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COMPACT CPW-BASED ZEROTH-ORDER RESONANT ANTENNA WITH INTERLEAVING CRLH UNIT CELLS

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Abstract—This paper proposes a compact zeroth-order resonant (ZOR) antenna with improved gain and efficiency. The proposed CRLH unit cell is based on the coplanar waveguide (CPW) structure. The proposed ZOR antenna is designed for a 2.45 GHz frequency band, and it has the characteristic of monopolar radiation. Shunt inductance is implemented by microstrip short-circuit stubs, and a metal-isolator-metal (MIM) capacitator provides series capacitance, where a large capacitance can be achieved in a small footprint. The proposed antenna comprises two interleaving composite right-/left-handed CRLH unit cells, where the size of one unit cell is measured at only $0.12\lambda_0 \times 0.098\lambda_0$. Because the field is loosely confined within the CPW-based unit cell, a good antenna peak gain of 2.03 dBi, and a radiation efficiency of over 68% is achieved when fabricated on a thin substrate. The proposed antenna did not require an additional matching network, reducing the total antenna footprint. This paper presents antenna parameters such as the return loss, radiation pattern, antenna gain, and radiation efficiency to validate the proposed design, which achieved good simulation results.

1. INTRODUCTION

Monopole antennas are widely used in modern communication systems because of their low cost and easy fabrication, and a linear polarized radiation pattern with a high co-polar to cross-polar ratio. The omnidirectional radiation characteristic in the horizontal plane makes it a good candidate for application in communication systems. Wireless devices are currently manufactured to be small and compact, and

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antennas have become one of the largest components in wireless communication systems. The traditional monopole antenna is a quarter wavelength long, and numerous studies have attempted to miniaturize antenna designs. However, the size of those antenna designs is related to the operating frequency, and the size reduction is limited.

Another approach to designing an electrically small antenna is to use the composite right-/left-handed transmission line (TL). Similar to the resonant-type antenna, open- or short-ended circuits can terminate the CRLH TL. With an open-circuit CRLH TL, the zeroth-order resonant frequency is determined using the shunt LC resonator, which is provided by the right-handed shunt capacitance and the left-handed shunt inductance. In contrast, with a short-circuit CRLH TL, the zeroth-order resonant frequency is determined using the series LC resonator, which is provided by the right-handed series inductance and the left-handed series capacitance. The advantage of this type of antenna is that the resonant frequency of the antenna is not related to the physical length of the CRLH TL, but to the values of the capacitance and inductance of the CRLH unit cell. The zeroth-order resonant antenna has a monopolar radiation pattern, which is similar to that of the traditional monopole antenna; thus, it is suitable for adoption on wireless devices requiring an omnidirectional radiation characteristic. Studies have presented zeroth-order resonant antennas based on microstrip technology [1–9] and a coplanar waveguide structure [10–14]. In those designs, the interdigital capacitator or the couple between the adjacent patches provided the left-handed series capacitance. However, a small capacitance provided by weak edge coupling limits the practicability and application of these structures. In addition, these design have a wide ground width, which is unsuitable for replacing the traditional monopole antenna. The authors in [7] presented a compact zeroth-order resonant antenna based on a dual-arm spiral configuration. In this paper, the proposed CRLH antenna is composed of two unit cells, where the gap coupling between the spiral arms contributes to the series capacitance, and the metallic via hole at the end of one arm results in the shunt inductance; therefore, the footprint in the transverse direction can be reduced. However, the antenna gain, impedance bandwidth, and radiation efficiency are also downgraded.

This paper presents a compact co-planar waveguide (CPW)-based zeroth-order resonant antenna with interleaving CRLH unit cells. The proposed CRLH unit cell provides a large series capacitance, which can be used to adjust the input impedance of the antenna; therefore, an additional matching network is not required for impedance matching.

This design provides a compact size, a good gain, and radiation efficiency in a small antenna footprint. The novel CRLH unit cell has the same pattern on both sides of the circuit board. The microstrip shorting stubs provide the shunt inductance, and the metal-insulator-metal (MIM) structure provides the series capacitance, increasing the practicability of application where a large capacitance is required. This paper presents details on the fabrication of the proposed antenna, as well as the measured and simulated results to validate the proposed design.

