losses in the material is greatly increased amplitude in a reflected signal of the incident pulse of constant amplitude. With an increase in the imaginary part of relative

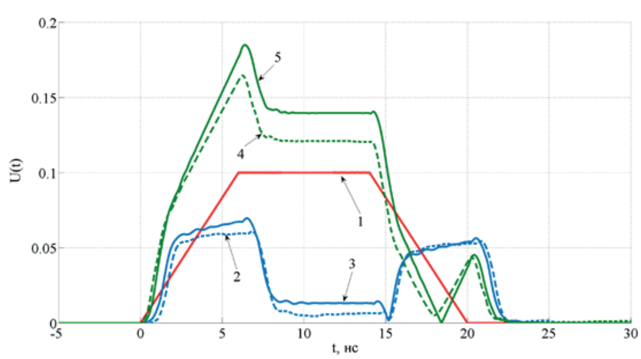

Рис. 11. *Огибающая отраженного сигнала: 1 – падающий сигнал; 2 – экспериментальная кривая для слоя из фторопласта; 3 – теоретическая кривая для слоя из фторопласта; 4 – экспериментальная кривая для слоя из полиамида; 5 – теоретическая кривая для слоя из полиамида.*

dielectric constant increases the difference pulses generated by reflection from the dielectric layer of the front and rear fronts of the incident signal. Fig. 11 clearly shows that even if losses in the half-wavelength layer exists a time when the reflected signal amplitude is close to zero.

2.4.2. Influence of layer thickness on non-stationary reflection

On amplitude reflected from the dielectric layer with signal loss affects the settling time of a stationary process in the layer. an increase of the reflected signal intensity at this time increases. For the experimental study of the effect of the dielectric plate optical thickness on the process of non-stationary reflection amplitude modulated signal used three samples made from PTFE. The thickness of the samples was 30 mm, 60 mm, 90 mm. The samples were mounted in a rectangular waveguide, completely filling the cross-section. For a frequency ν = 8.4 GHz, the wavelength in units of layers have a thickness of λ, 2λ, 3λ, respectively. In the experiment on a layer of the incident electromagnetic pulse with a trapezoidal envelope of 10 ns. Pulse rise time was 3 ns. The center frequency of the pulse ν = 8.4 GHz. **Fig. 12** shows the experimentally obtained envelopes of the reflected signal.

For clarity, shows the envelope of the incident signal, decreased in 10 times. From the results presented in Fig. 12 shows that with increasing layer thickness d = λ d = 2λ to lead to an increase in the reflected signal amplitude is twice (40). On the other hand, a further increase of the layer thickness to 3λ 2λ does not lead to a significant increase of the amplitude of the reflected signal and distorts the shape of the envelope in front of the incident pulse. This is because in this case the duration of the falling edge of the signal becomes comparable to the time of passage of a wave layer.

2.4.3. Influence of the waveguide dispersion in the non-stationary reflection

In the experimental study of non-stationary process of reflection is convenient to use

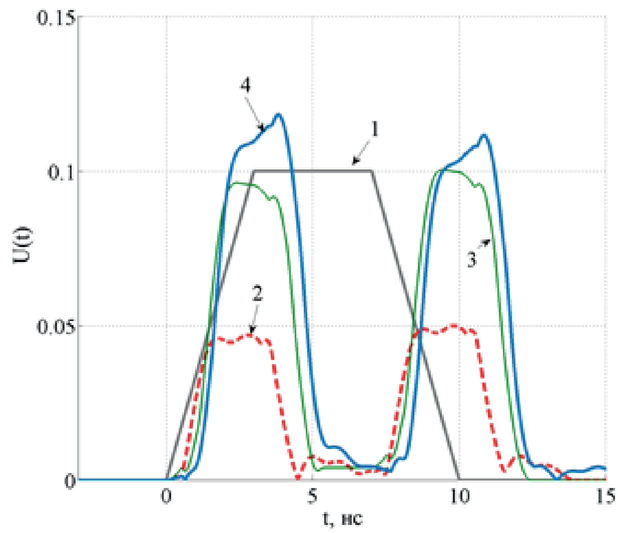

Рис. 12. *Импульсы, отраженные от слоев различной толщины: 1 — падающий сигнал, 2 — толщина слоя d = λ; 3 — толщина слоя d = 2λ; 4 — толщина слоя d = 3λ.*

multilayer structures collected in the waveguide path. This approach allows to fix the layers of the multilayer structure at a desired distance from each other with high accuracy. This raises the need to consider the influence of the waveguide dispersion in the non-stationary process of reflection.

One way analysis of variance effect on unsteady reflection process is to change the carrier frequency signal from the region with weak dispersion to an area with strong dispersion. Since the carrier frequency of the signal must coincide with a frequency of minimum reflectance MIS, it is necessary that the reflectance of the layer had several minima in this frequency range.

Consider the non-stationary process of reflection on the layer thickness of 3λ mounted in a rectangular waveguide section 23 × 10 mm 2. Said waveguide section has a cutoff frequency of 6.5 GHz ≈ νs. In the frequency range to the frequency and νs νs2 ≈ 14.4 GHz it only excited fundamental mode H10. Waveguides of this section are applied, typically in the frequency range from 8 to 12 GHz. This is due to the fact that in the areas of 6.5-8 GHz significant impact on the dispersion of electromagnetic wave propagation in the waveguide, and in the 12-14.5 GHz band can be excited more waveguide mode. Excitation of higher mode significantly affect the dispersion characteristics, leading to strong oscillations of the waveguide transmission ratio. Oscillations gain cause additional difficulties in dealing with applications.

