Photon tunneling and transmittance resonance through a multi-layer structure with a left-handed material*

He Ying (何 英)†, Zhang Xia(张 霞), Yang Yan-Fang(杨艳芳), and Li Chun-Fang(李春芳)

Department of physics, Shanghai University, Shanghai 200444, *China*

(Received 29 April 2010; revised manuscript received 22 October 2010)

This paper investigates the photon tunneling and transmittance resonance through a multi-layer structure including a left-handed material(LHM). An analytical expression for the transmittance in a five-layer structure is given by the analytical transfer matrix method. The transmittance is studied as a function of the refractive index and the width of the LHM layer. The perfect photon tunneling results from the multi-layer structure, especially from the relation between the magnitude of the refractive index and the width of the LHM layer and those of the adjoining layers. Photons may tunnel through a much greater distance in this structure. Transmittance resonance happens, the peaks and valleys appear periodically at the resonance thickness. For an LHM with inherent losses, the perfect transmittance is suppressed.

Keywords: left-handed material, photon tunneling, transmittance resonance, analytical transfer matrix method

PACS: 41.20.Jb, 78.20.Ci, 42.70.Qs **DOI:** 10.1088/1674-1056/20/5/054103

1. Introduction

The novel materials exhibiting both negative dielectric permittivity and negative magnetic permeability are first predicted theoretically by Veselago in 1968.[1] The materials possess a negative refractive index. The wave vector creates a left set of vectors with electric and magnetic fields, so the materials are termed as left-handed materials (LHMs). The LHMs have been fabricated in experiments by Shelby *et al.* in 2001.[2] Since then the fabrication and unusual properties of the LHMs have attracted the most interest due to their potential applications. Chen *et al.* have provided a route to the fabrication of isotropic negative refractive index material at optical frequencies by theoretical investigation.[3] Nonresonant transmission line structures made of lumped inductors and lumped capacitors are one of the main approaches to realising LHMs artificially for the gigahertz range of frequency.[4,5] New LHMs structures have been verified recently by numerical simulation and experiments in the visible region and the x-band.[6,7] Krowne has studied the anisotropy effect of LHM on guided wave electromagnetic fields and suggested potential LHM device applications.[8] Long wave and short wave resonance have been achieved in a second-order nonlinear negative refractive index medium and it could be applied to the generation of terahertz waves from optical pulses.[9]

Multilayer structures including LHMs have been widely investigated in recent years. The structures which have excited heated discussion are those which consist of periodic stacks created by alternating slabs of two types of materials, with positive and negative refractive indexes.[10] The periodic multilayer structures consisting of LHMs with simultaneous nonlinear electronic and magnetic responses are also taken into account.[11,12] Besides the periodic structure, quasiperiodic multilayer photonic structure has been investigated and the optical transmission spectra have been calculated.[13] Other multilayer structures do not consist of periodic stacks, however some stacks are created by LHMs.[14−16] These structures have demonstrated some novel properties, which deserve our deep investigation.

When light is shone on a medium from another denser medium at an angle greater than the critical angle, total internal reflection occurs. When a third medium with a sufficiently large refractive index is placed behind the second medium with a lower refrac-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60877055 and 60806041) and the Innovation Funds for Graduates of Shanghai University, China (Grant No. SHUCX102016).

†Corresponding author. E-mail: heying@staff.shu.edu.cn

© 2011 Chinese Physical Society and IOP Publishing Ltd

tive index and a small thickness, photons can tunnel through the second into the third. This well-known phenomenon is called photon tunneling. The tunneling time and lateral shift of photon tunneling through the frustrated total internal reflection structure containing indefinite LHMs have been investigated.[17] Zhang and Lee have studied photon tunneling by the energy streamline method recently.[18] Tunneling provides insight into many interesting processes such as radioactive decay, frustrated total internal reflection, lasing in quantum-well laser structures and electron transport in planar doped barrier devices, etc.[19–22] In this study, we use the analytical transfer matrix method to determine the transmittance in a multilayer structure including LHMs. Photon tunneling and transmittance resonance are analysed in detail. Absorption is inevitable. The effect of the loss of the LHM on the tunneling is investigated.

