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A Compact Multi-Band Monopole Antenna for 5G NR Coal Mine Applications

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ABSTRACT: At present, 5G technology is gradually applied in coal mine applications. Under this circumstance, a microstrip patch antenna based on a multi-branch structure is firstly designed which can operate at the allocated 5G NR (2.51–2.68 GHz, 3.40–3.60 GHz, and 4.80–4.90 GHz) for coal mine. Nevertheless, this antenna exhibits a large size, even at the lowest operating frequency ($0.41\lambda \times 0.41\lambda$ at 2.51 GHz). To reduce the size of the antenna, the three branches are separately bent into C, S, and L shapes from left to right, and a size of $0.33\lambda \times 0.33\lambda$ at 2.51 GHz is realized, i.e., 35% size reduction is achieved. To further achieve a compact size, a new structure is designed. In particular, two inverted J-shaped branches and a rectangular branch acting as radiating portion are respectively arranged and optimized to cover the above three frequency bands where the rectangular branch is located between the two inverted J-shaped branches. To enhance the impedance matching characteristic of the antenna, a T-shaped structure is loaded on the other side of the substrate. The resultant size of this antenna is $0.20\lambda \times 0.16\lambda$ at 2.51 GHz, which is around 81% and 71% smaller than the first and second designed antennas. The measured results of the antennas are in good agreement with the simulated ones. Therefore, the third antenna is a good candidate for coal mine applications due to its relatively small size, low profile, and easy integration with equipment.

1. INTRODUCTION

With the demand of intelligent coal mining, the 5G technique possessing the advantages of higher transmission rate, lower latency, and higher reliability has been gradually applied in some of the large coal mine [1, 2]. 5G NR has been assigned for coal mine applications including three frequency bands, which are 2.51–2.68 GHz, 3.40–3.60 GHz, and 4.80–4.90 GHz [3, 4]. As the front end of an electronic equipment, an antenna simultaneously operating at these three bands can guarantee the applications of 5G technology in coal mine. Therefore, it is of significant worth to design such an antenna with high performance.

In the state-of-the-art, numerous investigations have been conducted to explore the realization of a multi-band antenna [5–16]. In [5–7], multi-band antennas are designed on the basis of ultra-wide band (UWB) antennas by notching out of some specified frequency bands. Stacking some parasitic structures around the resonant frequency is commonly utilized in the design of multi-band antennas [8, 9]. Metamaterials are also adopted in the design of multi-band antennas [10–12]. Through the literature review, it is found that planar monopole structure is very prevailing in the design of a multi-band antenna due to the advantages of low profile, low cost of fabrication, and ease of integration with electric equipment. By loading or etching out different shapes, such as square rings and T-shaped strips [13], Y-shaped branch and L-shaped slot [14], L-shaped branches [15], inverted T-shaped and E-shaped branches [16], a multi-band antenna can be easily designed.

Meanwhile, it is known that an antenna with compact size is always popular since it can save space for other components in an equipment. After literature review, it is found that typical approaches to miniaturize antenna size include adopting shorting pins [17–20], bending technique [21–23], loading metasurface structures [24–26], accepting fractal structures [27–29], etc. In particular, a U-slot patch antenna is halved by loading shorting pins in its center [17]. Combining with a shorting pin and a ground slot, a miniaturized triple-band implantable antenna for biomedical applications is presented in [18]. In [21], size reduction is achieved by employing a modified meandered slot. In [22], size miniaturization is accomplished by bending a straight monopole to create a meandered antenna. In [24], a miniaturized wideband antenna is presented by using a hybrid L/T-shaped metasurface structure. In [25], the miniaturization of a patch antenna is extensively explored by loading a metasurface. In [27], a modified 2-order Minkowski structure is loaded to reduce the size of a magneto-electric dipole antenna, and 57.1% aperture size reduction is achieved. In [28], the theories of Koch and Sierpinski are combined to realize a size reduction up to 77.1% for a square patch antenna.

