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Metamaterials with temporal heterogeneity for controlling optical fields

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The interaction of an electromagnetic wave with a nonstationary medium is studied. The reflectances and transmittance of light through a material that experiences a one-time refraction index switch are calculated. It is shown that by adjusting the parameters of the switching time profile, it is possible to control the amplitudes of the reflected and transmitted waves. It has been specified that for efficient conversion of light using this class of media, the switching duration must be an order of magnitude shorter than the wave period.

Keywords: photonics, metamaterials, nonstationary media, spatiotemporal heterogeneity.

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Introduction

Metamaterials (artificial structured media [1]) provide unique opportunities for controlling light. In recent years, a number of unusual effects have been discovered in metamaterials, for example, negative refraction [2], diffraction-free bending of obstacles, etc. Due to this, these media are widely used in photonics and optoelectronics. Recently, laminar metal-insulator structures have been proposed for radiation-induced cooling [3]. The unusual properties of metamaterials are due to the presence of spatial heterogeneity in them, which is determined by the geometry of the structural elements and their relative position. Tunable plasmonic media [4] are increasingly being used as the material from which structural elements are made, allowing further optimization of the optical response. Recently , another class of artificial media, which are homogeneous in space but heterogeneous in the time domain, has become very popular [5]. This is achieved by modulating the properties of the environment over time using external influences.

The properties of nonstationary media can be illustrated by comparison with a material that has spatial heterogeneity. The simplest example of spatial heterogeneity is a flat interface between two media (spatial interface) (Fig. 1, *a*). When light passes through this structure, two waves are formed: reflected and transmitted. There is a similar effect for the case of a temporary interface (Fig. 1, *b*). When the refraction index of the entire medium abruptly switches, the wave propagating in it is converted into two others, which have opposite directions of propagation. By analogy with the case of spatial heterogeneity, these waves are usually called reflected and transmitted. In this case, the frequency of these waves changes, while the wave vector remains unchanged [6,7]. This property is diametrically opposed to the case of a spatial interface.

At the moment, most published works [8,9] use the ultrafast switching approximation, when the properties of the medium change instantly. However, in any real system the switching speed is finite, which is due to the presence of inertia.

In this work, we study the influence of time interface parameters, such as the duration and time profile of dielectric permittivity switching, on the processes of light reflection and refraction.

Results and discussion

To describe the passage of light through the time interface, the transmittance (T) and reflection (R) coefficients are introduced in the following form:

$$R = \left|\frac{\mathbf{E}^R}{\mathbf{E}^0}\right|, \quad T = \left|\frac{\mathbf{E}^T}{\mathbf{E}^0}\right|, \tag{1}$$

where $\mathbf{E}^0$, $\mathbf{E}^R$ and $\mathbf{E}^T$ — electric field strengths of the incident, reflected and transmitted waves, respectively. In the instantaneous switching approximation, the coefficients R and T are related as follows:

$$T^2 - R^2 = \left(\frac{n_1}{n_2}\right)^3, \tag{2}$$

where n_1 and n_2 — refraction indices before and after switching, respectively.

In the work, the influence of the time profile of switching the dielectric permittivity$\varepsilon(t)$ on the coefficients R and T was studied. For this purpose, the following cases are considered (Fig. 2): sigmoid (dash-dotted line), triangular (dashed line) and two-stage (solid line) profiles.

The sigmoid profile was specified in the following form:

$$\varepsilon(t) = \varepsilon_0 + \frac{\Delta\varepsilon}{1 + e^{-\frac{(t-t_0)}{\tau}}}. \tag{3}$$

