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Intrinsic optical bistability between left-handed material and nonlinear optical materials*

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The electromagnetic properties of the interface between a left-handed material and a conventional nonlinear material were investigated theoretically and numerically. We found a new phenomenon—optical bistability of the interface. It was shown that the incident intensity, incident angle and permeability ratio between the left-handed and the nonlinear materials could dramatically affect the optical bistable behaviour. We also compared the bistable behaviours of different electromagnetic modes. The results indicated that the TE mode was prior to the TM mode to obtain optical bistability for the same parameter.

Keywords: left-handed material, negative refraction, optical bistability
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1. Introduction

Recently, much attention has been paid to a new type of composite materials, which in a certain frequency region can be described by a negative effective permittivity ε and a permeability μ simultaneously.[1] These materials are often referred to as left-handed materials (LHM) or materials with negative refractive index, which were first named by Veselago[2] over 30 years ago to emphasize the fact that the intensity of the electric field $\boldsymbol{E}$, the magnetic field $\boldsymbol{H}$ and the wave vector $\boldsymbol{k}$ are related by a left-handed rule. As was shown by Veselago,[2] the left-handed materials possess a number of peculiar properties, such as negative refraction, reverse Doppler shift and reverse Cherenkov radiation. But, because of the unavailability of LHMs at that time, his idea did not attract much attention until Pendry *et al*[3] predicted that certain man-made composite structure could possess, in a given frequency interval, a negative effective magnetic permeability $\mu_{\rm eff}$. Combination of such a structure with a medium with negative effective permittivity $\varepsilon_{\rm eff}$, for instance the regular array of thin metallic wires,[1] enabled the construction of metamaterials with negative effective permittivity and permeability. This was confirmed by experiments.[4]

One of the potential applications of negative refractive index materials is to fabricate the so-called superlenses (perfect lenses): specifically, a slab of such materials may have the power to focus all Fourier components of a two-dimensional image, even those that do not propagate in a radiative manner.[5] So the resolution can indeed be much better than that of a conventional lens. The improved resolution of a left-handed (LH) slab and the corresponding amplification of evanescent modes in a lossy left-handed material can be understood from simple physics. Indeed, the near field of an image, which cannot be focused by a normal lens, can be transferred through the slab of a LHM due to the excitation of surface waves at both interfaces of the slab.[6] Some important work has been done by using such a "perfect lens" instead of the conventional one in optical processing systems.[7] Therefore, it is important to study the variation in properties of the electromagnetic field between LHM and

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the conventional material (or right-handed material RHM). Some preliminary studies in this direction included the calculation of linear dispersion properties[6] and nonlinear surface waves[8] in a slab of LHM.

In this paper, we discuss the characteristic of electromagnetic wave propagation in the interface between LHM and nonlinear material (NM), using the macroscopic Maxwell equations, pertaining to the behaviour of optical bistability. Since the first observation of optical bistability,[9] there has been increasing interest in the study of the optical response of nonlinear materials because of its potential applications in optical switching, optical memories, optical transistors, optical limiters and optical logic gates, etc.[10] In most configurations, optical bistability is achieved by the combined action of the nonlinear response of a material medium and the feedback of an optical resonator. However, the use of an external resonator is undesirable in many aspects, for instance it slows down the temporal response of the bistable device so it requires careful alignment. Mirrorless or intrinsic optical bistability was first considered by Bowden and Sung[11] who pointed out that a system comprised of a collection of identical two-level atoms interacting with an electromagnetic field can show optical bistable behaviour without external feedback. Another approach for achieving intrinsic optical bistability was proposed by Kalyaniwalla *et al*[12] and by Bergman *et al*[13] based on local field enhancement in a metal and dielectric composite. Instead of Bergman's variational approach, Gao *et al*[14] presented a general framework based on a spectral representation method[15] and a self-consistent mean-field theory[16,17] to investigate the optical bistability in a nonlinear two-phase composite. Yoon *et al*[18] found that optical bistability could occur from a single thin film of the nonlinear material situated in vacuum. Based on these results, one might suppose that optical bistability could occur in the interface between the semi-infinite LHM and NM. In this paper we report the results of our theoretical investigation of this conjecture. In particular, we find that intrinsic optical bistability can be predicted for some range of incident intensities, incident angles or permeability ratio between LHM and NM.

