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COMPACT COPLANAR WAVEGUIDE (CPW)-FED TUNABLE WIDEBAND RESONANT ANTENNAS USING METAMATERIAL TRANSMISSION LINE

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Abstract—A wideband resonant antenna loaded with coplanar waveguide (CPW) epsilon negative transmission metamaterial line (ENG MTL) unit cells is proposed. The CPW geometry provides high design freedom, and the metamaterial resonant antenna is designed on a CPW single layer where vias are not required. The novel ENG unit cell on a vialess single layer simplifies the fabrication process. The dispersion analysis of the metamaterial unit cell reveals that increasing right hand capacitance and left hand inductance can decrease the half-wavelength resonance frequency, thus reducing the electrical size of the proposed antenna. Based on the proposed ENG MTL unit cell, the wideband antenna is verified by a commercial EM simulator HFSS11 and developed. Comparing the measured performances with those resonant antennas, it is noticed that the proposed antenna achieves high bandwidth and further size reduction, higher efficiency and easier manufacturing. The realized antenna has a compact size of $0.32\lambda_0 \times 0.20\lambda_0 \times 0.012\lambda_0$ ($26.6\,\mathrm{mm} \times 16.\,\mathrm{mm} \times 1\,\mathrm{mm}$) at 3.65 GHz, and operates over the frequency ranges 3.38–4.23 GHz suitable for WiMAX applications. Good agreement between the simulated and measured results is obtained.

1. INTRODUCTION

Metamaterials have been widely studied for microwave circuit and antenna applications [1–7]. The planar meta-structured transmission line is the consequence of extraordinary permittivity and permeability. As well known, metamaterials have unique properties in comparison with conventional nature materials, such as anti-parallel phase and

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group velocities, and a zero propagation constant [3–8], and can be realized by means of split-ring resonators (SRRs) or composite right/left-handed transmission line (TL) which is composed of unit cells with a series capacitance and a shunt inductance based on conventional transmission line. The series capacitance and shunt inductance provide left-handed propagation characteristic which supports the backward wave [9]. By using the features of the anti-parallel phase and group velocities, CRLH TL can be applied to dominant mode leaky-wave antennas radiating in the backward and forward directions [10]. Also, the DNG MTL has right-handed propagation property because the DNG MTL has inevitable series inductance and shunt capacitance of the conventional transmission line. More importantly, the DNG MTL has unique property of an infinite wavelength wave at specific non-zero frequency where permittivity and permeability are zero. Various applications including filters, mixers, couples and resonant antennas have been reported. The ENG MTL with series inductance and shunt inductance provides the epsilon negative bandstop region and the right-handed region. At the boundary of ENG bandstop region and right-handed region, the ENG MTL can also provide the zeroth-order mode. Though the design of DNG or ENG ZOR resonant does not depend on its physical length, the narrow operation band is the major reason for restricting application.

To achieve a wideband characteristic, left-handed metamaterial was used as a compact radiating element [11]. However, the proposed antenna requires an additional match circuit, which increases the overall antenna size. Also, coplanar waveguide-fed monopole antennas with metamaterial loading were reported in [12]. A wideband microstrip patch antenna loaded with a planar CRLH unit cell is presented in [13], the wideband composed of two orthogonally mode working bands, and the frequency band not tunable.

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 [14]. Also, CPW transmission lines have lower radiation losses and less dispersion than microstrip lines. Since a CPW structure 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 simple fabrication process compared with that of the broad metamaterial resonant antennas proposed in [6]. This paper makes the best use of the CPW' coplanar characteristic and presents a novel compact coplanar waveguide (CPW)-fed resonant antenna with two ENG unit cells metamaterial loading for wideband resonant performance operating at the +1 order mode. To confirm the resonant mode of the resonator, the theoretic analysis and circuit simulation are executed using the equivalent circuit. The properties of the wideband antenna such as input impedance, radiation pattern and gain are simulated by means of the commercial EM simulator HFSS11. The antenna is implemented, and its characteristics are discussed. This paper is organized as follows. Section 2 discusses and demonstrates the principle of CPW-based ENG MTL unit cell. Section 3 concerns the design and the simulation of the proposed antenna. Fabrication and experiment properties of the wideband antenna are provided in Section 4, and conclusions are drawn in Section 5.

