

Numerical study of high reflection coatings with negative and positive refractive indexes

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In this communication, we intend to create a stratified coatings comprised of negative and positive refractive indexes, NRI and PRI, to achieve high reflection. The emphasis of this work is on the reflection feature and how it can be increased. Generally, quarter wave length longs of high and low refractive index media are applied to the substrate to form NRI-PRI multilayer stacks. By choosing the proper indexes, the various reflected wave fronts can be made to interfere gainfully to generate a well-organized reflector. The reflectance peak depends on the ratio of refractive indexes of two media, as well as the number of stack pairs. The coatings and computations are performed and determined using the theory of transfer matrix method. Numerical results of this work show that the coatings are effective for both parallel and perpendicular polarization components, and can be designed for a wide frequency range. In addition, this communication also provides to be able to decrease/increase the frequency range to the desired band and to make size reduction in the layer number.

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1. Introduction

Recently, there have been many studies on metamaterials having simultaneously negative permittivity and permeability which yields negative refractive index over a certain frequency ranges. These metamaterials are generally known as left-handed (LH) or negative refractive index (NRI) materials and theoretically started to discuss first by Veselago in 1968 [1]. In his paper, the possibility of negative refractive index is discussed in detail. He showed that the electric field vector \mathbf{E} , the magnetic field vector \mathbf{H} , and the wave vector \mathbf{k} form a left-handed triplet of vectors, and the Poynting vector \mathbf{S} and vector \mathbf{k} are in opposite directions. In addition, it is illustrated that the Doppler Effect and Vavilov-Cerenkov radiation is reversed in NRI materials. He also showed the negative refraction and backward waves in such materials. Furthermore, wave propagation in NRI materials was also given in his paper. His study had major results and the development of such artificial materials was accelerated by his proposal and suggestions. His predictions were confirmed approximately thirty years later when Pendry and his colleagues presented their studies on the possibility of the realization of the negative permittivity and the negative permeability, respectively. They demonstrated that the negative electric permittivity can be achieved

artificially by suitable arrangement of the periodic metallic wires in 1996 [2]. Beside that, they proposed that how to design structures made from non-magnetic thin sheets of metal to acquire negative magnetic permeability in 1999 [3]. Next, Smith and his collaborators created a composite material with NRI by inspiring the proposal of Veselago and the studies of Pendry et. al. in 2000 [4]. In their study, they created a NRI medium, based on split ring resonators and continuous wires, that shows simultaneously negative permeability and permittivity in the microwave frequency region. They did many microwave experiments to test the Doppler Effect, Cherenkov radiation, and Snell's law using this new NRI material to present the unconventional features of the created structure. In 2001, Ziolkowsky and Heyman presented their analytical and numerical study on the propagation of electromagnetic waves in NRI media [5]. They illustrated the analytical continuation based choices of the square roots associated with the refraction index and introduced the wave impedance. Furthermore, the 1D plane wave scattering from a NRI interface and a NRI slab; and the 2D line source cylindrical wave excitation of the NRI slab were presented throughout their study. Then, Kong provided an extensive study on the electromagnetic wave interaction with NRI media by starting to analyze the oblique wave incidence from semi-infinite free space upon a semi-infinite NRI medium

and continuing with the detail analysis of the plane wave incident on a stratified isotropic NRI media [6]. After that, a brief overview of electromagnetic properties of NRI media and some ideas for potential applications of NRI materials were discussed by Engheta in 2002 [7].

The problems of radiation, scattering, and guidance of electromagnetic waves in NRI materials, and the combined NRI-PRI layers for future potential applications such as phase conjugators, unconventional guided-wave structures, compact thin cavities, thin absorbing layers, and high-impedance surfaces were presented in his study. Afterward, Chew studied the energy conservation property and loss condition of a NRI material in 2005 [8]. In his study, energy conservation, the equivalence of the loss and the Sommerfeld far-field radiation conditions for NRI material, and the realistic Sommerfeld problem of a point source over an NRI half space and an NRI slab were demonstrated. Additionally, the numerical study on the propagation and refraction of a cylindrical wave through a NRI slab [9], the investigation of the time-domain electric and magnetic energy stored in a frequency dispersive NRI medium [10], the analysis of the reflection and transmission characteristics of a multilayered structure consisting of NRI material and dielectric slabs [11], and some interesting applications of NRI materials [12] can be given as additional references to the NRI material works and their potential applications as well as others. Furthermore, Sabah et. al. have been also studied the wave propagation through NRI media, scattering features of some constructions including NRI materials, and reflection and transmission characteristics of various configurations for particular applications [13-21]. In addition to all mentioned studies, many researchers continue to study the NRI materials and their future applications to build new constructions such as multilayer structures for special purposes.