2. Theoretical model

Consider the propagation of homogeneous plane electromagnetic waves from LHM with negative refractive index $n_0 = -\sqrt{\varepsilon\mu}$ ($\varepsilon < 0, \mu < 0$) to the NM occupying the half-space $z > 0$, as shown in Fig.1, and assume that Im(ε)=Im(μ) = 0 for the whole space. The directions of vector $\boldsymbol{k}$ for different rays are shown by arrows. They should be chosen in such a way that at both interfaces the tangential components of vector $\boldsymbol{k}$ for incident, reflected and refracted waves are the same. The refractive index n_1 in the NM has a form

$$n_1 = |n_0| + \Delta + \Delta n_{\mathrm{NL}}, \tag{1}$$

where $\Delta n_{\mathrm{NL}} = \frac{1}{2} n_2 |A_{\mathrm{t}}|^2$ denotes the nonlinear part of the refractive index difference between LHM and NM with A_{t} being the amplitude of the refractive wave, and Δ is the linear part of the refractive index difference. Let $\boldsymbol{H}$ and $\boldsymbol{E}$ be the magnetic and electric fields, and ω the frequency of light.

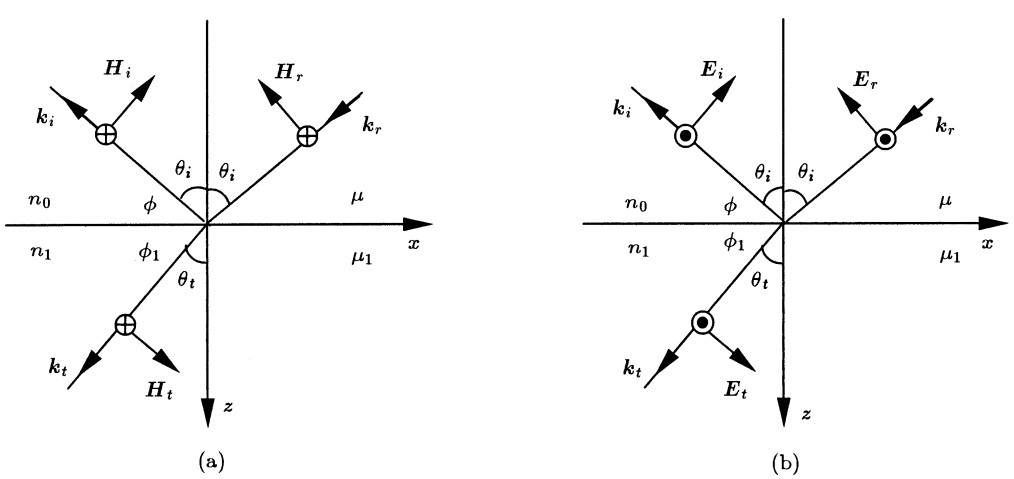


Fig.1. Reflection and transmission of a homogeneous plane wave at the interface between LHM and NM, (a) TE mode (b) TM mode.

TE mode We consider the TE mode first: i.e., $\boldsymbol{E}$ is perpendicular to the incident plane. The transverse electric solutions to the Maxwell equations, the so-called s-polarized incident and reflected waves, are given by

$$\boldsymbol{E}_{\mathrm{i}}(\boldsymbol{r},t)=\frac{1}{2}A_{\mathrm{i}}\boldsymbol{e}_y\exp\left(-\mathrm{i}\omega t-\mathrm{i}k_{\mathrm{i}x}x-\mathrm{i}k_{\mathrm{i}z}z\right)+\mathrm{C.C}, \tag{2a}$$

$$\boldsymbol{E}_{\mathrm{r}}(\boldsymbol{r},t)=\frac{1}{2}rA_{\mathrm{i}}\boldsymbol{e}_y\exp\left(-\mathrm{i}\omega t-\mathrm{i}k_{\mathrm{i}x}x+\mathrm{i}k_{\mathrm{i}z}z\right)+\mathrm{C.C}, \tag{2b}$$

where r is the reflection coefficient and $k_{\mathrm{i}x}=k_{\mathrm{i}}\sin\theta_{\mathrm{i}}$, $k_{\mathrm{i}z}=k_{\mathrm{i}}\cos\theta_{\mathrm{i}}$, $k_{\mathrm{i}}=\dfrac{|n_0|\omega}{c}$. Because the refractive index in a nonlinear medium is a function of light intensity, the reflection coefficient r must be a function of intensity.

