DUAL-WIDEBAND LINEAR OPEN SLOT ANTENNA WITH TWO OPEN ENDS FOR THE LTE/WWAN SMARTPHONE

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ABSTRACT: *A linear open slot antenna with two open ends for the dual-wideband LTE/WWAN operation in the 698–960 and 1710–2690 MHz bands is presented for the smartphone application. The proposed antenna is referred to as a dual-opening slot (DOS) antenna and is especially suitable for the modern slim tablet device, such as a 5.5-inch smartphone. The DOS antenna has a slot length of 75 mm and a narrow slot width of 2 mm, and can be disposed with a short distance of 8 mm to the top or bottom edge of the smartphone. The DOS antenna will hence not overlap the display panel in the smartphone. This makes it promising and attractive for practical smartphone applications. As the DOS antenna has two open ends, two open slots [a first (longer) open slot and a second (shorter) open slot] can be created using a metal pad to short-circuit the DOS across its two parallel edges at a proper position. The first and second open slot antennas are then respectively excited by a first feed and a second feed. By further with the aid of wideband matching networks in the two feeds, the DOS antenna can provide two wide operating bands to cover the LTE/WWAN operation. Details of the DOS antenna are described in this study.* © 2015 Wiley Periodicals, Inc. Microwave Opt Technol Lett 57:1269–1274, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29077

Key words: *mobile antennas; open slot antennas; slot antennas; smartphone antennas; LTE/WWAN antennas*

1. INTRODUCTION

The open slot antenna has been a promising internal antenna for the handheld terminal device for mobile communication. Some promising open slot antennas for the smartphone have been reported to achieve the wideband wireless area network (WWAN) operation in the 824–960 and 1710–2170 MHz bands [1–5]. The reported open slot antennas are generally embedded in the system ground plane of the terminal device and have an opening at the ground edge thereof. The open slot antenna can operate at its quarter-wavelength resonant mode to achieve a reduced antenna size, as compared to the traditional half-wavelength slot antenna with two closed ends. In addition, the metal portion around the open slot can be reused to accommodate the associated electronic elements [6], making it attractive to achieve compact integration inside the mobile device. However, to the authors' knowledge, the open slot antenna for the smartphone application to cover the whole LTE/WWAN operation in the 698–960 and 1710–2690 MHz bands is very scant or still not available in the open literature.

Also, in order for the open slot antenna to be more attractive for the modern slim smartphone application, the antenna should be able to be disposed close to the top or bottom edge of the smartphone, and good antenna performance can still be obtained. In this case, the open slot will not overlap the display panel, making it promising for practical applications. However, when the open slot is disposed close to the edge of the smartphone, that is, the open slot is close to the top or bottom edge of the system ground plane therein, wideband operation of the open slot antenna is usually not feasible to obtain. This causes a design challenge for the open slot antenna to cover the LTE/WWAN operation in the modern slim smartphone.

In this article, we present a new linear open slot antenna with two open ends for the application in the modern slim smartphone, such as a 5-5-inch slim smartphone, to cover the LTE/WWAN operation in the 698–960 and 1710–2690 MHz bands. The linear open slot with two open ends is referred to as a dual-opening slot (DOS) in this study. The DOS antenna has a narrow slot width of 2 mm only and can be disposed with a short distance of 8 mm to the top or bottom edge of the system ground plane of the smartphone. Its two open ends are located at the two opposite side edges of the system ground plane. In this study, a 5.5-inch smartphone with the system ground plane of dimensions 75×130 mm^2 is considered. In this case, the DOS antenna will not overlap the display panel, making it promising for practical applications.

The proposed DOS antenna can be configured into a first (longer) open slot antenna and a second (shorter) open slot antenna to generate multiple resonant modes for the LTE/WWAN operation. The multiple resonant modes can be easily excited and controlled using a first feed for the longer open slot and a second feed for the shorter open slot. The bandwidths of the multiple resonant modes are enhanced by the wideband matching networks in the first and second feeds, thereby leading to a dual-wideband operation covering the 698–960 and 1710–2690 MHz bands. Details of the DOS antenna are described in this study. The working principle of the antenna is addressed. The experimental and simulation results are also presented and discussed.

