Communication

Mode-Controlled Wideband Slot-Fed Ground Radiation Antenna Utilizing Metal Loads for Mobile Applications

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***Abstract*— In this communication, we introduce a mode-controlled ground radiation antenna comprised of a resonance-controlled ground plane and a nonradiating feeding slot for wideband applications in mobile devices. A 110 mm × 50 mm ground plane for 850-MHz operation is studied as a test case. The resonant frequency of the ground plane is lowered by adding metal loads at the top and bottom intended for strong coupling with a miniature feeding slot located at one end, so that the ground plane is resonant as a half wavelength dipole-type radiator. The metal loads can be the structures of strips, plates, or wires, and they can take the form of broken metal rims or frames with cuts or gaps in smartphones. In addition, the metal loads are connected to the ends of the ground plane by lumped elements (inductors and/or capacitors) for easy control of the resonance mode and compact design. Equivalent circuit model and corresponding equations are provided for theoretical analysis. The impedance bandwidth based on 3:1 VSWR is 210 MHz (from 760 to 970 MHz), with an average efficiency of 77%. Geometrical characteristics of the metal loads are shown to be important parameters for the antenna performance.**

***Index Terms*— Compact design, ground radiation antenna, metal loads, mode-controlled, strong coupling, wideband applications.**

I. Introduction

Although the ground plane can be used as a good radiator [1]–[4], the printed circuit board (PCB) ground plane with 80–120 mm length (corresponding to about 0.24λ–0.36λ at 900 MHz) in most mobile devices is too small to be resonant as a half wavelength radiator for frequency bands below 1 GHz. To excite the ground plane as a dipole-type radiator [3]–[9], an antenna element is usually used, efficiently coupled with the ground mode in an antenna-chassis combination [3]–[6]. There are two principal techniques to ensure strong coupling with the ground plane: electric coupling [4]–[7], e.g., patch antennas and planner inverted-F antennas; and magnetic coupling [4], [8]–[11], e.g., loop antennas and ground radiation antennas (GradiAnt) [8]–[11].

High performance can be realized when the antenna is strongly coupled to the ground plane and the resonant frequencies of the antenna element and the ground mode are equal, which is difficult to achieve because of the limited size of the ground plane and compact volume of the antenna element. Most studies focus on improving the coupling by the optimization of the antenna design [3], [10], [11]. In other studies, the ground plane was modified, either by cutting a slot in the ground plane [4], [12]–[14], attaching large loading or plate to extend the electrical length of the ground plane [15], [16], or inserting wavetraps [17]–[19] to shorten the ground plane. For ground mode resonance tuning, the end-loaded structure is more likely to be a promising candidate compared with cutting slots inside the ground plane. In [15], the capacitive loading has been proven to be effective for the resonance tuning of the ground plane, and an alternate approach using an inductor-connected coupled plate has been proposed for bandwidth enhancement [16], however, their biggest drawback is that they occupy too much space, and the height of their loads is more than 10 mm, which is not suitable for integration into the housing of the mobile devices. Therefore, it is necessary to introduce a practical technique with compact loads so that they can be implemented in the housing of mobile devices. Herein, we propose the lumped elements-connected metal loads that can be various structures, such as strips, plates, or wires surrounding the ground plane. More importantly, they can be applicable in the broken metal rims or frames with few cuts or gaps, for example, as in iPhone 6, providing a new insight to the previous metal-rimed antenna design [20]. To maintain high performance, the ground mode resonance is tuned to be the center frequency of the operating band and is then excited by a feeding slot with the same frequency, so strong coupling between the feeding slot and the ground plane is generated ensuring the input power maximally coupled to the ground plane radiator.

Consequently, in this communication, we proposed a mode-controlled ground radiation antenna with an inductive feeding slot for wideband applications [21]. Lumped inductors and capacitors are used to connect the ground plane with metal loads, which provide parasitic inductance and capacitance for open-end extension of the ground plane and ground mode resonance tuning; the feeding slot is also tunable by inductors for ground mode excitation and impedance matching. Moreover, we outline a versatile ground radiation antenna design technique when the resonant frequency of the ground plane is far above the operating frequency band, and a 110 mm × 50 mm ground plane operating at 850 MHz is chosen as a case study for verification. This communication is organized as follows. In Section II, the proposed mode-controlled ground radiation antenna is analyzed with an equivalent circuit model using characteristic mode theory. Frequency controlling and impedance matching are introduced in Section III, and the simulated and experimental results are described and compared. In Section IV, the effects of varying geometrical properties of the metal loads, such as the width, gap, and span, as well as the length and the width of the ground plane are discussed. Further discussion and future study are also given in this part.