In the case that the second medium is nonlinear, from the boundary conditions it can be easily shown that the refracted wave should maintain the same polarization as the incident wave. So for s-polarized incident wave, the refracted wave also s-polarized and the electric field $\boldsymbol{E}_{\mathrm{t}}(\boldsymbol{r},t)$ of the refracted wave can be expressed as

$$\boldsymbol{E}_{\mathrm{t}}(\boldsymbol{r},t)=\frac{1}{2}A_{\mathrm{t}}(z)\boldsymbol{e}_y\exp\left(-\mathrm{i}\omega t-\mathrm{i}k_{\mathrm{t}x}x+\mathrm{i}\int k_{\mathrm{t}z}(z)\mathrm{d}z\right)+\mathrm{C.C}, \tag{3}$$

where $k_{\mathrm{t}x}=k_{\mathrm{t}}\sin\theta_{\mathrm{t}}$, $k_{\mathrm{t}z}=k_{\mathrm{t}}\cos\theta_{\mathrm{t}}$, $k_{\mathrm{t}}=\dfrac{|n_1|\omega}{c}$.

Therefore, from the expression for electric field $\boldsymbol{E}$, we can obtain the corresponding magnetic field using $\boldsymbol{H}=\dfrac{1}{\mathrm{i}\omega\mu}\nabla\times\boldsymbol{E}$,

$$\boldsymbol{H}_{\mathrm{i}}=\frac{1}{\omega\mu}\left(-k_{\mathrm{i}z}\boldsymbol{e}_x+k_{\mathrm{i}x}\boldsymbol{e}_z\right)E_0(\boldsymbol{r},t), \tag{4a}$$

$$\boldsymbol{H}_{\mathrm{r}}=\frac{1}{\omega\mu}\left(k_{\mathrm{i}z}\boldsymbol{e}_x+k_{\mathrm{i}x}\mathbf{e}_z\right)E_{\mathrm{r}}(\boldsymbol{r},t), \tag{4b}$$

$$\boldsymbol{H}_{\mathrm{t}}=\frac{1}{\mathrm{i}\omega\mu_1}\left\{\left[\frac{\partial A_{\mathrm{t}}(z)}{\partial z}\frac{1}{2}\times\exp\left(-\mathrm{i}\omega t-\mathrm{i}k_{\mathrm{t}x}x+\mathrm{i}\int k_{\mathrm{t}z}(z)\mathrm{d}z\right)+\mathrm{i}k_{\mathrm{t}z}E_{\mathrm{t}}(\boldsymbol{r},t)\right]\boldsymbol{e}_x+\mathrm{i}k_{\mathrm{t}x}E_{\mathrm{t}}(\boldsymbol{r},t)\boldsymbol{e}_z\right\}, \tag{4c}$$

where μ is the permeability of the LHM and μ_1 is the permeability of the NM.

From the Maxwell boundary conditions, one has

$$(1+r_\perp)A_{\mathrm{i}}=A_{\mathrm{t}}(0), \tag{5a}$$

$$A_{\mathrm{i}}k_{\mathrm{i}z}(1-r_\perp)=\left[A_{\mathrm{t}}(0)k_{\mathrm{t}z}(0)-\mathrm{i}\frac{\partial A_{\mathrm{t}}(0)}{\partial z}\right]\times\frac{-\mu}{\mu_1}. \tag{5b}$$

The subscript $\perp$ indicates the component of the electric field $\boldsymbol{E}_{\mathrm{i}}(\boldsymbol{r},t)$ perpendicular to the incident plane. Since the transmitted light in the NM also is a homogeneous plane wave, $\partial A_{\mathrm{t}}/\partial z=0$, $k_{\mathrm{t}}(z)=\mathrm{const}$. Then we can obtain the Snell refractive formulary at the interface $z=0$,

$$\frac{\sin\theta_{\mathrm{i}}}{\sin\theta_{\mathrm{t}}}=-\frac{n_1}{n_0}=1-\frac{\Delta}{n_0}-\frac{n_2|A_1|^2}{2n_0}=1+\frac{1}{2}\Delta_{\mathrm{I}}^2+\frac{1}{8}\Delta_{\mathrm{E}}^2\tau_\perp^2, \tag{6}$$

where

$$\Delta_{\mathrm{E}}^2=-4n_2|A_{\mathrm{i}}|^2/n_0, \tag{7a}$$

$$\Delta_{\mathrm{I}}^2=-2\Delta/n_0. \tag{7b}$$

We name Δ_{E}^2 the intensity factor and Δ_{I}^2 the linear refractive index factor. Then the transmission coefficient $\tau_\perp$ and reflection coefficient $r_\perp$ can be written as

$$\tau_\perp=\frac{2\mu_1\mathrm{tg}\theta_{\mathrm{t}}}{\mu_1\mathrm{tg}\theta_{\mathrm{t}}-\mu\mathrm{tg}\theta_{\mathrm{i}}}, \tag{8a}$$

$$r_\perp=\frac{\mu_1\mathrm{tg}\theta_{\mathrm{t}}+\mu\mathrm{tg}\theta_{\mathrm{i}}}{\mu_1\mathrm{tg}\theta_{\mathrm{t}}-\mu\mathrm{tg}\theta_{\mathrm{i}}}. \tag{8b}$$

