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2004 J. Phys.: Condens. Matter 16 4743

(http://iopscience.iop.org/0953-8984/16/26/008)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **16** (2004) 4743–4751 PII: S0953-8984(04)74691-3

Surface polaritons and imaging properties of a multi-layer structure containing negative-refractive-index materials

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Received 13 January 2004
Published 18 June 2004
Online at stacks.iop.org/JPhysCM/16/4743
doi:10.1088/0953-8984/16/26/008

Abstract
Using the transfer-matrix method, we investigate the surface polaritons and imaging properties of a multi-layer structure consisting of alternating positive- and negative-refractive-index materials. It is shown numerically that the amplification of evanescent waves is due to the excitation of the surface polaritons. Moreover, we make a detailed investigation of how the variations in the real parts of the permittivity and permeability and the absorption of negative-*n* materials affect the image quality. The image quality of a lens made of a multi-layer structure is generally improved in comparison with that of a single slab. Our investigation may be useful for near-field imaging by the lens of such a multi-layer structure if the negative-*n* materials are necessarily dispersive.

1. introduction

Novel physical effects in composite materials with both negative permittivity and negative permeability were analysed a long time ago by Veselago [1]. Such materials are variously dubbed as left-handed materials [1], negative-refractive-index (negative-*n*) materials [2], double-negative media [3], backward media [4], and negative-phase-velocity media [5], and so forth. A discussion of this issue was given by Lakhtakia *et al* [6]. The media have attracted extensive interest, especially since the 'perfect lens' was proposed by Pendry [7]. The perfect lens could overcome the diffraction limit of conventional imaging systems because it amplifies the evanescent waves from a near-field object and restores them at the image plane. But this was later questioned by a number of authors [8–12]. For example, Garcia *et al* [11] argued that the unavoidable loss [13] in negative-*n* materials, no matter how tiny it is, would suppress the amplification of evanescent waves and thus the perfect lens does not exist in the real world. Ye [12] believed that the influence of the deviation of the real parts of the permittivity and permeability in negative-*n* materials from the perfect lens condition should be considered when imaging the near field using non-monochromatic waves. Despite this debate, more and more interest was focused on the perfect lens [14–21]. In this connection, many scholars [15, 18, 19] attributed the amplification of evanescent waves to the interactions between the evanescent waves and the surface polaritons at the interfaces between negative-n materials and positive-refractive-index (positive-n) materials. Therefore, it would be of great interest to investigate the surface polaritons supported by a structure with negative-n materials.

Ruppin has studied the surface polaritons of a semi-infinite negative-n material [22] and a negative-n slab [23]. Later, the spectra of surface polaritons in composite media with time dispersion of permittivity and permeability were discussed in [24]. In this paper, with the aid of the transfer-matrix method [25], we would like to study the surface polaritons of a multi-layer stack of alternating positive-n and negative-n media. Actually, Pendry has shown that this structure can effectively minimize the influence of the unavoidable loss in negative-n materials on the near-field imaging [26]. Here, following Pendry's work, we cut a single negative-n slab and separate the thin slices from one another, and thus the total thickness of the negative-n layers is kept constant. Then, we will show numerically that the divergences in the transmission coefficient occur at wavevectors corresponding to the excitation of the surface polaritons. Finally, we will investigate how the deviations of the real parts of the permittivity and permeability from the perfect lens conditions influence imaging properties in such a multi-layer structure. It is well known that the quality of imaging can be described by such physical parameters as the amplitude of the recovery rate and the phase shift of the evanescent waves arriving at the image plane from the object plane [12], which should be, respectively, 1 and 0, when the perfect lens conditions are satisfied. One can see that the deviation will give rise to many sharp peaks in the amplitude of the recovery rate because of the coupled surface polaritons, excited by the evanescent waves at the interfaces of the thin slices of negative-n materials.

The rest of the paper is organized as follows. In section 2, on the basis of the transfer-matrix method, we establish the theoretical formulation for obtaining the surface polaritons and describing the imaging properties of the multi-layer structure containing negative-n materials. In section 3, the spectra of surface polaritons, the amplitude of the recovery rate, and the phase shift are numerically calculated. Finally, a summary of our results and a discussion will be given in section 4.

