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Phase dependent coherent control of group delay in a doped metamaterial slab

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ABSTRACT

A scheme is proposed for the coherent control of the group delay for a light beam traveling through a double-negative metamaterial (DNM) slab. By doping three-level atoms into the DNM slab, phase control over the transmission and reflection behaviors of the active layer is achieved. This way, tunable and simultaneous subluminal and superluminal transmission and reflection are achievable. We discuss the effect of the relative phase of the applied fields and the rate of incoherent pumping on the group delay of a probe pulse propagating through the DNM slab. It is shown that group delays of the transmitted and reflected beams are completely phase dependent. We also find that transmission of a probe field propagating through the DNM slab is actively controllable in a wide range by controlling the relative phase of the incident fields with no need to alter physical parameters of the metamaterial.

1. Introduction

Light propagation through a dispersive medium can be subluminal (group velocity is smaller than c) or superluminal (the group velocity is larger than c or even becomes negative), where c is the free-space light velocity [1]. Superluminal phenomenon has been experimentally observed in absorptive media [2], and pulse tunneling through one-dimensional photonic band gaps (1D PBGs) [3, 4]. Longhi et al. [5] observed superluminal reflection of an optical pulse by using a double-Lorentzian fiber Bragg grating. Some literatures have paid attention to the slab systems [6–9]. Wang et al. [10] considered a pulse incident on a slab system doped with two-level or three-level atoms. They found that the reflected pulse can be tuned from subluminal to superluminal by controlling the thickness of the slab (or the background dielectric constant of the slab). Jafari et al. [9] proposed a scheme for controlling the group velocity of a weak probe beam traveling through a doped conventional slab. They took benefit of the three-level ladder-type dopant atoms and quantum interference for switching the group velocity by the relative phase of the applied fields.

Coherent control of light propagation in usual right-handed systems such as slab systems and photonic crystals promises a route for controlling the absorption and dispersion of metamaterials.

A medium in which both the permittivity ε and the permeability μ are simultaneously negative in a frequency band is called the double-negative medium (DNM). The electromagnetic features of such a material are not found in the nature and are only artificially constructed. There are several terminologies used in the literature referring to the double-negative medium such as metamaterial, left-handed medium (LHM), backward wave medium, negative refractive index material (NIM), etc. These kinds of materials were first predicted theoretically by Veselago [11] in 1968, and after three decades designed by Pendry [12]. In the past few years, metamaterials have been demonstrated across the electromagnetic spectrum, from zero frequency to optical frequencies [13–15]. One of the important challenges has been to make the metamaterials less absorptive which is crucial to most applications. Several literatures have paid attention to compensating of loss in metamaterials by including a gain medium [16–19]. The possibility of compensating the absorption in negative-index metamaterials (NIMs) doped by the resonant nonlinear-optical centers is shown by Popov et al. [16]. The role of quantum interference and the extraordinary properties of four-wave parametric amplification of counter-propagating electromagnetic waves in NIMs have been discussed. Fang et al. [17] numerically showed the possibility of loss compensation by incorporating a gain material inside the fishnet structure. They exploited a pumping field for loss compensation. Wuestner et al. [18] introduced a frequency band where the nonbianisotropic metamaterial becomes amplifying by appropriate placing of optically pumped laser dyes into the metamaterial structure. Haung et.al. [19]

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proposed a new approach for pump-probe simulations of metallic metamaterials coupled to the gain materials. Using a four-level gain system, they have studied the light amplification of arrays of metallic split-ring resonators (SRRs) with a gain layer underneath.

Realization of the superluminal and also the subluminal propagation in metamaterials have been proven [20–22]. Woodely and Mojahedi [20] designed two DNM slab samples operating in the K-band ($18-26$ GHz). They showed that in the negative index of refraction region these media can support positive or negative group velocities and group delays. Dolling et al. [21] investigated the propagation of femtosecond laser pulses through a metamaterial that has a negative index of refraction for wavelengths around 1.5 μm. They proved that in a spectral region, phase and group velocities are negative simultaneously. This means that both the carrier wave and the pulse envelope peak of the output pulse appear at the rear side of the sample before their input pulse counterparts have entered the front side of the sample. Gennaro et al. [22] showed remarkably slow propagation of microwaves in two different classes of left-handed materials that was reported from microwave-pulse and continuous-wave transmission measurements. Microwave dispersion in a composite LHM made of split-ring resonators and wire strips revealed the group velocity $v_g = c/50$.

Here, we propose a scheme for the coherently active control of the group delays of the transmitted and reflected pulses from a DNM slab. In this paper, we show that the absorptive and dispersive properties of a DNM slab can be controlled by an embedding three-level Λ-type atomic system through the slab. We find that the transmission profile, and also the transmission and reflection group delays of the probe pulse at resonance frequency are strongly sensitive to the relative phase of the applied fields. So, the group velocity of the propagating probe pulse can be switched from positive to negative just by the relative phase of the applied fields. We also show that for a probe pulse traveling through an active slab the switching from almost complete transmission to almost zero transmission is accessible from the phase control of the doped atomic systems to the left-handed slab. Our proposed system prepares a convenient approach for controlling the simultaneity of sub/superluminal propagation of the transmitted and reflected pulses. Coherent control over the light propagation inside the metamaterials and also the loss control in this novel class of materials has potential applications in all-optical storage, all-optical switching and control of dispersive effects in telecommunication systems.