Fig. 13 shows the results of the experimentally measured reflection spectrum of the Teflon layer 90 mm thick, as well as the theoretical calculation. The calculation was made by the method of impedance characteristics for the value of ε = 2.03 + 0.003i. At a frequency of 8.4 GHz, viewed dielectric layer has a thickness of 3λ.

Fig. 13 that at the beginning and end of the frequency range of accuracy predicted by theory, the somewhat lower. This is due to the fact that the agreed load and coaxial-waveguide transition are designed to work in a range of 8-12 GHz. Outside this frequency range matching the quality falls. It also shows that in the strong waveguide dispersion coefficient of reflection increases.

In this range there are several values of the frequency at which the reflection coefficient vanishes. Frequencies minimum reflectance for the case have values: 8.38 GHz, 9.37 GHz, 10.4 GHz, 11.48 GHz and 12.55 GHz. We note that these frequencies are not equidistant. This effect is due to the presence of the waveguide dispersion. Let us write the dispersion relation by dependence of the group velocity of propagation of an electromagnetic pulse in the waveguide on the frequency. To get fashion H10:

$$V = \frac{c}{n}\sqrt{1-\left(\frac{\nu_c}{\nu}\right)^2}, \quad \text{by} \quad \nu \in (\nu_c, \nu_{c1}); \qquad (46)$$

here - the speed of light, ν - the frequency of the signal, νs - critical frequency for fashion H10, νc1 - critical frequency for fashion H01, n - refractive index of the substance filling the waveguide. From the relation (46) shows that the wave propagation velocity decreases when approaching to νc ν and the layer becomes thicker as it for the incident wave, with the result that the resonances are often, but narrows the bandwidth.

For the frequencies corresponding to the zero reflection, will produce an experimental measurement of the envelope of the reflected signal. As in the case study of the effect of thickness on the process of reflection of non-stationary, use a trapezoidal pulse with an envelope 10 ns, c duration of 3 ns fronts. The carrier frequency ν express in terms of relative frequency νc critical for ease of analysis.

Fig. 14 shows the envelope of the reflected signals fluoroplastic plates, for different values of carrier frequency. In addition, in the graph in Fig. 14 shows the envelope of the incident signal, decreased by 10 times. From the results presented in Fig. 14 shows that the presence of the waveguide dispersion of the signal envelope shape changes its form.

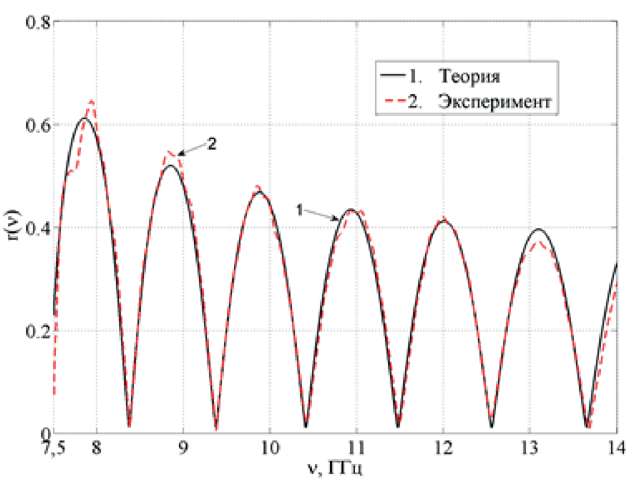

Рис. 13. *Спектр отражения от тефлонового слоя: 1 – расчет методом импедансных характеристик; 2 – эксперимент.*

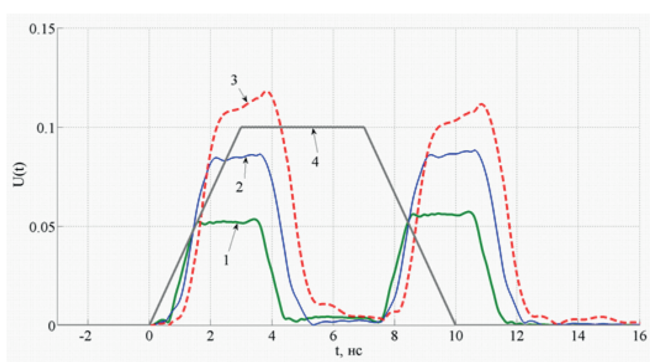

Рис. 14. *Амплитуда огибающей отраженных сигналов для разного значения несущей частоты импульса: 1 – частота падающего импульса* $\nu = 1.92\nu_c$ *; 2 – частота падающего импульса* $\nu = 1.44\nu_c$ *; 3 – частота падающего импульса* $\nu = 1.29\nu_c$ *; 4 – падающий импульс.*

With increasing dispersion (approaching the critical wavelength $\nu \to \nu c$) amplitude of the reflected signal increases and increases its durability. Also in the area there are additional strong dispersion of the oscillation amplitude of the reflected signal. It is easy to note that at a frequency $\nu > 1.44\ \nu c$ envelope shape of the reflected signal does not change its nature. Unlike the above case of increasing the transit time through the structure, the approach to the critical frequency does not increase the losses in the layer.

