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Design of Wideband and High-Gain Slotline Antenna Using Multi-Mode Radiator

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ABSTRACT In this paper, a novel wideband slotline antenna with high gain characteristic is presented by using a multi-mode radiator under the circumstance of the optimized ground plane. The proposed antenna is analyzed from a traditional slot antenna with one full-wavelength radiation mode. Subsequently, two pairs of slot stubs are symmetrically loaded along the arms of the initial antenna near the nulls of the magnetic current of the full-wavelength radiation mode. By suitably choosing the lengths of the loaded stubs, extra two radiation modes can be introduced and merged with the full-wavelength one, resulting in a wide impedance bandwidth with three resonances. Finally, the size of the ground plane and locations of stubs are investigated to suppress the sidelobes and ensure high gain within the impedance bandwidth. For validation, a prototype antenna is fabricated and its electrical performances are measured. The experimental results show that the operating fractional bandwidth (FBW) of the proposed antenna can be effectively increased to 40.8% while keeping the inherent narrow slot structure. Besides, the measured average peak gain and its corresponding ripple within the impedance bandwidth are 6.2 dBi and 1.1 dB, respectively, and the radiation patterns are maintained constant. Compared with the reported works, the proposed design can allow a slotline antenna to achieve high gain and constant radiation patterns in a wide bandwidth simultaneously.

INDEX TERMS High gain, multi-mode radiator, slotline antenna, wideband antenna.

I. INTRODUCTION

Due to the numerous promising features including small size, low profile, and easy integration with other planar and non-planar surfaces, the planar slot antennas have been widely used in various modern telecommunication systems since the 1950s [1]–[3]. As the length of the traditional slot antenna is much longer than its width and only one radiation mode can be employed, such antenna suffers from the inherent narrow impedance bandwidth [4]. To tackle this issue, two types of methods have been proposed. The first one is to decrease the quality of antennas by widening their radiation slot [5]–[7]. For instance, a slot antenna with 120% fractional bandwidth (FBW) has been successfully designed by using an arc-shaped slot and square-shaped feed approach [6]. However, the radiation mechanism of wide-slot antennas is different from the one of traditional slot antennas. Similar to the de-sign of wideband filters and patch antennas by using multi-mode structures [8]–[12], the second method is to introduce extra radiation modes into a single radiator. By employing the fictitious short circuit concept [13], utilizing multipole-slot combination [14], [15], introducing a parasitic resonator or via hole [16], [17], adding extra feedlines [18], and using multi-mode resonance concept [19]–[23], a variety of wideband slotline antennas have been proposed and designed. Although the slot antennas in [13]–[23] can maintain the basic properties of a traditional slot antenna and own wide operating bandwidth simultaneously, their realized gain is either low or unstable. Until now, it is still a great challenge to widen the operating bandwidth of a slotline antenna while ensure its realized gain to be high and stable.

In this paper, a novel wideband slotline antenna with high gain and constant radiation patterns is theoretically studied and designed. In a center-fed slotline antenna with one radiation mode, two pairs of slot stubs are symmetrically

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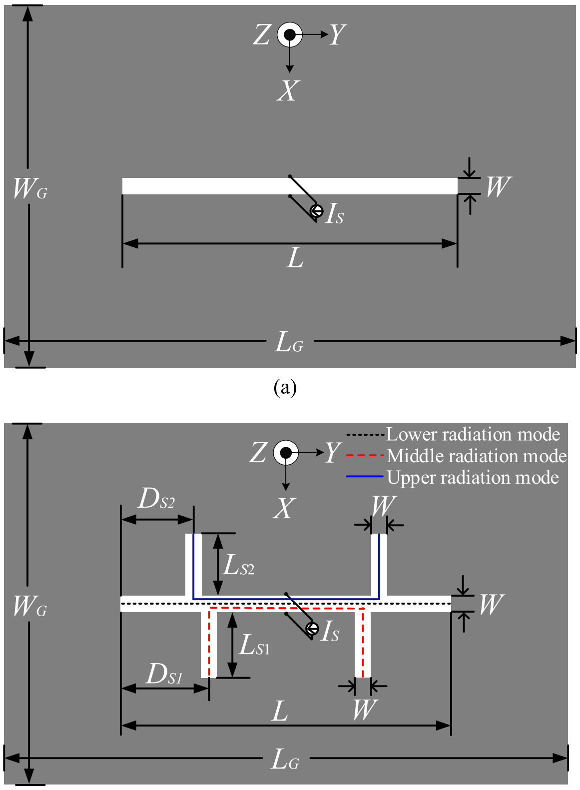


FIGURE 1. Geometries of the (a) initial antenna and (b) proposed slot-line antenna.

