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Permanent storage of light in a double-slab structure

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ABSTRACT

In this paper, we shall demonstrate firstly that a normal incidence can be totally reflected from a slab made of active metamaterial with purely-imaginary-impedance. Then we shall predict that a localized steady state of electromagnetic wave dependent on initial input can exist in a double-slab structure, which relates to the non null solution of equations formed by electromagnetic field boundary conditions. These results may provide a feasible way to effectively treat loss and/or gain problems and thus store electromagnetic wave (light) permanently at room temperature. In addition, our work indicates that metamaterials with purely-imaginary-impedance may enable remarkable electromagnetic phenomena and merit further study.

1. Introduction

Stopping and storing light is one of the most interesting issues to the modern physical sciences and correlated technologies [1–9]. The maximal storage time is an important benchmark for optical (quantum) information processing, e.g., in deterministic single photon sources, quantum networks, or quantum repeaters [1]. Many efforts have focused on the challenging demands with regard to the storage duration [2–6]. However, so far most of the usual methods bear inherent upper limitation of possible storage times that may hinder their practical deployment [4,6].

Recently, the approaches of trapping light at room-temperature by applying metamaterials have attracted more and more attentions [7–9]. The passive metamaterials are usually lossy, the trapped light will decay exponentially. Active (inverted or gain) metamaterials have been suggested to overcome the loss problems [10,11]. However, it is still necessary to develop the feasible way to effectively treat the loss and/or gain problems and thus achieve large storage times.

Reflection of light from an active medium has been studied early [12,13]. It is demonstrated experimentally [12] and theoretically [13–17] that light can be totally reflected from an active medium. On the other hand, advent of metamaterials enable researchers to realize the materials with unconventional values of electromagnetic parameters and discover novel electromagnetic phenomena [18–22]. These studies offer the opportunity to develop new scheme to effectively treat the loss and/or gain problems and thus extend storage times by adopting or designing appropriate active metamaterials.

In this work, we shall demonstrate firstly that a normal incidence can be totally reflected from a slab made of active metamaterial with purely-imaginary-impedance. Then we shall predict that a localized steady state of electromagnetic wave dependent on initial input can exist in a double-slab structure. In principle, this double-slab structure can be used to store electromagnetic wave (light) permanently at room-temperature. The remainder of the paper is organized as follows: In Section 2, theoretical analyses of existence of a localized steady state of electromagnetic wave in a double-slab structure are presented. In Section 3, numerical simulations and discussions are performed. In Section 4, the realizable experiments are suggested to test the theories. Finally, some conclusions are drawn in Section 5.

2. Theoretical analyses

Let us begin by considering the case of a plane wave in vacuum, normally incident to a slab, see Fig. 1. The slab is assumed to be made of linear, isotropic and homogeneous material, the electric and magnetic response properties are described by parameters of $\widetilde{\varepsilon} = |\widetilde{\varepsilon}_r|\varepsilon_0 \exp\left(-j\alpha_\varepsilon\right)$ and $\widetilde{\mu} = |\widetilde{\mu}_r|\mu_0 \exp\left(-j\alpha_\mu\right)$, respectively. Here, the complex valued parameters are marked with superscript "∼", $\alpha_{\varepsilon(\mu)}$ is electric (magnetic) damping angle. For passive media, both α_ε and α_μ are constrained within the range of $[0, \pi]$. Correspondingly, both electric lossy energy density ($\propto \sin\alpha_\varepsilon$) and magnetic lossy energy density ($\propto \sin\alpha_\mu$) are greater than zero [11]. Whereas, for active media, at least one of the two damping

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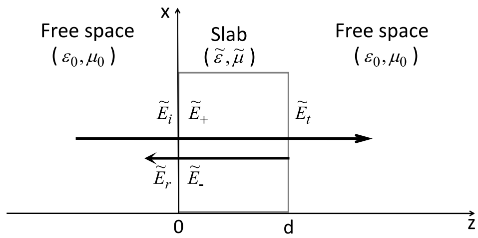

Fig. 1. Sketch of a plane wave normally traveling through a slab of thickness d.

