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A Compact GPS/WLAN Antenna Design for Mobile Terminal with Full Metal Housing

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Abstract—Miniaturization and metal-housing environment are the two most critical problems in the design of antennas, because they can highly deteriorate the performances of antenna, which not only affects the antenna efficiency, but also influences the bandwidth. In this paper, a compact size antenna with full metal housing for GPS/WLAN applications is studied. The proposed antenna can excite triple-band operation that covers the GPS (1.575 GHz), WLAN 2.45 GHz and WLAN 5.2/5.8 GHz bands, and its corresponding measured average efficiencies over these three desired bands were 40%, 41%, and 70%, respectively. The proposed antenna has a volume of $20.5 \times 5 \times 4\,\mathrm{mm}^3$, which is probably the smallest antenna in the industry for full metal housing applications.

1. INTRODUCTION

Due to the rapid growth in wireless communications, there is an increasing demand for a single antenna that can offer multiple operating bands, especially when the terminal devices have very limited space for the antenna. Therefore, miniaturization of multi-band antenna is an inevitable trend at the moment for any mobile terminal devices. The miniaturization techniques of antennas have been carried out over the past decade, and the design technique such as planar inverted-F antenna (PIFA) type is frequently used to reduce the size of the antenna [1–3]. Even though the PIFA design can significantly reduce the antenna size to 1/4 wavelength, the length of a GPS antenna at 1/4 wavelength of 1575 MHz is still approximately 47 mm, which is not compact enough for small mobile terminal device.

The mobile device industry is looking for antenna solutions with very compact size, tri-band support at 1.575, 2.4 and 5 GHz for GPS and WLAN a/b/g band. However, there are very few solutions in the published art to work for this requirement. Several WLAN antennas were reported to work at WLAN a/b/g band but not at GPS band [4–8]. Other GPS/WLAN antennas were reported to cover 1.575 and 2.4 GHz but not include 5 GHz band [9–13]. There are several papers introduced tri-band antenna design but having fairly large size compared with the proposed antenna as shown in Table 1 [14–19].

Moreover, in recent years, mobile terminals with metal housing or full metal cover are applied more frequently in the antennas industry because of its good aesthetic appearance and excellent mechanical robustness; however, the metal housing or metal cover will also highly deteriorate the antenna's performances. Therefore, a number of mobile antenna designs with metal cover have been studied [20–23], However, this metal housing is not a complete piece of metal with 4 side walls, and they are either a simple metal frame or metal ring structure, or the metal housing bottom plane is cut into 3 pieces which are not favorable for mechanical strength. As far as we observed, there are very few papers to address compact tri-band antenna design at this full metal housing environment.

In this paper, we propose a very compact tri-band antenna with size of only $20.5 \times 5 \times 4\,\mathrm{mm}^3$ to support GPS and WLAN b/g/a bands positioned at corner of mobile phone environment with full

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Table 1. The comparisons of referred GPS/WLAN b/g/a antennas.

Referred Antenna	Antenna size (mm)	Occupied area (mm^2)	Cover Band
Ref. [14]	45×15	675	GPS, WiMAX, WLAN 5.2G/5.8G
Ref. [15]	45×12	540	GPS, WLAN2.4G, 5.8G
Ref. [16]	10×37	373	WLAN2.4G, WiMAX
Ref. [17]	17×17	243	GPS, WLAN2.4G
Ref. [18]	45×5	225	GSM850/900, GPS, UMTS, WLAN2.4G
Ref. [19]	16×12	190	WLAN2.4G/5.2G/5.8G
Proposed	20.5×5	102.5	GPS, WLAN2.4G/5.2G/5.8G

metal housing. Antenna miniaturization and multiband realization are realized by combining capacitive feeding structure, LC band stop circuit and band enhancement techniques with parasitic structures. The theory of the antenna is analyzed with the methods of semi-analytical [24–26]. Both simulation and experiment results show that this antenna is very promising for mobile application with full metal housing.