3. NON-STATIONARY REFLECTION UNDER STRONG WAVEGUIDE DISPERSION

To enhance reflection unsteady - increasing pulse duration and intensity used line waveguide dispersion properties when introduced into the waveguide highly reflecting graphite loading of matching dielectric layer (Teflon) with small losses (**Fig. 15**). TO waveguide section 23×10 mm 2 through a smooth transition waveguide connected waveguide sections 16×8 mm 2 in order to reduce the impact of the effects associated with the excitation of the waveguide at frequencies close to the critical. Operating frequency range used by the OHR was from 8.15 GHz to 12.05 GHz, and the frequency at which the measurements were taken - from 8.5 GHz to 12 GHz. For the partial suppression of spurious reflections in the waveguide channel was introduced attenuator with low attenuation coefficient $k \approx 1.5$ dB. The use of the attenuator has significantly increased the accuracy of the amplitude of the reflectance values of the agreed highly reflecting load,

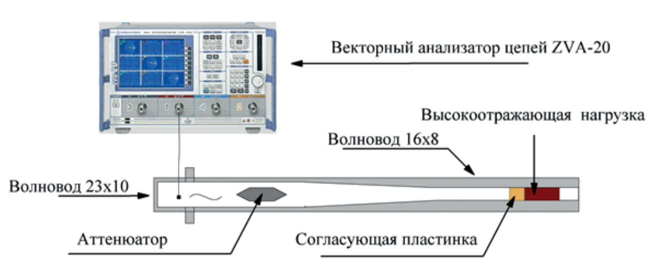

Рис. 15. *Схема установки с высокоотражающей нагрузкой.*

thus making it difficult to measure its phase. Test stand allowed to obtain the dependence of the complex reflection coefficient of frequency.

The experiment was set in two stages. The first phase was measured reflectance of highly reflecting load and calculates the effective conductivity, as well as the measured cut-off frequency of the waveguide. The data used to calculate the thickness of the matching layer. In the second stage, building on the results of the calculation, it produces a series of dielectric layers. Next, we measured the reflectance of a harmonized system for layers of various thicknesses. Thus, the experimentally select the optimum thickness of the matching layer.

The results obtained in the first stage showed that the effective conductivity $\sigma \approx 130$ load (ohm-m) -1, the critical frequency $\nu s = 9{,}339$ GHz. For this conductivity and the known thickness of the matching layer critical frequency was calculated, which was $d = 7.715$ mm. When measuring the reflectance of the system matching layer minimum reflectance was obtained for the frequency $\nu = 9.383$ GHz and a layer thickness of 8 mm, which agrees well with the theoretically calculated values.

Fig. 16 shows the measurement results depending on the reflection coefficient of frequency for an agreed vysokotrazhayuschey load and the result of numerical simulation.

As can be seen from Fig. 16, the results of a theoretical calculation are in good agreement with data obtained in the experiment. Considered the method of matching loads with highly reflective waveguide line is a simple, compact and easy to implement MIS. The proposed matching structure has a significant advantage over other types of MIS: choice of material for a quarter of the dielectric layer is limited almost exclusively the only requirement $\varepsilon l < 1/Zs$. Of course,

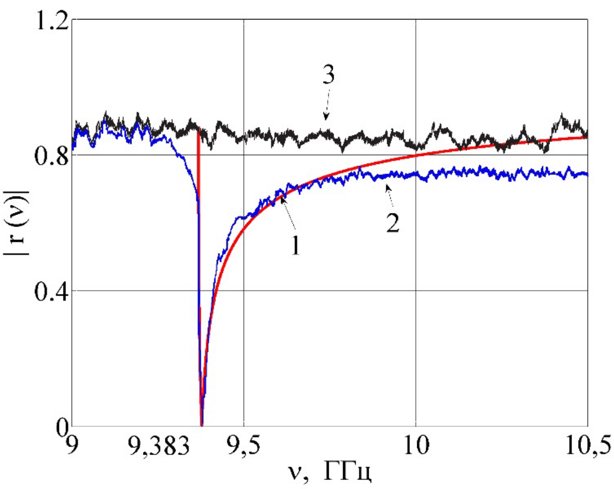

Рис. 16. *Зависимость коэффициента отражения от частоты для согласованной нагрузки: 1 – расчет методом импедансных характеристик; 2 – экспериментально измеренный коэффициент отражения от согласованной высокоотражающей нагрузки; 3 – экспериментально измеренный коэффициент отражения от высокоотражающей нагрузки без согласующего слоя.*

this loss in the fiber, as with any other method should be minimal.

When you study the influence of a strong waveguide dispersion in the process of reflection of non-stationary electromagnetic pulse from a highly reflecting agreed with the waveguide attenuator Load established between the OHR and the waveguide section with a matching structure was removed. The experiment measured the complex reflection coefficient of the highly reflecting the agreed load r (ν). During the experiment, on the layer of the incident electromagnetic pulse with a super-Gaussian envelope. The duration of the incident pulse varied from 50 ns to 250 ns. Central pulse frequency coincides with the optimum coordination with the waveguide highly reflecting load ν = 9.339 GHz. **Fig. 17** shows the results of theoretical modeling and experimental envelopes received reflected pulses, and also shows the envelope of the incident signal U reduced by fourfold axis for clarity.

