COUPLED-FED SHORTED STRIP ANTENNA WITH AN INDUCTIVELY COUPLED BRANCH STRIP FOR LOW-PROFILE, SMALL-SIZE LTE/WWAN TABLET COMPUTER ANTENNA

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Received 6 September 2013

ABSTRACT: *A low-profile, small-size (10 × 40 mm^2 on a thin dielectric substrate) planar LTE/WWAN antenna suitable for slim tablet computer application is presented. The antenna is formed by a coupled-fed shorted strip antenna and an inductively coupled branch strip, with a chip inductor of 22 nH connected therebetween. At higher frequencies, owing to the high inductive reactance provided by the chip inductor, the branch strip will have very small effects on the antenna performances, and the coupled-fed shorted strip antenna alone can provide a high-band operation of 1710–2690 MHz. At lower frequencies, the embedded chip inductor can decrease the antenna's required resonant length, and the coupling feed can greatly widen the bandwidth of the excited resonant mode such that the antenna can cover a low-band operation of 704–960 MHz. Good radiation characteristics of the antenna in the low-band and high-band operations are also obtained. Details of the proposed antenna and its experimental and simulated results are presented.*
 Microwave Opt Technol Lett 56:1041–1046, 2014; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.28257

Key words: *mobile antennas; coupled-fed antennas; LTE/WWAN antennas; tablet computer antennas; low-profile antennas; small-size antennas*

1. INTRODUCTION

The shorted strip antenna or inverted-F antenna has been a promising internal antenna for mobile communications [1] in the handheld devices, such as the handsets, smartphones, phone tablets, notebook computers, tablet computers, and the like. To achieve multiband or wideband operation for the shorted strip antenna, several bandwidth-enhancement techniques, such as using two radiating strips [2–4], multibranch radiators [5,6], or a coupling feed [7,8], have been reported. The coupling-feed design has also been applied in achieving size reduction by decreasing the antenna's resonant length to be about 0.12 wavelength only [9,10], which is much less than the generally required 0.25 wavelength. In these reported shorted strip antennas for handheld devices, the technique of using multibranch radiators has also been applied to cover the long-term evolution (LTE) and wireless wide area network (WWAN) operation with a planar antenna structure occupying an area of 96 × 11.2 mm^2 for laptop computer applications [6]. Although the antenna can cover the LTE/WWAN bands, the antenna size is still large, which may cause problems in embedding two such antennas inside the handheld devices for multi-input multi-output (MIMO) or diversity operations.

Other promising LTE/WWAN tablet computer antennas with a planar structure have also been demonstrated [11–14], which includes using a folded monopole antenna (size 10 × 69 mm^2) configured into a loop-like configuration [11], a coupled-fed shorted strip antenna (size 15 × 40 mm^2) having an internal loop matching circuit [12], an inverted-F antenna (size 10 × 45 mm^2) having a feeding strip with a chip capacitor embedded therein and a radiating strip with a coupled section disposed therein [13], and a half-wavelength loop antenna (size 12 × 75 mm^2) having a feeding patch embedded therein to capacitively excite the loop strip [14]. To achieve low profile and small size (e.g., antenna height no larger than 10 mm and occupied size no larger than 10 × 40 mm^2) for the LTE/WWAN tablet computer applications, promising antenna designs are still demanded.

In this article, a new coupled-fed shorted strip antenna especially promising for tablet computer applications to cover the LTE/WWAN operation with low profile and small size is presented. The antenna is formed by a coupled-fed shorted strip antenna and an inductively coupled branch strip, with a chip inductor connected therebetween. The inductance of the chip inductor is properly selected such that, owing to its high inductive reactance in the desired higher band, the branch strip will have small or negligible effects on the antenna performances, and the coupled-fed shorted strip antenna alone can provide a wide operating band to cover the desired 1710–2690 MHz band. In addition, in the proposed design, the antenna profile or antenna height above an edge of the device ground plane in the tablet computer is determined by the coupled-fed shorted strip antenna, which has a low profile of 10 mm only, thereby resulting in a low profile for the proposed antenna for tablet computer applications. The low-profile property can make the proposed antenna especially promising for applications in the slim tablet computer having a narrow spacing between its display and housing.

