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To cite this article: Koray Aydin *et al* 2007 *New J. Phys.* **9** 326

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Transmission characteristics of bianisotropic metamaterials based on omega shaped metallic inclusions

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New Journal of Physics **9** (2007) 326
Received 21 June 2007
Published 14 September 2007
Online at http://www.njp.org/
doi:10.1088/1367-2630/9/9/326

Abstract. The authors report the transmission properties of omega shaped metallic inclusions on a dielectric medium that exhibits bianisotropic properties. The resonance frequencies of single omega resonators are investigated experimentally and numerically. The resonance frequency of an Ω structure depends on its orientation with respect to the incident electric field. Increasing the tail length of the Ω resonator causes a decrease in resonance frequency. Band gaps due to the magnetoelectric resonances are observed for various types of periodic omega arrays. A transmission band is observed when a periodic Ω media is combined with a negative permittivity media of periodic thin wires. The transmission band appears below the band gap of periodic omega media, in turn indicating right-handed behavior. A dual transmission band is obtained by composing two different types of metamaterials that are arranged periodically.

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Contents

1. Introduction

Artificially structured metamaterials have gained burgeoning interest from the scientific community due to their intriguing and exotic electromagnetic (EM) properties. Metamaterials are composites that can be engineered at will, with unit cells that are much smaller than an operation wavelength and widely used to obtain the desired fascinating properties that are not attainable with natural materials. Among these unprecedented behaviors are negative permeability [1]–[5], negative refractive index [6]–[9], backward wave media [10]–[12], sub-diffraction limited imaging with superlenses [13]–[17], magnifying hyperlenses [18, 19], and cloaking with metamaterial coatings [20, 21]. Composite metamaterials (CMM) are usually designed as a combination of two elements that provide effective-medium response with a permittivity of $\varepsilon(\omega) < 0$ and permeability of $\mu(\omega) < 0$ simultaneously over a certain frequency range, so that the resulting refraction index of the effective medium becomes $n_{\text{eff}} = \sqrt{\varepsilon}\sqrt{\mu} < 0$. Negative permittivity in the microwave regime is achieved by using periodic thin wire media [22]. It is rather difficult to obtain negative permeability due to the absence of magnetic charges. Pendry *et al* [1] came up with a solution to this problem, where they employed an array of split ring resonators (SRRs) exhibiting negative effective permeability (μ_{eff}) values for frequencies close to the magnetic resonance frequency (ω_{m}) of the SRRs. In general, SRRs and thin wires are used together to obtain a left-handed metamaterial [2]–[9]. Different types of resonators are also used as metamaterial building blocks, such as S-shaped resonators [23], labyrinth resonators [24], and omega-shaped metallic inclusions [25]–[29].

Omega media are of special interest due to their interesting EM properties. Omega structures were firstly proposed by Saadoun and Engheta [30, 31]. These types of structures are composite EM materials with a proper combination of Ω-shaped metallic inclusions in a host dielectric medium. The omega structure consists of a C-shaped ring resonator with two wires connected to both ends as shown in figure 1(a). These metamaterials could be regarded as bianisotropic or pseudochiral media [30]. Electric and magnetic polarizations are induced by both electric and magnetic fields in bianisotropic media. In some applications, the bianisotropic effects are not desirable, in which several designs have been proposed to overcome the magnetoelectric coupling [25, 26, 32, 33]. However, in a recent paper by

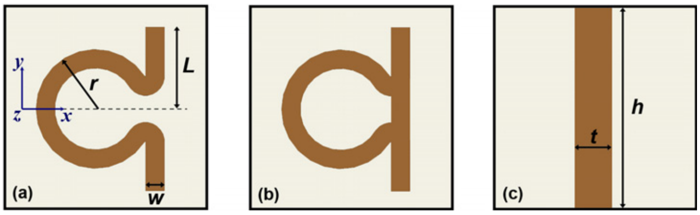

Figure 1. Schematic drawings of (a) single Ω unit cell, (b) single closed Ω unit cell and (c) single thin wire unit cell.

