A Bidirectional Endfire Array With Compact Antenna Elements for Coal Mine/Tunnel Communication

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***Abstract*—A six-element endfire array is proposed for coal mine or tunnel communication in this letter. To further decrease the end cross section, which has adverse effect on air ventilation, meander-line folded dipoles are used as antenna elements. By the antenna itself, the cross section toward the ventilation direction is only 100×1 mm^2. A prototype array is fabricated and tested. Bidirectional endfire radiation patterns with low cross-polarization levels in the azimuth and elevation plane are achieved. The measured -10-dB bandwidth is approximately 7.5% (834–899 MHz), and the corresponding peak gain is 8.05–9.05 dBi.**

***Index Terms*—Bidirectional, endfire, high gain, meander-line dipole, tunnel communication, ventilation.**

I. Introduction

ELECTROMAGNETIC waves do not propagate well in underground mines because either the dielectric constant or the conductivity of the tunnel walls is relatively high, which results in high attenuation. The reflections from the tunnel walls and diffractions from other objects bring severe multipath effect [1], [2]. Traditionally, leaky coaxial cables (LCX) or low-capacity conducting wires are used in tunnels [2]. However, the cost of deploying LCX is quite high. In continuously shifting operation areas, such as gallery excavating faces and working faces, the LCX system is quite inconvenient and, in some circumstances, impractical. Furthermore, it is well known that wired communication system is easily damaged in case of a disaster, such as fire and sidewall collapse. If the path loss issue can be appropriately addressed, a wireless system can be an attractive alternative or at least a backup in coal mine communication. By deploying a bidirectional high-gain antenna at wireless base stations, both path loss issues and multipath effect can be mitigated. The most commonly used bidirectional antenna is composed of two back-to-back Yagi–Uda antennas. For example, the gain of a 12-element Yagi–Uda with total length of 2.2λ is 12.25 dBi [3]. To generate a bidirectional radiation pattern with two such antennas, the total length is doubled to be about 4.5λ, but the gain is halved to 9.25 dBi.

In the past decades, a lot of work [4]–[7] has been done to realize low-profile bidirectional antennas. Arai *et al.* presented a bidirectional notch antenna, whose gain was 5.71 dBi with three parasitic elements serving as directors on both sides, and crank-shaped antenna modified from such an antenna achieved improved cross-polarization levels of 17.6 dB in the H-plane [4]–[6]. In [7], a simple and cost-effective bidirectional antenna using a probe-excited circular ring was proposed to obtain moderate gain, and the capability of directivity enhancement was investigated by using a linear array of the above antenna element with on-axis and off-axis geometries.

In most mines, hazardous gases leak out spontaneously. Methane may explode under high pressure or above certain concentration levels. Carbon monoxide at high concentrations is likely to suffocate people to death. In order to maintain a safe level of oxygen (19.5%–23.5% by volume) and reduce content of other harmful gases, ventilation with wind velocity of 2–6 m/s must be guaranteed. However, many bidirectional antennas [4]–[7] are planar structures with their main beam direction perpendicular to the antenna surface. When installed in the tunnels, they can produce an adverse effect on the ventilation air flow. Furthermore, coal dust is easily accumulated on the antennas, which will deteriorate their radiation performance gradually. In this letter, we propose a high-gain bidirectional endfire array whose center frequency is about 860 MHz. The total size of the array is $854 \times 100 \times 1$ mm^3; the cross section facing the ventilation direction is only 100×1 mm^2. Details of the simulated and measured results are presented and discussed in the following sections.

II. Antenna Design

A. Transmission Line and Array Design

It is well known that an array with an in-phase excitation has a broadside radiation pattern. By changing the excitation to the alternative opposite-phase and keeping the distance between adjacent elements at $0.5\ \lambda_0$, the broadside radiation peak can be eliminated, and an endfire pattern is obtained. Even elements must be guaranteed to achieve better gain. The gain of an array is proportional to the element number. However, as the element number increases, the design and fabrication become more complicated. In this letter, six elements is selected for the convenience of designing and manufacturing.