We assume that the incident wave is incident at a small glancing angle $\phi=\dfrac{\pi}{2}-\theta_{\mathrm{i}}$ and $\Delta\ll|n_{\mathrm{o}}|$, $|\Delta n_{\mathrm{NL}}\ll|n_{\mathrm{o}}|$. Then the glancing angle of the transmitted light can be expressed as $\phi_1=\dfrac{\pi}{2}-\theta_{\mathrm{t}}$ $\left(\phi_1\ll\dfrac{\pi}{2}\right)$, and Eqs.(8) can be simplified

$$\tau_\perp\simeq\frac{2\mu_1\phi}{\mu_1\phi-\mu\phi_1}, \tag{9a}$$

$$r_\perp\simeq\frac{\mu_1\phi+\mu\phi_1}{\mu_1\phi-\mu\phi_1}. \tag{9b}$$

So another expression of Snell refractive formulary can be obtained:

$$\frac{\cos\phi}{\cos\phi_1}=1+\frac{1}{2}\Delta_{\mathrm{I}}^2+\frac{1}{2}\Delta_{\mathrm{E}}^2\left(\frac{\mu_1\phi}{\mu_1\phi-\mu\phi_1}\right)^2, \tag{10}$$

which can be simplified by neglecting the high-order terms. Then, the Snell formulary and Fresnel formulary for the interface of nonlinear material are given as follows:

$$(\mu_1\phi-\mu\phi_1)^2\left(\phi^2+\Delta_{\mathrm{I}}^2-\phi_1^2\right)+\Delta_{\mathrm{E}}^2\mu_1^2\phi^2=0, \tag{11a}$$

$$4\Delta_{\mathrm{I}}^2(1+r_\perp)^2+4\phi^2\left[(1+r_\perp)^2-\frac{\mu_1^2}{\mu^2}(1-r_\perp)^2\right]+\Delta_{\mathrm{E}}^2(1+r_\perp)^4=0. \tag{11b}$$

TM modes For TM waves, the magnetic wave is perpendicular to the incident plane and the electric field is related to the magnetic field by $\boldsymbol{E} = -\frac{1}{\mathrm{i}\omega\varepsilon}\nabla \times \boldsymbol{H}$. The argument is similar to those discussed above which apply as well to the transverse magnetic or p-modes. Thus, we have

$$\left(\mu_1\phi_1 - \mu\phi\right)^2\left(\phi^2 + \Delta_{\mathrm{I}}^2 - \phi_1^2\right) + \Delta_{\mathrm{E}}^2\mu_1^2\phi^2 = 0, \quad (12a)$$

$$4\Delta_{\mathrm{I}}^2\left(1+r_{\parallel}\right)^2 + 4\phi^2\left[\left(1+r_{\parallel}\right)^2 - \frac{\mu^2}{\mu_1^2}\left(1-r_{\parallel}\right)^2\right] + \frac{\mu_1^2}{\mu^2}\Delta_{\mathrm{E}}^2\left(1+r_{\parallel}\right)^4 = 0. \quad (12b)$$

The subscript $\parallel$ indicates the electric field $\boldsymbol{E}_{\mathrm{i}}(\boldsymbol{r}, t)$ parallel to the incident plane. In the following section, for convenience we define $f = \left|\frac{\mu}{\mu_1}\right|$ as the absolute value of permeability ratio between LHM and NM.

3. Numerical results and discussion

The numerical calculations based upon the analytical relations have been performed for both self-focusing, i.e. $n_2 > 0$ ($\Delta_{\mathrm{E}}^2 > 0$), and self-defocusing i.e. $n_2 < 0$ ($\Delta_{\mathrm{E}}^2 < 0$), nonlinear systems to obtain an insight into the wave solutions. For the purpose of this paper, the defocusing system is mainly considered here and concentrated on the TE mode, as it is an attractive candidate for all-optical switching and optical bistability.