Tretyakov *et al* [12], it was shown that it is possible to obtain backward wave media due to the bianisotropic characteristic of Ω resonators. Therefore, one can use Ω media to obtain an alternative metamaterial, although the refractive index might not be negative.

Here, we present a systematic study of the transmission properties of various omega based metamaterials. Firstly, we will report on the frequency response of omega unit cells, with different orientations and tail lengths and investigate the changes in the resonance frequencies. Then, we will present our experimental and numerical results on the periodic omega media and metamaterials of omega structures combined with a proper thin wire array. Finally, we will show the possibility for obtaining a dual transmission band within the negative permittivity regime by using two different types of CMMs.

2. Frequency response of omega unit cells

In this section, we investigate the frequency response of various omega unit cells of different orientations regarding the incident to EM fields. A unit cell of omega structure is shown in figure 1(a). The parameters as given in the figure are $r = 1.19$ mm, $w = 0.45$ mm and $L = 1.8$ mm. Omega inclusions are copper that are deposited on a FR4 printed circuit board. The thickness of the copper and FR4 are 30 μm and 1.6 mm.

Two monopole antennae are used to transmit and detect the EM waves through the single Ω unit cell [34]. The length of the monopoles are arranged to work at the frequency range covering the resonance frequencyof the Ω structures. Monopole antennae are connected to the HP-8510C network analyzer to measure the transmission coefficients.

2.1. Effect of the orientation of the omega structure on resonance frequency

A dip in the transmission spectrum of Ω unit cells can be attributed to the resonant nature of these structures. We performed transmission measurements on the omega unit cell that is shown in figure 1(a). The incident field propagates along the x-direction, with **E** and **H** along the y- and z-directions, respectively. At 10.75 GHz, we observed a dip for the omega structure, in which the tails of the omega structure are oriented parallel to the E-field, i.e. along the y-axis. As a convenience, we named this structure ‘normal Ω parallel’, in which, the result is shown in figure 2(a) with a red line. In order to understand the effect of the orientation of an Ω unit cell with respect to the incident EM field, we performed further measurements on an Ω medium that is rotated by 90° around the z-axis. This structure is called ‘normal Ω perpendicular’, meaning that the tails are perpendicular to the E-field in this case. The corresponding structure can be seen in the inset of figure 4(b). The resonance frequency of the rotated Ω unit cell was observed

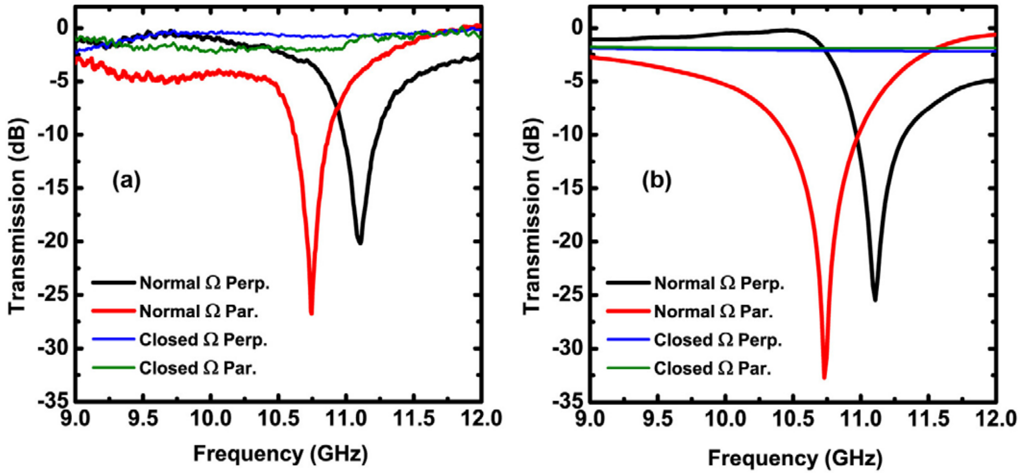

Figure 2. (a) Measured and (b) simulated frequency response of a normal Ω unit cell with perpendicular (black line) and parallel (red line) orientations with respect to the incident electric field. The blue and green lines correspond to the perpendicular and parallel orientations of the closed Ω unit cell.