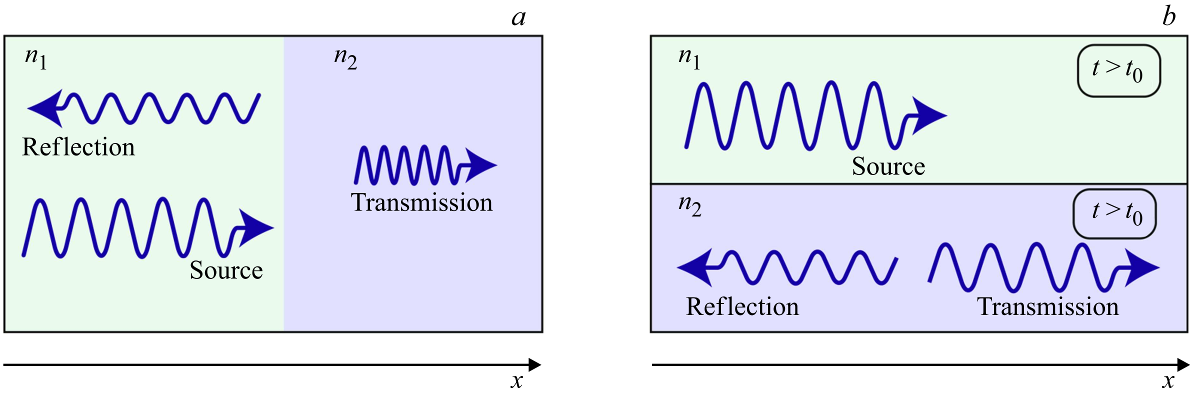

Figure 1. Illustration of spatial (a) and temporal (b) interfaces. (a) The interface between two media with refraction indices n_1 and n_2, (b) shows the case of switching the refraction index from n_1 to n_2 at the moment of time t_0.

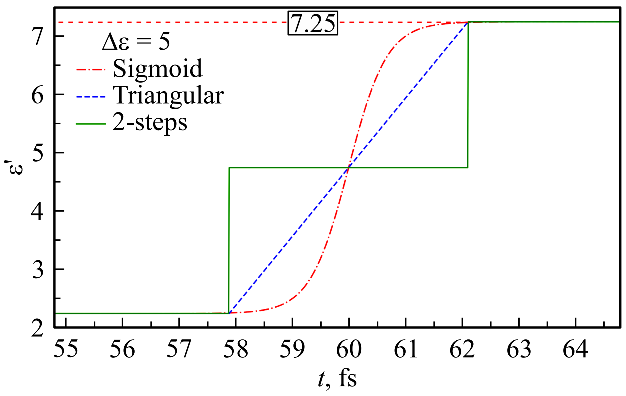

Figure 2. Dependences of the dielectric constant ε' on time t for various switching profiles: dash-dotted line — sigmoidal, dashed line — triangular, solid line — two-stage.

Here ε_0 — dielectric permittivity value before switching, $\Delta\varepsilon$ — change in dielectric permittivity as a result of switching (switching depth), t_0 — point in time at which the medium has switched halfway. Parameter τ describes the characteristic switching duration.

The reflectance and transmittance of light through the time interface were calculated by numerical simulation using the finite difference time domain method. The commercial Ansys Lumerical FDTD software package was used. To study electromagnetic phenomena in nonstationary environments, a computer code was created in the form of a plug-in for the software applied. The code is a dynamic library with which you can change the dielectric permittivity of the medium at each time step in a finite-difference diagram. Calculations were performed in the approximation that the starting material has no dispersion and absorption. The switching depth of the dielectric permittivity $\Delta\varepsilon$ for all profiles was set to 5. As a result of the study, the dependences of the square of the transmittance and reflection coefficients on the switching duration were obtained (Fig. 3). The data were obtained for various switching profiles, the characteristic form of which is shown in Fig. 2. Let us note that each point on the graph (Fig. 3) corresponds to a separate simulation, where the coefficients R and T were calculated for a specific profile and switching duration.

As follows from the data obtained (Fig. 3, a), at short switching durations (orders of magnitude shorter than the wave period), the values of the calculated coefficients R and T are consistent with the results of previous works in which instantaneous switchings were reviewed. However, the coefficients R and T decrease with increasing switching duration. In particular, the reflectance acquires a value close to zero, which occurs already at times comparable to the period of wave oscillation. Thus, to observe a reflected wave in materials with temporal heterogeneity, the switching duration should be an order of magnitude shorter than the wave oscillation period. For a given switching duration, the amplitudes of the reflected and refracted waves strongly depend on the switching time profile. It can also be concluded that relation (2) is satisfied for any switching duration.

In the case of a triangular profile (Fig. 3, b) for long-term switchings, there are oscillations in the dependence graphs R and T. This effect is even more expressed for two-stage switching (Fig. 3, c). This behavior can be explained by the following. In both profiles there are two jumps in the derivative of the refraction index with respect to time. Reflected and refracted waves are formed with each jump. As a result, a pair of reflected (refracted) waves interfere with each other. The phase difference between successively reflected (refracted) waves is determined by the time between switchings. Thus, waves can strengthen or weaken each other. This effect can be used to create anti-reflective coatings and ideal absorbers.

