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A three-dimensional backward-wave network matched with free space

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Abstract

A backward-wave slab based on a capacitively and inductively loaded three-dimensional transmission-line network is designed in such a way that impedance-matching with free space is obtained. To enable field propagation from free space to the network and vice versa, the use of a transition layer is proposed. Matching of the designed network with free space and negative refraction occurring at the slab interfaces are confirmed with full-wave simulations.

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Keywords: Transmission-line network; Backward wave; Negative refraction

1. Introduction

As suggested by Veselago [1], a material with negative permittivity ε and permeability μ (a backward-wave material) can be used as a flat lens that focuses propagating electromagnetic waves. Due to the negative ε and μ, the wave propagation in this material differs significantly from any material found in nature, since the phase and group velocities are antiparallel. Furthermore, as shown by Pendry [2], a slab of such material can be used as a superlens that, besides focusing the propagating waves, enhances the evanescent waves of a source.

First experimental demonstration of negative refraction, that occurs on the interface between a material with positive ε and μ and a material with negative ε and μ, was achieved with a slab made of a composite material consisting of metal wires and split-ring-resonators [3]. The use of resonant particles in creating the wanted negative μ has the drawback of very narrow operation bandwidth and high sensitivity to losses. An alternative approach to creating a "material" with negative ε and μ, based on networks of loaded transmission lines (TLs), has been proposed [4,5]. The benefit of this approach is the fact that the exotic wave propagation is not due to use of resonant particles and thus the operational bandwidth and losses are not so critical issues. The drawback of such structures in superlens applications is that coupling of waves from free space to such a network is not trivial. Indeed, superlenses proposed in the literature, that are based on the TL-method, have mostly used sources which are embedded in a TL network as well, see, e.g., [6]. Recently, also three-dimensional extensions of the TL-method have been proposed [7–11] and realized [11,12].

Recently, a design of a TL network with negative index of refraction, that can be matched with free space, was proposed [13]. This approach can be realized for two-dimensional TL networks, i.e., a set of two-dimensional TL networks can be stacked on top of each other creating a volumetric slab. In this Letter, we propose a transition layer to couple waves from free space to a TL network such as proposed in [6] (two-dimensional TL network) and in [9] (three-dimensional TL network). The transition layer is effectively an array of antennas that covers the whole interface between free space and the TL network. This approach, as compared to the previous design [13], has the benefit of freedom in the design of the TL network, since the network itself does not have to be coupled with free space. Moreover, there are no parasitic forward waves, since fields are concentrated in the TLs only.

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2. Design of the loaded transmission-line network

In this Letter we study the structure presented in [9,12], although the proposed method of matching a TL network with free space can be used for other types of networks as well, see, e.g., [14]. In [14] this method was used to match an unloaded TL network with free space in order to obtain broadband cloaking of small objects in the microwave region. As compared to the previous designs in [9,12], here we do not have an unloaded network representing a material with positive ε and μ, but instead, a transition layer that enables electromagnetic waves from free space to propagate into the TL network and vice versa.

To optimize matching with free space, we need to design the TL network in such a way that its impedance equals that of free space ($120\pi\ \Omega \approx 377\ \Omega$). Using the previously derived dispersion and impedance equations [9], we have found suitable dimensions and parameters for the network operation in the microwave region, see Table 1. The reader should note that throughout this Letter we assume the lossless situation. For analysis of this type of networks with taking into account the losses see, e.g., [10].

The resulting dispersion and impedance curves are presented in Fig. 1. From Fig. 1 we can conclude that the optimal operation frequency for the network studied in this example case is around 4 GHz, since there we obtain matching of the wavenumbers and impedances of the network and free space. The operation frequency can be changed by varying the values of the lumped capacitances (C) and inductances (L) and by tuning the impedance of the transmission lines.

Although in Fig. 1(a) only the axial propagation is plotted (the total wavenumber $k = k_z$ while $k_x = k_y = 0$), the network can be considered to be isotropic in a relatively large band near the operating frequency, as was shown in [10]. The isotropy is achieved at frequencies at which the period of the network is much smaller than the wavelength inside the network. Isotropy of these networks is discussed more thoroughly in [10].

