A BROADBAND PIFA WITH ZEROTH-ORDER RESONATOR LOADING

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Abstract—A printed broadband planar inverted-F antenna (PIFA) with zeroth-order resonator (ZOR) loaded is proposed, whose shorting strip of the PIFA is replaced by an interdigital capacitor and thin inductive strip in series. The loaded interdigital capacitor and thin inductive strip act as a shorting strip at the 3.1 GHz, which allows the antenna to maintain its regular performance. Around 2.0 GHz, the antenna with the interdigital capacitor and thin inductive strip works on the zeroth-order resonance mode, which makes the physical size be independent of the wavelength. By merging the two modes, a broadband performance can be achieved. The size of the antenna is only 12.5 mm × 7.81 mm × 1.6 mm with single layer. The measured antenna bandwidth is 1.63 GHz (about 65%), total gain is above 2.5 dBi and the simulated radiation efficiency is over 90% in the working band. Especially the antenna has same direction of the radiation patterns in the broadband. In the end, the antenna with lumped elements loading is also discussed.

1. INTRODUCTION

The novel electromagnetic properties of metamaterials have been widely applied to RF device. From a practical application standpoint, the composite right and left handed (CRLH) transmission line (TL) is useful in planar circuit [1, 2]. CRLH-TL structures also provide a new method for implementing small resonant antennas. It has the unique property of an infinite wavelength wave at the frequency of the boundary of the LH and RH bands. Using the infinite wavelength property of the CRLH-TL [3, 4], zeroth-order resonator (ZOR) and ZOR antennas [5–10] have been reported. Especially a kind of
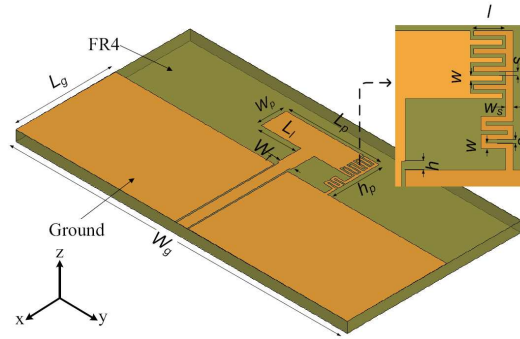
Figure 1. Broadband PIFA with ZOR loading. All dimensions are in mm: $L_P = 12.5$, $W_P = 3.8$, $L_G = 15.0$, $W_G = 50.0$, $L_l = 4.5$, $h_P = 7.8$, $W_f = 2.0$, $w = 0.3$, $s = 0.2$, $h = 0.5$, $l = 1.8$, $W_s = 0.4$.

monopole antenna with one cell metamaterials loading can be useful for the wideband and multiband antenna design [11, 12], but these antenna exhibit orthogonal polarizations at the different modes, which limit the applications.

The planar inverted-F antenna (PIFA) is attractive for mobile handheld devices because it has a compact size and an omnidirectional radiation pattern. But is has insufficient bandwidth. Thus a more complex structure is often used for enhancing the bandwidth [13–16]. This increases the manufacture difficulty and cost. In this paper, a zeroth-order resonator unit is introduced into printed CPW-fed PIFA. As show in Fig. 1. The short strip of the PIFA is replaced by an interdigital capacitor and a thin inductive strip in series. The antenna acts as a PIFA at the upper band, because the capacitor and the inductor in series resonant like the short strip. At the lower band, the antenna works on the ZOR mode because of the loading. Broadband performance can be achieved in a compact and low profile design by merging the ZOR and the regular PIFA modes that does not require the use of any lumped elements. Moreover the antenna has same direction of the radiation patterns in the broadband.

2. ANTENNA DESIGN

2.1. Theoretical Background

The design of the broadband PIFA is based on the ENG (epsilon negative)-TL unit cell. Similar to the CRLH-TL unit cell, an ENG-TL unit cell has same zero-order resonant nonzero frequency [17].
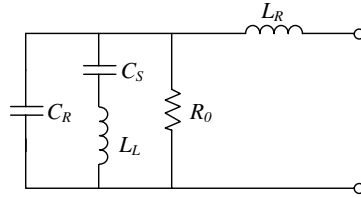
Figure 2. Equivalent circuit of the proposed PIFA on ZOR mode.

