Numerical Investigation of Equivalent Circuit Models for Complementary Omega-Like Structures Loaded Microstrip Line

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Abstract

In this work, equivalent circuit models for a microstrip line loaded with single and two unit cells of complementary omega-like structure (COLS) are proposed. In each case, full wave electromagnetic as well as electrical simulation results are presented. Reasonable agreement has been obtained between them. The models have been found to provide a very good description for the COLS and its coupling to the host microstrip transmission line.

1. Introduction

In recent years, the possibility of creating materials that demonstrate the property of negative refraction over a certain band of frequency has received much attention. These artificial materials that pay respect to unconventional properties are called metamaterials. A particular example of these materials is the media in which both parameters of permittivity and permeability have negative real parts in a certain band of frequency. Such materials were hypothesized in 1968 by a Russian physicist Victor Veselago [1], who termed these peculiar materials left-handed media. In a left-handed medium, the Poynting vector of the electromagnetic (EM) wave is antiparallel to the propagation vector. This leads to some interesting extraordinary EM wave phenomena such as the reversal of Doppler shift and the reversal of Čerenkov radiation [1].

Recently, the implementation of metamaterial in microstrip technology has been presented in [2-4]. To obtain a left-handed microstrip transmission line, two separate elements are introduced in microstrip environment. Series capacitive gaps are etched in the conductor strip to achieve negative permittivity; and complementary split-ring resonators (CSRRs) are etched in the ground plane under the positions of the gaps to achieve negative permeability.

Very recently, a new constituent particle for left-handed microstrip transmission line design has been proposed by the authors in [5,6]. This particle is called complementary omega-like structure (COLS). The COLS is the negative image of the omega-like structure, i.e., the COLS is the dual counterpart of the original metallic omega-like structure. Figure 1 shows the typical geometry for a single original metallic omega-like particle and its complement. By properly coupled COLS to a host planar microstrip transmission line, planar structure with effective negative constituent parameters can be obtained. The main purpose of this paper is to provide a simple model that can describe the COLSs and their coupling to the host microstrip transmission line.

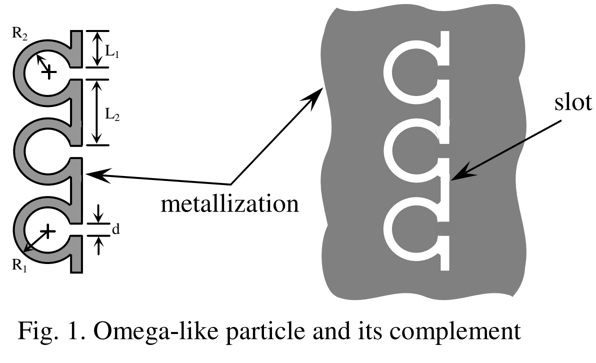


Fig. 1. Omega-like particle and its complement

2. COLS Loaded Microstrip Line

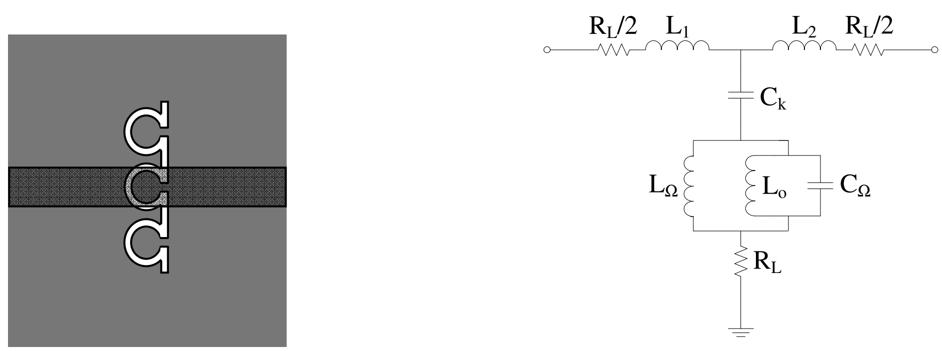
In order to obtain strong electric and magnetic responses from the COLS, it is necessary to excite it with an external electric field in the axial direction of the rings as well as external magnetic field in the direction of the stems. Therefore, the proper method for its excitation is to introduce the particle where it can be successfully excited by the EM fields propagating in the microstrip line. According to the previous comments, by etching this particle on the ground plane of a microstrip line, as illustrated in Fig. 2(a), good coupling can be expected [5,6]. By doing so, the stems of the COLS behave as magnetic dipoles that are excited by a parallel magnetic field, and the split rings of the COLS behave as electric dipoles that are excited by an axial electric field.