2. PROPOSED ANTENNA

2.1. Antenna Structure

Figure 1 shows the geometry of the DOS antenna for the smartphone application. The DOS antenna is disposed on an FR4 substrate of relative permittivity 4.4, loss tangent 0.02, and dimensions 75×130 mm^2, which can be treated as the system circuit board of a 5.5-inch smartphone. The DOS antenna has a slot length of 75 mm and a narrow slot width of 2 mm, with its two open ends located at the two opposite side edges of the system ground plane printed on the system circuit board. With the inclusion of the slot width, the DOS antenna is close to the top or bottom edge of the system ground plane with a short distance of 10 mm. In this case, the DOS antenna will generally not overlap the display panel (see the dashed box on the back surface of the system circuit board), making it promising for practical applications in the modern smartphone. Note that the dashed box is shown to illustrate the display panel only and is not included in the study.

Also note that a vertical edge metallic plate is present at the edge near the DOS antenna. The edge metallic plate having a width of 6 mm can be formed as a part of the metallic frame of the smartphone or can be disposed on the inner surface of the casing of the smartphone. The edge metallic plate is connected to the ground plane printed on the back surface of the system circuit board and is helpful in achieving good impedance matching of the DOS antenna. The proposed antenna can be seen more clearly in Figure 2, in which the photos of the front and back views of the fabricated antenna in the experiment are shown.

The DOS has a simple linear shape and occupies a small board space of 150 mm^2. It is embedded in the ground plane on the back surface of the system circuit board. With a 3-mm metal pad short-circuiting the DOS across its two parallel edges, the DOS is configured into a longer slot (slot 1) of length 50 mm and a shorter slot (slot 2) of length 22 mm. Slot 1 is excited by

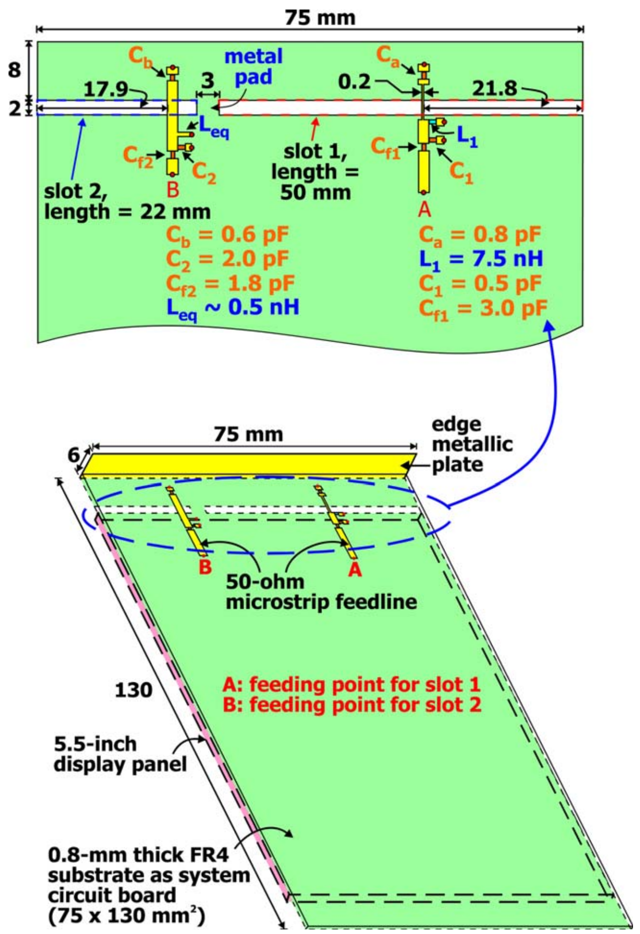

Figure 1 Geometry of the DOS antenna for the LTE/WWAN smartphone application. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

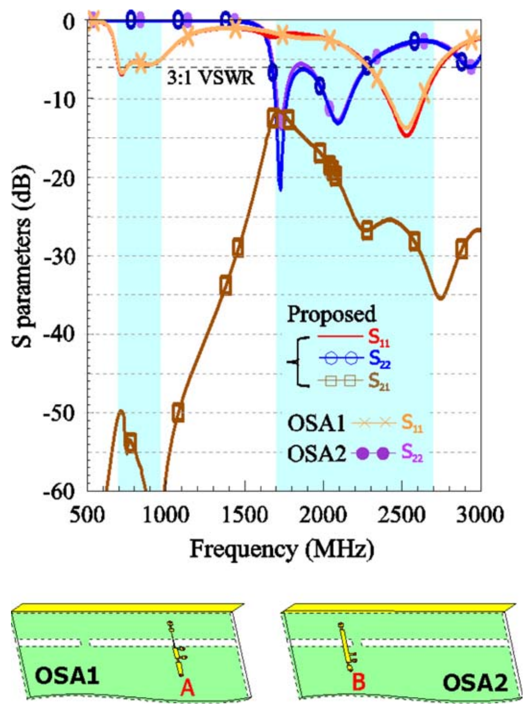

Figure 3 Simulated S parameters for the DOS antenna, the case with the first feed for slot 1 only (OSA1) and the case with the second feed for slot 2 only (OSA2). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

