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# RADIATIVE PROPERTIES OF MULTILAYER THIN FILMS WITH POSITIVE AND NEGATIVE REFRACTIVE INDEXES

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In 1968, Veselago [1] predicted that there could still be propagating waves in a medium that had simultaneously negative permittivity $\varepsilon$ and permeability $\mu$, because the product of $\varepsilon$ and $\mu$ would be positive. However, to ensure energy conservation, he concluded that the refractive index must use the negative square root of the product of $\varepsilon$ and $\mu$ (i.e., $n = -\sqrt{\varepsilon\mu}$). A consequence is certain unusual optical features in negative-index media. The electric field vector **E**, magnetic field vector **H** and wave vector **k** are a left-handed triplet, the basis for calling materials with simultaneously negative $\varepsilon$ and $\mu$ "left-handed materials" (LHMs). LHMs would have novel optical properties. Light at non-normal incidence would bend to the side opposite that in a normal RHM; positive lenses would become negative; a flat slab could focus. The phase velocity of an electromagnetic wave would be opposite to the direction of energy flux, resulting in a reversed Doppler effect. Photons would have negative momentum and apply tension to the interface upon reflection. Recently, this kind of material has been demonstrated experimentally to exist. Shelby *et al.* [2] measured the scattering angle of the transmitted beam through a prism manufactured from a composite material consisting of a two-dimensional array of copper wires and split ring resonators and showed that the effective refractive index of the material is negative at microwave frequencies. Recent theoretical studies also showed that some photonic crystals might have negative-refraction properties in the near infrared spectral region [3].

Although it has not been shown that a material would exhibit negative refraction at optical frequencies, the experimental discovery has stimulated interest in the application of negative refraction materials for images and energy conversions. Pendry [4] hypothesized that, in an extreme situation, a parallel slab fabricated from a negative-refraction material would make a perfect lens because the evanescent modes of EM waves could be amplified on passing through the slab, making the resolution of an image be only a few nanometers and breaking down the far-field diffraction limit. Zhang and Fu [5] showed by numerical simulation that the effect of photon tunneling could be enhanced by a layer of negative refraction; hence one could have a greater value of transmittance or a greater spacing width in a four-layer system as compared with the corresponding values when the negative-refraction layer does not exist. However, a detailed understanding of the wave propagation through positive- and negative-refraction thin films has not been established.

This work presents a systematic investigation of the reflection and transmission of a plane wave by multilayer thin films containing both positive and negative refractive materials. Attention is paid to the effects of absorption, interference, and photon tunneling on the radiative properties when LHMs exist. The effect of spectral dispersion is also considered using appropriate dielectric function models.

A medium of negative refraction only occurs when $\varepsilon$ and $\mu$ are both strongly frequency dependent [1]. The dispersive nature of a negative-refraction medium will be considered in our analysis. The following set of equations was used to describe the electric and magnetic characteristics of the negative-refraction composite material [6]:

$$\varepsilon(\nu) = 1 - \frac{\nu_p^2}{\nu^2 + i\gamma\nu} \tag{1}$$

and

$$\mu(\nu) = 1 - \frac{F\nu^2}{\nu^2 - \nu_0^2 + i\gamma\nu} \quad , \tag{2}$$

where the plasma frequency $\nu_p$ = 10 GHz, the resonant

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frequency $\nu_0$= 4 GHz, the scattering rate $\gamma$ = 30 MHz, and the parameter $F$ = 0.56. The transfer-matrix formulation is modified to incorporate LHMs and applied for calculating the transmittance, reflectance, and absorptance of a multilayer structure. It avoids the inconsistency of the selection of sign for wave vector components as was done in Ref. [4]. Some results of our numerical simulation are discussed below.