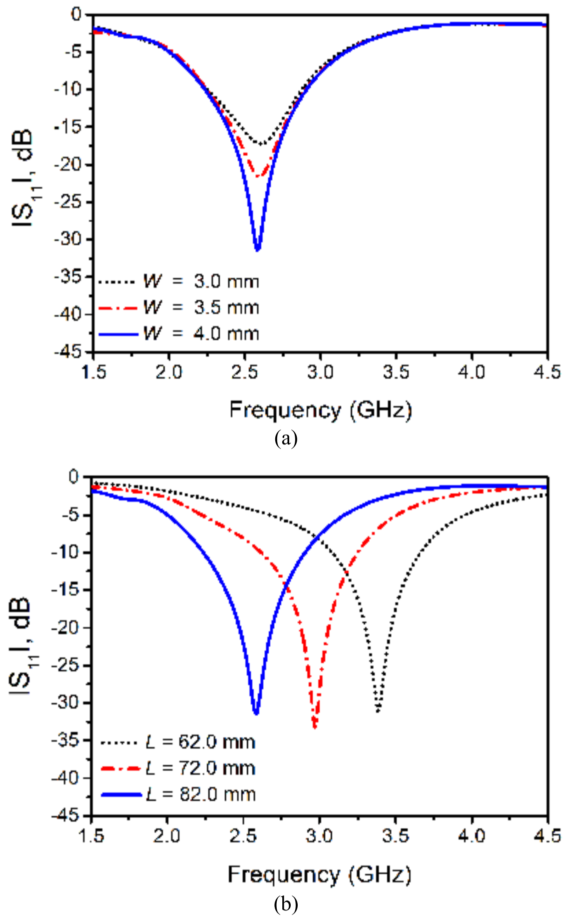


FIGURE 2. Reflection coefficient S_{11} of a center-fed slotline antenna with respect to different (a) W ($L = 82.0$ mm); and (b) L($W = 4.0$ mm). The other parameters are: $L_G = 140.0$ mm, and $W_G = 90.0$ mm.

etched along the bilateral sides near the nulls of the magnetic current of the full-wavelength mode in order to introduce extra two radiation modes. As the introduced modes are controlled by the lengths of the corresponding slot stubs, they can be reallocated in proximity to the full-wavelength one. Hence, the wide impedance bandwidth with three resonances can be realized. To ensure high gain and constant radiation patterns, the sidelobes should be suppressed within the impedance bandwidth. Thus, the size of ground plane and locations of stubs are studied. For verification, a prototype is fabricated and measured. To the best knowledge of authors, the triple-mode wideband slotline antenna simultaneously achieving high gain and constant radiation patterns has not been reported.

II. ANTENNA GEOMETRY AND WORKING MECHANISM

In Fig. 1, the geometries of the initial and proposed antennas are plotted. The initial antenna is a center-fed slotline antenna with length L and width W. The size of ground plane is $L_G \times W_G$. To incorporate this initial antenna for the proposed one, two pairs of symmetrical slot stubs are loaded along the arms of the initial radiator. The widths (W) of the loaded stubs are the same as the one of the initial antennas. For the initial slot antenna, it is used to provide the lower radiation mode and determine the main radiation patterns of the proposed slot antenna. For the loaded stubs, they contribute the middle and upper radiation modes. The loaded stubs are placed near the nulls of the magnetic current generated by the full-wavelength mode of the initial antenna. Introducing the stubs can, on one hand, ensure the radiation patterns of the proposed slotline antenna are stable compared with the ones of the initial antenna near the lower radiation-mode frequency, and on the other hand, improve the radiation patterns of the proposed antenna near the middle and upper radiation-mode frequencies by controlling the magnetic current over the slot of the initial antenna.

After elaborately loading two pairs of symmetrical slot stubs along the arms of the initial antenna and optimizing the ground plane size, extra two radiation modes are introduced. Besides, the magnetic current density at any arbitrary point over the slot of the initial antenna can be maintained in the same level as a half-wavelength slot, which renders an electrically long slotline antenna radiates as a series of half-wavelength slot dipoles with in-phase electrical-field on the slot aperture. In this condition, the proposed antenna can provide some promising features: the impedance bandwidth of the proposed antenna can be widened, while the realized gain is kept in a high and stable level. To better understand the

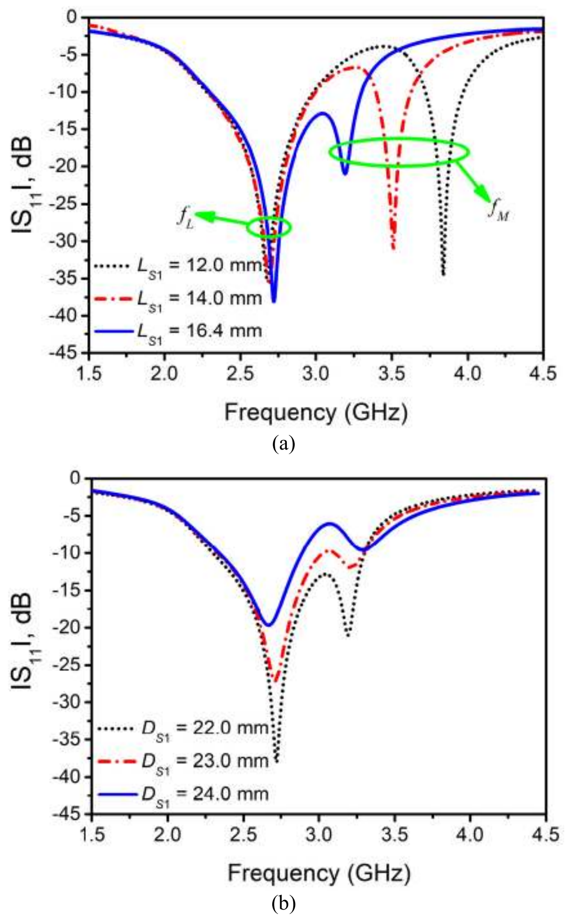


FIGURE 3. Reflection coefficient S_{11} of a dual-band slotline antenna with respect to different (a) L_{S1} (D_{S1} = 22.0 mm); and (b) D_{S1} (L_{S1} = 16.4 mm). The other parameters are: L = 82.0 mm, W = 4.0 mm, L_{S2} = 0, L_G = 140.0 mm, and W_G = 90.0 mm.

