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Arbitrarily thin metamaterial structure for perfect absorption and giant magnification

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Abstract: In our common understanding, for strong absorption or amplification in a slab structure, the desire of reducing the slab thickness seems contradictory to the condition of small loss or gain. In this paper, this common understanding is challenged. It is shown that an arbitrarily thin metamaterial layer can perfectly absorb or giantly amplify an incident plane wave at a critical angle when the real parts of the permittivity and permeability of the metamaterial are zero while the absolute imaginary parts can be arbitrarily small. The metamaterial layer needs a totally reflective substrate for perfect absorption, while this is not required for giant magnification. Detailed analysis for the existence of the critical angle and physical explanation for these abnormal phenomena are given.

OCIS codes: (160.3918) Metamaterials; (310.0310) Thin films; (260.0260) Physical optics.

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1. Introduction

When a wave propagates in a lossy material, it is absorbed gradually. To reduce the interface reflection, absorbers usually possess tapered micro-structures [1]. Recently, some thin flat metamaterial absorbers have been demonstrated [2–5], which can easily fulfill impedance match and large loss. In these cases, strong absorption in a short distance requires large loss, but perfect absorption (100%) cannot be archived. As another type of absorbers based on resonance, the well-known Salisbury screen can perfectly absorb a normally incident plane wave theoretically [1], but the spacer between the resistive sheet and the perfect electric conductor (PEC) substrate cannot be very thin (typically of the order of the wavelength in the spacer). Here we want to raise an interesting fundamental question, namely, can perfect absorption be realized with an arbitrarily thin structure whose material loss can be very small? If the answer is positive, an absorber can physically be made arbitrarily thin, and one can greatly improve the performance of e.g. detectors since their dependence on material loss can be greatly relaxed. Similarly, another interesting question can be raised, that is, whether giant amplification can be achieved with an arbitrarily thin structure of low gain. Usually, large gain is expected for strong amplification, but the gain cannot be very large in practice. A special material of zero permittivity ε or permeability μ provides us some special properties [6–10]. Several interesting applications have been reported, such as directive radiation and spatial filtering [6–8], squeezing electromagnetic energy [9] and nonlinear optics [10]. Here we will show that special materials with zero real(ε) and real(μ) (hereinafter referred to as ZRMs) can find amazing applications in absorption and magnification. With the assumption of a time harmonic factor $\exp(-i\omega t)$, positive imag(ε) and imag(μ) represent loss, and negative ones represent gain. A lossy or active ZRM layer can perfectly absorb or strongly amplify an incident plane wave, while amazingly the thickness of the ZRM layer, as well as |imag(ε)| and |imag(μ)|, can be arbitrarily small. Metamaterials hold the potential to realize ZRMs. By careful tuning the electric and magnetic resonant units that form a metamaterial [11], both real(ε) and real(μ) may vanish at some frequency. At some Dirac point with a zero Bloch wave vector, a specially designed photonic crystal may be homogenized as a metamaterial with both effective ε and μ approaching zero [12]. As a special metamaterial composed of small atoms, a gas of electromagnetic induced transparency (EIT) may possess negative ε and μ [13]. By choosing appropriately some EIT parameters, it is also possible to make real(ε) and real(μ) vanish.

2. Perfect absorption and giant magnification

Figure 1(a) illustrates the investigated structure. A slab is sandwiched between two semi-infinite layers, and the top layer, the slab, and the bottom layer are denoted as layers 0, 1 and 2, respectively. The permittivity and permeability of layer n are denoted by ε_n and μ_n, respectively. The magnetic field is along the z axis (TM polarization). When a plane wave impinges in the downward direction on the slab (the incident angle is θ and the corresponding transverse wave vector is k_y), the magnetic and electric fields in layer n can be expressed as

$$\begin{cases} H_{n,z}(\mathbf{r}) = (H_n^+ e^{ik_{n,x}x} + H_n^- e^{-ik_{n,x}x})e^{ik_y y} \\ E_{n,x}(\mathbf{r}) = -(k_y / \omega\varepsilon_n)(H_n^+ e^{ik_{n,x}x} + H_n^- e^{-ik_{n,x}x})e^{ik_y y}, \\ E_{n,y}(\mathbf{r}) = (k_{n,x} / \omega\varepsilon_n)(H_n^+ e^{ik_{n,x}x} - H_n^- e^{-ik_{n,x}x})e^{ik_y y} \end{cases} \tag{1}$$