In this letter, an array serial-fed by air-filled transmission lines is proposed. As depicted in Fig. 1, the array is composed of

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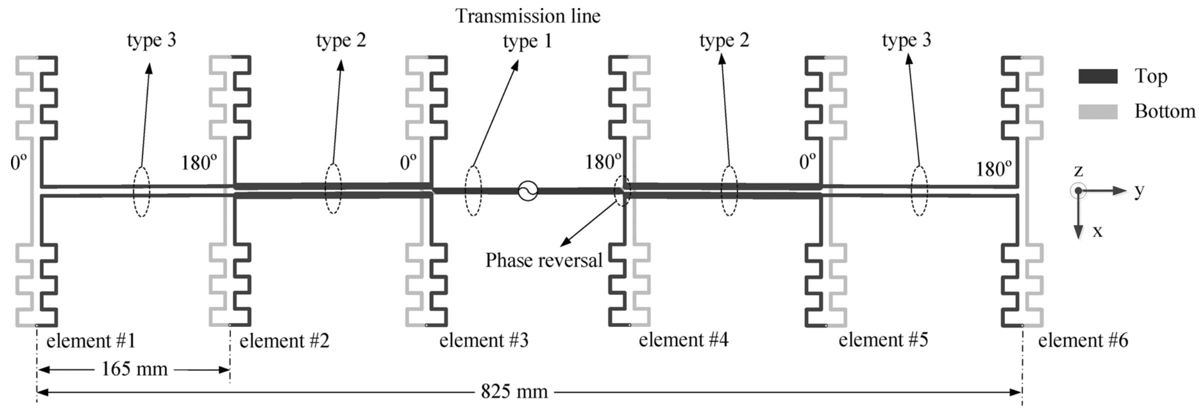

Fig. 1. Schematic of the proposed array.

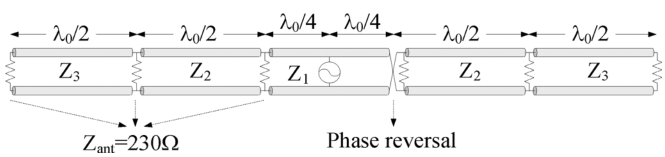

Fig. 2. Equivalent circuit model of the proposed array.

six equally separated elements and fed in the center to keep the symmetry of the array. The distance between adjacent elements is 165 mm. All elements are identically folded meander-line dipoles, which will be discussed in detail in Section II-B. Considering the feasibility of manufacturing, two kinds of transmission lines are used, which are coplanar parallel transmission line (CPTL) and double-sided parallel transmission line (DSPTL).

Fig. 2 shows the equivalent circuit model of the proposed array. The input impedance of the proposed folded meander-line dipole is 230 Ω. The characteristic impedance of the central transmission line (type 1, Z1) is about 87 Ω, which is realized by a DSPTL as shown in Fig. 3(a). This line has multiple functionalities. First, it works as a balun, which converts the unbalance current inside a coaxial line to a balanced DSPTL current. Second, it also provides the 180° phase reversal between antenna elements numbered 3 and 4. Lastly, because the distance between adjacent elements is half a wavelength, it is a quarter of a wavelength from the center to either element numbered 3 or 4. This transmission line also serves as a quarter-wavelength impedance transformer.

The characteristic impedances of type 2 (Z2) and type 3 (Z3) transmission lines are 115 and 230 Ω, respectively, which are realized by CPTL. The schematics of these two types of lines are shown in Fig. 3(b) and (c). The serial feeding network is designed to minimize the standing wave on transmission lines. Except the central line, the impedances of all transmission lines are approximately the same as the combined antenna impedances at respective locations. Detailed dimensions of all transmission lines are shown in Table I. All transmission lines are made of sheet copper with thickness of 0.1 mm.

