Novel Architecture for Waveguide Based Metamaterials

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Abstract—A novel architecture for waveguide based double-negative (DNG) metamaterials has been proposed. Periodic waveguide structures loaded with double strips printed on dielectric exhibit a DNG passband where both electrical permittivity and magnetic permeability are negative. The printed strips contribute to negative permeability whereas dielectric layer inside waveguide produce negative permittivity. The printed periodic waveguide structure also shows negative index of refraction and backward wave propagation. The efficient and accurate hybrid MoM-Immittance approach has been employed for material parameter extraction.

Key-words—DNG metamaterials, periodic waveguide structures, backward waves and hybrid MoM-Immittance approach.

I. INTRODUCTION

Artificial materials with unusual electromagnetic properties like negative electric permittivity, magnetic permeability and negative index of refraction that are not found in naturally occurring materials were theoretically hypothesized by V. Veselago [1] in 1968. Such artificial materials, also called as double-negative (DNG) metamaterials, has been a topic of high research interest recently. Several theoretical and experimental verifications of the existence of DNG metamaterials have been reported [2]-[6]. Available architectures/configurations/geometries for DNG metamaterials are quite complex. Here, we propose a novel simplified structure/architecture for DNG metamaterials in shielded waveguide environment. X-band waveguide structure loaded with double strip layers printed on dielectric substrate shows a passband characteristic where electric permittivity, magnetic permeability and refractive index are negative.

Full-wave hybrid MoM-Immittance approach [7] has been developed for efficient and accurate analysis of printed waveguide structures. It has been used here for the extraction of material parameters like effective electric permittivity, magnetic permeability and refractive index. The scattering parameters obtained for a unit cell of the proposed DNG metamaterial architecture are transformed to ABCD parameters and effective electric permittivity, magnetic permeability, refractive index are extracted from the ABCD parameters. The dispersion diagram for the proposed DNG metamaterial exhibits visible backward wave propagation in DNG metamaterials frequency region.

II. EXTRACTION OF MATERIAL PARAMETERS

A two-port network realization of the DNG metamaterial loaded microstrip transmission line is presented in [5]. There are two possible two-port network representations. First one, two-port T-network representation using three set of impedances Z_1, Z_2 and Z_3. Second approach in two port network realization is the lossless transmission line of length p. In waveguide configuration, two-port T-network representation of printed waveguide structures for equivalent circuit parameter extraction has been investigated [7]. We have also studied the two-port network representation in the form of lossless transmission line (waveguide) of length p for the printed periodic waveguide structure [8]. Fig. 1(a) illustrates 3-D geometry of rectangular waveguide loaded with double strips printed on dielectric layer and dimensions for three cases under investigation are illustrated in Table I. As mentioned in [5], equivalent circuit parameter extraction using T-network representation as depicted in Fig. 1(b) assumes that Z_1, Z_2 and Z_3 are independent of each other, i.e., there is no coupling between the impedance elements. It is not the best representation for DNG metamaterials and hence will not be discussed here. Instead, we will consider two-port network representation of a lossless transmission line (waveguide) of length p for a unit cell of the periodic waveguide based structure as depicted in Fig. 1(c).

Table I Dimensions of three cases under investigation of the newly proposed DNG metamaterials

Parameters	w	l	h	p	ε_r
Case I	8.00mm	6.00mm	1.00mm	3.00mm	3.78
Case II	8.00mm	6.00mm	2.00mm	3.00mm	3.78
Case III	8.00mm	6.00mm	1.00mm	3.00mm	7.00