where $k_{n,x} = (k_n^2 - k_y^2)^{1/2}$, k_n is the wave number in layer n, and $H_n^{\pm}$ is the magnetic field amplitude of a down- or up-going plane wave component in layer n as shown in Fig. 1. According to the electromagnetic boundary conditions, one can obtain $H_n^{\pm}$ and the corresponding field distribution in layer n. Due to the symmetry of the structure, it is sufficient to study the electromagnetic response for $k_y \geq 0$.

First we assume that layer 0 is of free space, layer 1 (ZRM) is lossy with $\varepsilon_1 = i\varepsilon_{1,r}''\varepsilon_0$ and $\mu_1 = i\mu_{1,r}''\mu_0$ ($\varepsilon_{1,r}'' \geq 0$ and $\mu_{1,r}'' \geq 0$), and layer 2 is a PEC. The reflection coefficient of the slab is

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$$R_{loss} = H_0^- / H_0^+ = [1/\tanh(\gamma d_1) - \gamma / \varepsilon_{1,r}"k_{0,x}] / [1/\tanh(\gamma d_1) + \gamma / \varepsilon_{1,r}"k_{0,x}], \quad (2)$$

where $\gamma = (\varepsilon_{1,r}"\mu_{1,r}"k_0^2 + k_y^2)^{1/2}$. Since all the variables on the right-hand side of Eq. (2) are real numbers when $k_y<k_0$, the reflected wave is either in phase or out of phase with respect to the incident wave. The numerator on the right-hand side of Eq. (2) is denoted by f_{loss}, and may become zero for some $k_y<k_0$ (corresponding to some incident angle) in some situations. The first term in f_{loss} decreases as k_y increases from 0 to k_0, and is always larger than or equal to 1. The second term in f_{loss} increases from a minimal value of $(\mu_{1,r}"/\varepsilon_{1,r}")^{1/2}$ to infinity as k_y increases from 0 to k_0. Thus, when $\mu_{1,r}"/\varepsilon_{1,r}"\le 1$, there always exists some value of k_y ($<k_0$) making f_{loss} zero, no matter how small d_1 becomes. Then R_{loss} also becomes zero. This means that there exists an incident angle at which the incident plane wave is completely (100%) absorbed by the lossy slab since the absorptivity is equal to $1-|R_{loss}|^2$. This incident angle is referred to as the critical angle (denoted by θ_c) hereafter. When $\mu_{1,r}"/\varepsilon_{1,r}">1$, the existence of θ_c depends on the value of d_1. If d_1 is too large compared with the wavelength in free space (λ_0), θ_c does not exist, because the first term in f_{loss} is smaller than $1/\tanh[(\varepsilon_{1,r}"\mu_{1,r}")^{1/2}(k_0 d_1)]$, which approaches 1 when d_1 is very large, whereas the second term is always larger than 1. When $\varepsilon_{1,r}"$ and $\mu_{1,r}"$ are given with $\mu_{1,r}"/\varepsilon_{1,r}">1$, the threshold of d_1 allowing the existence of θ_c is determined by the following equation

$$\tanh(\sqrt{\varepsilon_{1,r}"\mu_{1,r}"}k_0 d_1) - \sqrt{\varepsilon_{1,r}"/\mu_{1,r}"} = 0. \quad (3)$$