In this work, it is intended to create a stratified structure comprised of NRI and PRI layers for high reflectivity coatings for microwave applications. High reflection coatings are formed from N pieces of NRI and PRI slabs with different material properties and thicknesses. In general, quarter wave length thicknesses of alternately high and low refractive index materials are applied to the substrate to form a NRI-PRI coating. By selecting the materials of appropriate refractive indexes, the various reflected wave fronts can be made to interfere constructively to produce a highly efficient reflector. The peak reflectance value is dependent upon the ratio of the refractive indexes of the two materials, as well as the

number of layer pairs. Increasing either increases the reflectance. The larger the ratio is, the wider the high reflectance region will be. Furthermore, the coatings are effective for both parallel and perpendicular polarization components, and can be designed for a wide angle of incidence range. In the theory, the incident electric field is assumed a monochromatic plane wave with any arbitrary polarization. Transfer matrix method will be used in the analysis. Simply, the electric and magnetic fields both inside and outside the multilayer structure are obtained by imposing the boundary conditions and then the transfer matrix is achieved. Note that, the elements of the transfer matrix are expressed as a function of the incidence angle, the structure parameters, the thickness of each slab, and the frequency (for details see [18-21]). All computations are based on the mentioned theoretical analysis. Propagation properties in multilayered structures consisting of metamaterial and dielectric layers are studied in [11]. A structure containing several identical pairs of alternating dielectric and metamaterial slabs is demonstrated to maximize the reflection for the high frequency range ($\times 10^{11}$). It was found that for these metamaterial dielectric high reflection structures the pass band is larger and the effects of angle of incidence and polarization was less dominant as compared to the all dielectric structures. Moreover, these structures show no ripples and a monotonous quasi symmetric rise in their transmittance to the left and to the right of central frequency was observed. This kind of structures is further studied in our work to decrease the frequency range and to reduce the number of layers.

2. Numerical results

In the computations, the incident electric field is assumed as the plane electromagnetic wave with the perpendicular polarization ($E_{\parallel} = 0$). The operation frequency is selected to be $f_o = 10$ GHz. The thicknesses are arranged to become quarter wave length long at the operation frequency. In our configuration, seven NRI and PRI layers embedded in air are considered.

First of all, the frequency response of all dielectric structure with the high and low refractive indexes is shown. The permittivity and permeability of are selected 12.2500 and 1.0 (silicon-Si) for high index layers; and 1.8225 and 1.0 (cryolite- Na_3AlF_6) for low index layers [23]. Figure 1 presents the reflectance and transmittance for all dielectric layers as a function of the frequency for the incidence

angles of 0° , 20° , and 40° . Solid lines correspond to 0° , dotted lines to 20° , and dashed lines to 40° . As it is seen from the figure, the reflectance becomes unity and the transmittance becomes zero at and around the central frequency. The symmetry shifts in frequency to the right side when the incident angle increased. The reflectance region is wider than the coating investigated in [11]. In addition, there are more ripples in the frequency behavior of the reflectance and transmittance.