2. STRUCTURE ENG TRANSMISSION LINE

2.1. ENG Unit Cell Structure and Equivalent Circuit

A certain cell is produced and analyzed to prove the working principle of the antenna. Figure 1 shows the structure of CPW ENG unit. The unit is composed of series inductance (L_R) as well as a shunt capacitance (C_R) and inductance (L_L). It is designed in one unit cell and on a low-cost P4BM-2 substrate. We assumed that the P4BM-2 dielectric constant is 2.2, and the declared board thickness is equal to 1 mm.

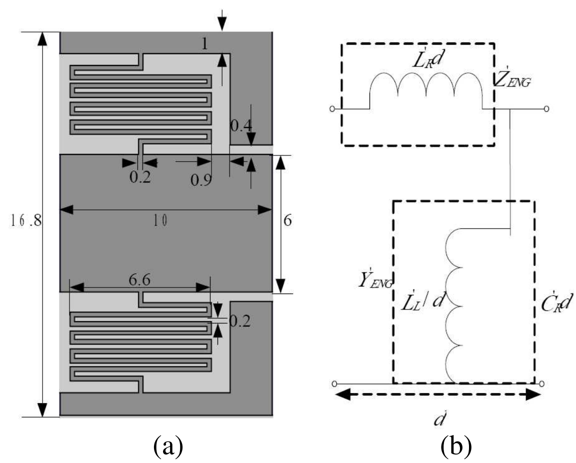


Figure 1. Structure of CPW ENG MTL (unit: mm). (a) Unit cell. (b) Equivalent circuit model.

2.2. Theory

Analysis by Equivalent Circuit

Applying the periodic boundary condition related with the structure of ENG MTL unit cell, an infinitesimal lossless circuit model ($R = 0$ and $G = 0$) is shown in Figure 1. The ENG MTL model can be represented as the combination of a per-unit length series inductance L'_R, shunt capacitance C'_R, and a shunt inductance L'_L.

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

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

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-Cloquet theorem to the equivalent circuit of the unit cell, the dispersion is obtain 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 and β are a length of the unit cell and a phase constant for Bloch waves, respectively. Then the artificial MTL for resonance modes n can be obtained by the following condition.

$$\beta_n d = \frac{n\pi d}{l} = \frac{n\pi}{N} ENG : \quad n = 0, 1, 2, \ldots, (N-1) \tag{6}$$

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 9.35 nH, C_R of 0.48 pF and L_L of 10.48 nH, respectively. The dispersion diagrams for the symmetric CPW ENG unit cell are presented in Figure 3. The red line represents dispersion curve calculated from equivalent circuit model, and the black 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 in EM HFSS11 is a distributed parameter circuit, there are some differences between the theory curve and the simulation curve.

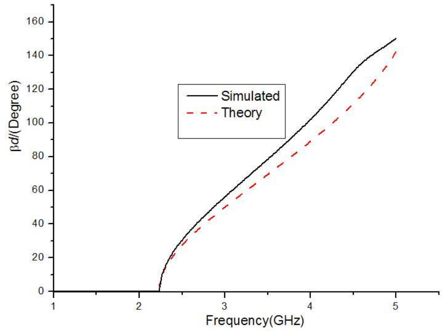


Figure 2. Dispersion curves of the CPW ENG MTL.

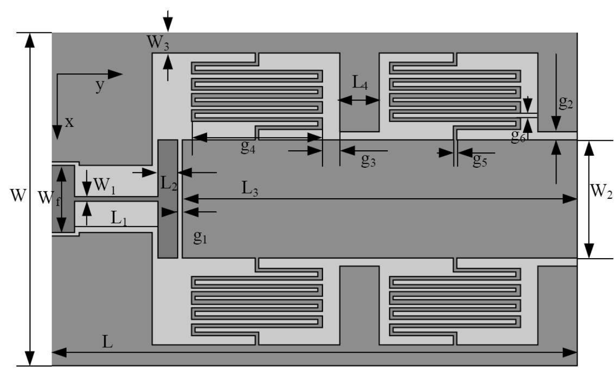
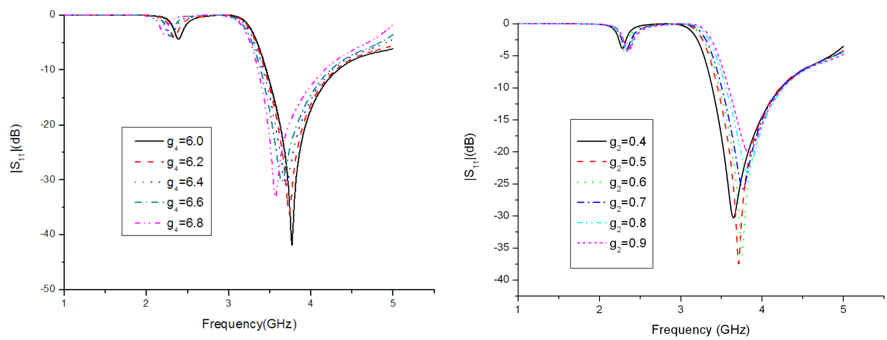


Figure 3. Configuration of the proposed CPW wideband antenna (unit: mm).