As can be seen from Fig. 17, the theoretical calculation results are in good agreement with the experimental data. It is evident that with a decrease in the duration of the incident pulse "distortion" of the reflected pulse is increased, which can be explained by the strong influence of the waveguide dispersion. As in the case of unsteady reflection without dispersion systems [17, 23, 42], the reflection signal formed by the structure discussed in the two pulse leading and trailing edges. Comparing the experimental results with the results for a system without dispersion [17, 23, 42], we see that the duration of these pulses has grown substantially. There is a time when the amplitude of the reflected signal tends to zero, but it occurs at the leading edge reflection and not adjustable, as

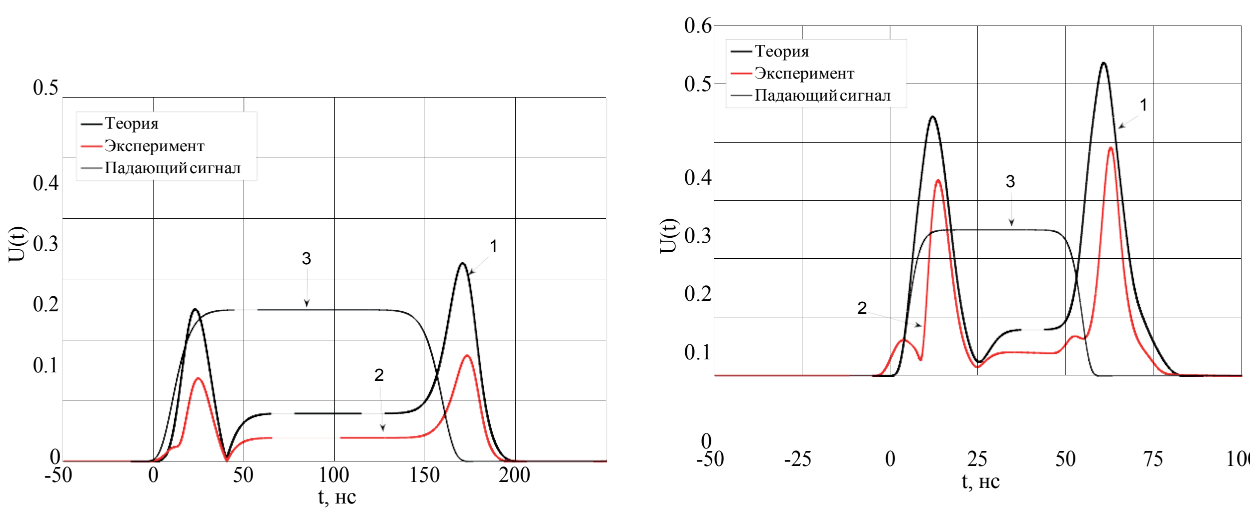

Рис. 17. *Амплитуды огибающих отраженных сигналов от согласованной всокоотражающей нагрузки; а) длительность падающего импульса 150 нс.; б) длительность падающего импульса 50 нс.; 1 – теоретически рассчитанный отраженный сигнал; 2 – экспериментально измеренный отраженный сигнал; 3 – падающий импульс.*

in the case of absence variance discussed in section 2. Another important feature when compared to systems without dispersion is a high intensity of reflected signals . From Fig. 17 shows that the maximum amplitude of the pulses generated during unsteady reflection reaches a value of 50% of the incident signal amplitude. Recall that the maximum value of the amplitude of the reflected signal, resulting in section 2, does not exceed 15% of the incident pulse amplitude. The high intensity of the reflected signal indicates the prospects of using strong waveguide dispersion to enhance the effects of non-stationary reflection. Studies have demonstrated the possibility in principle to provide the almost complete absorption of wave energy in highly reflective load, using interference phenomena in layered structures and waveguide dispersion properties of the line. In areas of changing the amplitude of the incident signal (front area) in the response generated short pulses whose duration corresponds to the duration of fronts. Unlike the case of the dispersion systems without return signal pulses generated at the time of the incident signal reflected fronts have a different amplitude for the leading and trailing edges. The amplitude of the first pulse is always smaller than the pulse amplitude formed trailing edge, and the envelope has a complex shape.

4. UNSTEADY REFLECTED IN THE MULTILAYER INTERFERENCE FILTERS

Unsteady reflection of the pulse signal of short duration in the multilayer structure of the non-reflective class as opposed to the signal reflection from one layer is characterized by a complex frequency dependency of the incident signal, as well as a significant dependence on the losses in the layers of the reflective structure.

In our paper [43] it was shown that the optimum condition for the non-stationary reflection from the multilayer structure is to use a band-pass filter of the second order with a maximally flat frequency response (AFR), well-known in the literature on the synthesis filters and antireflection coatings [44-46].

The simplest implementation of a multi-layer structure with a maximally flat frequency response of a filter consisting of two resonators, which is implemented between the critical connection [45, 47]. structure consisting of two half-wave lossless

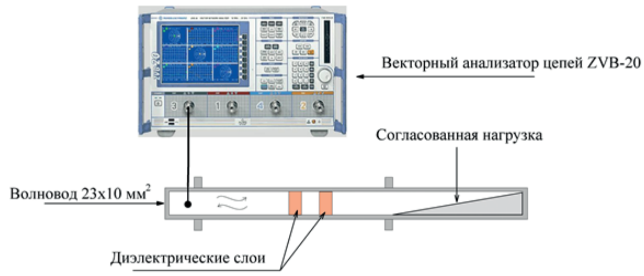

Рис. 18. *Схема установки с многослойным фильтром.*

dielectric layers, which are arranged in the free space to each other at a distance of a quarter wave length (**Fig. 18**) was used.