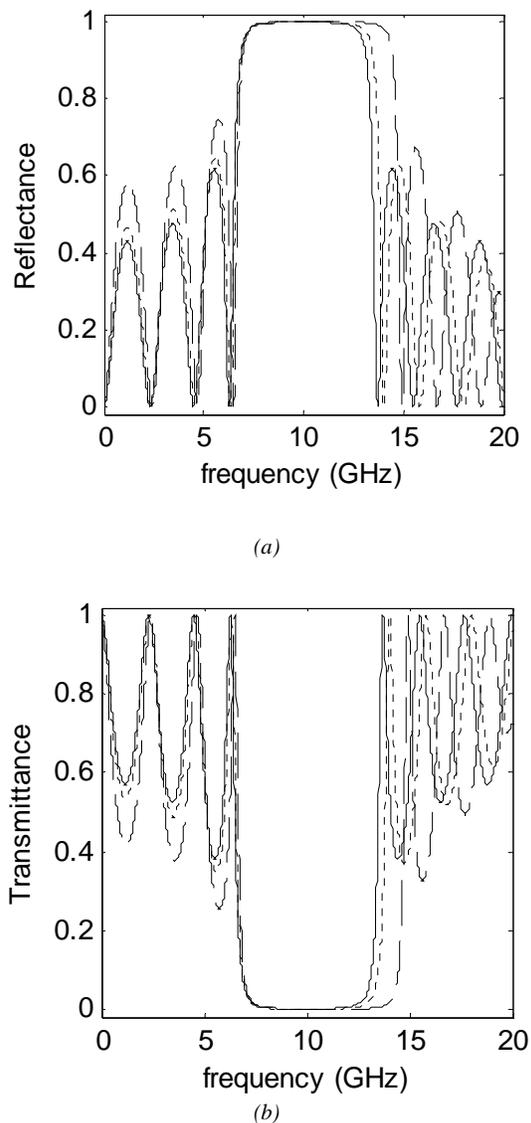


Fig. 1 Reflectance and transmittance for all dielectric layers as a function of the frequency for the incidence angles of 0° , 20° , and 40° . Solid lines correspond to 0° , dotted lines to 20° , and dashed lines to 40° .

Secondly, the frequency response of seven NRI and PRI layers is presented. The permittivity and permeability

are -12.2500 and -1.0 for NRI layers and 1.8225 and 1.0 for PRI layers, respectively. Fig. 2 shows the reflectance and transmittance for the combination of NRI and PRI layers versus frequency for the incidence angles of 0° , 20° , and 40° . Solid lines correspond to 0° , dotted lines to 20° , and dashed lines to 40° . It is found that, for this NRI-PRI high reflection structures the pass band is larger and the effect of the incident angle is less dominant as compared to the all dielectric structures. In addition, these structures have no ripples and no sharp shifts and therefore they can be used as high reflection coatings. Furthermore, the reflectance band achieved here is wider than the region obtained for the coating investigated in [11].

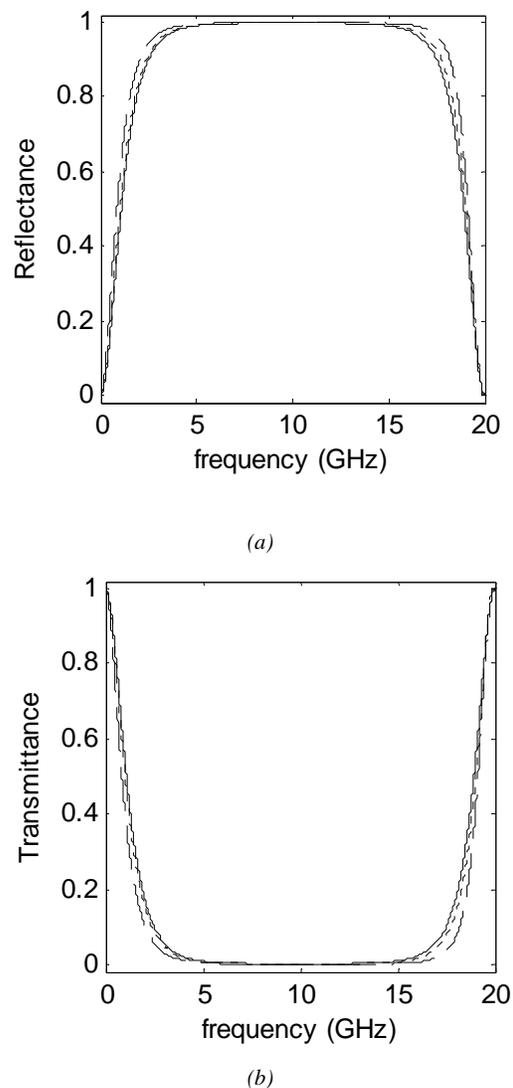


Fig. 2. Reflectance and transmittance for NRI and PRI layers versus frequency for the incidence angles of 0° , 20° , and 40° . Solid lines correspond to 0° , dotted lines to 20° , and dashed lines to 40° .

The reflectance and transmittance for stratified structures consisting of half wavelength long NRI and PRI layers are also computed to show the effect of the layer thickness. The same parameters are used as in the previous example except the thicknesses. The computed results are presented in Fig. 3. From the figure, the frequency band for high reflectance is narrow and split into two parts in this example. The reflectance has two peaks instead of the main one opposite to the previous example because of the new thicknesses arrangement. Also, there is high transmission at the operation frequency. Fig. 3 recommends creating high transmission coatings using NRI and PRI layers.