3. WIDEBAND ANTENNA STRUCTURE AND FULL WAVE SIMULATION

From the CPW ENG MTL unit cell discussed in Section 2, the configuration of the proposed wideband resonant antenna is shown in Figure 3. The realized resonant antenna has a compact size of 16.8 mm × 26.6 mm. The proposed CPW based wideband metamaterial antenna using two CPW ENG MTL unit cells which are composed of top metallic patches, meander lines and CPW ground planes. In order to realize the L_L, the meander lines are connected between the top patch and the CPW grounds as the shorted stub. The meander lines of the antenna are symmetrically aligned on both sides of the CPW GND. The feed line for impedance matching between 50 Ω port and the antenna is designed by impedance transition line and a coupling capacitance (C_C). According to Equation (6), the +1 order resonant mode occurs at $\beta d = 90°$. The antenna is simulated by means of HFSS11 electromagnetic simulation software. The optimized values for the parameters marked on the antenna structure in Figure 3 are the following: $W_f = 3.4$ mm, $W = 16.8$ mm, $L = 26.6$ mm, $W_1 = 0.2$ mm, $W_2 = 6$ mm, $W_3 = 1$ mm, $L_1 = 4.2$ mm, $L_2 = 1$ mm, $L_3 = 20$ mm, $L_4 = 2$ mm, $g_1 = 0.2$ mm, $g_2 = 0.4$ mm, $g_3 = 0.9$ mm, $g_4 = 6.6$ mm, $g_5 = 0.2$ mm, $g_6 = 0.2$ mm.

According to the resonant theory, the +1 order resonant mode is affected by the right handed inductance (L_R) as well as the right handed shunt capacitance (C_R) and left handed inductance (L_L). Then this paper mainly discusses operation band influenced by the different C_R and L_L. Figure 4 shows the return loss' variation for different values of g_4 and g_2. Other parameters values are fixed. Subsequently, the operation band can be adjusted by changing the value of C_R (g_2) and L_L (g_4), rather than changing the size of the antenna.



(a) return loss as g_4 (b) return loss as g_2

Figure 4. Return loss as parameters' change (Other parameters values are fixed).

4. FABRICATION AND EXPERIMENTS

Figure 5 shows the prototype of the proposed antenna fabricated on a low-cost P4BM-2 substrate with a dielectric constant of 2.2 and thickness of 1 mm where $g_2 = 0.4$ and $g_4 = 6.6$ are selected. The simulated and measured return losses characteristics of the proposed antenna are shown in Figure 6. The measured data are in good agreement with those of the simulation. The measured 10 dB return loss bandwidth of the proposed antenna extends from 3.38 GHz to

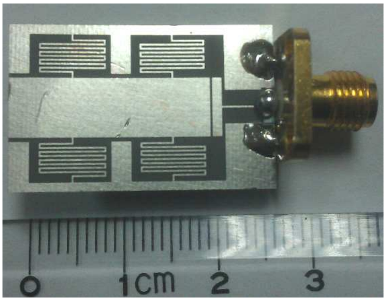


Figure 5. Fabricated wideband antenna.

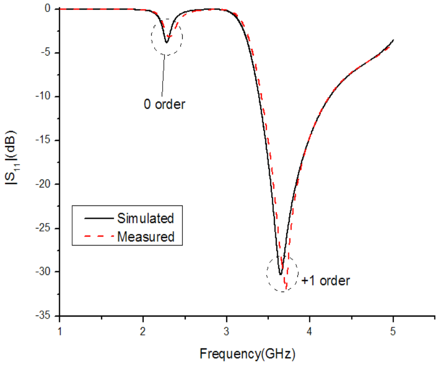


Figure 6. Simulated and measured return loss of the proposed CPW ENG MTL wideband antenna.