Conclusion

In this work, the transmission of light in a medium with heterogeneity in the time domain is studied. The reflectance and transmittance coefficients were calculated

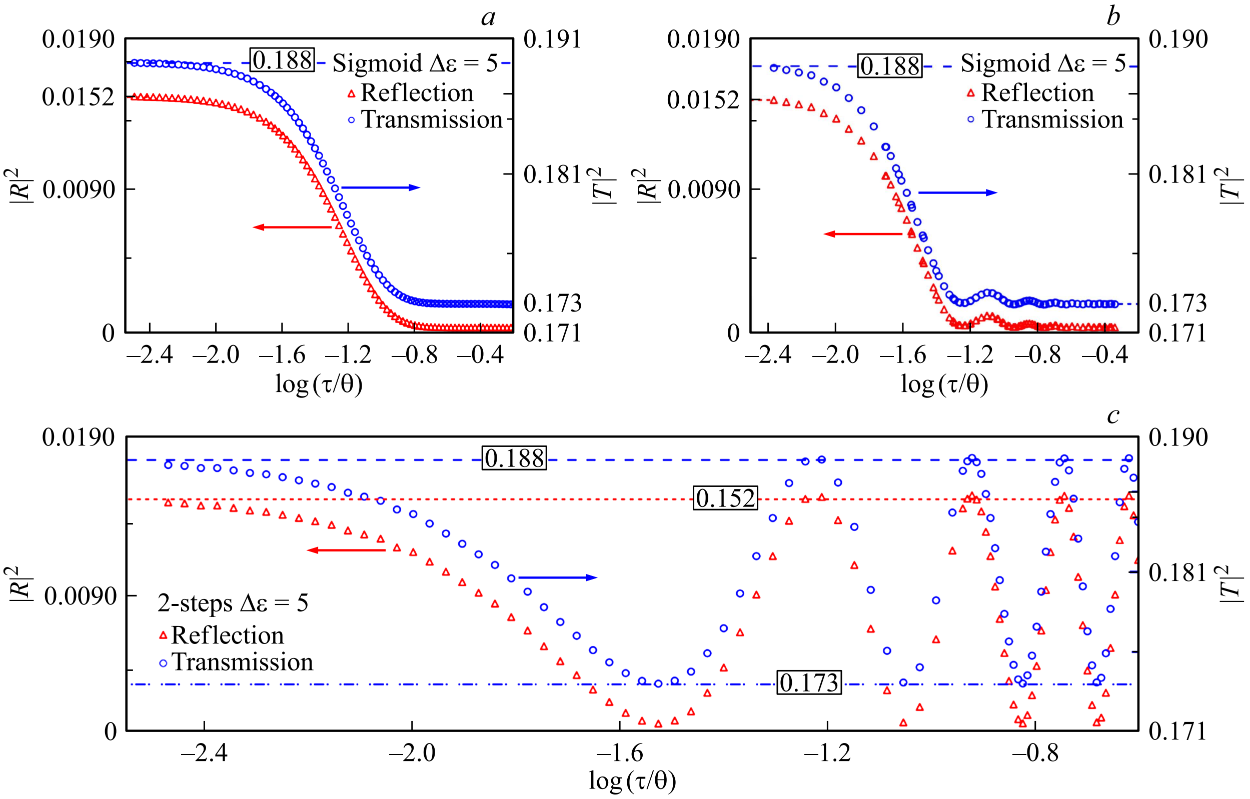

Figure 3. Dependence of the squared coefficients of transmittance $|T|^2$ and reflection $|R|^2$ on $\log(\tau/\theta)$, where τ — switching duration, θ — oscillation period of the incident wave. Sigmoid (*a*), triangular (*b*) and two-stage (*c*) profiles.

through temporary interfaces representing a one-time refraction index switch. The influence of switching duration and profile was studied. It has been specified that to observe the reflected wave, the switching duration should be less than or comparable to the period of the incident wave. It has been demonstrated that at a given switching duration, the amplitudes of the reflected and refracted waves strongly depend on the switching time profile. An important task is to develop a method for calculating the optimal parameters of switching profiles, which depend on the specific task. Thus, the creation of temporary heterogeneities in the medium opens up new degrees of freedom in controlling optical fields. This will allow to transition from nanostructured metamaterials to optical devices with simple geometry.

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Conflict of interest

The authors declare that they have no conflict of interest.

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