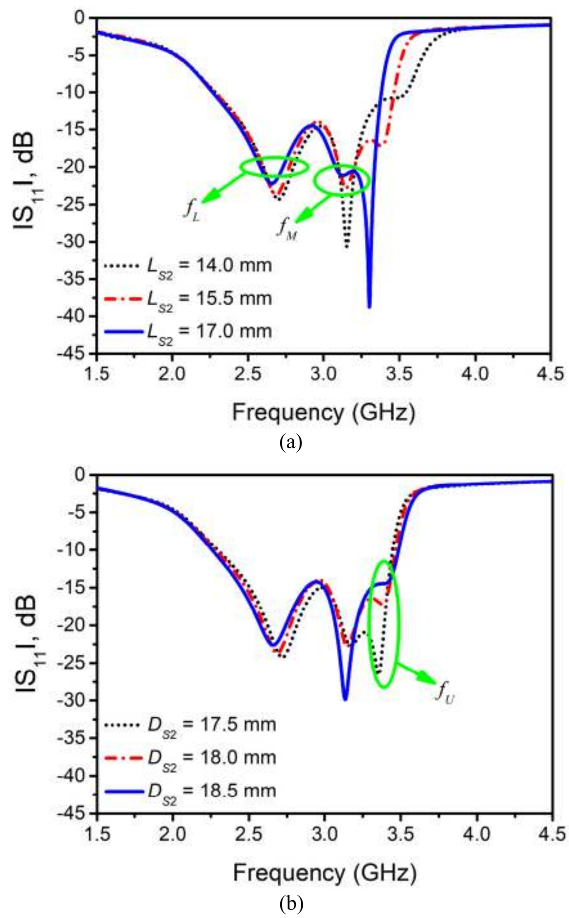


FIGURE 4. Reflection coefficient S_{11} of a triple-mode slotline antenna with respect to different (a) L_{S1} (D_{S2} = 18.0 mm); and (b) D_{S1} (L_2 = 15.5 mm). The other parameters are: L = 82.0 mm, W = 4.0 mm, L_{S1} = 16.4 mm, D_{S1} = 22.0 mm, L_G = 140.0 mm, and W_G = 90.0 mm.

working mechanism, a parametric study of the effects of L, W, L_{S1}, L_{S2}, D_{S1}, D_{S2}, L_G, and W_G on the impedance bandwidth and radiation patterns are discussed in detail in the following two sections.

III. IMPEDANCE BANDWIDTH

In this section, the effects of the aforementioned parameters on the impedance bandwidth are investigated. The proposed antenna is configured on Rogers RO4003C with relative permittivity $\varepsilon_r = 3.38$ and thickness of 0.813 mm. The full- wave electromagnetic solver HFSS is used to simulate the frequency response of its reflection coefficient.

A. EFFECTS OF W AND L

When the stub lengths L_{S1} and L_{S2} equal to zero, the initial antenna is a center-fed and full-wavelength slotline antenna with length L and width W, as shown in Fig. 1(a). The lower radiation mode of the proposed antenna is provided by this initial antenna. The effects of W and L on the lower radiation-mode frequency of the proposed slot antenna, f_L, are shown in Fig. 2. When the initial antenna's width W is much shorter than its length L, the lower radiation-mode frequency f_L is little affected by W, but mainly determined by L. Besides, the relationship between the lower radiation-mode frequency f_L and length L can be approximately written as [24]:

$$f_L \approx \frac{c}{\sqrt{\varepsilon_{re}} \bullet L} \tag{1a}$$

$$\varepsilon_{re} \approx \frac{c_0\varepsilon_r + (2 - c_0)}{2}, 1 < c_0 < 1.6 \tag{1b}$$

where c represents the light speed in free space, and c_0 is a constant varied from 1 to 1.6.

B. EFFECTS OF L_{S1} AND D_{S1}

When only one pair of slot stubs with length L_{S1}, i.e., $L_{S1} \neq 0$ and $L_{S2} = 0$, are symmetrically loaded along the arms of the initial antenna, extra radiation mode will be introduced into the previous single-mode radiator. Similar to the lower radiation mode of the proposed antenna, i.e., full-wavelength one of the initial antennas, the middle radiation mode can be