2. Theory

A multilayer structure with N layers including both conventional materials and LHMs is shown in Fig. 1. The first layer and the Nth layer are semi-infinite conventional materials. The refractive index and the relative permeability are n_l, μ_l respectively for the lth layer. In the ideal case n_l, μ_l are real numbers. When absorption is considered, n_l, μ_l are imaginary.

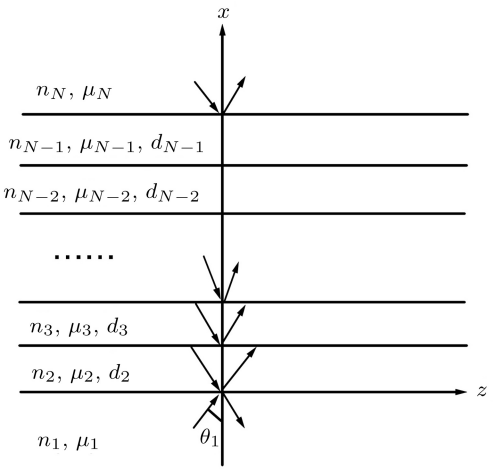


Fig. 1. The multilayer structure with LHMs.

For a monochromatic plane wave originating in medium 1, either a transverse electric (TE) or a transverse magnetic (TM) wave, the wave vector is $\boldsymbol{k}_l = k_{lx}\boldsymbol{x} + k_{lz}\boldsymbol{z}$, whose magnitude is $2\pi n_l/\lambda$, where λ is the wavelength in vacuum, $k_0 = 2\pi/\lambda$. The wave number for each layer is the same, i.e., $k_{lz} = \beta = k_0 n_1 \sin\theta_1$, where θ_1 is the angle of incidence. The dependence of the monochromatic field on the time is $\exp(-\mathrm{i}\,\omega t)$. The electric field in the lth layer can be written as $E_l(x)\exp[\mathrm{i}(\beta z - \omega t)]$ with

$$E_l(x) = A_l \mathrm{e}^{\mathrm{i}\,k_{lx}(x-x_{l-1})} + B_l \mathrm{e}^{-\mathrm{i}\,k_{lx}(x-x_{l-1})}, \quad (1)$$

where x_0, x_1 are assumed to be 0, $x_l = x_{l-1} + d_l$ ($l = 2, 3, \ldots$) and d_l is the thickness for the lth layer, A_l, B_l are the amplitudes at the interface for the forward and backward waves respectively.

in particular, the electric field in layer 1 and layer N can be written as

$$\begin{aligned} E_1(x) =& A_1 \exp[\mathrm{i}\,k_{1x}(x - x_0)] \\ &+ B_1 \exp[-\mathrm{i}\,k_{1x}(x - x_0)], \quad (2) \\ E_N(x) =& A_N \exp[\mathrm{i}\,k_{Nx}(x - x_{N-1})] \\ &+ B_N \exp[-\mathrm{i}\,k_{Nx}(x - x_{N-1})], \quad (3) \end{aligned}$$

where $x_0 = 0$, $x_{N-1} = x_{N-2} + d_{N-1}$.

According to the analytical transfer matrix method,[23,24] the electric field and its derivative derived by the corresponding permeability at the interface between the first and the second layer are related to those between the $(N-1)$th and Nth layers by

$$\begin{bmatrix} E_1(x_0) \\ \dfrac{1}{\mu_1} E_1'(x_0) \end{bmatrix} = \prod_{l=2}^{N-1} \boldsymbol{M}_l \begin{bmatrix} E_N(x_{N-1}) \\ \dfrac{1}{\mu_N} E_N'(x_{N-1}) \end{bmatrix}. \quad (4)$$

