A Bidirectional High-Gain Cascaded Ring Antenna for Communication in Coal Mine

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***Abstract*—In this letter, a bidirectional high-gain antenna is proposed for wireless communication in tunnels or coal mines. The antenna consists of six rectangular rings in cascade and works in a standing-wave mode. The high-gain bidirectional radiation property is realized by the currents distributed in-phase on the vertical edges. The dimensions of the proposed ring are $300 \times 16 \times 0.6$ mm^3 ($2.4\lambda \times 0.128\lambda \times 0.005\lambda$ at 2.4 GHz). The measured -10-dB bandwidth is approximately 290 MHz (2.33–2.62 GHz), the measured peak gain is 9.5 dBi, and the 1-dB gain bandwidth is about 110 MHz (2.34–2.45 GHz). The experimental results are presented and discussed, and it is shown that the proposed bidirectional antenna inherits the merits of high directional radiation gain, low profile, easy fabrication, and low wind resistance.**

***Index Terms*—Bidirectional antenna, loop antenna, tunnel communication.**

I. Introduction

IN TUNNELS, coal mines, or long streets, the size of microcell zones can be efficiently increased by using bidirectional antennas, which preferentially radiate the antenna beam along the longitude [1], [2]. In recent years, the bidirectional antenna has also gained a lot of interest with respect to wireless communication in coal mines. The special channel property and safety production in coal mines bring up new challenges in antenna design, such as low profile, low cost, easy fabrication, low wind resistance, anti-explosion, and good bidirectional radiation pattern.

The basic bidirectional radiation character can be realized by employing two unidirectional antennas such as Yagi–Uda [3] pointing in opposite directions. On the other hand, an array antenna such as a dipole array excited in-phase is an alternative solution [4]. However, such techniques need additional feed network. Additional circuit board would be introduced, and the whole design would not be compact.

It is known that a slot antenna etched on a finite ground has a bidirectional radiation pattern, and that the maximum gain is usually around 5 dBi [5]. A back-to-back patch antenna with a simple feeding method was reported in [6], where the max gain was noted to be about 5 dBi. When working in low-frequency band, large cross-section size of such broadside bidirectional planar antennas [5], [6] is inevitable. However, it would hinder ventilation when applied in coal mines, where wind velocity of 2–6 m/s must be guaranteed.

A spiral antenna [7] is known as a wideband circularly polarized bidirectional antenna. However, the max gain is low. A bidirectional narrow patch antenna (BNPA) with narrow patches of the same size on both sides of a thin substrate (0.02λ) was presented in [8]. However, it also suffers from low gain (about -2 dBi), and parasitic elements are needed to improve the gain. To achieve high bidirectional gain, waveguides are a good candidate. Theoretical analysis and experiments have been performed in [9] and [10].

Bruce array [11] has a high-gain (8.5 dBi) bidirectional pattern due to the in-phase electrical/magnetic current. The grid antenna [12]–[15], which was first introduced by Kraus as early as 1964, has high directivity due to the in-phase excitation of all the radiation elements. It is classed as a traveling wave antenna. Most of them are etched onto a conductor-backed printed circuit board to support the special traveling wave mode, which makes the antenna radiate only in broadside. As far as it is known to the authors, nothing has been published concerning the working state of such grid antennas without the presence of the back ground. It should also be noted that the circumference of the loops presented in these works is basically 3λ.

Based on the above-mentioned discussion, this letter presents a low-cost, easy-to-fabricate, low-profile, and high-gain bidirectional antenna that consists of six rectangular rings in cascade. The antenna is designed to work in a special standing wave mode, and the currents in-phase on the vertical edges become the main radiators and form the bidirectional radiation pattern with high directivity. The circumference of each ring is about 1λ, and the dimensions of the proposed antenna are $300 \times 16 \times 0.6$ mm^3. The measured -10-dB bandwidth is approximately 290 MHz (2.33–2.62 GHz), the measured peak gain is 9.5 dBi, and the 1-dB gain bandwidth is 120 MHz (2.33–2.45 GHz).

II. Antenna Design

The origin of the proposed design is shown in Fig. 1, which is based on the classic 1λ loop mode. The in-phase currents on

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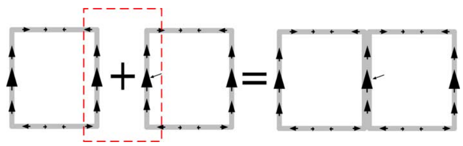

Fig. 1. Origin of the proposed antenna.