II. Mode-Controlled Ground Radiation Antenna Design and Its Equivalent Circuit Model

A 110 mm × 50 mm ground plane for typical mobile phones is taken as a reference case study, as shown in Fig. 1. The ground plane is printed on a low-cost FR4 substrate with a thickness of 1 mm and dielectric constant $\varepsilon_r = 4.4$. Symmetrical T-shaped metal loads are installed at the top and bottom ends of the ground plane, and are connected by inductors L_r in the center of the short side of the ground plane. To achieve a compact volume, all the metal loads are placed along the x-axis with span S. The metal loads are separated from

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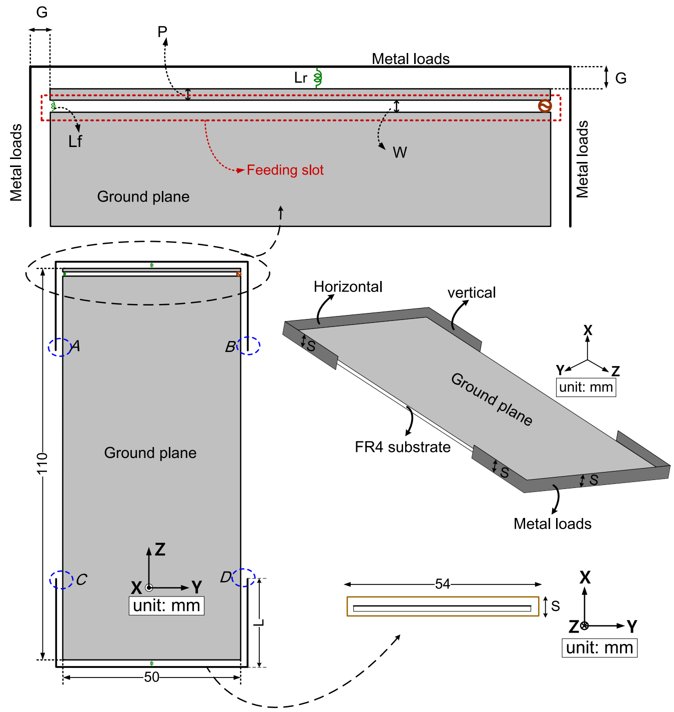

Fig. 1. Geometry of the proposed mode-controlled ground radiation antenna.

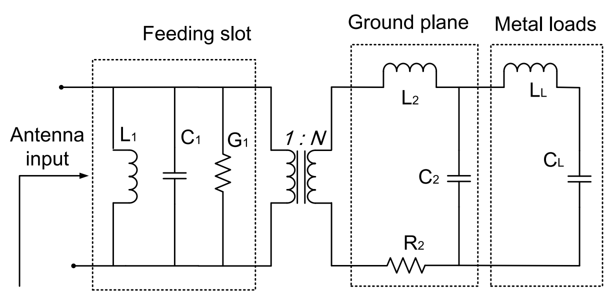

Fig. 2. Equivalent circuit model for the proposed mode-controlled ground radiation antenna.

the ground plane by a gap G for both the horizontal and the vertical loads. The ground mode resonance can be tuned either by adjusting the length of the vertical loads L, or by controlling the inductance L_r. The metal loads are similar to the well-known capacitance hats [22] used to extend the ground plane and lower the resonant frequency of the ground mode. A feeding slot with width W in series with an inductor L_f at position P away from the top edge of the ground plane is used to excite the ground mode resonance. In this design, the ground plane with metal loads acts as a resonant antenna and the feeding slot acts as a matching circuit. The values of G, L, S, L_r, L_f, W, and P are 2 mm, 25 mm, 4 mm, 3 nH, 2 nH, 1 mm, and 1 mm, respectively. Implementation of the proposed mode-controlled ground radiation antenna only occupies a small clearance of 1 mm × 50 mm on the PCB.

In the proposed ground radiation antenna design, the ground plane is directly fed by an inductive slot [23], [24], which is responsible for the strong coupling to the ground plane and impedance matching. Fig. 2 shows the equivalent circuit for the mode-controlled ground radiation antenna, where the ground plane is modeled as a series circuit with shunt inductance L_L and capacitance C_L provided by the metal loads and lumped elements, and the feeding slot is represented by a parallel circuit coupled to the ground plane by an ideal transformer.

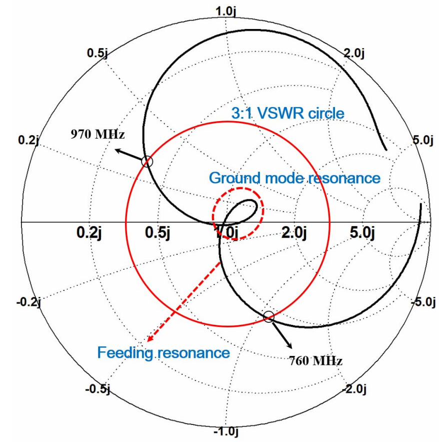

Fig. 3. Simulated input impedance of the proposed mode-controlled ground radiation antenna in a Smith chart.