At lower frequencies, both the coupled-fed shorted strip antenna and the inductively coupled branch strip are reconfigured into a new shorted strip antenna having a chip-inductor-loaded radiating strip and a coupling feed. The loaded chip inductor provides an inductance, which can greatly decrease the required length of the branch strip [15–18] to aid the antenna in generating a resonant mode in the desired low band. This allows the antenna to generate a resonant mode at about 800 MHz with a smaller size. Further, the coupling feed can lead to bandwidth enhancement of the excited resonant mode to provide a wide operating band to cover the desired 704–960 MHz band. The proposed antenna can hence cover the LTE/WWAN operation with a low profile, small size of 10 × 40 mm^2 on a thin FR4 substrate. The required antenna size for the LTE/WWAN operations in the 704–960 and 1710–2690 MHz bands in this study is even smaller than those of the reported penta-band WWAN tablet computer antennas for operating in the 824–960 and 1710–2170 MHz bands [19,20]. The small size and low profile will make it easy to embed two such planar antennas in the slim tablet computer for MIMO or diversity applications. The antenna structure and operating principle of the proposed design are discussed, and results of the proposed antenna are presented.

2. PROPOSED ANTENNA AND ITS OPERATING PRINCIPLE

Figure 1 shows the geometry of the proposed LTE/WWAN tablet computer antenna. The antenna is printed on a 0.8-mm-thick FR4 substrate of size 10 × 40 mm^2, relative permittivity 4.4, and loss tangent 0.024. The antenna is mounted along an edge of the device ground plane of the tablet computer for experimental testing (see the photo of the fabricated antenna shown in Figure 4 in the next section). The device ground plane is selected to have a size of 150 × 200 mm^2, which is a reasonable size for the tablet computer with a 10-in-display panel. In the experimental study, the device ground plane was cut from a 0.2-mm-thick copper plate.

The antenna is formed by a coupled-fed shorted strip antenna and a branch strip of length 42 mm (section EF), with a chip