Here we will analyse the TE field in particular, the TM field can be discussed similarly. In the layers with the refractive index $|n_l| > \beta/k_0$, $k_{lx} = \sqrt{k_0^2 n_l^2 - \beta^2}$ for a propagating wave, the transfer matrices can be written as

$$\boldsymbol{M}_l = \begin{bmatrix} \cos(k_{lx} d_l) & -\dfrac{\mu_l}{k_{lx}} \sin(k_{lx} d_l) \\ \dfrac{k_{lx}}{\mu_l} \sin(k_{lx} d_l) & \cos(k_{lx} d_l) \end{bmatrix}. \quad (5)$$

In the layers with the refractive index $|n_l| < \beta/k_0$, $k_{lx} = \mathrm{i}\sqrt{\beta^2 - k_0^2 n_l^2} = \mathrm{i}\,\alpha_l$ for an evanescent wave, the transfer matrices can be written as

$$\boldsymbol{M}_l = \begin{bmatrix} \cosh(\alpha_l d_l) & -\dfrac{\mu_l}{\alpha_l} \sinh(\alpha_l d_l) \\ -\dfrac{\alpha_l}{\mu_l} \sinh(\alpha_l d_l) & \cosh(\alpha_l d_l) \end{bmatrix}. \quad (6)$$

Substituting Eqs. (2) and (3) into Eq. (4), we obtain

$$\begin{bmatrix} A_1 + B_1 \\ \dfrac{1}{\mu_1} \mathrm{i}\,k_{1x}(A_1 - B_1) \end{bmatrix} = \prod_{l=2}^{N-1} \boldsymbol{M}_l \begin{bmatrix} A_N \\ \dfrac{1}{\mu_N} \mathrm{i}\,k_{Nx}(A_N - B_N) \end{bmatrix}. \quad (7)$$

For $B_N = 0$, no wave gets through the structure. The transmission coefficient can be written as $t = A_N/A_1$ and the reflection coefficient can be calculated by $r = B_1/A_1$. The power transmittance and reflectance can be obtained by $T = (n_N \cos\theta_N/n_1 \cos\theta_1)tt^*$ and $R = 1 - T$.

Consider a five-layer system where an LHM is sandwiched between two general dielectrics, the top and bottom layers are semi-infinite dielectrics with positive refractive indexes. The refractive indexes and permeabilities of each layer are n_i and μ_i ($i = 1, 2, \ldots, 5$) respectively. The thickness of the middle layers are d_2, d_3 and d_4 respectively. The k_{1x} and k_{5x} are the transverse wave number in the top and bottom layers respectively, which are noted as k_1 and k_5 in the following for simplicity.

For a five-layer system with $N = 5$, the analytical expression for the transmission coefficient $t = A_5/A_1$ for the TE wave can be obtained from Eq. (7). The formula for the transmission coefficient is

$$t = \frac{2}{a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 + a_8}, \tag{8}$$

where the denominator is composed of eight terms, which are

$$a_1 = \Big(1 + \frac{\mu_1 k_5}{\mu_5 k_1}\Big) \cosh(\alpha_2 d_2) \cosh(\alpha_3 d_3) \cosh(\alpha_4 d_4), \tag{9}$$

$$a_2 = \Big(-\mathrm{i}\,\frac{\mu_4 k_5}{\mu_5 \alpha_4} + \mathrm{i}\,\frac{\mu_1 \alpha_4}{\mu_4 k_1}\Big) \cosh(\alpha_2 d_2) \cosh(\alpha_3 d_3) \sinh(\alpha_4 d_4), \tag{10}$$

$$a_3 = \Big(\frac{\mu_3 \alpha_4}{\mu_4 \alpha_3} + \frac{\mu_1 \mu_4 \alpha_3 k_5}{\mu_5 \mu_3 \alpha_4 k_1}\Big) \cosh(\alpha_2 d_2) \sinh(\alpha_3 d_3) \sinh(\alpha_4 d_4), \tag{11}$$