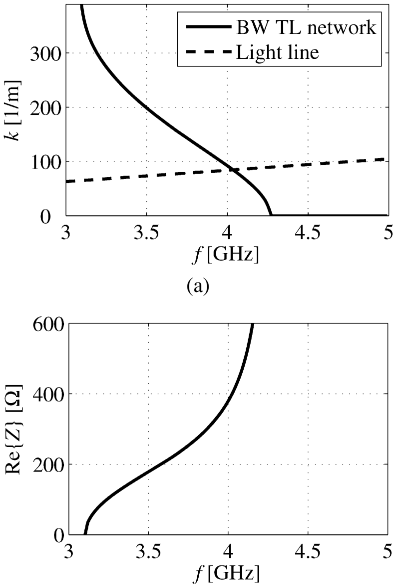
3. Transition layer and simulation model

As the TL network that is used here is similar to previous designs [9,12], it can be conveniently realized using the microstrip technology. The transition layer can therefore be realized with parallel-plate-waveguide type of TLs at the ends of the network, as illustrated in Fig. 2(a). Naturally, this way we can obtain operation for one polarization only as in [13]. The benefit of this method is its simplicity.

We have made full-wave simulations of the proposed backward-wave slab (the three-dimensional TL network with a finite thickness) with the transition layers and sections of free space on both sides of the slab. The simulations were done using Ansoft's High Frequency Structure Simulator (HFSS). The studied slab has a finite thickness in the direction of the z-axis and is infinite in the transversal directions. The simulation of the transversally infinite slab can be greatly simplified by using periodical boundary conditions. This way we can simulate only one "unit cell" of the slab, as shown in Fig. 2(a).

Table 1
Transmission-line network parameters

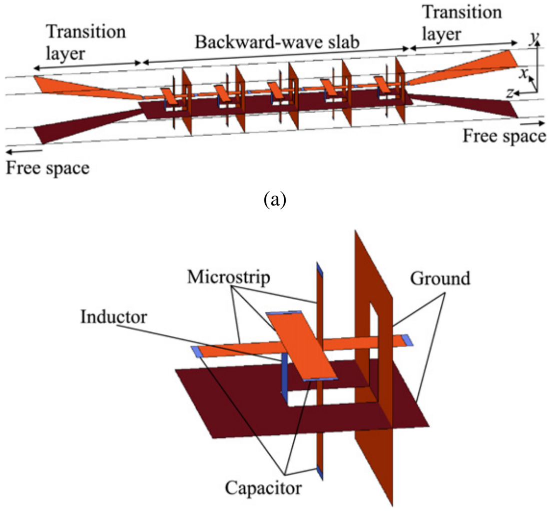
Period	TL impedance	C	L	ε_r
8 mm	150 Ω	0.1 pF	2.5 nH	1



(a)

(b)

Fig. 1. Wavenumber (a) and impedance (b) as functions of the frequency in a three-dimensional loaded transmission-line network with parameters as shown in Table 1. Here $k = k_z$ (axial propagation in the network).



(a)

(b)

Fig. 2. (Color online.) (a) HFSS model of one "unit cell" of the backward-wave slab. (b) HFSS model of one unit cell of the backward-wave transmission-line network. The microstrip lines of the unit cell in (b) are loaded by six capacitors (one capacitor at each end of the line, with capacitance equal to $2C = 0.2$ pF) and one inductor (connected from the center node to the ground, with inductance equal to $L = 2.5$ nH).

The TL network has the same parameters as shown in Table 1. The metal strips are made of infinitely thin perfect electric conductors and have the width of 1.3 mm with the distance from the ground being 2 mm. Small holes are cut into the horizon-

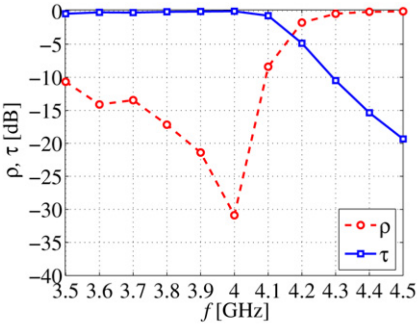


Fig. 3. Simulated reflection and transmission through the backward-wave slab as a function of frequency for the normal incidence.

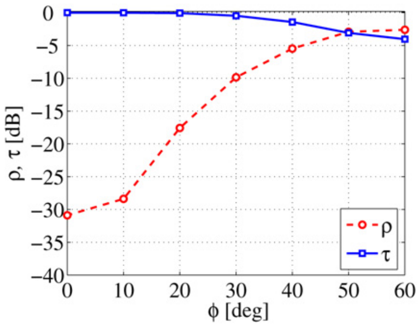


Fig. 4. Simulated reflection and transmission through the backward-wave slab as a function of the incidence angle at the frequency 4 GHz.

tal and vertical ground planes to allow wave propagation in all axial directions, see Fig. 2(b). As shown in Fig. 2(a), the thickness of the slab is five periods in the direction of the z-axis. The width of the TLs of the transition layer gradually changes from 2 mm to 7.988 mm, with their length being 16 mm. The width and height (in the xy-plane) of the whole simulation model, shown in Fig. 2(a), are both equal to the period of the network, i.e., 8 mm. The neighboring TLs of the transition layer are not in contact, since there are approximately 12 μm and 4 μm gaps between them in the x- and y-directions, respectively.