a first 50-Ω microstrip feedline (the first feed) disposed with a distance of 21.8 mm to the open end thereof. Slot 2 is also excited by a second 50-Ω microstrip feedline (the second feed) with a distance of 17.9 mm to the open end thereof. Each microstrip feedline is loaded with a wideband matching network to achieve wideband resonant mode excitation. Slot 1 can contribute a wide lower band to cover the 698–960 MHz band. In addition, slot 1 can also generate a wideband higher-order resonant mode at about 2.5 GHz to combine with a wideband resonant mode excited by slot 2 at about 2 GHz to form a wide higher band to cover the 1710–2690 MHz band.

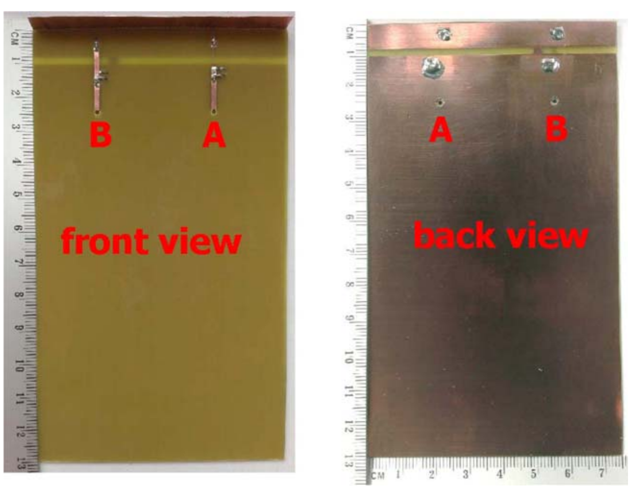

Figure 2 Photos of the fabricated antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Note that the metal pad connects the upper ground portion and the lower ground portion separated by the DOS. The upper ground portion can be reused to accommodate associated electronic elements such as the speaker, the camera lens, the USB connector, and the like [3]. The associated electronic elements can be connected to the modules in the lower ground portion by the circuitry passing through the metal pad. In this case, compact integration of the DOS on the system circuit board can be obtained.

The two microstrip feedlines for slot 1 and slot 2 are also grounded to the upper ground portion at their terminal ends. This can limit the required tuning length of the microstrip feedlines, making it occupy less board space in the upper ground portion. For slot 1, the wideband matching network includes a series chip capacitor C_a of 0.8 pF at the grounded end, a band-pass circuit formed by a parallel chip capacitor C_1 of 0.5 pF and a parallel chip inductor L_1 of 7.5 nH, and a series chip capacitor C_{f1} of 3.0 pF at the feeding end. The feedline section across slot 1 is also narrowed to have a width of 0.2 mm to contribute additional inductance to fine adjust the impedance matching seen at the feeding point A. The capacitor C_a mainly leads to good excitation of a resonant mode in the desired lower band and a higher-order resonant mode in the desired higher band. The bandwidth of the excited resonant mode in the lower band is enhanced to cover the 698–960 MHz band by the band-pass circuit (L_1 and C_1) and the capacitor C_{f1}. The bandwidth of the excited higher-order resonant mode can also cover the frequency range of about 2.3–2.7 GHz in the higher band.

