

Time-spatial structure of airy pulse in non-stationary environment

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Abstract The transformation of an electromagnetic pulse in a triply asymmetric electrodynamic problem is considered. Asymmetry is specified by an initial Airy pulse with asymmetric behaviour in the past and in the future, by the presence of a boundary between two dielectric media, and by the temporal behaviour of refractive index in one of them.

Keywords Airy pulse · Integral equation · Transient bounded dielectric

1 Introduction

There has been active interest in the paraxial propagation of optical Airy pulses (Siviloglou and Christodoulides 2007) for almost a decade due to their unusual properties. At the same time interest in ordinary Airy pulses has not been lost due to their asymmetry form, especially if there is another asymmetry in the phenomenon considered. Such asymmetry may be caused by the appearance of a medium boundary or by the non-stationarity of its features (Barwick 2011; Kaminer et al. 2011, 2012; Aleahmad et al. 2016; Alonso and Bandres 2014; Liang et al. 2014; Li et al. 2014). Parametric phenomena in active media have attracted a great deal of attention for a long time in connection with the generation

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and amplification of electromagnetic waves due to the time modulation of medium parameters (Morgenthaler 1958; Felsen and Whitman 1970; Fante 1971; Ostrovsky and Stepanov 1971; Averkov and Boldin 1980; Stolyarov 1983; Borisov 1987; Nerukh 1995; Kalluri 1999; Nerukh et al. 2001, 2013). Investigation of transient electromagnetic phenomena is important for the control of an electromagnetic signal by the temporal adjustment of medium parameters in connection with the development of optoelectronic systems. The fundamental question of what is the spatiotemporal limit of a macroscopic model that describes the optoelectronic interaction at the interface between different media has become relevant for time-dependent photoemission from solid surfaces (Zhao et al. 2012). To construct the desired behaviour of the field one has to use a complex modulation of medium parameters. However, the main features of the wave transformation can be revealed by considering the simple case of an abrupt change of medium parameters with time. It is known, since the first publication by (Morgenthaler 1958), that a single abrupt change of medium parameters leads to a changing of the wave frequency and amplitude or the pulse shape. Analysis of the results obtained with known changes in wavelength, wave energy and pulse compression, allowed the authors of (Xiao et al. 2011, 2012, 2014) to claim the identification of a correct set of boundary conditions that seemingly resolved a discrepancy existing in the literature. But, as noted by (Bakunov and Maslov 2014) “the boundary conditions discarded in (Xiao et al. 2014) as incorrect have been used in the literature for rapidly growing plasma” and the material model of (Xiao et al. 2014) misinterprets results from the literature by opposing two sets of boundary conditions that are related to different material models of the temporal boundary.

The time-domain concept enables the reshaping of an ultrashort optical pulse into a desired complex (amplitude and phase) and arbitrary temporal pulse waveform using a single temporal amplitude modulator between two media (Fernández-Ruiz et al. 2016). The propagation and transformation of electromagnetic waves through spatially homogeneous, yet smoothly time-dependent media within the framework of classical electrodynamics is explored in (Hayrapetyan et al. 2016). By modelling the smooth transition as a phenomenologically realistic change of the dielectric permittivity, an analytically exact solution to Maxwell’s equations is derived that shows the possibility of the amplification and attenuation of waves, and associates this with the decrease and increase of the time-dependent permittivity. Such an energy exchange between waves and non-stationary media paves the way towards controllable light-matter interaction in time-varying structures. Wave control is usually performed by spatially engineering the properties of a medium. Because time and space play similar roles in wave propagation, manipulating time boundaries provides a complementary approach (Bera et al. 2016). The relevance of this concept was experimentally demonstrated by introducing instantaneous time mirrors which explain the effect of any time disruption on wave propagation. It was shown that sudden changes of the medium properties generate instant wave sources that emerge instantaneously from the entire space at the time disruption. The time-reversed waves originate from these ‘Cauchy sources’, which are the counterpart of Huygens virtual sources on a time boundary (Bacot et al. 2016). Recently time-domain techniques have been actively discussed in the literature for solving such electromagnetic problems, mainly owing to their superiority in solving wide-band problems in comparison to frequency-domain methods. Numerical demonstration of the wavelength conversion of light via the simple dynamic refractive index tuning of an optical cavity in a photonic crystal has been described by (Lucchini et al. 2015).