2. ANTENNA DESIGN

The lumped element equivalent circuit of a CRLH unit cell comprises a series LC resonator and a shunt LC resonator, as shown in Fig. 1 [15]. Therefore, an unbalanced CRLH TL can provide two zeroth-order resonances. Because the CRLH TL is either open- or short-circuited, only one resonance is practical in impedance matching. For an open-circuit CRLH TL, only the shunt resonance, determined using the right-handed capacitance (C_R) and left-handed inductance (L_L), is considered. The resonant frequency of the shunt resonance is given by

$$\omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \quad [\text{rad/s}] \tag{1}$$

Therefore, the CRLH unit cell can be rendered unbalanced to reduce the design complexity. Because of the infinite-wavelength wave at the zeroth-order resonance, the unloaded Q-factor is obtained as

$$Q_0^{open} = \frac{1/NG}{\omega_{sh}(L_L/N)} = \frac{1/G}{\omega_{sh} L_L} = \frac{1}{G}\sqrt{\frac{C_R}{L_L}} \tag{2}$$

where N is the number of unit cells, and G is the dielectric loss caused by the non-ideal dielectric material [15]. This formula shows the benefit of metamaterials; for an open-circuit zeroth-order resonant antenna,

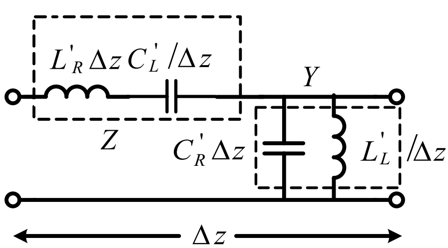
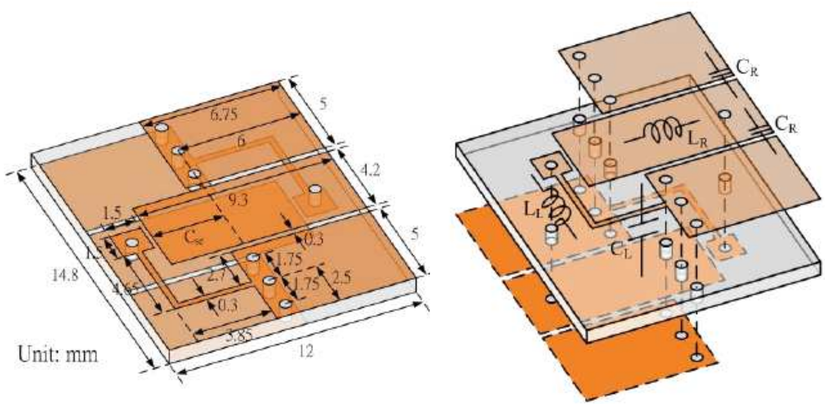


Figure 1. Typical equivalent circuit model for the CRLH-TL.

the unloaded Q is dependent only on the loss in the shunt LC tank, not on the loss in the series tank circuit because the radiation efficiency is inversely proportional to the Q factor. Therefore, a ZOR antenna with a higher gain and efficiency can be obtained by designing a CRLH unit cell with a lower loss in the substrate and with a larger left-handed inductance.

Figure 2 shows the proposed CRLH unit cell, which was developed on a 0.8-mm-thick RO4003 substrate with a dielectric constant of 3.55 and a loss tangent of 0.0027. All vias used here have a diameter of 0.54 mm. This design is based on the CPW structure, which provides a lower substrate loss than the microstrip. In this interleaving structure, the series capacitance can be implemented easily using the MIM capacitor, and the shunt inductance is implemented by the metallic shorting strips that connect the traces to the CPW ground conductor. The CPW grounds on the top and bottom layer are connected by vias, and the overlapped area contributed by the top- and bottom-layer trace form the series MIM capacitor. This configuration can effectively reduce the antenna footprint. The characteristic impedance of the CPW with a finite ground width can be calculated [16]. The selected length of the CRLH unit cell is 14.8 mm because the CRLH unit cell must be shorter than a quarter wavelength of the operating frequency to satisfy the homogeneity condition [15]. Therefore, the right-handed series inductance L_R and the right-handed shunt capacitance C_R can be calculated, as well as the left-handed series capacitance C_L and the



(a) (b)

Figure 2. Configuration of the proposed CRLH unit cell. (a) Three-dimensional view. (b) Layer view with equivalent circuit illustration.