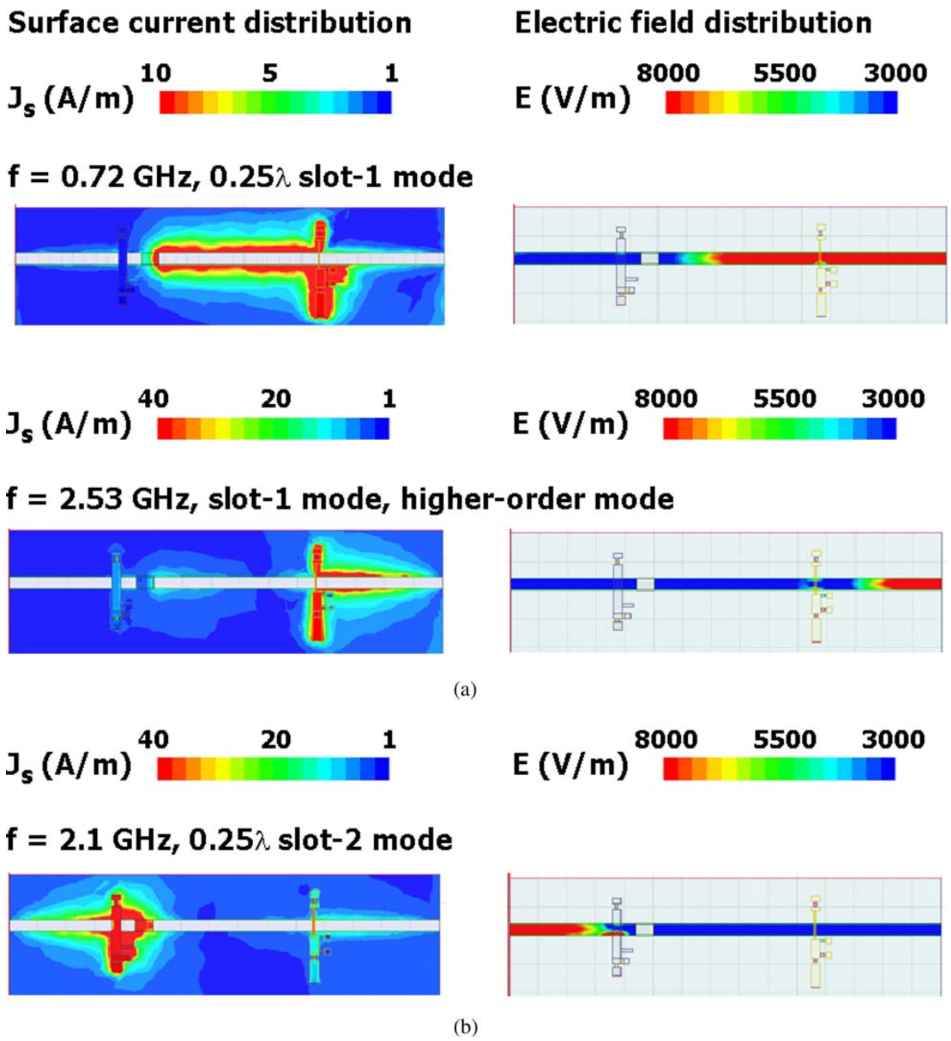

Figure 4 Simulated electric field and surface current distributions for the DOS antenna. (a) Resonant modes at 0.72 and 2.53 contributed by slot 1. (b) Resonant mode at 2.1 GHz contributed by slot 2. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Conversely, the wideband matching network for slot 2 includes a series chip capacitor C_b at the grounded end, a band-pass circuit formed by an equivalent parallel inductor L_{eq} of about 0.5 nH (a 5-mm narrow strip short-circuited to the lower ground portion on the back surface) and a parallel chip capacitor C_2 of 2.0 pF, and a series chip capacitor C_{f2} of 1.8 pF at the feeding end. The matching network leads to good excitation of a dual-resonance mode covering the frequency range of about 1.7–2.3 GHz in the higher band. By combining this dual-resonance mode generated by slot 2 and the higher-order resonant mode contributed by slot 1, the desired higher band of 1710–2690 MHz is covered. The working principle, matching network effects and the case of using an inverted-L edge metallic plate replacing the simple vertical edge metallic plate for the DOS antenna are discussed in the following subsections.

2.2. Working Principle

Figure 3 shows the simulated S parameters for the DOS antenna, the case with the first feed for slot 1 only (OSA1), and the case with the second feed for slot 2 only (OSA2). The simulated results are obtained using the full-wave electromagnetic field simulator HFSS version 15 [7]. In the figure, S_{11} and S_{22} show for OSA1 and OSA2, respectively. The shaded frequency ranges indicate the desired operating bands of 698–960 and 1710–2690 MHz. With the excitation of OSA1 and OSA2, it is seen that the dual-wideband LTE operation can be covered. Acceptable isolation with $S_{21} < -12$ dB in the higher band and $S_{21} < -50$ dB in the lower band between the two feeding points of A and B is also obtained. The results indicate that OSA1 and OSA2 can be designed separately, making it easy for the proposed DOA antenna to cover the desired dual-wideband LTE/WWAN operation. Also note that the impedance matching for frequencies in the higher band is all better than -6 dB. For frequencies in the lower band, although the impedance matching is not better than -6 dB for the whole lower band, the obtained antenna efficiency is all better than 55% (see the results in Figure 8, which will be discussed in Section 3) and is acceptable for practical applications.