In Fig. 2, the input admittance of the equivalent circuit model without metal loads can be expressed as

$$\begin{aligned} y_{\text{in}} &= \frac{1}{j\omega L_1} + j\omega C_1 + G_1 + \frac{N^2}{j\omega L_2 + \frac{1}{j\omega C_2} + R_2} \\ &= G_1\left[1 + jQ_s\left(\frac{\omega}{\omega_s} - \frac{\omega_s}{\omega}\right)\right] \\ &\quad + \frac{N^2}{R_2\left[1 + jQ_g\left(\frac{\omega}{\omega_g} - \frac{\omega_g}{\omega}\right)\right]} \end{aligned} \tag{1}$$

where Q_s and Q_g are the modal quality factors of the feeding slot and the ground plane, respectively. The Q values can be numerically obtained by using the equation in [6]. ω_s and ω_g are the resonant frequencies of the feeding slot and ground plane, respectively. The numerator N can be represented by [25], [26]

$$\langle a, b\rangle = \iiint (\bar{E}_0 \cdot \bar{J}^i - \bar{H}_0 \cdot \bar{H}^i)d\tau \tag{2}$$

where $\boldsymbol{E_0}$ and $\boldsymbol{H_0}$ are the characteristic fields of the fundamental dipole mode along the length of the ground plane, which is the most favorable mode for low frequency operation. $\boldsymbol{J^i}$ and $\boldsymbol{M^i}$ are the induced current distributions due to the feeding slot. The second term of (1) can be seen as the mutual coupling between the feeding slot and the ground plane, and the coupling increases as ω_g approaches ω, demonstrating that strong coupling can be obtained by tuning ω_g. Equation (1) denotes that the maximum bandwidth can be achieved if $\omega = \omega_g = \omega_s$ [27], and this finding enables us to fully understand the proposed ground radiation antenna.

In this circuit model, the metal loads provide shunt capacitance and inductance in the ground plane, lowering ω_g to ω_0, the resonant frequency of the proposed mode-controlled ground radiation antenna. Meanwhile, the feeding slot can be tuned to the same frequency so that dual-resonance is achieved [28]–[30].

III. Controlling Mechanisms and Results

The input impedance of the proposed mode-controlled ground radiation antenna is analyzed in a Smith chart in Fig. 3. The small impedance locus in the center is the ground mode resonance due to strong coupling, and the outer impedance locus is obtained by tuning the impedance and frequency of the feeding slot. The frequency from 760 to 970 MHz falls in the 3:1 VSWR circle, and an impedance bandwidth of 25% (210 MHz) is obtained. Wideband is achieved even though the ground mode resonance (impedance) locus is small, and performance can be further improved with optimum impedance

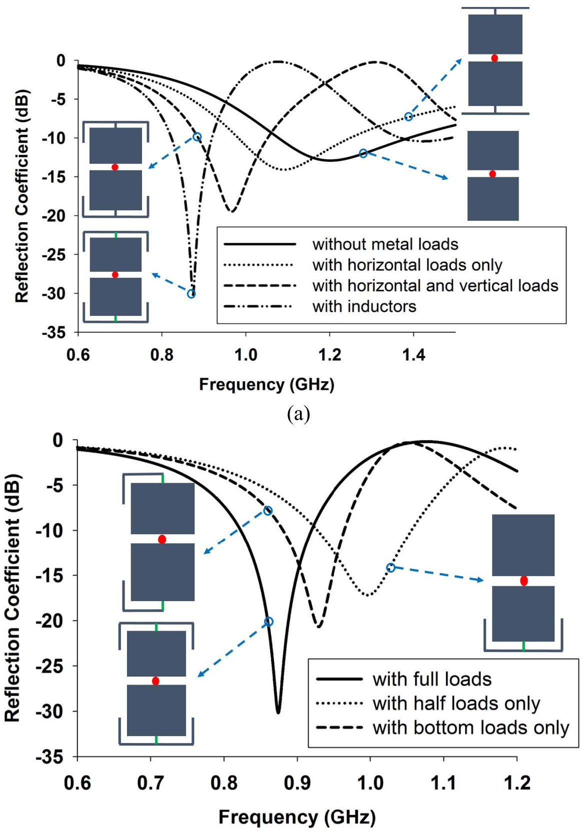

Fig. 4. Controlling the frequency of the proposed mode-controlled ground radiation antenna. (a) Frequency variation with horizontal loads, vertical loads and inductors. (b) Frequency variation with full loads, half loads and bottom loads.

matching [28]–[30]. The techniques of frequency controlling and impedance matching are introduced in Sections III-A and III-B, respectively.