In this paper the problem of the electromagnetic field transformation in a medium whose refractive index changes in time is solved by the Volterra integral equation method

which takes into account the initial and boundary conditions for the electromagnetic field. It is important that the spot shape considered is described by an Airy function, and not by a Gaussian function, since there are in fact no free propagating Gaussian beams. The reason for this is that a Gaussian profile has a Gaussian Fourier spectrum which is never zero, and only asymptotically approaches zero as the wavenumber tends to infinity. This pulse is symmetric relative to its argument, that is it behaves identically when its argument tends to plus or minus infinity. Thus, for a Gaussian profile one needs to include evanescent components, even if their contribution is small. The oscillations in the Airy profile arise from the hard cut-off at high frequencies (Novotny and Hecht 2006).

2 The start parameter p

We consider the transformation of an electromagnetic pulse $E_0(t, x)$ caused by a plane boundary of a dielectric half-space ($x > 0$) which appears at zero moment of time in a previously homogeneous medium characterised by a refractive index n . After zero moment the medium becomes inhomogeneous due to a temporal jump-like change of the refractive index from n to n_1 in the half-space $x \geq 0$, Fig. 1a. The initial pulse $E_0(t, x)$ propagates normally to the boundary of the non-stationary dielectric. Such a problem statement gives asymmetry in time and space: i.e. the situation is different in the future ($t \rightarrow \infty$) and in the past ($t \rightarrow -\infty$) as well as in the direction $x \geq 0$ and the opposite direction, $x \leq 0$. A third asymmetry is raised by the initial pulse as the Airy function of the first kind

$$E_0(t, x) = \text{Ai}(-t/T + x/vT - p) \tag{1}$$

as discussed below. Here, $v = c/n$ is the wave velocity in the primary medium and c is the light velocity in vacuum, T is a time scale and $p = (x_0/v - t_0)/T$ is a start parameter conditioned by the moment of the pulse initiation t_0 and the source point location x_0 .

The behaviour of the Airy function in the opposite directions

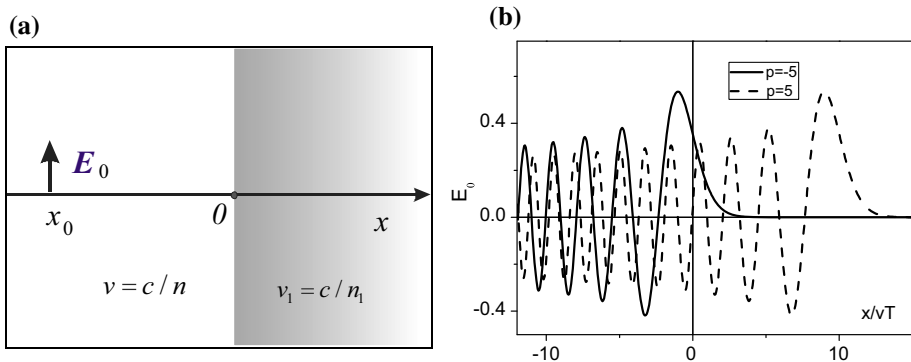


Fig. 1 **a** The geometry of the problem. The medium with a refractive index n_1 appears at zero moment. **b** The spatial form of the initial pulse at the moment $t/T = 5$ for two values of the start parameter: $p = -5$ (solid line) and $p = 5$ (dash line)

$$Ai(t) \approx \begin{cases} 2^{-1}\pi^{-1/2}t^{-1/4}\exp(-2t^{3/2}/3), & t \rightarrow +\infty \\ \pi^{-1/2}|t|^{-1/4}\sin(2|t|^{3/2}/3 + \pi/4), & t \rightarrow -\infty \end{cases} \tag{2}$$

gives the third asymmetry in the problem statement, Fig. 1b. So, we describe a triply asymmetric electromagnetic phenomenon: an asymmetric initial electromagnetic signal, an asymmetric object of diffraction and the asymmetric behaviour of this object in time.