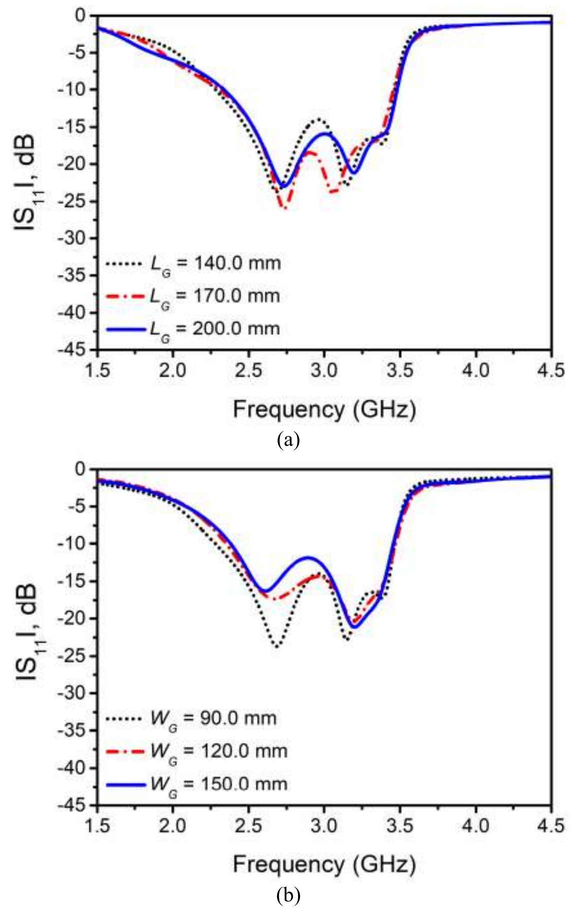


FIGURE 5. **Reflection coefficient S_{11} of a triple-mode slotline antenna with respect to different (a) L_G(W_G = 90.0 mm); and (b) W_G(L_G = 140.0 mm). The other parameters are: L = 82.0 mm, W = 4.0 mm, L_{S1} = 16.4 mm, D_{S1} = 22.0 mm, L_{S2} = 15.5 mm, D_{S2} = 18.0 mm.**

treated as the full-wavelength one of other radiator, which is composed of the loaded stubs and part of the initial antenna. The assumed radiator is marked in Fig. 1(b) (red line). Thus, the newly introduced mode mainly determined by the length L_{S1} and spacing D_{S1}, and can be used to provide the middle radiation mode. Fig. 3 illustrates the effects of the length L_{S1} and spacing D_{S1} on the lower and middle radiation-mode frequencies of the proposed antenna. As seen from Fig. 3(a), the new radiation mode frequency, f_M, tends to move downwards progressively as the stub length L_{S1} increase while the lower one f_L is rarely changed. When L_{S1} equals to 16.4 mm, the lower and middle radiation modes are merged, resulting in a wider impedance bandwidth with two resonances. As the spacing between the end of the initial antenna and slot stubs D_{S1} increases, the middle radiation-mode frequency f_M tends to move upwards progressively while the lower resonance f_L is slightly changed, as shown in Fig. 3(b). In addition, the relationship among the middle radiation-mode frequency f_M, spacing D_{S1}, and length L_{S1} can be approximately expressed as:

$$f_M \approx \frac{c}{\sqrt{\varepsilon_{re}} \cdot (L - 2D_{S1} + 2L_{S1})} \tag{2}$$

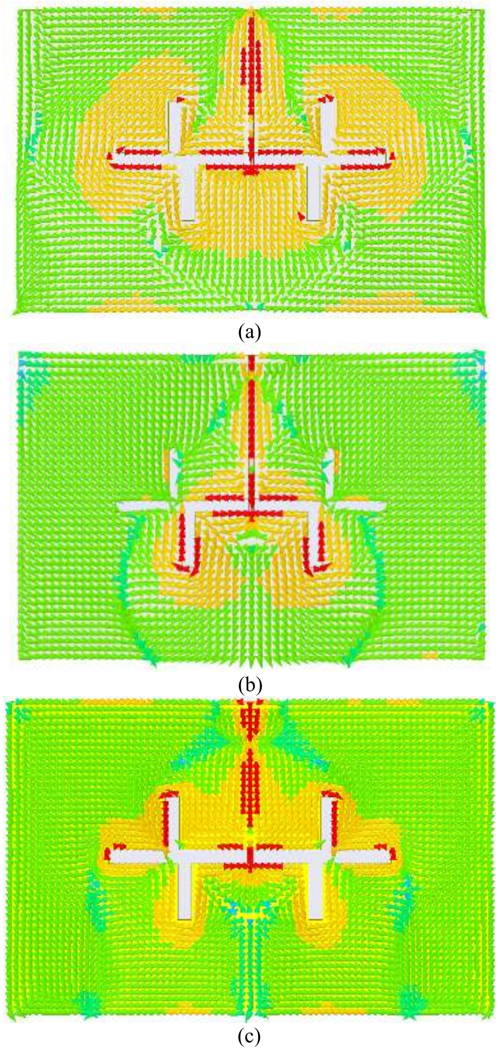
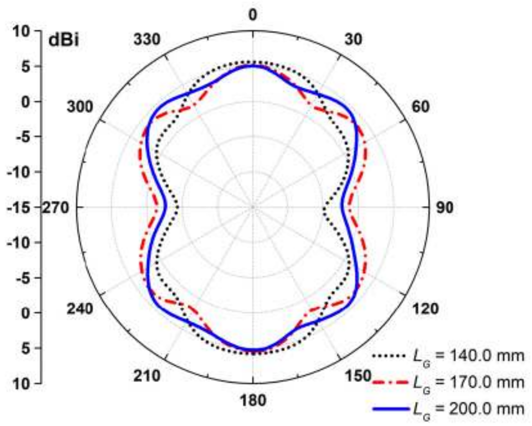


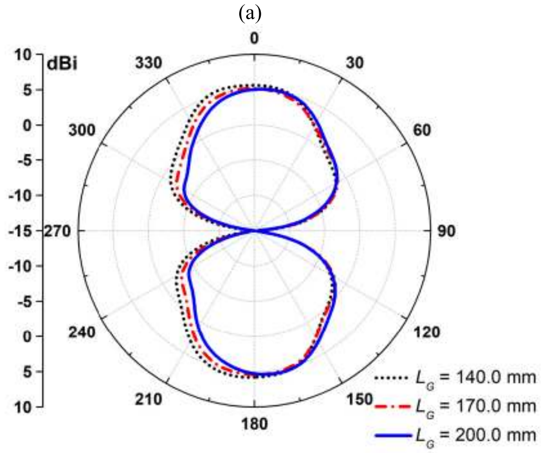
FIGURE 6. **Simulated current distributions of the proposed antenna for (a) lower-radiating mode, (b) middle radiation mode, and (c) upper radiation mode. The parameters are recorded as: L_G = 140.0 mm, W_G = 90.0 mm, L = 82.0 mm, W = 4.0 mm, L_{S1} = 16.4 mm, D_{S1} = 22.0 mm, L_{S2} = 15.5 mm, and D_{S2} = 18.0 mm.**

