Design of a dual-band monopole antenna enclosed in a 2D-chiral metamaterial shell

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Abstract

The application of 2D-chiral metamaterial structure aiming at controlling the radiation parameters of a monopole wire antenna in the microwave region is investigated. We show that an alumina substrate shell covered with the 2D-chiral metamaterials can significantly improve the antenna response in terms of gain and return loss. In addition, the simple rotation of the inclusions around their respective axes opens the possibility of controlling the return loss (S_{11}), gain and input impedance. Also, it is possible to obtain a second resonant frequency, which is quite attractive for telecom applications.

1. Introduction

The field of metamaterials has caused a tremendous impact in the scientific community in the last few years, particularly due to remarkable electromagnetic (EM) properties such as negative electric and magnetic responses, and negative index of refraction [1]. Many important EM devices are now making use of these peculiar properties, such as waveguides, sensors, invisibility cloaks, and antennas, just to mention a few.

Antenna technology, in particular, has strongly benefited from the technological advances experienced recently with metamaterials. For example, power radiated from a cylindrical electric dipole as well as from a monopole antenna over an infinite ground plane could be increased by means of a spherical shell of homogeneous, isotropic negative permittivity (ENG) material [2]. Under proper excitation conditions, the energy radiated by a source embedded in a slab of metamaterial can be concentrated in a narrow cone in the surrounding media, therefore controlling the antenna directivity [3].

Besides the conventional metamaterials, chiral metamaterials are also of great interest, mainly due to the possibility of polarization azimuth rotation of the incident wave. In addition, they are a more attractive alternative to obtain negative or zero index of refraction, which demonstrates that they can also be used to improve the overall performance of an antenna.

In this contribution, we investigate how an alumina shell substrate containing a periodic arrangement of two-dimensional (2D) chiral metamaterial influences the antenna parameters. We show that the proposed structure can indeed substantially improve not only the antenna gain but also its return loss. In addition, by a proper choice of the chiral angle the antenna can be designed to operate at dual-resonance.

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2. Design of the structure

The chiral metamaterial adopted in this study was originally introduced by Plum et al. [4], and was designed for the microwave range of 3.0-9.0 GHz. As depicted in Fig. 1(a), this planar structure has an asymmetry in both arcs and gaps and the resulting 2D-chiral metamaterial has no line of mirror symmetry. In this structure, the metal inclusions are located on just one side of the alumina substrate (different from conventional chiral metamaterials, composed of metal inclusions on both sides of the substrate, and rotated by an angle φ with respect to each other). The dimension of the unit cell adopted here is $w_u = 2\lambda_0/15$, where $\lambda_0 = c/f$, c is the speed of light in vacuum, and f is the operating frequency. The metallic inclusion has $w_c \approx 0.27$ mm and radius $r_c = 1.9$ mm.

The monopole wire antenna above a finite ground plane Fig. 1(b) oriented in the positive z-axis is designed to operate at 8 GHz. The dimensions adopted for the monopole are: length $l = \lambda_0/4.6$, wire radius $r \approx \lambda_0/150$, and ground plane width $w = 8\lambda_0/5$. The antenna is fed as a lumped element, with resistance and reactance values of 25 Ω and 0 Ω, respectively. This is based on the assumption that the radiation resistance of the monopole antenna may be modelled by the method of images as a dipole with one-half the input impedance [5]. This lumped element has the same length of the wire radius, and is centered in the xyz origin below the cylindrical monopole antenna. In order to use the 2D-chiral metamaterials as a shell device, we first designed a polyhedron substrate with 8 sides 1.6 mm thick and 25 mm height, as illustrated in Fig. 1(c). The substrate adopted was the 96% aluminium oxide, also known as alumina ($\varepsilon_r = 9.4$, $tan\delta = 0.006$), where $tan\delta$ is the loss tangent of the material. The distance between the lumped element (xyz origin) and the polyhedron walls is $3\lambda_0/4$. The total number of unit cells over the structure is 160. The chiral metamaterials were modelled as perfect electric conductors (PEC) with zero thickness. This is a fair approximation, due to the low skin depth effect compared to the wavelength at microwave frequencies. The structure was enclosed in an air box of $\lambda_0/0.44 \times \lambda_0/0.44 \times \lambda_0/0.77$ with radiation boundary condition, so that scattering parameters and input impedance could be obtained. A smaller air box of $\lambda_0/0.56 \times \lambda_0/0.56 \times \lambda_0/1.2$, whose faces were set as an infinite radiation, was also included to compute the far-field parameters.

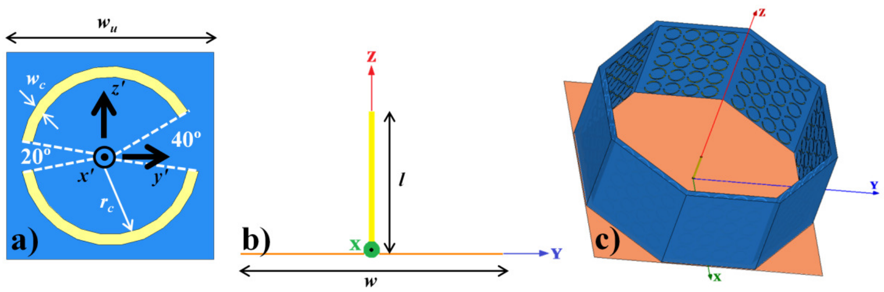

Fig. 1: (a) Unit cell of the 2D-chiral metamaterial at $\alpha = 0°$; (b) Monopole wire antenna above a finite ground plane; (c) Overall structure with the 2D-chiral metamaterial shell inserted around the monopole wire antenna above a finite ground plane.