2. GEOMETRY OF THE PROPOSED ANTENNA

The proposed antenna is designed on a standard mobile phone terminal with size of $120 \times 65 \times 7\,\mathrm{mm}^3$. Unlike iPhone 6 having a metal housing with two cut slots in the top and bottom parts, our metal housing is a whole piece consisting of a full metal back cover and four side walls, where only a small portion of the bottom left side wall is removed for antenna positioning (Figure 1(a)). The whole model includes full metal housing, PCB, antenna carrier and antenna. The PCB is the same size as full metal housing bottom plane and is connected to the side walls, only a small portion of PCB underneath antenna is removed to better radiation (Figure 1(b)). The antenna is positioned at the left bottom corner of the device and mounted on the surface of an L-shaped plastic antenna carrier ($\varepsilon_r = 2.3$ and $\tan\delta = 0.01$) with size of about $15 \times 15\,\mathrm{mm}^2$ surface area and 7 mm height from the metal housing plane at the bottom (Figure 2).

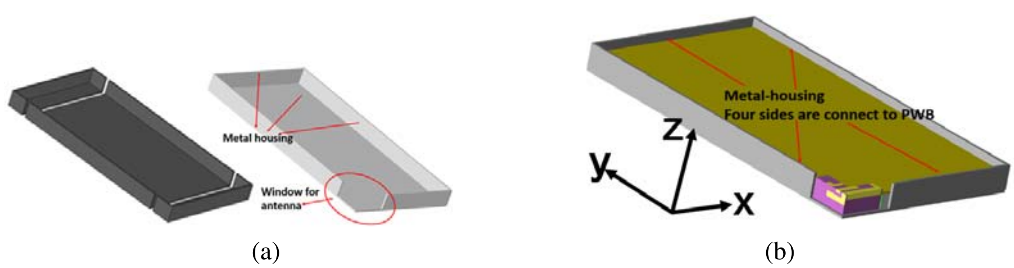


Figure 1. (a) The simplified metal housing model of iPhone 6 (left) and proposed model (right). (b) The PCB, antenna and antenna carrier locations relative to the metal housing.

To give a good sight of the proposed antenna, the antenna carrier and metal housing are set invisible. Figure 3(a) shows the final antenna structure in the mounted condition on the surface of the plastic antenna carrier, and Figure 3(b) shows the antenna design in an unfolded position for better explanation of the antenna design principles.

In Figure 3, the proposed antenna consists of four parts (Part I, Part II, Part III and Part IV). There are four points (A, B, C and D) labeled in the figure, where A is the feed point of the antenna; B and C are the short points; D is the ground point. As shown in Figure 3, Part I is directly fed by signal source. Part II and Part IV are grounded to the PCB, and Part II and Part III are connected by an

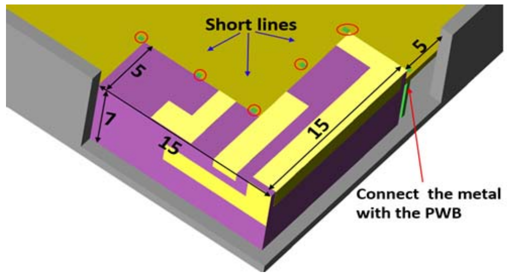
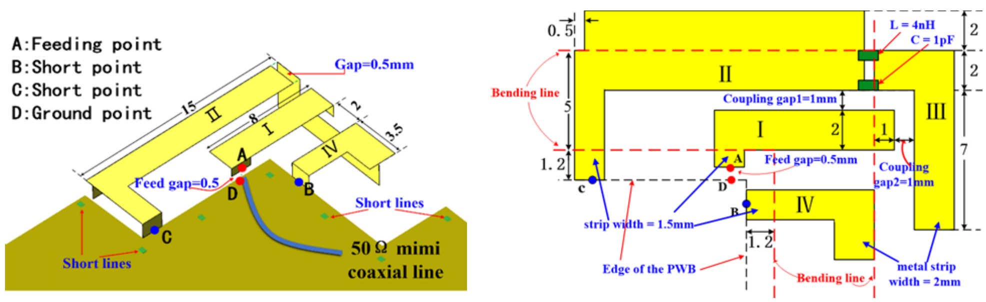


Figure 2. The L-shaped plastic antenna carrier and the antenna at the mounted position on the carrier surface.



(a) (b)

Figure 3. The antenna geometry and dimension details. (a) Folded position. (b) Unfolded position.

inductor L and a capacitor C. Each part will function differently at band of interest, and all together they create tri-band performance with a very compact size and metal–resistive performance.