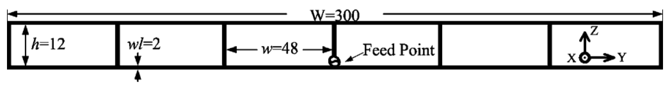

Fig. 2. Geometry of the proposed antenna (unit: millimeter).

the two vertical edges are the main radiators. The radiation character can be controlled by the aspect ratio of the rectangular ring. If the two loops are excited simultaneously, higher bidirectional gain can be obtained. A power divider network is a considered candidate. However, a power divider network would introduce additional cost on the circuit board. The whole design would not be compact. Thus, a design without a feeding network is needed. Consider two loops aligned, as shown in Fig. 1. The two vertical currents of the two loops in the dashed line box are in-phase. If the two loops are merged together, as shown in the right side of the graphical equation, then there is a possibility that the current distribution of the antenna after merging is just the simple combination of the original ones because the two loops can share the two in-phase currents. Now, by sacrificing one radiating edge, three in-phase currents are excited without any feeding network. If this assumption is right, more loops can be cascaded together for higher antenna gain.

Based on the above-mentioned assumption, an antenna design is proposed in this letter with six rectangular loops cascaded, as shown in Fig. 2. The structure is made up of copper with the thickness of 0.6 mm. The simulated electric current distribution, shown in Fig. 3, validates the assumption and addresses a reasonable insight into the bidirectional radiation mechanism. As shown in Fig. 3, at resonant frequency, distinct 1λ current mode is observed on each ring. Without the back ground plane present in [12]–[15], no traveling mode can be supported. The current mode is induced by the coupling between the loops. The combination of the rings and the current mode of each ring are merged perfectly, which make the whole structure work in a special standing-wave mode, and higher directivity is realized by the radiation of seven in-phase vertical currents. Table I shows the simulated directivity varying with the number of the loops. The directivity gets high as more loops are cascaded. However, the advantage of eight loops is not significant compared to six loops. As more loops are cascaded, the energy coupled to the loops in the end gets lower, and the 1λ standing wave mode is hard to maintain. Thus, the total length needs to be controlled, and the amount of the loops is chosen to be six.

There are two benefits for 1λ resonant mode of the loop element. First, the 1λ mode is the lowest resonant mode that a ring structure can support, which helps to control the overall antenna length after cascading. Second, when the rings in the same dimensions are cascaded in the way shown in Fig. 2, all the rings can still remain in the 1λ mode synchronously. It means that currents on all the vertical edges are in-phase. It should be noted that the magnitudes of the currents on the vertical edge decrease progressively from the center to the end. Such a phenomenon can be explained by the view of traveling wave, although the whole structure works in a standing-wave mode. As the energy is pumped into the antenna in the center, the currents distributed away from the center suffer radiation loss and ohmic loss along the path from the feeding point to the end of the antenna structure. From the point of view of the array antenna, such a current distribution may have some impact on the maximum directivity that can be achieved.

III. Simulated and Experiment Results

The geometry of the proposed antenna is shown in Fig. 2. It consists of six rectangular rings in series. The width and length of each rectangular ring are 48 and 12 mm, respectively. All the lines have the same width of 2 mm. A coaxial cable is used to feed the antenna right in the center.

The effect of the key geometrical parameters on antenna radiation and impedance matching performance has been studied by Ansoft's HFSS.

Based on the above-mentioned description, it can be noted that all the rings used are with the same dimensions; thus, the adjustable important parameters left are the aspect ratio S of the rectangular rings (h/w) and the line width. Figs. 4 and 5 show the impedance and directivity behavior with the variation of S. As mentioned earlier, the in-phase currents on the vertical edges are the main radiators. When S gets smaller, the distance between the two vertical edges gets longer, and the directivity gets higher based on the array factor, which is verified by the simulated results shown in Fig. 5. Basically, the impedance of the whole antenna is determined by the single ring. When S gets smaller, the distance between the two horizontal edges gets shorter. As the cancellation between the currents like the ones shown in the dashed box of Fig. 3 gets more severe, more energy will be stored in the near-field, and the Q value of the antenna gets larger. Consequently, the inherent bandwidth of the antenna gets narrower. Hence, there is a tradeoff between the directivity and the inherent bandwidth.