3. Radiation results

The design and simulation were performed with the finite element method based on Ansoft High Frequency Structure Simulator (HFSS v11.2). The antenna operating frequency was 8 GHz. All the unit cells of the chiral metamaterial in the substrate were rotated in the x'-axis by $\alpha = 0^o, 45^o, 90^o$. The results for the return loss (S_{11}) and radiation pattern of the monopole antenna with and without the shell are shown in Fig. 2. It can be seen that depending on the rotational angle α the overall system response changes dramatically. The results for the minimum S_{11}, gain, input impedance and radiation efficiency (η) for each case and the respective resonance frequencies (first f_{r1} and second f_{r2}) are summarized in Table I. It can be observed that a second resonance appears around 10.4 GHz for the chiral structures. This can be very useful for telecom applications where different transmission/reception frequencies are required. The resonances can be controlled by modifying the size and numbers of the chiral cells, and the shell distance to the antenna. It's interesting to note that with $\alpha = 0^o$ the structure is matched to

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the feedline with approximately zero input reactance. The S_{11} values for $\alpha = 45^o$ and $\alpha = 90^o$ in the first resonance are not practical, because they are above the -10 dB limit. The dual-band case occurs for $\alpha = 0^o$, where there is a band below this limit ranging from 7.85 to 8.17 GHz in the first resonance, and from 10.36 to 10.61 GHz in the second resonance. We are now working on the optimization of the response of the chiral shell antenna aiming at equalizing the gain and return loss for a wider frequency band. It is worth mentioning that η may be somewhat overestimated since we are assuming the metal as PEC.

Table I: Results for the conventional monopole and for the shell with $\alpha = 0°$, $45°$ and $90°$.

Type	f_{r1} (GHz) / S_{11} (dB)	Gain$_{fr1}$ (dB)	Zin$_{fr1}$ (Ω)	η_{fr1}	f_{r2} (GHz) / S_{11} (dB)	Gain$_{fr2}$ (dB)	Zin$_{fr2}$ (Ω)	η_{fr2}
Monopole	8.23 / -18.50	3.79	31.25	1	---	---	---	---
α = 0°	7.98 / -41.31	3.75	24.60	0.88	10.48 / -12.99	5.90	39.44	0.99
α = 45°	8.00 / -5.05	6.89	7.10	0.99	10.43 / -21.55	6.97	29.55	0.99
α = 90°	7.99 / -5.14	7.55	7.27	0.99	10.36 / -43.72	5.86	24.96	0.99

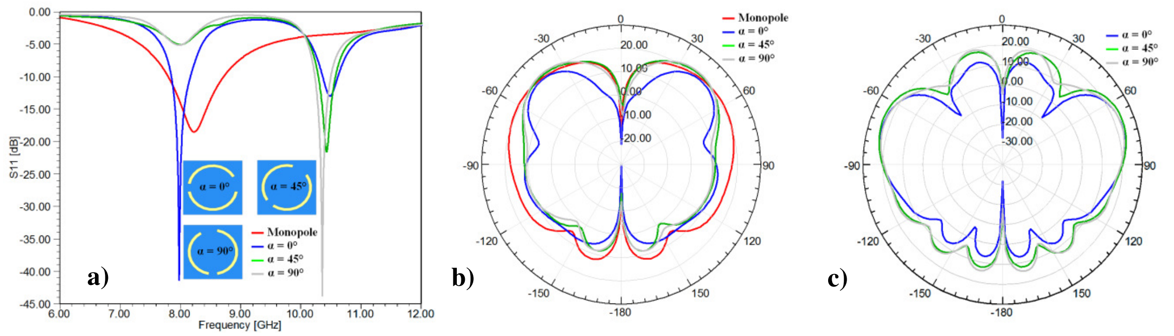

Fig. 2: Results for the 8 GHz monopole antenna with and without the 2D-chiral metamaterial structure - (a) Return loss (S_{11}); (b) Radiation pattern (dB) for $\phi = 90^o$ at f_{r1}; (c) Radiation pattern (dB) for $\phi = 90^o$ at f_{r2}.

4. Conclusion

The feasibility of using monopole antennas with a 2D-chiral metamaterial shell has been demonstrated. It was shown that by properly adjusting the rotation of the chiral cell with respect to its center, it is possible not only to control antenna parameters but also to obtain a second resonant frequency (dual-band operation). Using this technique, we have confirmed that it is a potential candidate to improve the performance of a conventional monopole antenna. In addition, it is expected that this structure can be successfully applied to other types of antennas.

Acknowledgments

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