C. EFFECTS OF L_{S2} AND D_{S2}

When an additional pair of symmetrical stubs with length L_{S2} are loaded on the other side of the former antenna's arms, another radiation mode is introduced into the dual-mode radiator, which has been discussed in Section III-B. Under this condition, $L_{S1} \neq 0$ and $L_{S2} \neq 0$. Analogue to the radiation-modes of the dual-mode antenna, this newly additional mode can be treated as a full-wavelength mode of another radiator, which is formed by the added stubs with length L_{S2} and part of the initial antenna. This assumed radiator is also marked in Fig. 1(c) (blue line). This introduced mode can be used to provider the upper radiation mode of the proposed antenna, and its corresponding frequency, f_U, is mainly determined by the length L_{S2} and spacing D_{S2}. The effects of L_{S2} and D_{S2} on the three radiation-mode frequencies are plotted in Fig. 4. Similar to L_{S1} and D_{S1}, the relationship among the upper radiation-mode frequency f_U, spacing D_{S2}, and length L_{S2}

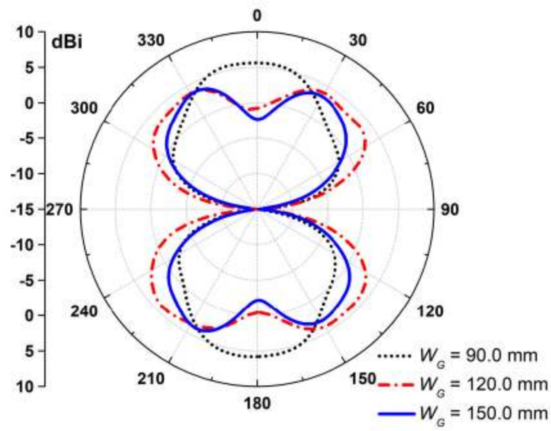


(a)

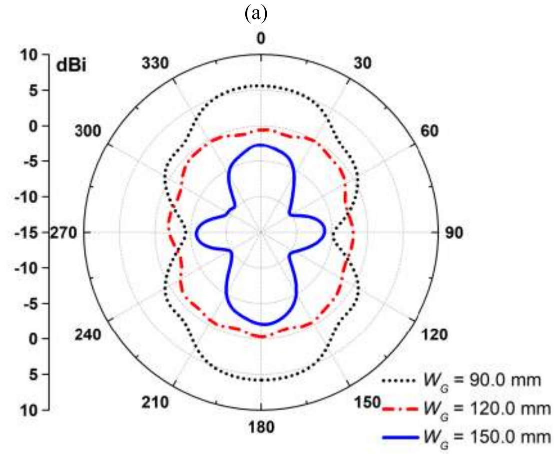


(b)

FIGURE 7. **Simulated radiating patterns of the proposed antenna respect to different L_G @ 3.4 GHz. (a) *E*-plane; (b) *H*-plane. The rest parameters are: $L = 82.0$ mm, $W = 4.0$ mm, $W_G = 90.0$ mm, $L_{S1} = 16.4$ mm, $D_{S1} = 22.0$ mm, $L_{S2} = 15.5$ mm and $D_{S2} = 18.0$ mm.**



(a)



(b)

FIGURE 8. **Simulated radiating patterns of the proposed antenna respect to different W_G @ 3.4 GHz. (a) *E*-plane; (b) *H*-plane. The other parameters are: $L = 82.0$ mm, $W = 4.0$ mm, $L_G = 140.0$ mm, $L_{S1} = 16.4$ mm, $D_{S1} = 22.0$ mm, $L_{S2} = 15.5$ mm, and $D_{S2} = 18.0$ mm.**

can be approximately summarized as

$$f_U \approx \frac{c}{\sqrt{\varepsilon_{re}} \cdot (L - 2D_{S2} + 2L_{S2})} \tag{3}$$

D. EFFECTS OF L_G AND W_G

The effects of L_G and W_G on the impedance bandwidth are illustrated in Fig. 5. As observed from the figure, the impedance bandwidth of the proposed antenna is not affected by the size of ground plane significantly, through the impedance bandwidth becomes slightly narrower with the increase of the width W_G and length L_G.

To better understand the operation principle, the current distributions of the proposed antenna for different radiation modes are shown in Fig. 6. From it, three full-wave radiation modes can be clearly observed in the proposed multi-mode radiator. Hence, the above theoretical analysis can be proved.

IV. RADIATION PATTERNS

For the proposed antenna, its radiation patterns are mainly affected by the size of ground plane and the locations of slot stubs. In the following two sub-sections, the relationships among the radiation patterns and parameters L_G, W_G, D_{S1}, D_{S2} are investigated.

A. EFFECTS OF L_G AND W_G

For the proposed antenna, its ground plane size must be larger than the proposed multi-mode resonator to maintain the basic properties of a traditional slot antenna. However, the radiation patterns of the proposed antenna will become deteriorate when the ground plane size is too big. The reason is: although the width of a center-fed slotline antenna is much shorter than its length and wavelength, the currents are not only confined to the edges of the slots but also spread out over the ground plane. Thus, the size of ground plane should be carefully chosen to ensure the good radiation patterns of the proposed antenna. In this part, we will investigate the effects of length L_G and width W_G on the radiation patterns of the proposed antenna near the upper radiation-mode frequency (3.4 GHz).