at a higher frequency, 11.1 GHz, as plotted by a black line in figure 2(a). In a previous work, we developed a method to check the resonance of SRRs, in which we closed the splits of the SRR structure [4]. Here, we follow a similar method and close the gap region of the Ω structure by connecting the tails as shown in figure 1(b). The resulting structure is called a closed Ω throughout the present paper. The measured frequency response of perpendicular and parallel closed Ω structures are shown in figure 2(a) with blue and green lines. In both cases, the incident EM field is transmitted throughout the frequency range of interest. Therefore, no resonance behavior is observed for closed Ω.

We also performed numerical simulations to check the validity of the experimental results. Simulations were performed by using the commercial software, CST Microwave Studio, which is a 3D full-wave solver that employs the finite integration technique. A single layer of the Ω structure along the propagation direction is subjected to an incident plane wave. Open boundary conditions are employed along the propagation direction. The structure is assumed to be periodic and infinite along the directions that are perpendicular to the propagation direction. The transmission amplitudes are obtained by probing the fields at a distant point from the structure. The simulation results plotted in figure 2(b) are in good agreement with the experimental results. The Ω structure with tails parallel to the *E*-field has a lower resonance frequency compared to the Ω structure with tails perpendicular to the *E*-field.

In the simulations, we used the field monitor facility of CST to calculate the electric field within the Ω unit cell. The absolute value of the *E*-field is provided in figure 3(a). The intensity of the incident field is unity in the simulations, and one can easily see that the *E*-field is localized along the wires of an Ω structure by a factor of 40. A similar simulation is performed for an SRR structure and the enhancement in the *E*-field is found to be of the order 150 [35]. This result is expected since an SRR is composed of more capacitive elements compared to an Ω resonator. Figure 3(b) displays the distribution of *E*-field with arrows. The video shows the change of the field distribution with the phase change of an incident *E*-field.

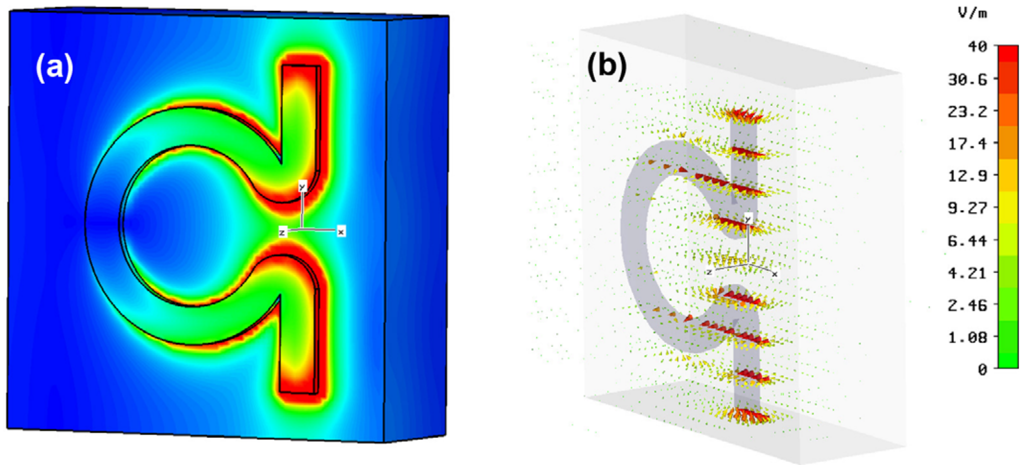

Figure 3. (a) Absolute value of the *E*-field and (b) *E*-field intensity distribution at the resonance frequency of an Ω structure that were obtained from the simulations (see video).