A. Ground Mode Resonance Controlling

It is known that the physical length of a resonant ground plane at 850 MHz is much longer than 110 mm [1]–[4]. To study the effect of the metal loads on the resonant frequency of the ground plane, direct feeding in the center of the short side is adopted by cutting the ground plane into two halves, as shown in Fig. 4.

Fig. 4(a) shows that the resonant frequency of the ground plane without the metal loads is 1.25 GHz. Without the inductors and only the horizontal metal loads at the top and bottom shorted to the ground plane, the resonant frequency is lowered to 1.1 GHz; when the vertical loads are included, it is further lowered to 0.97 GHz; finally, inserting the inductors lowers the resonant frequency to 0.85 GHz. We see that the lumped inductors make this design more compact and controllable. A 400-MHz shift (from 1.25 to 0.85 GHz) has been achieved by utilizing the proposed metal loads. In Fig. 4(b), the resonant frequency increases to 0.92 GHz if the top loads are removed, and to 1 GHz if half of the inductors are removed from both top and bottom metal loads.

Note that with the open-end extension of the ground plane, the current distribution on the ground plane moves toward the ends, so that an inductor at the end of the ground plane can affect the resonant frequency. Similarly, capacitors can be inserted at each end of the metal loads connected to the ground plane, shown as Portion ABCD in Fig. 1, to achieve an even more compact design.

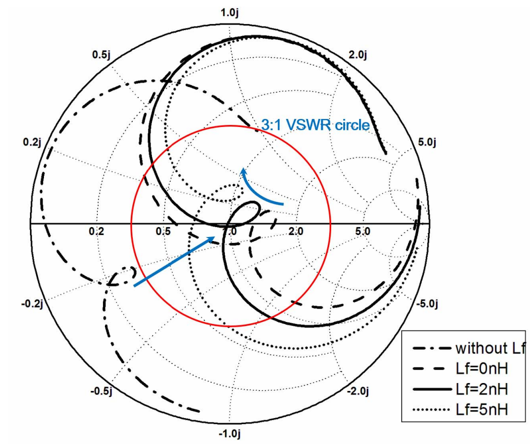

Fig. 5. Impedance matching in a Smith chart.

B. Impedance Matching Controlling

A suitable miniature feeding circuit is studied to obtain good bandwidth performance for the mode-controlled ground radiation antenna. With the open-end extension of the ground plane, the current distribution on the ground plane moves toward the ends, so that an inductive excitation is preferred to excite the ground radiation antenna [23], [24].

If the ground plane is direct fed at the location of the feeding slot without the inductor L_f, the ground mode resonance is observed as a small impedance locus in a Smith chart, as shown in Fig. 5. This impedance locus should be converted into the 3:1 VSWR circle for impedance matching and maximum bandwidth. A 1-mm-wide slot in series with an inductor L_f is adopted as a feeding circuit, with the equivalent circuit model shown in Fig. 2. The inductor L_f can be adjusted for the rotation of the impedance locus of the ground mode resonance, and the impedance locus rotates clockwise as L_f is increased from 0 to 5 nH. Note that the shunt capacitance in the feeding slot is provided both by the slot and by the gap between the ground plane and the top loads. Therefore, the ratios of inductance and capacitance [28] can be controlled by W and G as well as inserted capacitors if necessary.

C. Simulated and Measured Results

To test the proposed mode-controlled ground radiation antenna, surface current distributions at 0.85 GHz are simulated, as shown in Fig. 6. Dipole-type current distributions are observed in the ground plane, and current is introduced onto the metal loads flowing through the inductors L_r. From the surface current distribution, the ground plane with the metal loads works as a dipole-type radiator curved inside.

The mode-controlled ground radiation antenna (shown in Fig. 7), in which the metal loads were connected to the ground plane with inductors by copper strips for easy fabrication, was tested using Agilent 8753ES network analyzers. Simulated and measured reflection coefficients are shown in Fig. 8, where the measured impedance bandwidth based on 3:1 VSWR ranges from 730 to 970 MHz, in good agreement with the simulation. The radiation efficiency and the peak gain from 730 to 960 MHz have been measured using a 6 m × 3 m × 3 m 3-D CTIA OTA chamber, and are shown in Fig. 9. The measured total antenna efficiency ranges from 62% to 94%, averaging 77%, and the peak gain ranges from 0.9 to 2.8 dBi, indicating good radiation performance. It can be expected that the high efficiency and high gain are due to the strong ground mode-excitation. The measured radiation pattern at 0.85 GHz (Fig. 10)

