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A COMPACT COPLANAR WAVEGUIDE (CPW)-FED DUAL-FREQUENCY ANTENNA WITH SINGLE-CELL METAMATERIAL LOADING

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Abstract—A compact waveguide (CPW)-fed dual-frequency planar monopole antenna is proposed, which can excite two modes. The antenna is composed of a epsilon negative (ENG) meta-structured transmission line (MTL) unit cell and a monopole. The first resonance is zeroth-order mode, which is described using dispersion relation of ENG MTL based on Bloch and Floquet and designed on a CPW single layer where vias are not required. And the second is electromagnetically coupled monopolar mode. The zeroth-order resonant phenomenon is employed to reduce the antenna size. To design and analyze the proposed antenna, the circuit simulation of the ENG MTL unit resonator is executed by the equivalent circuit, and the results are compared with those of full wave simulation and experiment. The results show that the presented antenna has a reasonable radiation characteristics of bandwidth gain and size, verified by a commercial EM simulation software HFSS11, and is suitable for compact dual-frequency antenna. Then the antenna is fabricated and measured. The realized antenna has a compact size of $0.288\lambda_0 \times 0.199\lambda_0 \times 0.011\lambda_0$ (25.1 mm × 17.4 mm × 1 mm) at 2.43 GHz. Simulated and experimentally measured results show that the proposed antenna can operate at 2.41 (2.43) GHz and 4.11 (4.14) GHz bands, respectively. Good agreement between the simulated and measured results is obtained.

1. INTRODUCTION

Dual-frequency antennas with good radiation characteristics have been developed widely and rapidly for Modern Wireless communication such

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as wireless local area network (WLAN) and personal communication transceiver system. They are often used in multi-functional wireless products to reduce the number and volume of required antennas. Several designs related to dual-frequency antenna have been reported [1–6]. Fractal antennas have been successfully designed as a compact high-performance multiband planar antenna [7–11]. These antennas based on conventional transmission lines (TLs) with single branch of dispersion curve use multi separate resonant paths of different lengths of resonators operated at half or quarter wavelength modes to obtain the dual resonances. Electromagnetically (EM) coupled techniques are available to miniaturize microstrip antennas [12, 13]. On the other hand, research into metamaterials based on periodic unit-cell for microwave circuit and antenna application has grown rapidly with the verification of left-handed (LH) metamaterials [14–20]. The double negative (DNG) and epsilon negative (ENG) meta-structured transmission line (MTL) can support the zeroth-order resonance mode. The ENG MTL with series inductance, capacitance and shunt inductance provides the epsilon negative bandstop region and right-handed region. At the boundary of ENG bandstop region and right-handed region, the ENG MTL has zeroth-order resonance mode, and the radiation principle of ENG MTL antenna can be demonstrated by using the infinitesimal circuit model.

Coplanar waveguide (CPW)-fed antennas are one of the most popular kinds of antennas as they can be easily integrated with microwave integrated circuits and monolithic microwave integrated circuits [21]. Also, CPW transmission lines have lower radiation losses and less dispersion than microstrip lines. Since a CPW stricture gives a lot of design freedom, it provides the benefit of easy design to implement the desired circuit parameters. Moreover, the use of a via free and signal layer process results in a simpler fabrication process compared with that of the broad metamaterial resonant antennas proposed in [19, 20]. This paper makes the best use of the CPW'coplanar characteristic and presents a novel compact coplanar waveguide (CPW)-fed resonant antenna with single-cell metamaterial loading for dual-frequency performance. To analyze the resonant modes of the resonator, the theoretic analysis and circuit simulation are executed using the equivalent circuit. To confirm the properties of the dual-frequency antenna such as input impedance, radiation pattern, and gain, the antenna is implemented, and its characteristics are discussed. The compared results of theory, simulation, and experiment will be presented. This paper is organized as follows. Section 2 discusses and demonstrates the principle of CPW-based ENG MTL unit cell. Section 3 is the implementation of the proposed antennas.

Simulated and measured properties of the dual-frequency antenna is provided in Section 4, and conclusions are drawn in Section 5.

2. CPW STRUCTURE ENG TRANSMISSION LINE

2.1. ENG Unit Cell Structure and Equivalent Circuit

Figure 1 shows the CPW view of the unit cell of ENG MTL and equivalent circuit model with parameters. The unit is composed of inductance (L_R) as well as a shunt capacitance (C_R) and inductance (L_L). It is designed in one unit cell and designed on a low-cost P4BM-2 substrate. We assumed that the P4BM-2 dielectric constant is 2.2 and that the declared board thickness is equal to 1 mm.