$$a_4 = \Big(\mathrm{i}\,\frac{\mu_3 k_5}{\mu_5 \alpha_3} + \mathrm{i}\,\frac{\mu_1 \alpha_3}{\mu_3 k_1}\Big) \cosh(\alpha_2 d_2) \sinh(\alpha_3 d_3) \cosh(\alpha_4 d_4), \tag{12}$$

$$a_5 = \Big(\frac{\mu_2 \alpha_3}{\mu_3 \alpha_2} + \frac{\mu_1 \mu_3 \alpha_2 k_5}{\mu_5 \mu_2 \alpha_3 k_1}\Big) \sinh(\alpha_2 d_2) \sinh(\alpha_3 d_3) \cosh(\alpha_4 d_4), \tag{13}$$

$$a_6 = \Big(\frac{\mu_2 \alpha_4}{\mu_4 \alpha_2} + \mathrm{i}\,\frac{\mu_1 \alpha_2}{\mu_2 k_1} + \mathrm{i}\,\frac{\mu_2 k_5}{\mu_5 \alpha_2}\Big) \sinh(\alpha_2 d_2) \cosh(\alpha_3 d_3) \cosh(\alpha_4 d_4), \tag{14}$$

$$a_7 = \Big(\mathrm{i}\,\frac{\mu_2 \mu_4 \alpha_3 k_5}{\mu_5 \mu_3 \alpha_2 \alpha_4} + \mathrm{i}\,\frac{\mu_1 \mu_3 \alpha_2 \alpha_4}{\mu_2 \mu_4 \alpha_3 k_1}\Big) \sinh(\alpha_2 d_2) \sinh(\alpha_3 d_3) \sinh(\alpha_4 d_4), \tag{15}$$

$$a_8 = \frac{\mu_1 \mu_4 \alpha_2 k_5}{\mu_5 \mu_2 \alpha_4 k_1} \sinh(\alpha_2 d_2) \cosh(\alpha_3 d_3) \sinh(\alpha_4 d_4). \tag{16}$$

The power transmittance $(n_5 \cos\theta_5/n_1 \cos\theta_1)tt^*$ can also be calculated from the above equations.

3. Photon tunneling and transmittance resonance

In the five-layer system the LHM is put in the middle as the third layer. The permeability and permittivity of the LHM are respectively

$$\mu = \mu_1 + \mathrm{i}\,\mu_2, \quad \varepsilon = \varepsilon_1 + \mathrm{i}\,\varepsilon_2, \tag{17}$$

where $\mu_1(\varepsilon_1)$ and $\mu_2(\varepsilon_2)$ are respectively the real parts and imaginary parts. In the ideal case $\mu_2(\varepsilon_2)$ is zero. When the absorption is included, $\mu_2(\varepsilon_2)$ is not zero. In our calculation the permeability is lossless and the loss is due to the complexity of permittivity. The formulas (8)–(16) for the transmission coefficient are applicable to the five-layer structure including the lossy LHM.

In the five-layer system $n_1 = n_5 = 1.5$, $n_2 = n_4 = 1.0$. The angle of incidence θ_1 is 60°. We set $\lambda = 2\pi$ to let k_0 be unitary. The constant $\beta = k_0 n_1 \sin\theta_1 = 1.30$ is the same for all layers. The refractive index of the LHM is n_3.

The transmittance for the five-layer system is shown in Fig. 2 as a function of $(d_3 - d_2 - d_4)/\lambda$ for three different values of n_3. The peak transmittances all reach unity, however the $(d_3 - d_2 - d_4)/\lambda$ corresponding to the peaks varies. For $n_3 = -1$, i.e., the amplitude of the LHM layer is equal to the adjoining layers, the transmittance reaches unity and perfect transmission happens when $d_3 = d_2 + d_4$. It must be pointed out that $k_{3x} = -k_{2x} = -k_{4x}$ for propagating waves and the phase difference caused by traveling through medium 3 is the opposite of the sum of that through mediums 2 and 4 when $d_3 = d_2 + d_4$. All interferences are constructive. Photon can tunnel through much greater distance in the presence of LHM. For