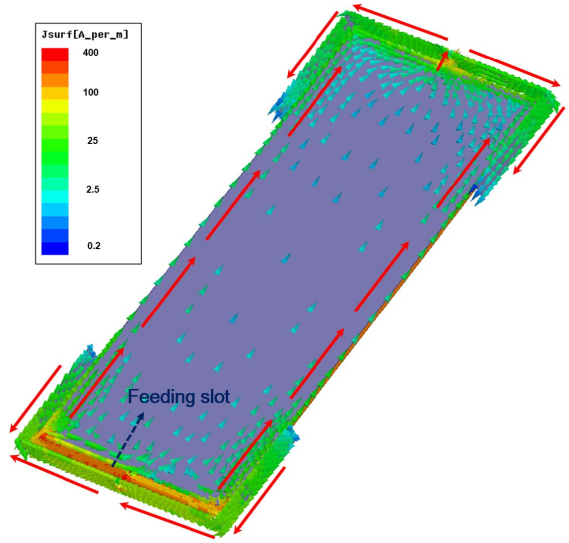

Fig. 6. Simulated surface current distribution at 0.85 GHz in the proposed mode-controlled ground radiation antenna.

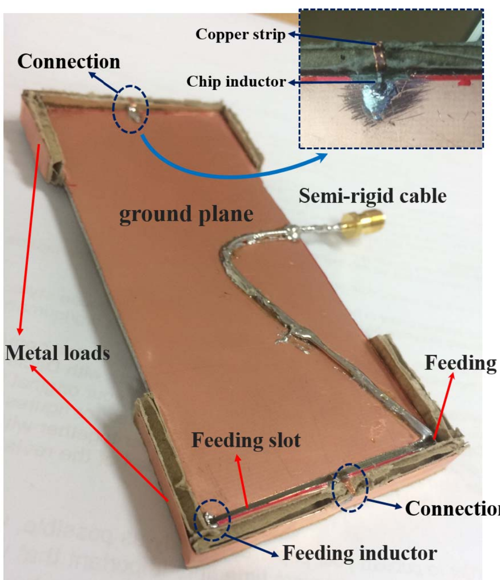

Fig. 7. Prototype of the proposed mode-controlled ground radiation antenna.

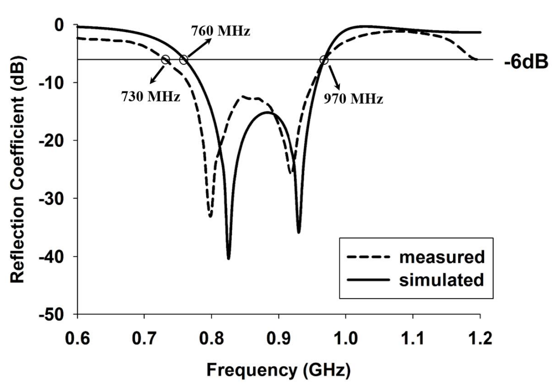

Fig. 8. Simulated and measured reflection coefficients.

shows an omnidirectional radiation pattern for E-Theta in the xy-plane, and symmetrical patterns for the theta and phi components in the xz-plane, verifying dipole-type current distributions in the ground plane, as shown in Fig. 6.

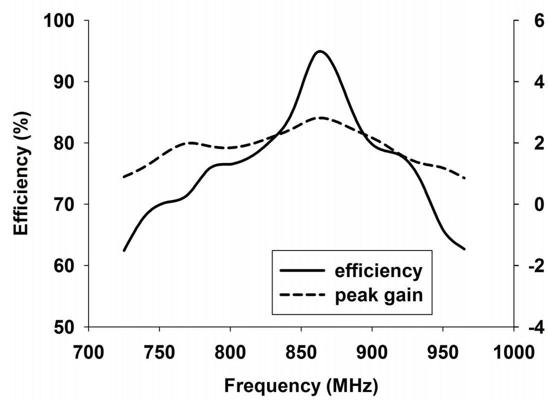

Fig. 9. Measured efficiency and peak gain.

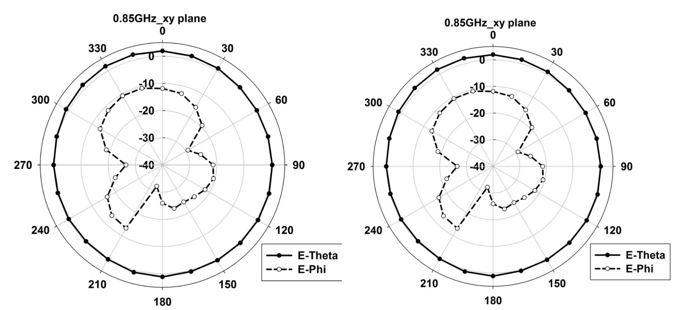

Fig. 10. Measured radiation pattern at 0.85 GHz. (a) *xy* plane. (b) *xz* plane.