2.2. Theory

2.2.1. Analysis by Equivalent Circuit

By applying the periodic boundary condition related with the structure of ENG MTL unit cell and an infinitesimal circuit model of lossless ($R = 0$ and $G = 0$) artificial are expressed as shown in Figure 1. The

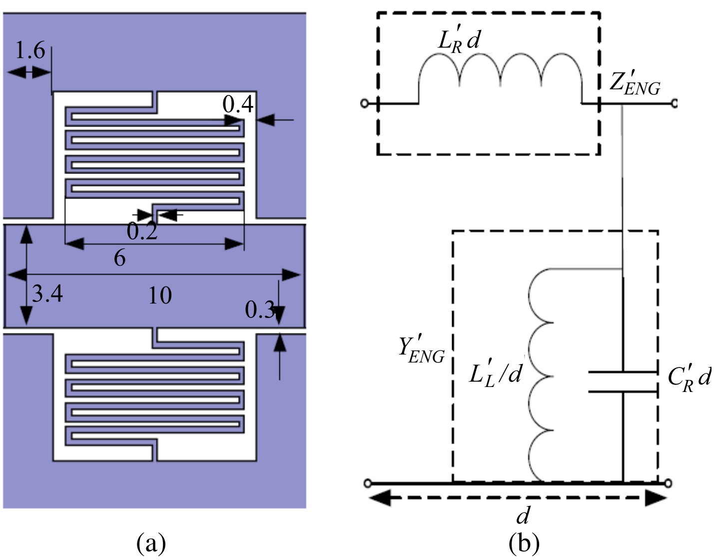

Figure 1. Structure of CPW ENG MTL (unit: mm). (a) Unit cell. (b) Equivalent circuit model.

ENG MTL model can be represented as the combination of a per-unit length series inductance L'_R, shunt capacitance C'_R, and shunt inductance L'_L as shown in Figure 1.

$$Z'_{ENG} = j\omega L'_R \tag{1}$$

$$Y'_{ENG} = j\left(\omega C'_R - \frac{1}{\omega L'_L}\right) \tag{2}$$

According to lossless transmission line theory, the propagation constant of ENG MTL is given by (3), where Z'_{ENG} and Y'_{ENG} are the per-unit length impedance and admittance, respectively.

$$\gamma = j\beta = \sqrt{Z'_{ENG}Y'_{ENG}} \tag{3}$$

By applying the periodic boundary condition related with Bloch-Floquet theorem to the equivalent circuit of the unit cell, the dispersion is obtained as

$$\beta_{ENG}(\omega) = \frac{1}{d}\cos^{-1}\left(1 + \frac{Z'_{ENG}Y'_{ENG}}{2}\right) \tag{4}$$

$$\beta_{ENG}(\omega) = \frac{1}{d}\cos^{-1}\left\{1 - \frac{1}{2}\left(\frac{\omega^2 - \omega_E^2}{\omega_R^2}\right)\right\} \tag{5}$$

where $\omega_R = 1/\sqrt{L'_R C'_R}$, $\omega_E = 1/\sqrt{L'_L C'_R}$, and d is a length of the unit cell and β a phase constant for Bloch waves.

For the zeroth-order resonance of an open-ended boundary condition, the input impedance is given by [17]

$$\begin{aligned} Z_{in} &= -jZ_0 \cot \beta l|_{\beta=0} = -jZ_0\frac{1}{\beta l} \\ &= -j\sqrt{\frac{Z'_{ENG}}{Y'_{ENG}}}\left(\frac{1}{-j\sqrt{Z'_{ENG}Y'_{ENG}}}\right)\frac{1}{l} = \frac{1}{Y'_{ENG}}\frac{1}{Nd} \end{aligned} \tag{6}$$

where $Z'_{ENG} = j\omega L_R/d$, $Y'_{ENG} = (j\omega C_R + 1/j\omega L_L)/d$, $L_R = L'_R d$, $C_R = C'_R d$, $L_L = L'_L/d$ and $Y = Y'_{ENG}d$. Then the artificial MTL for resonance modes n can be obtained by the following condition.

$$\beta_n d = \frac{n\pi d}{l} = \frac{n\pi}{N} ENG : n = 0, 1, 2, \ldots, (N-1) \tag{7}$$

Because Z_{in} can be expressed by the impedance of the LC anti-resonant tank, the zeroth-order resonance frequency is given as

$$\omega_{ZOR} = \omega_E = 1/\sqrt{L_L C_R} \tag{8}$$

Therefore, zeroth-order resonance occurs when the MTL has zero permittivity at non-zero frequency.