The sign of the start parameter p has a great influence on the pulse transformation process. A location of the initial pulse front in (1) can be determined by the inequality $-t + x/v - pT > 0$. It defines a region in time-spatial coordinates with the near zero field that is marked by the bold ‘double point and dashed’ line in Fig. 2. If $p > 0$ then the initial field is deep inside the region where a dielectric has changed at zero moment of time, Fig. 2a. On the other hand, for $p < 0$, Fig. 2b, the initial front does not reach at $t = 0$ the medium boundary and the pulse front does not see the medium appearing at this moment at all, Fig. 2b.

To solve the whole problem it is convenient to use the Volterra integral equation method (Nerukh 1995; Nerukh et al. 2001, 2013) which takes into account the initial and boundary conditions for the electromagnetic field and is universal with respect to the form of the initial pulse. In the case when the medium refractive index changes abruptly at a zero moment of time inside a region $x > 0$, that is the medium becomes inhomogeneous, the field is described by the equation

$$E(t, x) = E_0(t, x) + \frac{v_1^2 - v^2}{2vv_1^2} \frac{\partial^2}{\partial t^2} \int_0^\infty dt' \int_0^\infty dx' \theta\left(t - t' - \frac{|x - x'|}{v}\right) E(t', x') \tag{3}$$

where $\theta(t)$ is the Heaviside unit function. Inside the non-stationary medium, $x \geq 0$, where the refractive index experiences a temporal jump, the expression (3) is the integral equation for the field inside this part of the medium. The solution to the Eq. (3) when the

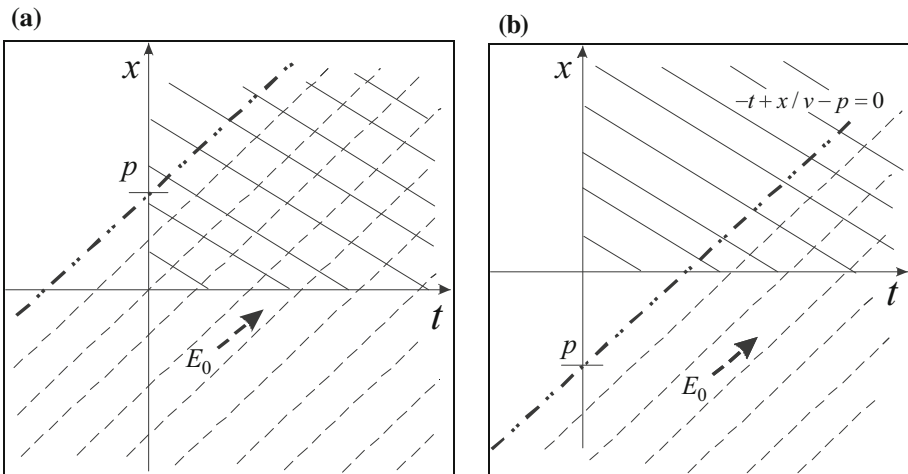


Fig. 2 The initial pulse position with respect to a medium with changing refractive index at the zero moment of time for the start parameter of different signs: **a** $p > 0$, **b** $p < 0$. Hatching by solid lines marks a time-spatial region corresponding to a new state of the medium where the permittivity changes at zero moment of time. Hatching by dash lines marks a time-spatial region occupied by the initial pulse

observation point (t, x) belongs to the non-stationary medium $(t > 0, x > 0)$, gives a transmitted field. If the observation point (t, x) is outside the non-stationary medium, $(t > 0, x < 0)$, then (3) is the formula for calculating the reflected field using the transmitted field found. For $t < 0$ the kernel in (3) is equal to zero and, so, $E(t, x) = E_0(t, x)$.