In an ideal structure of the filter reflection from the layered structure can be calculated for the signal whose envelope has a symmetrical trapezoidal shape with linear edges. Let half-wave filter made of dielectric layers with a real and imaginary part of the relative dielectric constant equal to ε'= 2, ε"= 0.00, respectively. We assume that the length of the trapezoidal pulse τ a lot more time passes wave double layer thickness. At the same time as a result of non-stationary reflection will be generated pulse propagating toward the incident wave. Define half-wave layers of equal thickness d = 30 mm, while the thickness of the quarter-wave layer d1 = 21 mm.

Fig. 19 shows the result of calculation of the field Er (t) of the reflected pulse finite-difference time-domain method tensions. For clarity, the reflected signal amplitude is increased by 20 times.

It can be seen that the reflected signal consists of four short pulses. The maxima of the reflected signal pulse corresponds to the time when the envelope of

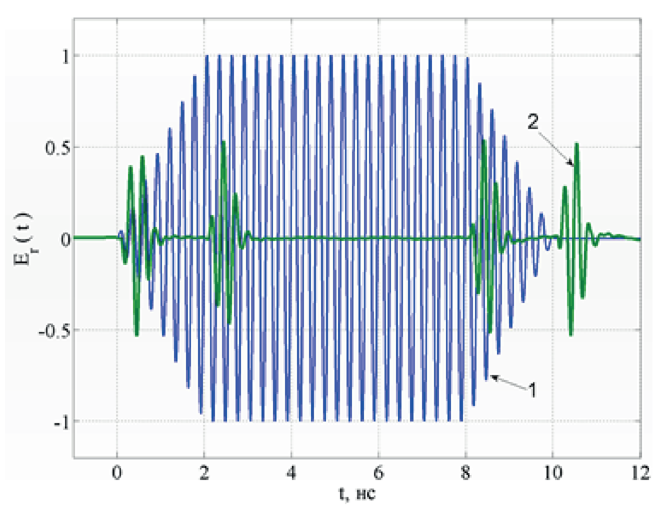

Рис. 19. *Расчет поля $E_r(t)$ отраженного импульса, методом конечных разностей во временной области: 1 – падающий сигнал; 2 – отраженный сигнал.*

the incident signal has the maximum derivative. It also shows that the two central pulse have the same phase and are in antiphase with the first and last pulse.

In the practice of the multilayer structure may be necessary to include additional physical phenomena. For example, in the experimental conditions in the head space may be significant diffraction phenomenon on the edges of the plates and the deviation of the wave front of the incident plane. In addition, there will be additional requirements for accuracy and positioning of the plates to their thickness. Equally important, as it is evident from [42], is a real need to take account of losses in the layers of the multilayer structure.

Driving the practical implementation of the considered filter is strongly dependent on the frequency range for which it is applied. Thus in the optical domain using a substrate on which the layers are sequentially sputtered in the multilayer filter synthesis. In this case, the synthesis filter is necessary to consider not only the loss of structure layers, and the dispersion material as layers and the substrate. In the microwave range of wavelengths such structures can be realized in a waveguide. In this case, you must additionally consider the impact of the waveguide dispersion in the reflectance. On the other hand, it solves the problem of taking into account diffraction at the edges of plates and shapes of the incident wave front, as the plate completely covers the section of the waveguide.

In our case, the model was studied waveguide filter, as the most convenient for the pilot study. Consider this model more and carry out its numerical analysis based on the waveguide dispersion and loss of structure layers.

Let the layers are set in a free rectangular waveguide in which the excited fundamental mode H10. We assume that the layers are made of a dielectric with low losses.

Then the expression for the relative permittivity will be in the form $\varepsilon = \varepsilon' - i\varepsilon''$, where ε'' and ε' - imaginary and real part of the relative permittivity, respectively. We assume that the losses in the layers of the structure are small $\varepsilon''/\varepsilon' < 1$.

In [42] it was shown that the small loss in the sample do not affect its optical thickness, in this case - to the resonant frequency of a half-wave layer. Then, to calculate the thickness of the layers can be taken into account only the waveguide dispersion. In this case, for the calculation of the layer thickness, we have:

$$d = \mathrm{Re}(Z)\frac{c}{2\nu}, \tag{47}$$

where Re (Z) - the real part of the impedance layer.

Analysis of non-stationary reflection process requires a shift in the time domain. For this we use the inverse Fourier transform. As shown by numerical simulation method of impedance characteristics, the presence of losses in the structure of the layers leads to a reflection in the field of constant incident amplitude of the signal.

When measuring non-stationary reflection bandpass filter was used, consisting of two wave plates of fotoroplasta. Polyacetal has low loss in the microwave frequency range [48, 49]. The plates were mounted on a distance of a quarter wavelength from each other in the middle of the rectangular waveguide to minimize the influence of waves on the measured gap reflectance. The filter was tuned to the frequency 8.4 GHz and had the following geometrical dimensions: thickness fluoroplastic plates - 30.0 mm, the thickness of the air gap between the plates - 14.5 mm. The dielectric constant of PTFE for this frequency has been previously measured and accounted for $\varepsilon 1 = 2.05 - 0.015i$.