As a demonstration, Figs. 2(a) and 2(b) show the reflectivity ($|R_{loss}|^2$) of the slab for various k_y. When $\mu_{1,r}"/\varepsilon_{1,r}"\le 1$, there are always deep dips representing perfect absorption on the reflectivity curves [see curves 1–4 in Fig. 2(a) and curves 1 and 2 in Fig. 2(b)]. When $\mu_{1,r}"/\varepsilon_{1,r}">1$ and d_1 is large enough, such dips disappear [see curve 5 in Fig. 2(a) and curve 3 in Fig. 2(b); note that perfect absorption is still possible for some appropriate thickness d_1 when $\mu_{1,r}"/\varepsilon_{1,r}">1$]. Comparing Figs. 2(a) and 2(b), one sees that when $\mu_{1,r}" = \varepsilon_{1,r}"$ (i.e., matched impedance), if $\varepsilon_{1,r}"$ and $\mu_{1,r}"$ are large, θ_c is near to zero (i.e., perfect absorption at nearly normal incidence) and strong absorption over a wide range of incidence angle can be achieved. If $\varepsilon_{1,r}"$ and $\mu_{1,r}"$ are small (i.e., small loss), perfect absorption near normal incidence can still be achieved when $\varepsilon_{1,r}"$ is much smaller than $\mu_{1,r}"$ (see curve 4 of Fig. 2(a)). Note that contrary to all the absorbers reported previously, the values of d_1, $\varepsilon_{1,r}"$ and $\mu_{1,r}"$ can be very small (arbitrarily small) in the situation of perfect absorption.

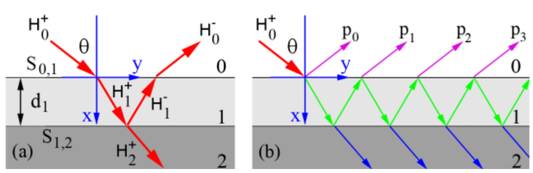

Fig. 1. (a) Configuration for a slab of ZRM sandwiched between two semi-infinite layers. (b) Wave decomposition of the reflected or transmitted field.

The value of θ_c depends on d_1, $\varepsilon_{1,r}"$ and $\mu_{1,r}"$ as illustrated well in Fig. 2(a). The second term in f_{loss} is approximately inversely proportional to $\varepsilon_{1,r}"$. As $\varepsilon_{1,r}"$ decreases gradually (with fixed $\mu_{1,r}"$ and d_1), θ_c should approach zero so that the first term in f_{loss} can cancel the second term. If $\varepsilon_{1,r}"$ decreases further and becomes smaller than some value which satisfies Eq. (3) with the other parameters given, θ_c will not exist. Similarly, as $\mu_{1,r}"$ increases, the second term in f_{loss} also increases, and θ_c should approach zero in order to make f_{loss} zero. And if $\mu_{1,r}"$ increases further, θ_c will not exist. When d_1 is gradually reduced with fixed $\varepsilon_{1,r}"$ and $\mu_{1,r}"$, θ_c becomes larger. Note that the first term in f_{loss} is very large when d_1 is very small. To make the second term in f_{loss} also large, $|k_y|$ needs to approach k_0 (i.e., θ_c approaches 90 degrees). On the other hand, θ_c approaches zero as d_1 increases. θ_c will not exist any more when d_1 increases further and becomes larger than some value satisfying Eq. (3).

The above perfect absorption can be understood by coherent cancelling. As shown in Fig. 1(b), the reflected wave in Fig. 1(a) can be considered as a composition of infinite plane wave

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components. One component is from the direct reflection (denoted by p_0) when the incident plane wave impinges on surface $S_{0,1}$. When the incident plane wave enters the slab and is multi-reflected between surfaces $S_{0,1}$ and $S_{1,2}$, a part of it is refracted out of surface $S_{0,1}$ and forms the other components which are denoted by p_n (n = 1,2,…). Based on this interpretation, R_{loss} can be rewritten as

$$R_{loss} = r_{0,1} + t_{0,1}t_{1,0}[e^{-2\gamma d_1} + r_{1,0}e^{-2(2\gamma d_1)} + r_{1,0}{}^2 e^{-3(2\gamma d_1)} + ...], \tag{4}$$