Equivalent circuit of the PIFA on ZOR mode is shown in Fig. 2. The capacitance C_S models the interdigital capacitor. The inductance L_L models the thin inductive strip. The parasitic series inductance and shunt capacitance effects is modelled by L_R and C_R. R_0 is the radiation resistance of the antenna. The propagation constant is given by

$$\beta = \frac{1}{p}\cos^{-1}\left\{1 - 0.5\left(\frac{\omega^2 L_R C_S}{1 - \omega^2 L_L C_S} + \omega^2 L_R C_S\right)\right\} \qquad (1)$$

The resonance of ENG-TL for resonance modes can be obtained by the following condition:

$$\beta_n p = \frac{n\pi p}{l} = \frac{n\pi}{N} \quad n = 0, 1, 2, \cdots, (N-1) \qquad (2)$$

where $N(= l/p)$ and l are the number of unit cell and total length of the resonator, respectively. In this antenna, there is only one unit cell. So it only has the ZOR mode. In this mode, there is zero phase velocity at nonzero frequency. The ZOR frequency is given as

$$\omega_{ZOR} = \sqrt{\frac{C_S + C_R}{L_L C_S C_R}} \qquad (3)$$

It is determined by shunt inductance and shunt capacitance in the unit cell and it is independent of the total physical length of resonator. Thus, a small antenna can be achieved.

2.2. Design Procedure

The antennas considered in this work were designed on an FR4 substrate with parameters $h = 1.6\,\text{mm}$, $\epsilon_r = 4.4$ and $\tan\delta = 0.02$. First as a reference comparison, an unloaded CPW-fed printed PIFA was first designed and simulated in Ansoft HFSS, which has the same dimensions as the one shown in Fig. 1. It has 20% bandwidth of the return-loss below $-10\,\text{dB}$ at $3.25\,\text{GHz}$. The bandwidth performance of the PIFA is not quite wide, so an approach using ZOR loading was pursued in order to extend the bandwidth. The short strip of the PIFA
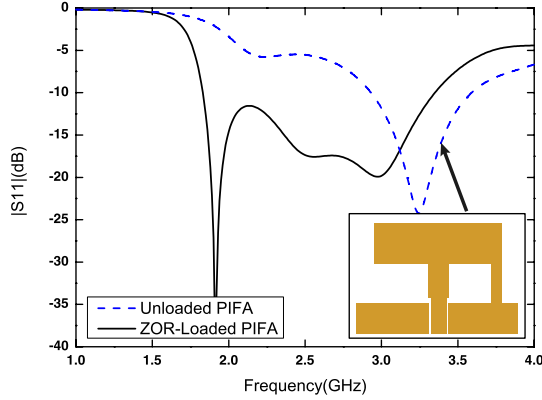
Figure 3. Simulated return-loss characteristics of the unloaded and ZOR-loaded PIFA from Ansoft HFSS.

is replaced by an interdigital capacitor and a thin inductive strip in series as shown in Fig. 1. This type of loading acts as an unit ZOR cell together with the PIFA, and enables the ZOR-loaded PIFA maintain its small size while decreasing its operating frequency and extending its bandwidth effectively.

The simulated return-loss characteristics for the unloaded and ZOR-loaded PIFA are both shown in Fig. 3. It can be observes that the regular PIFA without ZOR loading exhibits a single resonance around 3.25 GHz, and the ZOR-loaded PIFA exhibits a wide bandwidth for dual-resonance, including the resonance around 3.0 GHz together with an additional resonance around 1.9 GHz. The ZOR-loaded PIFA has a simulated return-loss bandwidth below -10 dB of 1.5 GHz, from 1.8 to 3.3 GHz. Thus it can be observed that the addition of the ZOR loading to the PIFA not only reduces the operating frequency from 3.25 to 3.0 GHz, but also introduces another resonance around 1.9 GHz. The bandwidth is extended by merging the two resonance frequencies together in a single passband.