3 Transformed pulses

To find the transmitted field in the newly created medium we use the resolvent method

$$E(t, x) = E_0(t, x) + \int_0^\infty dt' \int_0^\infty dx' R(t, t', x, x') E_0(t', x') \tag{4}$$

with the resolvent operator kernel (Nerukh 1995)

$$\hat{R} = \frac{v_1^2 - v^2}{2v^2v_1} \theta(x) \frac{\partial^2}{\partial t^2} \left[\theta\left(t - t' - \frac{|x - x'|}{v_1}\right) + \frac{v - v_1}{v + v_1} \theta\left(t - t' - \frac{x + x'}{v_1}\right) \right] \theta(x') \tag{5}$$

Integration of (4) gives the field in the transient medium

$$\int_0^\infty dt' \int_0^\infty dx' \hat{R}(t, t', x, x') E_0(t', x') = -E_0(t, x) + E_T(t, x), \quad t > 0, \quad x > 0 \tag{6}$$

where the first term $-E_0(t, x)$ is a virtual pulse which extinguishes the initial pulse $E_0(t, x)$ in agreement with the Ewald–Oseen extinction theorem (Born and Wolf 1999). The second term is, in fact, the transmitted field which consists of four terms.

The first term

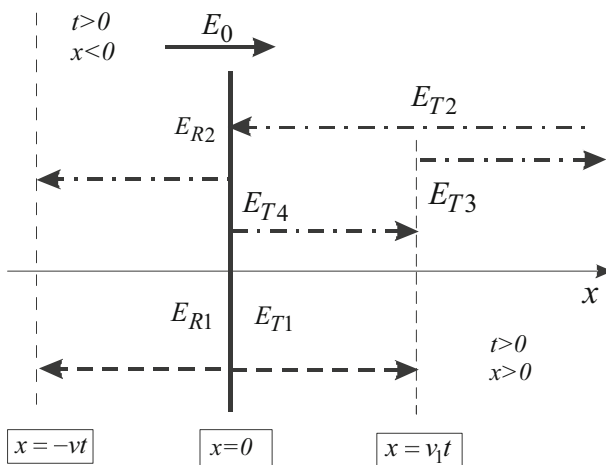


Fig. 3 An arrangement of diffracted pulses. Ordinary transmitted and reflected pulses are marked by dash arrows, pulses caused by a temporal change of a medium are marked by dash-dot arrows

$$E_{T1} = \frac{2v_1}{v_1 + v} \text{Ai} \left(-t/T + \frac{x}{v_1 T} - p \right) \quad (7)$$

represents transmission of the initial pulse through the medium boundary that appears, Fig. 3. It propagates in the same direction as the initial pulse but with a new velocity corresponding to the new value of the refractive index. The amplitude of this wave is equal to the Fresnel wave one.

The terms

$$E_{T2} = \frac{v_1(v_1 - v)}{2v^2} \text{Ai} \left(\frac{v_1}{vT} \left(t + \frac{x}{v_1} \right) - p \right), \quad E_{T3} = \frac{v_1(v_1 + v)}{2v^2} \text{Ai} \left(-\frac{v_1}{vT} \left(t - \frac{x}{v_1} \right) - p \right), \quad (8)$$

are the results of the initial pulse $E_0(t, x)$ splitting into two pulses propagating into opposite directions as a consequence of a refractive index time jump at the zero moment of time (Morgenthaler 1958; Felsen and Whitman 1970; Fante 1971; Borisov 1987). They propagate in opposite directions but the wave E_{T3} exists in the region $x > v_1 t$ only as it has been created in the changed medium. This pulse keeps the same propagation direction as the initial pulse, contrary to the pulse E_{T2} , which has the opposite direction, towards the boundary that has appeared. This pulse reflects from the boundary that appeared ($x = 0$) giving rise to the pulse E_{T4} reflected towards the newly created medium in the region $0 < x < v_1 t$

$$E_{T4} = -\frac{v_1(v - v_1)^2}{2v^2(v + v_1)} \text{Ai} \left(\frac{v_1}{vT} \left(t - \frac{x}{v_1} \right) - p \right) \quad (9)$$