To analyze the resonant modes excited in the lower and higher bands, Figure 4 shows the simulated electric field and surface current distributions for the DOS antenna. Figure 4(a) shows the results for the resonant modes at 0.72 and 2.53 GHz contributed by slot 1. It is seen that strong electric field occurs at the open end of slot 1 at 0.72 and 2.53 GHz. Symmetric surface currents excited along the two parallel edges of slot 1 are also seen. The observed behavior indicates that open slot resonant modes are excited, and the resonant mode at 0.72 GHz is a

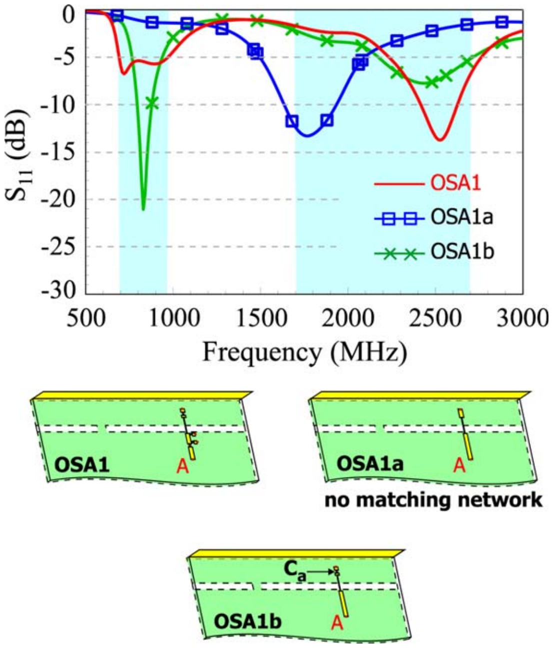

Figure 5 Simulated S11 for OSA1, the case of OSA1 without the matching network (OSA1a) and the case of OSA1a with Ca only (OSA1b). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

0.25-wavelength slot mode and that at 2.53 GHz is a higher-order slot mode [8–12].

Conversely, Figure 4(b) shows the results for the resonant mode at 2.1 GHz contributed by slot 2. From the results, strong electric field is seen at the open end of slot 2. Symmetric surface currents excited along the two parallel edges of slot 2 are also observed. Again, this indicates that the open slot resonant mode is excited, and the resonant mode at 2.1 GHz is a 0.25-wavelength slot mode [8–12].

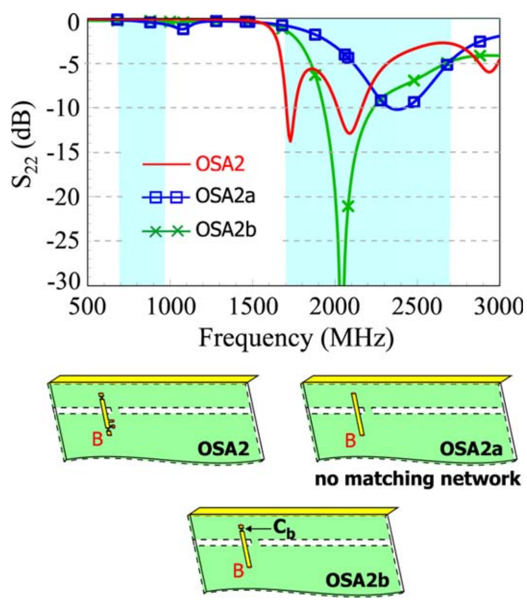

Figure 6 Simulated S22 for OSA2, the case of OSA2 without the matching network (OSA2a) and the case of OSA2a with C_b only (OSA2b). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