The experiment measured the complex reflection coefficient of the structure. inverse Fourier transform was used to obtain the envelope of the reflected signal. **Fig. 20** shows the result of a theoretical model and experimentally measured envelope pulse reflected from the structure under study. As can be seen, the theoretical calculation results are in good agreement with the experimental data. Experimental results have shown that during unsteady reflection of an electromagnetic pulse from a three-layer filter with maximally flat frequency response are formed by four short pulse. The provisions of pulses coincides with the maximum derivative of the envelope of the incident signal. The signal generated during unsteady considered reflections from structures fundamentally different from the signal reflected from a single layer filter.

As in the case of half-wave filter, a loss of structure layers have a significant influence on the unsteady reflection. It also shows that there is a time

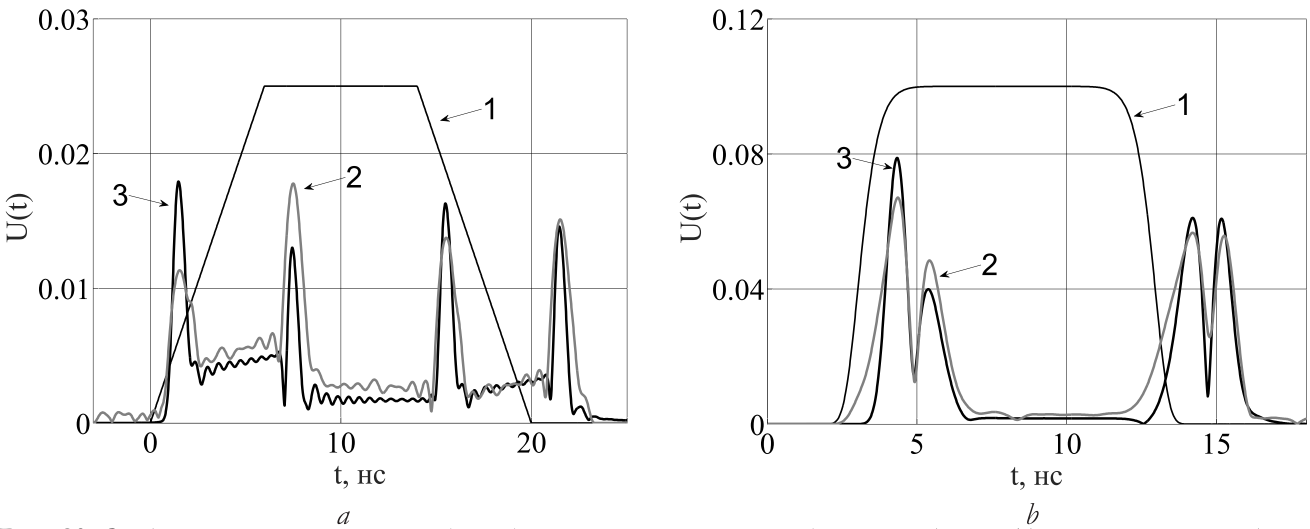

Рис. 20. *Огибающая отраженного сигнала для падающего импульса с трапецеидальной огибающей (a) и с супергауссовой огибающей (b) от трехслойного фильтра: 1 – огибающая падающего сигнала; 2 – эксперимент; 3 – теория.*

when the amplitude of the reflected signal tends to zero.

5. CONCLUSION

This paper presents an overview of the main results of our studies in recent years the phenomenon of non-stationary reflection of short and ultrashort (about 100 periods of the field oscillations) of electromagnetic pulses of microwave laminates. This phenomenon is particularly observed in a contrasting comparability duration nonstationary transient interference waves in a multilayer structure with the duration of the incident pulse.

In the course of research it has been refined a theory of non-stationary reflection pulse signals from interference multilayer structures. The existing theoretical apparatus is supplemented with the influence on the process of non-stationary reflection losses in the layers of the multilayer interference structure and strong waveguide dispersion.

Developed experimental methods for studying non-stationary process of reflection of ultrashort electromagnetic pulses from multilayer interference structures in the microwave range. results of experimental observation of the phenomenon of non-stationary reflection amplitude modulated signal from interference multilayer structure obtained for the first time in the microwave range.

It was found that the reflection amplitude-modulated signal by a half-wave layer lossy always exists a time when the non-zero amplitude when the amplitude of the incident signal reflected signal tends to zero and that the phase changes by π. In the presence of small losses in the layers of the multilayer structure the amplitude reflection coefficient depends linearly on the magnitude of the losses, while the formation of the phase pattern of the interfering wave occurs in this case as well as in the absence of losses.

The task of matching loads with highly reflecting waveguide due to strong waveguide dispersion. The possibility to ensure complete containment of the incident wave energy into a load with virtually any reflectance via a matching structure consisting of only one layer, the thickness of which is close to a quarter-wave.

It revealed the presence of a more complex process in unsteady reflection multilayer structures with non-reflective class maximally flat frequency response, compared to multilayer structures having other functional dependence of the amplitude-frequency response.

It is shown that for small losses in the layers of the structure of a maximally flat frequency response envelope of the reflected signal can be approximately described by the N-th derivative of the envelope of the incident signal.

REFERENCES

1. Petrich JW, Fleming GR. Ultrafast processes in biology. *Photochemistry and photobiology,* 1984, 40(6):775-780.
2. Kling MF, Vrakkin MJ. Attosecond Electron Dynamics. *Annual Review of Physical Chemistry,* 2008, 59(1):463-492.