2. Formalism

Let us consider a multi-layer structure made up of alternating layers of two materials, which is shown in figure 1. One of them (the odd layers) is a positive-n material whose relative permittivity ε_{p} and permeability μ_{p} are both equal to 1. The other (the even layers) is a negative-n material with the relative permittivity $\mu_{\mathrm{n}} = \mu'_{\mathrm{n}} + \mathrm{i}\mu''_{\mathrm{n}}$ and permeability $\varepsilon_{\mathrm{n}} = \varepsilon'_{\mathrm{n}} + \mathrm{i}\varepsilon''_{\mathrm{n}}$, where μ'_{n} ($\varepsilon'_{\mathrm{n}}$) and μ''_{n} ($\varepsilon''_{\mathrm{n}}$), respectively, are the real and imaginary parts of μ_{n} (ε_{n}). Without loss of generality, we take a two-dimensional light beam of transverse electric (TE) polarization (transverse magnetic (TM) polarization can be discussed in a same way) with its wavevector in the x–z plane. Thus the wavevector in the lth layer is $\mathbf{k}_l = k_{lx}\mathbf{e}_x + k_{lz}\mathbf{e}_z$ ($l = 1, 2, \ldots, N$), where $\mathbf{e}_x$ and $\mathbf{e}_z$ are the unit vectors in the x and z directions respectively. Note that for all layers, the component k_{lx} has the same value, k_x.

For odd layers with positive n, according to the Maxwell equations, the transverse wavevectors can be written as

$$k_{\mathrm{p}z} = \begin{cases} \sqrt{k_0^2\epsilon_{\mathrm{p}}\mu_{\mathrm{p}} - k_x^2} & \text{for propagating waves (i.e., } k_0^2\epsilon_{\mathrm{p}}\mu_{\mathrm{p}} - k_x^2 > 0\text{)}, \\ \mathrm{i}\sqrt{k_x^2 - k_0^2\epsilon_{\mathrm{p}}\mu_{\mathrm{p}}} & \text{for evanescent waves (i.e., } k_x^2 - k_0^2\epsilon_{\mathrm{p}}\mu_{\mathrm{p}} > 0\text{)}, \end{cases} \tag{1}$$

where k_0 is the wavenumber in vacuum.

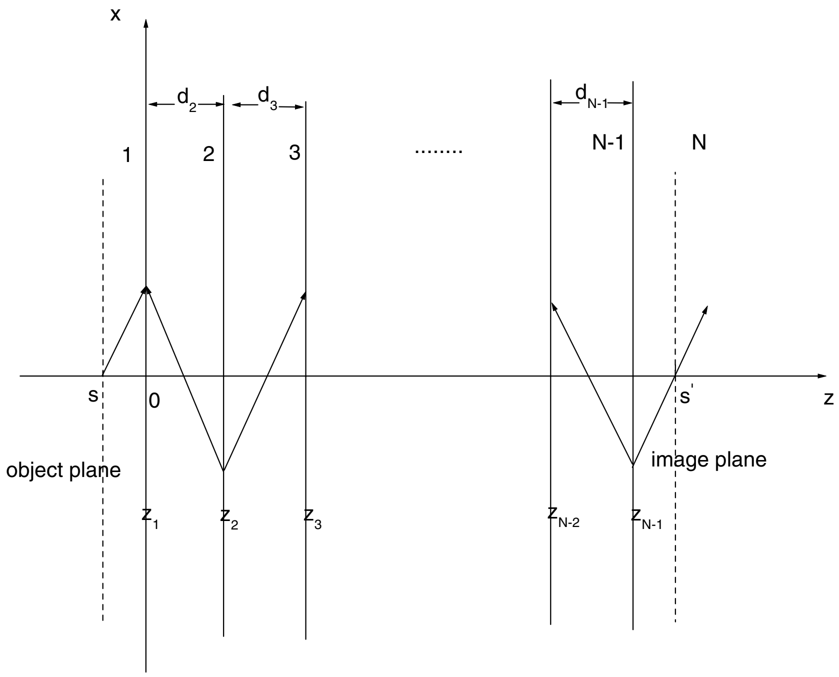

Figure 1. An N-layered structure consisting of alternating positive-n and negative-n materials.

