TRANSMISSION ENHANCEMENT BY USING A NEGATIVE-REFRACTIVE-INDEX LAYER

Z. M. Zhang and C. J. Fu
Department of Mechanical Engineering
University of Florida
Gainesville, Florida 32611, USA

The existence of matter with negative refractive index has been experimentally demonstrated recently by a group from the University of California, San Diego.[1] In their experiments, Shelby *et al.* used a material consisting of a two-dimensional array of repeated unit cells of copper strips and split ring resonators on interlocking strips of standard circuit board material. By measuring the scattering angle of the transmitted beam through a prism fabricated from the material, they showed that the effective refractive index is negative at X-band microwave frequencies where the relative permittivity (ε) and relative permeability (μ) are simultaneously negative. This discovery directly confirmed the theoretical predictions of Veselago[2]. In his paper, Veselago predicted that materials with simultaneously negative permittivity and permeability have unusual electromagnetic-wave propagation properties. The refractive index (n) should take the negative square root of $\varepsilon \cdot \mu$. The electric field vector **E**, magnetic field vector **H,** and wave vector **k** form a left-handed triplet of vectors. For this reason, materials with simultaneously negative values of ε and μ are called Left-Handed Materials (LHM). In LHMs, the phase velocity of a propagating wave is opposite to the direction of its energy flux, thus causing reversed Doppler and reversed Vavilov-Cerenkov effects. In LHMs, photons will have negative momentum and exert a negative pressure (tension) upon reflection. Light incident from a conventional right-handed material (RHM) to a LHM will be bent to the same side as the incident beam, and the refraction angle should be negative for Snell's law to hold. Recent theoretical studies also showed that photonic crystals might exhibit anomalous refractive properties, including a negative refractive index in the near infrared spectral region.

Apart from these unusual properties of propagating waves in a medium whose refractive index is negative, another phenomenon of importance is the behavior of evanescent waves in this kind of medium. Evanescent waves arise from the total internal reflection that occurs when light comes from an optically denser material to another material at incidence angles greater than the critical angle determined by the ratio of the refractive indexes of the two materials. Although no energy is transferred into the second medium, there exists an electromagnetic field whose amplitudes decay exponentially away from the interface. This exponentially decaying field is called an evanescent wave. Recently, Pendry[3] made a case that, in an extreme situation, an evanescent wave could be amplified through a slab of a negative refraction medium. The impact of this discovery on radiative energy transfer may rely on the effect of photon tunneling. Suppose there exists an evanescent wave in the second medium concerned above. If a third medium with sufficiently large refractive index is placed very close to the first one, radiation can tunnel through the second medium into the third. This phenomenon is called photon tunneling. Many people have studied the use of the effect of photon tunneling to enhance radiative energy transfer in microscale devices. Due to the characteristics of evanescent waves, the contribution from photon tunneling is insignificant unless the gap between the 1st and 2nd media is extremely small (i.e., the width of the gap is much less than the wavelength λ). With an additional layer of negative refraction medium, photons may tunnel through a much greater distance as pointed out by the present authors earlier.[4] In our previous study, however, the effect of varying the magnitude of the refractive index was not considered.

We have systematically analyzed the directional (to hemispherical) transmittance and the hemispherical (to hemispherical) transmittance of a 4-layer structure in which the 1st and 4th layers are two semi-infinite dielectrics with the same refractive index; the 2nd layer is a vacuum gap while the 3rd layer is a medium fabricated from a material with a negative refractive index. The enhancement of radiative energy transfer can be achieved with this kind of 4-layer structure at a much larger distance between the two dielectrics as compared to the case without the LHM. The method used for the computation is a modified transfer-matrix formulation. The effects of the magnitude of the refractive index of the LHM and layer thickness on the directional and hemispherical transmittance are predicted. Some numerical results are shown in Figs. 1 and 2. The results, which need experimental verification, show negative refractive index materials could be used to build microscale energy conversion devices of high efficiency.

