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A Novel Compact Dual Open-Sleeve Multiband Antenna for Coal Mine Communication with Large Frequency Ratio

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ABSTRACT: In this paper, a novel compact dual open-sleeve multiband monopole omnidirectional antenna specifically designed for coal mine communication is proposed. Its core innovation lies in the structural optimization that enables multiband operation across a wide frequency range. To adapt to the confined mine tunnel environment, the antenna employs an ultra-small diameter design, which poses significant challenges for impedance matching below 1 GHz. Additionally, the substantial electrical size disparity between the sub-1 GHz and above-5 GHz bands further complicates multiband matching. The proposed open-sleeve monopole antenna consists of top and bottom dual open-sleeve structures along with resistive loads. Four length-adjustable thin copper columns replace the conventional sleeve, forming an open-sleeve structure. Through coordinated tuning of the two longest columns in the bottom open-sleeve structure together with the resistor loads, the antenna achieves favorable impedance matching in the low-frequency band (0.515–0.845 GHz). Furthermore, by adjusting the dimensions of the second-longest and shortest columns in the bottom open-sleeve, the antenna covers the 1.370–1.485 GHz and 4.660–6.000 GHz bands, respectively, while tuning the central monopole enables matching in the 2.210–2.525 GHz band. Ultimately, through independent adjustment of the four bottom column lengths and coordinated optimization of the resistor loads, the antenna effectively operates in four bands: 0.515–0.845 GHz, 1.370–1.485 GHz, 2.210–2.525 GHz, and 4.660–6.000 GHz, with the ratio between the lowest and highest operating frequencies reaching 10 : 1. Simultaneously, the top open-sleeve structure enhances the antenna's gain in the low-frequency band. Measured results show good agreement with simulation, demonstrating a gain of 1.21–4.59 dBi and radiation efficiency of 44%–77.7%. Moreover, the antenna exhibits omnidirectional radiation characteristics. This antenna shows potential for coal mine communication applications and also supports WLAN (2.4/5.2/5.8 GHz), WiMAX (2.3/5.8 GHz), and 5G NR (n5/n12/n28/n71/n79).

1. INTRODUCTION

Wireless communication technology is an important means in the coal mine environment. The optimal communication frequency bands for mines with different cross-sections are 580–600 MHz, 806–826 MHz, 1427.9–1447.9 MHz, 2401.5–2481.5 MHz, and 5150–5600 MHz [1]. Moreover, the 590 and 810 MHz frequency bands have good signal penetration, suitable for long-distance communication. The 1.4 GHz frequency band balances penetration and data rate, used for positioning systems. The 2.4 and 5.5 GHz frequency bands support high-speed transmission, suitable for short-range communication, and combined with the narrow coal mine environment, the compact multiband omnidirectional radiation mine antenna has aroused great interest among engineers and researchers. There are various types of multiband antennas, such as dipole antennas [1–4], loop antennas [5–7], and monopole antennas [8–16, 19–24]. Monopole antennas are widely used in multiband designs due to their wide bandwidth and omnidirectional coverage advantages. The design of multiband monopole antennas has been extensively studied in recent years. The tri-band antennas are formed by etching L-shaped and U-shaped slots in a rectangular patch, sequentially introducing L-shaped slots and reactive loading, etching two F-shaped slots, optimizing the current path to create circular loops, and etching inverted U-shaped slots, square ring slots, and interdigital inductor slots on the patch and feedline [8–12]. A miniaturized single-feed patch antenna is proposed, utilizing edge-loaded vias and etched slots to achieve qual-band operation. The design attains a 60% size reduction with stable radiation patterns [13]. A dual-band monopole antenna with dual sleeves has been proposed to form a short circuit between the two sleeves at low frequency [14]. Additionally, another antenna achieves dual-band notch characteristics by combining a rectangular slot in the radiator with a folded stepped resonator embedded in the ground plane [15]. A compact multiband antenna integrating defected ground structure (DGS) and patch slits is proposed, generating six distinct bands for 5G/X-band use. It features a peak gain up to 6.48 dBi within a minimal footprint of $0.35\lambda_0 \times 0.35\lambda_0$ [16].