On the other hand, taking the cross polarization effects of the omega shaped in consideration, since generally the omega medium is bianisotropic medium [7], the split rings/stems of the COLS should act not only as electric/magnetic dipoles, but also as electric/magnetic dipoles. Thus, as a consequence of the cross polarization effects, the existence of magneto-electric coupling in the particle should be considered in the modeling of the particle and its coupling to the host line. Once the interaction between the COLS and the applied EM fields becomes well known, equivalent circuit model for a microstrip line loaded with COLSs can be developed.

3. Equivalent Circuit Model for a COLS Loaded Microstrip Line

The basic unit cell for a COLS loaded microstrip line is shown in Fig. 2(a). The dimensions of the particle as given in Fig. 1 are R_1=0.7 mm, R_2= 0.5 mm, L_1=0.75 mm, L_2=1.45 mm, and d=0.2 mm. The substrate has a dielectric constant ε_r=10.5, and thickness h_s=1.27 mm. The conductor strip has a width of 1.1474 mm corresponding to a characteristic impedance of 50 Ω. As long as the electrical size of the COLS is small, it can be described by means of lumped elements. The proposed lumped element equivalent circuit model of the basic cell of the structure is shown in Fig. 2(b).

In the proposed model, the COLS is described by parallel combination of L_Ω, L_o, and C_Ω. This circuit model is the complementary counterpart for the lumped equivalent circuit model for metallic omega structure exhaustively explained in [8]. To be more specific, the stems of the COLS are modeled by L_Ω, while the split rings are described by parallel resonant tank with inductance L_o and capacitance C_Ω [9]. It is worth to mention that, the equivalent circuit model of the split rings of the COLS is the same as the equivalent circuit used in the modeling of the CSRR [9].



(a) (b)

Fig. 2. A microstrip line loaded with a COLS (a) Lay out (top view) and (b) Equivalent-circuit model

From the particle excitation point of view, on the basis of the concepts explained in the previous section, the COLS is electrically coupled to the host microstrip line through the line capacitance C_k since it is etched in the ground plane, whereas the magnetic coupling can be modeled by the mutual inductance M_1 between the line and L_Ω as well as mutual inductance M_2 between the line and L_o. Note that, L_1 and L_2 model the inductance of the microstrip line (L), where L_1=L_2=L/2. Accordingly, it is worthwhile to conclude that, the split rings/wires are electrically and magnetically coupled to the microstrip line through the capacitance C_k and the mutual inductance M_2/M_1, respectively. Finally, conductor losses can be incorporated into the model by means of loss resistance R_L, taking into account the copper conductivity for the conductor strip and the ground plane. By doing this, our proposed model is completely general.

4. Equivalent Circuit Model for Two COLSs Loaded Microstrip Line

To further advance in the knowledge and behavior of the complementary omega-like particles, let us now consider two complementary omega-like unit cells loaded microstrip line. The structure under study is shown in Fig. 3(a) which is realized by cascading two unit cells rather than considering single cell structure (Fig. 2(a)). The separation between cells D is 0.2 mm. All previous dimensions of the particle as well as the parameters of the substrate have been considered the same. The proposed model is presented in Fig. 3(b). For instance, this model provides the same electrical parameters as those proposed when only one unit cell has been considered. Therefore, the physical meaning of these electrical parameters is the same as those explained earlier. The only difference between the two circuits is the electric coupling between the two unit cells which is modeled by means of the mutual coupling capacitance C_M.

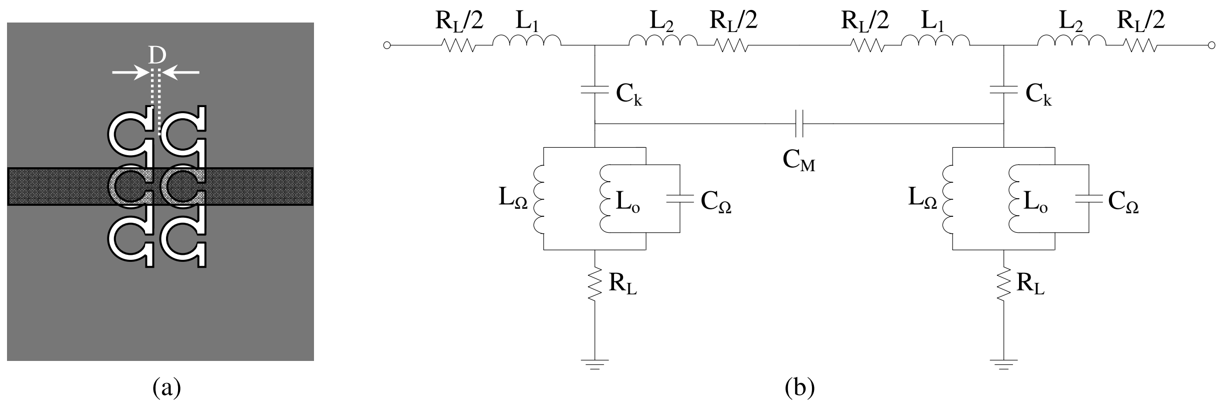


Fig. 3. A microstrip line loaded with two COLSs (a) Lay out (top view) and (b) Equivalent-circuit model

