Numerical Studies of Transmission Characteristics of Omega and Omega-Like Structures and Their Dual Counterparts

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Abstract- **A new particle is introduced called complementary omega structure (COS). Transmission characteristics of omega and omega-like structures and their complementary structures have been numerically studied. Several numerical simulations are also performed and presented in order to conceive the interaction between these particles with the applied electromagnetic (EM) fields. All simulation results obtained confirm that the omega/omega-like structure and its complement are dual.**

Keywords- Complementary Omega Structure (COS); Complementary Omega-like Structure (COLS); Duality; Omega Structure; Omega-Like Structure

I. INTRODUCTION

Artificially structured metamaterials exhibiting simultaneously negative permittivity and negative permeability over a certain frequency band have been realised in the past few years. A Russian physicist Victor Veselago [1] was the first one who made a systematic study of electromagnetic (EM) properties of materials with negative parameters, whose paper was published in 1967 in Russian, and a year later in English. In his pioneering paper, he postulated a negative refractive index material, a possibility never considered before. Metamaterials possess properties that are not observed in naturally occurring materials. For instance, the backward wave character of the EM waves in negative refractive index materials is introduced. For a backward wave, the phase velocity and the Poynting vector are in opposite direction. Although the term metamaterial has not been strictly defined, metamaterials are also commonly referred to as left-handed materials [1].

Actually, left-handed material is a composite periodic structure with a lattice constant that is much smaller than the wavelength of the incident EM radiation. The first realization of a negative permittivity material was introduced by Pendry et al. [2], which consists of a periodic array of metallic wires. Three years later, Pendry et al. [3] further proposed a negative permeability material which consists of periodic array of split-ring resonators (SRRs). The first realization and experimental verification of a negative refractive index material based on the Pendry's ideas were made by Shelby et al. in 2001 [4]. Such material is composed of both arrays of metallic wires and SRRs to achieve negative permittivity and negative permeability, respectively.

Design of metamaterials based on two separate metallic inclusions is difficult in fabrication and assembly processes. Therefore, single part inclusions can be used to easily perform the fabrication process. Such inclusions include omega and non-local omega structures [5], and omega-like structures [6]. The basic idea behind such inclusion is to combine both shapes of the Pendry's structures into a single part inclusion. That is, it includes parts like wires (or stems) and parts like rings, and thus both negative permittivity and negative permeability can be achieved, respectively. Whether single part or two separate parts inclusions are considered, the operational principle is basically the same. The stems interact with the applied parallel electric fields, and the loops interact with the applied axial magnetic fields. Therefore, maximum interaction with the applied EM fields is attained.

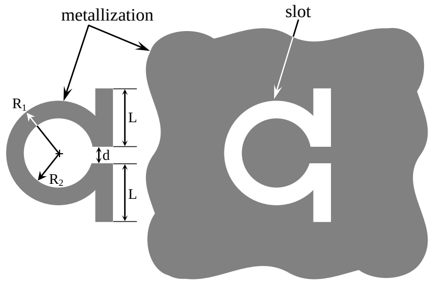
However, from a fabrication point of view, it is easier to design and build a metamaterial in microstrip environment. Therefore, recently, the design of metamaterials in microstrip configurations has received the most attention [7-9]. From this point, the authors have proposed a new particle called complementary omega-like structure (COLS) to artificially fabricate metamaterials in microstrip technology [10-12].

In this paper, a new particle called complementary omega structure (COS) is introduced. Such a single particle interacts with electric and magnetic fields simultaneously like the COLS. The COS/COLS is the negative image of the omega/omega-like structure and thus its EM behaviour is almost the dual of the omega/omega-like structure. Accordingly, the stems interact with the applied parallel magnetic fields, and the loops interact with the applied axial electric fields [10-12]. The interactions of the omega/omega-like structure and its complement with the applied EM fields are also illustrated to confirm the duality.