The aforementioned studies on multiband antennas have mainly focused on antennas above 1 GHz. However, actual tests on frequency selection and optimization for underground mine wireless transmission show that in certain coal mine tunnels, such as auxiliary transport tunnels and comprehensive mining tunnels, the optimal operating frequency range is usually below 1 GHz [17, 18]. Therefore, covering frequencies below 1 GHz is essential for coal mine communications. At the same time, the large electrical size difference between frequencies below 1 GHz and above 5 GHz makes it difficult to achieve

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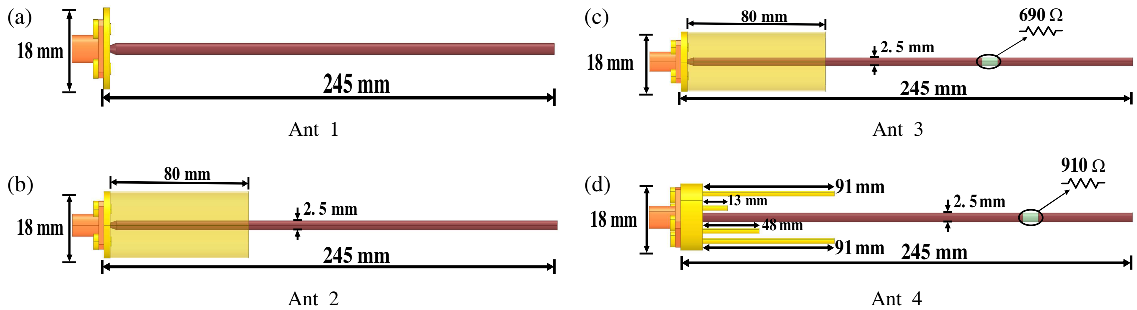


FIGURE 1. The formation process of the single open-sleeve antenna. (a) Whip antenna. (b) Whip antenna with traditional sleeve. (c) Whip antenna with traditional sleeve and resistive loading. (d) Whip antenna with novel open-sleeve.

good multi-band matching within a very small lateral size. To improve antenna impedance matching, sleeve and resistor loading have been proposed in the literature. A wideband dual-sleeve antenna has been developed to achieve extended bandwidth [2]. A sleeve monopole antenna with a choke structure and single-sleeve structure, applying top-loading technique, is proposed for broadband wireless communication applications. It effectively broadens the impedance bandwidth to 0.24–0.95 GHz [19]. In addition, a wideband coverage ranging from 30 to 512 MHz has been realised using inductor/resistor loading circuits [3], and a broadband whip antenna suitable for the VHF/UHF bands has been realized through multi-stage passive loading and a wideband impedance matching network [20].

Meanwhile, current literature addressing the study of coal mine communication antennas include: a coal mine antenna using six cascaded rectangular rings has been proposed to improve communication performance in coal environments [5], while another design employs six folded dipoles specifically for mining applications [4]. For improved Through-the-Earth communication in coal mines, a novel antenna based on a multi-turn planar Archimedean spiral ring structure is proposed. The design enables enhanced magnetic field penetration along with a 50% reduction in size [7]. To achieve miniaturization, printed inverted-F and L-shaped structures have been utilized in antenna designs for coal mine systems [21]. Significant size reduction of multi-band microstrip antennas has also been gradually realized through multi-branch folding, the combination of radiating and non-radiating branches, and T-shaped loading [22]. Furthermore, a quad-band multiple-input multiple-output (MIMO) antenna has been developed by integrating a monopole with multiple L-shaped branches, forming a quadrilateral multi-branch configuration [23]. A dual-band high-isolation MIMO antenna is proposed for coal mine 5G new radio (NR) systems. Utilizing a dual-tooth monopole antenna with an adjustable LC network structure, it significantly enhances communication performance [24].

In this paper, Section 2 discusses the basic structure of the proposed antenna. Section 3 presents the proposed antenna's fabrication and measurement.

2. ANTENNA DESIGN

The target is to design a multiband omnidirectional antenna covering 580 $\sim$ 600 MHz, 806 $\sim$ 826 MHz, 1427.9 $\sim$ 1447.9 MHz, 2401.5 $\sim$ 2481.5 MHz, and 5150 $\sim$ 5600 MHz [1]. The design idea of antenna is as follows:

(1) First, based on the whip antenna, the traditional sleeve structure and resistor loads are introduced to cover the two lower bands of the five coal mine communication bands.

(2) Adjusting the traditional sleeve and resistor loads alone failed to achieve five-band impedance matching. Therefore, an open-sleeve structure composed of four bottom columns with different lengths is proposed, in which each column controls a specific operating frequency band. By jointly tuning the four columns and introducing resistor loading, effective impedance matching across five frequency bands is achieved. However, simulations indicate that the antenna exhibits low gain in the low-frequency bands.