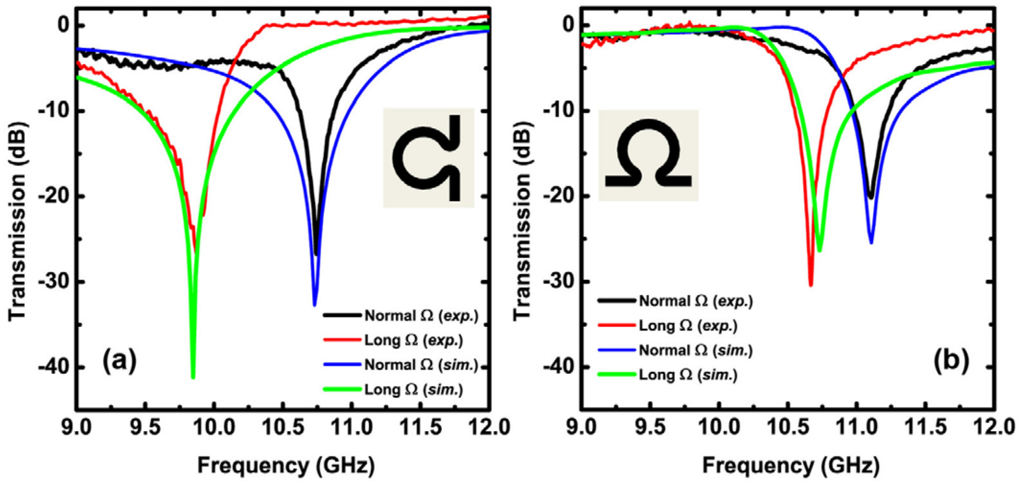

Figure 4. Measured and simulated frequency response of normal and long Ω structures with tails (a) parallel and (b) perpendicular to the electric field (*y*-axis). Inset: the corresponding configurations are shown.

2.2. Effect of the tail length of the omega structure on resonance frequency

The omega structure is composed of a split ring and two wires connected to this ring. We will call these wires tails throughout the present paper. We increased the tail length in order to investigate its effect on the resonance frequency of an Ω resonator. The normal Ω has a length of $L = 1.8$ mm. We increased L to $L_{\text{long}} = 2.2$ mm. Note that L is measured from the center of Ω, i.e. $y = 0$ point and it is not the actual length of the tails. We performed transmission measurements and numerical simulations for the configuration where the *E*-field is parallel to the Ω tails. The results are given in figure 4(a) with the inset showing the configuration. The resonance frequencies for normal and long Ω in the simulations and measurements agree well. The resonance frequency for long Ω is at 9.87 GHz for parallel orientation. Normal Ω is resonant at around 10.75 GHz. There is a 0.88 GHz change in the resonance frequency with a 0.4 mm increase in the tail length.

When the orientation of the omega unit cell is perpendicular (inset of figure 4(b)), the resonant frequency still shifts downward, but the amount of change is less compared to the case of a parallel configuration. Long Ω structure is resonant at around 10.67 GHz, whereas the normal Ω has a resonance frequency at 11.10 GHz for the perpendicular orientation of Ω with respect to an *E*-field. The change in the resonance frequency is 0.43 GHz. Increasing the tail length of an Ω structure increases the total inductance of the system. Since the resonance frequency is proportional to the inverse square of the total inductance and capacitance, the resonant frequency decreases. The difference between the parallel and perpendicular orientations can be explained with the interaction of the wires with the *E*-field. The *E*-field interacts with the wires for the parallel orientation and the longer wires become resonant at a lower frequency. However, the perpendicular orientation interaction of an *E*-field with the wires is not significant. On the other hand, in the case of the perpendicular orientation, the electric dipole mode of the loop can be effectively excited, and this mode resonates at a higher frequency.