IV. Parametric Study and Discussion

To gain a deeper understanding of the proposed mode-controlled ground radiation antenna design and to achieve better performance, critical geometrical parameters, such as the gap G and the span S of the metal loads, and different sizes of ground planes are studied. We show that the proposed technique has universal application for wideband characteristics.

A. On the Metal Loads

The gap G between the ground plane and the proposed metal loads determines whether or not the ground plane is open to the far field. Simulated results for different values of G are shown in Fig. 11(a), where the bandwidth ranges from 21% (180 MHz from 0.79 to 0.97 GHz at $G = 1$ mm) to 35% (300 MHz from 0.69 to 0.99 GHz at $G = 5$ mm) as G varies from 1 to 5 mm, indicating that the mode-controlled ground radiation antenna with larger G behaves as a better radiator. Note that these results are obtained by only tuning the inductors L_r and L_f while maintaining the load length $L = 25$ mm, the slot width $W = 1$ mm, the span $S = 4$ mm, and the position of the feeding slot $P = 1$ mm.

In Fig. 11(b), the effect of the load span S on the bandwidth is studied in simulation. The bandwidth varies from 22% (190 MHz from 0.80 to 0.99 GHz at $S = 2$ mm) to 30% (250 MHz from 0.73 to 0.98 GHz at $S = 6$ mm) as S varies from 2 to 6 mm. Therefore, the span S is another important contributing factor to the radiation performance of the mode-controlled ground radiation antenna. Note that these results are obtained by only tuning the inductors L_r and L_f while keeping the load length $L = 25$ mm, the slot width $W = 1$ mm, the gap $G = 2$ mm, and the position of the slot $P = 1$ mm.

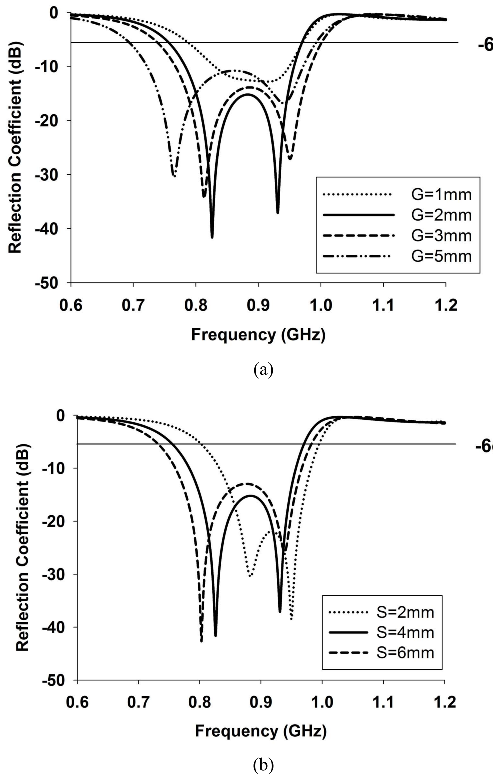

Fig. 11. Parameter study on (a) gap G and (b) span S of the metal loads.

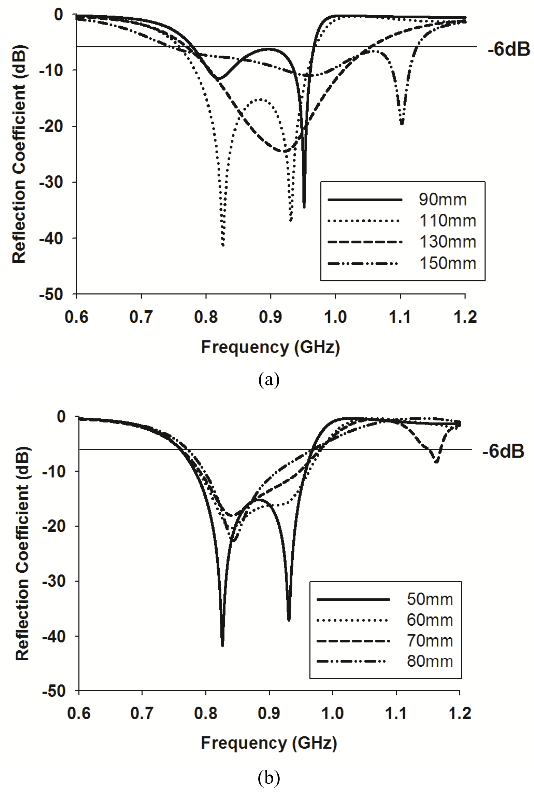

Fig. 12. Parameter study on the length and width of the ground plane. (a) Ground length. (b) Ground width.