(3) Finally, another top open-sleeve structure is added to balance the gain at the center frequencies of the five bands, ensuring that the gain at the center frequencies are all greater than 0 dBi.

All designs are discussed in detail in Sections 2.1–2.3.

2.1. Initial Whip Sleeve Antenna

To fit within the narrow coal mine tunnels, the whip antenna is made longer to excite higher-order resonance modes, while its diameter is reduced to cover multiple frequency bands. The whip antenna (Ant 1) shown in Figure 1(a) is the initial structure of the design. The blue dotted line in Figure 2 represents the S_{11} of Ant 1. When antenna diameter is small, multiple narrow resonant bands appear between 1 and 5 GHz. However, below 1 GHz, poor impedance matching prevents resonance. To improve impedance matching in the low-frequency band, sleeve structure and resistor loads are effective methods. As shown in Figure 1(b), Ant 2 adds a grounded sleeve to the design of Ant 1. Furthermore, a resistor is added to Ant 2, as shown in Figure 1(c).

Figure 2 illustrates the reflection coefficients of three antennas: Ant 1 (blue dotted line), Ant 2 (purple solid line), and Ant 3 (red dashed line). The initial whip antenna demonstrates potential for multiband resonance but exhibits a narrow impedance

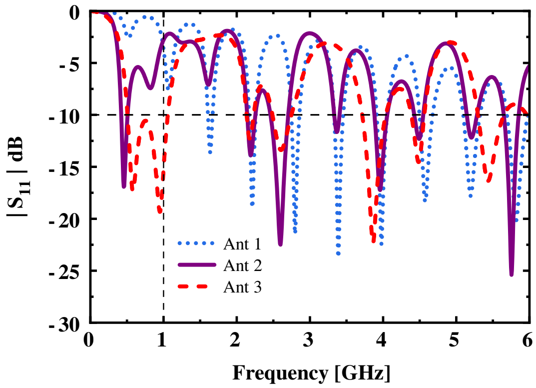


FIGURE 2. S_{11} of Ants 1, 2, and 3.

bandwidth. Adding a traditional sleeve structure to Ant 1 lowers the minimum resonance frequency but does not significantly improve the bandwidth. Consequently, resistor load is introduced to optimize the impedance matching of Ant 3, resulting in a bandwidth of 540 MHz (69.2%, 0.51–1.05 GHz) and improved impedance matching at lower frequencies.

2.2. Antenna with Open-Sleeve Structure at the Bottom

For a multiband antenna with a frequency ratio of 10 (0.55–5.5 GHz), traditional sleeve structures and resistor loads fail to achieve impedance matching. This paper introduces a novel open-sleeve structure with resistor loads (Figure 1(d)). The traditional sleeve structure is replaced with shorter columns placed near the central monopole. These columns function similarly to the original sleeve. Their substitution results in a new open-sleeve antenna. It focuses on combined tuning of sleeve columns and resistor, as well as current distribution across bands. Unlike traditional designs, the new structure allows the independent tuning of columns for resonance frequency control, while a thicker ground plane facilitates reliable column connections. The analytical design begins with calculating the resonant length of the open-sleeve columns. For the antenna to resonate at the target frequency bands, the resonant length of the whip monopole antenna for the target frequency bands is given by:

$$\begin{cases} l_i = \lambda_i/4; \quad \lambda_i = \frac{c}{f_i} \\ i = a, b, c, d, \ldots \end{cases} \tag{1}$$

Here l_i is the length of the ith column, and λ_i is the wavelength of the i-th resonant frequency. The length l_a of the first column is chosen to resonate at the center frequency of the band 580–600 MHz: for $f_a = 590$ MHz, $l_a = 127$ mm. The l_b is selected to resonate at the center frequency of the band 806–826 MHz: for $f_b = 816$ MHz, $l_b = 92.6$ mm. For l_c, it resonates at the center frequency of the band 1427.9–1447.9 MHz: for $f_c = 1440$ MHz, $l_c = 52$ mm. Lastly, l_d is selected to resonate at the center frequency of the band 5150–5600 MHz: for $f_d = 5375$ MHz, $l_d = 14$ mm. The 2401.5–2481.5 MHz band is primarily controlled by the central monopole. By partitioning the five required coal mine communication bands into separate segments, more flexible impedance matching is achieved.

Furthermore, to minimize interaction between the columns that form the bottom sleeve, their number was limited to four. As shown in Figure 1(d), the sleeve structure formed by the four columns at the bottom constitutes a single open-sleeve antenna.