4.23 GHz. So a −10 dB bandwidth of 23.3% is achieved. The bandwidth of the proposed antenna is more than eight times wider than that of a conventional patch antenna operating at the same frequency band. The electric size of the resonant antenna is $0.32\lambda_0 \times 0.20\lambda_0 \times 0.012\lambda_0$ (26.6 mm × 16.8 mm × 1 mm) at 3.65 GHz. Owing to the +1 resonant mode based on CPW ENG MTL, a 60% reduction in antenna size has been achieved, as compared to a conventional patch antenna size.

The wideband antenna directed along the y-direction at the +1 order resonant mode has a monopolar pattern in yz-plane and an omnidirectional pattern in xz-plane. Figure 7 shows the simulated and experimental radiation patterns of the proposed antenna at 3.38 GHz, 3.65 GHz, and 4.23 GHz. The maximum gains of the wideband antenna in E-plane (y-z plane) are simulated (measured) as 2.73 (2.5) dBi at 3.38 GHz, 2.56 (2.4) dBi at 3.65 and 2.45 (2.2) dBi at 4.23 GHz,

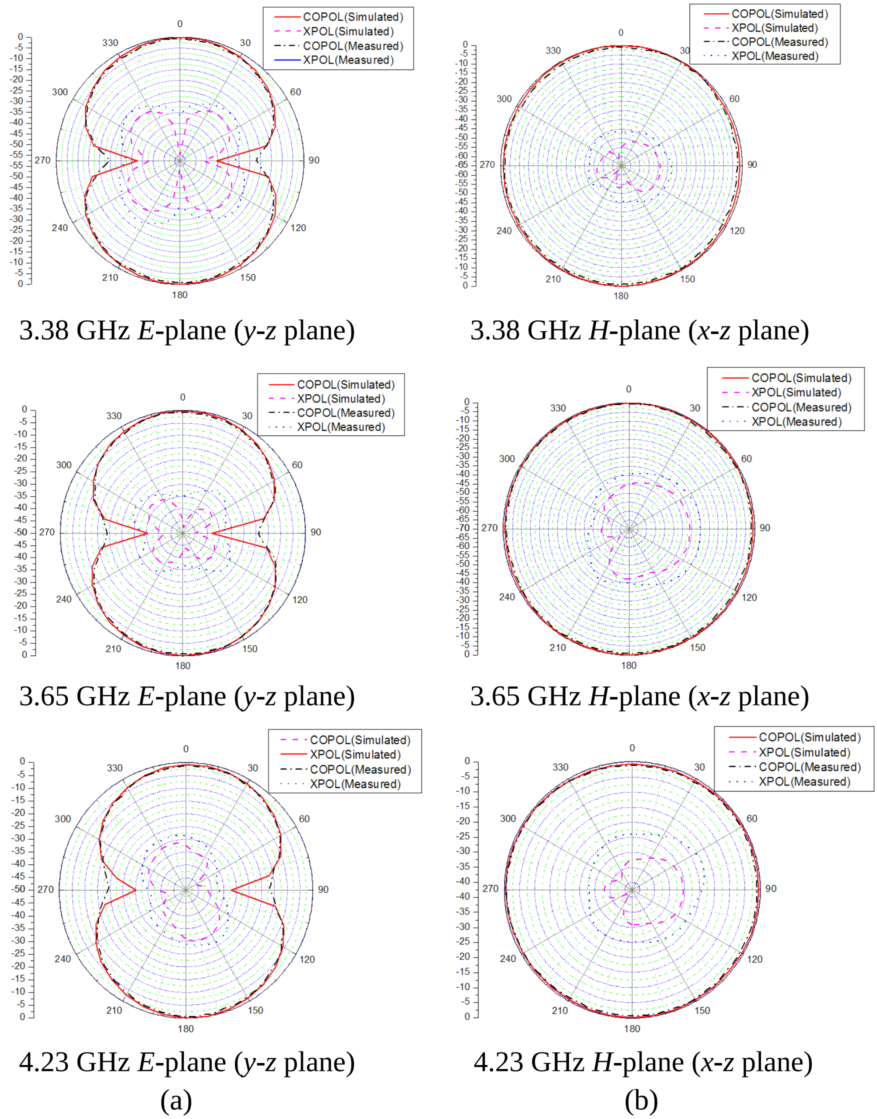


Figure 7. Simulated and measured radiation patterns of the proposed dual-frequency antenna at 3.38 GHz, 3.65 GHz, and 4.23 GHz: (a) *E*-plane, (b) *H*-plane.

respectively. Furthermore, the measured radiation patterns show that the cross-polarization level of the proposed antenna is higher than the simulated ones. These differences are also due to the fine meander lines and the measurement error resulting from the much smaller size of the aperture compared with that of the RF cable in the test environment.