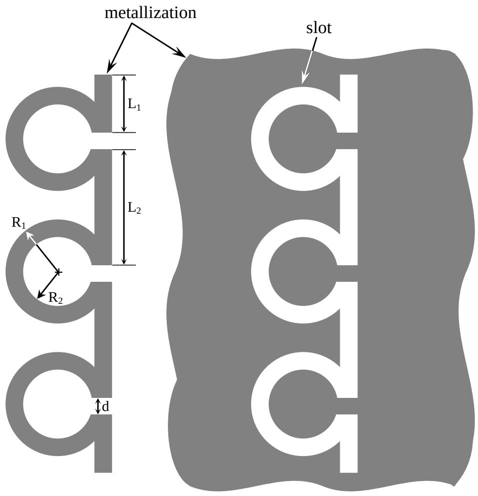
In this work, ANSOFT's High Frequency Structure Simulator (HFSS) tool, a commercial finite-element-based EM mode solver, has been used for these purposes.

II. OMEGA AND OMEGA-LIKE STRUCTURES AND THEIR DUAL COUNTERPARTS

The elementary cell of omega and omega-like structures and their complementary structures are shown in Fig. 1. In order to investigate the frequency responses of these particles, a host dielectric medium is required. A dielectric material with permittivity equal to 10.5 is considered. The HFSS is used to simulate a transverse electromagnetic (TEM) environment for the particles excitation.



(a)



(b)

Fig. 1 Schematic drawing of (a) omega structure and its complement (COS) and (b) omega-like structure and its complement (COLS)

Note: geometrical parameters of the structures are also shown.

In order to properly excite the original metallic structures (omega and omega-like structures), the applied electric field should be parallel to the particles' stems, whereas the applied magnetic field should be parallel to the loops' axes. This is contrary to the excitation required for the COS and COLS, because in the complement structures, the metal parts are replaced with apertures parts, and vice-versa [10, 11]. Accordingly, the role of the electric and magnetic fields are interchanged in both cases. Therefore, in this case, the stems should be excited by parallel magnetic fields, whereas the loops should be excited by axial electric fields.

III. TRANSMISSION CHARACTERISTICS OF OMEGA AND COMPLEMENTARY OMEGA STRUCTURES

The dimensions of the omega structure as given in Fig. 1(a) are R_1=1.75 mm, R_2= 1.25 mm, L=1.75 mm, and d=0.5 mm. The simulated frequency responses of the original omega particle as well as the complementary omega one are shown in Fig. 2. It can be observed that there is a dip in the transmission spectrum at approximately 4.4 GHz. This dip is an indicator to the resonant nature of these structures. It can be seen that the two particles almost have the same resonant frequency of about 4.4 GHz. It is also shown that the behaviour of the frequency response of omega structure above the resonance frequency is similar to that of the COS below the resonance frequency and vice-versa.

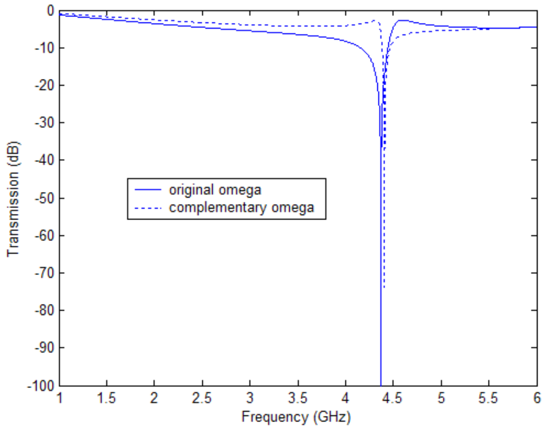


Fig. 2 Simulated frequency response of omega and complementary omega unit cells

Numerical simulations are also performed in order to illustrate the interaction between these particles with the incident EM fields. Figure 3 shows the magnitudes of the electric and magnetic fields (E- and H-fields) within the original omega structure at the resonant frequency. It can be observed that the stems are excited by the electric fields, whereas, the loop is excited by the magnetic fields. The magnitudes of the E- and H-fields within the COS at the resonant frequency are also shown in Fig. 4. It is clearly seen that the loop is excited by the electric fields, whereas, the stems are excited by the magnetic fields. Therefore, proper excitation is satisfied for both cases, and hence maximum interactions between the particles and the applied EM fields occur.