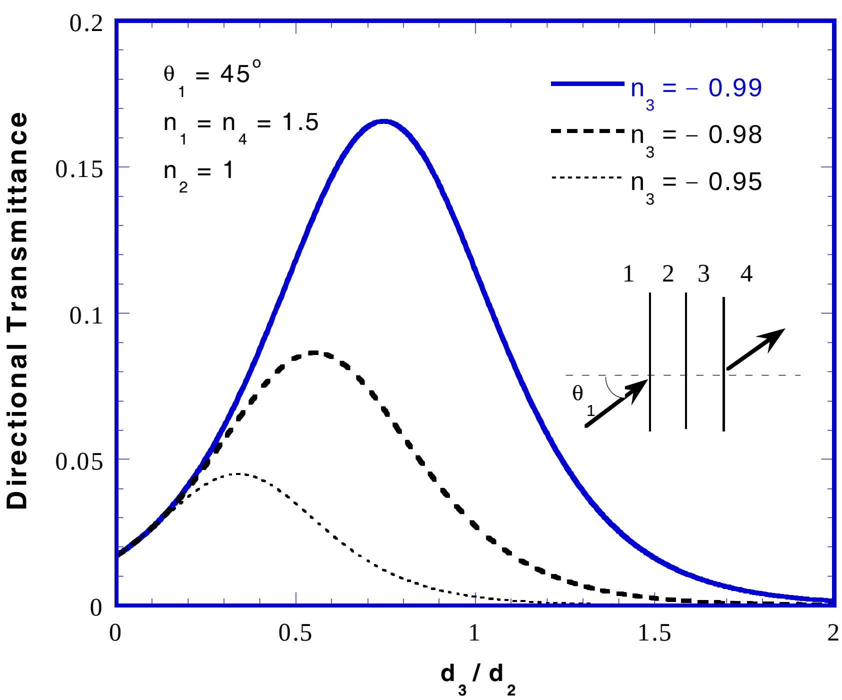

Figure 1. The directional transmittance at 45º angle of incidence of the 4-layer structure, where d_2 is the thickness of vacuum gap and d_3 is the thickness of the LHM. The wavelength λ is set equal to d_2. The refractive indices of the 1st and 4th semi-infinite layers are 1.5. The critical angle is ≈ 42º. This figure demonstrates the effect of the refractive index (n_3) and thickness (d_3) of the LHM on the transmittance due to photon tunneling.

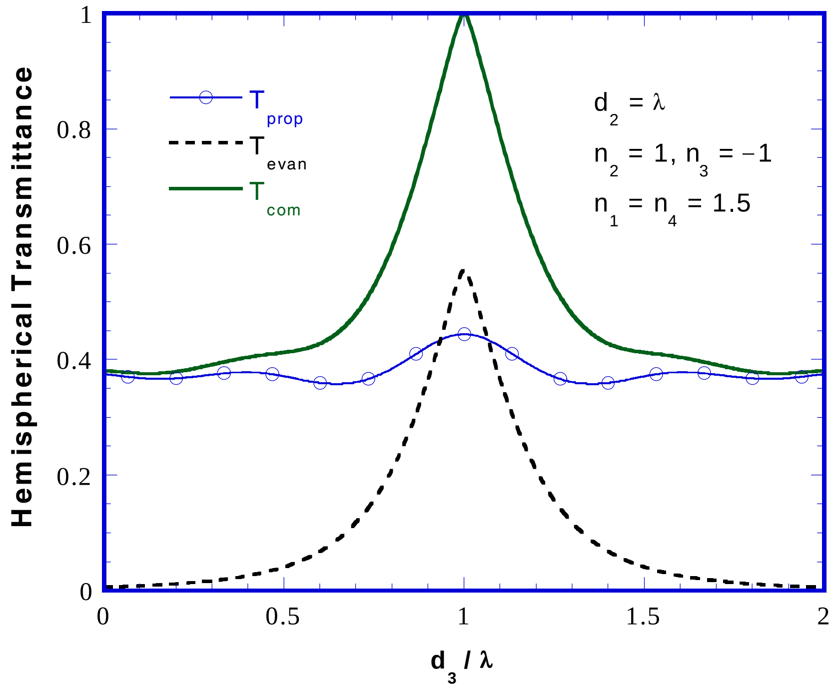

Figure 2. The hemispherical transmittance of the 4-layer structure as a function of d_3 for $n_3 = -1$. The other parameters are the same as those used in Fig. 1. T_{prop}, T_{evan}, and T_{com} denote the hemispherical transmittance contributed from propagating waves, evanescent waves, and the combination of the two parts, respectively. When $d_3 = \lambda$ $(= d_2)$ and $n_3 = -n_2$, the transmittance becomes unity. The contribution of photon tunneling is very sensitive to the thickness mismatch or refractive index mismatch.

The authors thank the National Science Foundation for the financial support through grants CTS-9875441 and CTS-0082969.

REFERENCES

1. Shelby, R.A., Smith, D. R., and Schultz, S., Experimental Verification of a Negative Index of Refraction, *Science*, Vol. 292, pp. 77-79, 2001.
2. Veselago, V.G., The Electrodynamics of Substances with Simultaneously Negative Values of ε and μ, *Sov. Phys. Usp.* Vol. 10, pp. 509-514, 1968.
3. Pendry, J.B., Negative Refraction Makes a Perfect Lens, *Phys. Rev. Lett.* Vol. 85, pp. 3966-3969, 2000.
4. Zhang, Z.M. and Fu, C.J., Unusual Photon Tunneling in the Presence of a Layer with a Negative Refractive Index, *Appl. Phys. Lett.*, 2002 (in press).