3. Transmission characteristics of omega media based metamaterials

In the previous section, we investigated the resonance characteristics of single omega unit cells. Here, we will take a further step and compose a periodic omega media and study their transmission properties in free space.

3.1. Transmission spectrum of only periodic omega media

We arranged Ω-resonator units periodically with 5, 30 and 40 unit cells in the *x*-, *y*- and *z*-directions, respectively. The lattice spacing in all directions is $a_x = a_y = a_z = 5$ mm. Transmission measurements were performed in free space using an HP 8510-C network analyzer. Microwave horn antennae were used as transmitters and receivers, in which transmission through the samples was measured.

Figure 5(a) shows the measured transmission spectra of various periodic Ω media. The parameters of normal and long Ω resonators are provided in the previous section. We also fabricated a larger Ω structure that has the parameters of normal Ω scaled by a factor of 1.2. Periodic normal Ω media has a band gap of between 10.05 and 11.62 GHz (blue line), which is not present in the transmission spectrum of a closed Ω structure (black line). Note that the resonance frequency of normal Ω is 10.75 GHz. When the Ω unit cells are arranged periodically, the strong coupling between the neighboring resonators results in a band gap where no EM wave passes through. The band gap appears between 9.05 and 10.98 GHz for long Ω media (red line). The band gap for long Ω is wider compared to that of normal Ω. The transmission spectrum for periodic large Ω exhibits a band gap between 8.18 and 10.02 GHz (green line). Since the size of the structures is increased, the resonance occurred at a higher wavelength. The simulation results plotted in figure 5(b) are in good agreement with the measurements. In the simulations, we employed 5 unit cells of an Ω structure along the propagation direction and used periodic boundary conditions with a periodicity of 5 mm along the *y*- and *z*-axes.

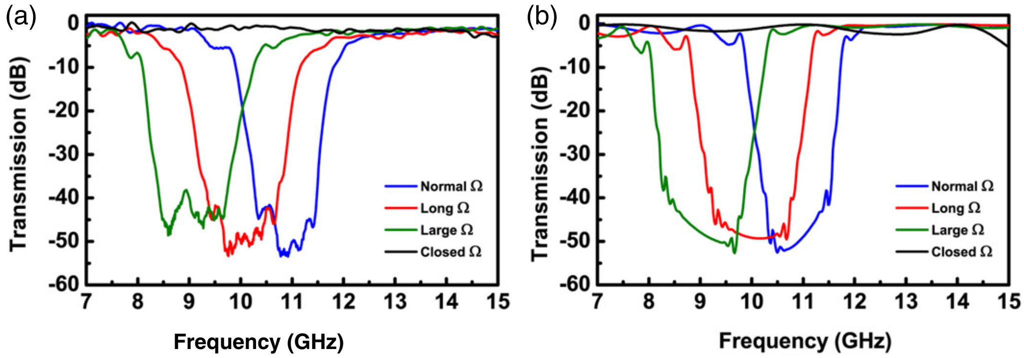

Figure 5. Transmission spectra of periodic arrangements of normal (blue line), long (red line), large (green line) and closed (black line) Ω structures obtained from: (a) measurements and (b) simulations.

The observed band gaps were due to the coupled magnetic and electric resonances. However, the contribution of magnetic resonance in Ω media is not as strong as in the case of SRR structures. SRR structures are composed of high capacitive elements, splits and gaps that enhance the magnetic response. Therefore, one may not have negative permeability values inside the band gap, even in the presence of magnetic resonance. In a recent work, the retrieved effective permeability of periodic Ω media does not possess negative values even though it exhibits resonance behavior due to a magnetic response [12]. It was shown that for existence of a backward wave the sum $\mathrm{Re}(\varepsilon + \mu)$ has to be negative at a certain frequency instead of having both parameters negative.