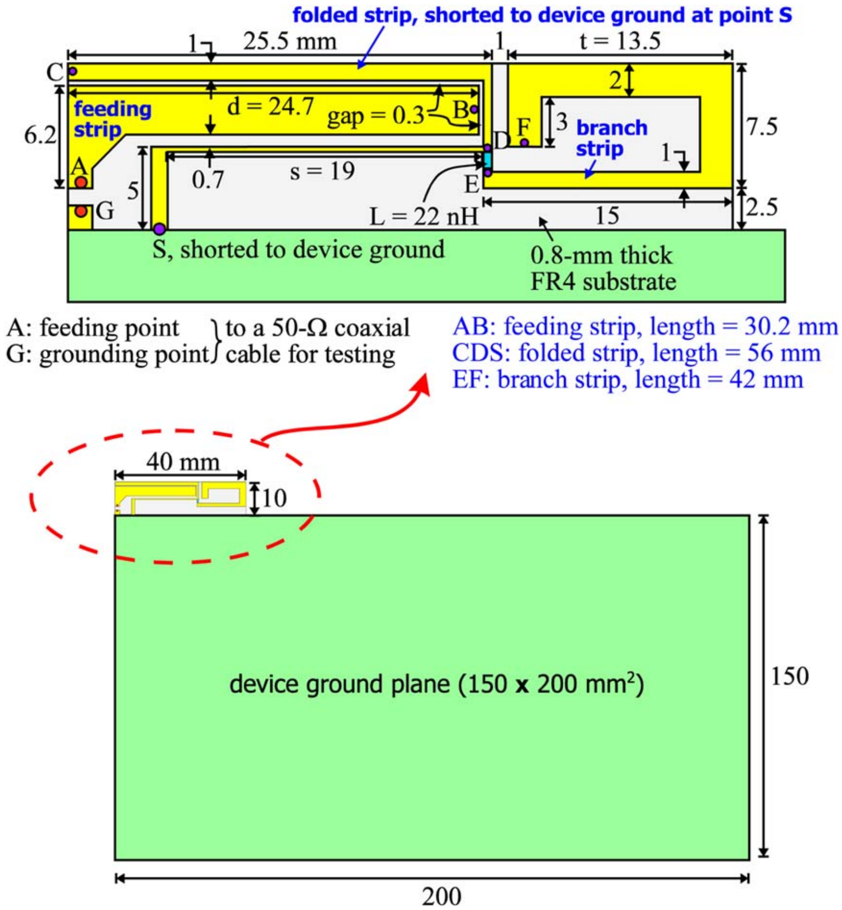

Figure 1 Geometry of the proposed LTE/WWAN tablet computer antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

inductor of 22 nH (L) embedded therebetween. Note that the branch strip is configured into a spiral shape of size about 7.5 $\times$ 14.5 mm^2 to achieve a compact size for the proposed antenna. The coupled-fed shorted strip antenna alone occupies a small area of 10 $\times$ 25.5 mm^2, and comprises a folded strip of length 56 mm (section CDS) short-circuited to the device ground plane and an inverted-L feeding strip of length 30.2 mm (section AB). The feeding strip is enclosed by the folded strip and is a coupling feed for the folded strip. It should be noted that at higher frequencies, such as the antenna's higher band, owing to the high inductive reactance provided by the chip inductor, the excitation of the branch strip will be suppressed. Hence, at higher frequencies, the branch strip will have small effects on the antenna's high-band operation. In this case, with the coupled-fed shorted strip antenna excited alone, the antenna can provide a wide operating band to cover the desired 1710–2690 MHz band. While at lower frequencies, such as the antenna's lower band, both the coupled-fed shorted strip antenna and the branch strip are excited. The proposed antenna is reconfigured into a new shorted strip antenna having a chip-inductor-loaded radiating strip (section CDEF) of length about 72 mm, which is short-circuited to the device ground plane through the section DS of length 25 mm and coupled-fed by the feeding strip of length 30.2 mm (section AB). Also note that at point G, there is a small metal pad to be connected to the device ground plane, and a 50-Ω coaxial line is applied with its central conductor and outer grounding sheath connected, respectively, to point A and G for the experimental testing in this study.

To analyze the operating principle of the antenna, the simulated results of the return loss for Ant1 (the coupled-fed shorted strip antenna only) are shown in Figure 2, for comparison with

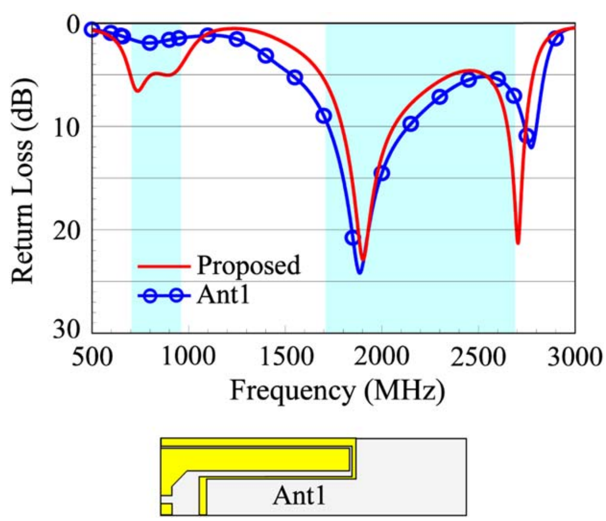

Figure 2 Simulated return loss for the proposed antenna and the case with the coupled-fed shorted strip antenna only (Ant1, no branch strip). Corresponding dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