In order to clearly show the dual behavior of the original omega and its complement with the applied EM fields, a comparison between the E- and H-fields vectors excited in these particles are shown in Fig. 5. Note that, the values of the E- and H-fields intensities excited in omega and complementary omega particles are the same as those shown in Figs. 3 and 4, respectively.

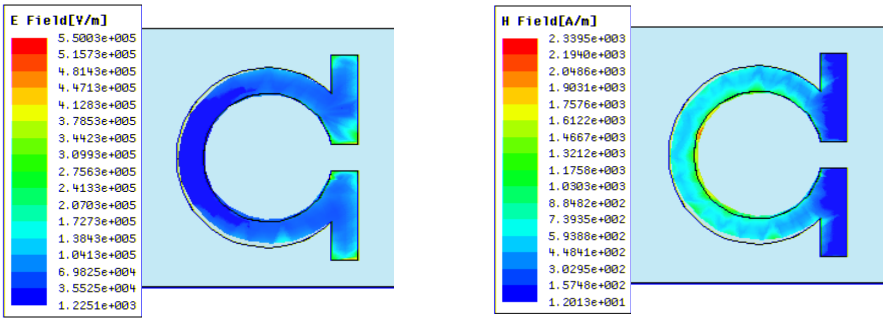


Fig. 3 Magnitude of the electric and magnetic fields at the resonant frequency of the original omega structure

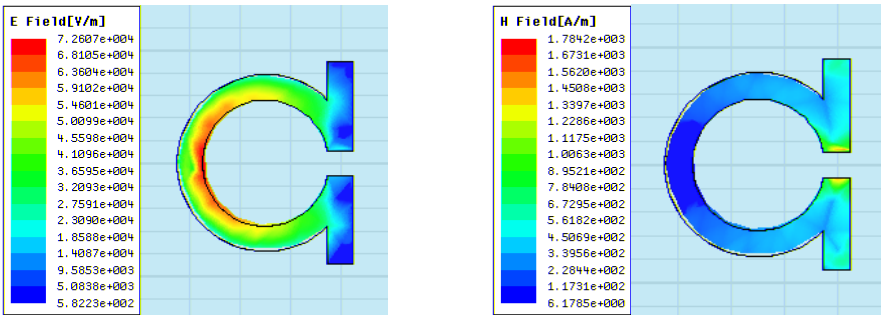
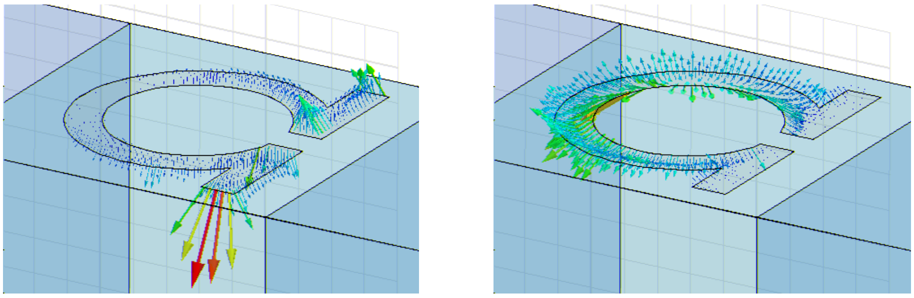
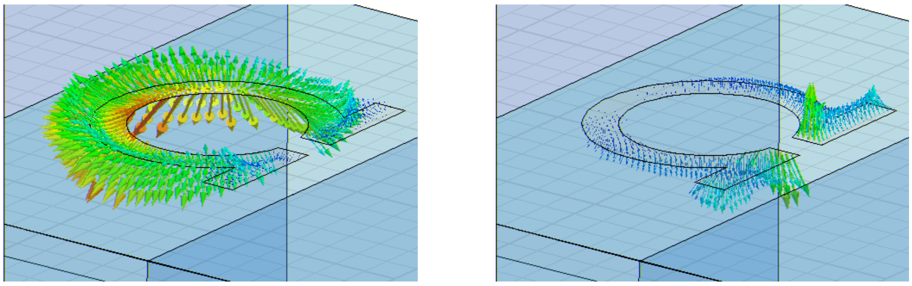