2.3. Principle of Operation

The different operation mode of the antenna can be explained by considering the current distribution on the ZOR-loaded PIFA at each of the resonant frequencies, as shown in Fig. 4. These figures were sketched from the surface current distributions observed in Ansoft HFSS. At 3.0 GHz, the interdigital capacitor and a thin inductive strip in series resonate like the short strip. Thus the antenna acts as the regular PIFA. The current which distribute along the x-axis on the
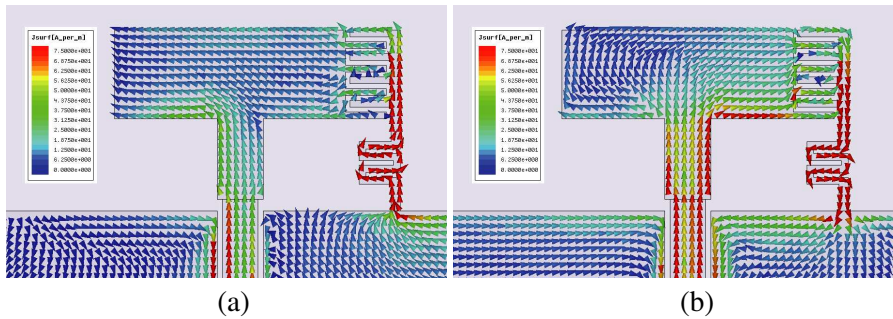
(a)   (b)

Figure 4. HFSS-simulated surface current distribution on the conductors of the broadband PIFA with ZOR loading at the resonant frequencies of (a) 3.0 GHz and (b) 1.9 GHz. (a) Regular PIFA mode (3.0 GHz). (b) ZOR mode (1.9 GHz).

antenna is obtained. The resonant frequency can be controlled by the length of the antenna L_P.

At 1.9 GHz, the antenna no longer acts as a PIFA, but rather as a small loop with current in phase for the ZOR mode. The current distribution has the uniform phase on the right part of the antenna. The right top of the antenna is the main radiator. This produces the same radiation pattern direction together with the pattern at 3.0 GHz, as will be shown in the next section. Because of the thin strip shorted to the ground plane, the current distribute uniformly on the ground plane. Thus the size of the ground plane can be used to change the input impedance level. The equivalent circuit for antenna at ZOR mode is shown in Fig. 2. The unit ZOR cell has a small Q factor for the series capacitor C_S which will be useful to enhance the bandwidth [18].

3. SIMULATION AND EXPERIMENTAL RESULTS

The broadband ZOR-loaded PIFA was fabricated and tested. The fabricated prototype is shown in Fig. 5, and the measured versus the simulated magnitude of S_{11} from Ansoft HFSS shown in Fig. 6. Due to the fabrication tolerance and the loss of the SMA connector, the measured bandwidth of the ZOR-loaded PIFA does not match the simulated so perfect. The unloaded PIFA exhibits a simulated −10 dB bandwidth of 0.65 GHz, from 2.94 to 3.59 GHz, while the ZOR-loaded PIFA exhibits a measured −10 dB bandwidth of 1.63 GHz, from 1.82 to 3.45 GHz. The simulated radiation efficiency and gain as a function of frequency is also shown in Fig. 7. In the working band, the antenna acts with a high efficiency above 90% and gain above 2.5 dBi.
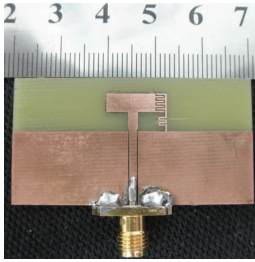
Figure 5. The fabricated prototype of the broadband PIFA with ZOR-loading.
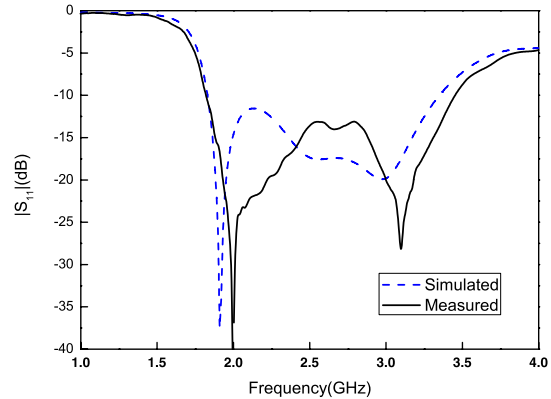
Figure 6. Simulated and measured return-loss characteristics of the broadband PIFA with ZOR-loading.
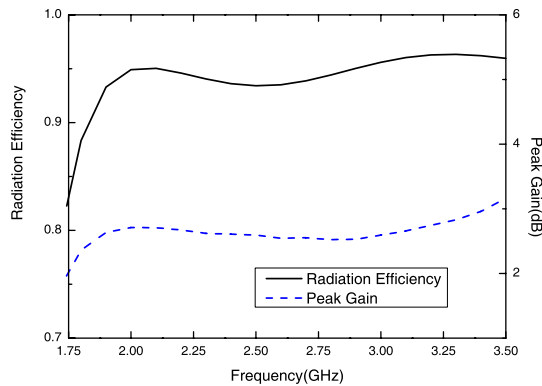

Figure 7. Simulated radiation efficiency and gain of the broadband PIFA with ZOR-loading.