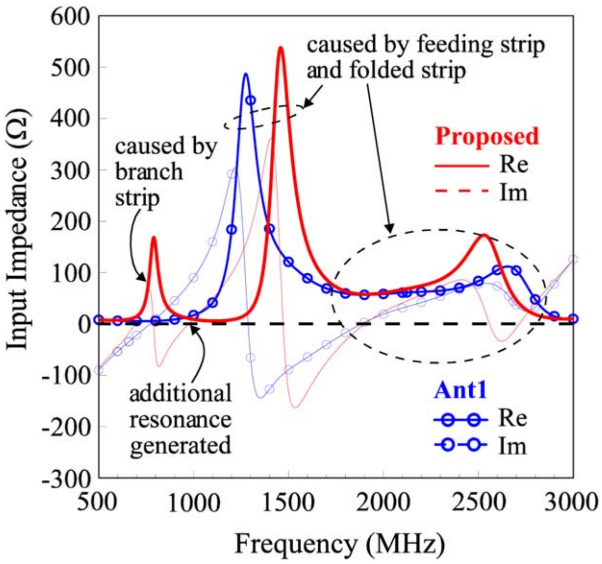

Figure 3 Simulated input impedance for the proposed antenna shown in Figure 1 and Ant1 shown in Figure 2. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

the results of the proposed antenna. The simulated input impedance results for the proposed antenna and Ant1 are also presented in Figure 3. The simulated results are obtained using the full-wave electromagnetic field simulator HFSS version 14 [21]. The shaded frequency ranges at lower and higher frequencies in the figure are the desired lower band (704–960 MHz) and higher band (1710–2690 MHz). For both the proposed antenna and Ant1, it is seen that two resonant modes at about 1.9 and 2.7 GHz contributed by the coupled-fed shorted strip antenna are excited and combined into a wide operating band, which can cover the desired higher band for the GSM1800/1900/UMTS/LTE2300/2500 operations. Also, the inductively coupled branch

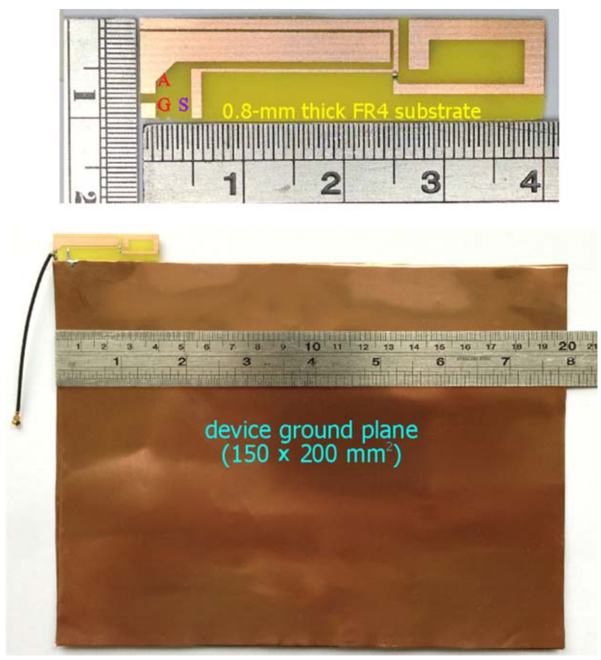

Figure 4 Photos of the fabricated antenna and the same with the device ground plane for experimental testing. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

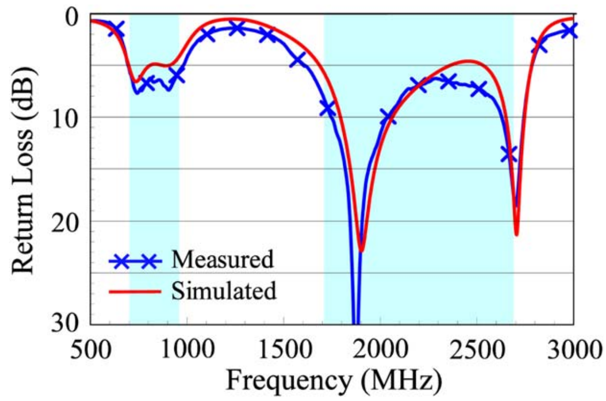

Figure 5 Measured and simulated return loss of the fabricated antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

strip causes small effects on the obtained higher band. This confirms that the added chip inductor can suppress the excitation of the branch strip. In addition, please note that, although the return loss for part of the frequencies of the operating bands is not better than 6 dB, the measured antenna efficiency (with mismatching loss included) is better than 40% over the lower band and better than 59% over the higher band (see Fig. 6 in Section 3), which is acceptable for practical mobile communication applications [22,23].