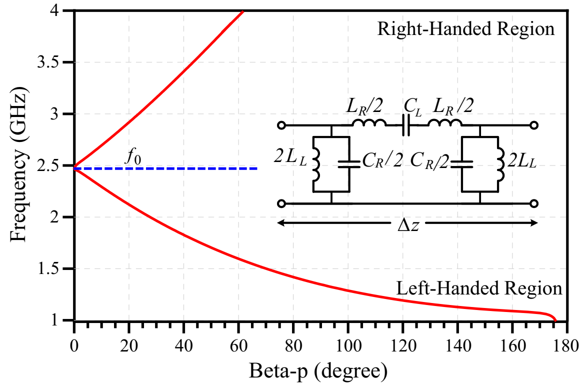


Figure 3. Equivalent circuit model and simulated dispersion diagram of the proposed CRLH unit cell.

left-handed shunt inductance L_L. Fig. 3 shows the equivalent circuit model of the proposed CRLH unit cell, and the simulated dispersion diagram obtained by applying periodic boundary conditions related to the Bloch-Floquet theorem [17], which is obtained by

$$\beta(\omega) = \frac{1}{p}\cos^{-1}\left[1 - \frac{1}{2}\left(\frac{\omega_L^2}{\omega^2} + \frac{\omega^2}{\omega_R^2} - \frac{\omega_L^2}{\omega_{se}^2} - \frac{\omega^2}{\omega_{sh}^2}\right)\right] \tag{3}$$

where

$$\begin{aligned} \omega_L &= \frac{1}{\sqrt{C_L L_L}}, \quad \omega_R = \frac{1}{\sqrt{C_R L_R}} \\ \omega_{se} &= \frac{1}{\sqrt{C_L L_R}}, \quad \omega_{sh} = \frac{1}{\sqrt{C_R L_L}} \end{aligned} \tag{4}$$

The dispersion diagram shows that zeroth-order resonance occurs at 2.45 GHz. Because only the shunt resonance ω_{sh} is practical for the impedance matching of an open-circuit ZOR antenna, the left-handed series capacitance related to the series resonance ω_{se} can be removed or easily implemented by using a small gap to reduce the design complexity. However, the proposed design uses the MIM capacitor to implement the left-handed series capacitance, and the CRLH unit cell is designed to be balanced to show its potential application in short-circuit zeroth-order resonant antennas, which requires sufficient series capacitance. Furthermore, the series capacitance can be used to adjust the input impedance of the ZOR antenna.

As shown in Fig. 4, the proposed compact CPW-based ZOR antenna comprises two CRLH unit cells. The second stage is rotated

180° around the x-axis (cascade direction) to connect with the previous stage. In this open-circuit case, the input impedance of the resonator as β approaches zero is given by

$$Z_{in}^{open} = \frac{1}{NY} \tag{5}$$

where Y is the admittance of the CRLH unit cell, which is given by

$$Y = j\left(\frac{\omega C_R - 1}{\omega L_L}\right) \tag{6}$$

Equation (5) shows that for an open-circuit zeroth-order resonant antenna, the input impedance is related only to the right-handed shunt capacitance (C_R) and the left-handed inductance (L_L). However, as the left-handed series capacitance (C_L) decreases to a small value,

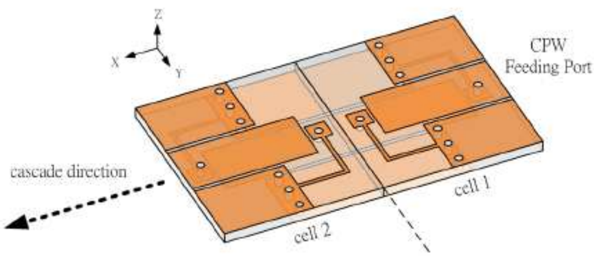


Figure 4. Illustration of cascading CRLH unit cells to form a ZOR antenna.