From (8), the zeroth-order resonance frequency of the ENG ZOR is determined by shunt inductance and shunt capacitance in the unit cell and independent of the total physical length of resonator. Thus, a small antenna using ENG ZOR can be obtained.

With those dimensions shown in Figure 1, the equivalent circuit parameters, which are extracted from the full-wave simulation data of the unit cell, are L_R of 7.40 nH, C_R of 0.48 pF and L_L of 9.05 nH. The dispersion diagrams for the symmetric CPW ENG unit cell are presented in Figure 2. The red dashed line represents dispersion curve calculated from equivalent circuit model, and the black solid line represents simulation curve calculated from the S parameters obtained from simulation in EM HFSS11. As shown in Figure 2, since the CPW ENG MTL unit cell simulated with EM HFSS11 is a distributed parameters circuit, there are some differences between the theory curve and simulation curve.

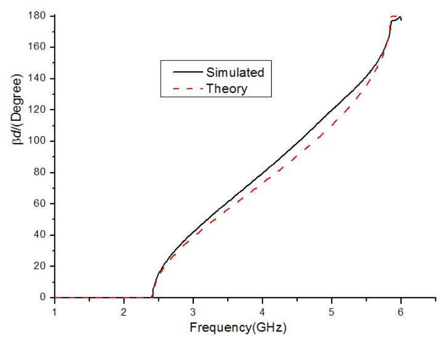

Figure 2. Dispersion curves of the CPW ENG MTL.

3. SIMULATION FOR THE TWO RESONANT MODE

In this section, all the antennas are designed on a low-cost P4BM-2 substrate. We assumed that the P4BM-2 dielectric constant is 2.2 and that the declared board thickness is equal to 1 mm.

3.1. ENG ZOR Mode Simulation

From the CPW ENG MTL unit cell discussed in Section 2, the configuration of the proposed ENG ZOR antenna is shown in Figure 3(a). The proposed ENG ZOR antenna is realized by using one CPW ENG MTL unit cell. From (6), the ZOR resonant frequency is determined by shunt shunt capacitance (C_R) and inductance (L_L). In order to realize L_L, the top patch and CPW grounds are connected by meander lines. The meander lines of the ZOR antenna are symmetrically aligned on both sides of the CPW GND. From the simulated results as shown in Figure 3(b), one resonant frequency occurs at the 2.41 GHz related to the ZOR mode.

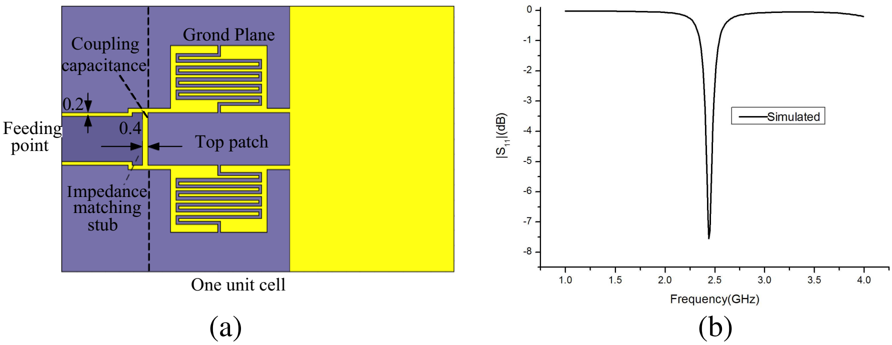

Figure 3. (a) Model of the ENG ZOR antenna (unit: mm). (b) Simulated S_{11} for the ENG ZOR antenna.

3.2. EM-coupled Monopole Structure Simulation

In this part, the second operation mode of the proposed antenna is described. Figure 4 shows the plane view of the proposed EM-coupled monopole structure. In order to realize the miniaturization of the structure, the coupled monopole takes advantage of Minkowski fractal curve. The deep and the light colour parts are printed on each side of the substrate. From the results as shown in Figure 5, one resonant frequency occurs at the 4.11 GHz related to the EM-coupled monopole mode.

4. FULL WAVE SIMULATION AND MEASUREMENT OF THE DUAL-FREQUENCY ANTENNA

According to part 3, the dual-frequency resonant antenna is proposed. Figure 6 shows the proposed and fabricated dual band antennas. The impedance matching feed line is designed by a transmission line and coupling gap between 50 Ω port and the antenna.