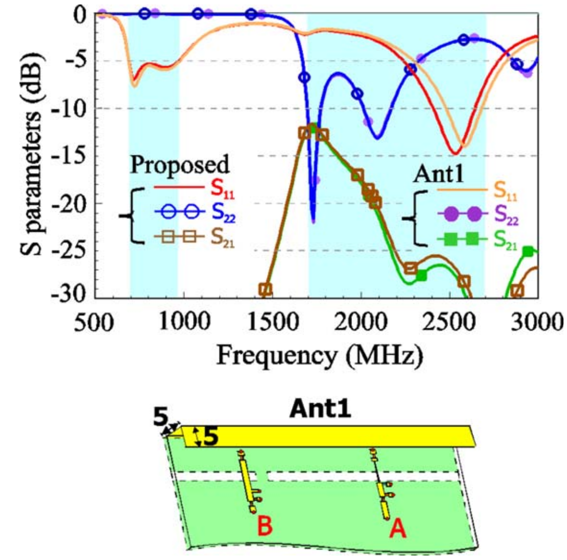

Figure 7 Simulated *S* parameters of the proposed DOS antenna with a simple vertical edge metallic plate in Figure 1 and the case of an inverted-L edge metallic plate (Ant1). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

2.3. Matching Network Effects

In this subsection, the effects of matching networks for the excitation of slot 1 and 2 to obtain wideband resonant modes are analyzed. Figure 5 shows the simulated S_{11} for OSA1, the case of OSA1 without the matching network (denoted as OSA1a in the figure), and the case of OSA1a with C_a only (denoted as OSA1b). For OSA1a, no resonant mode is excited in the desired lower band, although there is a wideband resonant mode occurred at about 1.75 GHz. When the capacitor C_a is added to OSA1a to form OSA1b, the strong inductance owing to the grounded end of the microstrip feedline can be compensated [13], and the 0.25-wavelength open slot resonant mode can be excited with good impedance matching. In addition, a higher-order resonant mode can be generated at about 2.5 GHz to cover the frequency range of about 2.3–2.7 GHz.

By further adding the band-pass circuit (L_1, C_1) and the capacitor C_{f1} to OSA1b (that is, OSA1 is formed), a dual-resonance behavior for the excited resonant mode in the lower band is obtained, and the obtained bandwidth can cover the desired 698–960 MHz band. At the same time, there are small effects on the excited higher-order resonant mode.

Effects of the matching network on OSA2 are also analyzed. Figure 6 shows the simulated S_{22} for OSA2, the case of OSA2 without the matching network (denoted as OSA2a), and the case of OSA2a with C_b only (denoted as OSA2b). For OSA2a, a resonant mode occurs at about 2.4 GHz. By adding C_b to OSA2a, a dual-resonance behavior for the excited resonant mode is seen (see OSA2b curve in the figure). However, the obtained bandwidth cannot cover the frequency range close to 1.71 GHz. This is owing to the limited length of slot 2 being 22 mm only in this study. By further adding the band-pass circuit (L_{eq}, C_2) and the capacitor C_{f2} to OSA2b to form OSA2, the dual-resonance mode can be shifted to cover the frequency range of about 1.7–2.3 GHz with improved impedance matching. In this case, the desired higher band of 1710–2690 MHz can be covered by the 0.25-wavelength open slot mode contributed by slot 2 and the higher-order open slot mode contributed by slot 1.

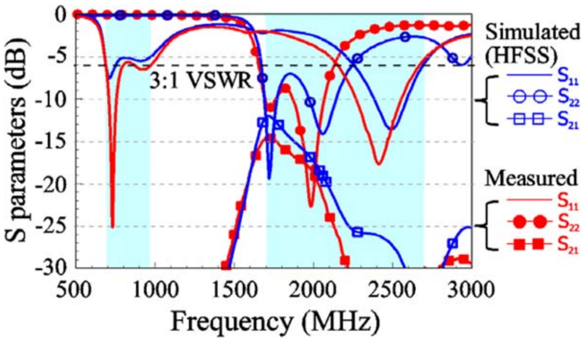

Figure 8 Measured and simulated S parameters for the fabricated DOS antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

2.4. Effects of Using an Inverted-L Edge Metallic Plate

In the proposed DOS antenna shown in Figure 1, the vertical edge metallic plate has a width of 6 mm. An inverted-L edge metallic plate can also be used to replace the simple vertical edge metallic plate. In this case, the width of the edge metallic plate can be decreased from 6 to 5 mm, more attractive for slim smartphones. For this study, the simulated S parameters of the proposed DOS antenna with a simple vertical edge metallic in Figure 1 and the case of an inverted-L edge metallic plate (Ant1) are shown in Figure 7. For both cases, similar results have been observed. In the lower band, the impedance matching for Ant1 is even slightly better than that for the proposed antenna in Figure 1. The use of the inverted-L edge metallic plate can hence be an alternative design for the DOS antenna in practical applications.