The measured and simulated radiation patterns for the ZOR-loaded PIFA for the three principal planes at 3.1 GHz are shown in Fig. 8(a). At 3.1 GHz, the antenna exhibits radiation patterns with a horizontal y-directed linear electric field polarization, consistent with y-directed currents along the main radiation strip and the thin inductive strip, as show in Fig. 4(a). Thus the radiation patterns verify that at 3.1 GHz the loaded interdigital capacitor and thin inductive strip enables the antenna to operate as a regular PIFA.

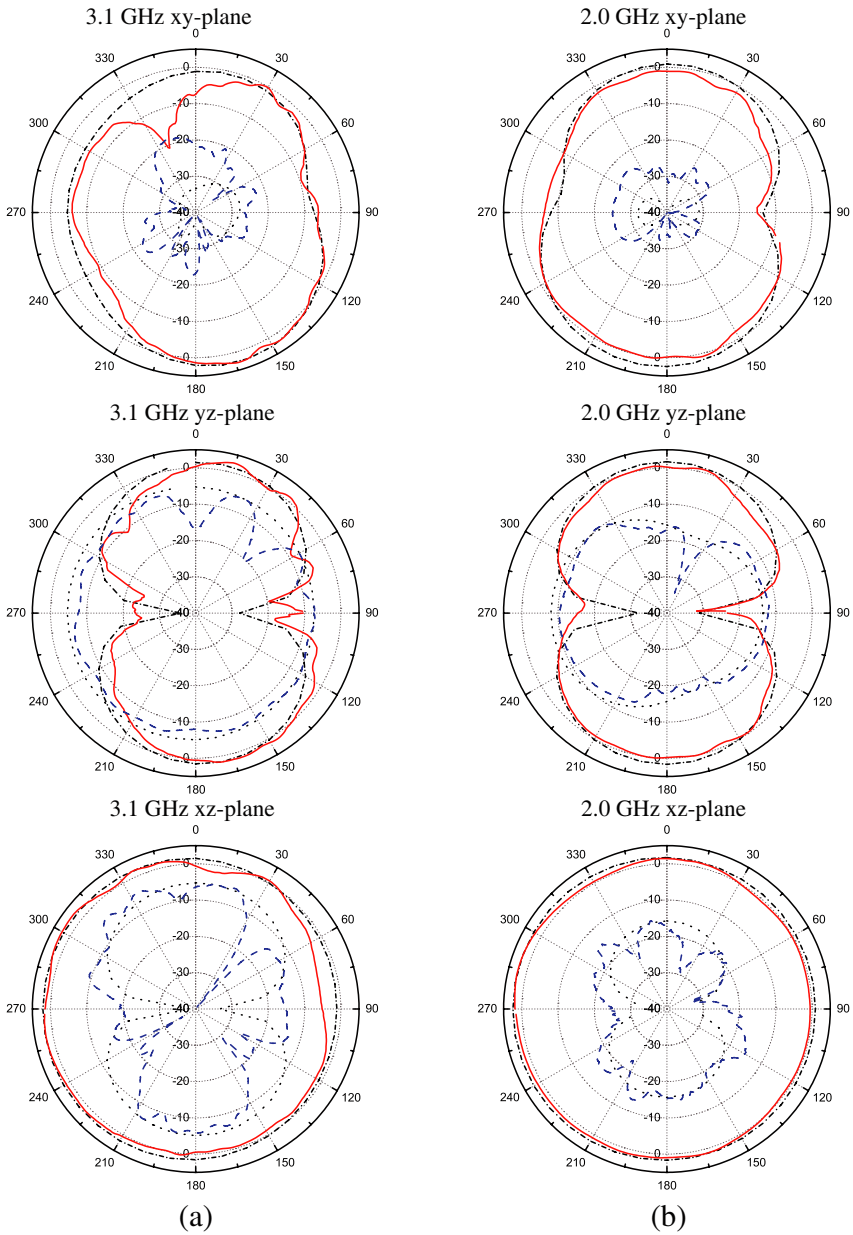The radiation patterns in the xy- and the yz-planes, which

Figure 8. Simulated radiation patterns for the broadband PIFA with ZOR-loading. Solid red line: measured co-polarization, dashed blue line: measured cross-polarization, dashed black line: simulated copolarization, dash-dot black line: simulated cross-polarization.

correspond to the two E-planes of the PIFA, reveal that the patterns are not completely symmetric. This is an expected result, since the PIFA is a bending structure. In the xz-plane, which corresponds to the H-plane of the PIFA, the radiation pattern is as expected omnidirectional. The simulated efficiency from HFSS at 3.1 GHz was 96%.