The blue solid line and red dashed line in Figure 3 show the S_{11} and gain of Ant 4. The -10 dB impedance bandwidth of Ant 4 is 0.530–0.910 GHz, 1.310–1.480 GHz, 2.067–2.487 GHz, and 4.60–5.90 GHz, fully covering the five coal mine communication bands. The gain of Ant 4 at the center frequencies of the five coal mine communication bands is -0.695 dBi, 1.29 dBi, 3.76 dBi, 3.7 dBi, and 6.94 dBi, respectively.

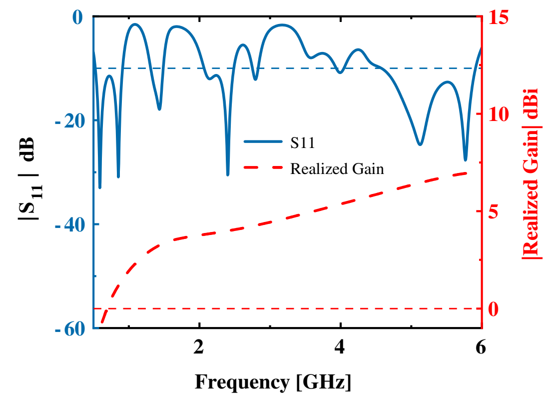


FIGURE 3. Simulated S_{11} and realized gain of single open-sleeve antenna.

2.3. Final Dual Open-Sleeve Antenna

Finally, an open-sleeve structure is added to the top of Ant 4 to balance the gain at the center frequencies of five coal mine communication bands. As shown in Figure 5, the four columns at the bottom and the four columns at the top of the monopole collectively form a dual open-sleeve antenna structure. The final antenna structure consists of a monopole, open-sleeve structures at both the top and bottom, a ground plane, and a loading resistor, and it is fed through an SMA connector. Each open-sleeve structure is composed of four columns with identical diameters. The top open-sleeve, consisting of four columns, is

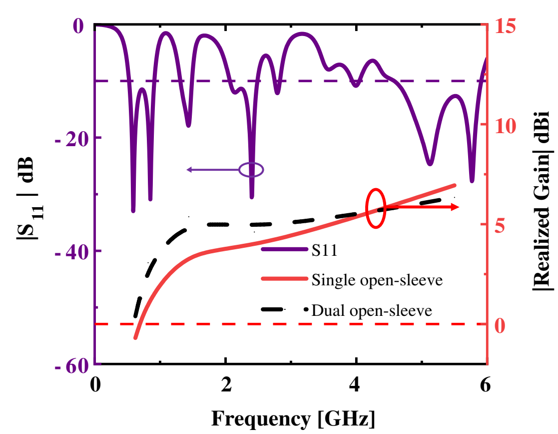


FIGURE 4. Simulated S_{11} for the dual open-sleeve antenna structure and gain of single open-sleeve and dual open-sleeve antenna structure.

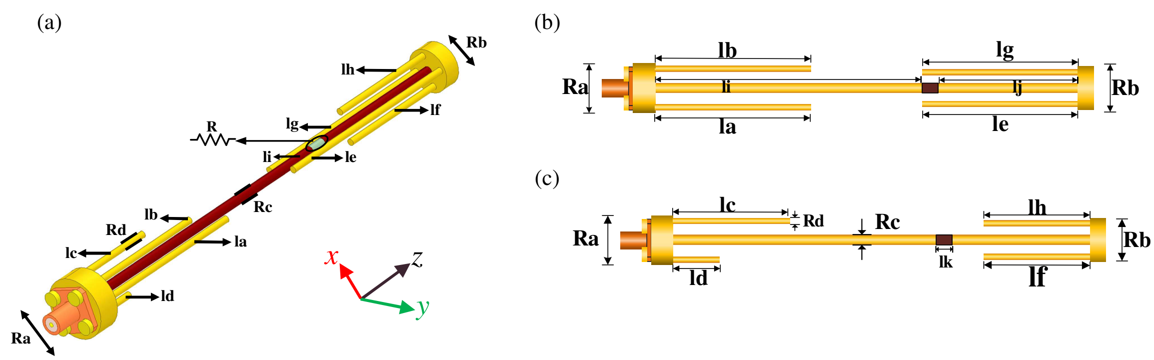


FIGURE 5. The geometric model of the proposed antenna. (a) The isometric view of the all antenna. (b) The y-z plane of proposed antenna. (c) The x-z plane of proposed antenna.