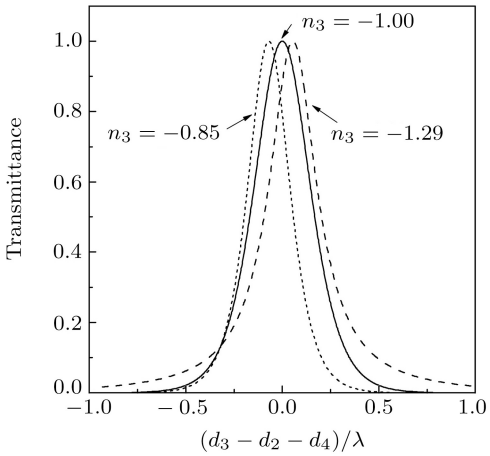


Fig. 2. The transmittance as a function of $(d_3-d_2-d_4)/\lambda$ in a five-layer system with $n_1 = n_5 = 1.5$, $n_2 = n_4 = 1$, $\mu_1 = \mu_2 = \mu_4 = \mu_5 = 1$, $\mu_3 = -1$ and $d_2 = d_4$. The angle of incidence is 60°.

$n_3 = -1.29$, which satisfies $n_2 < |n_3| < \beta$, the $(d_3 - d_2 - d_4)/\lambda$ corresponding to the peak transmittance shifts to 0.05. The thickness d_3 is larger than the sum of d_2 and d_4, which means that photons are allowed to tunnel through greater distance than the case $n_3 = -n_2 = -n_4 = -1$. In this case $|n_3| > n_2$, $|k_{3x}| < |k_{2x}|$, the perfect transmittance happens when $d_3 > d_2 + d_4$. When $n_3 = -0.85$, which satisfies $|n_3| < n_2 < \beta$, the relative thickness shifts to -0.07. The thickness d_3 of the LHM must be decreased to achieve the peak transmittance. In this case, $|n_3| < n_2$, $|k_{3x}| > k_{2x}$, so the perfect photon tunneling happens when $d_3 < d_2 + d_4$. In the five-layer structure the photon tunneling takes place when $k_0^2 n_3^2 < \beta^2$, furthermore the transmittance reaches unity and perfect transmittance is achieved. The second and fourth layers of the five-layer system are phase-nullified by the LHM layer. The transmittance peaks migrate in the five-layer system, which gives us flexibility to choose n_3 and d_3 to achieve the perfect transmittance and make the photons travel much longer distance.

The transmittances for $n_3 < -\beta$ and $-\beta < n_3 < 0$ are compared in Fig. 3. It is shown that more than one peak appears for $n_3 = -1.07$, when transmittance resonance takes place. The transmittance peaks appear periodically. The transmittance exhibits oscillatory behaviour, with resonances where the reflectivity vanishes. The oscillating structure of the transmittance for $n_3 < -\beta$ is a notable difference from that for $-\beta < n_3 < 0$ when photon tunneling takes place.

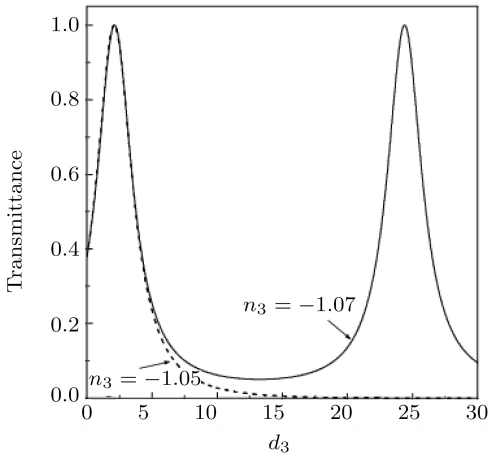


Fig. 3. The transmittance as a function of d_3 in a five-layer system with $n_1 = n_5 = 1.5$, $n_2 = n_4 = 1$, $\mu_1 = \mu_2 = \mu_4 = \mu_5 = 1$, $\mu_3 = -1$, $d_2 = d_4 = 1$ and $\lambda = 2\pi$. The angle of incidence is 45°.