Another new issue created from metal housing is that it can form a cavity with PCB board (conductive), which can create unwanted band from the cavity characteristic mode. The simulation shows that the distribution of the electric current on the PCB and the metal-cover near the antenna is very strong. To overcome this potential effect, several short lines are added to connect the PCB with the bottom plane of the metal housing as shown in Figure 2 and Figure 3(a).

3. ANTENNA DESIGN GUIDELINE

To have a better understanding of the antenna theory, the equivalent circuit of the antenna is shown in Figure 4. Part I is directly fed, which also has the coupling to the ground, Part II and Part III. Part III is connected to Part II by an inductance and a capacitance, which also has a coupling from Part II. The antenna design is started from WLAN a band operation at 5 GHz using a direct-fed antenna arm with length of about $1/4\lambda$ of 5.2 GHz (Part I), and it creates the first resonance with bandwidth of

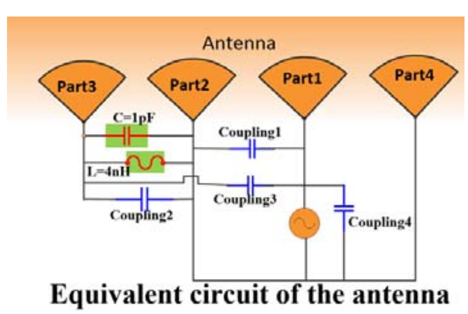


Figure 4. The equivalent circuit of the antenna.

700 MHz from 5.2 to 5.9 GHz. After that, the next step is to design WLAN b/g band at 2.4 GHz and GPS band at 1.575 GHz. Instead of using IFA or PIFA type of structure where the antenna occupies a large space, we adopt one single structure with two short arms (Part II and Part III) and an LC circuit in between to realize the dual resonances with minimum space (Figure 3).

In the actual design, resonance of 2.4 GHz is firstly implemented by using Part I to couple-feed Part II where Part II is a grounded structure with length about 22 mm. The next thing is to create GPS resonance at 1.575 GHz. Knowing that $1/4\lambda$ is about 49 mm, too large at this metal housing environment, if Part II can be reused as part of the GPS operation, it will reduce the antenna volume. After simulation study, it is shown that extending Part II can make the antenna operate at 1.575 GHz. However, the 2.45 GHz resonance disappears. To keep both resonances, an LC band stop circuit design at 2.45 GHz is wisely designed on the antenna, and dual-band operations at 1.575 and 2.4 GHz is achieved with Part II, Part III and LC circuit (Figure 3).

Finally, to improve the bandwidth further, a grounded structure (Part IV) is designed adjacent to Part I with a length about $1/4\lambda$ at 5.8 GHz to create the second resonance. Properly adjusting Part I and Part IV lengths can merge these two separate resonances together to achieve a bandwidth wide enough to cover frequency from 4.9 to 5.8 GHz for WLAN a band application.

To better understand the antenna design principles, the antenna return loss at each critical design step and final stage in simulation are shown in Figure 5, and the simulated surface current distribution and direction of the antenna at critical frequency are plotted in Figure 6. It is very clear that Parts I and IV work for WLAN a band around 5 GHz; Part II is important for WLAN b/g band around 2.4 GHz; Parts II and III together work for GPS at 1.575 GHz.

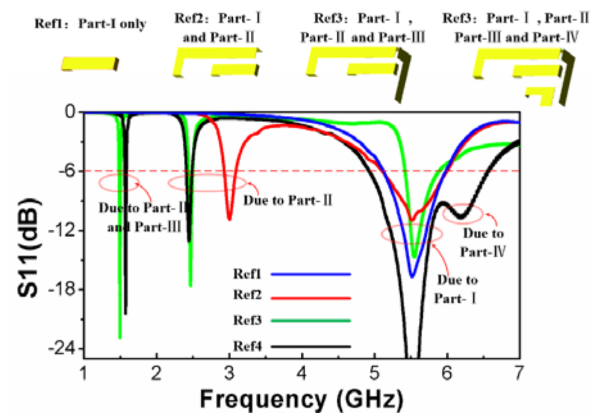


Figure 5. The antenna return loss at each critical design step and final stage in simulation.

