Design of Wideband Elliptical Ring Monopole Antenna Using Characteristic Mode Analysis

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Abstract

This paper presents the systematic design of an elliptical ring monopole wideband antenna using characteristic mode analysis. The modal analysis is used to analyze the bandwidth and the radiation performance of the radiating patch. The resonance frequencies of three characteristic modes are close to each other with similar modal current distributions and characteristic fields. These three characteristic modes are simultaneously excited by an effective feeding technique. The proposed model achieves wideband characteristics. The proposed model is printed on an inexpensive FR4 substrate with a size of 20 mm × 18 mm × 1.6 mm and has a wide impedance bandwidth of 124.4% in the range of 3.6–15.46 GHz. The prototype has been fabricated and the measured results show good agreement with simulated results. The antenna will cover WLAN, WiMAX, Wi-Fi, and X-band applications.

Key Words: Characteristic Modes, Elliptical Ring Patch, Surface Currents, Tapered Feed, Wideband Antenna.

I. INTRODUCTION

Recently, microstrip patch antennas (MSAs) have become more popular and attractive in mobile communication, global positioning system, satellites, military applications, and modern wireless systems due to their exciting attributes they are lightweight, have low production costs, are low profile, have conformal configuration, and are ease to integrate and fabricate [1]. Designing antennas with wideband characteristics is an important aspect to ensuring high data rates. However, microstrip antennas intrinsically have narrow bandwidth and low gain. However, practical applications currently require wider impedance bandwidth and small antennas. Many approaches have been tried to improve the bandwidth of various microstrip antennas [2–4]. These antenna designs have been performed through simulation and experimental studies. The initial design

procedure was based on engineering experience and parametric research but was not carried out systematically.

The Theory of Characteristic Modes (TCM) was initiated by Garbacz [5] in 1965 and subsequently revised by Harrington and Mautz [6, 7] in the 1970s. TCM can provide physical insights into the potential radiation properties of a conductive object. A conductive object naturally consists of characteristic modes (CMs), which are calculated numerically before using the source. Each CM consists of a characteristic angle or an eigenvalue that provides information about the mode resonance and resonant behavior. CMs depend only on the shape and size of the radiation element to govern the performance of the antenna design. TCM has been involved in the design of antennas for wireless applications [8].

The potential of TCM has been successfully extended to enhance the bandwidth of antennas including the bowtie antenna

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[9], an antenna with circular aperture [10], a dodecagonal-shaped antenna [11], a circular ring antenna [12], and an H-shaped slot antenna [13]. TCM was used to design a metallic loop wideband antenna with a size of $36 \text{ mm} \times 36 \text{ mm} \times 0.8 \text{ mm}$, in which two CMs were combined to improve the impedance bandwidth by 51.6% [14]. A combination of a dipole and a loop antenna with a size of $80 \text{ mm} \times 40 \text{ mm} \times 0.8 \text{ mm}$ was proposed, in which a wide impedance bandwidth reached up to 44.2% by simultaneous excitation of the first two modes [15]. TCM was used to analyze the resonance behavior of the rectangular U-slot patch antenna with the various feed techniques, exciting the modes that contribute to the total radiation [16]. The size of the proposed model was $140.17 \text{ mm} \times 134.54 \text{ mm} \times 7.62 \text{ mm}$, which aimed to achieve a wide impedance bandwidth of 96% by exciting three CMs such as 1, 3, and 4. These antennas have a complex feed structure to excite the desired modes and improve the antenna impedance bandwidth. The present paper aims to improve the bandwidth of a simple and small antenna structure by simultaneously exciting the first two modes with higher order modes using a simple microstrip feed technique.

II. CHARACTERISTIC MODE ANALYSIS

CM analysis is a process of solving an eigenvalue problem. The eigenvalues describe the radiation behavior of a radiating structure. Two important parameters involved in CMA for evaluating each CM of a given object are presented as per Chen and Wang [17].

Modal significance (MS) is represented as

$$MS = \frac{1}{|1 + j\lambda_n|}, \text{ a real quantity.} \quad (1)$$

In this case, λ_n is real eigenvector and n is the index of the order of each mode. MS is an inherent characteristic of each mode, specifying the ability to connect each mode to external sources. It measures each mode's contribution to the total electromagnetic response regarding a particular source. In some cases, it is easier to use the MS in addition to eigenvalues to examine the resonance of a structure. Regions of the frequency spectrum with $MS > 0.7$ are considered significant modes that are suitable for radiation. Ideally, the perfect radiating mode should be $MS = 1$ for $\lambda_n = 0$.