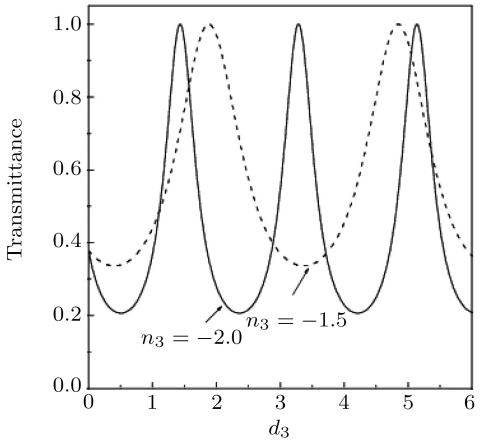


Fig. 4. The transmittance as a function of d_3 in a five-layer system with $n_1 = n_5 = 1.5$, $n_2 = n_4 = 1$, $\mu_1 = \mu_2 = \mu_4 = \mu_5 = 1$, $\mu_3 = -1$, $d_2 = d_4 = 1$ and $\lambda = 2\pi$. The angle of incidence is 45°.

The transmittances for $n_3 = -1.5$ and $n_3 = -2$ are shown in Fig. 4. It is interesting that the transmittance peaks reach a maximum of unity at several thickness of d_3. The transmittance valleys also appear periodically. It is shown that the intervals of the transmittance peaks for $n_3 = -1.5$ are larger than those for $n_3 = -2$. According to the transfer matrix method,[25] the resonant condition is

$$k_3 d_3 = m\pi + \mathrm{Re}\left[2\arctan\left(\frac{\mu_3 p_3}{\mu_2 k_3}\right)\right], \qquad (18)$$

where

$$k_3 = \sqrt{k_0^2 n_3^2 - \beta^2}, \qquad (19)$$

$$p_3 = \frac{\alpha_2 \sinh(\alpha_2 d_2) + \mathrm{i}\, k_1 \cosh(\alpha_2 d_2)}{\cosh(\alpha_2 d_2) + \mathrm{i}\, k_1 \sinh(\alpha_2 d_2)/\alpha_2}, \qquad (20)$$

$$\alpha_2 = \sqrt{\beta^2 - k_0^2 n_3^2}, \qquad (21)$$

and Re means the real parts. When m is an integer and $m = 1, 2, 3, \ldots$, the transmittance peaks appear. For $m = (2L-1)/2,\ L = 1, 2, 3, \ldots$, the transmittance valleys appear.

For $n_3 = -2$, the transmittance peaks appear at $d = 1.43,\ 3.28,\ 5.13, \ldots$. All the interferences are constructive and the transmittances reach unity. The transmittance valleys appear at $d_3 = 0.51,\ 2.36,\ 4.21, \ldots$, and the transmittances are equal to the minimum 0.207. In this case the interference is destructive. The transmittance peaks and valleys separate at regular intervals. It keeps oscillating between unity and the minimum value 0.207. For $n_3 = -1.5$, the transmittance peaks appear at $d_3 = 1.88,\ 4.84, \ldots$, and the transmittance valleys appear at $d_3 = 0.40,\ 3.36, \ldots$. The reflection and interference induce the transmittance resonance. It can be seen from Eqs. (18)–(21) that the oscillation of the transmittance with respect to the thickness is the periodical occurrence of transmittance peaks and valleys at

$$d_3 = \{m\pi + \mathrm{Re}[2\arctan(\mu_3 p_3)/(\mu_2 k_3)]\}/k_3,$$

where $m = L/2,\ L = 1, 2, 3, \ldots$.