The effects of length L_G on the radiation patterns of the proposed antenna are illustrated in Fig. 7. It is apparently that the sidelobes of the proposed antenna slightly becomes larger as the length L_G increases, while antenna gains at the bi-boresight directions (0° and 180°) are almost not affected.

The effects of width W_G on the radiation patterns are shown in Fig. 8. It is obviously that the sidelobes of the

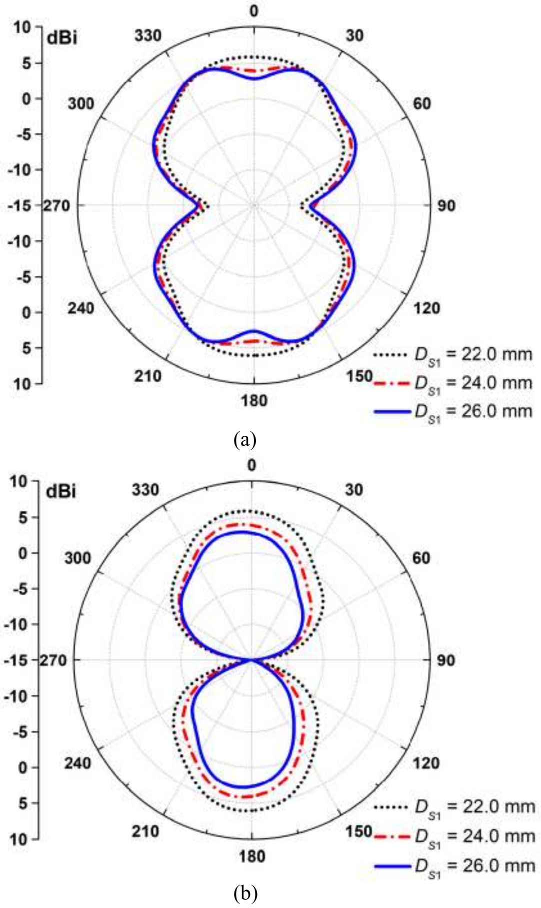


FIGURE 9. Simulated radiating patterns of the proposed antenna respect to different D_{S1} @ 3.15 GHz. (a) E-plane; (b) H-plane. The other parameters are: $L = 82.0$ mm, $W = 4.0$ mm, $L_G = 140.0$ mm, $W_G = 90.0$ mm, $L_{S1} = 16.4$ mm, $L_{S2} = 15.5$ mm, and $D_{S2} = 18.0$ mm.

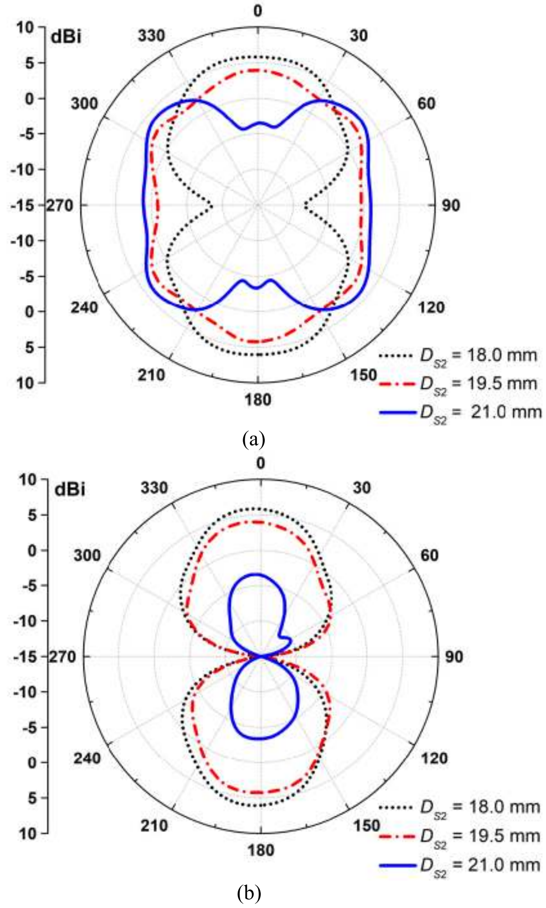


FIGURE 10. Simulated radiating patterns of proposed antenna respect to different W_G @ 3.4 GHz. (a) E-plane; (b) H-plane. The other para-meters are: $L = 82.0$ mm, $W = 4.0$ mm, $L_G = 140.0$ mm, $W_G = 90.0$ mm, $L_{S1} = 16.4$ mm, $D_{S1} = 22.0$ mm, and $L_{S2} = 15.5$ mm.

proposed antenna become higher with the increase of W_G, while the gains at the bi-boresight directions degrade a lot. In particular, the main beams tend to be split in two as W_G enlarging enough. Therefore, the size of ground plane should be suitably chosen for high gain and good radiation patterns.

B. EFFECTS OF D_{S1} AND D_{S2}

As the magnetic current over the slot of the initial antenna will be changed when two pairs of stubs are symmetrically added, the locations of slot stubs should be investigated to improve the radiation patterns of the proposed antenna. At first, the slot stubs should be loaded near the nulls of the magnetic current of the full-wavelength mode appearing at the initial antenna. The reason is that the magnetic current density over the slot of the initial antenna is not affected by the added slot stubs near the lower radiation-mode frequency significantly. Thus, the radiation patterns of the proposed antenna can be kept similar compared with the one of a full-wavelength slotline antenna near the lower radiation-mode frequency. Under this case, the spacing D_{S1} and D_{S2} mainly affect the radiation patterns of the proposed antenna near the middle and upper radiation-mode frequency.