On the other hand, for even layers with negative n, the component k_{lz} has the form [12]

$$k_{nz} = \frac{A\delta}{2}\left(\frac{2}{\sqrt{(A-k_x^2)^2 + A^2\delta^2} - (A-k_x^2)}\right)^{1/2} + \mathrm{i}\left(\frac{\sqrt{(A-k_x^2)^2 + A^2\delta^2} - (A-k_x^2)}{2}\right)^{1/2}, \tag{2}$$

where $A = k_0^2(\mu_n'\varepsilon_n' - \mu_n''\varepsilon_n'')$ and $\delta = (\mu_n'\varepsilon_n'' + \mu_n''\varepsilon_n')/(\mu_n'\varepsilon_n' - \mu_n''\varepsilon_n'')$.

The layer number N of the multi-layer structure is assumed to be odd. The electromagnetic field in the lth layer can be expressed as follows:

$$\begin{aligned}
\mathbf{E}_l &= [A_l \mathrm{e}^{\mathrm{i}k_{lz}(z-z_{l-1})} + B_l \mathrm{e}^{-\mathrm{i}k_{lz}(z-z_{l-1})}]\mathrm{e}^{\mathrm{i}(k_x x - \omega t)}\mathbf{e}_y, \\
\mathbf{H}_l &= -\frac{k_{lz}}{\omega\mu_l}[A_l \mathrm{e}^{\mathrm{i}k_{lz}(z-z_{l-1})} - B_l \mathrm{e}^{-\mathrm{i}k_{lz}(z-z_{l-1})}]\mathrm{e}^{\mathrm{i}(k_x x - \omega t)}\mathbf{e}_x \\
&\quad + \frac{k_x}{\omega\mu_l}[A_l \mathrm{e}^{\mathrm{i}k_{lz}(z-z_{l-1})} + B_l \mathrm{e}^{-\mathrm{i}k_{lz}(z-z_{l-1})}]\mathrm{e}^{\mathrm{i}(k_x x - \omega t)}\mathbf{e}_z
\end{aligned} \tag{3}$$

where $z_l = z_{l-1} + d_l$ is the position of the lth interface with $z_0 = 0$ and $d_1 = 0$. For simplicity, we set $d_l = d$ ($l = 2, 3, \ldots, N-1$). Note that B_N should be zero because no backward waves exist in the last layer. The complex amplitudes of the adjacent layers are related by

$$\begin{pmatrix} A_l \\ B_l \end{pmatrix} = (M_l)\begin{pmatrix} A_{l+1} \\ B_{l+1} \end{pmatrix}, \tag{4}$$

where M_l is the transfer matrix. Using the boundary conditions

$$\begin{aligned}
\mathbf{e}_z \times (\mathbf{E}_{l+1} - \mathbf{E}_l)_{z=z_l} &= 0, \\
\mathbf{e}_z \times (\mathbf{H}_{l+1} - \mathbf{H}_l)_{z=z_l} &= 0,
\end{aligned} \tag{5}$$

we obtain

$$M_l = \frac{1}{2}\begin{pmatrix} \left(1+\frac{k_{(l+1)z}\mu_l}{k_{lz}\mu_{l+1}}\right)\mathrm{e}^{-\mathrm{i}k_{lz}d_l} & \left(1-\frac{k_{(l+1)z}\mu_l}{k_{lz}\mu_{l+1}}\right)\mathrm{e}^{-\mathrm{i}k_{lz}d_l} \\ \left(1-\frac{k_{(l+1)z}\mu_l}{k_{lz}\mu_{l+1}}\right)\mathrm{e}^{\mathrm{i}k_{lz}d_l} & \left(1+\frac{k_{(l+1)z}\mu_l}{k_{lz}\mu_{l+1}}\right)\mathrm{e}^{\mathrm{i}k_{lz}d_l} \end{pmatrix}. \tag{6}$$

Then, the relation between the complex amplitudes of the first layer and these of the last layer can be simplified as follows:

$$\begin{pmatrix} A_1 \\ B_1 \end{pmatrix} = \frac{1}{4}\begin{pmatrix} 1+\frac{k_{nz}\mu_p}{k_{pz}\mu_n} & 1-\frac{k_{nz}\mu_p}{k_{pz}\mu_n} \\ 1-\frac{k_{nz}\mu_p}{k_{pz}\mu_n} & 1+\frac{k_{nz}\mu_p}{k_{pz}\mu_n} \end{pmatrix}\begin{pmatrix} a & b \\ c & d \end{pmatrix}^{\frac{N-3}{2}}\begin{pmatrix} \left(1+\frac{k_{pz}\mu_n}{k_{nz}\mu_p}\right)\mathrm{e}^{-\mathrm{i}k_{nz}d} \\ \left(1-\frac{k_{pz}\mu_n}{k_{nz}\mu_p}\right)\mathrm{e}^{\mathrm{i}k_{nz}d} \end{pmatrix} A_N, \tag{7}$$