Characteristic angle (CA) is defined as

$$CA = 180^\circ - \tan^{-1}(\lambda_n). \quad (2)$$

CA can provide information about the behavior of the mode near the resonance. For $CA = 180^\circ$, the mode will be resonant. CA values are between 90° and 180° or 180° and 270° ; the modes are inductive or capacitive, respectively. For a good radiator, the $CA = 180^\circ$ for $\lambda_n = 0$.

III. CMA OF THE ANTENNA STRUCTURE

The CMA of antenna structures was analyzed using a multi-layer solver of the full-wave simulator. In the case of a multilayer solver, the radiating elements and ground plane were set as perfect electric conductors with a zero thickness, and the substrate component was set at loss-free with a thickness of 1.6 mm. CMA was applied to the antenna structure without a feed port. The basic structure of antenna-1 used for CMA is shown in Fig. 1 with the x-radius and the y-radius of the ellipse set to 5 mm and 6 mm, respectively. The geometry of the antenna-1 consisted of an ellipse-shaped patch and the partial ground plane, which were arranged on the top and bottom of the FR4 substrate.

The MS of the first six CMs is shown in Fig. 2. In this, modes 1, 2, 5, and 6 have large MS values at frequencies of 4.9, 8, 14.6, and 12 GHz; these modes are good radiators. Modes 3 and 4 have small MS values, so these modes are not good radiators. Here, surface currents are only considered for the radiating patch.

According to Fig. 3, the surface currents of the first six modes of antenna-1 are described as follows:

- Mode 1 consists of medium current density at the bottom of the ellipse contour.
- Modes 2 and 5 have more current density on the left and

Fig. 1. Geometry of basic antenna-1.

Fig. 2. Modal significance of the first six CMs of basic antenna-1.

Fig. 3. Surface currents of the first six CMs of basic antenna-1.

right contours and less inside the ellipse. The surface current direction for mode 2 is vertical upward, while for mode 5, it is the opposite. The centers of the top and bottom edges have null currents.

- Modes 3 and 4 form the current loops, indicating that these modes are not involved in radiation.
- Mode 6 has more current density on the top and bottom contour and less inside the ellipse. The surface current direction for mode 2 is horizontal. There are null currents at the centers of the left and right edges.

To reconfigure the surface currents of antenna-1, the dimensions of the ellipse in antenna-1 change according to the x- and y-radius of 8 mm and 4 mm, respectively, (as shown in Fig. 4). The geometry of antenna-2 is the same as that of antenna-1 with a modified dimension of the ellipse-shaped patch.

Compared with Fig. 2, Fig. 5 shows that mode 1 is almost identical at 4.9 GHz; however, mode 2 shows a shift from 8 GHz to 9.3 GHz. In addition to modes 5 and 6, mode 4 also has a large MS value at 14.6 GHz. Like antenna-1, mode 3 has a small MS value, so this mode is not a good radiator.

Fig. 6 describes the surface currents of the first six modes of antenna-2 as follows:

- Mode 1 consists of medium current density at the lower edge of the ellipse contour, which corresponds to that of mode 1 in antenna-1, and nulls appear in the upper area.

Fig. 4. Geometry of antenna-2.

Fig. 5. Modal significance of the first six CMs of antenna-2.

Fig. 6. Surface currents of the first six CMs of antenna-2.

- Mode 2 has a current density at the bottom of the ellipse and flows in the opposite direction to the null current.
- Mode 3 forms the current loop and indicates that this mode is not involved in the radiation.
- Mode 4 has a current distribution over the entire area of the ellipse in the horizontal direction. Null currents are present in the upper left and right angles.
- In mode 5, null is in the middle of the ellipse and medium current is present at the lower center.
- In mode 6, the current flow along the x-axis is split about null in the middle of the y-axis in the opposite direction.

Antenna-1 and antenna-2 are not suitable for wideband operation because the modes do not have common surface current areas for excitation. Therefore, to reconfigure the surface currents, the geometry of the new antenna-3 is formed by subtracting the radiating patch on antenna-2 from the radiating patch on antenna-1; then the resulting structure is rotated 90°. The proposed elliptical ring antenna is presented in Fig. 7.

