DB Boundary Based on Resonant Metamaterial Inclusions

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Abstract

Recently introduced DB boundary is a hypothetical surface, on which cancelling of normal components of the **D** and **B** field occurs. Such a DB surface behaves either as a PEC or a PMC, depending whether the incident plane wave is polarized TE or TM, respectively. A possible planar, single-layer, realization of the DB surface based on metamaterial inclusions such as SRR's and inductively loaded dipoles is proposed. Results of a full-wave analysis reveal that electromagnetic properties of the proposed planar structure are, at one particular frequency, very similar to the properties of a hypothetical DB boundary.

1. Introduction

An interesting concept of a DB boundary was recently proposed in [1]. It is an artificial surface that simultaneously cancels normal components of both the electric flux density (**D**) and the magnetic flux density (**B**). Probably the simplest practical realization of such boundary surface would be a slab made of continuous uniaxial meta material (Fig. 1a). In order to achieve vanishing of the normal components of fluxes, the components of permittivity and permeability tensor in a direction perpendicular to the material surface (ε_{ry} and μ_{ry}, Fig. 1a) of the DB material should be equal to zero:

$$\vec{D}\cdot\hat{n}=\varepsilon_{ry}\cdot\vec{E}\cdot\hat{n}=0 \quad\Rightarrow \varepsilon_{ry}=0, \qquad \vec{B}\cdot\hat{n}=\mu_{ry}\cdot\vec{H}\cdot\hat{n}=0 \quad\Rightarrow \mu_{ry}=0. \tag{1}$$

However, the field components in the other two directions may have arbitrary values. Thus, the DB surface is in fact an anisotropic structure.

Following the well known boundary condition for continuity of normal components of flux density through the interface between any two materials

$$\hat{n}\cdot\left(\vec{D}_{out}-\vec{D}_{in}\right)=0, \quad \hat{n}\cdot\left(\vec{B}_{out}-\vec{B}_{in}\right)=0 \tag{2}$$

one finds that zero values for both **D** and **B** field are also preserved outside the DB boundary. Here, $\mathbf{D}_{\text{out}}$ and $\mathbf{D}_{\text{in}}$ ($\mathbf{B}_{\text{out}}$ and $\mathbf{B}_{\text{in}}$) stand for the flux densities outside and inside the DB material, respectively. This is possible only if normal components of the electric and magnetic fields on the upper and lower surfaces of a DB slab are also equal to zero.

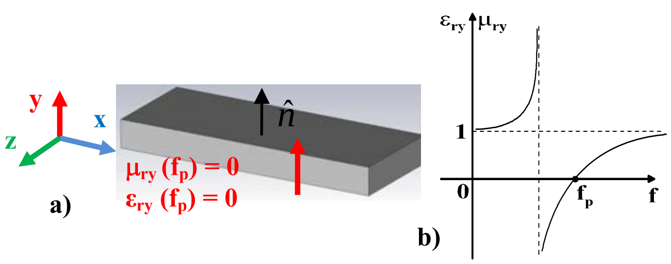

Fig. 1: a) DB material aligned with axes of the coordinate system
b) Lorentz dispersion model for permittivity and permeability (f_p denotes the plasma frequency).

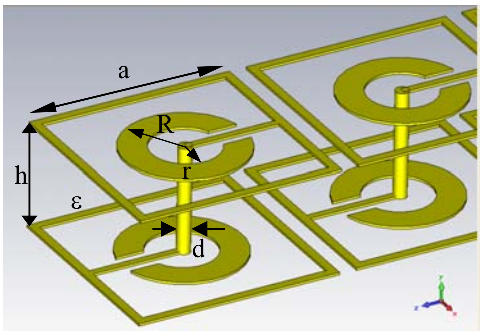

Fig. 2: Composite unit cell that simultaneously behaves as an ENG and MNG particle. a=6mm, R=1,8mm, r=1mm, d=0,4mm, h=3mm, ε_r=1.