Fig. 4 Magnitude of the electric and magnetic fields at the resonant frequency of the COS



(a)



(b)

Fig. 5 Electric and magnetic field vectors at the resonant frequency of the (a) original omega, and (b) complementary omega particles

IV. TRANSMISSION CHARACTERISTICS OF OMEGA-LIKE AND COMPLEMENTARY OMEGA-LIKE STRUCTURES

Similar numerical simulations for original omega-like unit cell and its complementary one are also performed as done in the previous section. The dimensions of the omega-like structure under investigation as given in Fig. 1(b) 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 results are shown in Figs. 6-8. It can be seen that the resonant frequency of these particles is equal to 5 GHz (Fig. 6). Once again, the resonant frequency of the omega-like structure is equal to its dual counterpart, as the case of the original omega structure and its dual counterpart. Furthermore, proper excitation is also satisfied which is clear from Figs. 7 and 8.

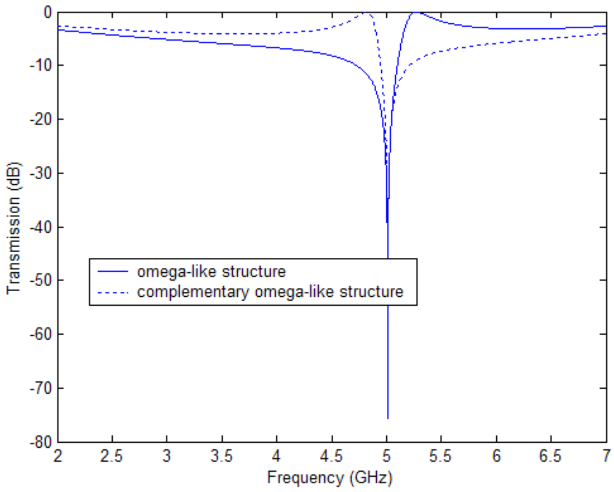


Fig. 6 Simulated frequency response of omega-like and complementary omega-like unit cells

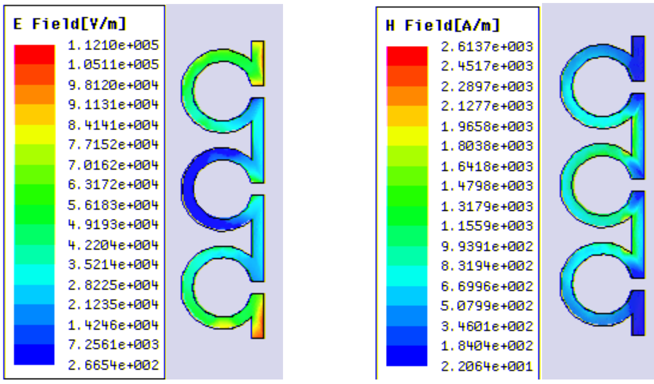


Fig. 7 Magnitude of the electric and magnetic fields at the resonant frequency of the original omega-like structure