So, the whole transmitted field is represented by the formula

$$E_T = \theta(x) [\theta(t - x/v_1)(E_{T1} + E_{T4}) + E_{T2} + \theta(x/v_1 - t)E_{T3}] \quad (10)$$

Calculation of the integral in (3), by using the formula (10) for the inner field inside the transient half-space, gives the field of reflected pulses as

$$E_R = \theta(t)\theta(-x)\theta(t + x/v)\{E_{R1} + E_{R2}\} \quad (11)$$

Here,

$$E_{R1} = \frac{v_1 - v}{v + v_1} \text{Ai} \left[-\left(t + \frac{x}{v} \right) / T - p \right], \quad E_{R2} = \frac{v_1 v_1 - v}{v + v_1} \text{Ai} \left[\frac{v_1}{v} \left(t + \frac{x}{v} \right) / T - p \right] \quad (12)$$

The first pulse E_{R1} has the ordinary argument $(-t + x/v)/T - p$ and the other pulse E_{R2} has a (new) argument that is changed by the time jump of the refractive index: $v_1(t + x/v)/vT - p$.

The schematic arrangement of all diffracted pulses is shown in Fig. 3. The temporal jump of the refractive index leads to a split of the initial pulse into two new ones E_{T2} and E_{T3} propagating in opposite directions. The pulse E_{T3} , existing in the region $x > v_1 t$, moves away from the boundary. The pulse E_{T2} moving towards the boundary passes partly through this boundary and gives rise to the pulse E_{R2} in the region of the reflected field $x < 0$. The pulse E_{T2} reflects also partly from the boundary inside the non-stationary medium and gives rise to the pulse E_{T4} . This pulse reflects from the medium appearing boundary and exists in the region $0 < x < v_1 t$. The initial pulse E_0 induces the pulse E_{T1} in the region $0 < x < v_1 t$ and the reflected pulse E_{R1} in the region $-vt < x < 0$.

It is easy to make sure from (10) and (11) that the transformed electric field is continuous on the spatial boundary between the two media, $(E_0 + E_R)|_{x=-0} = E_T|_{x=+0}$, as well as at the moment of the temporal jump of the refractive index, $(v_1/v)^2 E|_{t=-0} = E|_{t=+0}$.

4 Pulses in the transitional zone

The character of the transmitted and reflected pulses depends very strongly on the sign of the starting parameter p . This can be seen easily for the reflected pulses existing in the time-spatial zone $-vt < x < 0$ which is provoked by the boundary appearance and shown in Fig. 4. For a positive value of the starting parameter, $p > 0$, both components of the reflected pulse, E_{R1} and E_{R2} , are present, but the reflected pulse with the changed phase $E_{R2} = \frac{v_1 v_1 - v}{v v + v_1} \text{Ai}(\frac{v_1}{vT}(t + \frac{x}{v}) - p)$ occupies only the area restricted by inequalities $x/v + t - pTv/v_1 < 0$ and $x/v + t > 0$ (the double hatching in Fig. 4a). In the case of a negative parameter, $p < 0$, the transitional area is a stripe in the time-spatial coordinates $(x/v + t - pT < 0, x/v + t > 0)$ which is free from the field, Fig. 4b.

The field distribution of all diffracted pulses near the boundary of the transient medium $E = E_T + E_R$ is shown in Fig. 5: (a) for $p = 5$ and (b) for $p = -5$.

The character of the whole field distribution is complex, and very different for two cases, $p > 0$ and $p < 0$. The complicated character of the field distribution is explained by the different arguments in the Airy functions: $\pm (v_1 t \pm x)/vT - p$ and $\pm (t \pm x/v_1)/T - p$ in the transmitted field and $-(t + x/v)/T - p$ and $v_1(t + x/v)/vT - p$ in the reflected field.