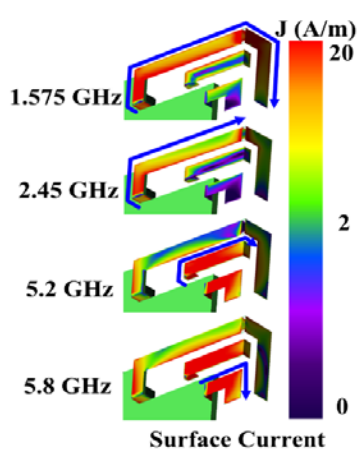


Figure 6. Surface current distributions of the proposed antenna at 1.575, 2.45, 5.2 and 5.8 GHz.

The LC band stop circuit is designed based on the formula

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where f is the band stop frequency at 2.45 GHz. Selecting proper L and C values will create a high impedance at 2.45 GHz and low impedance at other frequencies, in our design, which means that Part III will be "electrically disconnected" at frequency around 2.45 GHz but behaves as being connected with Part II around 1.575 GHz. As a result, dual resonances at 2.45 and 1.575 GHz are created.

Besides the band stop feature, adding LC on antenna can also make the antenna smaller especially for GPS implementation. As shown in Figure 7, when Parts II and III are directly connected, they create one resonance at 2 GHz, and when LC circuit is added between them, the 2 GHz resonance is moved to 1.575 GHz and also, an additional resonance at 2.45 GHz created. After balancing the design and practical available component, the 4 nH inductor and 1 pF capacitor are selected.

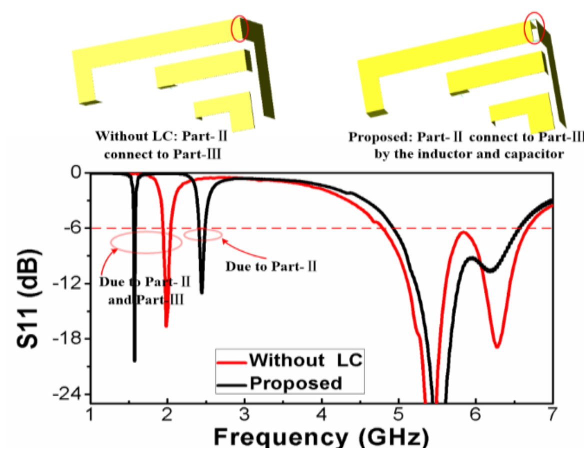


Figure 7. The S_{11} comparisons for cases when Part II and III are connected directly VS connected with shunt LC circuit.

The gap between Parts I and II is one of the important parameters in the antenna design (called gap1 in Figure 7), because Part I is not only functioned for the first resonance of 5 GHz, but also acts as the coupled feed to Part II. As a result, gap1 size will impact the antenna return loss. Figure 8 shows the simulated return loss when gap1 is set as 1, 1.5, 2 mm. It is observed that reducing gap size can shift frequency lower for all three resonances, because of higher capacitance created in series at the antenna feed area.

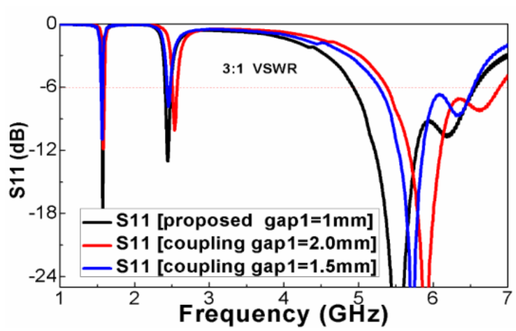


Figure 8. Study gap1 size impact to antenna S_{11} in simulation.

4. PROTOTYPE FABRICATION AND MEASUREMENT

A prototype of the mobile phone is fabricated at our lab as shown in Figure 9. The PCB is a standard FR4 board with 0.8 mm thickness, and the antenna carrier is made by ABS plastic material. The metal housing structure is covered with copper for better conduction performance. The antenna is positioned on the surface of a plastic carrier. It is hand-made by copper and fed by a standard $50\,\Omega$ coaxial cable. To eliminate extra resonance and improve antenna efficiency, several short lines are added to connect PCB and metal housing on at the corner area close to the antenna as marked inside the red circle area.