The TLs of the transition layer are simply parallel metal strips with their width equal to their separation, thus having approximately the impedance of free space (note that no dielectric filling is used between the strips of the network or the transition layer). The length of these lines can in principle be chosen arbitrarily. Matching problems may arise if the transition layer is too short, i.e., if the angle of the tapering is very large. That is why in this example case we have chosen the length of the TLs in the transition layer to be 16 mm. This enables relatively smooth transition while having a reasonably short distance between free space and the TL network.

4. Simulation results

First the case of the normal incidence was studied, i.e., a plane wave in free space with the wave vector $\bar{k}$ parallel to the z-axis and electric field $\bar{E}$ parallel to the y-axis illuminates the backward-wave slab. By studying the reflection (ρ) and transmission (τ) coefficients, it was found that the optimal operation frequency for the structure was approximately 3.6 GHz (the frequency point where most of the power goes through the slab). This implies that the impedance of the network was best matched to free space at that frequency, since the transition layer impedance does not depend on the frequency. By changing the inductance value of the lumped inductors to $L = 2$ nH, the reflection and transmission curves shown in Fig. 3 were obtained, showing good correspondence with Fig. 1(b).

We believe that the slight difference in the value of the inductance with which operation at 4 GHz is achieved, as compared to the analytical study, is a result of differences between the analytical and simulation models. The analytical equations do not take into account the finite size of the lumped elements and the equations used to calculate the data presented in Figs. 1(a) and 1(b) do not take into account the finite thickness of the slab [9]. The study of this inaccuracy is out of the scope of this Letter, since here we wish to illustrate the feasibility of the proposed matching method as such.

From Fig. 3 it is seen that the optimal frequency of operation (for normal incidence) is approximately 4 GHz. To study the dependence of the transmission and reflection on the incidence angle, we have made simulations with the same model for oblique plane-wave illumination. The polarization of the illuminating wave is kept the same, i.e., $\bar{E}$ is parallel to the y-axis and therefore the incidence angle ϕ is the angle in the xz-plane. See Fig. 4 for the results when $\phi = 0^\circ \ldots 60^\circ$. We can conclude that the transition layer operates very well also for fairly large oblique incidence angles, although the transmission clearly reduces when ϕ grows.

With the model shown in Fig. 2(a) the refraction on the interface between free space and the backward-wave slab may not be visible due to the small size of the simulation model in the transversal direction. To observe negative refraction, we have extended the simulation model to encompass three “unit cells” of the slab in the x-direction. See Fig. 5 for the simulated phase distribution in this larger simulation model at the frequency 4 GHz and with incidence angle of $\phi = 30^\circ$. The relative refractive index of the slab seems to be close to -1, which is expected based on the dispersion curve shown in Fig. 1(a).

Preliminary simulations show that at least for small angles of incidence also in the yz-plane (angle θ), the transition layer operates well. For instance, for the incidence angle of $\theta = 20^\circ$ (with $\phi = 0^\circ$) the reflection from the backward-wave slab is below -15 dB at the frequency 4 GHz.

5. Conclusions

We have proposed and studied a transition layer for matching a slab of a backward-wave transmission-line network with free space. We have analytically studied how the network impedance can be tuned to match that of free space. The proposed network and transition layer have been simulated using a commercial full-wave simulator. The simulation results show that the layer can be used to match a backward-wave transmission-line network with free space and verify the negative refraction occurring at the interfaces between free space and the network.

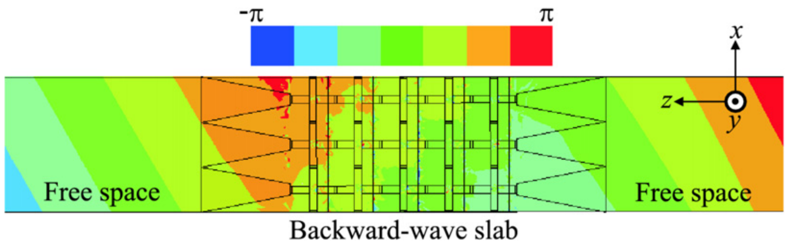


Fig. 5. (Color online.) Simulated phase distribution in free space and inside the backward-wave slab, at the frequency 4 GHz. Incidence angle $\phi = 30^\circ$.

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