The realized resonant antennas have a compact size of 17.4 mm × 25.1 mm, and simulated in the EM simulation software HFSS11. Figure 7 shows the simulation and measured return losses of the antenna with single-cell metamaterial loading. Small differences come from the fabrication errors and dimensional tolerance. The

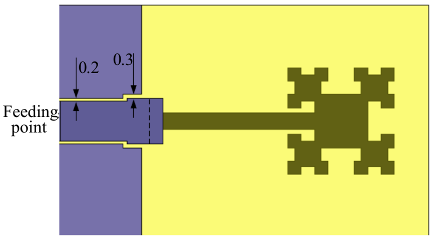

Figure 4. Coupled monopole structure (unit: mm).

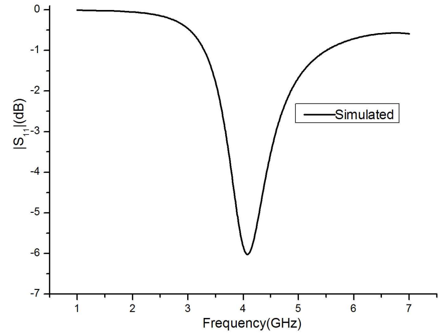

Figure 5. Simulation S_{11} for the EM-coupled monopole antenna.

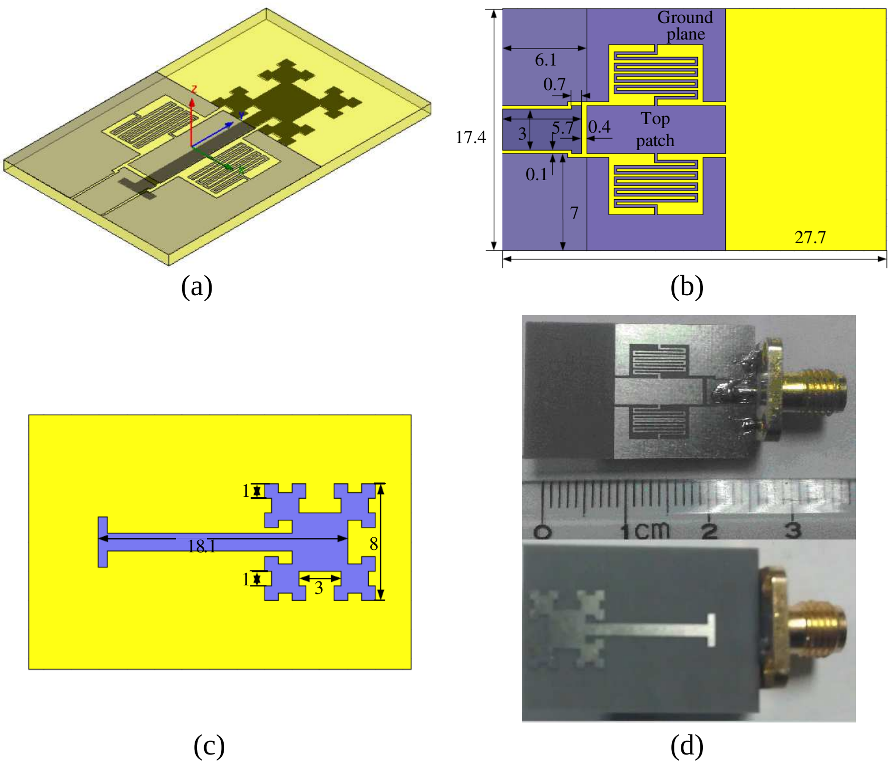

Figure 6. Configuration of the proposed CPW dual-frequency antenna (unit: mm). (a) 3-D view. (b) Top view. (c) Bottom view. (d) Fabricated dual-frequency antenna.

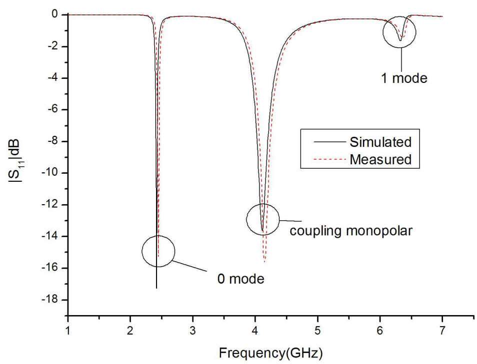

Figure 7. Simulated and measured return loss of the proposed CPW dual-frequency antennas.

simulated (measured) resonance frequencies are 2.41 (2.43) GHz and 4.11 (4.14) GHz. The first resonant frequency's measured and simulated results show good agreement with theoretical results from the dispersion curves in Figure 2. The -10 dB bandwidth of 2.425–2.45 GHz (1%) and 4.080–4.198 GHz (2.8%) are achieved, repectively. Thus, a -10 dB bandwidth of 1% and 2.8% are achieved. The narrow operation band is due to the resonant modes and high input resistance of the proposed antenna. The first resonant frequency f_0 can be tuned by changing the meander lines values and the gap between the top patch and CPW grounds. The electrical size of the unit cell of ENG MTL is $0.199\lambda_0 \times 0.114\lambda_0$ at 2.43 GHz. The overall area of the antenna is approximately $0.288\lambda_0 \times 0.199\lambda_0 \times 0.011\lambda_0$.