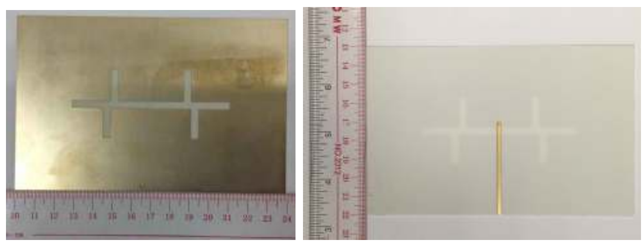


FIGURE 11. Photograph of the prototype antenna fed by a 50-Ω short-ended microstrip line.

The simulated radiation patterns of the proposed antenna in E- and H-planes respect to different D_{S1} and D_{S2} are shown in Fig. 9 and Fig. 10 respectively. The sidelobes become higher as the spacing D_{S1} and D_{S2} increase, while the maximum gain changes smaller. Besides, the maximum gains are not locating at the bi-boresight any more. Therefore, the locations of the loaded slot stubs should be chosen for high gain and constant radiation patterns within the impedance bandwidth.

V. FABRICATION AND MEASUREMENT

To verify the design principle. a prototype slotline antenna is fabricated and experimentally measured. The

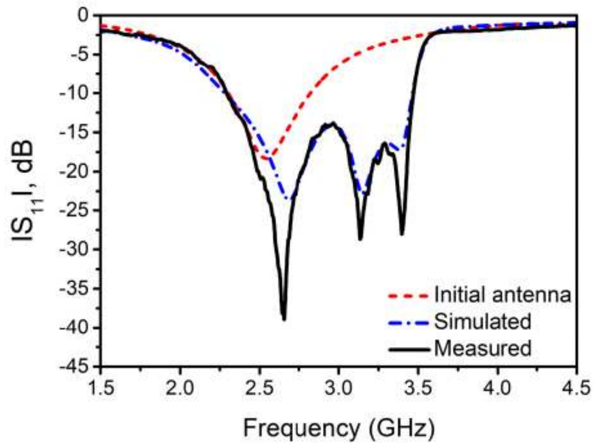


FIGURE 12. Simulated and measured reflection coefficient of the pro-posed triple-mode antenna in comparison with the simulated one of the initial antennas.

proposed slot-line antenna is fabricated on a substrate Rogers RO4003C with thickness of 0.813 mm and relative permittivity of 3.38. The optimized dimensions of the proposed antenna can be recorded as: $W = 4.0$ mm, $L = 82.0$ mm, $W_G = 90.0$ mm, $L_G = 140.0$ mm, $L_{S1} = 16.4$ mm, $D_{S1} = 22.0$ mm, $L_{S2} = 15.5$ mm, $D_{S2} = 18.0$ mm. The top- and bottle-view photographs of the fabricated antenna are shown in Fig. 11, which is fed by a 50-Ω microstrip line.

The simulated and measured reflection coefficient S_{11} of the proposed antenna are demonstrated in Fig. 12. The simulated results of the initial antenna are also concluded. It is noted that the measured and simulated results are in good agreement with each other. As predicted in the theoretical analysis above, three resonances can be clearly observed within its impedance bandwidth, locating at 2.66 GHz, 3.14 GHz, and 3.40 GHz respectively. The measured $|S_{11}|$ is lower than -10 dB over a frequency range from 2.30 GHz to 3.48 GHz. Compared to a traditional center-fed slot antenna with $L_{S1} = L_{S2} = 0$, i.e., the initial antenna, the fractional bandwidth (FBW) of the proposed antenna can be significantly increased from 17.9% to 40.8%.

In Fig. 13, the simulated and measured radiation patterns of the proposed antenna at 2.4 GHz and 3.4 GHz are