It is also noted that with the added inductively coupled branch strip, a new resonant mode at about 800 MHz is generated (see the results of the proposed antenna in Fig. 3), and an additional resonance at about 1 GHz is also generated. This behavior leads to two resonant modes occurred in the antenna's lower band with a wide bandwidth to cover the LTE700/GSM850/900 operations. In addition, the resonant mode at about 800 MHz can be adjusted by selecting a proper inductance L of the chip inductor and tuning the length of the branch strip (section EF). Conversely, the additional resonance at about 1 GHz can be adjusted by tuning the dimensions of the coupling feed (i.e., the portion without the branch strip in the proposed design). Details of the experimental results and parametric studies of the proposed antenna are presented in the next section.

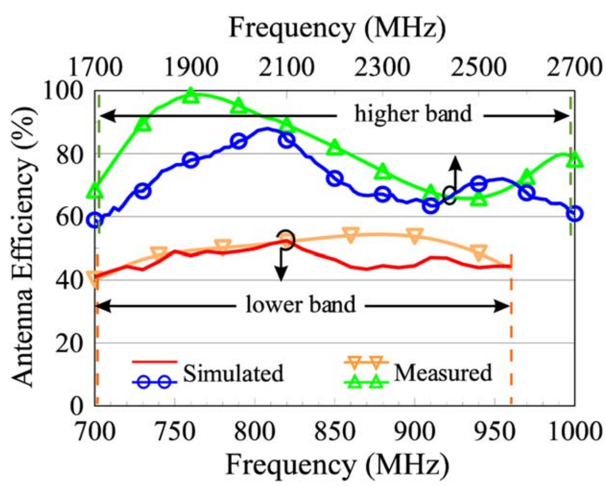

Figure 6 Measured antenna efficiency of the fabricated antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