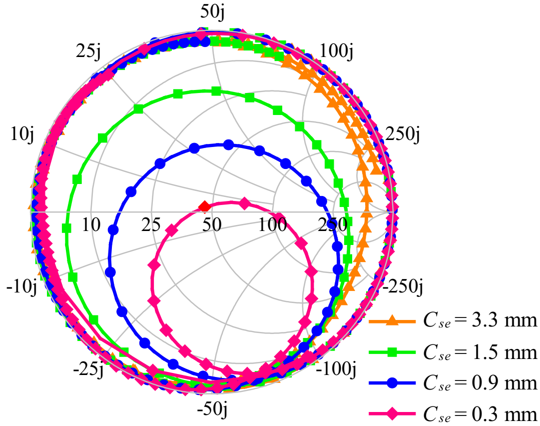


Figure 5. Parametric study with different value of MIM capacitor.

the coupling coefficient can be adjusted for impedance matching. Therefore, the chip capacitor and the 10-mm CPW can be removed to reduce the size. A parametric study of the two-cell ZOR antenna with varying values of the MIM capacitor is shown in Fig. 5. The findings showed that as C_{se} decreased to 0.3 mm, good impedance matching at 2.45 GHz could be achieved. Therefore, the proposed ZOR antenna can be matched either by using a 0.3 pF series chip capacitor fed by a 10-mm-long CPW or simply by adjusting the left-handed series capacitance of the CRLH unit cell to further reduce the size of the ZOR antenna without requiring a matching circuit.

3. MEASURED AND SIMULATED RESULTS

The proposed compact CPW-based ZOR antenna with interleaving CRLH unit cells was fabricated and tested. Fig. 6 shows a photograph of two prototypes, where prototype (A) was constructed using balanced CRLH unit cells, and prototype (B) was constructed using unbalanced unit cells. Both prototypes contain two unit cells, but prototype (A) requires a matching chip capacitor of 0.3 pF and a 10-mm CPW, whereas prototype (B) does not. The proposed CRLH unit cell is measured at only $0.12\lambda_0 \times 0.098\lambda_0 \times 0.007\lambda_0$, where λ_0 is the free-space wavelength at the zeroth-order resonance. In addition, the antenna footprint is measured at $0.12\lambda_0 \times 0.278\lambda_0$ for prototype (A) and $0.12\lambda_0 \times 0.196\lambda_0$ for prototype (B), which are extremely compact. Fig. 7 shows the measured and simulated reflection coefficients of

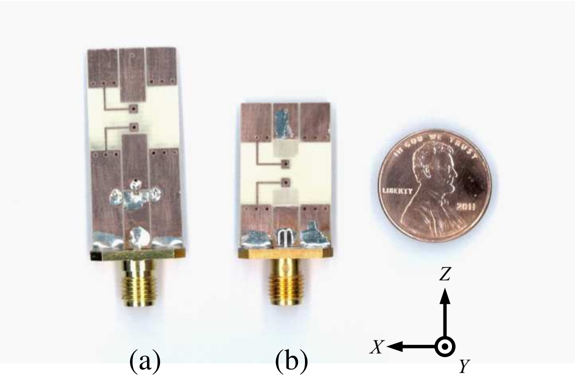


Figure 6. The fabricated prototypes. (a) ZOR antenna with balanced unit cells and a matching section. (b) ZOR antenna with unbalanced unit cells but no matching section is needed.

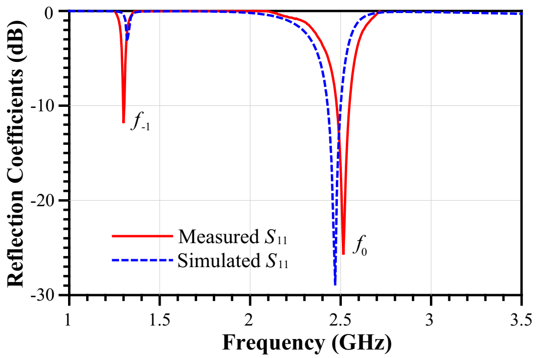


Figure 7. Measured and simulated reflection coefficients.