We are now in a position to study the effects of incident angles and intensities on optical bistability behaviour by solving Eqs.(10a) and (10b) numerically. Choose CN2 (azo liquid crystal polymer) as a numerical illustration. It is shown that the CN2 exhibits very strong nonlinear refractive index[19] n_2 ($\sim -10^{-4}\mathrm{cm}^2/\mathrm{W}$). So we could take $|n_2| = 9.98 \times 10^{-5}\mathrm{cm}^2/\mathrm{W}$. In calculations, we assume $n_0 = -2$ and $\Delta_{\mathrm{I}}^2 = 0$ for simplicity, i.e. the linear refractive index difference between LHM and NM is zero.

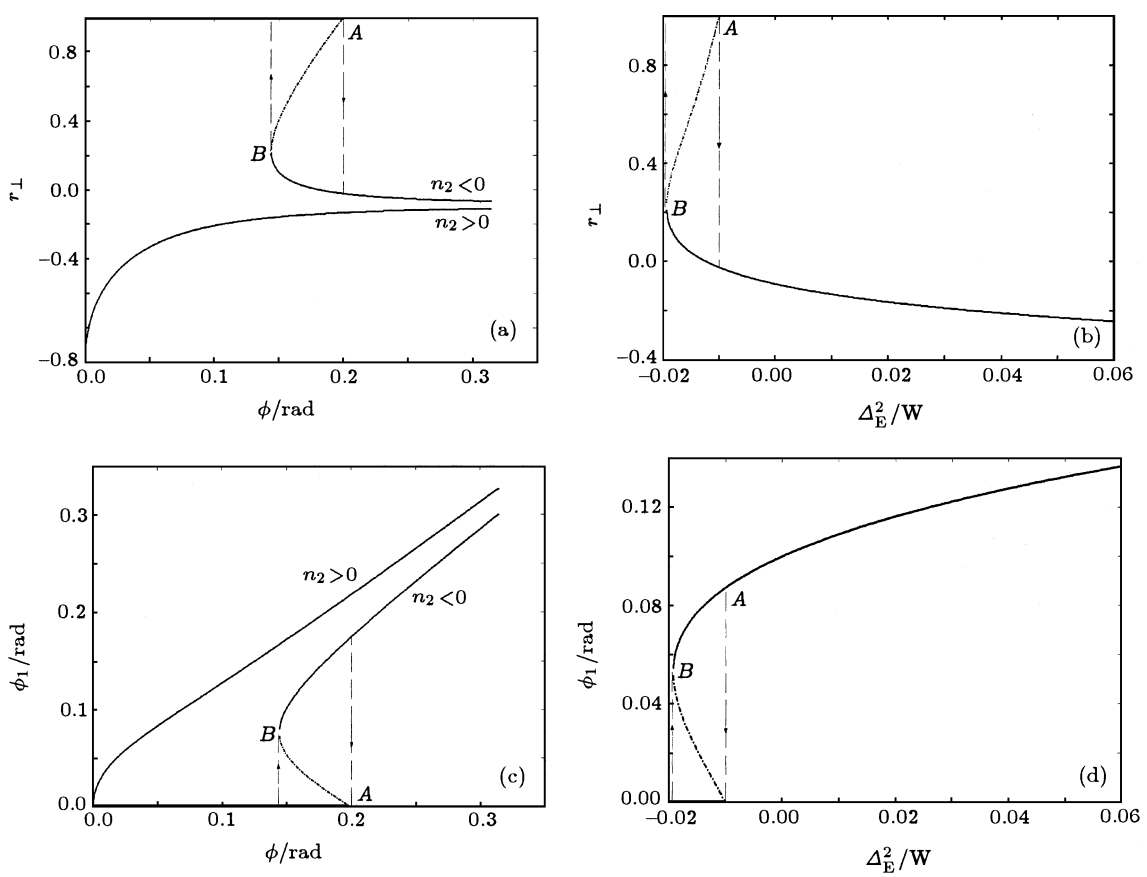


Fig.2. Bistability curves of TE mode for permeability ratio $f = 1.2$. (a) Reflection coefficient $r_\perp$ versus the incident glancing angle ϕ, calculated at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04\mathrm{W}$. (b) Reflection coefficient $r_\perp$ versus the intensity factor Δ_{E}^2, calculated at $\phi = 0.1\mathrm{rad}$. (c) The transmitted glancing angle $\phi_1$versus the incident glancing angle ϕ, calculated at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04\mathrm{W}$. (d) The transmitted glancing angle ϕ_1 versus the intensity factor, Δ_{E}^2 calculated at $\phi = 0.1\mathrm{rad}$.