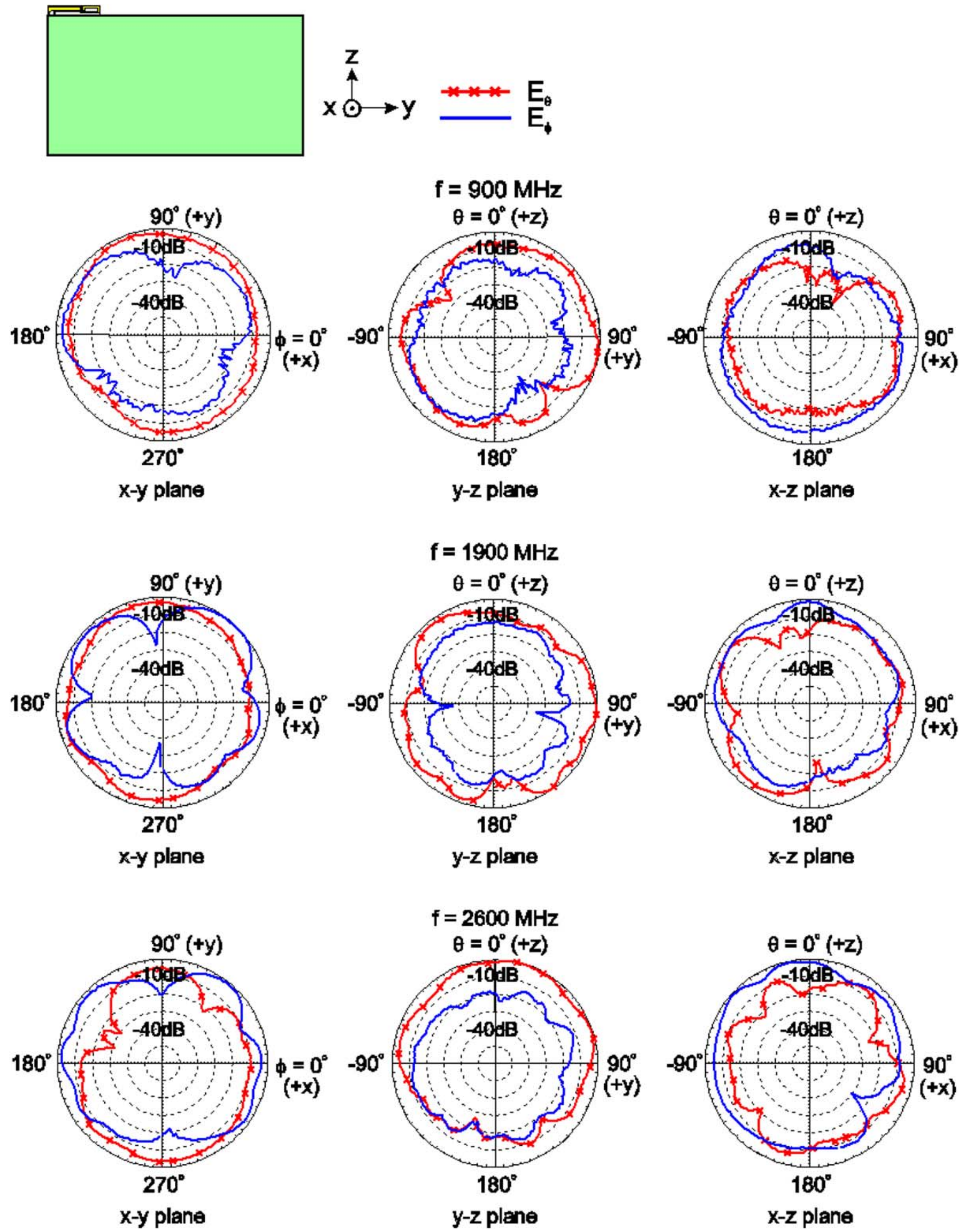

Figure 7 Measured radiation patterns at 900, 1900, and 2600 MHz of the fabricated antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

3. EXPERIMENTAL RESULTS AND PARAMETRIC STUDIES

Figure 4 shows the photos of the fabricated antenna. For the experimental testing, the antenna is mounted along an edge of the device ground plane as shown in Figure 1, and a 50-Ω coaxial cable is connected across point A and G for testing. The device ground plane is a 0.2-mm-thick copper plate of size 200×150 mm^2. Results of the measured and simulated return loss of the antenna are shown in Figure 5. Agreement between the measured data and the simulated results obtained using the full-wave electromagnetic field simulator HFSS version 14 [21] is seen. The measured antenna efficiency of the fabricated antenna is shown in Figure 6. The antenna efficiency includes the mismatching loss and was measured in a far-field anechoic chamber. The antenna efficiency is, respectively, about 41–52 and 59–88% for the lower and higher bands, and is acceptable for practical applications [22,23].

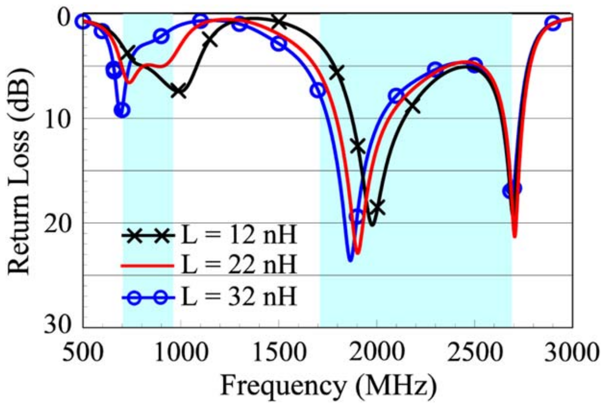

Figure 8 Simulated return loss as a function of the inductance L of the chip inductor. Other dimensions are the same as in Figure 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

