Multi-band multi-mode end-fire antenna based on mirroring and scaling method

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Abstract: One multi-functional antenna with multi-band multi-mode property based on mirroring and scaling method (MSM) is proposed in this letter. The design procession could be divided into three steps: firstly, one former periodic end-fire antenna with bowtie dipoles is mirrored on the same substrate; then the mirrored part is scaled into about two thirds of the original size; finally, parameters are optimized for fine tuning target. This antenna has three different radiation modes at three different bands respectively, i.e. one \(+y\) directional mode in the lower band, one \(-y\) directional mode in the higher band and one bidirectional mode along both \(\pm y\) direction in-between the two bands. Both the field distribution and parameter analysis are given to explore the working principle. One prototype is fabricated for verification. With the advantages of planar structure, wide bandwidth and radiation pattern selectivity, the proposed antenna has a potential application in wireless communication system in the future.

Keywords: bowtie dipoles, periodic end-fire antenna, triple-band triple-mode

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Along with the coming of 5G era, traditional antennas have not satisfied the practical needs of large-volume and multi-function. In the wireless communication systems in tunnels, by deploying a bidirectional antenna at wireless base stations, both path loss issues and multipath effect can be mitigated [1]. In the military realm, in order to strengthen the maneuverability and concealment of equipment in electronic countermeasure (ECM), antennas with high-performance and multi-function have also become the development trend. With the higher request of portability, there will be less and less room for the antennas to be accommodated on mobile terminal devices. Among them, multi-band multi-mode (MBMM) antennas with different radiation patterns at each band are developed recently. MBMM antennas were usually designed based on microstrip antennas for their valuable advantages of low profile, low cost and easy integration [2, 3, 4, 5, 6].

For now, most of published MBMM antennas are designed based on metamaterial, multi-layers and complex feed network. In [7], a capacitive coupling-fed dual-band dual-mode antenna is proposed by introducing a circular radiating patch ring of modified mushroom cells. In [8], a dual-band dual-mode patch antenna with a CPW feed structure sharing a ground plane is proposed. In [9], the proposed MBMM antennas are designed by dual-layer and loaded with metamaterial structures. In [10], a four way power divider is designed to feed the antenna with two
different operating modes at two different frequency bands. However, all the modes of these antennas are a monopole mode with omnidirectional radiation pattern and a patch mode with patch-like radiation pattern.

Then a quasi-Yagi antenna with two opposite end-fire modes of unidirectional radiation patterns at two bands is proposed and it is based on loading with two split-ring resonators (SRRs) [11]. Nevertheless, the modes of the two bands are close with limited bandwidths and gains. In recent years, the bowtie dipoles or bowtie slot dipoles have been widely studied for their simple structure and broad impedance bandwidth [12, 13]. In [14], one broadband end-fire antenna with three dipole elements based on the idea of log-periodic antenna was proposed with an impedance bandwidth of 51.4\% for SWR ≤ 2.

In this letter, one novel MBMM antenna is realized by using the mirroring and scaling method (MSM). Based on the design in [14], three end-fire modes in three different bands are obtained by mirroring and scaling the antenna part into two thirds of the original size. Thus one +\( y \) directional mode in the lower band, one −\( y \) directional mode in the higher band and one bidirectional mode along both ±\( y \) direction in-between the two bands are achieved in one single substrate. One antenna prototype is fabricated and measured. Measured results show that −10 dB impedance bandwidths of 26\%, 24.8\% and 15.6\% with the maximum gains of 4.1 dBi, 6.0 dBi and 6.3 dBi are achieved for the three bands, respectively. High frequency structure simulator (HFSS) software based on the finite element method is used to design the antenna.

2 Antenna configuration and analysis

2.1 Mirrored geometry

As shown in Fig. 2, a symmetric structure is achieved by mirroring the geometry in Fig. 1. The antenna consists of a microstrip feed line, a transition from the microstrip line to a simple parallel strip line (PSL), a metal ground plate and three bowtie elements in different size. The three bowtie elements are arranged along the PSL with an equal flare angle. The parameters of the mirrored antenna are shown in Table I. It is fabricated on a substrate with thickness of 1.5 mm and a relative permittivity of 2.2. Fig. 3 shows the simulated results. Fig. 3(a) shows the −10 dB impedance bandwidths is 1.3 GHz (14\% at the center frequency of 9.15 GHz). Fig. 3(b) shows the current is distributed in the whole antenna, and, apparently, it is a bidirectional radiation pattern which is described in Fig. 3(c).
2.2 Mirrored and scaled geometry

The geometry of the proposed antenna is shown in Fig. 4. It is made up of two parts: the structure with original size in the right and the mirrored and scaled one in the left. The metal ground plate acts as a reflector to produce unidirectional radiation patterns [10]. Their radii are R1, R2, R3, R4, R5 and R6, respectively. The

| Symbol | Value | Symbol | Value | Symbol | Value |
|-------|-------|-------|-------|-------|-------|
| R1 (mm) | 9.2 | L0 (mm) | 6 | L4 (mm) | 9.3 |
| R2 (mm) | 7.5 | L1 (mm) | 10 | L5 (mm) | 3 |
| R3 (mm) | 5.625 | L2 (mm) | 4 | D (mm) | 2 |
| g (mm) | 1.4 | L3 (mm) | 11.5 | α (deg) | 70 |

Fig. 2. The mirrored structure.

Fig. 3. The simulated results of the mirrored antenna. (a) the simulated reflective coefficient. (b) the electric field distribution. (c) 3D pattern.