where $r_{0,1}$ = $(1-\gamma/\varepsilon_{1,r}"k_{0,x})/(1 + \gamma/\varepsilon_{1,r}"k_{0,x})$, $r_{1,0} = -r_{0,1}$, $t_{0,1} = 2\varepsilon_{1,r}"k_{0,x}/(\varepsilon_{1,r}"k_{0,x} + \gamma)$, $t_{1,0} = 2\gamma/(\varepsilon_{1,r}"k_{0,x} + \gamma)$. The first term on the right-hand side of Eq. (4) represents component p_0 in Fig. 1(b), and the second term represents the composition of the other components, p_n (n = 1,2,…). From Eq. (2), one sees that $\gamma/\varepsilon_{1,r}"k_{0,x}$ must be larger than 1 to make f_{loss} zero since $\tanh(\gamma d_1)<1$. Thus, $r_{0,1}$ is negative and $r_{1,0}$ is positive. Then, all components p_1, p_2, … are in phase, and they are out of phase with component p_0. At critical angle θ_c, the two groups cancel each other. This leads to the disappearing of the reflected wave in layer 0, and the incident plane wave is perfectly absorbed by the lossy slab. From Eq. (1), one sees that inside the slab, $E_{1,x}(\mathbf{r})$ is out of phase with $H_{1,z}(\mathbf{r})$, and time-averaged energy stream density $\mathbf{P}_1(\mathbf{r})$ has a zero component along the y axis. This indicates that when the incident plane wave enters the slab, it will just be normally multi-reflected by surface $S_{0,1}$ and $S_{1,2}$ and repeatedly absorbed. During this process, there is no phase introduced, leading to a result that the exponents in the square on the right-hand side of Eq. (4) just possess negative real variables (instead of complex variables). There is no transverse shift along the y axis among components p_0, p_1, … in Fig. 1(b). As a numerical example, Figs. 2(c)-2(e) show the electric and magnetic fields and time-averaged energy stream density (represented by arrows) around the slab when $d_1 = 0.4\lambda_0$, $\varepsilon_{1,r}" = 0.3$, $\mu_{1,r}" = 0.1$, and $\theta_c \approx 19.8$ degrees. To show clearly the distributions of the field and time-averaged energy stream density inside the slab, a relatively large value of d_1 is chosen for Figs. 2(c)-2(e). The distributions inside a thinner slab are similar. These distributions clearly show that there is no wave reflected by the slab. When the position approaches surface $S_{1,2}$, $E_{1,y}(\mathbf{r})$ has to tend to zero as required by the boundary condition at PEC surface $S_{1,2}$, and so is $\mathbf{P}_1(\mathbf{r})$, whereas $E_{1,x}(\mathbf{r})$ and $H_{1,z}(\mathbf{r})$ have no such tendency. For perfect absorption, a PEC as the substrate of the slab is necessary. If it is removed, the plane wave components refracted into the substrate (after being multi-reflected by surfaces $S_{0,1}$ and $S_{1,2}$) cannot cancel each other, and the incident plane wave can partially transmit through the slab as a total effect.

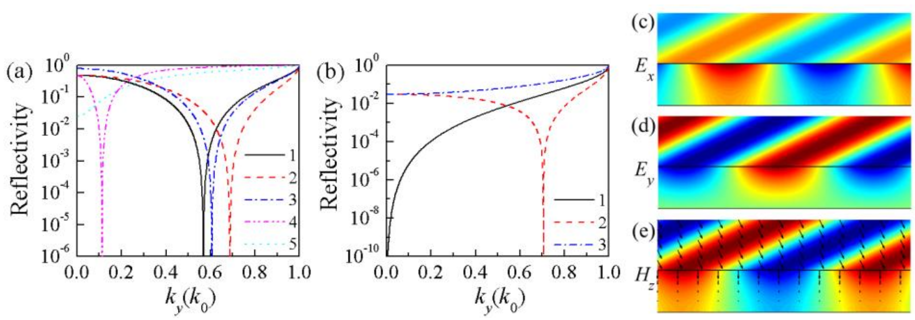

Fig. 2. Reflectivity and field distributions of a slab with a PEC substrate. In (a), $d_1 = 0.1\lambda_0$ for curves 1–4 and $d_1 = \lambda_0$ for curve 5, and $(\varepsilon_1/\varepsilon_0, \mu_1/\mu_0)$ has small values of i(0.3, 0.3), i(0.5, 0.3), i(0.3, 0.1), i(0.01, 0.3), and i(0.1, 0.3) for curves 1–5, respectively. In (b), $d_1 = 0.1\lambda_0$, and $(\varepsilon_1/\varepsilon_0, \mu_1/\mu_0)$ has large values of i(20, 20), i(20, 10), and i(10, 20) for curves 1–3, respectively. In (c)–(e), $d_1 = 0.4\lambda_0$, $(\varepsilon_1/\varepsilon_0, \mu_1/\mu_0) = i(0.3, 0.1)$.