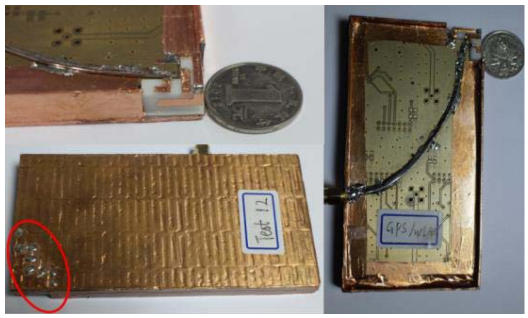


Figure 9. The antenna fixture.

The final simulated and measured return losses (S_{11}) of the proposed antenna are shown in Figure 10. The antenna has three resonances at the bands of interest. By following the bandwidth definition ($S_{11} < -6\,\text{dB}$) used by most of mobile phone antenna design papers, the measured bandwidth at GPS is 130 MHz from 1.56 to 1.69 GHz; the measured bandwidth at WLAN b/g band is 80 MHz from 2.41 to 2.49 GHz; WLAN a band is 1.156 GHz from 4.95 to 6.51 GHz. Compared with the simulated S_{11}, the measured one is matched very well with simulation at 1.575 and 2.45 GHz. At 5 GHz, the measured S_{11} has a similar bandwidth to simulation. Because of the complicated metal-housing environment and the deviation between the simulated model and the experiment model, the experiment antenna has to be slightly adjusted to make it perform as well as the simulated antenna. Both Parts I and IV of the experiment antenna are slightly longer than those in simulation, which leads to the bandwidth of the measured shifting little bit to lower frequency. Overall, the measured antenna S_{11} is correlated reasonably well with simulation result.

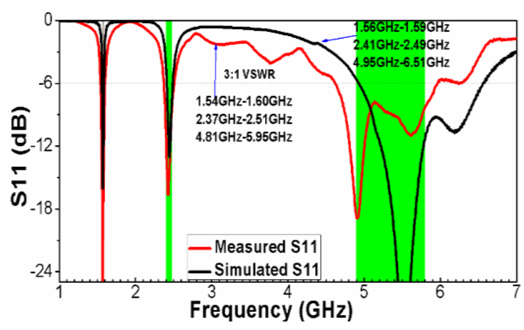


Figure 10. The final antenna's simulated and measured S_{11}.

To confirm the antenna's radiation performance, the standard ETS AMS 8500 commercial chamber is used for measurement. The antenna's efficiency and gain are measured as plotted in Figure 11, and the 2-D radiation patterns were also measured as shown in Figure 12. The average measured efficiencies at GPS, WLAN b/g and a band are 40%, 41% and 70%, respectively, and the average measured gains at the three bands are about 0.5, 3 and 3.5 dBi, respectively. The measured 2D patterns at 1.57 GHz, 2.45 GHz and 5.45 GHz, the middle frequency of each band, are plotted in Figure 12. The radiation pattern is more directive with the increase of frequency, which is understandable because metal housing will behave electrically larger than the antenna, therefore, provide more reflection in radiation. Overall, this antenna achieves reasonable performance for practical applications.

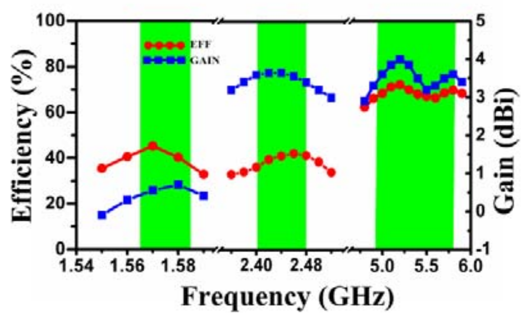
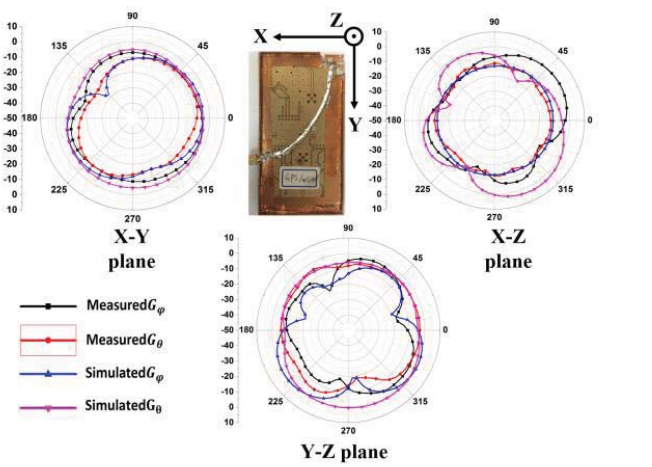
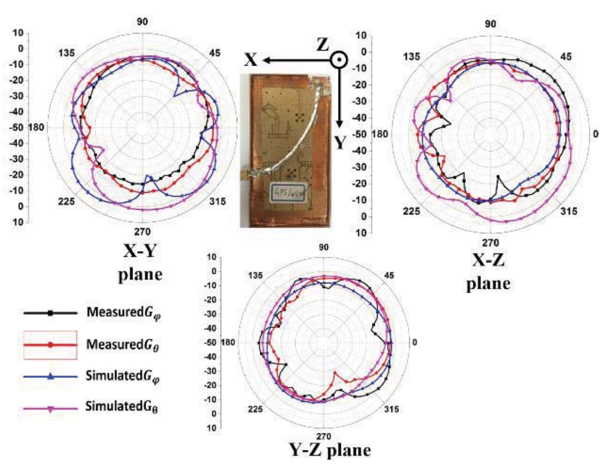