where

$$a = \frac{1}{4k_{nz}k_{pz}\mu_n\mu_p}\left[(k_{nz}\mu_p + k_{pz}\mu_n)^2\mathrm{e}^{-\mathrm{i}(k_{nz}+k_{pz})d} - (k_{nz}\mu_p - k_{pz}\mu_n)^2\mathrm{e}^{-\mathrm{i}(k_{nz}-k_{pz})d}\right],$$

$$b = \frac{1}{4k_{nz}k_{pz}\mu_n\mu_p}\left[(k_{nz}^2\mu_p^2 - k_{pz}^2\mu_n^2)(\mathrm{e}^{-\mathrm{i}(k_{nz}-k_{pz})d} - \mathrm{e}^{-\mathrm{i}(k_{nz}+k_{pz})d})\right],$$

$$c = \frac{1}{4k_{nz}k_{pz}\mu_n\mu_p}\left[(k_{nz}^2\mu_p^2 - k_{pz}^2\mu_n^2)(\mathrm{e}^{\mathrm{i}(k_{nz}-k_{pz})d} - \mathrm{e}^{\mathrm{i}(k_{nz}+k_{pz})d})\right],$$

$$d = \frac{1}{4k_{nz}k_{pz}\mu_n\mu_p}\left[(k_{nz}\mu_p + k_{pz}\mu_n)^2\mathrm{e}^{\mathrm{i}(k_{nz}+k_{pz})d} - (k_{nz}\mu_p - k_{pz}\mu_n)^2\mathrm{e}^{\mathrm{i}(k_{nz}-k_{pz})d}\right].$$

Now, we are in a position to investigate the surface polaritons of such an N-layer structure. Following Ruppin's work [23], we give the electromagnetic fields in the first layer in the form

$$\begin{aligned} \mathbf{E}_1 &= B_1\mathrm{e}^{\mathrm{i}k_{pz}(z-z_0)}\mathrm{e}^{\mathrm{i}(k_x x-\omega t)}\mathbf{e}_y, \\ \mathbf{H}_1 &= \frac{B_1}{\omega\mu_p}[-k_{pz}\mathrm{e}^{\mathrm{i}k_{pz}(z-z_0)}\mathbf{e}_x + k_x\mathrm{e}^{\mathrm{i}k_{pz}(z-z_0)}\mathbf{e}_z]\mathrm{e}^{\mathrm{i}(k_x x-\omega t)}. \end{aligned} \tag{8}$$

For the electromagnetic fields in other layers, equation (3) can still be used. In this case, equation (7) becomes

$$\begin{pmatrix} 0 \\ B_1 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1+\frac{k_{nz}\mu_p}{k_{pz}\mu_n} & 1-\frac{k_{nz}\mu_p}{k_{pz}\mu_n} \\ 1-\frac{k_{nz}\mu_p}{k_{pz}\mu_n} & 1+\frac{k_{nz}\mu_p}{k_{pz}\mu_n} \end{pmatrix}\begin{pmatrix} a & b \\ c & d \end{pmatrix}^{\frac{N-3}{2}}\frac{1}{2}\begin{pmatrix} \left(1+\frac{k_{pz}\mu_n}{k_{nz}\mu_p}\right)\mathrm{e}^{-\mathrm{i}k_{nz}d} \\ \left(1-\frac{k_{pz}\mu_n}{k_{nz}\mu_p}\right)\mathrm{e}^{\mathrm{i}k_{nz}d} \end{pmatrix} A_N. \tag{9}$$

Equation (9) admits

$$0 = f(k_x)A_N, \tag{10}$$

where $f(k_x)$ is only a function of k_x once the physical and geometric parameters of the materials are given. For evanescent waves, there will exist some k_x which can make equation (10) hold. These k_x correspond to the surface polaritons supported by such an N-layer structure. For the case of $N = 3$, equation (10) yields the dispersion relations of surface polaritons:

$$\begin{aligned} \mu_n &= -\mu_p\frac{k_{nz}}{k_{pz}}\coth\left[\frac{k_{nz}d}{2}\right], \\ \mu_n &= -\mu_p\frac{k_{nz}}{k_{pz}}\tanh\left[\frac{k_{nz}d}{2}\right]. \end{aligned} \tag{11}$$

It is obvious that equation (10) reduces to equations (19) and (20) in [23].