angles of α_ε and α_μ may fall in the range of $(\pi, 2\pi)$ [10,11,16,17,22]. Thus electric (if $\alpha_\varepsilon \in (\pi, 2\pi)$, thus $\sin \alpha_\varepsilon < 0$) and/or magnetic (if $\alpha_\mu \in (\pi, 2\pi)$, thus $\sin \alpha_\mu < 0$) lossy energy densities/density become(s) to be negative, which refers to the gain of electric (if $\alpha_\varepsilon \in (\pi, 2\pi)$) and/or magnetic (if $\alpha_\mu \in (\pi, 2\pi)$) energies [11] and provides the possibility to overcome the loss problems. Adopting the coordinate system given in Fig. 1, distribution of electric field intensities of the plane wave traveling through the slab can be written as [16]

$$\tilde{E}_x(z,t)/E_{i0} = \begin{cases} \exp\left(j\omega t - jk_0 z\right) + \tilde{R}\exp\left(j\omega t + jk_0 z\right) & (z<0) \\ \tilde{F}_+ \exp\left(j\omega t - j\tilde{k}z\right) & \\ \quad + \tilde{F}_- \exp\left(j\omega t + j\tilde{k}z\right) & (0 \le z \le d) \\ \tilde{T}\exp\left[j\omega t - jk_0(z-d)\right] & (z>d) \end{cases} \tag{1}$$

where, E_{i0} is amplitude of the incidence, ω is angular frequency, $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$ is wave vector of electromagnetic wave in free space, $\tilde{k} = \omega\sqrt{|\tilde{\mu}\tilde{\varepsilon}|\exp\left(-j\alpha_k\right)} = k' - jk''$ $(\alpha_k = (\alpha_\mu + \alpha_\varepsilon)/2)$ is wave vector of electromagnetic wave in the slab, and d is thickness of the slab. According to electromagnetic field boundary conditions, the reflection coefficient $\tilde{R}$, parameters of $\tilde{F}_+ \equiv \tilde{E}_+(z=0^+, t=0)/E_{i0}$ for forward wave and $\tilde{F}_- \equiv \tilde{E}_-(z=0^+, t=0)/E_{i0}$ for backward waves in the slab, and transmission coefficient $\tilde{T}$ presented in Eq. (1) are, respectively, derived as [16]

$$\tilde{R} = \frac{\left(\tilde{\eta}^2 - \eta_0^2\right)\exp\left(j\tilde{k}d\right) - \left(\tilde{\eta}^2 - \eta_0^2\right)\exp\left(-j\tilde{k}d\right)}{\left(\tilde{\eta} + \eta_0\right)^2\exp\left(j\tilde{k}d\right) - \left(\tilde{\eta} - \eta_0\right)^2\exp\left(-j\tilde{k}d\right)}, \tag{2a}$$

$$\tilde{F}_+ = \frac{2\tilde{\eta}\left(\tilde{\eta} + \eta_0\right)}{\left(\tilde{\eta} + \eta_0\right)^2 - \left(\tilde{\eta} - \eta_0\right)^2\exp\left(-2j\tilde{k}d\right)}, \tag{2b}$$

$$\tilde{F}_- = \frac{2\tilde{\eta}\left(\tilde{\eta} - \eta_0\right)}{\left(\tilde{\eta} - \eta_0\right)^2 - \left(\tilde{\eta} + \eta_0\right)^2\exp\left(2j\tilde{k}d\right)}, \tag{2c}$$

$$\tilde{T} = \frac{4\tilde{\eta}\eta_0}{\left(\tilde{\eta} + \eta_0\right)^2\exp\left(j\tilde{k}d\right) - \left(\tilde{\eta} - \eta_0\right)^2\exp\left(-j\tilde{k}d\right)} \tag{2d}$$

where, $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is impedance of free space, and $\tilde{\eta} = \sqrt{|\tilde{\mu}|/|\tilde{\varepsilon}|\exp\left(-j\alpha_\eta\right)} = \eta' - j\eta''(\alpha_\eta = (\alpha_\mu - \alpha_\varepsilon)/2)$ is impedance of the slab.

It is noted from Eq. (2) that, whatever $k'' > 0$ or $k'' < 0$, increasing slab thickness d, $\tilde{R}$ approaches a constant of either $\frac{\tilde{\eta}-\eta_0}{\tilde{\eta}+\eta_0}$ (for $k'' > 0$) or $\frac{\tilde{\eta}+\eta_0}{\tilde{\eta}-\eta_0}$(for $k'' < 0$), $\tilde{T}$ becomes negligible, one of parameters of $\tilde{F}_+$ and $\tilde{F}_-$ becomes negligible too, and the other approaches a nonzero constant [16,17]. Apparently, if impedance of the slab is chosen as $\tilde{\eta} = \mp j\eta''$ and thickness d is large sufficiently, $|\tilde{R}| = 1$ and $|\tilde{T}| = 0$ may be achieved, i.e., a normal incidence is totally reflected from a slab with purely-imaginary-impedance and sufficient thickness. The impedance value of $\tilde{\eta} = \mp j\eta''$ means that $\alpha_\eta = (\alpha_\mu - \alpha_\varepsilon)/2 = \pm\pi/2$. Thus, usually, one of damping angles of α_ε and α_μ may be in the range of $(\pi, 2\pi)$, i.e., the slab is made of active material [10]. Apparently, here, conditions of total reflection are significantly different from that of the usual total internal reflection [13–15,23], which offers additional degrees of freedom of designing electromagnetic devices, e.g., to archive total reflection, the incident angle no longer needs to be larger than the critical angle, thereby allowing unprecedented control over the flow of electromagnetic waves.