2. Method

In this section, we introduce the proposed DNM slab, and the doped atomic system through the left-handed slab.

2.1. DNM slab

Consider a DNM slab with boundaries, $z=0$ and $z=d$ that its left and right semi-infinite dielectrics are vacuum. Interfaces are in the $x-y$ plane, and the origin of the z coordinate is taken at the left interface of DNM slab. Note that DNMs physically are dispersive; also there are firm conditions for them to be double negative in a specific frequency. We define the slab's permittivity (ε), permeability (μ) and refractive index (n) as $\varepsilon = \varepsilon' + i\varepsilon''$, $\mu = \mu' + i\mu''$, and $n = n' + in''$, respectively. Using the relation $n = \sqrt{\varepsilon}\sqrt{\mu}$, the real and imaginary parts of ε, μ, and n should meet the conditions given below to result in a negative refractive index for the slab:

$$n'^2 - n''^2 = \varepsilon'\mu' - \varepsilon''\mu'' \tag{1}$$

and

$$n'n'' = \frac{\varepsilon'\mu'' + \varepsilon''\mu'}{2}. \tag{2}$$

Eqs. (1) and (2) imply that the real and imaginary parts of the refractive index of DNM slab depend on the real and imaginary parts of its permittivity and permeability. Solving Eqs. (1) and (2) with respect to the real and the imaginary parts of the refractive index leads to

$$n' = \pm \left\{ \frac{(\varepsilon'\mu' - \varepsilon''\mu'') + \sqrt{(\varepsilon'\mu' - \varepsilon''\mu'')^2 + (\varepsilon'\mu'' + \varepsilon''\mu')^2}}{2} \right\}^{1/2} \tag{3}$$

and

$$n'' = \pm \frac{1}{2}(\varepsilon'\mu'' + \varepsilon''\mu') \left\{ \frac{(\varepsilon'\mu' - \varepsilon''\mu'') + \sqrt{(\varepsilon'\mu' - \varepsilon''\mu'')^2 + (\varepsilon'\mu'' + \varepsilon''\mu')^2}}{2} \right\}^{-1/2}. \tag{4}$$

In the limit of $\varepsilon'' \to 0$ we have

$$n' = \pm \sqrt{\varepsilon'} \left\{ \frac{\mu' + \sqrt{\mu'^2 + \mu''^2}}{2} \right\}^{1/2} \tag{5}$$

and in the limit of $\mu'' \to 0$ we reach to

$$n' = \pm \sqrt{\mu'} \left\{ \frac{\varepsilon' + \sqrt{\varepsilon'^2 + \varepsilon''^2}}{2} \right\}^{1/2}. \tag{6}$$

According to Eqs. (5) and (6) for a double negative metamaterial slab ($\varepsilon', \mu' < 0$) setting ε'' or μ''exactly equal to zero leads to a mathematical contradiction (left sides of Eqs. (5) and (6) are real amounts while the right sides of them take imaginary values). This contradiction implies that one should care when dealing with the frequencies near to the singularities of the refractive index of a metamaterial [23]. However, one can manipulate the permittivity and permeability for decreasing the losses in the DNMs. Dispersion and absorption behaviors of a traveling wave through any material strictly depend on the real and the imaginary parts of its refractive index. So, optical manipulation of the real and imaginary parts of the permittivity of the DNM slab introduces a new scheme for controlling the group velocity and the transmission of a laser pulse propagating through the slab. This aim can be achieved by doping the DNM slab by the dispersive centers. According to the required application and the issues of fabrication, several dispersive centers including quantum wells, quantum dots, liquid crystals and resonant atomic systems can be used for optical control of the group delay and the transmission behavior of the DNM slab. In our proposal, the group delay of a laser pulse through the slab is controlled by the optical control of the susceptibility of the doped three-level atoms to the DNM layer. Schematic of the DNM slab and the energy diagram of doped atoms to the slab are shown in Fig. 1.

Now we discuss the transmission and reflection of the probe pulse through the DNM slab. We consider that the incident light is normal to the surface of the slab; so the final relations for the transmission and reflection coefficients will be the same for both the TE and TM polarizations. Transmission and reflection coefficients at the interface between an ordinary medium and a left-handed medium can be found using standard electromagnetic techniques. Here we will follow the transverse transmission matrix method. Consider normal incidence of a probe field to left-handed slab and the z-axis to be the propagation direction. For a given z, the complete transfer matrix T for wave propagation relates the complex amplitudes of fields just before the left side