Next, we take one step forward to evaluate the quality of imaging by this multi-layer structure. Again, we consider the two-dimensional model. When this structure is used to image the near field, it is equivalent to a single slab of negative-n material if the perfect lens conditions (i.e., $\mu_n = -\mu_p$ and $\epsilon_n = -\epsilon_p$) are satisfied. However, the perfect lens conditions cannot be satisfied generally because the negative-n materials must be dispersive to maintain the causality of the waves propagating in the media [13]. Any deviation of the permittivity ϵ_n and permeability μ_n of negative-n materials from the perfect lens conditions will exert an influence on the quality of imaging. The quality can be characterized by the recovery rate q of the evanescent waves [12], defined as

$$q = \frac{A_N e^{0.5ik_{Nz}d}}{A_1 e^{-0.5ik_{1z}d}}. \tag{12}$$

Here, we mention that the distance between the object (S) and the first interface is assumed to be $0.5d$, so the distance between the image (S') and the last interface is also $0.5d$ [26]. To evaluate the quality of imaging, we will carry out numerically calculations of the amplitude of the recovery rate and the phase shift of the evanescent waves arriving at the image plane from the object plane, which are given by

$$R = |q| \tag{13}$$

and

$$\theta = \arctan(q''/q'), \tag{14}$$

where q' and q'' are the real and imaginary parts of q, respectively. It is evident that, for the perfect lens, the amplitudes of the recovery rate and the phase shift will be 1 and 0, respectively.

3. Numerical results

First, on the basis of equation (10) we present the dispersion spectra of the surface polaritons for the TE mode supported by the multi-layer structure in figure 2. It is evident that the number of surface polariton branches is the same as the number of interfaces between positive-n and negative-n materials. Thus, we can conclude that a multi-layer structure is capable of exciting more surface polaritons due to the existence of more interfaces. Moreover, with increasing N, the thickness of each thin slice becomes low, and thus the surface modes, localized near the surface of each thin slice, become close to each other. Again, in the case of $N = 3$, our numerical results are in agreement with those in [23].

Then, we will show numerically that the existence of the surface polaritons is responsible for the amplification of evanescent waves. A similar conclusion has been reached in [19]. In figure 3, we plot the absolute values of $f(k_x)$ and the transmission coefficient (i.e., A_N/A_1) as a function of k_x/k_0. It is seen from figure 3(a) that, for some k_x, the absolute value of $f(k_x)$ is almost zero. These values of k_x correspond to the coupled surface polaritons excited by the evanescent waves at the interfaces. Conversely, the surface polaritons result in the amplification of the evanescent waves, characterized by the divergences in the transmission coefficient (see figure 3(b)). Comparing figure 3(a) with figure 3(b), we can see that the sharp peaks of the transmission coefficient are just located at the wavevectors k_x corresponding to the surface polaritons.

Next, we investigate the effect of the deviation of the real parts of the permittivity and permeability from the perfect lens conditions on the near-field imaging of this multi-layer structure. Figures 4 and 5, respectively, give the amplitude of the recovery rate R and the phase shift θ of the evanescent waves as a function of k_x/k_0 for four different kinds of deviation. We obtain the divergences in the amplitude recovery rate R and significant distortions in the phase shift θ at some k_x, corresponding to the surface modes at the interfaces. It is well known that with increase of the number of layers, the number of surface polariton branches increases correspondingly. As a result, the resonant divergences in R and distortions in θ dominate the image resolution in the near field. On the other hand, the first sharp peak in R occurs at a large k_x/k_0 for large N, which indicates that both the amplitude of the recovery rate ($R \approx 1$)