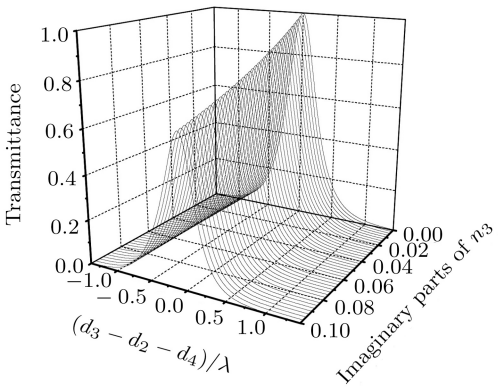


Fig. 5. The transmittance as a function of $(d_3-d_2-d_4)/\lambda$ and the imaginary parts of n_3 in a five-layer system with the lossy LHM. The angle of incidence is 45°, the real parts of n_3 are -1.

Loss is inevitable and we will discuss the photon tunneling through the five-layer structure with the lossy LHM as the middle layer. The thickness and refractive index for the second and the fourth layer are fixed and the same as those in the lossless case. The real parts of the refractive index of the LHM are -1 and the amplitude of the real part is the same as the refractive index of the adjoining layers. The transmittance as a function of the difference of the width $(d_3 - d_2 - d_4)/\lambda$ and the imaginary parts of the refractive index of the LHM is plotted in Fig. 5. It is shown that with the increase of the imaginary parts the transmittance peaks decrease greatly and the $(d_3 - d_2 - d_4)/\lambda$ corresponding to the peaks also decreases. When the imaginary part of the refractive index of the LHM increases to 0.10, the peak transmittance decreases to 0.656 and the corresponding difference between d_3 and $d_2 + d_4$ is -0.08. Perfect transmission does not happen when loss is included in the system. It is indicated that the photon can not tunnel through the structure completely due to the losses. The transmittance peaks shift left with the increasing loss. It means that the thickness of the LHM must be reduced when the photon tunneling takes place and the photons can not tunnel through great distance as that in the ideal case. Some energy has been dissipated in the LHM due to the absorption.

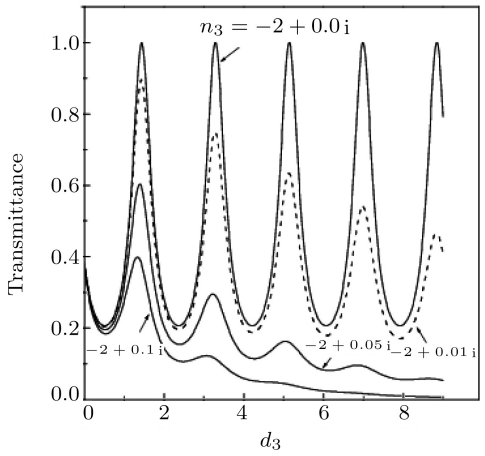


Fig. 6. The transmittance as a function of d_3 in a five-layer system with the lossy LHM. The parameters are $n_1 = n_5 = 1.5$, $n_2 = n_4 = 1$, $\mu_1 = \mu_2 = \mu_4 = \mu_5 = 1$, $\mu_3 = -1$, $d_2 = d_4 = 1$ and $\lambda = 2\pi$. The angle of incidence is 45°.

The transmittance as a function of the thickness d_3 is plotted in Fig. 6 to show the influence of loss on the transmittance resonance. It exhibits the essential difference from the lossless case. The absorption suppresses the transmittance resonance, especially for a large thickness of LHM. The LHM with large thickness undergoes more absorption, which results in less peaks and less maximums in the resonance transmittance. In the lossy system the peak transmittance is less than unity and the right transmittance peaks are lower than the left ones. It can be seen from Fig. 6 that the transmittance peaks decrease with the increasing losses and the transmittance peaks shift left with the increasing losses. For the refractive index

$n_3 = -2 + 0.1\,\mathrm{i}$, the right transmittance peaks disappear quickly. Energy is absorbed by the lossy LHM.