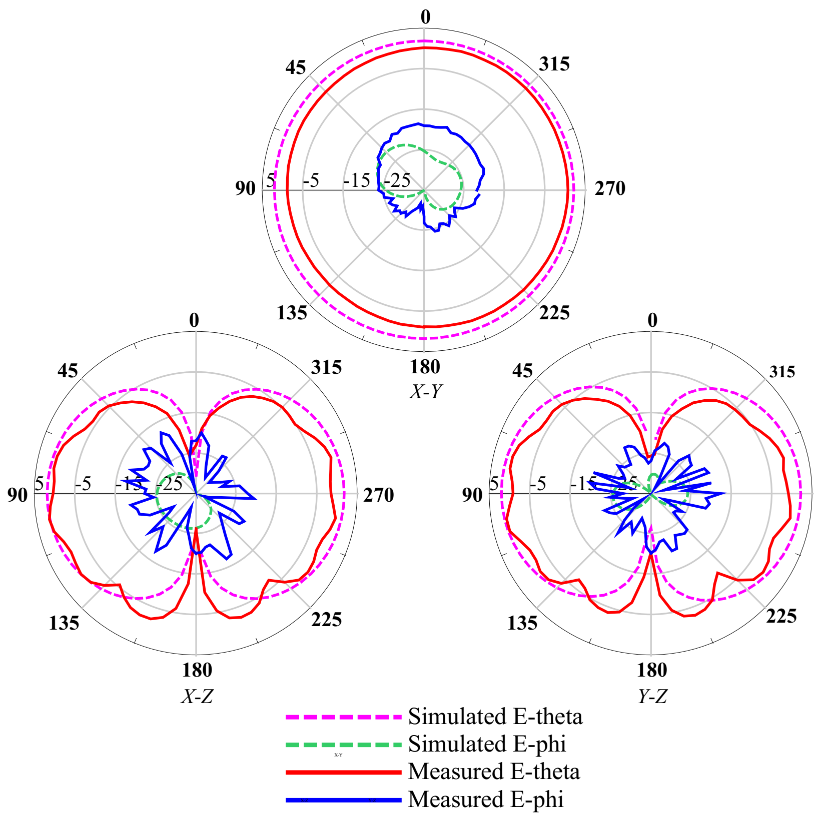


Figure 8. Measured and simulated far-field radiation patterns in x-y plane, x-z plane, and y-z plane.

Table 1. Comparison between various compact ZOR antennas.

	This work	[7]	[10]
Frequency [GHz]	2.45	2.42	2.03
Unit Cell Size (λ_0)	$0.12 \times 0.098 \times 0.007$	$0.066 \times 0.053 \times 0.013$	$0.053 \times 0.097 \times 0.011$
Ant. Dimension (λ_0)	0.12×0.196	0.218×0.082	0.172×0.145
Bandwidth (%)	2.99	1	6.8
Gain (dBi)	2.01	-0.53	1.35
Efficiency (%)	68	53	62
	[5]	[6]	
Frequency [GHz]	2.3	2.44	
Unit Cell Size (λ_0)	$0.054 \times 0.105 \times 0.012$	$0.052 \times 0.069 \times 0.024$	
Ant. Dimension (λ_0)	0.23×0.146	0.325×0.325	
Bandwidth (%)	1.3	1.44	
Gain (dBi)	-0.28	-6.83	
Efficiency (%)	62	15.21	

prototype (B); its simulation was performed using Ansoft HFSS [18], and the measurement was conducted using an HP vector network analyzer (E8364B). The resonance at 2.45 GHz corresponds to the zeroth-order resonance, and the other resonance observed at 1.8 GHz corresponds to the negative first-order resonance. The measured results are in good agreement with the simulated results, and only a slight frequency shift was observed, which may be attributed to a fabrication error. The achieved -10 dB bandwidth is approximately 2.99%, which was measured from 2.475 to 2.55 GHz. The far-field radiation characteristics of the proposed ZOR antenna were measured in an anechoic chamber. Fig. 8 shows the measured and simulated radiation patterns in the x-y plane, the x-z plane, and the y-z plane. Excellent agreement was obtained. The proposed antenna is shown to exhibit a monopolar radiation characteristic, and small cross-polarization was observed. The simulated antenna peak gain is 2.01 dBi, whereas the measured antenna peak gain is 1.87 dBi. In addition, compared to the simulated efficiency of 84%, the measured result is 68%. The difference between the measured and simulated results may be attributed to the inaccuracy of the small antenna efficiency measurement calculated using the directivity/gain method [19]. Table 1 shows a comparison of the proposed design and the designs of small ZOR antennas presented in published papers. The table shows that the proposed antenna not only performs well but is also compact.