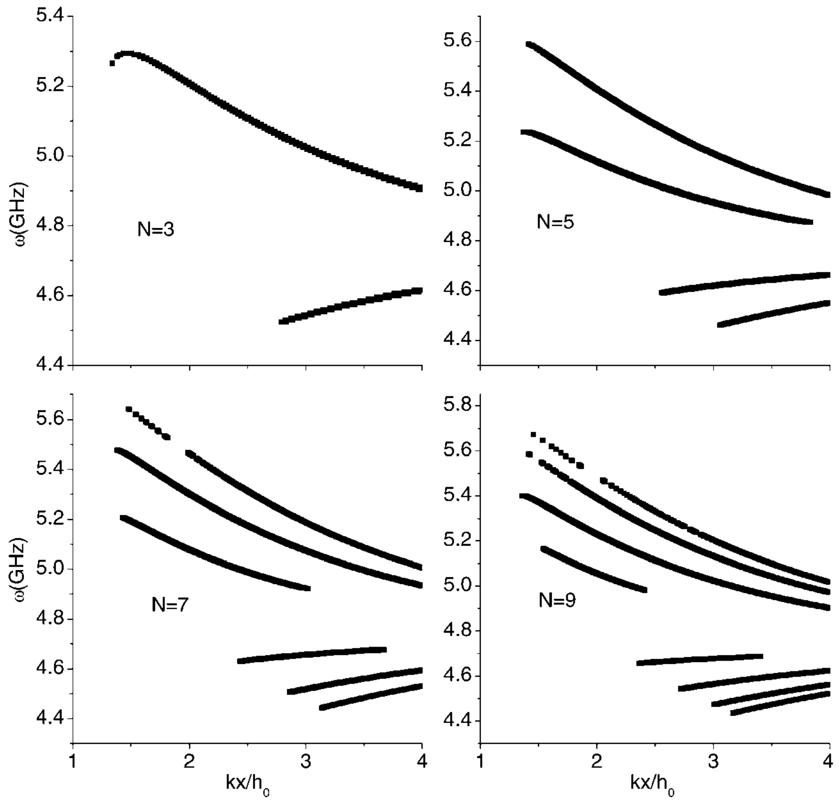

Figure 2. The dispersion curves of the surface polaritons. The parameters are chosen to be the same as for figure 1 in [23], namely $\epsilon_{\rm n}(w) = 1 - w_{\rm p}^2/w^2$ and $\mu_{\rm n}(w) = 1 - Fw^2/(w^2 - w_0^2)$ for $w_{\rm p} = 10$ GHz, $w_0 = 4$ GHz, and $F = 0.56$. The total thickness of the negative-n materials is $w_0 d/c = 0.5$. Note that we only consider the region of 4 GHz $< w <$ 6 GHz, in which $\epsilon_{\rm n}(w) < 0$ and $\mu_{\rm n}(w) < 0$ simultaneously.

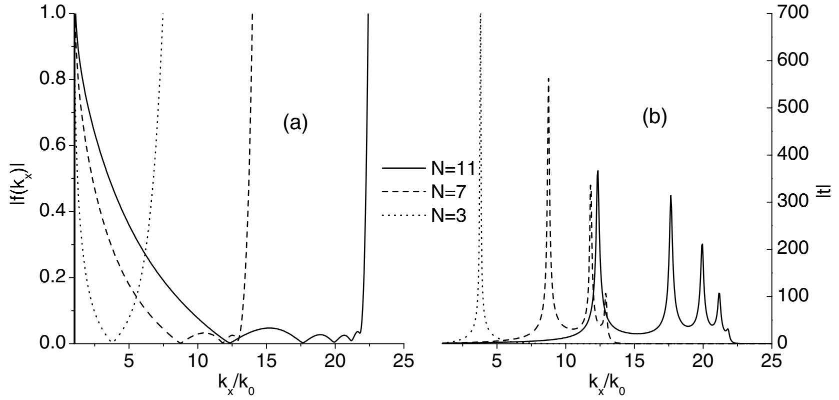

Figure 3. The absolute values of $f(k_x)$ and the transmission coefficient $t = A_N/A_1$ as a function of k_x for $\epsilon_{\rm n} = -1.05 + {\rm i}0.001$ and $\mu_{\rm n} = -1.05 + {\rm i}0.001$. We mention that the total thickness of the negative-n materials is chosen to be $wd/c = 0.5$ in this and the following numerical calculations.

and the phase shift ($\theta \approx 0$) keep flat over a large range of k_x/k_0. Therefore, more evanescent waves before the first peak can be reconstructed, and better image resolution may be obtained