The contribution of the pulses determined by the temporally changing medium manifests itself clearly if one omits the pulses with ordinary arguments $-(t + x/v_1)/T - p$ in the transmitted field and $-(t + x/v)/T - p$ in the reflected field and considers only the pulses with the new arguments $\pm (v_1 t \pm x)/vT - p$ and $v_1(t + x/v)/vT - p$. It means

$$E_{Tnew} = \theta(x)[\theta(t - x/v_1)E_{T4}(v_1(t - x/v_1)/vT - p) + E_{T2}(v_1(t + x/v_1)/vT - p) + \theta(x/v_1 - t)E_{T3}(-v_1(t - x/v_1)/vT - p)] \tag{13}$$

for the transmitted field and

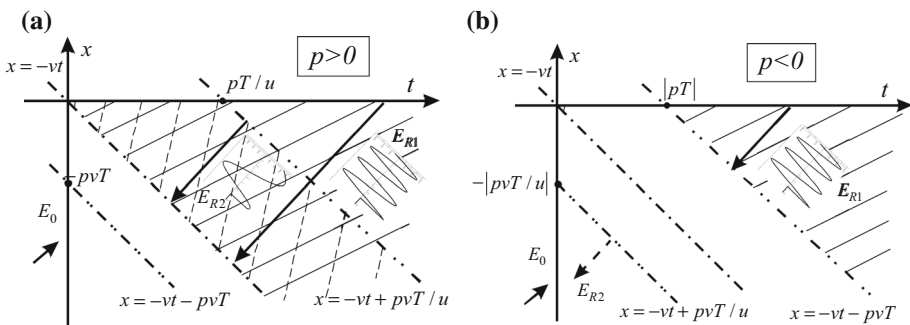


Fig. 4 The time-spatial zones in the reflected field region for the different signs of the start parameter. In the case of the positive start parameter (Fig. 4a), $p > 0$, the double hatching marks the region of two ways existence, E_{R1} and E_{R2} (the dash-dot lines are this region boundary). In the opposite case, $p < 0$, such a zone is free from the field. In both cases the parameter $u = n/n_1$ is equal to 0.8

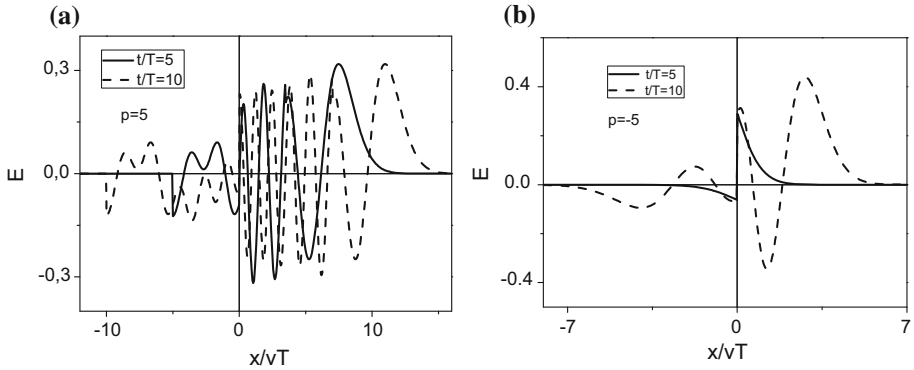


Fig. 5 The transmitted and reflected pulses in the transitional zone near the boundary at two moments, $t/T = 5$ (solid) and $t/T = 10$ (dash); **a** for $p = 5$, **b** for $p = -5$. The parameter $u = n/n_1$ is equal to 0.8

$$E_{Rnew} = \theta(t)\theta(-x)\theta(t + x/v)E_{R2}(v_1(t + x/v)/vT - p) \tag{14}$$

for the reflected field. The field spatial distribution at the moments $t/T = 5$ and $t/T = 10$ is shown in Fig. 6: (a) for start parameters $p = 5$ and (b) for start parameter $p = -5$. It is seen that in the stripe ($x/v + t - pT < 0, x/v + t > 0$), the reflected field is almost zeroth, Fig. 6b.