B. On the Ground Plane

As shown in Fig. 12(a), the length of the ground plane is varied from 90 to 150 mm while keeping the width unchanged. At each length, frequency tuning and impedance matching are obtained based on the controlling mechanism discussed in Section III. In simulation, the bandwidth varies from 21% (186 MHz from 0.78 to 0.966 GHz when the length is 90 mm) to 44% (374 MHz from 0.75 to 1.124 GHz when the length is 150 mm). The best performance is achieved when the length of the ground plane is close to half of a wavelength. The simulated data in Fig. 12(b) indicate that the bandwidth is not as sensitive to the width of the ground plane, which can be seen as the width of the ground plane is varied from 50 to 80 mm.

Further discussion on the proposed technique is considered. Although the analysis has concentrated on the ground mode tuning and excitation for single band, the proposed technique can be compatible with traditional antenna design techniques to achieve multiband operations using multiband loop/slot antennas [10], [11], [31], [32], and multiband ground mode resonance tuning is now under study. Since the dipole mode along the width of the ground plane (the mode along the y-axis) is orthogonal to the dipole mode along the length of the ground plane (the mode along the z-axis), excitation of the orthogonal modes using the proposed technique could be a rational option to dual-antenna design for good diversity and high isolation. Further study was done to verify the applicability of the proposed technique in different test cases at different frequencies, and it was shown that the proposed ground radiation antenna can be seen as a versatile technique when the resonant frequency of the ground plane is far above the operating frequency band.

V. Conclusion

In this communication, a compact slot-fed ground radiation antenna is proposed. The mode-controlled ground radiation antenna utilizes metal loads to lower the resonant frequency of the ground plane and generates strong coupling with the antenna element, which is a feeding slot in a miniature size located at the end portion of the ground plane. Metal loads are connected to the ground plane by lumped inductors and/or capacitors for ground mode resonance control and for compact design in practical applications. High radiation efficiency and peak gain for wideband applications have been achieved due to the strong coupling with the ground plane. Further study was discussed on multiband/multiantenna designs, and it was shown that the proposed technique is compact, practical, and high performing.

References

[1] T. Taga and K. Tsunekawa, "Performance analysis of a built-in planar inverted F antenna for 800 MHz band portable radio units," *IEEE J. Sel. Areas Commun.*, vol. 5, no. 5, pp. 921–929, Jun. 1987.

[2] K. Sato, K. Matsumoto, K. Fujimoto, and K. Hirasawa, "Characteristics of a planar inverted-F antenna on a rectangular conducting body," *Electron. Commun. Jpn.*, vol. 72, no. 10, pp. 43–51, 1989.

[3] B. S. Yarman, *Design of Ultra Wideband Antenna Matching Networks*. New York, NY, USA: Springer, 2008.

[4] P. Vainikainen, J. Ollikainen, O. Kivekas, and I. Kelander, "Resonator-based analysis of the combination of mobile handset antenna and chassis," *IEEE Trans. Antennas Propag.*, vol. 50, no. 10, pp. 1433–1444, Oct. 2002.

[5] J. Villanen, J. Ollikainen, O. Kivekas, and P. Vainikainen, "Coupling element based mobile terminal antenna structures," *IEEE Trans. Antennas Propag.*, vol. 54, no. 7, pp. 2142–2153, Jul. 2006.

[6] C. T. Famdie, W. L. Schroeder, and K. Solbach, "Numerical analysis of characteristic modes on the chassis of mobile phones," in *Proc. 1st Eur. Conf. Antennas Propag. (EuCAP)*, Nice, France, Nov. 2006, pp. 1–6.

[7] J. Holopainen, R. Valkonen, O. Kivekas, J. Ilvonen, and P. Vainikainen, "Broadband equivalent circuit model for capacitive coupling element–based mobile terminal antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 716–719, Jul. 2010.

[8] Y. Liu, X. Lu, H. Jang, H. Choi, K. Jung, and H. Kim, "Loop-type ground antenna using resonated loop feeding, intended for mobile devices," *Electron. Lett.*, vol. 47, no. 7, pp. 426–427, Mar. 2011.

[9] O. Cho, H. Choi, and H. Kim, "Loop-type ground antenna using capacitor," *Electron. Lett.*, vol. 47, no. 1, p. 1, Jan. 2011.

[10] L. Qu, R. Zhang, H. Lee, and H. Kim, "Compact triple-band ground radiation antenna using two inner rectangular loops enclosed by two outer loops," *Electron. Lett.*, vol. 52, no. 10, pp. 790–792, May 2016.

[11] L. Qu, R. Zhang, H. H. Kim, and H. Kim, "Compact dual-band antenna using inverted-L loop and inner rectangular loop for WLAN applications," *Electron. Lett.*, vol. 51, no. 23, pp. 1843–1844, Nov. 2015.

