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Pulse reflection from a weakly absorbing and dispersing dielectric slab

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ABSTRACT

Group delay for a reflected and a transmitted pulse from a weakly absorbing and dispersing dielectric slab was theoretically investigated, and it was shown that the effects of absorption and dispersion are different in resonant and off resonant slabs. Also we obtained the condition in which superluminal and subluminal pulses are propagated through resonant dielectric slab, simultaneously.

1. Introduction

The control of pulse propagation in different kinds of media has received extensively attentions for several decades [1,2]. It is now well established that the group delay of the reflected and transmitted pulses can be manipulated from subluminal to superluminal propagation by controlling the dispersive properties of a medium. Most literatures have been focused on the transmitted pulse from a medium. Recently, superluminal reflected pulses were also theoretically studied in different circumstances: such as the unstable regime of optical phase-conjugating mirror [3], low-finesse Fabry Perot cavities containing absorbing atoms [4], a dielectric slab system doped with absorptive two-level or three-level atoms [5], asymmetric photonic band gaps [6], and asymmetric single quantum barriers [7].

In experiments, Vetter et al. [8] verified the existence of the negative phase time for scattering at quantum wells from a microwave analogy experiment. Longhi et al. [9] have also observed superluminal reflected pulse from a double-Lorentzian fibre Bragg grating. Recently, Gevorgyan found the anomalies of radiation absorption and superluminal propagation of light in an isotropic layer. Li [10] noticed that the reflected wave from a lossless dielectric slab undergoes a phase discontinuity (a sudden phase change of π) at resonant transmission, and he pointed out that the discontinuity of the reflected phase with null reflection has no practical meaning. In the view of continuity, there is a large finite slope of the change of phase with a nonzero, albeit small, reflection if the dielectric slab is weakly absorbing.

Li-Gang Wang et al. [11] reported that the negative group delay, which can be large, for the reflected pulse near resonances from the weakly absorbing dielectric slab. The negative group delay indicates that the superluminal pulse reflection can be observed when a light pulse is reflected from the weakly absorbing dielectric slab. Also they were theoretically investigated the saturation absorption effect on group delay time for both the reflected and transmitted pulses.

The propagation of an electromagnetic pulse through a dielectric slab doped with three-level ladder-type atomic systems was investigated. It is shown that the group velocity of the reflected and transmitted pulses can be switched from subluminal to superluminal light propagation by the thickness of the slab or the intensity of the coupling field. Furthermore, it is found that, in the presence of quantum interference, the reflected and transmitted pulses are completely phase dependent. So, the group velocity of the reflected and transmitted pulses can only be switched from subluminal to superluminal by adjusting the relative phase of the applied fields [12].

The effect of absorption and gain in pulse propagation through dielectric slab were studied. Then the effect of dispersion in light propagation through resonant and off resonant slab were investigated. The way of manipulation of light propagation through dielectric slab was given.

2. Model and result

Consider a light pulse normally incidents on the weakly absorbing and non-magnetic slab (extended from $z=0$ to $z=d$ in z direction) with the complex relative permittivity, $\epsilon=\epsilon_r+i\epsilon_i$, where ϵ_r and ϵ_i represent the dispersion and absorption parts, respectively. Both sides of the slab are vacuum. We assume that, the incident pulse is an analytical pulse, and its spectrum is sufficiently

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narrow so that the pulse distortion is very small and negligible. The transfer matrix for the electric and magnetic components of a monochromatic wave of frequency ω through the slab is given by [11–13]:

$$\begin{pmatrix} \cos[kd] & i\frac{1}{q}\sin[kd] \\ \mathrm{iq}\sin[kd] & \cos[kd] \end{pmatrix} \quad (1)$$

where k is the complex wave number in slab, $q=\sqrt{\varepsilon}$ for *TE* polarization, and $q=1/\sqrt{\varepsilon}$ for *TM* polarization. The reflection and transmission coefficients for the *TE* wave can be evaluated with the help of the transfer matrix method [11–13]:

$$r(\omega)=-\frac{\left(\frac{i}{2}\right)\left(\frac{1}{\sqrt{\varepsilon}}-\sqrt{\varepsilon}\right)\sin(kd)}{\cos(kd)-\left(\frac{i}{2}\right)\left(\frac{1}{\sqrt{\varepsilon}}+\sqrt{\varepsilon}\right)\sin(kd)}, \quad (2)$$

$$t(\omega)=\frac{1}{\cos(kd)-\left(\frac{i}{2}\right)\left(\frac{1}{\sqrt{\varepsilon}}+\sqrt{\varepsilon}\right)\sin(kd)}, \quad (3)$$

We assume that the incident pulse is a Gaussian pulse. In a very narrow spectrum, the group delays for the reflected and transmitted pulses are defined by [4,14–17]:

$$\tau_{r,t}=\left[\frac{\partial\phi_{r,t}}{\partial\omega}\right]_{\omega=\omega_c} \quad (4)$$

where ω_c is the carrier frequency of the incident pulse. Also ϕ_t and ϕ_r are the phases of the transmission and reflection coefficients, respectively. By define

$$g_1\equiv|g_1|e^{i\phi_1}=\cos(kd)-\frac{i}{2}\left[1/\sqrt{\varepsilon}+\sqrt{\varepsilon}\right]\sin(kd)=x+iy \quad (5)$$