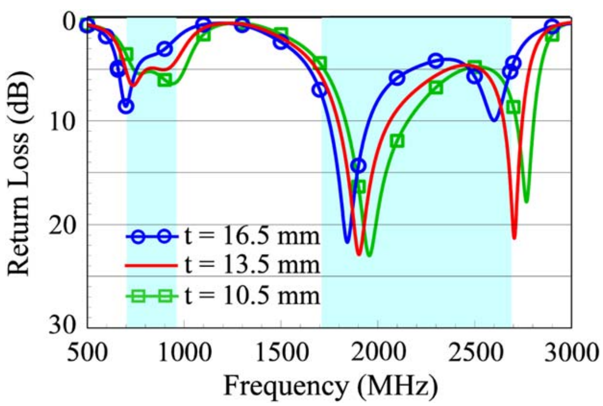

Figure 9 Simulated return loss as a function of the length t in the branch strip. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 7 shows the measured radiation patterns of the fabricated antenna at typical frequencies of 900, 1900, and 2600 MHz. When considering both E_θ and E_ϕ components for the total radiated power, near-omnidirectional radiation in the *x-y* plane is seen for the three frequencies. In the *y-z* and *x-z* planes,

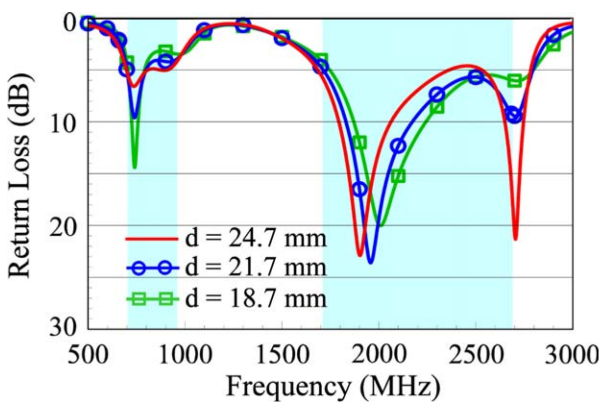

Figure 10 Simulated return loss as a function of the length d in the feeding strip. Other dimensions are the same as in Figure 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

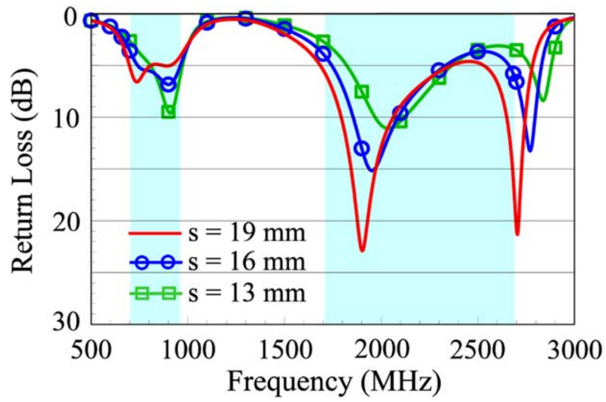

Figure 11 Simulated return loss as a function of the length s in the shorted folded strip. Other dimensions are the same as in Figure 1.

there are also no large dips in all directions. This radiation characteristic is advantageous for mobile communications to have good coverage in practical applications.

Effects of varying the inductance L of the chip inductor are analyzed using HFSS simulated results. Figure 8 shows the simulated return loss for the inductance L varied from 12 to 32 nH. For the antenna's higher band, larger effects on the resonant modes therein are seen for $L = 12$ nH than for $L = 22$ and 32 nH. The results indicate that in order to suppress the effects of the added branch strip on the antenna's high-band operation, the embedded chip inductor should have a large inductance (in this study, it is selected to be 22 nH). For the antenna's lower band, it is seen that the resonant modes therein are very sensitive to the variations in the inductance L. This is mainly because varying the inductance of the added chip inductor affects the effective resonant length of the section CDEF, and therefore the resonant modes in the lower band will be greatly affected. Similar effects can be seen for varying the length t in the branch strip. Figure 9 shows the simulated return loss for the length t varied from 10.5 to 16.5 mm. Note that in this study, the spacing between the branch strip and the folded strip are all fixed to be 1 mm (see Fig. 1 with $t = 13.5$ mm), and the total antenna length along the edge of the device ground plane becomes 37 and 43 mm for $t = 10.5$ and 16.5 mm, respectively. The resonant modes in the lower bands are shifted to higher frequencies with a decrease in the length t. Similar results are observed for the