Let us first consider a four-layer system, where the first and fourth layers are semi-infinite and made of the same dielectric material with a refractive index of 1.5 ($n_1 = n_4$ =1.5), the intermediate layers are a vacuum ($n_2$ = 1) and a negative-refraction medium, whose frequency-dependent refractive index can be calculated from Eqs. (1) and (2). Figure 1 shows the transmittance, reflectance, and absorptance of the four-layer system versus the frequency of the incident wave. The absorption is only within the LHM. The angle of incidence is equal to 45$^o$, in which case evanescent waves exist in the vacuum gap and maybe in the LHM. The thicknesses of the vacuum and LHM are 0.8 cm. A large transmittance is observed when the real part of the refractive index for the LHM (the third layer) is negative, at frequencies from 4 to 6 GHz, corresponding to the wavelength range of 5 cm < $\lambda$ < 7.5 cm. This behavior is very similar to the reversed band-gap structure of photonic crystals [3]. Its unique feature offers further insight to the understanding of wave coupling in negative/positive index multilayer thin films. There also exists an absorption peak near the resonance frequency (4 GHz).

Figure 2 shows the calculated normal transmittance and reflectance of another two-layer composite, this time in vacuum ($n_1$ = $n_4$ = 1). We assume that the composite is made of a dielectric material and a lossless LHM whose refractive index has the same magnitude as the dielectric material, here taken to be $n_2$ = 3 and $n_3 = -n_2$. The thickness of the composite is fixed and is equal to a quarter of the wavelength. The transmittance and reflectance oscillate as the fraction of the thickness of the LHM is varied; this is caused by interference.

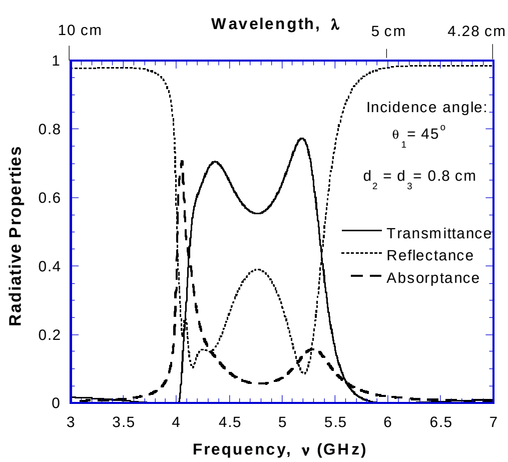


Fig. 1. Calculated radiative properties of a four-layer system.

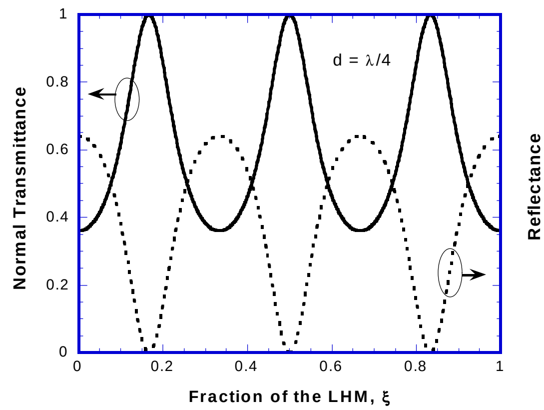


Fig. 2. Normal transmittance and reflectance of a two-layer composite in vacuum as functions of $\xi$ which is the ratio of the thickness of the LHM to the total thickness of the composite.

The oscillation has a period $\Delta\xi = \lambda/(4n_2)$. The transmittance is 1 when $\xi$ = 0.5 and the curve is symmetric with respect to $\xi$ = 0.5. For given $\lambda$, $n$, and $d$, Fig. 2 suggests the possibility of constructing anti-reflection or total-transmission coatings by tuning the fraction of the negative-refraction layer.

In conclusion, we have presented numerical simulations in the investigation of radiative properties of multilayer thin films with positive/negative refractive indexes. The results show that negative-refraction materials can be used in layered structures for constructing anti-reflection or total-transmission coatings or radiation-tunneling band gaps.

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