mounted at the top of the antenna without increasing its total height, functioning as both a top load and a matching element. Compared to the traditional sleeve structure [18], the open-sleeve structure enhances the antenna's stability and flexibility, while also reducing its overall volume. The final dimensions of the antenna are determined through full-wave simulation analysis in Computer Simulation Technology (CST) Microwave Studio, as shown in Table 1. In Figure 4, the black dashed line represents the antenna gain after the addition of the top open-sleeve structure. The gain improves at 0.59 GHz, 0.816 GHz, 1.44 GHz, and 2.44 GHz, but decreases at 5.375 GHz. The simulated S_{11} of the proposed antenna is shown by the pure solid line in Figure 4. The antenna covers four operational bands: 0.550–0.867 GHz, 1.380–1.485 GHz, 2.233–2.495 GHz, and 4.476–6.000 GHz.

TABLE 1. Dimensional parameters of antenna. (Unit: mm).

la	91	lg	97	Rb	13	le	97
lb	91	lh	53	Rc	2.5	lj	78
lc	48	li	158	Rd	1.4	lf	53
ld	13	lk	5	R	910 Ω	Ra	18

Figure 6 illustrates the simulated surface current distribution of the proposed antenna at 0.590 GHz, 0.816 GHz, 1.44 GHz, 2.44 GHz, and 5.375 GHz. The current is primarily concentrated on the cylindrical conductors at the centre of the antenna. However, the distribution of current across the sleeve columns varies with frequency. At low frequency bands ($580 \sim 600$ MHz and $806 \sim 826$ MHz), the strongest current is observed on the two longest bottom conductors. At the mid-frequency band (1427.9–1447.9 MHz), the second-longest conductor dominates, while at the high-frequency band (5150–5600 MHz), the shortest column carries the strongest current. The distribution of this surface current closely matches the design analysis results obtained from Equation (1). This demonstrates that the current can be flexibly concentrated on different columns of the open-sleeve structure, allowing the antenna to achieve multiband operation.

3. MEASUREMENT OF PROPOSED ANTENNA

The proposed antenna was fabricated as shown in Figure 7. All antenna components are made from pure copper, and the open-sleeve columns are installed using threaded connections. Measured results are acquired by using a vector network analyser (PNA-X N5242A).

Figure 8 shows the measured and simulated S_{11}, demonstrating good agreement between them. The measured frequency bands of the proposed antenna are shown in Table 2.

TABLE 2. The measurement bands of the proposed antenna.

Frequency Band	Simulation (GHz)	Measurement (GHz)	Meas-BW (GHz)
First band	0.550–0.867	0.515–0.845	0.330
Second band	1.380–1.485	1.370–1.485	0.115
Third band	2.233–2.495	2.210–2.525	0.315
Fourth band	4.476–6.000	4.660–6.000	1.340

The first band is 0.515–0.845 GHz (measured) and 0.550–0.867 GHz (simulated). The second band is 1.370–1.485 GHz (measured) and 1.380–1.485 GHz (simulated). The third band is 2.210–2.525 GHz (measured) and 2.330–2.495 GHz (simulated). The fourth band is 4.660–6.000 GHz (measured) and 4.474–6.000 GHz (simulated). Minor differences are caused by manufacturing tolerances and measurement environment. The frequency range of 3.93–4.03 GHz is not commonly found in mainstream public communications bands and is not discussed in this paper.

Figure 9 shows that the gain at the center frequencies of five coal mine communication bands are 1.21 to 4.59 dBi, both greater than 0 dBi. This study adopts the maximum gain of 5.2 dBi reported in [21] for coal mine communication antennas as the safety design benchmark. The measured maximum gain of the proposed antenna is 4.59 dBi, which falls below this safety threshold. Measured results demonstrate that under identical input power conditions, the radiation field strength of the proposed antenna complies with coal mine safety regulations, thereby eliminating potential safety hazards associated with excessive gain at the physical level. This result shows that the