3.2. Transmission spectrum of a metamaterial composed of periodic omega and thin wire media

Left-handed metamaterials are generally designed by using SRR and wire media together. The prior is responsible for effective negative permeability, and the latter for negative permittivity. Connected omega media are shown to exhibit left-handed properties by verifying that they have a negative refractive index at certain frequencies. However, the compositions of omega and wire media are not studied. We aim to close this gap by investigating the transmission characteristics of CMMs, in which periodic omega and thin wire arrays are brought together.

Negative permittivity at microwave frequencies is achievable by the periodic arrangement of thin wires [22]. The unit cell of a continuous wire is shown in figure 1(c). The width and height of the thin wire is $w = 1.44$ mm and $h = 5$ mm. The thickness of the metal is the same as the omega structure, 30 μm. The lattice constants and number of layers in the *x*- and *z*-directions are equal to that of periodic omega media. Along the *y*-direction, the wires are continuous and the total length of the wires is 150 mm. The transmission spectrum of the wire media is shown in figure 6(a) with a black line. Below 14.5 GHz, the EM waves are not transmitted through the wire structure. It is well known that this specific frequency is the plasma frequency of the wire media, below which the effective permittivity becomes negative. The simulated result for the wire media is consistent with the measurements as plotted in figure 6(d).

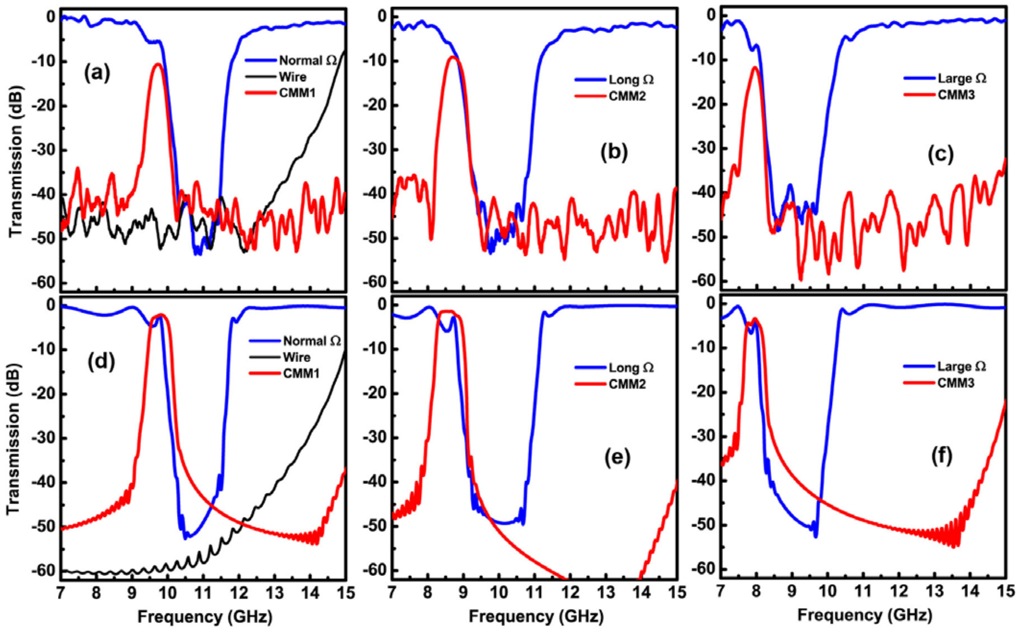

Figure 6. (a)–(c) Measured and (d)–(f) simulated transmission spectra of normal, long and large Ω (blue line) media and corresponding CMMs obtained by adding thin wire media (red line). The black line on (a) and (d) represents the transmission spectrum of only thin wire media.