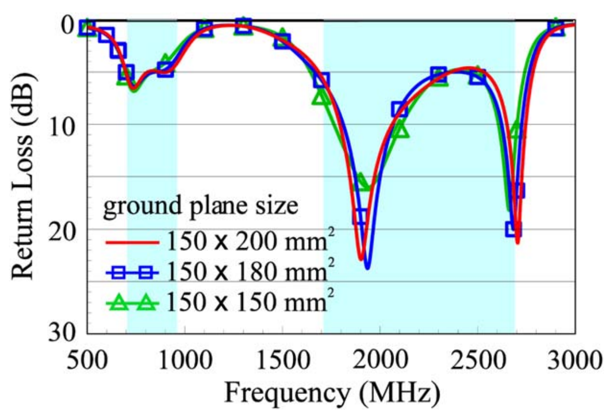

Figure 12 Simulated return loss as a function of the device ground plane size. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

resonant modes in the higher band. This is largely because the variations in the length of the branch strip will still cause some variations of the excited surface current distributions in the section CD for the antenna operated in the higher band, thereby causing some effects on the resonant modes in the higher band, which are mainly contributed by the coupled-fed shorted strip antenna formed by the shorted folded strip (section CD and DS) and the feeding strip.

Effects of the feeding strip are also studied. Figure 10 shows the simulated return loss for the length d in the feeding strip varied from 18.7 to 24.7 mm. For $d = 18.7$ and 21.7 mm, the gap between the feeding strip's open end (point B) and the folded strip becomes 6.3 and 3.3 mm, respectively, and other dimensions are the same as in Figure 1. As the length of the section CDEF is not changed, the first mode in the lower band still occurs at about the same frequency for different lengths of d. However, mainly owing to the coupling between the feeding strip and the section CDEF being varied, the impedance matching of the two resonant modes in the lower band is affected. In other words, it is also effective to fine adjust the impedance matching of the antenna's lower band by adjusting the length d of the feeding strip. In addition, as the coupling between the feeding strip and the shorted folded strip (section CDS) is affected when the length d is varied, some effects on the resonant modes in the antenna's higher band is also seen.

Figure 11 shows the simulated return loss as a function of the length s in the shorted folded strip. Results of the length s varied from 13 to 19 mm are shown, and other dimensions are the same as in Figure 1. For $s = 13$ and 16 mm, the section DS is still of an inverted-L shape, and the shorting point S is moved away from the feeding point A. Probably because the variations in the length s will vary the effective resonant length of the coupled-fed shorted strip antenna (section CD, DS, and AB) and also affect the excited surface current distributions on the section CDEF, large effects on the resonant modes in both the antenna's higher and lower bands are seen.

Figure 12 shows the simulated return loss as a function of the device ground plane size. Results for the ground plane size varied from 150×200 to 150×150 mm^2 are presented, in which the length of the top edge where the antenna is mounted is varied from 200 to 150 mm. For different ground plane sizes, the antenna dimensions are all the same as in Figure 1. Small effects on both the antenna's lower and higher bands are seen, expect that there are some degradation in the impedance matching of the second mode in the lower band for the case of 150×150 mm^2. However, by tuning the typical dimensions of the antenna as studied in this section, it is possible to improve the impedance matching of the antenna for the practical tablet computers with different ground plane sizes.

4. CONCLUSION

A planar LTE/WWAN tablet computer antenna with low profile and small size has been proposed. The antenna has a low profile of 10 mm, and the antenna size is 10×40 mm^2 only. The antenna is formed by adding a branch strip inductively coupled to a small coupled-fed shorted strip antenna. The latter is simply formed by a shorted, folded strip enclosing a feeding strip as a coupling feed, and can provide two resonant modes to cover the desired 1710–2690 MHz band. The inductively coupled branch strip leads to a wide lower band generated for the antenna to cover the 704–960 MHz band. The operating principle of the proposed antenna has been described, and acceptable radiation characteristics for mobile communications have also been observed. The proposed antenna is especially suitable for applications in the LTE/WWAN slim tablet computers.

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