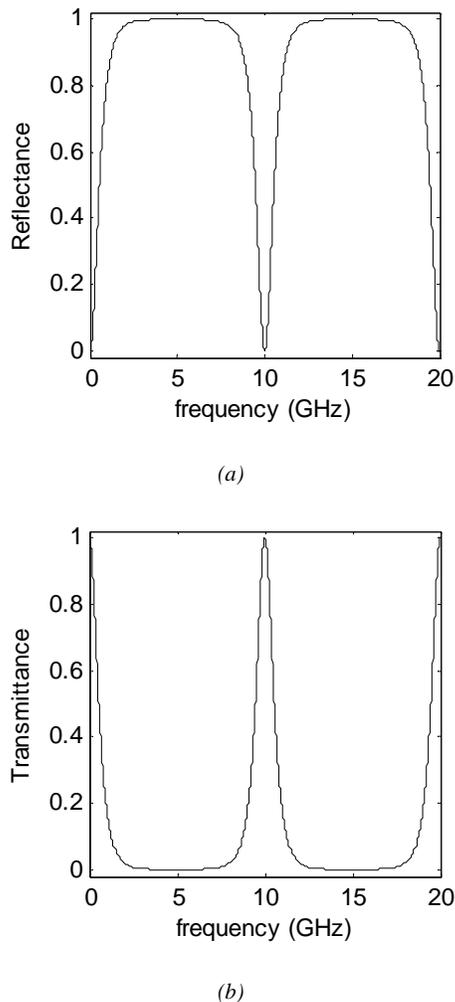


Fig. 3. Reflectance and transmittance for half wavelength long seven NRI and PRI layers against the frequency.

Using the results of the previous example, we tried to create high transmission coatings using NRI and PRI layers. After proper combination of seven NRI and PRI layers, a high transmission coating can be created. To do this, NRI layers is selected to be a quarter wavelengths long while PRI layers are a half wavelengths long. The

permittivity and permeability of are selected -5.0625 and -1.0 for high index layers and 2.1025 and 1.0 for low index layers. The results are shown in Fig. 4. According to the figure, high transmission occurs in many frequency bands. At these bands, transmittance sometimes becomes unity while the reflectance vanishes. At some bands shown in the figure, the reflectance becomes greater than the transmittance. Thus, the structure can be utilized as high and partially transmission coatings.

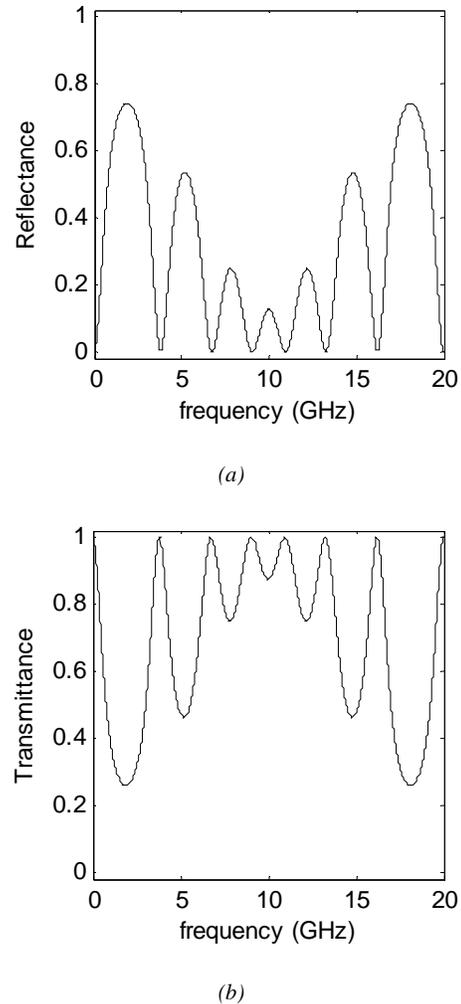


Fig. 4. Reflectance and transmittance for half wavelength long NRI and quarter wavelength long PRI layers versus the frequency.

Note that, the numerical computations obtained here can easily be extended for the incident wave with the parallel polarization.

4. Conclusions and discussion

This communication addresses the optical properties of the stratified coating comprised of NRI and PRI layers.

The coating containing several identical pairs of NRI-PRI stacks is demonstrated in order to optimize the reflection characteristic of the structure for the microwave frequency range. It is found that for NRI-PRI high reflection coatings, the pass band is larger and the effect of angle of incidence and polarization is less dominant as compared to the all PRI structures. Furthermore, these structures display no ripples but a monotonous quasi symmetric rise in the transmittance to the left and to the right of operation frequency is observed. Moreover, a high transmission coating comprised of NRI and PRI layers, with multi-bands behavior, can be created using the results obtained in this communication. A numerical example is already presented in the previous section. The mentioned high transmission coating can be further studied and it can be considered for future studies. Note that, the presented topic has very rapid progress in telecommunication, information processing, and storage of energy and therefore it can easily find many potential applications for the microwave and optical systems.

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