According to the above descriptions, it can be easily found that adopting a multi-branch structure is an effective method in designing a multi-band antenna, and bending technology can reduce the size appropriately. Under this circumstance, Ant. 1 is firstly designed which can simultaneously operate at the three bands of the allocated 5G NR. Then the three branches of Ant. 1

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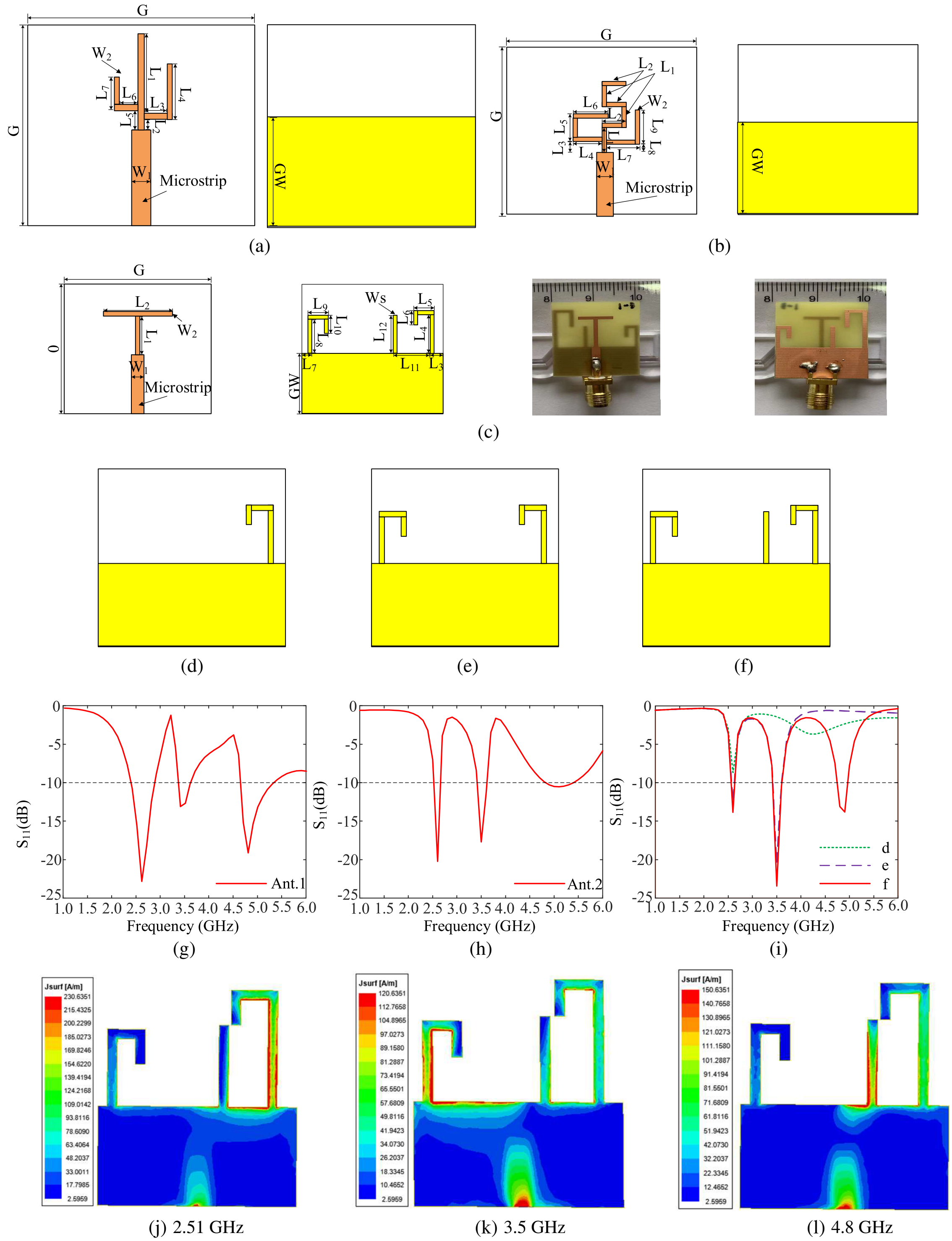

FIGURE 1. (a)–(c) Ant. 1–Ant. 3, structures of the three designed antennas. (d)–(f) Design procedures of the third designed antenna. (g)–(i) $|S_{11}|$ of the three designed antennas. The current distributions of Ant. 3, at (j) 2.51 GHz, (k) 3.5 GHz, (l) 4.8 GHz.