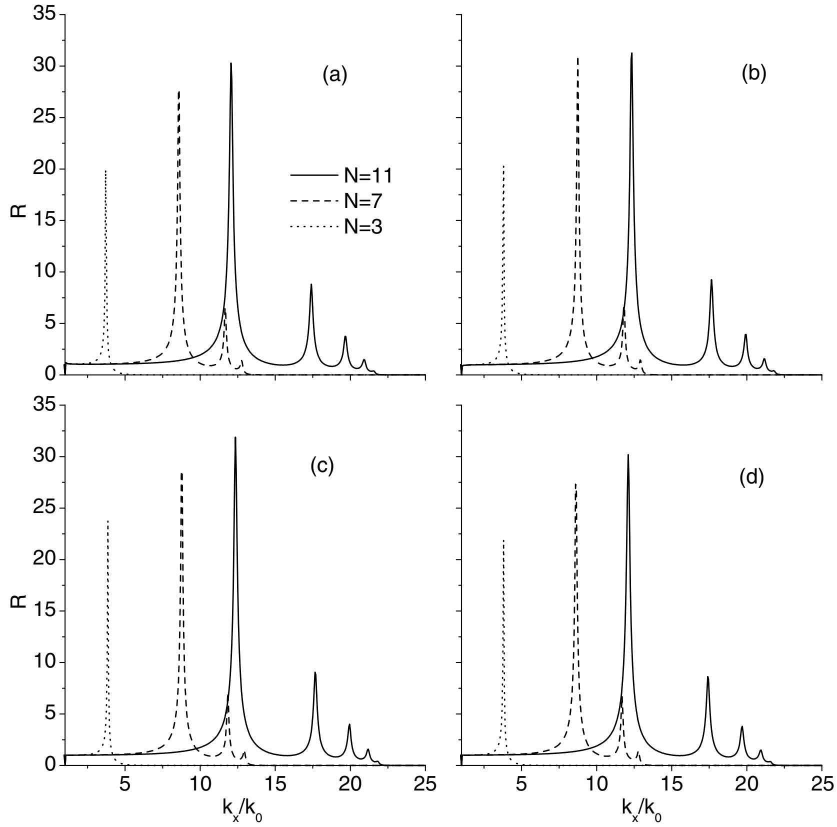

Figure 4. The amplitude of the recovery rate of the evanescent waves R as a function of k_x when $\mathrm{Im}[\epsilon_\mathrm{n}] = \mathrm{Im}[\mu_\mathrm{n}] = 0.001$. Here we take four different deviations: (a) $\mathrm{Re}[\epsilon_\mathrm{n}] = \mathrm{Re}[\mu_\mathrm{n}] = -0.95$; (b) $\mathrm{Re}[\epsilon_\mathrm{n}] = \mathrm{Re}[\mu_\mathrm{n}] = -1.05$; (c) $\mathrm{Re}[\epsilon_\mathrm{n}] = -0.95$ and $\mathrm{Re}[\mu_\mathrm{n}] = -1.05$; and (d) $\mathrm{Re}[\epsilon_\mathrm{n}] = -1.05$ and $\mathrm{Re}[\mu_\mathrm{n}] = -0.95$.

if we use a multi-layer system consisting of very thin slices of negative-n materials when the real parts of the permittivity and permeability are not -1. As far as the variations in the real parts of the permittivity and permeability are concerned, we find that the amplitude recovery rate is more sensitive to permeability than to permittivity.

As we have shown in figures 4 and 5, when the real parts of the permittivity and permeability are not equal to -1, there exist many resonant peaks in R, or many significant transitions in θ. Thus, the evanescent waves near these peaks will be subject to excess amplification and large phase shift, which is not beneficial for improving the image resolution. However, if we take into account the absorption in the negative-n materials, the magnitude of the resonant peaks decreases with increasing absorption; moreover, the peaks can even be removed for large absorption. This can be seen from figure 6. In this regard, further study is needed ascertain whether the image quality is improved.

4. Conclusion and discussion

In conclusion, we have studied the surface polaritons of a multi-layer structure consisting of alternating positive-n and negative-n materials, and shown that the amplification of evanescent waves is due to the excitation of the surface polaritons. The enhancement of the stationary wave amplitude at the rear of such a structure was found to originate from the excitation of