Next we investigate an opposite case, namely, ε_1 and μ_1 are only of negative imaginary parts (i.e., $\varepsilon_1 = -i\varepsilon_{1,r}"\varepsilon_0$ and $\mu_1 = -i\mu_{1,r}"\mu_0$). Recently, there have been some efforts in active metamaterials [14,15]. Then, an incident wave is magnified by the active metamaterial slab. The reflection coefficient of the slab is $R_{gain} = [1/\tanh(\gamma d_1) + \gamma/\varepsilon_{1,r}"k_{0,x}]/[1/\tanh(\gamma d_1)-\gamma/\varepsilon_{1,r}"k_{0,x}]$, which is reciprocal to Eq. (2) for R_{loss}. When R_{loss} is zero, R_{gain} is infinite. Then, there exists a

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critical angle θ_c at which the plane wave impinging on the slab is infinitely magnified. The relation between θ_c and the values of d_1, $\varepsilon_{1,r}$" and $\mu_{1,r}$" is similar to that for the previous lossy slab. Especially, when $\mu_{1,r}"/\varepsilon_{1,r}"\leq 1$, θ_c always exists even if the thickness and gain of the slab are arbitrarily small. Curve 1 in Fig. 3(a) shows a numerical example. The infinite magnification can be understood as follows. The condition of $R_{gain} = \infty$ determines the dispersion equation of the slab waveguide. Now, special waveguide modes can exist for $k_y<k_0$. The energy stream inside the slab is normally reflected back and forth by surfaces S_1 and S_2 (instead of propagating along the slab). Some electromagnetic energy runs away from the slab, but it can be compensated by the energy generated by the gain. When an incident wave excites a waveguide mode, the total reflected wave will be infinite. The infinite magnification is from the time-harmonic solution. In practice, it may take an infinitely long time to obtain this effect. However, one can still obtain giant magnification after long enough time.

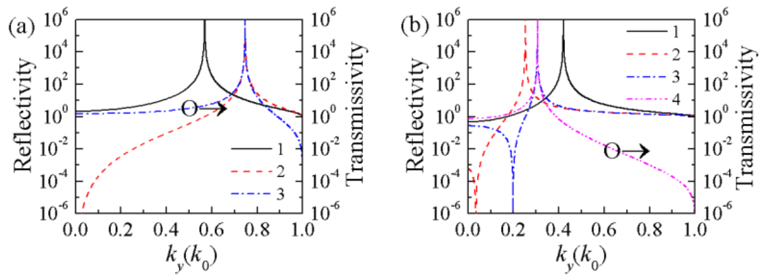

Fig. 3. Reflectivity and transmissivity of a slab. In (a), $d_1 = 0.1\lambda_0$, $(\varepsilon_1/\varepsilon_0, \mu_1/\mu_0) = (-0.3i, -0.3i)$, and layer 2 is a PEC for curve 1 and of free space for curves 2 and 3. In (b), $d_1 = 0.1\lambda_0$ for curve 1 and $d_1 = 0.5\lambda_0$ for curves 2–4, $(\varepsilon_1/\varepsilon_0, \mu_1/\mu_0) = (-0.1i, 0.3i)$, and layer 2 is a PEC for curves 1 and 2 and of free space for curves 3 and 4.