Figure 7 shows that the complicated field character, seen in the reflected and transmitted pulses in Fig. 5, is explained by the addition of the pulses with ordinary arguments,

$$E_{ord} = \theta(x)\theta\left(t - \frac{x}{v_1}\right)\frac{2v_1}{v_1 + v}\text{Ai}\left[-\left(t - \frac{x}{v_1}\right)/T + p\right] + \theta(-x)\theta\left(t + \frac{x}{v}\right)\frac{v_1 - v}{v + v_1}\text{Ai}\left[-\left(t - \frac{x}{v}\right)/T + p\right] \tag{15}$$

to the pulses with new arguments (13) and (14).

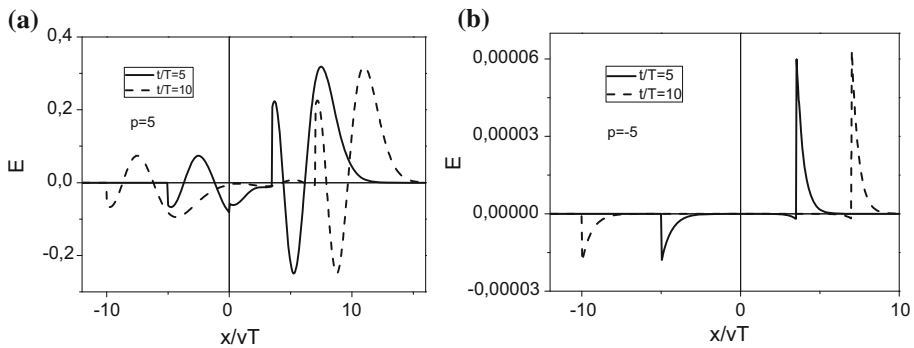


Fig. 6 Transmitted and reflected pulses with the new arguments in the transitional zone at two moments, $t/T = 5$ (solid) and $t/T = 10$ (dash). The start parameter equals to $p = 5$ (a) and $p = -5$ (b). The parameter $u = n/n_1$ is equal to 0.8

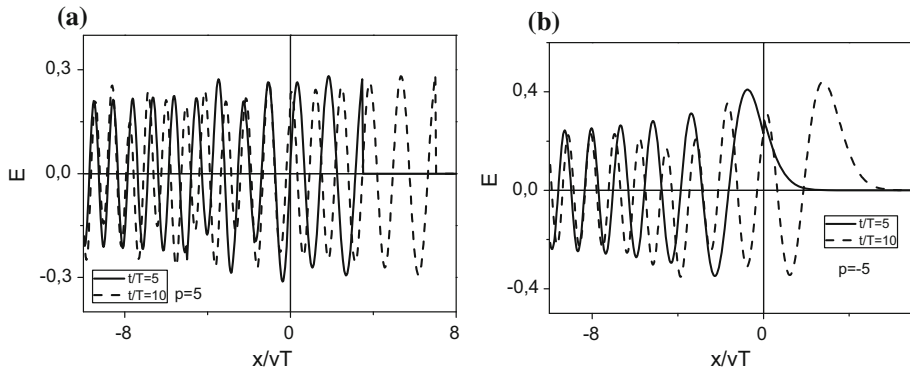


Fig. 7 Transmitted and reflected pulses in the transitional zone with ordinary arguments at two moments, $t/T = 5$ (solid) and $t/T = 10$ (dash) for the start parameter: $p = 5$ (a) and $p = -5$ (b). The parameter $u = n/n_1$ equals to 0.8

5 Conclusion

The electrodynamic problem with three types of asymmetry is considered. One type is determined by a form of an initial signal which behaviour to the past and to the future is qualitatively different. The second and third types of asymmetry is dictated by a state of a medium which turns out from a homogeneous medium into an inhomogeneous one at the zero moment of time. The problem of the electromagnetic field transformation is solved by the Volterra integral equation method which takes into account the initial and boundary conditions for the electromagnetic field and is universal with respect to the form of the initial pulse. Explicit expressions for the transmitted and reflected pulses are obtained. It is shown that the whole diffraction processes is very strongly controlled by the start parameter introduced. The peculiarities of this start parameter influence on the diffraction process are analysed. It is shown that all diffracted pulses consist of two kinds of pulses: pulses conditioned by the medium inhomogeneity and pulses conditioned by the temporally changing features in the medium.

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