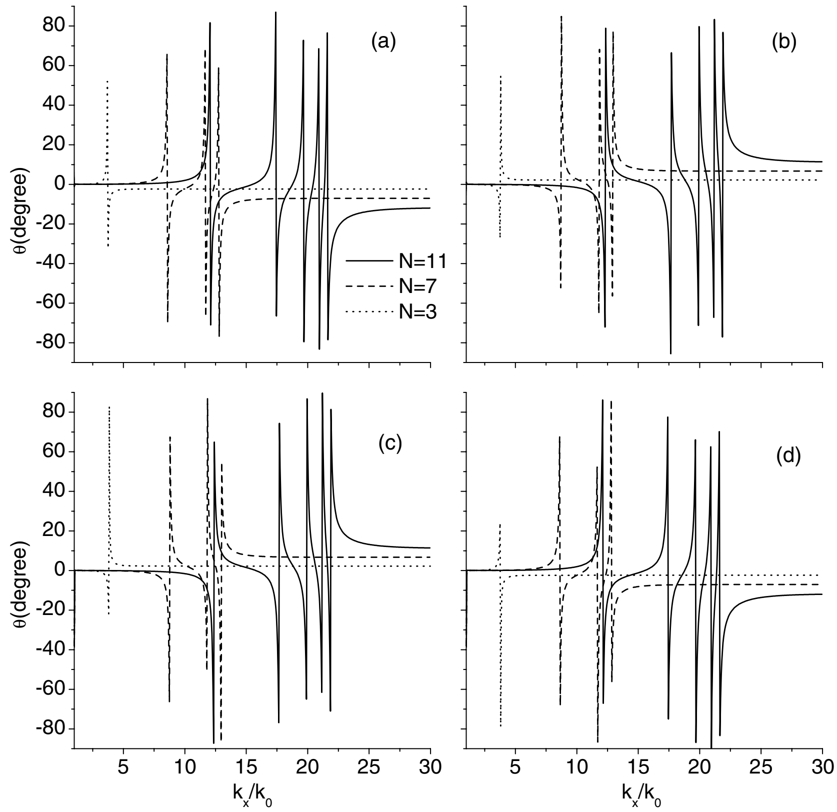

Figure 5. Similar to figure 4, but for the phase shift θ.

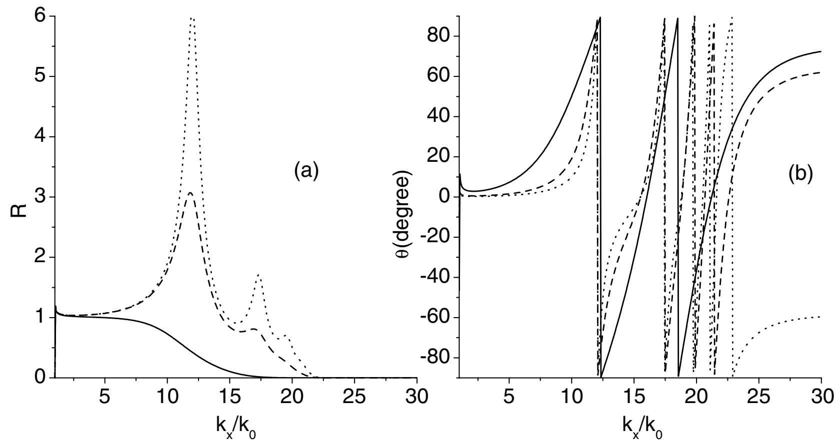

Figure 6. R and θ for three different losses: $\mathrm{Im}[\epsilon_n] = \mathrm{Im}[\mu_n] = 0.05$ (solid curve), $\mathrm{Im}[\epsilon_n] = \mathrm{Im}[\mu_n] = 0.01$ (dashed curve), and $\mathrm{Im}[\epsilon_n] = \mathrm{Im}[\mu_n] = 0.005$ (dotted curve). The other parameters are $\mathrm{Re}[\epsilon_n] = \mathrm{Re}[\mu_n] = -0.95$ and $N = 11$.

surface polaritons. On the basis of our calculated amplitude recovery rate and phase shift, we suggest that the image quality of a lens made as a multi-layer structure may be improved in comparison with that of a lens made of a single negative-n material. Furthermore, we have made a detailed analysis of how the variations in the real parts of the permittivity and permeability and the absorption of negative-n materials affect the image resolution. As these parameters are generally frequency sensitive, our investigation may be useful when performing near-field imaging with a lens made as a multi-layer stack using non-monochromatic waves.

Acknowledgments

We thank the National Natural Science Foundation of China for financial support under Grant No 10204017 and the Natural Science Foundation of Jiangsu Province for financial support under Grant No BK2002038.

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