To the point of impedance matching, the available -10-dB bandwidth is another issue. A good matching state of a single ring does not signify a good matching state after cascading; therefore, adjusting the S is important for impedance matching after cascading. Based on the above-mentioned discussion, $S = 0.28$ is selected in the design. In Fig. 6, the influence of the line width on the resonant behavior is investigated. As the line width gets wider, the inner perimeter of each loop gets smaller. Thus, the resonant frequency gets higher. A good matching state can be achieved by appropriate line width.

In fact, two different resonances are observed across the frequency band concerned. The resonance in the lower frequency band corresponds to the mode where all the vertical currents are in-phase. However, the vertical currents are not all in-phase during resonance in the higher frequency band. As a result, the maximum directivity drops down, although bidirectional radiation can still be observed.

An antenna prototype working at 2.4 GHz was fabricated and measured to experimentally verify our design. Fig. 7 shows a

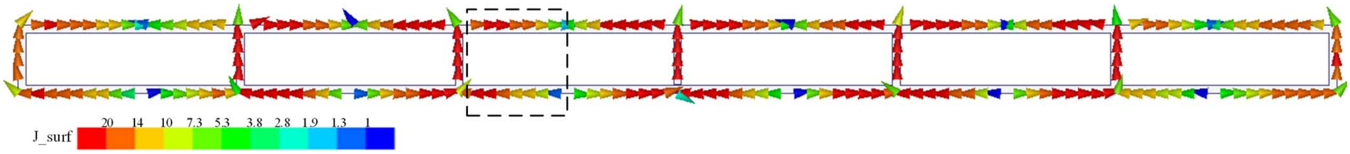

Fig. 3. Current distribution of the proposed antenna at 2.4 GHz.

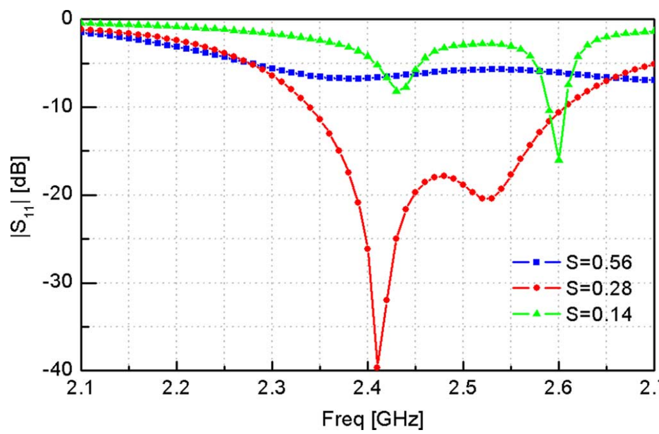

Fig. 4. Simulated $|S_{11}|$ varying with parameter aspect ratio S (h/w).

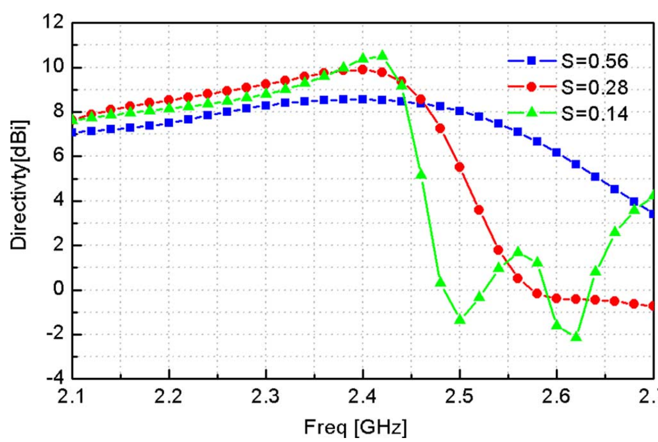

Fig. 5. Simulated directivity varying with aspect ratio S (h/w).

TABLE I
SIMULATED DIRECTIVITY VARYING WITH THE NUMBER OF THE LOOPS

The Number of the Loops	Directivity (dBi)
2	6.4
4	8.6
6	9.9
8	10.1

w= 48, h = 12, wl = 2.