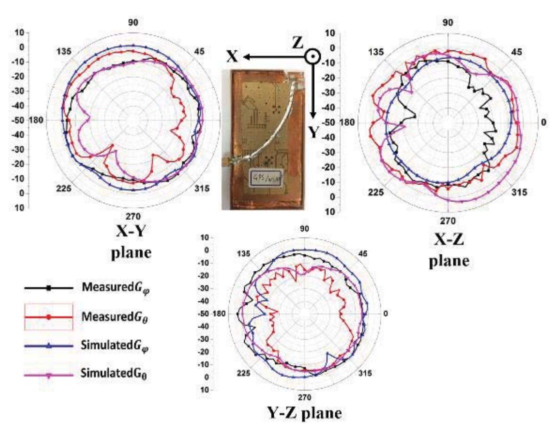
Figure 11. The antenna measured efficiency and gain.



(a)



(b)



(b)

Figure 12. (a) The measured 2D patterns at frequency of 1.57 GHz; (b) The measured 2D patterns at frequency of 2.45 GHz; (c) The measured2D patterns at frequency of 5.45 GHz.

5. CONCLUSION

In this paper, a contact tri-band antenna is proposed and fabricated at GPS, WLAN b/g and WLAN a bands for mobile phone application with full metal housing. The antenna's size miniaturization and multiband implementation are realized by integrating several methods including unique antenna structures, capacitive feeding technique and LC band stop circuit. The antenna's average measured efficiencies at 1.575, 2.45 and 5 GHz bands are 40%, 41% and 70%, respectively. The antenna size is 20.5×5 mm, only $1/8\lambda$ at GPS frequency. As far as we have observed, it is a very compact design for potential applications at full metal housing environment.