Figure 8 shows the simulated and measured radiation patterns of the antenna at ENG ZOR resonant mode and EM-coupled monopolar mode which are E-plane (y-z plane) and H-plane (x-z plane) at 2.43 GHz and 4.14 GHz. The measured result agrees with the simulated one. The maximum gains of the dual-frequency antenna in E-plane (y-z plane) are simulated (measured) as 2.54 (2.26) dBi at 2.43 GHz and 2.63 (2.35) dBi at 4.14, respectively. Furthermore, the simulated and measured radiation patterns show that the cross-polarization levels in low operation are higher than high operation band. The reasons are that the working principle of low operation band is ZOR mode and that the magnetic current on the top patch is a circle. Then the cross-polarization of the proposed antennas mainly comes from the magnetic current in y direction. And the measured cross-polarization results are higher than the simulated ones. These differences are also due to the measurement error resulting from the much smaller size of the aperture than that of the RF cable in the test environment.

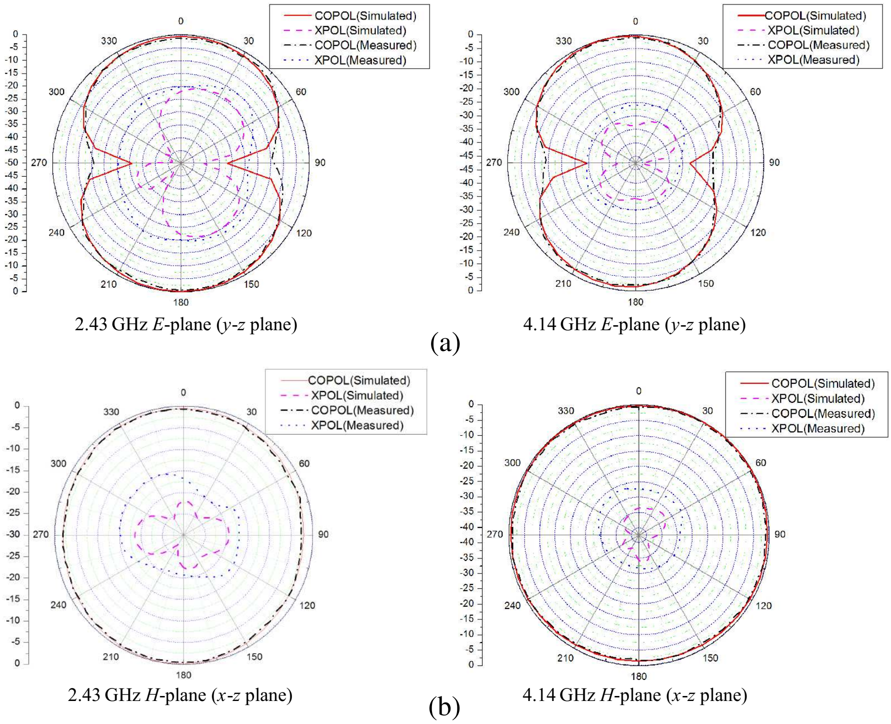

Figure 8. Simulated and measured radiation patterns of the proposed dual-frequency antennas at 2.43 GHz and 4.14 GHz: (a) E-plane, (b) H-plane.

5. CONCLUSIONS

In this paper, a novel dual-frequency antenna with single-cell metamaterial loading and EM coupled monopole has been proposed. The proposed antenna can be excited at two modes. The resonant characteristics of the proposed antenna are analyzed by ENG ZOR theory and EM coupling monopole mode. The design of ENG ZOR does not depend on its physical length, but on the reactance provided by its unit cell. Then the size of the proposed antennas can be reduced. When the ZOR antennas are realized using CPW technology, they allow for the design freedom of the shunt parameters in the equivalent circuit model. The radiation properties of the antenna, such as gains and bandwidth, are simulated and measured, respectively. The results show that the proposed antenna can be used as a compact dual-frequency antenna in wireless local area network (WLAN) and personal communication transceiver system.

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