[12] R. Hossa, A. Byndas, and M. E. Bialkowski, "Improvement of compact terminal antenna performance by incorporating open-end slots in ground plane," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 6, pp. 283–285, Jun. 2004.

[13] P. Lindberg, E. Ojefors, and A. Rydberg, "Wideband slot antenna for low-profile hand-held terminal applications," in *Proc. 9th Eur. Conf. Wireless Technol.*, Manchester, U.K., Sep. 2006, pp. 403–406.

[14] M. F. Abedin and M. Ali, "Modifying the ground plane and its effect on planar inverted-F antennas (PIFAs) for mobile phone handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, no. 1, pp. 226–229, 2003.

[15] W. L. Schroeder, T. Famdie, and K. Solbach, "Utilisation and tuning of the chassis modes of a handheld terminal for the design of multiband radiation characteristics," in *Proc. IEE Conf. Wideband Multi-Band Antennas Arrays*, Birmingham, U.K., Sep. 2005, pp. 117–121.

[16] C.-H. Chang and K.-L. Wong, "Bandwidth enhancement of internal WWAN antenna using an inductively coupled plate in the small-size mobile phone," *Microw. Opt. Technol. Lett.*, vol. 52, no. 6, pp. 1247–1253, Jun. 2010.

[17] S.-W. Su and T.-C. Hong, "Radiation improvement of printed, shorted monopole antenna for USB dongle by integrating choke sleeves on the system ground," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 4383–4388, Nov. 2011.

[18] P. Lindberg and E. Ojefors, "A bandwidth enhancement technique for mobile handset antennas using wavetraps," *IEEE Trans. Antennas Propag.*, vol. 54, no. 8, pp. 2226–2233, Aug. 2006.

[19] C. T. Lee and K. L. Wong, "Internal WWAN clamshell mobile phone antenna using a current trap for reduced ground plane effects," *IEEE Trans. Antennas Propag.*, vol. 57, no. 10, pp. 3303–3308, Oct. 2009.

[20] Q. Guo, R. Mittra, F. Lei, Z. Li, J. Ju, and J. Byun, "Interaction between internal antenna and external antenna of mobile phone and hand effect," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 862–870, Feb. 2013.

[21] H. Kim *et al.*, "Tunable self-resonant ground radiation antenna using T-shape metal rim for wideband applications," KR Patent 1020160031278, Mar. 16, 2016.

[22] R. D. Straw, *ARRL Antenna Book*, 21st ed. Newington, CT, USA: American Radio Relay League, 2007.

[23] R. Martens, E. Safin, and D. Manteuffel, "Inductive and capacitive excitation of the characteristic modes of small terminals," in *Proc. Antennas Propag. Conf. (LAPC)*, Loughborough, U.K., Nov. 2011, pp. 1–4.

[24] R. Martens and D. Manteuffel, "A feed network for the selective excitation of specific characteristic modes on small terminals," in *Proc. 6th Eur. Conf. Antennas Propag. (EuCAP)*, Prague, Czech Republic, Mar. 2012, pp. 1842–1846.

[25] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*. New York, NY, USA: McGraw-Hill, 1961.

[26] R. F. Harrington and J. R. Mautz, "Theory of characteristic modes for conducting bodies," *IEEE Trans. Antennas Propag.*, vol. 19, no. 5, pp. 622–628, Sep. 1971.

[27] L. Huang, W. L. Schroeder, and P. Russer, "Estimation of maximum attainable antenna bandwidth in electrically small mobile terminals," in *Proc. 36th Eur. Microw. Conf.*, Manchester, U.K., Sep. 2006, pp. 630–633.

[28] F. J. Witt, "Optimum lossy matching networks for resonant antennas," in *Antennas Propag. Soc. Int. Symp. (AP-S) Dig.*, vol. 3. San Jose, CA, USA, Jun. 1989, pp. 1360–1363.

[29] J. Villanen and P. Vainikainen, "Optimum dual-resonant impedance matching of coupling element based mobile terminal antenna structures," *Microw. Opt. Technol. Lett.*, vol. 49, no. 10, pp. 2472–2477, Jul. 2007.

[30] D. Kajfez, "Dual resonance," *IEE Proc. H, Microw., Antennas Propag.*, vol. 135, no. 2, pp. 141–143, Apr. 1988.

[31] Y. W. Chi and K. L. Wong, "Internal compact dual-band printed loop antenna for mobile phone application," *IEEE Trans. Antennas Propag.*, vol. 55, no. 5, pp. 1457–1462, May 2007.

[32] B. Yuan, Y. Cao, G. Wang, and B. Cui, "Slot antenna for metal-rimmed mobile handsets," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1334–1337, Nov. 2012.