3. EXPERIMENTAL RESULTS

The proposed DOS antenna was fabricated, and the photos of the fabricated antenna have been shown in Figure 2. The measured and simulated S parameters for the fabricated DOS antenna are presented in Figure 8. The measured data are seen to agree with the simulated results. The measured S_{11} (slot 1 excitation) and S_{22} (slot 2 excitation) indicate that the impedance matching is better than about -6 dB over the operating band of 698–960 and 1710–2690 MHz. The measured S_{21} between the two feeding ports is also small [< -14 dB in the higher band and less than -30 dB in the lower band (not shown in the figure due to its small values)], indicating that good isolation is obtained between the two feeding ports. This suggests that OSA1 and OSA2 can be designed separated and then combined into the proposed DOS antenna with small or no retuning required in the matching networks therein.

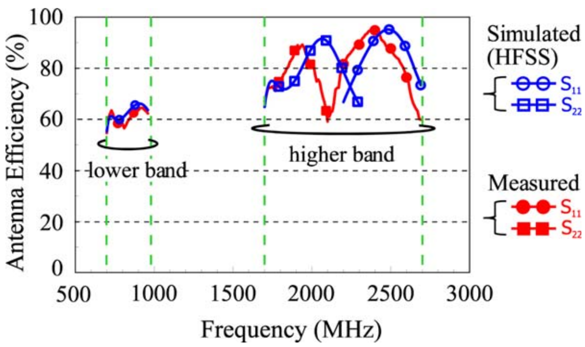

Figure 9 Measured and simulated antenna efficiencies for the fabricated DOS antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

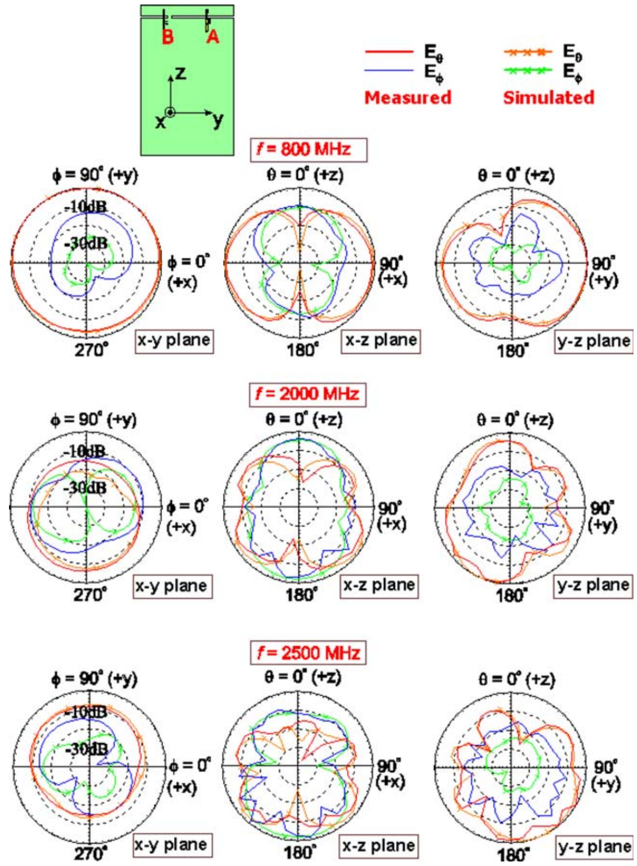

Figure 10 Measured and simulated radiation patterns for the fabricated DOS antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 9 shows the measured and simulated antenna efficiencies for the fabricated DOS antenna. The radiation characteristics are measured in a far-field anechoic chamber. Agreement between the measurement and simulation is also seen. The antenna efficiency includes the mismatching losses. The measured antenna efficiency is about 55–63% and 60–95% in the lower and higher bands, respectively, which is acceptable for practical mobile communication application.