3. Rulliere C. *Femtosecond Laser Pulses*. New York, Springer, 2004, 218 p.
4. Szipocs R., et al. Chirped multilayer coatings for broadband dispersion control in femtosecond lasers. *Photochemistry and photobiology*, 1994, 19(3):201-203.
5. Kartner FX, Matuschek N, Schibli T, Keller U. Design and fabrication of double-chirped mirrors. *Optics Letters,* 1977, 22(11):831-833.
6. Matuschek N, Kartner FX, Keller U. Analytical design of double-chirped mirrors with custom-tailored dispersion characteristics. *IEEE Journal of Quantum Electronics*, 1999, 35(2):129-137.
7. Vernon SP, et. al. Chirped multilayer coatings for increased x-ray throughput. *Optics Communications,* 1993, 18:672-674.
8. Dadashadze N, Romanov OG. Otrazhenie opticheskikh impulsov ot mnogosloynykh dielectricheskikh struktur i microrezonatorov: chislennoe reshenie uravneniy Maksvella [Reflection optical pulses from multilayer dielectric structures and microcavities: numerical solution of Maxwell's equations]. *Vestnik BGU*, 2014,1(1):825-834 (in Russ.).
9. Dennis WM, Liebig C. Simulation of High Intensity Ultrashort Pulse Interactions with Dielectric Filters. *Proc. of SPIE*, 2007:5989-23.
10. Liebig CM, Dennis WM. Simulation of interactions of high-intensity ultrashort pulses with dielectric filters. *Optical Engineering*, 2007, 46(2):023801.
11. Dunning Sarah. Optimizing Thin Film Filters for Ultrashort Pulse Shaping. *Ph.D. thesis*, The University of Georgia, 2003.
12. Michielssen E, Ranjithan S, Mittra R. Optimal multilayer filter design using real coded genetic algorithms. *IEE Proceedings-J. Optoelectronics,* 1992, 139(6):413-420.
13. Chen LR. Ultrashort optical pulse interaction with fibre gratings and device applications. *Ph.D. thesis,* University of Toronto, 1997.
14. Chen LR, Benjamin SD, et. al. Ultrashort pulse reflection from fiber gratings: a numerical investigation. *Journal of Lightwave Technology,* 1997, 15(8):1503-1512.
15. Bystrov RP, Cherepenin VA. Teoreticheskoe obosnovanie vozmozhnostey primeneniya metoda generatsii moshchnykh nanosekundnykh impulsov elektromagnitnogo izlucheniya pri sozdanii radiolokatsionnykh sistem elektronnoy bor'by dlya porazheniya ob'ektov [The theoretical justification of the possibility of generating high-power nanosecond pulses of electromagnetic radiation to create radar systems of electronic warfare for the destruction of objects]. *Journal radioelektroniki* (IRE RAS, the network edition), 2010, 4 (in Russ.).
16. Schamiloglu E. *High Power Microwave Sources and Technologies*. New York, Wiley&Sons, 2001.
17. Kozar AV, Bobrovnikov YuA, Gorokhov PN. Yavlenie nestatsionarnogo otrazheniya elektromagnitnykh voln s izmenyayushcheysya amplitudoy ot sloistykh struktur [The phenomenon of non-stationary reflection of electromagnetic waves with varying amplitude from layered structures]. *Izvestiya RAN, Ser. Fiz*, 2002, 12(1823):201-213 (in Russ.).
18. Bobrovnokov YuA, Gorokhov PN, Kozar AV. Preobrazovanie impulsov s pomoshch'yu tonkosloynykh struktur [Conversion of pulses via thin-layered structures.]. *Kvantovaya elektronika*, 2003, 53(11):1019 (in Russ.).
19. Weiner MA. Ultrafast optical pulse shaping: A tutorial review. *Optics Communications*, 2011, 284:3669-3692.
20. Bushuev VA. Vremennaya kompressiya impulsov rentgenovskogo lazera na svobodnykh elektronakh v usloviyakh breggovskoy difraktsii [Time compression of X-ray free-electron laser pulses under conditions of Bragg diffraction]. *Radioelektronika. Nanosistemy. Infomatsionnye tekhnologii* (*RENSIT*), 2014, 6(2):177-187 (in Russ.).
21. Dunning FB. *Atomic, Molecular, and Optical Physics: Electromagnetic Radiation*. London, Academic Press, 1997, 406 p.
22. Bobrovnikov YuA, Kozar AV, Gorokhov PN. Nestatsionarnoe otrazhenie elektromagnitnykh impulsov ot prosvetlyayushchikh tonkosloynykh struktur [Non-stationary reflection of electromagnetic pulses from the thin-layer anti-reflective structures]. *Trudy VIII Vserossiyskoy shkoly-seminara "Volnovye yavleniya v neodnorodnykh sredakh*", Moscow, MGU im. Lomonosova Publ., 2002, 1(5):53-54 (in Russ.).
23. Bobrovnikov YuA, Kozar AV, Gorokhov PN. Yavlenie nestatsionarnogo otrazheniya elektromagnitnykh voln ot prosvetlyayushchikh

tonkoslotnykh struktur [The phenomenon of non-stationary reflection of electromagnetic waves from the thin-layer anti-reflective structures]. *Sb. dokladov nauchnoy konferentsii "Lomonosovskie chteniya". Sektsiya fiziki, podsektsiya optiki i lasernoy fiziki*. Moscow, Lomonosov MGU Publ., 2004, 1:31-33 (in Russ.).