B. Element Design

To simplify design of the feeding network, folded dipoles that have high input impedance are used as antenna elements. To decrease the total size of the folded dipoles, meander-line

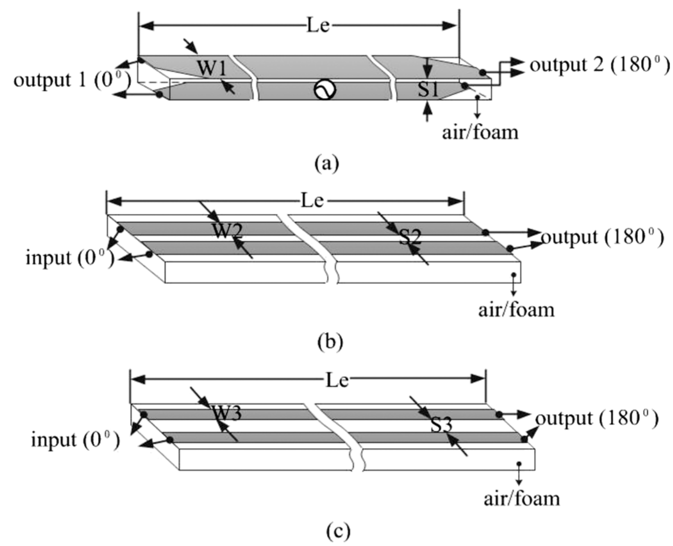

Fig. 3. Schematic of the transmission line structure. (a) Type 1. (b) Type 2. (c) Type 3 (unit: millimeters, not in scale).

TABLE I
DETAILED DIMENSIONS OF TRANSMISSION LINES

parameters	*Le*	*W1*	*S1*	*W2*	*S2*	*W3*	*S3*
units(mm)	165	2.2	1	2.2	1	1.2	2

technique [8]–[10] is adopted. The total height of the meander-line antenna has great influence upon the impedance bandwidth. Better impedance matching will be achieved as the total height increases. The total height is about 0.28 $\lambda 0$ in our final design, which is a tradeoff between the impedance bandwidth and the size of the antenna.

The geometry of the proposed element is illustrated in Fig. 4. The antenna element is fabricated on FR4 substrate with thickness $\mathrm{Hsub} = 1$ mm, relative permittivity $\varepsilon_r = 4.4$, and dielectric loss tangent $\tan\delta = 0.02$. In order to diminish the impedance discontinuity of the transmission line when passing from the air/foam to the FR4 substrate, dumbbell-shaped substrate is adopted, the widths of all metal lines are fixed to 1 mm, and the distance between the edge of the meander line and that of the substrate is kept at 0.5 mm. The element was designed and optimized using the full-wave simulator Ansoft HFSS. The final optimal design parameters are listed in Table II. The gap is

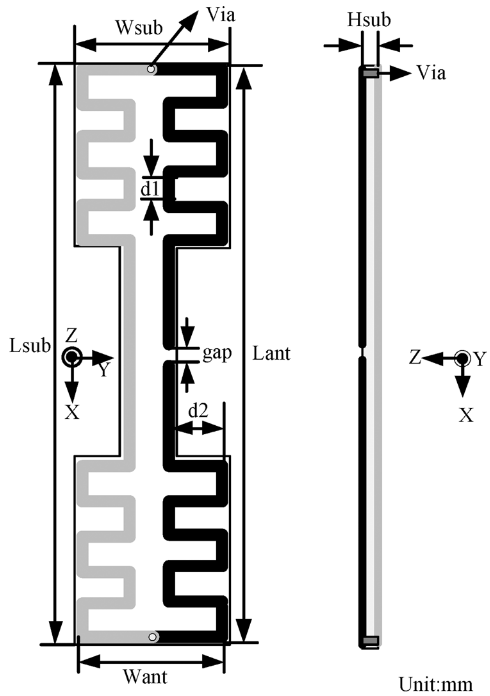

Fig. 4. Geometry of the proposed element. (a) Top view. (b) Side view (the dark line is printed on the top layer, while the gray is printed on the bottom layer).

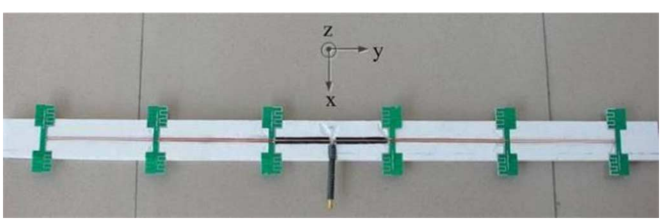

Fig. 5. Photograph of the proposed array.