5. CONCLUSIONS

In this paper, a novel wideband antenna with CPW ENG unit cells has been proposed. In the proposed antenna, the +1 order mode can be excited. Design guidelines to change the L_L and C_R values have been given; the operating band can be adjusted. The resonant characteristics of the proposed antenna are analyzed by ENG MTL theory. Design of ENG resonant does not depend on its physical length, but on the reactance provided by its unit cell. The resonant frequency in this case can be reduced. The proposed antenna achieves a 60% reduction in patch size compared to a conventional patch antenna. The radiation properties of the antenna such as gains and bandwidth are simulated and measured. The results show that the proposed antenna can be used as a compact wideband antenna in wireless local area network (WLAN) and personal communication transceiver system.

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REFERENCES

1. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*, Wiley, New York, Dec. 2005.
2. Lee, C.-J., K. M. K. H. Leong, and T. Itoh, "Composite right/left-handed transmission line based compact resonant antennas for RF module integration," *IEEE Trans. Antennas Propag.*, Vol. 54, No. 8, 2283–2291, 2006.
3. Lai, A., K. M. K. H. Leong, and T. Itoh, "Infinite wavelength resonant antennas with monopole radiation pattern based on periodic structures," *IEEE Trans. Antennas Propag.*, Vol. 55, No. 3, 868–876, Mar. 2007.
4. Park, J.-H., Y.-H. Ryu, J.-G. Lee, and J.-H. Lee, "Epsilon negative

zeroth-order resonator antenna," *IEEE Trans. Antennas Propag.*, Vol. 55, No. 12, 3710–3712, Dec. 2007.

5. Ryu, Y.-H., J.-H. Park, J.-H. Lee, and H.-S. Tae, "Multiband antenna using +1, −1, and 0 resonant mode of DGS dual composite right/left handed transmission line," *Microwave and Optical Technology Letters*, Vol. 51, No. 10, 2485–2488, Oct. 2009.
6. Jang, T., A. Choi, and S. Lim, "Compact coplanar waveguide (CPW)-fed zeroth-order resonant antennas with extended bandwidth and high efficiency on vialess single layer," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 2, 363–372, Feb. 2011.
7. Lai, C.-P., S.-C. Chiu, H.-J. Li, and S.-Y. Chen, "Zeroth-order resonator antennas using inductor-loaded and capacitor-loaded CPWs," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 9, 3448–3453, Sep. 2011.
8. Ghosh, B., S. K. Moinul Haque, and D. Mitra, "Miniaturization of slot antennas using slit and strip loading," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 10, 3922–3927, Oct. 2011.
9. Leftheriades, G. V. E., A. K. Iyer, and P. C. K. Remer, "Planar negative refractive index media using periodically L-C loaded transmission lines," *IEEE Trans. Microw. Theory Tech.*, Vol. 50, No. 12, 2702–2712, 2002.
10. Lim, S., C. Caloz, and T. Itoh, "Metmaterial-based electronically controlled transmission line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," *IEEE Trans. Microw. Theory Tech.*, Vol. 53, 161–173, Jan. 2005.
11. Palandoken, M., A. Grede, and H. Henke, "Broadband microtrip antenna with left handed metamaterial," *IEEE Trans. Antennas Propag.*, Vol. 57, No. 2, 331–338, Feb. 2009.
12. Zhu, J., M. A. Antoniades, and G. V. Eleftheriades, "A compact tri-band monopole antenna with single cell metamaterial loading," *IEEE Trans. Antennas Propag.*, Vol. 58, No. 4, 1031–1038, Apr. 2010.
13. Ha, J., K. Kwon, Y. Lee, and J. Choi, "Hybird mode wideband patch antenna loaded with a planar metamaterial unit cell," *IEEE Trans. Antennas Propag.*, Vol. 60, No. 2, 1143–1147, Feb. 2012.
14. Ghosh, B., S. K. Moinul Haque, and D. Mitra, "Miniaturization of slot antennas using slit and strip loading," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 10, 3922–3927, Oct. 2011.