Figure 10 shows the measured and simulated radiation patterns. Results at 800, 2000, and 2500 MHz are plotted. Three principal radiation patterns in the *x-y* plane (azimuthal plane), *x-z* plane (elevation plane orthogonal to the system circuit board), and *y-z* plane (elevation plane parallel to the system circuit board) at each frequency are presented. The measured data also generally agree with the simulated results. At 800 MHz, near-omnidirectional radiation is seen in the *x-y* plane, indicating that the system ground plane also contributes to the radiation in the lower band. This behavior is similar to the observation in many traditional handset antennas [14] and the open slot antennas reported for the smartphone application such as in [1, 3].

At higher frequencies of 2000 and 2500 MHz, relatively larger variations in the radiation, compared to those at 800 MHz, are seen. Also note that the radiation in the *y-z* plane shows that relatively stronger radiation in the –*y* direction is seen at 2000 MHz. Conversely, relatively stronger radiation in the $+y$ direction is seen at 2500 MHz. This behavior is largely because the resonant mode covering 2000 MHz is contributed by slot 2 with its open end directing to the –y direction, while the resonant mode covering 2500 MHz is contributed by slot 1 with its open end directing to the $+y$ direction. It is also noted that since there are no significant nulls in the radiation patterns, the obtained radiation patterns will be acceptable for mobile communication.

4. CONCLUSION

A dual-wideband linear open slot antenna with two open ends referred to as the DOS antenna has been proposed for the LTE/WWAN operation in the smartphone. The DOS antenna has been shown to be easily configured as two open slot antennas to contribute wideband resonant modes for the LTE/WWAN operation in the 698–960 and 1710–2690 MHz bands. The matching networks for achieving wider bandwidths of the excited resonant modes have been analyzed. Good radiation characteristics for the DOS antenna have also been obtained. Excluding the matching networks, the DOS antenna occupies a small board area of 150 mm^2 only. The total distance of the DOS antenna to the top or bottom edge of the system circuit board is also 10 mm only, which generally will not overlap the display panel in the modern smartphone. With the obtained results, the DOS antenna will be promising for practical smartphone applications.

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AN ULTRA-WIDEBAND SiGe BiCMOS LNA FOR W-BAND APPLICATIONS

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ABSTRACT: *This article presents the design steps and implementation of a W-band ultra-wideband low noise amplifier (LNA) for both automotive and imaging applications. Three amplifiers based on common-emitter topology with different configurations are manufactured using IHP 0.13 μm SiGe BiCMOS 300/500 GHz (f_t/f_{max}) SG13G2 technology. A three-stage single-ended structure is proposed for ultra-wideband imaging purposes. As the results are analyzed, this 0.2 mm^2 LNA can operate in a 25 GHz of measured 3-dB bandwidth in W-band with 21 dB peak gain and 4.9 dB average noise figure using 1.5 V supply voltage. It consumes 50 mW of power in the edge operation conditions and the output 1 dB compression point is found as −4 dBm. To the authors' knowledge, this chip achieves one of the best overall performances compared to other W-band LNAs.* © 2015 Wiley Periodicals, Inc.

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Key words: *automotive radar; imaging applications; SiGe BiCMOS 0.13 μm; W-band low noise amplifier*

1. INTRODUCTION

The advancements in SiGe technology has paved the way to high level of integration with high speed, low-cost, and high temperature resolution for mm-wave ICs [1, 2]. However, this technology still suffers from increased noise and higher power consumption compared with GaAs, InGaAs, and InP [3–6] (see Table 1). In recent years, there has been significant efforts on designing integrated on-chip W-band active phased array systems and TR (transmit / receive) modules for commercial, military, space, and medical purposes requiring high speed data communication. One such area is the use of these radars in automotive applications [9–11]; such as blind side detection and cruise control mechanisms, collision avoidance/mitigation systems, and automated driving units. In addition to automotive applications, other safety / security related field exist in imaging applications [7, 8]; such as concealed weapon-detection, security screening, and video enhancement of low-visibility scenes. Considering the wide range and importance of application fields, high quality, and low cost transceiver units are required. Therefore, LNAs are one of the quality determining components in this case due to their gain, ability of operation in multiple frequencies and noise figure performances in these units.

In this work, measurement results of the fabricated LNA structures to be used in W-band automotive and imaging applications are presented. The chips are built using a low-cost SiGe BiCMOS process providing a high-level of integration. The steps until designing a wideband amplifier are clearly explained by comparing fabricated chips. Finally, a three-stage single-ended ultra-wideband W-band HBT-based LNA is proposed and measurement results are discussed.

2. DESIGN PROCEDURE

There are various topologies with related trade-offs that can be used in LNA design; such as common base/gate, common