In Figs.2(a) and 2(c), the interfacial reflectivity $r_\perp$ and transmitted glancing angle ϕ_1 are plotted as functions of the incident glancing angle ϕ at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$, respectively, and in Figs.2(b) and 2(d) the interfacial reflectivity $r_\perp$ and the transmitted glancing angle ϕ_1 are plotted as functions of intensity factor Δ_{E}^2 at a glancing angle $\phi = 0.1$, respectively. These plots with $f = 1.2$ exhibit bistable response clearly and the parts of the curves with negative slope (dot-dashed lines) are unstable. The direction of upward-arrow denotes the switch-up and the direction of downward-arrow denotes the switch-down. As shown in Fig.2, points A are the total internal reflection points and points B are the knee points.

In Fig.3, we note that the absolute value of permeability ratio plays an important role in bistable behaviour. It is shown that with the change of f from 0.8 to 1.4, the switch-up threshold value of the bistability decreases but the switch-down threshold values maintain invariant. And we find that the phase transition of reflectivity occurs under certain conditions.

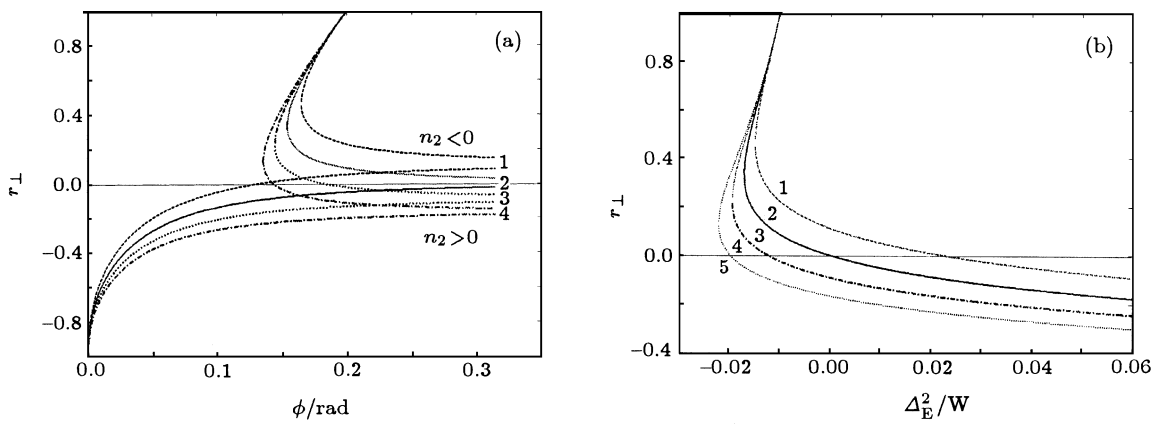


Fig.3. Bistability curves (1–4) at the absolute values of permeability ratio f=0.8, 1.0, 1.2, 1.4 respectively. (a) Reflection coefficient $r_\perp$ versus the incident glancing angle ϕ, calculated at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$W. (b) Reflection coefficient $r_\perp$ versus the intensity factor Δ_{E}^2, calculated at $\phi = 0.1$rad.

It is shown in Fig.4 that with increasing f, the switch-up threshold values are decreased but the bistable regions are increased, and the effect of f on switch-down threshold value is larger than on the switch-up threshold value. There exists a range of bistable behaviour within f. In Fig.4(a), with the fixed incident intensity at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$, f varies from 0.8 to 3.4; in Fig.4(b), however, with the fixed incident glancing angle $\phi = 0.1$, f varies from 0.2 to 2.4. Furthermore, with the same variance of f, we can find that the change in the value of bistable region in Fig.4(a) is larger than that in Fig.4(b). So for the same parameters, the influence of incident glancing angle ϕ on bistable behaviour is stronger than that of incident intensity.