The MS of the first six modes of antenna-3 is shown in Fig. 8. Here, only three modes 1, 2, and 4 are significant modes that

Fig. 7. Geometry of antenna-3.

Fig. 8. Modal significance of the first six CMs of antenna-3.

resonate at frequencies of 4.8, 6.7, and 7.54 GHz. Other modes are not significant. Unlike the surface current distributions of Figs. 3 and 6, Fig. 9 shows that the current distributions are concentrated in the four corners of the proposed antenna. The currents at four corners are described as follows:

- At the top left corner: the current flow of the three modes 1, 2, and 4 are in one direction.
- At the top right corner: the current flow of modes 1 and 4 is

Fig. 9. Surface currents of modes 1, 2, and 4 at frequencies of 4.8 GHz, 6.7 GHz, and 7.54 GHz of antenna-3.

in the same direction, but for mode 2, it is the opposite.

- At the bottom left corner: the current directions of modes 1 and 2 are the same, but for mode 4, it is the opposite.
- At the bottom right corner: the current directions of modes 2 and 4 are the same, but for mode 1, it is the opposite.

Through analysis of the surface currents of the CMs of the proposed antenna, four corners were found to be suitable for arranging the feed line in order to excite the desired modes. The bottom right corner of the radiating patch on antenna-3 was selected for placement of the microstrip feed line. This feed line had a width of 1.7 mm and length of 6 mm for wideband characteristics, as shown in Fig. 10. So that wider bandwidth can be achieved [18, 19], exciting multiple modes at their common current maximum with a suitable feeding technique and when they are proximally close enough is desirable.

Adding a microstrip line to antenna-3 creates a new mode 6 at 10 GHz along with modes 1, 2, and 4. This mode is called the feed mode. The modal significance of these modes, whose resonance frequencies are close to each other, is presented in Fig. 11. Fig. 12 show the surface current distributions for antenna-3 in the presence of the feed line. Fig. 12 shows that three modes 1, 2, and 6 have a similar current distribution through the feed line at their resonant frequencies of 4.8, 6.7, and 10 GHz. Fig. 13

Fig. 10. Geometry of antenna-3 with a microstrip line.

Fig. 11. Modal significance of the first six CMs of antenna-3 with a microstrip feed line.

Fig. 12. Surface currents of modes 1, 2, 4, and 6 at frequencies of 4.6, 5.4, 7.4, and 10 GHz of antenna-3 with a microstrip feed line.

Fig. 13. The 3D patterns of first six CMs of antenna-3.

shows that all modes have the maximum radiation in the z -direction, with the exception of mode 4, (the null current in the z -direction). As shown in Figs. 11–13, modes 1, 2, and 6 are significant modes and are likely to be excited due to their large MS values, similar current distribution on the feed line, and maximum radiation in the z -direction. Therefore, these three modes contribute more radiation in wideband operation. However, mode 4 is significant due to its large MS value, contributing less radiation to the total radiation of the antenna.

IV. WIDEBAND ANTENNA DESIGN

Characteristic mode analysis (CMA) can also provide insight into the physical aspects of the radiating patch. CMA also allows for change in the size and shape of the patch, offering use-

ful information regarding the optimization of the feed position of the basic antennas. By analyzing the modal significance of CMs and their surface currents, the four corners of the proposed structure are found to be well suited for the excitation of the desired modes. The same return loss S_{11} is obtained by placing the microstrip feed line at the four corners with the same dimensions of the substrate, feed line, and ground plane. Therefore, the microstrip line is considered properly selected at the bottom left corner of the proposed patch.

The geometry of the proposed antenna consists of an elliptical patch ring, microstrip feed line ($F_W \times F_L$), and the ground plane on the top and bottom of the substrate ($W_S \times L_S$) as shown in Fig. 14. The proposed antenna is printed on an FR-4 substrate of $18 \text{ mm} \times 20 \text{ mm} \times 1.6 \text{ mm}$, $\epsilon_r = 4.3$ and $\tan\delta = 0.025$ as shown in Fig. 15. The dimensions of the wideband monopole antenna are presented in Table 1.

1. Parametric Study

A parametric study was conducted to understand the performance of some parameters of the proposed design. The effect of

Fig. 14. Geometry of the proposed wideband monopole antenna: (a) top view and (b) bottom view.