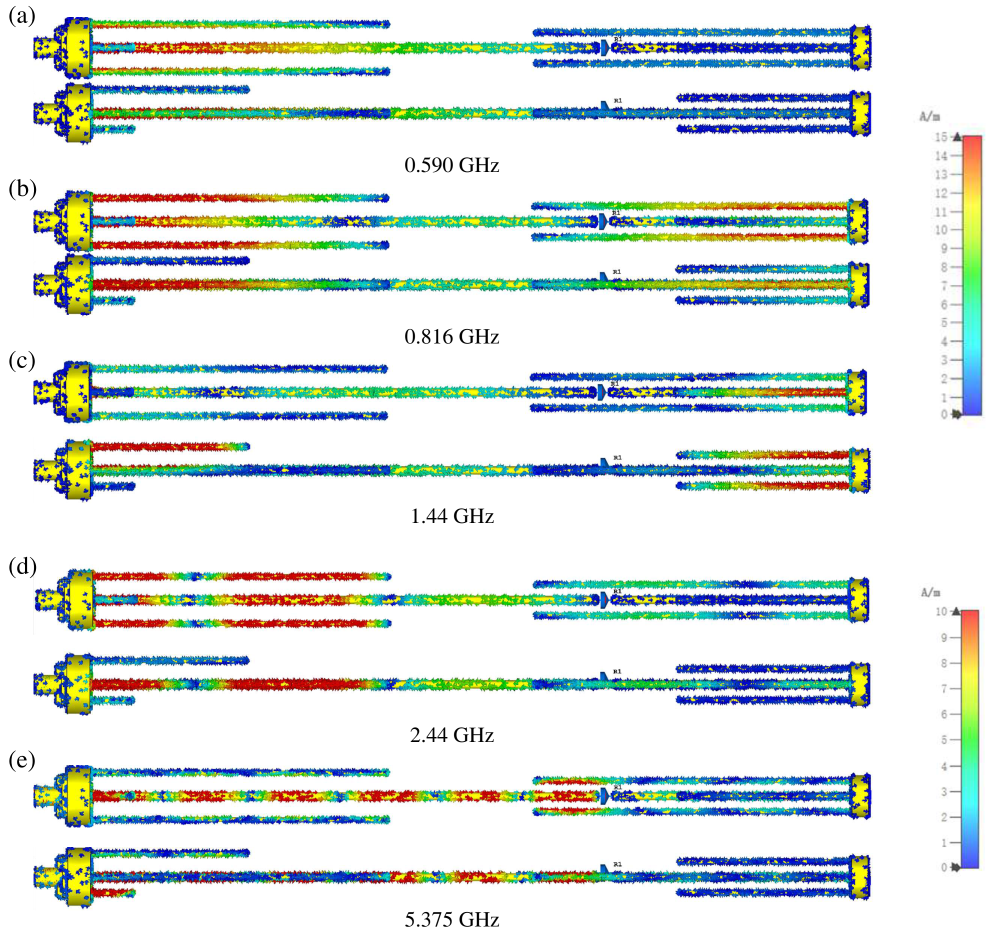


FIGURE 6. The surface currents for the simulation of the proposed antenna are distributed at five center frequency points.

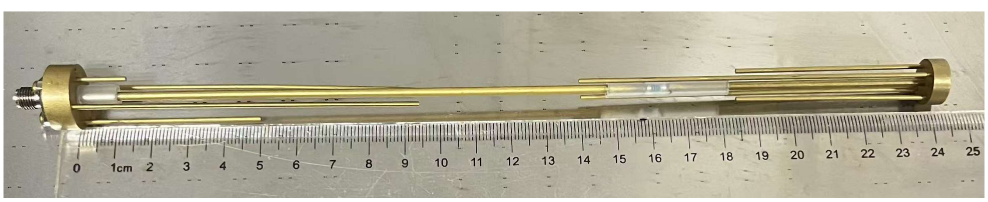


FIGURE 7. Photo of the fabricated dual open-Sleeve antenna.

antenna has good radiation capability in multiple operating frequency bands, and the designed antenna efficiency is between 44% and 77.7%. Meanwhile, when operating at higher frequencies (5 GHz), the proposed antenna exhibits relatively compact electrical dimensions, resulting in a superposition of current paths that leads to moderate gain attenuation. Nevertheless, simulation results confirm that the gain remains above 5 dBi, indicating sustained performance at an acceptable level.

Figure 10 shows the simulated and measured E-plane and H-plane radiation patterns at the center frequencies of the five coal mine communication bands. The measured and simulated results show good consistency, and the H-plane radiation pattern exhibits omnidirectional radiation.