Now, the hybrid cases are analyzed, that is, real(ε_1) and real(μ_1) possess different signs. Only the case of $\varepsilon_1 = -i\varepsilon_{1,r}"\varepsilon_0$ and $\mu_1 = i\mu_{1,r}"\mu_0$ is investigated here, and the contrary case can be analyzed similarly. The reflection coefficient of the slab then becomes

$$R_{hybrid} = [\text{ctan}(k_{1,x}d_1) - k_{1,x}/k_{0,x}\varepsilon_{1,r}"]/[\text{ctan}(k_{1,x}d_1) + k_{1,x}/k_{0,x}\varepsilon_{1,r}"] \ \ (\text{when } k_y^2 \leq \varepsilon_{1,r}"\mu_{1,r}"k_0^2), \quad (5)$$

$$R_{hybrid} = [1/\tanh(\beta d_1) + \beta/k_{0,x}\varepsilon_{1,r}"]/[1/\tanh(\beta d_1) - \beta/k_{0,x}\varepsilon_{1,r}"] \ \ (\text{when } k_y^2 > \varepsilon_{1,r}"\mu_{1,r}"k_0^2), \quad (6)$$

where $\beta = (k_y^2 - \varepsilon_{1,r}"\mu_{1,r}"k_0^2)^{1/2}$. In Eq. (5), ctan($k_{1,x}d_1$) is a periodic function with its value varying from $+\infty$ to $-\infty$. Thus, both the numerator and denominator on the right-hand side of Eq. (5) have a possibility to be zero when $k_y<k_0$. When d_1 is large enough, many critical angles may exist at which the numerator or denominator on the right-hand side of Eq. (5) is zero. At the right-hand side of Eq. (6), the numerator is always larger than zero, and the denominator can be zero at some value of k_y since $\beta/k_{0,x}\varepsilon_{1,r}"$ increases from zero to infinite in the range of $(\varepsilon_{1,r}"\mu_{1,r}")^{1/2}k_0<k_y<k_0$. This indicates that regardless of the values of d_1, $\varepsilon_{1,r}"$, and $\mu_{1,r}"$, there always exists a critical angle θ_c at which the incident plane wave can be infinitely magnified when $\varepsilon_{1,r}"\mu_{1,r}"<1$. This is a quite interesting result that although $\mu_{1,r}"$ may be very large (representing large loss), small $\varepsilon_{1,r}"$ (representing low gain) still can lead to infinite magnification, which may bring convenience in practical magnification. Curves 1 and 2 in Fig. 3(b) show the reflectivity for different thickness of the slab when $\varepsilon_{1,r}" = -0.1$ and $\mu_{1,r}" = 0.3$. When $d_1 = 0.1\lambda_0$, there is only one peak on curve 1. When the slab becomes thick, e.g., $d_1 = 0.5\lambda_0$, both one dip and one peak appear on curve 2, which indicates that one can obtain both strong absorption and magnification at different special values of the incident angle.

Finally, we give two remarks for the perfect absorption and giant magnification. The first remark is that the PEC substrate can be removed in the case of giant magnification (unlike the case of perfect absorption). When the substrate is also a free space, and $\varepsilon_1 = -i\varepsilon_{1,r}"\varepsilon_0$ and $\mu_1 = -i\mu_{1,r}"\mu_0$, one has the following reflection and transmission coefficients of the slab

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$$R_{gain} = [\gamma / k_{0,x}\varepsilon_{1,r}" - k_{0,x}\varepsilon_{1,r}" / \gamma] / [2 / \tanh(\gamma d_1) - (\gamma / k_{0,x}\varepsilon_{1,r}" + k_{0,x}\varepsilon_{1,r}" / \gamma)], \quad (7)$$

$$T_{gain} = H_2^+ / H_0^+ = [4 / (e^{\gamma d_1} - e^{-\gamma d_1})] / [2 / \tanh(\gamma d_1) - (\gamma / k_{0,x}\varepsilon_{1,r}" + k_{0,x}\varepsilon_{1,r}" / \gamma)]. \quad (8)$$