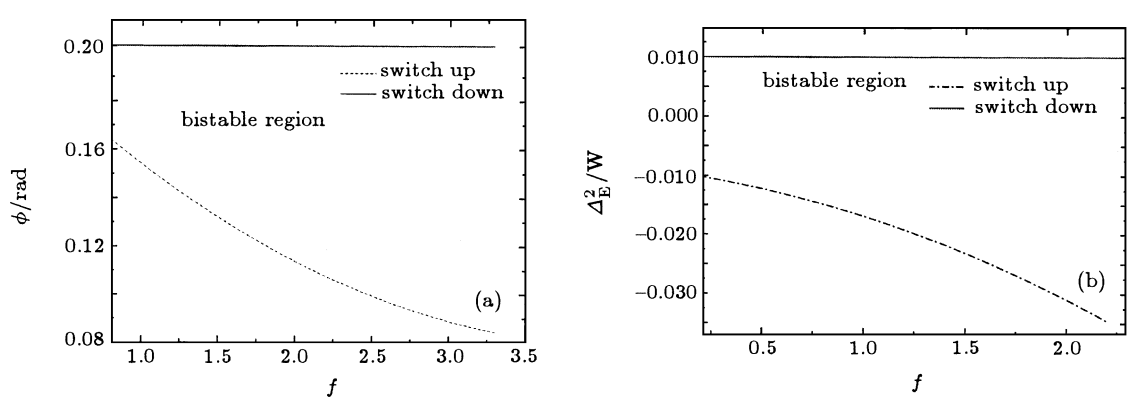


Fig.4. Switching values versus permeability ratio f. (a) Reflection coefficient at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$W, (b) intensity factor at $\phi = 0.1$rad.

Figure 5 shows that the bistable behaviour of TM wave at $f = 1.2$ is quite similar to that of TE wave. For $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$, the threshold values of TM mode are less than those of TE mode. As shown in Figs.2(a) and 5(a), the switch-up threshold value of TE mode is about $\phi = 0.14$, higher than that of TM mode, $\phi = 0.12$. And the switch-down threshold value of TE mode is about $\phi = 0.2$, also higher than that of the TM mode, $\phi = 0.14$. However, at a certain incident glancing angle $\phi = 0.1$, the situation is inverted. Thus for the case of the same physical parameters, it is also determined that the bistable behaviour is dependent on the electromagnetic modes.

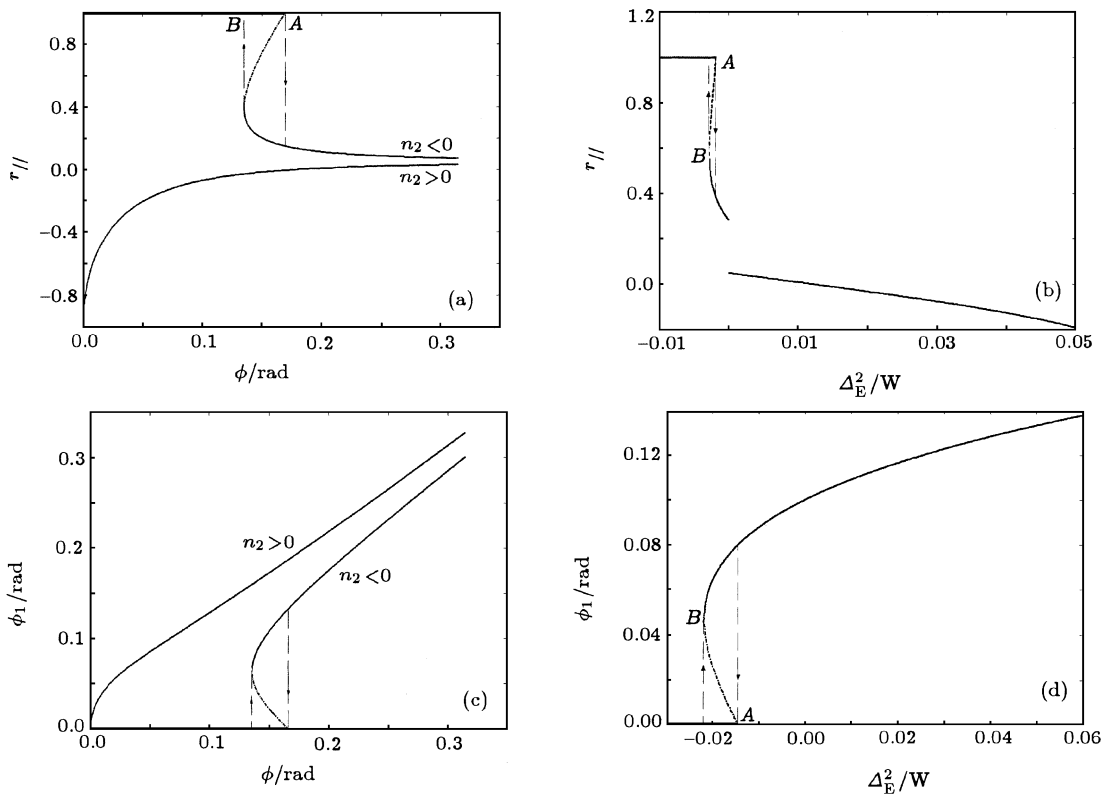


Fig.5. Bistability curves of TM mode for $f = 1.2$.