Figure 8(b) shows the measured and simulated radiation patterns for the ZOR-loaded PIFA for the three principal planes at 2.0 GHz. At this frequency the antenna exhibits radiation patterns with a horizontal y-directed current along right part of the antenna, considering the current on the feed line and the thin strip are opposite, as show in Fig. 4(b). This providing a radiation pattern which has the same characteristics to the one observed at 3.1 GHz.

The radiation patterns in the xy- and the yz-planes, which correspond to the two E-planes of the radiating mode at 2.0 GHz. In the xz-plane, which corresponds to the H-plane of the ZOR-loaded PIFA, the radiation pattern is as expected omnidirectional. The simulated efficiency from HFSS at 2.0 GHz was 92%.

4. ANTENNA WITH LUMPED ELEMENTS LOADING

The interdigital capacitor and thin inductive strip can be also replaced by lumped elements for further discuss. The lumped values C_s and L_l can be derived from the approximate expression for interdigital capacitance and meander inductor [19]. Compared to the EM-simulated result, the lumped value are: $C_s = 0.35$ pF, $L_l = 1.7$ nH.
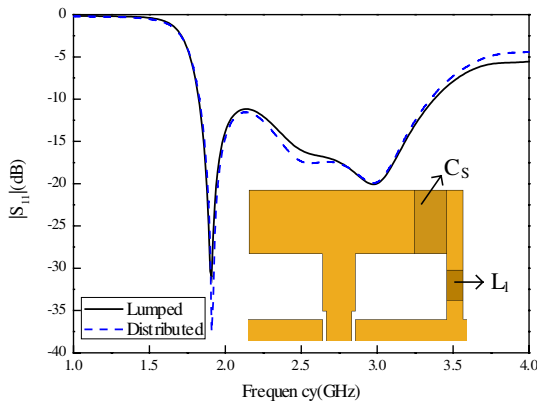

Figure 9. Simulated return-loss characteristics of the broadband PIFA with lumped and distributed elements loading.
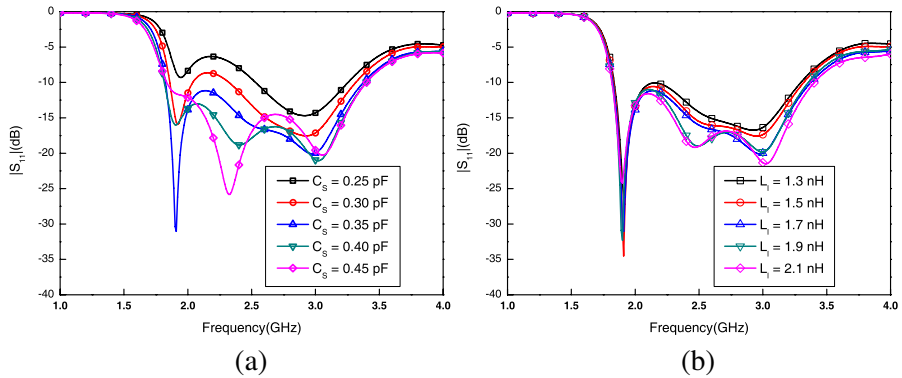
Figure 10. Simulated return-loss characteristics of the different lumped values.

In the EM-simulated model, lumped elements are modelled by lumped boundaries. The simulated return-loss characteristics of the lumped-elements and the distributed elements loaded PIFA are shown in Fig. 9. It can be observes that the results match well. By using the lumped-elements the design optimization will be much more convenient. As shown in Fig. 10, return-loss characteristics for the different lumped values are presented. This can be easily determined that what value should be chosen to fill the performance index. The difficulty of the antenna design can be decreased, because the value of the lumped elements can be easily changed compared with the distributed elements.