TABLE 1. Detailed parameter values of Ant. 1 (Unit: mm).

L_1	L_2	L_3	L_4	L_5	L_6
21.5	1.5	4	13	3	2
L_7	GW	G	W_1	W_2	H
9	25	50	1.5	1	0.8

TABLE 2. Detailed parameter values of Ant. 2 (Unit: mm).

L_1	L_2	L_3	L_4	L_5	L_6	L_7
5.6	5.2	0.8	5.8	5.6	6.4	0.4
L_8	L_9	G	W_1	W_2	GW	H
6.3	8	40	1.5	1	10	0.8

TABLE 3. Detailed parameter values of Ant. 3 (Unit: mm).

L_1	L_2	L_3	L_4	L_5	L_6	L_7
9	7.2	2	10.7	4.7	2.5	1.9
L_8	L_9	L_{10}	L_{11}	L_{12}	L	G
7.7	3.8	3.5	4.9	8.2	25	20
W_s	W_1	GW	W_2	H		
1	1.5	10	1	0.5		

are separately bent into C, S, and L shapes from left to right to form Ant. 2. Compared to the first antenna with multi-branches and the second antenna with bending technology, a novel microstrip structure is designed to realize a more compact size under the constraint of operating at the 5G NR. In particular, two inverted J-shaped branches and a rectangular structure acting as radiating elements are loaded on the same side of the substrate where the rectangular branch is located between the two inverted J-shaped branches, thus generating three required operating frequency bands. Meanwhile, a T-shaped branch is loaded on the other side of the substrate to enhance the impedance matching characteristic. The resultant size of this antenna is $0.20\lambda \times 0.16\lambda$, which is 81% and 71% smaller than the first and second antennas. To verify the performance of the designed antenna, the prototype of the third antenna is manufactured and measured. The measured results of the third antenna are in good agreement with the simulated ones.

2. ANTENNAS DESIGN AND SIMULATED RESULTS

Figures 1(a)–(c) illustrate the structures of the designed three antennas. Specifically, Figure 1(c) on the left side are the simulated models, while those on the right side are the corresponding prototypes. As can be clearly seen in these figures, three antennas are all composed of radiation branches, a $50\,\Omega$ microstrip feed line, and a metal ground. Each antenna is printed on an FR4 substrate ($\varepsilon_r = 4.4$ and $\tan\delta = 0.02$) with a thickness of H.

The most compact antenna is Ant. 3, which uses a novel microstrip structure. In particular, a T-shaped branch is loaded on one side of the substrate to enhance the impedance matching characteristic. Figures 1(d)–(f) illustrate the three design steps on the other side of substrate of the Ant. 3. First of all, loading an inverted J-shaped branch is depicted in Figure 1(d). In the sequel, load a new inverted J-shaped branch to the left of the previous branch presented in Figure 1(e). In the last step, a new rectangular branch is loaded in the middle of the two inverted J-shaped branches to form Ant. 3 as shown in Figure 1(f). The resultant size of this antenna is $0.20\lambda\times0.16\lambda$, which is 81% and 71% smaller than the first and second antennas. As can be seen from Figures 1(g)–(i), each of the three antennas can operate at the three bands of the allowed 5G NR, i.e., 2.51–2.68 GHz, 3.4–3.6 GHz, 4.8–4.9 GHz. The corresponding parameters of the three antennas after optimization are respectively listed in Tables 1 to 3.