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REFERENCES

1. Nashaat, D. M., H. Elsadek, and H. Ghali, "Single feed compact quad-band PIFA antenna for wireless communication applications," *IEEE Trans. Antennas Propag.*, Vol. 53, 2631–2635, 2005.
2. Nepa, P., et al., "Multiband PIFA for WLAN mobile terminals," *IEEE Antennas Wireless Propag. Lett.*, Vol. 4, 349–350, 2005.
3. Tseng, C. and Y. Chen, "Small pifa for ZigBee and wlan application," *Microwave Opt. Technol. Lett.*, Vol. 55, 1074–1077, 2013.
4. Lee, J. M., et al., "A compact ultrawideband MIMO antenna with WLAN band-rejected operation for mobile devices," *IEEE Antennas Wireless Propag. Lett.*, Vol. 11, 990–993, 2012.
5. Alam, T., M. R. I. Faruque, and M. T. Islam, "Specific absorption rate reduction of multi-standard mobile antenna with double-negative metamaterial," *Electron Lett.*, Vol. 51, 970–971, 2015.
6. Lotfi, P., M. Azarmanesh, and S. Soltani, "Rotatable dual band-notched UWB/triple-band WLAN reconfigurable antenna," *IEEE Antennas Wireless Propa. Lett.*, Vol. 12, 104–107, 2013.
7. Alhaddad, A. G., et al., "Folded loop balanced coplanar antenna for WLAN applications," *IEEE Trans. Antennas Propag.*, Vol. 60, 4916–4920, 2012.
8. Lim, J. H., et al., "A reconfigurable PIFA using a switchable PIN-diode and a fine-tuning varactor for USPCS/WCDMA/ m-WiMAX/WLAN," *IEEE Trans. Antenna Propag.*, Vol. 58, 2404–2411, 2010.
9. Li, R. L., et al., "A compact broadband planar antenna for GPS, DCS-1800, IMT-2000 and WLAN applications," *IEEE Antenna Wireless Propag. Lett.*, Vol. 6, 25–27, 2007.
10. Wu, J. G. and X. M. Zhou, "A design of miniaturization dual-frequency antenna for GPS and WLAN application," *IEEE International Conference on Microwave and Millimeter Wave Technology*, 1–3, 2012.
11. Ma, S. L. and J. S. Row, "Design of single-feed dual-frequency patch antenna for GPS and WLAN applications," *IEEE Trans. Antennas Propag.*, Vol. 59, 3433–3436, 2011.
12. Lai, Z. and J. Yuan, "Design of single-layer single-feed patch antenna for GPS and WLAN applications," *IEEE Proceedings of the International Symposium on Antennas and Propagation (ISAP)*, 737–739, 2013.
13. Lin, C. H., et al., "A novel on-glass antenna for mobile handset applications," *IEEE International Symposium on Computer, Consumer and Control (IS3C)*, 236–239, 2012.
14. Saeed, A. A., S. Shams, and A. Allam, "Compact multiband omni-directional printed antennas," *IEEE International Symposium on Antenna Technology and Applied Electromagnetics and the American Electromagnetics Conference*, 1–4, 2010.
15. Kim, J. I., Y. J. Chong, and J. I. Choi, "Printed multiband terminal antenna for multiple wireless services," *Antennas and Propagation,* No. 491, 324–327, 2003.

16. Abutarboush, H. F. and A. Shamim, "Wide frequency independently controlled dual-band inkjet-printed antenna," *IET Microwave Antennas Propaga.*, Vol. 8, 52–56, 2014.
17. Hady, L. K., A. Kishk, and D. Kajfez, "Dual-band compact DRA with circular and monopole-like linear polarizations as a concept for GPS and WLAN applications," *IEEE Trans. Antenna Propag.*, Vol. 57, 2591–2598, 2009.
18. Li, Y., et al., "A compact hepta-band loop-inverted F reconfigurable antenna for mobile phone," *IEEE Trans. Antenna Propag.*, Vol. 60, 389–392, 2012.
19. Wang, H. and M. Zheng, "A multi-band internal antenna," *IEEE Antennas and Propagation Conference (LAPC)*, 1–4, Loughborough, England, 2011.
20. Kim, S. H., et al., "A compact GPS and WLAN PIFA for full metal-rimmed mobile handset using the ground bridges," *IEEE Microwave Conference Proceedings (APMC)*, 648–650, 2013.
21. Wu, C. Y., Y. L. Kuo, and K. C. Lin, "Low-profile tunable WWAN antenna for Whole-Metal-Covered mobile phone applications," *IEEE International Symposium on Antennas and Propagation (ISAP)*, 275–276, 2014.
22. Chen, L. Y. and K. L. Wong, "2.4/5.2/5.8 GHz WLAN antenna for the ultra-book computer with metal housing," *IEEE Asia-Pacific Microwave Conference Proceedings (APMC)*, 322–324, 2012.
23. Chou, J. H., et al., "A compact loop-slot mode combination antenna for ultra-thin tablet computer with metallic bottom cover," *IEEE Antenna Wireless Propag. Lett.*, Vol. 13, 746–749, 2014.
24. Valagiannopoulos, C. A., "On examining the influence of a thin dielectric strip posed across the diameter of a penetrable radiating cylinder," *Progress In Electromagnetics Research C*, Vol. 3, 203–214, 2008.
25. Valagiannopoulos, C. A., "High selectivity and controllability of a parallel-plate component with a filled rectangular ridge," *Progress In Electromagnetics Research*, Vol. 119, 497–511, 2011.
26. Valagiannopoulos, C. A., "Study of an electrically anisotropic cylinder excited magnetically by a straight strip line," *Progress In Electromagnetics Research*, Vol. 73, 297–325, 2007.