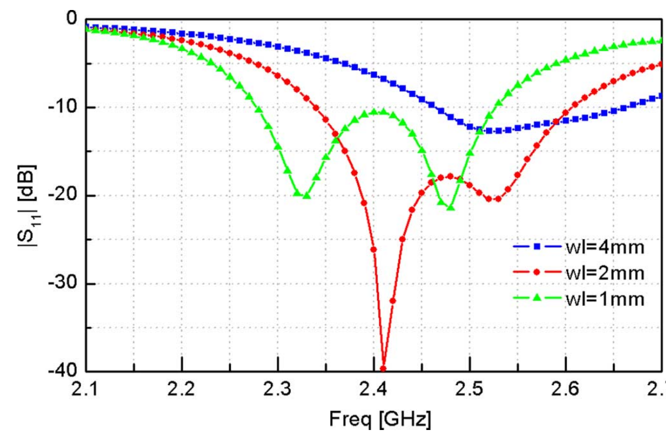

Fig. 6. Simulated $|S_{11}|$ varying with parameter wl.

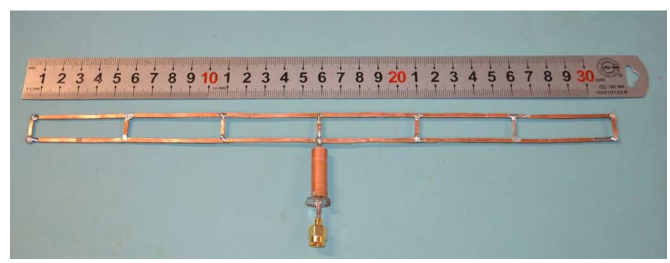

Fig. 7. Photograph of the proposed antenna.

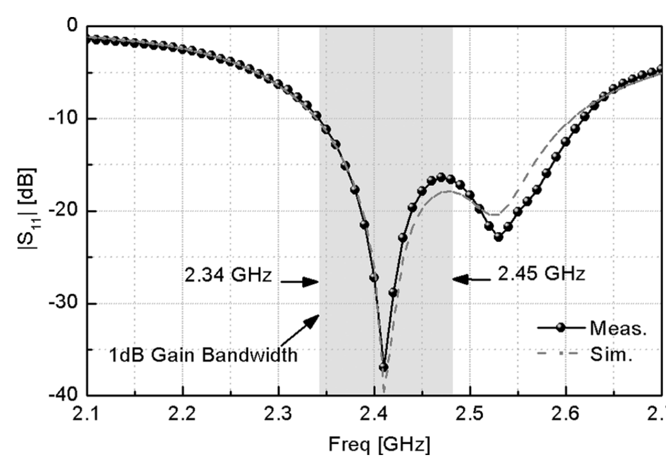

Fig. 8. Simulated and measured $|S_{11}|$ of the proposed antenna.

photograph of the antenna prototype. As a coaxial cable has been attached to the prototype as an excitation in the measurement, a $\lambda/4$ balun has been used to reduce the surface current along the coaxial cable. In the simulation, the balun and the loss have been included. The measured results were obtained using a vector network analyzer (Agilent ENA E5071B). The radiation patterns were measured in a standard anechoic chamber. Both the simulated and measured reflection coefficients are shown in Fig. 8, and the simulated and measured impedance bandwidths for $|S_{11}| \leq -10$ dB are 280 MHz (2.33–2.61 GHz) and 290 MHz (2.33–2.62 GHz), respectively. The simulated and the measured radiation patterns across the 1-dB gain bandwidth from 2.34 to 2.45 GHz, i.e., working band, are also compared in Fig. 9, which shows good agreement. The broad main lobe in the E-plane (xoz-plane) and the narrow main lobe in the H-plane