TABLE II
Optimal Design Parameters of Element

parameters	*Lant*	*Want*	*Lsub*	*Wsub*	*d1*	*d2*
units(mm)	99	28	100	29	5	10

a variable that varies according to the feeding transmission line $S1, S2, S3$ in Fig. 3(a)–(c). The gap makes little influence on the resonance frequency and input impedance of elements.

III. Simulated and Measured Results

In the simulation of the array, the relative permittivity of the foam is set to be 1.07. Fig. 5 is a photograph of the fabricated prototype. The measured results were performed by a vector network analyzer (Agilent ENA E5071B). The reflection coefficient was measured in a corridor of our laboratory, which is more similar to the long and narrow environment of mine tunnels. The experiments of the radiation patterns were performed in an anechoic chamber. Because a long coaxial cable is attached to the prototype array in the measurement, ferrite beads are used to reduce the surface current along the coaxial cable. Both the simulated and measured reflection coefficients are shown in Fig. 6. The simulated center frequency is 866 MHz, and -10-dB

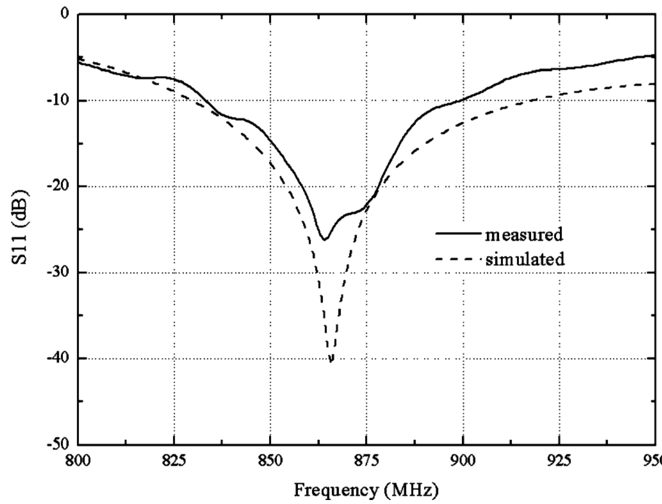

Fig. 6. Simulated and measured S_{11} for the proposed array.