To better understand the operating principle of Ant. 3, current distributions are provided at three frequencies. In particular, the simulated current distributions at 2.51 GHz, 3.5 GHz, 4.8 GHz are presented in Figures 1(j)–(l). As can be observed from Figure 1(j), the maximum current intensity appears on the right inverted J-shaped branch at 2.51 GHz. At 3.5 GHz, the current is concentrated in the left inverted J-shaped branch as depicted in Figure 1(k). At 4.8 GHz, current is distributed mainly on the rectangular branch as shown in Figure 1(l). The current distributions are in good agreements with the simulated $|S_{11}|$ provided in Figure 1(i).

3. EXPERIMENTAL RESULTS

In order to experimentally validate the simulation results of the third antenna, the structure of the planar multi-band antenna is fabricated and tested with a vector network analyzer (PNA-X N5244A). The simulated and measured $|S_{11}|$ of the third monopole antenna are presented in Figure 2(a). As can be seen from Figure 2(a), good agreement is achieved for the third antenna, and the third antenna can operate at the three bands of the allowed 5G NR, i.e., 2.51–2.68 GHz, 3.4–3.6 GHz, 4.8–4.9 GHz. Namely, the third antenna can cover the commercial coal mining 5G NR bands. The corresponding gain of the third antenna is provided in Figure 2(b). It is observed that the measured average gain of the third antenna is 1.21 dBi. Besides, it is seen that the simulated and measured results are also in good agreements for the gain of the third antenna.

The normalized simulated and measured radiation patterns of the third antenna are plotted in both E- and H-planes at different frequencies of 2.51 GHz, 3.5 GHz, and 4.8 GHz, as depicted in Figures 2(c)–(e). It is obviously seen from these figures that the third antenna shows a nearly omnidirectional radiation in the H-plane and bidirectional patterns in the E-plane at all of the three desired operating frequencies, and measured and sim-