Figure 6 gives the bistable behaviour of TM mode for different absolute values of permeability ratio f at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$. As shown in Fig.6(a), with the change of f from 1.0 to 1.6, both the switch-up and switch-down threshold values increase. Obviously, from Fig.6(b) with increasing f from 1.0 to 2.0, the bistable region is almost unchanged, which is totally different from that of the TE mode. The bistable behaviour could not occur out of this range of f, while at fixed incident glancing angle $\phi = 0.1$, the bistable range of f is from 1.0 to 1.2, much smaller than that of TE mode, as shown in Fig. 7.

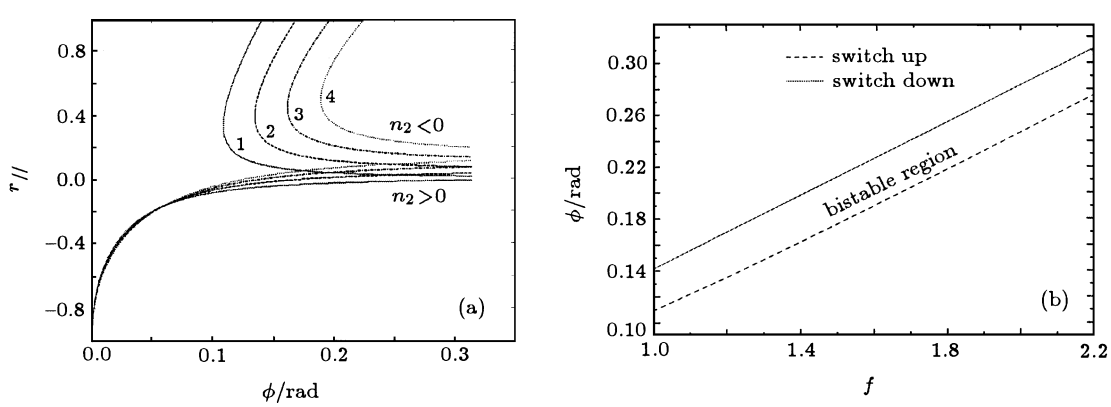


Fig.6. Bistability curves for permeability ratio f =1.0, 1.2, 1.4, 1.6 at $\left|\Delta_{\mathrm{E}}^2\right| = 0.04$ W. (a) Reflection coefficient versus the incident glancing angle, (b) switching values versus permeability ratio f.

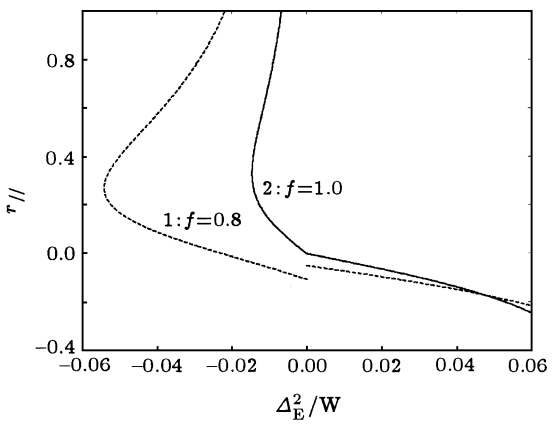


Fig.7. Reflection coefficient versus the intensity factor, calculated at $\phi = 0.1$rad for different $f(f$=1.0, 1.2).

The analysis of bistable properties on the interface between a right-handed material and a conventional nonlinear material is similar to that between the left-handed material and a conventional nonlinear material. In this case, the Snell formulation and Fresnel formulation shown in Eqs.(10) and (11) can be expressed just by replacing f with $-f$. However, in the case of left-handed material, the incident and transmitted waves are on the same side of the normal. Combining a left-handed material with a right-handed material, we can arrange the propagating direction of the transmitted wave with bistable properties to meet the specific requirement and flexibility of real optical devices and systems.

4. Conclusion

We have carried out a systematic study of electromagnetic bistability supported by an interface between a left-handed material and a conventional nonlinear material. Using macroscopic Maxwell equations, we performed the mathematic derivation in detail and simulated the behaviour of bistability numerically. Numerical results show that the incident intensities, incident angles and absolute value of permeability ratio f can greatly affect the bistable behaviour. For the TE mode, larger absolute value of permeability ratio f is favourable to reduce the switch-up threshold values and increase the bistable region. While for the TM mode, with increasing f, both the switch-up and switch-down threshold values are increased but the bistable region is almost invariant. We also noted that the bistable range of f in the TM case is smaller than that in the TE case. So it can be concluded that the optical bistable behaviour is dependent on the electromagnetic mode. In the case of having the same physical parameters, it is easier and more flexible to obtain bistability in TE mode than in TM mode. We expect that our study will be helpful to the research on the new application of LHM.

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