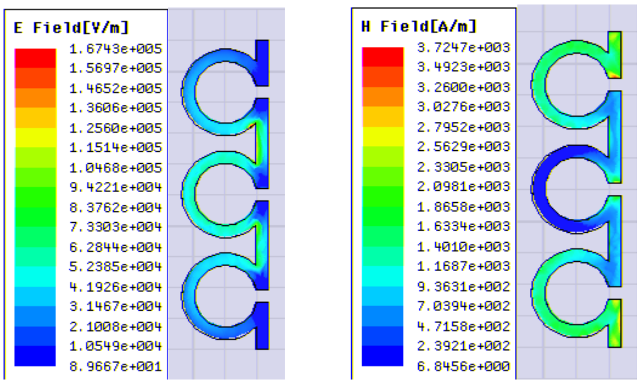


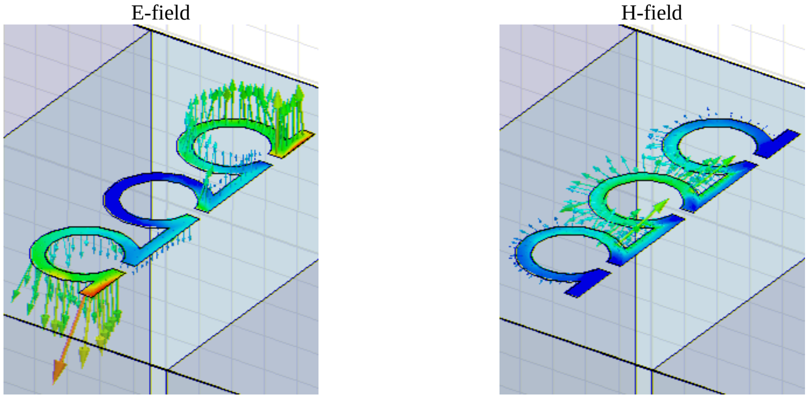
Fig. 8 Magnitude of the electric and magnetic fields at the resonant frequency of the COLS

Further illustrations are performed by showing the E- and H-field vectors along these particles (Fig. 9), where the values of the E- and H-field intensities excited in omega-like and complementary omega-like particles are the same as those shown in Figs. 7 and 8, respectively.

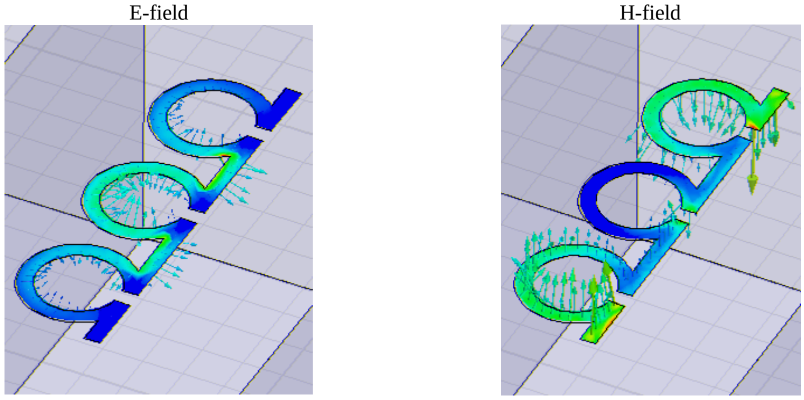
Referring to Figs. 7, 8 and 9, one can easily see that the electric field is localized along the stems of the omega-like particle and around the ring of the complementary omega-like one, whereas, the magnetic field is localized along the stems of the complementary omega-like particle and around the ring of the omega-like one, i.e., the role of the electric and magnetic fields are interchanged in both cases. Therefore, besides the same resonant frequency of both structures, one can conclude that, using duality theorem, the omega-like particle and its complementary one are dual. The key in obtaining these simulation results is that these particles have optimum excitation with the applied EM fields. This means that these particles did not resonate for other orientations, and hence did not affect the material parameters.

V. CONCLUSIONS

In this paper, a complementary omega structure (COS) is introduced. This new particle is the negative image of the original metallic omega structure, i.e. the metal parts are replaced with apertures, and vice-versa. Frequency responses of omega and omega-like particles as well as their dual counterparts are studied. Several full wave EM simulations have been performed and discussed. The obtained results show that each metallic structure has the same resonant frequency of the corresponding complementary one. To clearly illustrate the excitation of each particle, distributions of electric and magnetic fields excited at the resonant frequency in the four mentioned particles are sketched. The obtained results show that the expected interaction between the incident fields and each particle is obtained. The dual behaviour of the omega/omega-like structure and COS/COLS with the incident fields is clearly shown. Therefore, duality is confirmed by the obtained results.



(a)



(b)

Fig. 9 Electric and magnetic field vectors at the resonant frequency of the (a) original omega-like, and (b) complementary omega-like particles

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