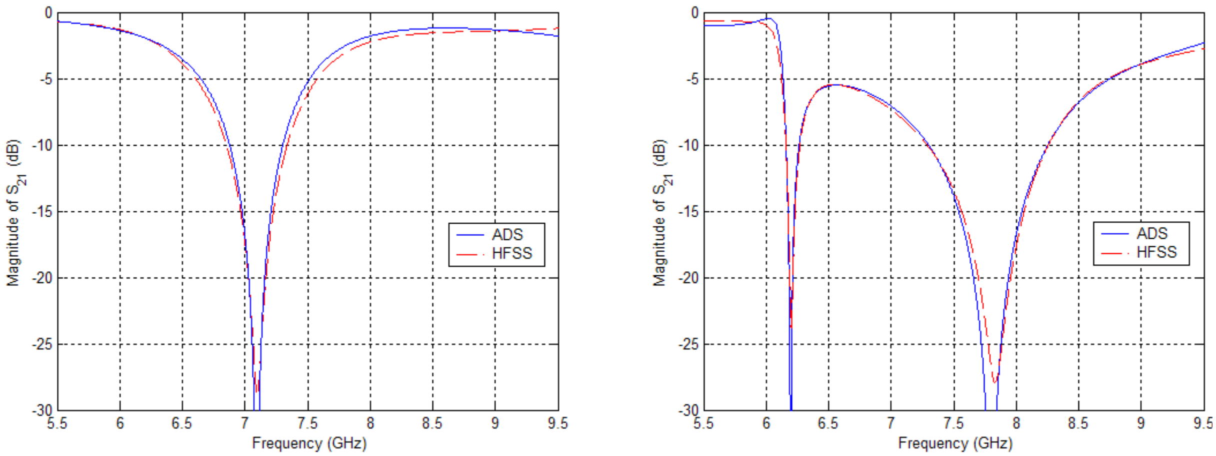
5. Numerical Simulation Results

In order to test our proposed equivalent circuits, the full wave EM simulation results obtained by means of ANSOFT's High Frequency Structure Simulator (HFSS) tool has been compared to the electrical simulation results of the equivalent circuit obtained by using the Agilent Advanced Design System (Agilent ADS) simulator tool. The first step taken in order to validate our models is the calculation of the parameters of the electrical circuit models. For a microstrip line loaded with single COLS, the parameters obtained by the aid of the Agilent ADS simulator are: L=2 nH, C_k=0.48 pF, L_Ω=5.75 nH, L_o=0.144 nH, C_Ω=2.98 pF, M_1=1.38 nH, M_2=0.02 nH and R_L=0.02 Ω. Figure 4(a) shows the full wave EM simulation (using HFSS) and the electrical simulation (using ADS) results for comparison. As it can be seen, there is a good agreement between both simulations which ratifies the validity of the proposed model.

For a microstrip line loaded with two unit cells of COLSs, the values of the electrical parameters of the lumped element equivalent circuit model are the same as those obtained previously for single cell structure except the value of C_Ω in order to consider the electric coupling between the two unit cells. In this case, by using ADS simulator, the values of C_Ω and C_M have been obtained which equal to 2.75 pF and 0.56 pF, respectively. The simulated frequency response of the structure under study (using HFSS) and the frequency response obtained through electrical simulation (using ADS) of the equivalent circuit are compared in Fig. 4(b). As it can be seen, there is a very good agreement between both simulations (electromagnetic and electrical). This ratifies the validity of our proposed model.

6. Conclusions

In order to properly model the behavior of complementary omega-like based left-handed microstrip lines, lumped element equivalent circuit models for single and two complementary omega-like unit cells loaded microstrip transmission line have been proposed. To accurately develop our proposed equivalent circuits, two main parts are considered. The first part is the modeling of the COLS and the second one is the modeling of its electric and magnetic coupling to the host microstrip transmission line. It has been found that electric coupling between the particles is very relevant and can't be neglected. Frequency responses provided by electrical simulations, obtained by using the ADS simulation tool, have been presented. In order to check our proposed models, full wave EM simulation results are also presented for comparison, which show that they are in agreement with the electrical simulation results.



(a) (b)

Fig. 4. Transmission coefficient of (a) a COLS and (b) two COLSs loaded microstrip line

7. References

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