2.2 Mirrored and scaled geometry

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size of the antenna is 90 mm × 28 mm and it is fabricated on a substrate with relative permittivity of 2.2 and thickness of 1.5 mm. To realize better impedance matching, the width of the metal ground plate is tuned. The inner pin of the Sub Miniature-A (SMA) is connected to the microstrip feed line on the top layer, and its outer conductor is connected to the metal ground plate on the bottom layer.

In order to view the working principle of the three modes, the electric field distributions of the designed antenna at the three different resonant bands are given in Fig. 5. According to Fig. 5, at 6.0 GHz, the current is mainly distributed in the right part and only little energy is leaked into the left part, thus the +y directional mode could be obtained in the lower band; at 12.1 GHz, the current is mainly distributed in the left part and only little energy is leaked into the right part, thus the −y directional mode could be realized in the higher band; at 9.3 GHz, the current is distributed in the whole antenna and one bidirectional end-fire mode along both ±y direction could be anticipated accordingly. Analysis could be further explored by parameter study. When L1 turns to a higher value, the impedance matching becomes better, however it can’t be set too large otherwise it will lead to worse impedance match in low band (6 GHz). Meanwhile if L1 turns to a higher value, the climax of the middle band moves left on the frequency coordinate, which can be seen clearly in Fig. 6(a). Fig. 6(b) shows that changing R1 will affect the low band and has no effect on other bands. Bigger R1 creates better reflection coefficient and makes the climax of the low band move left obviously. R4 is an important parameter for high band. Fig. 6(c) shows the bigger R4 creates worse reflection coefficient of high band. Thus the three bands could be tuned and controlled individually as is needed.

**Fig. 4.** The mirrored and scaled structure

![Fig. 4. The mirrored and scaled structure](image)

**Fig. 5.** The electric field distributions of the designed antenna at three resonant frequencies. (a) 6.0 GHz. (b) 9.3 GHz. (c) 12.1 GHz.

![Fig. 5. The electric field distributions of the designed antenna at three resonant frequencies](image)
Considering reflection coefficient and radiation patterns at the three resonant points of the antenna, detailed values of the size were determined after optimizing by the simulation software HFSS, which can be seen in Table II.

### 3 Experimental result and discussion

A sample of the proposed antenna was fabricated and measured to verify the analysis. Fig. 7 shows the fabricated patch antenna with both top and bottom layers.

![Photograph of proposed antenna](a) (b)

**Fig. 7.** Photograph of proposed antenna: (a) top view (b) back view.

The full-wave simulation tool HFSS has been used to optimize the proposed antenna and detailed values of the sizes were determined based on the consideration of reflection coefficients and radiation patterns at the three resonant bands. The optimized parameters are given in Table I and Table II. The S-parameters were measured by using an Agilent N5230A network analyzer.

Fig. 8(a) shows that the measured reflection coefficient of the proposed antenna agree with the simulated ones well. The measured $-10\,\text{dB}$ reflection coefficient bandwidths of the three modes are 1.57 GHz (26% at the center frequency of 6 GHz), 2.24 GHz (24.8% at the center frequency of 9.3 GHz) and 1.93 GHz.
As shown in Fig. 8(b), the maximum gains measured by comparing with a standard horn antenna are 5.2 dBi, 6.95 dBi and 7.51 dBi for the three bands, respectively. The measured reflection coefficient of the middle band is a little wider than the simulated one. This may be due to the fabrication tolerances and the losses introduced by the SMA components and the dielectric.

As is shown in Fig. 9, both the simulated and measured radiation patterns were taken and compared at 6.0 GHz, 9.3 GHz and 12.1 GHz for both two planes. The xoy-plane and yoz-plane are corresponding to the H-plane and E-plane. According to Fig. 8, at 6.0 GHz, the antenna radiates on positive direction of Y axis; at 12.1 GHz, the antenna radiates on negative direction of Y axis; at 9.3 GHz, the...
The antenna radiates on both positive and negative direction of Y axis. The copolarization of the main beam differs by 20 dB from cross-polarization at all bands.

The contrast between the other similar design and the proposed one is given at Table III. Conclusions can be made as follows: (i) In addition to two opposite end-fire radiation patterns, the proposed antenna has one more bidirectional radiation pattern. (ii) The bandwidth of the proposed antenna is wider than the other designs because it is designed based on MSM instead of metamaterials with strong resonant characteristic which may lead to limited bandwidth.

| Type | Modes | Bandwidth1 | Model | Bandwidth2 | Mode 2 | Bandwidth3 | Mode 3 |
|------|-------|------------|-------|------------|-------|------------|-------|
| [9]  | 3     | 2.4%(1.24) | monopole | 1.2%(1.585) | patch  | 4.5%(1.895) | monopole |
| [11] | 2     | 3.2%(2.11) | end-fire | 7.9%(2.3) | end-fire | —— | —— |
| [15] | 3     | 2.2%(4.4)  | patch   | 4.5%(7.8) | monopole | 2.6%(9.4) | patch |
| Ours | 3     | 26%(6)     | end-fire | 24.8%(9.3) | end-fire | 15.6%(12.4) | end-fire |

4 Conclusion

A new approach for end-fire antenna to realize multi-band and multi-mode is investigated in this letter. The three bands and three distinctive radiation directivities are produced by the resonance of the bowtie dipoles with different sizes. The antenna operates at three modes: radiates on +y direction at the low frequency band, radiates on −y direction at the high frequency band and radiates on ±y direction at the middle frequency band. The electric field distribution, reflection coefficient and radiation patterns are given for confirming the working principle of the antenna. The measured results of the fabricated antenna show good agreement with the simulated results. With the advantages of broad impedance bandwidth, simple structure, multiband and radiation pattern selectivity, this antenna owns potential application value in wireless communication systems.

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