24. Kozar AV. Interferentsionnye yavleniya v sloistykh strukturakh i ikh primenenie v zadachakh priema signalov i diagnostiki neodnorodnykh sred [Interference phenomena in layered structures and their application to problems of signal reception and diagnostics of inhomogeneous media.]. *Ph.D. thesis*, Moscow, Lomonosov MGU Publ., 2004.
25. Born M, Wolf E. *Principles of optics*. Oxford-London, Pergamon Press, 1964.
26. Kozar AV. Spectral characteristics of thin-layer interference matching systems. *Optics and Spectroscopy,* 1988, 64(5):1130-1134.
27. Kozar AV. Opticheskie i strukturnye svoystva tonkosloynykh interferentsionnykh soglasovateley [Optical and structural properties of thin-layer interference matchers]. *Optika i spektroskopiya,* 1985, 59(5):1132-1136 (in Russ.).
28. Akhmanov SA, Vysloukh VA, Chirkin AS. *Optika femtosekundnykh lazernykh impulsov* [Optics femtosecond laser pulses]. Moscow, Nauka Publ., 1988.
29. Vinogradova MB, Rudenko OV, Sukhorukov AP. *Teoriya voln* [Wave Theory]. Moscow, Nauka Publ., 1990, 432 c.
30. Chipman RA. *Transmission lines*. New York, McGraw-Hill book company, 1968.
31. Peres PLD, de Souza CR, Bonatti IS. ABCD matrix: a unique tool for linear two-wire transmission line modelling. *Intern. J. of Electrical Engineering Education*, 2003, 40(3):220-229.
32. Matey GL, Yang L, Dzhons EMT. *Filtry SVCH, soglasuyushchie tsepi, tsepi svyasi* [Microwave filters, matching networks, connection circuits]. Moscow, Svyaz' Publ., 1971.
33. Yee K. Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *Optical Engineering*, 1966, 14(2):302-307.
34. Weiland T. A discretization method for the solution of Maxwell's equations for six-component fields. *Electronics and Communications AEU*, 1977, 31(3):116-120.
35. Brekhovskikh LV. *Volny v sloistykh sredakh* [Waves in Layered Media.]. Moscow, Nauka Publ., 1973, 343 c.
36. Kozar AV, Kolesnikov BS, Pirogov YuA. O primenenii metoda impedansnykh kharakteristik dlya analiza rasprostraneniya voln v mnogosloynykh strukturakh s pogloshcheniem [Application of the method of impedance characteristics for the analysis of wave propagation in multilayer structures with absorption]. Vestnik Mosk. univ., ser. Fizika, astronomiya, 1978, 19(2):76-83 (in Russ.).
37. Tikhonravov AV, Trubetskov MK. Modern design tools and a new paradigm in optical coating design. Applied Optics, 2012, 51(30):7319-7332.
38. Vainstein LA. *Elektromagnitnye volny* [Electromagnetic waves.]. Moscow, Radio i svyaz' Publ., 1988.
39. Rohde and Schwarz. *ZVT Vector Network Analyzers Operating Manual*. Munich, Germany: Rohde&Schwarz GmbH, KG, 2011.
40. Agilent *Time Domain Analysis Using a Network Analyzer*. Application Note 1287-12. Agilent Technologies, Inc, USA, 2007:1-48.
41. Ayficher E, Dzhervis B. *Tsifrovaya obrabotka signalov: prakticheskiy podkhod* [Digital Signal Processing: A Practical Approach]. Moscow, ID "Vil'yams" Publ., 2004, 992 c.
42. Kozar AV, Trofimov AV. Yavlenie nestatsionarnogo otrazheniya impulsnykh signalov ot sloistykh struktur s poteryami [The phenomenon of non-stationary reflection of pulse signals from the layered structures with losses.]. Vestnik Mosk. univ., *ser. Fizika, astronomiya,* 2013, 5:38-43 (in Russ.)..
43. Kozar AV, Trofimov AV, Potapov AA. Protsess nestatsionarnogo otrazheniya korotkikh elektromagnitnykh impulsov ot mnogosloynykh filtrov s maksimalno ploskoy amplitudno-chastotnoy kharakteristikoy [The process of non-stationary reflection of short electromagnetic pulses from the multilayer filters with maximally flat amplitude-frequency response]. *Journal radioelektroniki* (IRE RAS, the network edition), 2016, 4:1-17 (in Russ.).
44. Macleod HA. *Thin-Film Optical Filters*. London, Macmillan, 1986, 772 p.

45. Feldstein AL, Yavich LR. *Sintez chetyrekhpolyusnikov i vos'mipolyusnikov na SVCH* [Synthesis of microwave quadri- and eightpoles]. Moscow, Svyaz' Publ., 1971, 352 c.
46. Krepelka J. Maximally flat antireflection coatings. *Jemná Mechanika A Optika*, 1992, 37:53-56.
47. Schulz U, Schallenberg UB, Kaiser N. Symmetrical periods in antireflective coatings for plastic optics. *Applied Optics*, 2003, 42(7):1346-1351.
48. Kikoin IK (ed.). Tablitsy fizicheskikh velichin. Spravochnik [Tables of physical quantities. Directory]. Moscow, Atomizdat Publ., 1976, 1008 c.
49. Bur AJ. Dielectric properties of polymers at microwave frequencies: a review. *Polymer*, 1985, 26(7):963-977.