4. CONCLUSION

This paper proposed a compact CPW-based zeroth-order resonant antenna with interleaving CRLH unit cells. The novel CRLH unit cell can be implemented easily with a large series capacitance in a small footprint. The proposed CRLH ZOR antenna consists of two CRLH unit cells, and this paper presented both a balanced type with a matching circuit and an unbalanced type without a matching circuit. Because the field is loosely confined within the proposed CPW-based unit cell, a good antenna gain and radiation efficiency can be achieved when the ZOR antenna is fabricated on a thin substrate with a small dimension. This paper presented antenna parameters such as the return loss, radiation pattern, antenna gain, and radiation efficiency to validate the proposed design, the measured results are in good agreement with the simulation. The compact design demonstrated good performance, making it suitable for use in wireless communication systems.

REFERENCES

1. Sanada, A., M. Kimura, I. Awai, H. Kubo, C. Caloz, and T. Itoh, "A planar zeroth-order resonator antenna using left-handed transmission line," *Proc. Eur. Microwave Conf.*, Amsterdam, The Netherlands, Oct. 2004.
2. Park, J.-H., Y.-H. Ryu, J.-G. Lee, and J.-H. Lee, "A zeroth-order resonator antenna using epsilon negative meta-structured transmission line," *IEEE Antennas and Propagation Society Int. Symp.*, 3480–3483, Honolulu, USA, Jun. 2007.
3. Choi, J. and S. Lim, "Frequency reconfigurable metamaterial resonant antenna," *Proc. Asia-Pacific Microwave Confe.*, Vol. 3, 798–801, Singapore, Dec. 2009.

4. Kim, T.-G. and B. Lee, "Metamaterial-based compact zeroth-order resonant antenna," *Electronics Letters*, Vol. 15, No. 1, 12–13, Jan. 2009.
5. Baek, S. and S. Lim, "Miniaturised zeroth-order antenna on spiral slotted ground plane," *Electronics Letters*, Vol. 45, No. 20, 1012–1013, Sep. 2009.
6. Dong, Y., H. Toyao, and T. Itoh, "Miniaturized zeroth order resonance antenna over a reactive impedance surface," *Proc. IEEE iWAT Int. Workshop*, 58–61, 2011.
7. Liu, C.-C., P.-L. Chi, and Y.-D. Lin, "Compact zeroth-order resonant antenna based on dual-arm spiral configuration," *IEEE Antennas Wireless Propag. Lett.*, Vol. 11, 318–321, 2012.
8. Shin, D. H. and T. Itoh, "A note on radiation loss of zeroth order resonators," *Progress In Electromagnetics Research C*, Vol. 2, 109–116, 2008.
9. Fashi, A. A., M. Kamyab, and M. Barati, "A microstrip smallsized array antenna based on the meta-material zeroth-order resonator," *Progress In Electromagnetics Research C*, Vol. 14, 89–101, 2010.
10. Jang, T., J. 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.
11. Lee, H. M. and T. J. Cho, "Co-planar waveguide-fed zeroth-order resonant antenna with improved gain and efficiency," *Proc. IEEE iWAT Int. Workshop*, 388–391, 2011.
12. Lee, H.-M., "A compact zeroth-order resonant antenna employing novel composite right/left-handed transmission-line unit-cells structure," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 1377–1380, 2011.
13. 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.
14. Zermane, A., B. Sauviac, B. Bayard, B. Payet-Gervy, J. J. Rouseau, and A. Benghalia, "Modeling and measurement of a zeroth-order-resonator and a composite right-left-handed transmission line in coplanar technology," *Progress In Electromagnetic Research C*, Vol. 14, 33–43, 2010.
15. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*, John Wiley & Sons, New York, 2006.

16. Cai, M., P. S. Kooi, M. S. Leong, and T. S. Yeo, "Symmetrical coplanar waveguide with finite ground plane," *Microwave Optical Tech. Lett.*, Vol. 6, No. 3, 218–220, Mar. 1993.
17. Lai, A., K. M. K. H. Leong, and T. Itoh, "Infinite wavelength resonant antennas with monopolar radiation pattern based on periodic structures," *IET Microw. Antennas Propag.*, Vol. 55, No. 3, 868–876, Mar. 2007.
18. Ansoft HFSS, Ansoft Corporation.
19. Pozar, D. M. and B. Kaufaman, "Comparison of three methods for the measurement of printed antenna efficiency," *IEEE Trans. Antennas Propag.*, Vol. 36, 136–139, Jan. 1988.