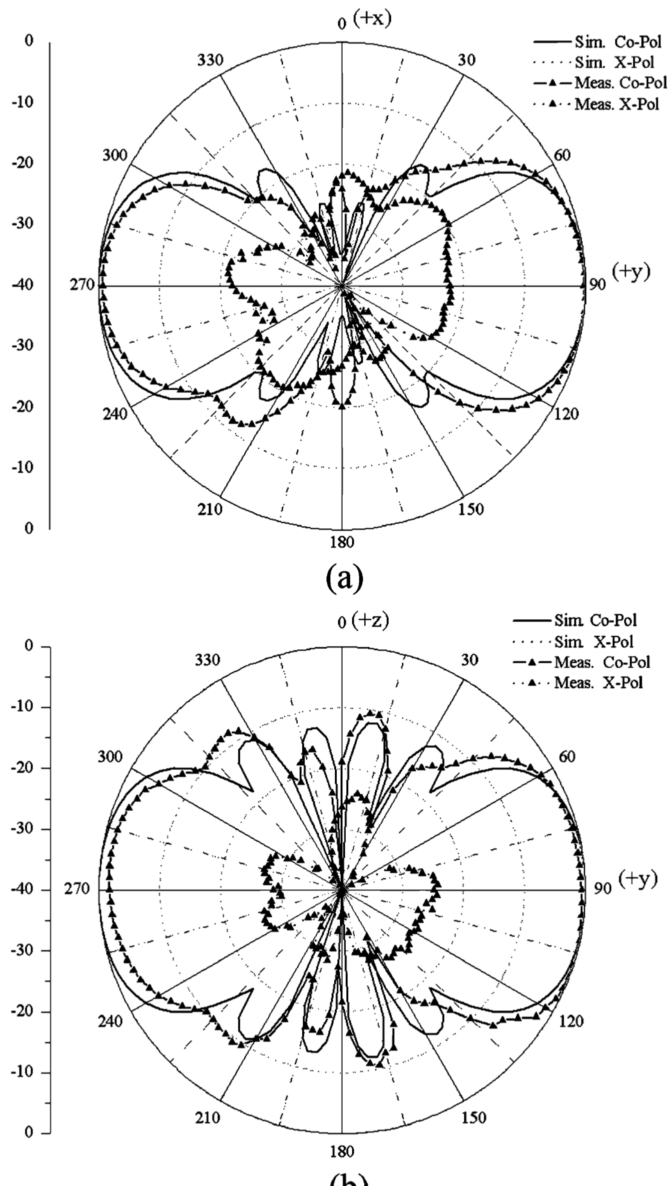

Fig. 7. Simulated and measured normalized radiation patterns at 860 MHz for the proposed array. (a) xy-plane. (b) yz-plane.

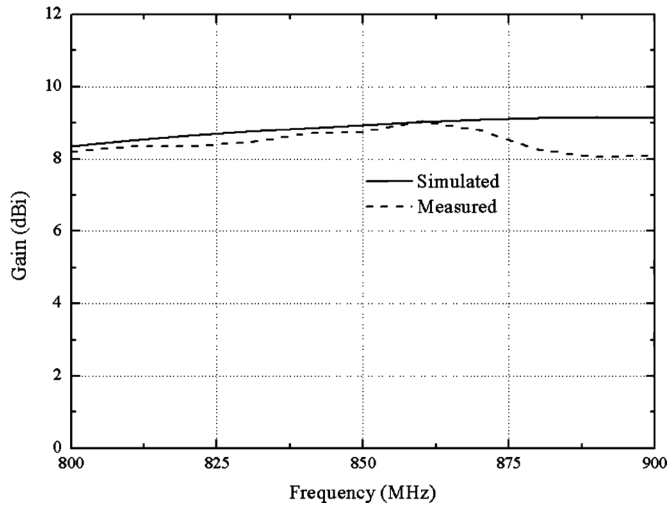

Fig. 8. Simulated and measured S_{11} for the proposed array.

impedance bandwidth is 87 MHz (830–917 MHz), while the measured center frequency is 864 MHz and -10-dB impedance bandwidth is 65 MHz (834–899 MHz). Discrepancies between the simulated and measured reflection coefficients results are probably caused by the fabrication tolerance. The simulated and measured normalized radiation patterns at 860 MHz in the xy- and yz-planes are shown in Fig. 7. Bidirectional endfire radiation patterns with low cross-polarization levels are achieved. Measured cross-polarization levels are higher than simulated ones as a result of the fabrication tolerance and dynamic range of the anechoic chamber. The asymmetry of measured radiation patterns is caused by a slight deformation of the supporting foam.

In addition, the simulated and measured peak gains of the proposed array versus frequency are shown in Fig. 8. The measured gain is better than 8 dBi from 800 to 900 MHz. There are some discrepancies between the simulated and measured results above 860 MHz. They are probably caused by the following factors: First, in the simulation, the feeding port is assumed to be a lumped port; the influence of the SMA is not taken into consideration. The soldering of the SMA will affect impedance matching and bring some discrepancy. Second, the relative permittivity of FR4 and foam used in the simulation may not be consistent with the fabricated prototype. Lastly, bend of the support foam may result in asymmetry of radiation patterns and cause the decreasing of peak gain.

IV. Conclusion

The design of a serial-fed array that is practical for coal mine/tunnel communication has been described in this letter. It consists of six meander-line-based folded dipole elements whose sizes are 100×29 mm^2, approximately $0.28 \times 0.08\ \lambda_0$. The cross section toward the ventilation direction is only 100×1 mm^2. This slim structure causes little effect on the ventilation air flow. The fabricated prototype provides a bandwidth of about 7.6% (834–899 MHz), and bidirectional endfire patterns with low cross-polarization levels in the azimuth and elevation plane are achieved. The peak gain is more than 8 dBi from 800 to 900 MHz.

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