As shown in Table 3, compared to multiband antennas and coal mine antennas in previous literatures. The proposed antenna design is more compact with ultra-narrow lateral dimensions, which not only covers the frequency band below 1 GHz but also achieves a relative bandwidth of 48.5%. Notably, the core advantage of the antenna proposed in this paper lies in achieving a synergistic balance among size, frequency band, and performance, thereby overcoming traditional design limitations. Its dimensions are only $\Phi 18 \times 241\,\text{mm}^2$, significantly outperforming similar configurations in [14, 16]. More critically, it covers four key frequency bands within such compact constraints, overcoming the limitations of single-band designs while outperforming bulkier multiband solutions. The antenna exhibits excellent impedance matching (VSWR $\leq$ 2) across its bands, combined with a peak gain of 4.59 dBi. This combination successfully demonstrates a balance of compact size, multiband operation, and high performance. The design ef-

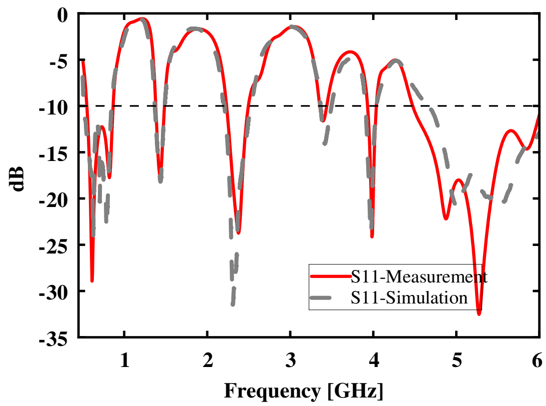


FIGURE 8. Reflection coefficient (S_{11}) of the dual open-Sleeve antenna, both simulated and measured results.

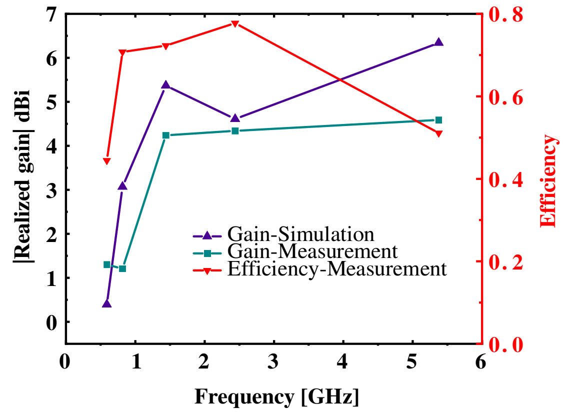
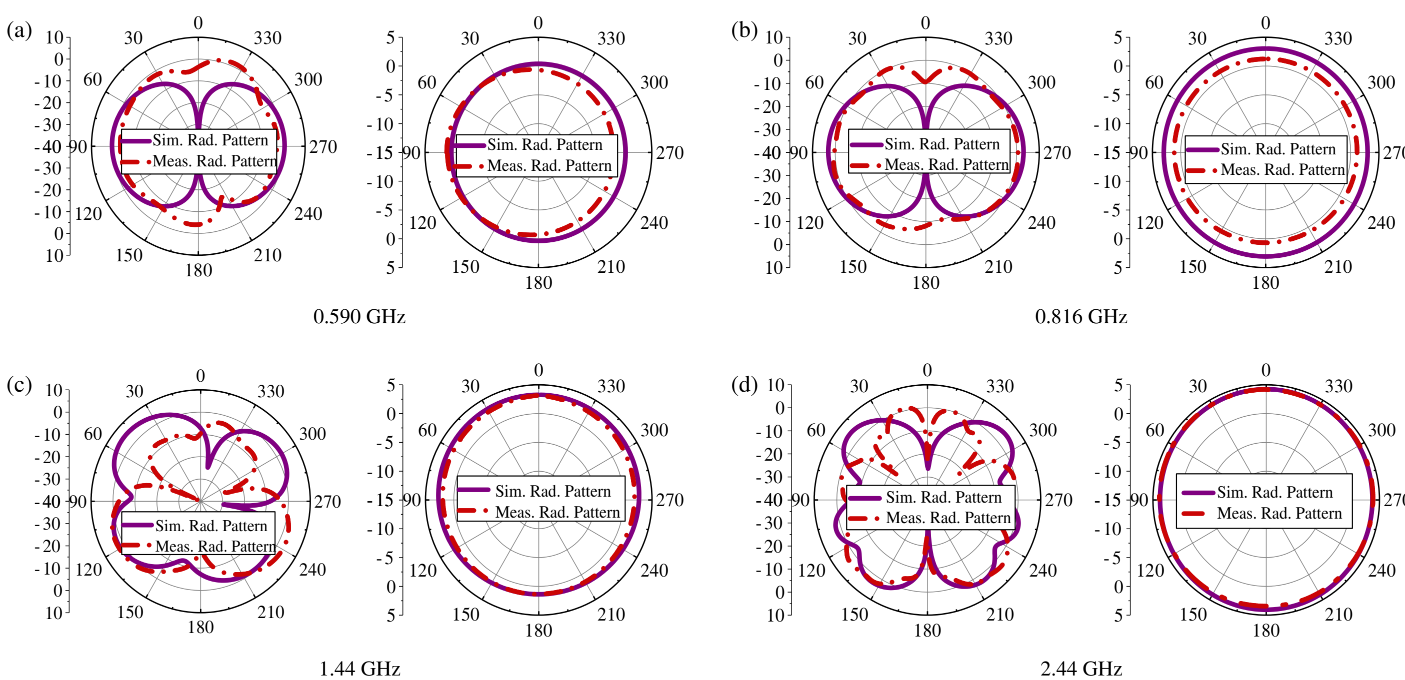