Therefore, as stated in [3], the DB surface shows properties similar to properties either of PMC or PMC boundary, depending on polarization of an incoming plane wave, which may find applications in antenna technology. It is important to stress that both permittivity and permeability in all types of passive metamaterials are always frequency dependent (they often follow Lorentz dispersion model as depicted in Fig. 1b.). Thus, the cancelation of the normal components of **D** and **B** vectors inside the DB material may happen at only one particular frequency, at which the values of permittivity and permeability become zero ('plasma frequency') [2].

In previous studies [3], a multi-layer realization of DB surface was proposed, however, it was found that the fabrication of this kind of structure would be very difficult. Here, we propose a planar, single-layer, realization of a DB boundary. It is based on a single resonant metamaterial inclusion that has properties of both ENZ and MNZ materials. Using commercial full-wave simulator, dimensions of proposed structure were optimized in order to achieve the equal values of plasma frequency for both polarizations of incident plane wave.

2. Single-layer realization of DB boundary

To construct a DB boundary, it is necessary to use material that simultaneously has both zero permittivity and zero permeability in the transversal direction. The basic idea, presented in [3], is to use two different electromagnetic unit cells: the first one, in which only electric polarization occurs in transversal direction (realized as an array of inductively loaded dipoles - called "D-layer") and the second one, in which only magnetic polarization occurs in the same direction (realized as an array of well- known SRRs - the "B-layer"). There are several ways to combine the D-layer with the B-layer in order to compose the DB material. The most obvious way is to place one layer above the other [3]. The mutual distance between the layers was found to be insignificant to overall properties of the structure, as long as it was much smaller than the wavelength. It is obvious the manufacturing of proposed dual-layer structure is difficult. That is the main reason why we propose new, single-layer design with modified unit cell (Fig. 5). This unit cell has a short dipole (a capacitor) based on a two frames (on the upper and lower plane of the substrates). The frames are mutually connected with two strips and a wire (a through hole). The series combination of these three elements increases the equivalent inductance and therefore lowers a resonant frequency. Due to symmetry, this structure should simultaneously show uncoupled electric and magnetic polarizations in transversal direction, while being excited with TM or TE polarized incident plane wave, respectively. The unit cells were placed at a mutual distance equal to the outer width of a metallic frame (a lattice constant).

3. Simulation results

In order to verify that proposed single layer structure indeed behaves as a DB boundary, a series of numerical simulations were performed using commercial full-wave simulator [7]. The model consisted of a DB structure placed inside a parallel plate waveguide. The TEM waves with two different types of the polarization (TE or TM) were generated at the waveguide port. Polarization (TE or TM) of incident TEM wave was chosen with appropriately selected boundary conditions. In the case of TE polarized incident wave (**H** field being perpendicular to the DB surface), a response of the novel unit cell on the magnetic field was monitored. In the same time, the unit cell should not respond on the electric field.

On the other hand, in the case of TM polarization (**E** being perpendicular to the DB surface), a response of the novel unit cell on the electric field was monitored. In the same time, the unit cell should not respond on the magnetic field.

In order to verify that proposed structure is indeed a good candidate for construction of DB surface, effective parameters of the composed DB structure for the both modes of excitation had to be extracted. Applied procedure was very similar to one originally described in [6]. Briefly, the DB structure was put inside a parallel plate waveguide and for the both modes of excitation and the input impedance of the waveguide while it was terminated with the open circuit (PMC) and a short circuit (PEC) was calculated. Knowing the input impedance one may calculate wave impedance of the waveguide. Finally, from the equivalent circuit for TEM mode, one may calculate both effective

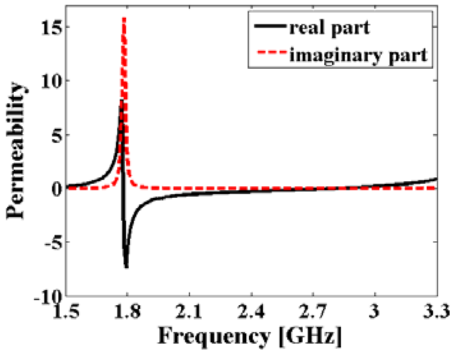

Fig. 3: Effective permeability extracted for the single-layer DB material (TE polarization).