where

$$x=\cos\left(\frac{\omega}{c}n_rd\right)\cosh\left(\frac{\omega}{c}n_id\right)+\frac{1}{2}\left(\frac{-n_i}{|n|^2}+n_i\right)\sin\left(\frac{\omega}{c}n_rd\right)\times\cosh\left(\frac{\omega}{c}n_id\right)+\frac{1}{2}\left(\frac{n_r}{|n|^2}+n_r\right)\sinh\left(\frac{\omega}{c}n_id\right)\cos\left(\frac{\omega}{c}n_rd\right), \quad (6)$$

and

$$y=-\sinh\left(\frac{\omega}{c}n_id\right)\sin\left(\frac{\omega}{c}n_rd\right)-\frac{1}{2}\left(\frac{n_r}{|n|^2}+n_r\right)\sin\left(\frac{\omega}{c}n_rd\right)\times\cosh\left(\frac{\omega}{c}n_id\right)-\frac{1}{2}\left(\frac{n_i}{|n|^2}-n_i\right)\sinh\left(\frac{\omega}{c}n_id\right)\cos\left(\frac{\omega}{c}n_rd\right), \quad (7)$$

here $n_r\equiv Re\left(\sqrt{\varepsilon}\right)$ and $n_i\equiv Im\left(\sqrt{\varepsilon}\right)$ are the real and imaginary parts of the complex refractive index of the slab, respectively. We have $\tau_t=\frac{\partial\phi_t}{\partial\omega}=-\frac{\partial\phi_1}{\partial\omega}$. It is defined

$$g_2\equiv|g_2|e^{i\phi_2}=-\frac{i}{2}[1/\sqrt{\varepsilon}-\sqrt{\varepsilon}]\sin(kd)=x_r+iy_r \quad (8)$$

where

$$x_r=-\frac{1}{2}\left(\frac{n_i}{|n|^2}+n_i\right)\sin\left(\frac{\omega}{c}n_rd\right)\cosh\left(\frac{\omega}{c}n_id\right)+\frac{1}{2}\left(\frac{n_r}{|n|^2}-n_r\right)\times\cos\left(\frac{\omega}{c}n_rd\right)\sinh\left(\frac{\omega}{c}n_id\right), \quad (9)$$

and

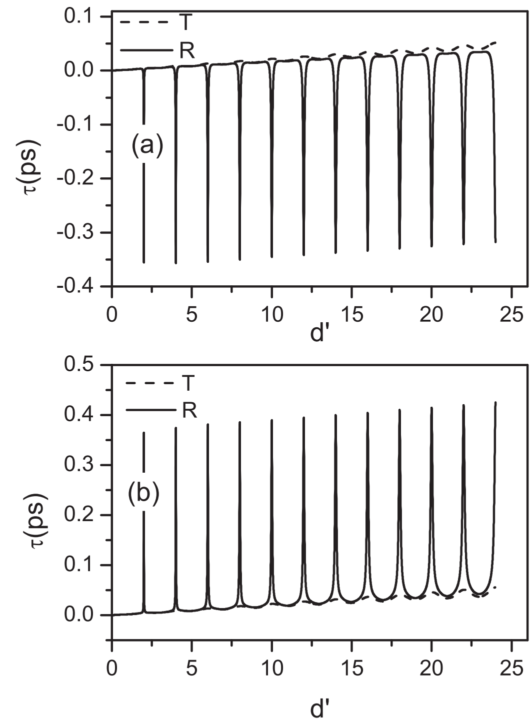

Fig. 1. Dependence of the reflected (solid line) and the transmitted (dashed line) group delay on the slab thickness d with $\varepsilon=3.0+0.02i$ (a), $\varepsilon=3.0-0.02i$ (b) and $\omega=2\pi*129.9$ THz.

$$y_r=-\frac{1}{2}\left(\frac{n_r}{|n|^2}-n_r\right)\sin\left(\frac{n_r\omega}{c}d\right)\cosh\left(\frac{n_i\omega}{c}d\right)-\frac{1}{2}\left(\frac{n_i}{|n|^2}+n_i\right)\times\cos\left(\frac{n_r\omega}{c}d\right)\sinh\left(\frac{n_i\omega}{c}d\right), \quad (10)$$

from Eq. (1), we obtain

$$\tau_r=\tau_t+\tau_1, \quad (11)$$

where τ_1 is given by

$$\tau_1=\frac{\partial\phi_2}{\partial\omega}. \quad (12)$$

τ_t and τ_r can be calculated simply.

Fig. 1 shows the group delays of the reflected and transmitted pulses in term of the generalized slab thickness, $d\prime=d/(\lambda/4\sqrt{\varepsilon_b})$. Owing to the absorption of the medium, the group delay of the reflected pulse is not equal to the transmitted pulse. When the slab thickness, d, approaches the resonance condition, in absorptive slab ($\varepsilon_i=0.02$), the group delay of the reflected pulse becomes large negative while the group delay of the transmitted pulse is still positive. In gain slab ($\varepsilon_i=-0.02$), the group delay of the reflected pulse becomes large positive, while the group delay of the transmitted pulse is similar to absorptive slab. So that, light propagation through the gain slab and absorptive slab are subluminal and superluminal or subluminal.

Fig. 1 shows that the delay time depends on thickness of the slab. So that, we choose two important thickness (i) $d=2m\frac{\lambda}{4\sqrt{\varepsilon}}$, resonant thickness and (ii) $d=(2m+1)\frac{\lambda}{4\sqrt{\varepsilon}}$, off resonant thickness. Here m is a integer number. The delay time of resonant and off resonant slabs were plotted in term of ε_i in Fig. 2. For the weakly absorptive slab with resonant thickness, the delay time of reflected pulse is very larger than transmitted pulse. However, in strong absorption, the delay time of them are similar. Also, reflected pulse in