5. CONCLUSION

A compact and broadband PIFA has been presented, which employs ZOR loading on a conventional printed CPW-fed PIFA design in order to create a dual-mode antenna. The ZOR unit can be formed both by distributed and lumped elements. It was demonstrated that the addition of the ZOR loading allows the PIFA remain its regular PIFA properties at 3.1 GHz, while at 2.0 GHz the loading makes the antenna work on the ZOR mode. Additionally, the PIFA achieves the same radiation direction in the broadband, which is very important for the wideband communication. The PIFA exhibits a measured −10 dB return-loss bandwidth of 1.5 GHz, while maintaining a high efficiency about 90%. It is therefore well suited for the wireless communication applications.

ACKNOWLEDGMENT

REFERENCES

1. Eleftheriades, G. V., A. K. Iyer, and P. C. Kremer, "Planar negative refractive index media using periodically L-C loaded transmission lines," *IEEE Trans. Microw. Theory Tech.*, Vol. 50, 2702–2712, 2002.

2. Sanada, A., C. Caloz, and T. Itoh, "Planar distributed structures with negative refractive index," *IEEE Trans. Microw. Theory Tech.*, Vol. 52, 1252–1263, 2004.

3. Sanada, A., C. Caloz, and T. Itoh, "Novel zeroth-order resonance in composite right/left-handed transmission line resonators," *Proc. Asia-Pacic Microwave Conf.*, Vol. 3, 1588–1591, 2003.

4. Choi, J. and S. Lim, "Ultra-wideband power splitting/combining technique using zero-degree left-handed transmission lines," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 14–15, 2119–2127, 2010.

5. Sanada, A., M. Kimura, I. Awai, C. Caloz, and T. Itoh, "A planar zeroth-order resonator antenna using a left-handed transmission line," *Proc. Eur. Microw. Conf.*, Vol. 3, 1341–1344, 2004.

6. Choi, J. and S. Lim, "Frequency and radiation pattern reconfigurable small metamaterial antenna using its extraordinary zeroth-order resonance," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 14–15, 2119–2127, 2008.

7. Dolatsha, N., M. Shahabadi, and R. Dehbashi, "Via-free cpw-based composite right/left-handed transmission line and a calibration approach to determine its propagation constant," *Journal of Electromagnetic Waves and Applications*, Vol. 22, No. 11–12, 1599–1606, 2008.

8. Zhou, H., S. Qu, Z. Pei, Y. Yang, J. Zhang, J. Wang, H. Ma, C. Gu, X. Wang, Z. Xu, W. Peng, and P. Bai, "A high-directive patch antenna based on all-dielectric near-zero-index metamaterial superstrates," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 10, 1387–1396, 2010.

9. Yu, A., F. Yang, and A. Elsherbeni, "A dual band circularly

polarized ring antenna based on composite right and left handed metamaterials," *Progress In Electromagnetics Research*, Vol. 78, 73–81, 2008.

10. Si, L.-M. and X. Lv, "CPW-fed multi-band omni-directional planar microstrip antenna using composite metamaterial resonators for wireless communications," *Progress In Electromagnetics Research*, Vol. 83, 133–146, 2008.

11. Antoniades, M. A. and G. V. Eleftheriades, "A broadband dual-mode monopole antenna using NRI-TL metamaterial loading," *IEEE Antennas Wireless Propag. Lett.*, Vol. 8, 258–261, 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, 2010.

13. Deng, S. M., C. L.Tsai, C. K. Yeh, and S. S, Bor, "CPW-fed PIFAS with a capacitively coupling slot for dual wide-band operations," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 5–6, 721–733, 2010.

14. Sanchez-Montero, R., S. Salcedo-Sanzand, J. A. Portilla-Figueras, and R. Langley, "Hybrid pifa-patch antenna optimized by evolutionary programming," *Progress In Electromagnetics Research*, Vol. 108, 221–234, 2010.

15. Yang, C. W. and C. W. Jung, "Broad dual-band PIFA using self-complementary structure for DVB-H applications," *Electron. Lett.*, Vol. 46, No. 4, 606–608, 2010.

16. Sim, D.-U. and J.-I. Choi, "A compact wideband modified planar inverted F antenna (PIFA) for 2.4/5-GHz WLAN applications," *IEEE Antennas and Wireless Propag. Lett.*, Vol. 5, No. 1, 391–394, 2006.

17. 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, 2007.

18. Huang, J.-Q. and Q.-X. Chu, "Small ZOR antenna with high efficiency based on epsilon negative transmission line," *Proc. of Int. Conf. on Microwave & Millimeter Wave Tech.*, 528–531, 2010.

19. Bahl, I., *Lumped Elements for RF and Microwave Circuits*, Artech House, Norwood, 2003.