FIGURE 9. Results of measured and simulated realized gains and measured radiation efficiency at the center frequencies of five communication bands.

TABLE 3. Comparison of antennas reported in literature.

Ref. No.	Dimension (mm^2)	No. of bands	Bandwidth (GHz)	VSWR	Peak gain (dBi)
[14]	ø800 × 78	2	0.12 GHz at 0.90 GHz, 0.14 GHz at 1.80 GHz	2	4.5, 4.8
[16]	45 × 45	6	2.03–2.51, 3.18–3.28, 5.65–6.09 7.38–7.75, 8.31–9.11, 9.58–11.96	2	2.02, 3.10, 5.37, 2.99, 3.11, 6.48
[19]	ø30 × 320	1	0.24–0.95	3	2.6
[21]	57 × 175	1	0.824–0.960	2	1.98
[22]	25 × 20	3	1.87–2.66, 3.33–3.69, 4.71–5.08	2	/
[23]	60 × 60	4	1.67–2.28, 2.39–2.79, 3.13–3.74, 4.69–5.34	2	5.6, 3.38, 3.78, 4.41
This antenna	ø18 × 241	4	0.515–0.845, 1.370–1.485, 2.21–2.525, 4.660–6.000	2	1.30, 4.24, 4.34, 4.59



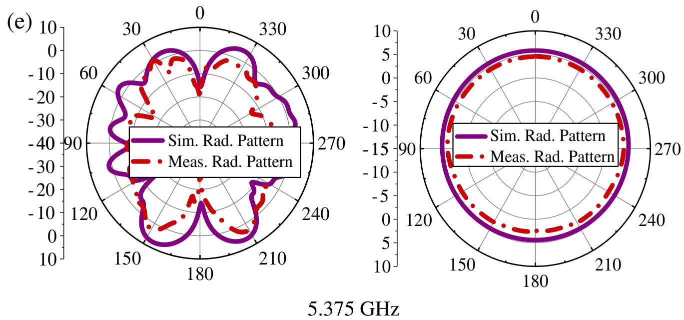


FIGURE 10. Measured and simulated (left) E-plane and (right) H-plane radiation patterns of the proposed antenna.

fectively addresses the issue that traditional multiband antennas and mining antennas cannot simultaneously accommodate both low-frequency and high-frequency operation. The proposed antenna exhibits exceptional compactness in the horizontal plane while maintaining excellent dimensional characteristics in the vertical plane relative to its low-frequency operating wavelength. Nevertheless, through in-depth optimization of the radiation column parameters within the open-sleeve structure, there remains potential for further reduction in the antenna's vertical dimensions.

4. CONCLUSION

In this paper, a novel multiband antenna based on sleeve structure is proposed. The design features an extended central monopole and a set of four columns that replace the traditional sleeve structure. The lengths of these columns are optimized to operate at 0.59, 0.81, 1.43, 2.44, and 5.3 GHz, thereby enabling coverage across five coal mine communication frequency bands. On this basis, an open sleeve structure is added to the top of the antenna to enhance low-frequency gain, ensuring that the gain remains above 0 dBi across all target bands. Compared with traditional sleeve structures, the proposed antenna effectively reduces overall size while enhancing the flexibility of resonance frequency tuning. Moreover, the proposed antenna has a compact size of $0.41\lambda \times 0.03\lambda$, where λ corresponds to the lowest operating frequency of 515 MHz. The proposed open-sleeve antenna fully covers the five frequency bands required for coal mine communication and can also support WLAN (2.4/5.2/5.8 GHz), WiMAX (2.3/5.8 GHz), and 5G NR (n5/n12/n28/n71/n79). Its promising performance holds potential applications for coal mine communication.

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