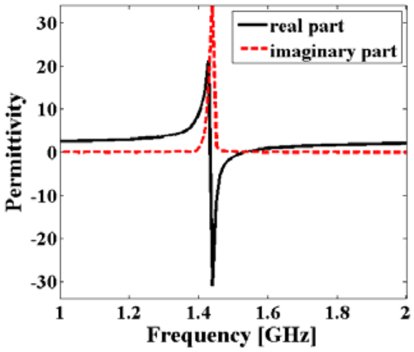

Fig. 4: Effective permittivity extracted for the single-layer DB material.

transversal permittivity and permeability. Using this procedure, properties of the newly designed single layer (Fig. 2) of the DB boundary were also analyzed. An array of 16 unit cells was placed inside a parallel plate waveguide and excited both in TE and TM mode. Dimensions of the unit cell denoted in Fig. 2 were chosen in order to achieve DB material properties at frequency of 1.5 GHz. Results obtained by extraction of effective parameters for TE and TM polarization are given in Fig. 3 and Fig. 4, respectively.

From the results obtained by effective parameter extraction procedure for the single-layer chain is obvious that proposed unit cell responds both to the normal components of the electric and magnetic field vectors and it is also obvious that obtained dispersion curves quantitatively follow predicted Lorentz models. However, it is also seen that the plasma frequencies for two polarizations are different (1.5 GHz for TE polarization and 2.7 GHz for TM polarization). Thus, this structure in its current form cannot operate as a DB boundary. However, a few additional numerical tests showed that is possible to significantly decrease the resonant frequency of the SRR part by tuning of its geometrical parameters. We believe that should be possible to match the resonant frequencies of the SRR part and the dipole part as, it was done in the case of a single-layer structure.

4. Conclusion

Basic properties of a novel concept of boundary condition called DB boundary have been reviewed. A metamaterial-based realization that comprised two layers of well known SRRs (the "B-layer") and inductively loaded dipoles (the "D-layer") has been briefly reviewed. A new, technologically simpler, single-layer concept has also been proposed. Numerical simulations have confirmed that the proposed unit cell has both electric and magnetic response, depending on polarization of incident plane wave, TM or TE, respectively. However, the plasma frequencies for both polarizations differ by 80%. Further efforts will be devoted to optimization of the design parameters in order to achieve matching. In addition, the experimental verification of the proposed design is in progress and the results will be reported soon.

References

[1] I. V. Lindell, A. Sihvola, “Electromagnetic DB boundary,” Proceedings of the URSI Finnish XXXI Convention on Radio Science and Electromagnetics, pp. 81-82., Espoo, Finland, 2008.
[2] W. Rotman, “Plasma simulation by artificial dielectrics and parallel-plate media,” IRE Trans. Antennas and Propagaion, vol. 10, pp. 82-95, January 1962.
[3] D. Zaluski, D. Muha, S. Hrabar, "Numerical Investigation and Possible Realization of Metamaterial- Based DB Boundary Surface", Proc. on ICECOM 2010, Dubrovnik, Croatia, pp. 251-253, 2010.
[4] I. V. Lindell, A. Sihvola, "Electromagnetic boundary and its realization with anisotropic metamaterial", Phys. Rev. E, Vol. 79, Is. 2, 2009.
[5] I. V. Lindell, A. H. Sihvola, “Perfect electromagnetic conductor,” J. Electromagn. Waves Appl., Vol. 19, No. 7, pp. 861–869, 2005.
[6] S. Hrabar, D. Zaluski, “Subwavelength Guiding of Electromagnetic Energy in Waveguide Filled with Anisotropic Mu-Negative Metamaterial“, Electromagnetics, Vol 28, Is. 7, pp. 494, 2008.
[7] CST Microwave Studio 2010, www.cst.com