The denominator on the right-hand side of Eqs. (7) and (8) is denoted by f_{gain}. The first term in f_{gain} decreases as k_y increases from 0 to k_0, and is always larger or equal to 2. The second term in f_{gain} is infinite when k_y approaches k_0, and reaches a minimal value of 2 when $\gamma/k_{1,x}\varepsilon_{1,r}" = k_{1,x}\varepsilon_{1,r}"/\gamma$. When $\mu_{1,r}"/\varepsilon_{1,r}" \leq 1$, this condition can be fulfilled by some k_y ($<k_0$), and a critical angle θ_c exists. Like in the case when layer 2 is a PEC, the incident plane wave at θ_c can be infinitely magnified regardless of the values of d_1, $\varepsilon_{1,r}"$ and $\mu_{1,r}"$. If $\mu_{1,r}"/\varepsilon_{1,r}" > 1$, this property disappears. As shown in Fig. 3(a), the value of θ_c without a PEC substrate is different from that with a PEC substrate. Similarly, giant magnification can still be obtained in a hybrid case when layer 2 is of free space, as shown by the peaks of curves 3 and 4 in Fig. 3(b) as a numerical example. These two curves also indicate that perfect absorption does not occur in this case since transmissivity curve 4 has no dip although there is a dip on reflectivity curve 3. The second remark is that the deviation of real(ε_1) and real(μ_1) from zero may cause the disappearance of perfect absorption and giant magnification. However, as illustrated in Figs. 4(a) and 4(b), if |real(ε_1)| and |real(μ_1)| are moderately small compared with |imag(ε_1)| and |imag(μ_1)|, respectively, strong absorption and magnification effect can still be obtained. As shown in Fig. 4, the influence of the deviation of real(ε_1) from zero on the absorption and magnification is different from that of real(μ_1). In general, when |imag(ε_1)| = |imag(μ_1)|, the influence of the same deviation of real(ε_1) and real(μ_1) from zero (i.e., with impedance match kept) on the absorption and magnification is smaller.

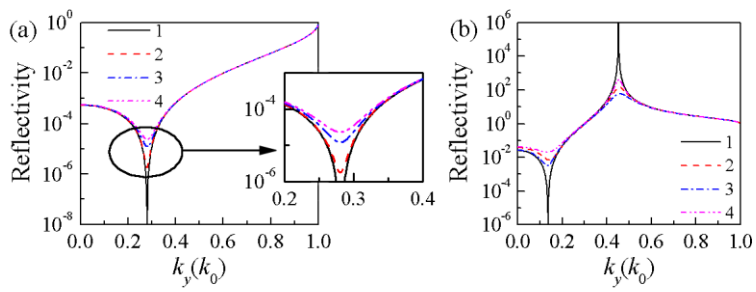

Fig. 4. Reflectivity of a slab with a PEC substrate when real(ε_1) and real(μ_1) deviate form zero. In (a), $d_1 = 0.1\lambda_0$, and ($\varepsilon_1/\varepsilon_0$, μ_1/μ_0) is ($3i$, $3i$), ($0.05 + 3i$, $0.05 + 3i$), ($0.05 + 3i$, $3i$) and ($3i$, $0.05 + 3i$) for curves 1–4, respectively. In (b), $d_1 = 0.5\lambda_0$, and ($\varepsilon_1/\varepsilon_0$, μ_1/μ_0) is ($-0.3i$, $0.3i$), ($0.05-0.3i$, $0.05 + 0.3i$), ($0.05-0.3i$, $0.3i$) and ($-0.3i$, $0.05 + 0.3i$) for curves 1–4, respectively.

3. Conclusion

In summary, we have shown that an incident plane wave can be perfectly absorbed or giantly amplified by a ZRM layer. The existence of a critical angle θ_c has been analyzed for various situations. The thickness of the ZRM layer, as well as |imag(ε)| and |imag(μ)|, can be arbitrarily small. This challenges our common understanding that strong absorption and magnification seems impossible in a very thin layer of material with finite or small |imag(ε)| and |imag(μ)|. It should be noted that in principle the homogeneous ZRM can be arbitrarily thin. In practical realization, the smallest thickness of a ZRM layer is determined by the dimension of the resonant metamaterial units, which is usually one or two order smaller than the wavelength. However, if the ZRM layer can be realized by an EIT gas, the thickness can be reduced even further. Even if the ZRM layer cannot be very thin, it is still rather significant, especially for giant magnification.

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