In the previous section, we observed band gaps in the transmission spectra of three different omega structures. Here, we combine these media with the periodic wire meshes in order to investigate the transmission characteristics of the resulting CMMs. The wires are placed on the opposite side of the omega structure such that center of the wire unit cell (figure 1(c)) coincides with the center of the omega unit cell (figure 1(a)). Figure 6(a) plots the transmission spectra of normal omega media (blue line) and corresponding CMM (red line), which we called CMM1. As clearly seen in the figure, the transmission band did not appear at frequencies where the normal omega media has a band gap. Instead, we observed a downward shift for the transmission band of CMM1 that was between 9.4 and 10.0 GHz. The upper edge of CMM1's pass band coincides with the lower edge of the normal Ω's band gap. We also performed measurements on long Ω and large Ω and their corresponding CMMs, CMM2 and CMM3. The results are plotted in figure 6(b) and (c), respectively. Similar results were obtained for both CMMs. The transmission band of CMM2 is between 8.35 and 9.10 GHz and CMM3 is between 7.65 and 8.15 GHz. The transmission peaks are below −10 dB for three CMM structures even the number of unit cells along the propagation direction is 5. The relatively low transmission is due to two reasons: one is the losses of the FR4 substrate. FR4 is a lossy substrate with a tangent loss around $\delta \sim 0.025$. The transmission peak could be increased if a less lossy substrate is used to construct the CMM structures. The second reason is that the impedance is not matched to the free space. The impedance matching could be satisfied by carefully designing the omega and wire medium such that the absolute values of the dielectric permittivity and the magnetic permeability of composite structure is equal or close to each other around the frequencies of highest transmission.

The existence of a pass band for the CMM within the respective stop bands of SRR-only and wire-only media is intuitively considered as evidence for left-handed behavior [4]. However, a transmission band within the negative permittivity and permeability region may not exhibit left-handed characteristics [36, 37]. Recently, π-shaped metamaterials have been reported to exhibit a transmission band with right-handed characteristics [38]. The metamaterials composed of π-shaped structures are also of the bianisotropic type. The transmission band in [38] is observed at the lower edge of the resonance band gap of π-shaped resonator. The effective permeability possess negative values above the resonance frequency. In our case, we observed a transmission band below the resonance frequency, which means that within the transmission band the omega metamaterial exhibits right-handed behavior [38]. On the other hand, it is still interesting to observe a pass band within negative permittivity region of thin wire media. This effect can be explained by the bianisotropic characteristic of Ω metamaterial. Following the analysis of Tretyakov *et al* [12], we believe that this transmission band may correspond to the backward wave regime, although the effective permeability and refractive index are not negative. However, the backward wave regime may not cover the whole transmission band but instead it may have a narrow bandwidth; because from [12], it can be seen that it is difficult to fulfill the backward wave condition $\mathrm{Re}(\varepsilon + \mu) < 0$ in a wide frequency band. The effect of losses will also affect the bandwidth of the backward wave regime.

In this study, we investigated the bianisotropic effects in omega type metamaterials for the parallel propagation of EM waves. However, bianisotropic metamaterials also present interesting properties even for the EM waves with normal incidence. SRR structures are bianisotropic metamaterials for certain types of polarizations. Such bianisotropic effects result in a band gap in the transmission spectrum of periodic SRR media around the magnetic resonance frequency. Omega type structures also present bianisotropic effects for the normal incidences of EM waves. These structures need to be investigated in detail experimentally and numerically, since bianisotropic materials are alternative metamaterials with exciting physical characteristics.

4. Dual transmission band within the negative permittivity regime

It is possible to obtain pass bands at different frequencies by combining different types of resonant structures that have different resonance frequencies. For this purpose, S-shaped metamaterials were previously shown to exhibit multiple pass bands [23]. We constructed a metamaterial consisting of two different composite structures. Normal Ω and large Ω structures are arranged periodically with alternating layers along the z-direction. The thin wire media are placed on the backside of the printed circuit boards. In other words, CMM1 and CMM3 structures with periodicities of $a_z = 10\,\mathrm{mm}$ are constructed. The distance between the neighboring layers, CMM1 and CMM3, is 5 mm.