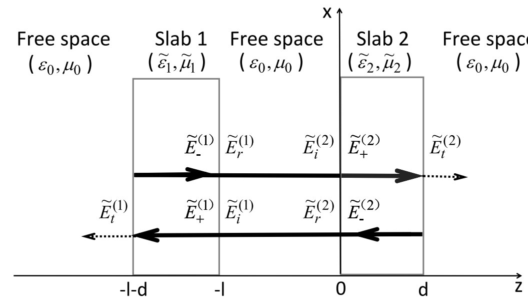

Fig. 2. Sketch of a localized steady state of electromagnetic wave existed in a double-slab structure.

Then we investigate the possibility to form a localized steady state of electromagnetic wave in a double-slab structure as shown in Fig. 2. To gain an insight into the physics of the problem at hand, we shall seek a special and concise solution, in which the electromagnetic waves existed in the left side of the double-slab structure can be simply taken as a result induced by a left-going progressive plane wave with electric field of $\tilde{E}_i^{(1)}$ normally incident to the slab 1, analogously, the electromagnetic waves existed in the right side of the structure can be taken as a result induced by a right-going progressive plane wave with electric field of $\tilde{E}_i^{(2)}$ normally incident to the slab 2. Therefore, according to Fig. 1, Fig. 2 and Eqs. (1)–(2), we have

$$\tilde{E}_r^{(1)} = \tilde{R}^{(1)}\tilde{E}_i^{(1)}, \tag{3}$$

$$\tilde{E}_r^{(2)} = \tilde{R}^{(2)}\tilde{E}_i^{(2)} \tag{4}$$

where, $\tilde{R}^{(1(2))}$ is reflection coefficient of electromagnetic wave reflected from slab 1 (2). In addition, adopting the coordinate system given in Fig. 2, there are

$$\tilde{E}_i^{(1)} = \exp\left(jk_0 l\right)\tilde{E}_r^{(2)}, \tag{5}$$

$$\tilde{E}_i^{(2)} = \exp\left(jk_0 l\right)\tilde{E}_r^{(1)} \tag{6}$$

where l is distance between the two slabs. Coexistence of Eqs. (3)–(6) requires that

$$\tilde{R}^{(1)}\tilde{R}^{(2)}\exp\left(j2k_0 l\right) = 1. \tag{7}$$

It has been demonstrated above that a normal incidence can be totally reflected from a slab with purely-imaginary-impedance and sufficient thickness, i.e., $|\tilde{R}^{(1)}| = |\tilde{R}^{(2)}| = 1$ is achieved. Thus Eq. (7) can be fulfilled by choosing appropriate distance l between the two slabs. Subsequently, setting a nonzero value of $\tilde{E}_i^{(1)}$, adopting the coordinate system given in Fig. 2, distribution of electric field intensities of the electromagnetic waves existed in the double-slab structure can be obtained as

$$\tilde{E}_x(z,t)/\tilde{E}_i^{(1)} = \begin{cases} \tilde{T}^{(1)}\exp\left[j\omega t + jk_0(z+l+d)\right] & (z<-l-d) \\ \tilde{F}_-^{(1)}\exp\left[j\omega t - j\tilde{k}(z+l)\right] & \\ \quad + \tilde{F}_+^{(1)}\exp\left[j\omega t + j\tilde{k}(z+l)\right] & (-l-d<z<-l) \\ \tilde{R}^{(1)}\exp\left[j\omega t - jk_0(z+l)\right] & \\ \quad + \exp\left[j\omega t + jk_0(z+l)\right] & (-l<z<0) \\ \tilde{R}^{(1)}\exp\left(-jk_0 l\right) & \\ \quad \times\left[\tilde{F}_+^{(2)}\exp\left(j\omega t - j\tilde{k}z\right)\right. & \\ \quad \left. + \tilde{F}_-^{(2)}\exp\left(j\omega t + j\tilde{k}z\right)\right] & (0<z<d) \\ \tilde{R}^{(1)}\exp\left(-jk_0 l\right)\tilde{T}^{(2)} & \\ \quad \times\exp\left[j\omega t - jk_0(z-d)\right] & (d<z). \end{cases} \tag{8}$$