Fig. 15. Photograph of the fabricated elliptical ring-shaped monopole wideband antenna: (a) top view and (b) bottom view.

Table 1. Dimensions of the proposed antenna

Parameter	Value (mm)
W_s	18
L_s	20
G_L	6.3
F_{Wt}	1.7
F_L	0.6
F_{Wt}	0.6

the tapered microstrip feed line and the length of the ground plane, G_L , on the return loss parameter, S_{11} were considered as discussed below.

Fig. 16 shows the variation in the width of the tapered microstrip feed line, F_{Wt} , from 0.2 to 1.0 mm and its effect on the return loss, S_{11} . The F_{Wt} value increases, the second resonant frequency shifts towards a higher frequency, while it decreases, the required bandwidth is smaller and the return loss does not fall below -10 dB. In both cases, the first resonant frequency does not significantly change. When $F_{Wt} = 0.6$ mm, the antenna has good return losses with a wide bandwidth. Therefore, $F_{Wt} = 0.6$ mm is chosen as the finest value of ground length over the operating frequency.

Fig. 17 shows the effect of a tapered microstrip line on the reflection coefficient. The proposed antenna is effectively excited by tapering the microstrip line (compared with no tapering) to achieve good return loss characteristics that provide a wide impedance bandwidth.

The effect of changing the ground length (G_L) on the return loss is shown in Fig. 18. With $G_L = 6.3$ mm, the antenna exhibits good return losses with a wide bandwidth. To decrease the value of G_L , the higher band moves toward a lower band of frequency and return loss does not fall below -10 dB. While in-

Fig. 16. Effect of the tapered microstrip line width F_{Wt} on the reflection coefficient.

Fig. 17. Reflection coefficient of the proposed antenna with and without tapered microstrip feed line.

Fig. 18. Effect of the ground length G_L on the reflection coefficient.

creasing, the return loss is smaller and the required bandwidth decreases. Therefore, ground length $G_L = 6.3$ mm is chosen as the finest value to achieve wide bandwidth.

V. RESULTS AND DISCUSSION

The network analyzer (Anritsu MS2037C/2) provided the measurement of electrical parameters of the proposed antenna. The wideband characteristics of the monopole antenna are discussed here.

The simulated and measured results of the return loss and gain of the elliptical ring wideband monopole antenna with good agreement are shown in Figs. 19 and 20. Fig. 19 describes the way that the lower resonant frequency of 5 GHz is almost the same in both cases, but the higher resonant frequency of 12 GHz shifts to a higher frequency compared to the simulation. The gain of the proposed model is maintained constant over the operating frequency range.

Fig. 19. Simulated and measured results of reflection coefficient.

Fig. 20. Simulated and measured results of gain.

The radiation patterns of H-plane and E-plane are presented at 5 GHz and 12 GHz resonant frequencies, respectively, as shown in Fig. 21. At higher frequencies, the radiation patterns are distorted due to higher order modes.

As shown in Table 2, the antenna size, number of modes excited, bandwidth, and gain of the proposed work are compared with the performance of existing antennas provided in existing literature [14–16].

VI. CONCLUSION

A new elliptical ring-shaped monopole wideband antenna was designed using CMA. The modal significance, surface currents, and modal patterns of first six CMs of the antenna structure were analyzed. The optimal feed position for driving multiple modes such as lower and higher order modes has been identified; a microstrip feed line was placed at respective current maximum to excite for wide bandwidth. The proposed antenna was shown to have a large impedance bandwidth of 124.4% in the range from 3.6 to 15.46 GHz, covering various wireless applications such as Wi-Fi and satellite communication.

Fig. 21. Radiation patterns: (a) 5 GHz for E-plane, (b) 5 GHz for H-plane, (c) 12 GHz for E-plane, and (d) 12 GHz for H-plane.

Table 2. Performance comparison between proposed work and existing antenna designs

Study	Size (mm ²)	No. of modes excited	Bandwidth ($S_{11} < -10$ dB) (GHz)	% BW	Gain (dB)
[14]	36×35	2	2.3–3.9	51.6	4
[15]	80×35	2	1.85–2.9	44.2	4
[16]	140.17×134.54	3	2.86–8.16	96	–
Proposed	20×18	3	3.6–15.46	124.4	4

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