Figure 7(a) shows the measured (blue line) and simulated (red line) transmission spectra of the new CMM. Two transmission bands are observed throughout the transmission spectra. These pass bands correspond to the transmission bands of constituting elements, CMM1 and CMM3. Expectedly, the transmission was reduced at the pass bands due to the reduced coupling of resonant Ω structures.

We constructed another CMM, which is the combination of CMM1 and CMM2. CMM2 is obtained by combining Ω with longer tails and thin wire media. A dual transmission band was observed for the combination of CMM1 and CMM2 as shown in figure 7(b). The transmission

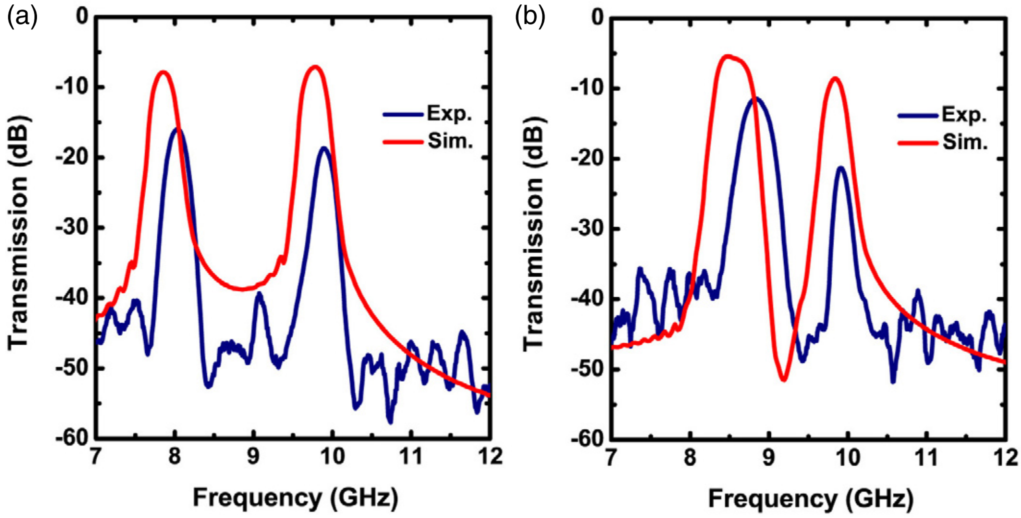

Figure 7. Transmission spectra of dual band metamaterial formed by alternating layers of (a) CMM1 and CMM3 and (b) CMM1 and CMM2. The blue and red lines represent the experimental and simulated results.

band that corresponds to the CMM1 is suppressed and the transmission band of the metamaterial with long Ω has a higher transmission.

5. Conclusion

We presented the experimental and numerical results on the transmission characteristics of single and periodic omega structures and metamaterials. The orientation of Ω tails with respect to the *E*-field, affects the resonance frequency. When the tails are parallel to the *E*-field the resonance frequency appears at a lower frequency due to an additional electric resonance arising from the tails of the Ω structure. The tail length significantly influences the resonance frequency. The longer tails result in lower resonance frequencies. Therefore, one can adjust the resonance of the frequency of Ω structures by changing the tail length of the Ω media. Periodic omega media are shown to exhibit a band gap in their transmission spectra. This band gap is due to magnetic and electric responses that are coupled, which is a fact of the bianisotropic nature of Ω structures. Thin wire media are used as a negative permittivity background media to combine with the omega structures in order to obtain a CMM. A transmission band is observed just below the band gap of periodic omega media. Two different CMMs with transmission bands at different frequencies are combined together. A dual transmission band within the negative permittivity frequency regime of thin wire media are then obtained.

Acknowledgments

This work is supported by the European Union under the projects EU-NoE-METAMORPHOSE, EU-NoE-PHOREMOST and TUBITAK under projects nos 104E090, 105E066, 105A005 and 106A017. The work of MH has been partly supported by the Grant

Agency of the Czech Republic under project 102/06/1106 'Metamaterials, nanostructures and their applications'. EO acknowledges partial support from the Turkish Academy of Sciences.

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