4. Conclusions

In conclusion, we have derived an expression describing the transmittance through the multilayer structure including the LHM with inherent losses. In this study we investigate the properties of photon tunneling through the five-layer structure and show that unusual photon tunneling takes place for $|n_3| < \beta$. For $n_2 < |n_3| < \beta$, photons are allowed to tunnel through greater distance than those for $n_3 = -n_2 = -n_4$. When $|n_3| > \beta$, transmittance resonance takes place and transmittance peaks and valleys appear periodically at the resonance thickness. The transmittances behave differently when n_3 varies across the critical value of $-\beta$. The losses of the LHM suppress the photon tunneling. The transmittance peaks decrease and shift left with the increasing losses. The photon can not tunnel through the structure completely in the presence of material losses. The transmission properties can be demonstrated in experiments with the LHMs for the gigahertz range of frequency. The unusual photon tunneling has potential applications including scanning photon tunneling spectroscopy and measuring optical near field for atom manipulation.

References

[1] Veselago V G 1968 *Sov.Phys.Usp.* **10** 509

[2] Shelby R A, Smith D R and Schultz S 2001 *Science* **292** 77

[3] Chen Y, Fischer P and Wise F W 2005 *Phys. Rev. Lett.* **95** 067402

[4] Eleftheriades G V, Iyer A K and Kremer P C 2002 *IEEE Trans. Microwave Theory Tech.* **50** 2702

[5] Iyer K and Eleftheriades G V 2008 *Appl. Phys. Lett.* **92** 261106

[6] Sun Y Z, Ran L X, Wang D X, Wang W G and Chen Q L 2010 *Acta Phys. Sin.* **59** 4602 (in Chinese)

[7] Zhuo S C and Yan C C 2010 *Acta Phys. Sin.* **59** 0360 (in Chinese)

[8] Krowne C M 2006 *J. Appl. Phys.* **99** 044914

[9] Chowdhury A and Tataronis J A 2008 *Phys. Rev. Lett.* **100** 153905

[10] Shadrivov I V, Zharova N A, Zharov A A and Kivshar Y S 2004 *Phys. Rev.* E **70** 046615

[11] Feng S and Halterman K 2008 *Phys. Rev. Lett.* **100** 063901

[12] Li G Q, Li H Y, Wang P C and Zhang Y W 2007 *Acta Phys. Sin.* **56** 6480 (in Chinese)

[13] de Medeiros F F , Albuquerque E L and Vasconcelos M S 2006 *J. Phys.: Condens. Matter* **39** 8737

[14] Chen L, He S L and Shen L F 2003 *Acta Phys. Sin.* **52** 2386 (in Chinese)

[15] Zhang Z M and Fu C J 2002 *Appl. Phys. Lett.* **80** 1097

[16] He Y, Zhang J and Li C F 2008 *J. Opt. Soc. Am.* B **25** 2081

[17] Xiang Y J, Dai X Y and Wen S C 2007 *J. Opt.* A: *Pure and Appl. Opt.* **9** 253

[18] Zhang Z M and Lee B J 2006 *Opt. Express* **14** 9963

[19] Verkhoturov S V, Schweikert E A, Chechik V, Sabapathy R C, Crooks R M and Parilis E S 2001 *Phys. Rev. Lett.* **87** 037601

[20] Ranfagni A , Ruggeri R, Agresti A, Ranfagni C and Sandri P 2002 *Phys. Rev.* E **65** 037601

[21] Bhattacharya P and Ghosh S 2002 *Appl. Phys. Lett.* **80** 3482

[22] He H, Pandey R and Pati R 2006 *Phys. Rev.* B **73** 195311

[23] He Y, Cao Z Q and Shen Q S 2005 *J. Phys.* A: *Math. Gen.* **38** 5771

[24] Wang J P, Jin Y X, Ma J Y, Shao J D and Fan Z X 2010 *Chin. Phys.* B **19** 054202

[25] Prade B, Vinet J Y and Mysyrowicz A 1991 *Phys. Rev.* B **44** 13556