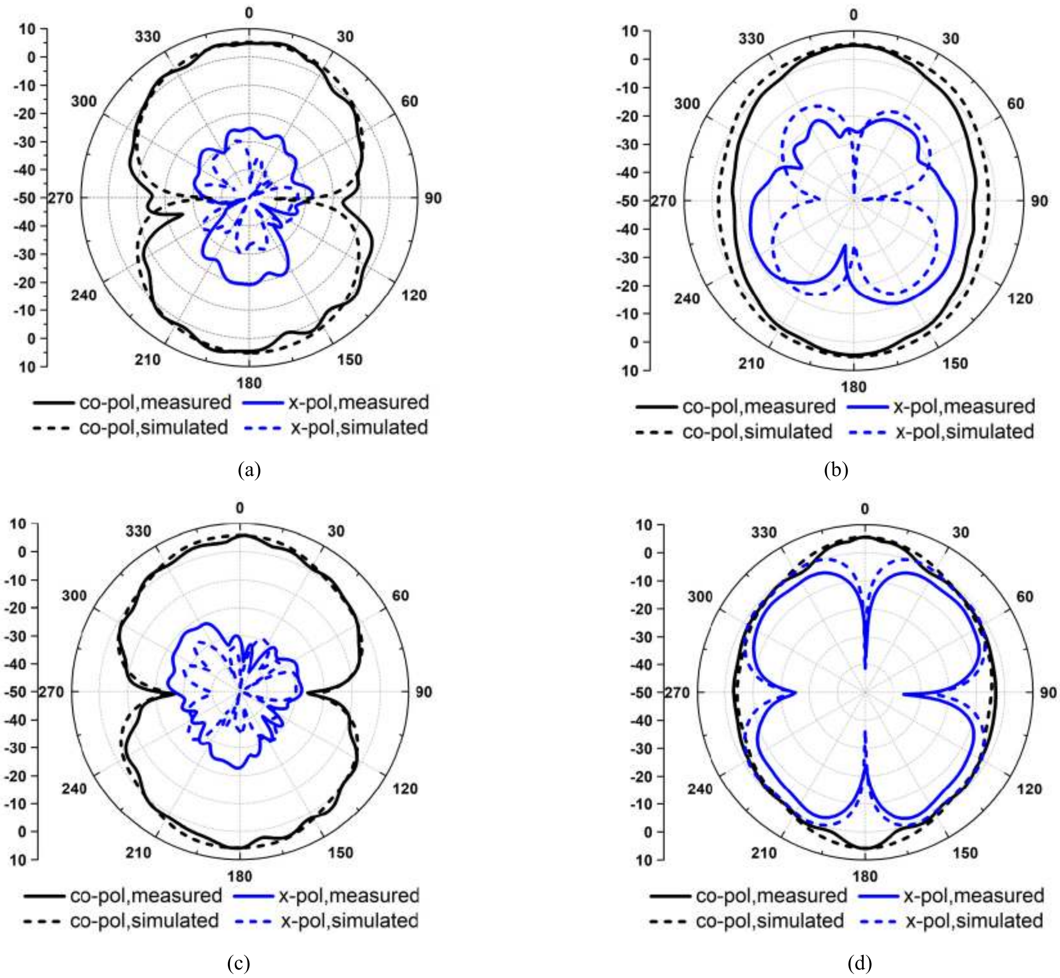


FIGURE 13. Simulated and measured radiation patterns of the proposed antenna: (a) *E*-plane, @2.4 GHz; (b) *H*-plane, @2.4 GHz; (c) *E*-plane, @3.4 GHz; (d) *H*-plane, @3.4 GHz.

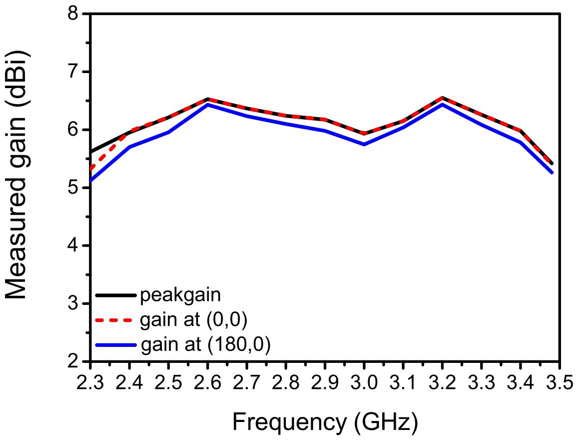


FIGURE 14. Measured gain of the proposed slotline antenna, including peak gain, forward boresight gain at $\varphi = 0°$, $\theta = 0°$ and backward bore-sight gain at $\varphi = 0°$, $\theta = 180°$.

TABLE 1. Comparison with Previous Works.

	Length-to-width ratio	Numbers of Poles	FBW (%)	Gain (dBi)	Flatness (dB)
[11]	2.73	2	47.29	3.0	N/A
[13]	4.8	2	32.00	N/A	N/A
[17]	5.17	3	57.14	2.0	3.5
[18]	20.5	2	32.70	4.0	6.0
This Work	20.5	3	40.83	6.2	1.1

illustrated. It is obviously that the measured and simulated results are in good agreement with each other. In addition, the sidelobes are effectively suppressed within the impedance bandwidth, and the co-polarization radiation patterns are kept constantly. As the loaded slot stubs are not symmetrical about y-axis of the initial radiator, the cross-polarization patterns at H-planes deteriorate near the middle and upper radiation-mode frequencies. The measured gains of the proposed antenna are shown in Fig. 13. It can be observed that the proposed antenna owns a high and stable gain within its impedance bandwidth at the bi-boresight direction. The average peak gain is 6.2 dBi, and the corresponding ripple is 1.1 dB. Due to the asymmetry of the substrate and feedline, the gain at the forward boresight direction (0°) is slightly smaller than the one at the backward boresight direction (180°). Due to the bend of the PCB and unexpected diffraction from the upper and lower edges of the finite ground plane, the measured maximum gains of the proposed is slightly shifted from the forward boresight direction at 2.30 GHz.

To highlight the significance of this study, a comparison with some previous work is presented in Table 1. It can be noticed that the proposed wideband slot antenna not only owns a high and stable gain within its impedance bandwidth, but also keeps the basic properties of the traditional slot antennas at the same time.

VI. CONCLUSION

In this work, a novel slotline antenna with high gain and constant radiation patterns is theoretically investigated and designed. By symmetrically loading two pairs of slot stubs along the arms of a center-fed slotline antenna, and suitably choosing the length and locations of the loaded slot stubs, three radiation modes can be excited, resulting in a wide impedance bandwidth with three resonances. It is found that the proposed slotline antenna could realize an FBW up to 40.8% compared with 17.9% of a single-mode radiator. Besides, high and stable peak gains can also be experimentally realized within the impedance bandwidth. The proposed principle and design approach are beneficial to the exploration of other wideband, high gain, and multi-mode slotline antennas with constant radiation patterns.

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