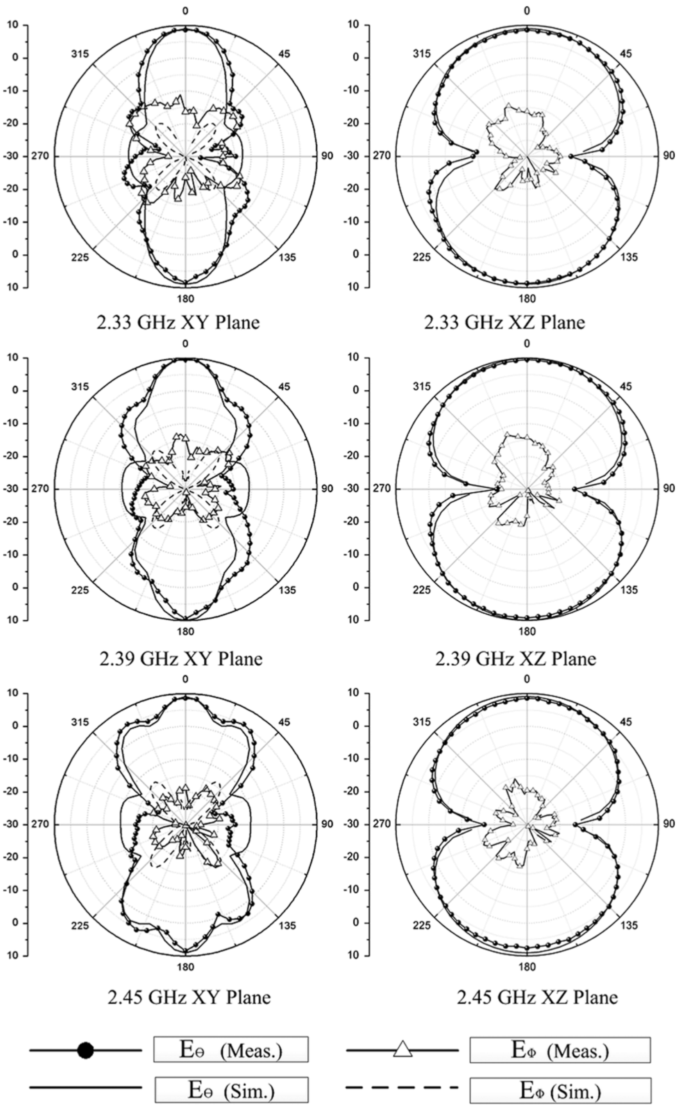

Fig. 9. Simulated and measured radiation pattern of the proposed antenna on H-plane (xy-plane) and E-plane (xz-plane).

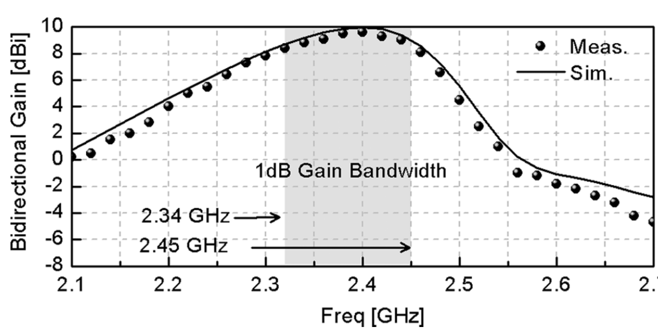

Fig. 10. Simulated and measured gain of the proposed antenna.

(xoy-plane) correspond to the radiation mechanism discussed earlier. As the frequency increases, the phase differences between the vertical currents get more distinct, which results in the split in main lobe and the decrease in directivity. The measured gains of bidirectional radiation are shown in Fig. 10, together with the simulation results. The maximum simulated and measured gains are 9.9 and 9.5 dBi, respectively. The simulated and measured 1 dB gain bandwidths are 120 MHz (2.33–2.45 GHz) and 110 MHz (2.34–2.45 GHz), respectively. The difference between the simulated and measured results mainly comes from the measure and fabrication error.

IV. Conclusion

This letter has presented a bidirectional high-gain antenna consisting of six rectangular rings in cascade. To realize high directivity, the major design challenge lies in two facts. First, the working mode of the single ring needs to be selected carefully considering the tradeoff between directivity and impedance matching. Second, the combination method of the six rings needs to be designed carefully to maintain the working mode of each ring and keep the currents on all vertical edges in-phase. Each ring of the proposed antenna works in 1λ mode. By combining the rings in series and adjusting the aspect ratio of the rectangular rings, good impedance matching and high bidirectional gain can be achieved. The proposed antenna inherits the merits of low profile, low cost, easy fabrication, low wind resistance, and high bidirectional gain, which is quite suitable for wireless communication in tunnels, long streets, or coal mines.

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