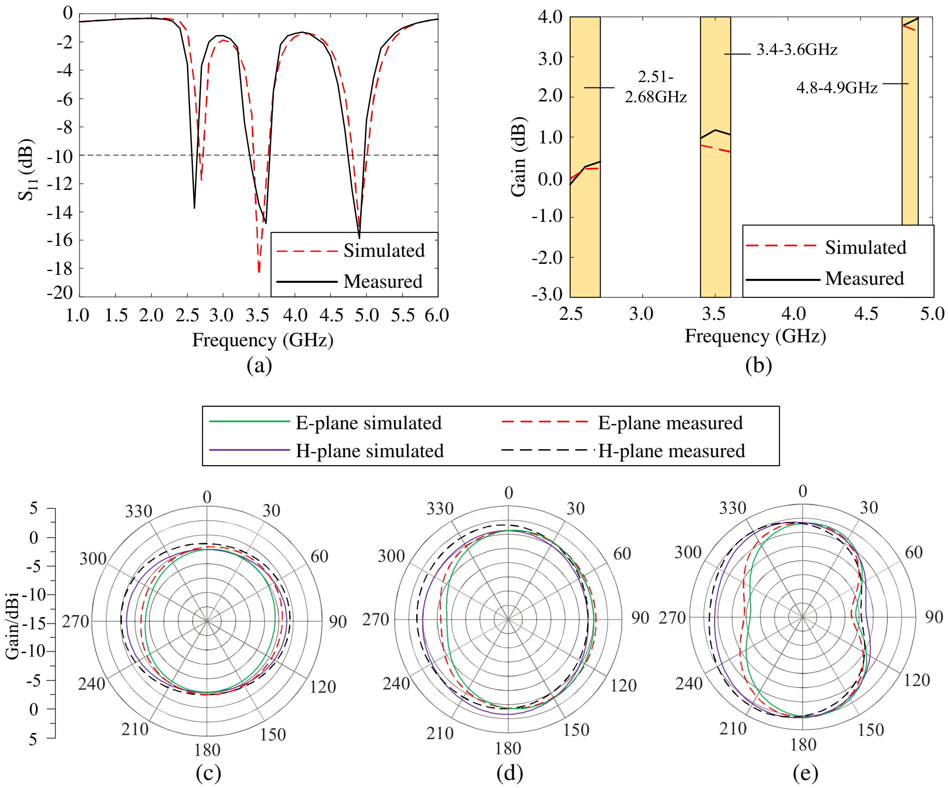

FIGURE 2. (a) Simulated and measured $|S_{11}|$ of the third antenna. (b) Simulated and measured gain of the third antenna. Simulated and measured radiation patterns of the third antenna at (c) 2.51 GHz, (d) 3.5 GHz, (e) 4.8 GHz.

TABLE 4. Comparison of designed antennas with other available antennas.

Ref.	Antenna Size (mm^2)	Electrical Size	IBW (GHz)	Operating bands
[5]	21×30	$0.48\lambda \times 0.69\lambda$	3.3–6.75; 8.5–10.15	Dual
[6]	42×50	$0.48\lambda \times 0.57\lambda$	3.3–3.8; 5.15–5.825; 7.1–7.9	Triple
[7]	32×32	$0.30\lambda \times 0.30\lambda$	2.8–2.85 GHz; 3.32–3.76 GHz; 5.9–10.6 GHz	Triple
[13]	33×17	$0.27\lambda \times 0.14\lambda$	2.41–2.54; 3–6.65	Dual
[14]	45×65	$0.22\lambda \times 0.35\lambda$	1.56–1.62; 1.98–2.08; 2.50–2.63	Triple
[15]	18×33	$0.15\lambda \times 0.27\lambda$	1.765–2.695; 3.01–3.91; 5.11–6.055	Triple
Third antenna	25×20	$0.20\lambda \times 0.16\lambda$	1.87–2.66; 3.33–3.69; 4.71–5.08	Triple

ulated results are similar within the operation bands. The measured peak gains of Ant. 3 > 0 dBi are achieved in each resonance. In addition, the pattern of H plane is approximately circular, and the signal coverage is good.

Antenna sizes of the second antenna and third antenna are reduced by 35% and 81%, respectively, compared with the first antenna. Besides, the designed triple-frequency antenna in terms of electrical size and operating bands has been compared with other available antennas as enlisted in Table 4. As shown in Table 4, it is also seen from the table that the designed third antenna has certain advantages such as more frequency bands than [5, 13], relatively small size, and simple structure. The third antenna possesses a compact electrical size compared to [6, 7, 14, 15] in comparison table.

4. CONCLUSION

In this article, a microstrip patch antenna based on a multi-branch structure is firstly designed which can operate at the allocated 5G NR (2.51–2.68 GHz, 3.40–3.60 GHz and 4.80–4.90 GHz) simultaneously. This antenna also exhibits a large size of $0.41\lambda \times 0.41\lambda$, where λ is the wavelength at the lowest operating frequency of 2.51 GHz. Considering the requirement of miniaturization of antenna in wireless communication system, bending technology is used to reduce the antenna size. The second one is realized by bending the three branches of the first antenna into C, S, and L shapes from left to right, and a size of $0.33\lambda \times 0.33\lambda$ at 2.51 GHz is realized, i.e., 35% size reduction is achieved. Because of the limited size reduction by bending technology, a new structure is designed. The third one is designed to make it more miniature by loading a T-shaped branch on the one side, and two inverted J-shaped branches and a rectangular branch acting on the other side of the substrate. The resultant size of this antenna is $0.20\lambda \times 0.16\lambda$, which is 81% and 71% smaller than the first and second antennas. Either of the three proposed antennas shows good performance with an acceptable gain over the desired frequency bands. Compared with the first two antennas, the third antenna is more practical for intelligent coal mines because of its most compact structure. The designed third antenna is a good candidate for coal mine applications due to the advantages of low profile, low cost, and ease of integration with the device.

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