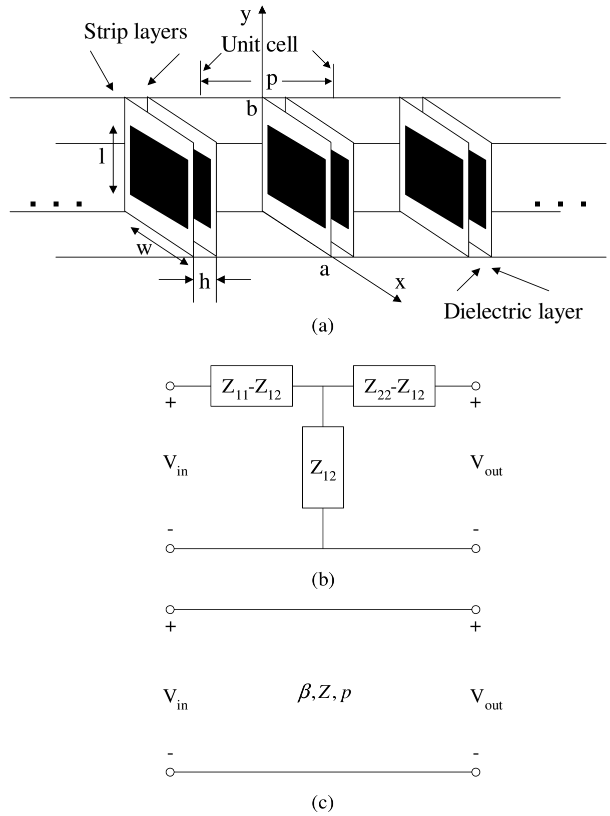

Fig. 1. (a) Proposed architecture for waveguide based DNG metamaterials (b) Equivalent two-port T-network representation for a unit cell and (c) Two-port network representation of a lossless transmission line (waveguide) of a periodic unit cell

A. Extracted Relative Permittivity and Permeability

Assuming that p/λ is small, we may obtain relative permittivity and permeability using the following equations [5] from ABCD parameters of a unit cell.

$$\varepsilon = \frac{C}{j\omega\varepsilon_0 pA} \tag{1a}$$

$$\mu = \frac{B}{j\omega\mu_0 pA} \tag{1b}$$

The ABCD parameters can be numerically calculated using full-wave hybrid MoM-Immittance approach. Real parts of the extracted relative permittivity and permeability vs frequency are plotted in Fig. 2 and Fig. 3 respectively. Amplitude of real part of relative permittivity ε_r reaches its most positive value, i.e., 400 at 10.87 GHz, passes through zero at 10.88GHz and then reaches its most negative value, i.e., -1000 at 10.9GHz for Case I and the similar pattern in plot is observed for Case II as shown in Fig. 2. The extremely large values of extracted material parameters are due to resonant nature of the response. For case III, there is a double resonance due to increased electromagnetic interaction between the two printed strips on dielectric whose electrical permittivity is higher than other two previous cases and hence there are two DNG passbands. The amplitude of real part of relative permeability μ_r reaches its most positive value, i.e., 30 at 8.4 GHz, passes through zero at 8.42GHz and then reaches its most negative value, i.e., -30 at 8.45GHz for Case II and similar pattern in plot for Case I as illustrated in Fig. 3. For case III, there is double resonance in plot of extracted relative magnetic permeability similar to the case of extracted electric permittivity. Here, double strips printed on two sides of dielectric layer of a unit cell of the periodic waveguide structure mainly produce effective magnetic permeability whereas dielectric layer gives main contribution to effective electric permittivity.

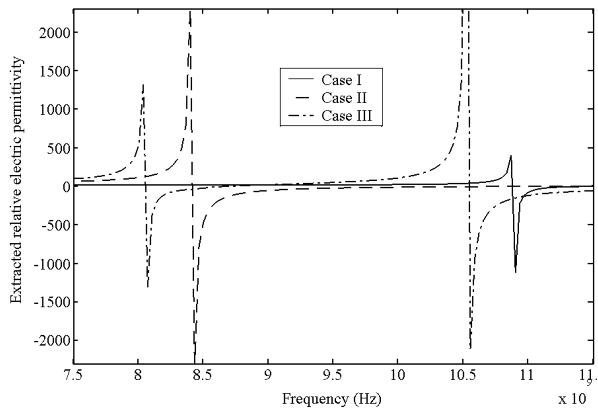

Fig. 2. Extracted relative electric permittivity

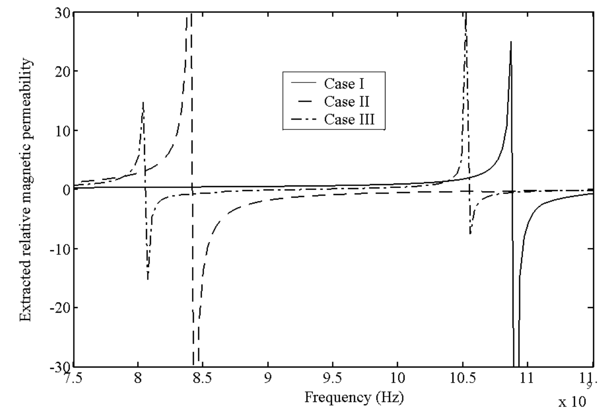

Fig. 3. Extracted relative magnetic permeability

B. Extracted Index of Refraction

The index of refraction of DNG metamaterials unit cell can be numerically calculated from ε and μ using the following formula:

$$n = \sqrt{\varepsilon}\sqrt{\mu} \tag{2}$$

n is a complex variable here. We show only real parts of extracted index of refraction for the sake of simplicity. For case II, real part of the amplitude of n reaches its most positive value, i.e., 400 at 8.4GHz, passes through zero at 8.425GHz and then reaches its most negative value, i.e., -400 at 8.43GHz as illustrated in Fig. 4. For other cases, the plot of extracted index of refraction vs frequency is shown in Fig. 4.

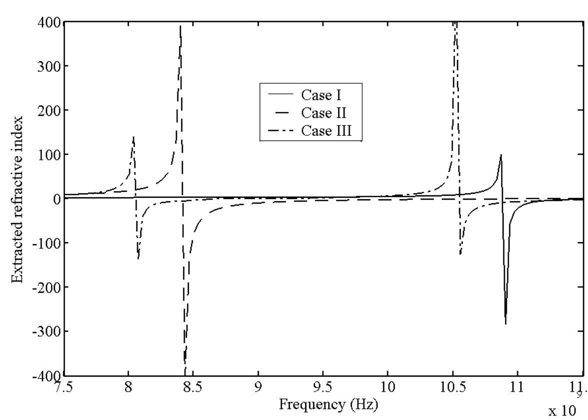

Fig. 4. Extracted index of refraction

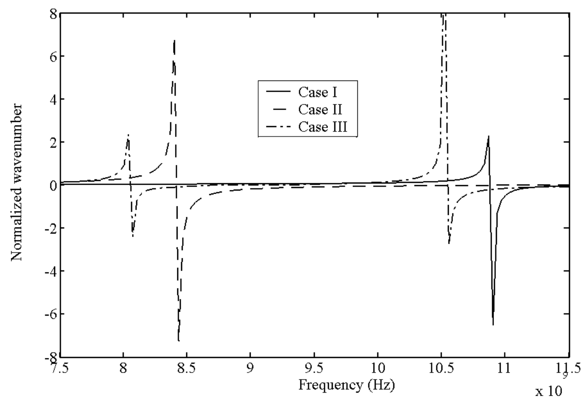

Fig. 5. Extracted ω-β diagram

C. Extracted ω-β diagram

Now let us consider wave propagation behavior along the proposed waveguide based DNG metamaterials.

$$\beta = \omega\sqrt{\varepsilon}\sqrt{\mu} \tag{3}$$

The dispersion diagram of the waveguide based DNG metamaterial obtained using (3) is plotted in Fig. 5. For case I, starting from 7.5GHz in Fig. 5, wave number β increases rapidly and reaches its maximum value 2.3 m^{-1} at 10.855GHz and crosses zero at 10.87GHz. It reaches minimum value -6.3 m^{-1} at 10.9GHz. Moreover, starting from 10.9GHz, wave number again increases rapidly and goes to zero at 11.3GHz. Clearly, in frequency range of 7.5GHz to 10.855GHz, phase and group velocities are both positive (forward wave behavior). In contrast, in frequency range from 10.9GHz to 11.3 GHz, phase velocity is negative whereas group velocity is positive thus bringing out the backward wave behavior. Notice that the two propagation behaviors are interchanged around 10.87GHz where resulting propagation constant β passes through zero. The other two plots of extracted normalized wavenumber vs frequency is shown in Fig. 5.

III. CONCLUSION

The material parameters of a periodic waveguide structure loaded with double printed strips on dielectric has been extracted and it exhibits the properties of metamaterials viz., negative electric permittivity, negative magnetic permeability, negative index of refraction and backward wave propagation in the DNG passband region.

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