Bandwidth Enhancement of a Dual-Polarized Slot Antenna Using Characteristic Modes

Chenghui Wang, Yikai Chen, Senior Member, IEEE, and Shiwen Yang, Senior Member, IEEE

Abstract—A wideband dual-polarized slot antenna is presented. The proposed antenna is designed in a systematic way using the theory of characteristic modes (TCM) for slot apertures. An H-shaped slot in an infinite ground plane is used as the initial structure for further optimization design. Magnetic characteristic currents for the first four modes of the slot are investigated. To enhance the bandwidth of the antenna, geometry of the slot antenna is then modified based on the clear physical insights obtained from the modal analysis. In addition, two pairs of differently-fed capacitive coupling elements are introduced to excite the first two modes of the slot and an integrated wideband feeding network is designed. An antenna prototype in WLAN 2.4-GHz band is fabricated. Experimental and simulated results show that the proposed dual-polarized slot antenna has a wide bandwidth and good dipole-like radiation characteristics. Compared with the initial H-shaped slot antenna, the bandwidth of the proposed antenna is enhanced from 17% to 46%. The measured port isolation over the entire frequency band is about 26 dB and the cross-polarization level is over 28 dB for the two polarizations.

Index Terms—Characteristic modes (CMs), magnetic modes, dual-polarized antenna, H-shaped slot, slot antenna

I. INTRODUCTION

Slot antennas attract great interest in many applications, especially in wireless communication systems where antennas with low profile height, light weight, and ease of integration with other microwave devices are highly demanded. Generally, slots are cut over a ground plane to obtain a slot antenna, and the slots are usually taken as the major radiation aperture. As a result, slot antennas with various types of slot shapes have been developed for many specific applications. For instance, slot shapes like ellipse [1], arc [2], fractal [3], and triangle [4] are proposed to realize wide impedance bandwidth. Square ring [5], circular ring [6], and cross-shaped slot [7] with two orthogonal microstrip feedlines are investigated for achieving dual-polarized radiations. Attempts to summarize design guidelines of slot antennas are reported in [8]. However, these design guidelines are proposed based on the simulation and experimental results reported in published literature. Investigations on the radiation mechanism are carried out based on the electric field distribution or current distribution of the slot antennas with excitation structures [9]. The initial design procedure is not performed in a systematic method.

Owing to the attractive features of the provided deep physical insights into the radiation mechanisms of antennas, the theory of characteristic modes (TCM) has been widely applied in antenna engineering. A comprehensive summary for the theoretical developments of TCM and its practical applications in antenna engineering is presented in [10]. Recently, there are

Fig. 1. Layout of the proposed dual-polarized slot antenna.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>DIMENSION PARAMETERS OF THE PROPOSED ANTENNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Param.</td>
<td>mm</td>
</tr>
<tr>
<td>SL1</td>
<td>6</td>
</tr>
<tr>
<td>W2</td>
<td>1.69</td>
</tr>
<tr>
<td>L4</td>
<td>29.5</td>
</tr>
<tr>
<td>L5</td>
<td>5</td>
</tr>
<tr>
<td>L</td>
<td>150</td>
</tr>
</tbody>
</table>

This work is supported by the Natural Science Foundation of China under Grant Nos. 61671127, 61631006, and 61721001. The authors are with the School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, P. R. China. Corresponding author: Yikai Chen. (e-mail: ykchen@uestc.edu.cn; ykchen@ieee.org).
quite a large number of papers discuss the applications of this modal analysis method in the design and optimization of many antennas [11]-[13]. As compared with the wide applications of the TCM in antennas with perfectly electric conducting (PEC) radiation apertures, a literature review found that there are only a few papers discussing the analysis and design of slot antennas using TCM. Systematic design of realistic antennas using the magnetic modal analysis directly conducted on slot apertures is rarely reported.

This letter focuses on how to apply the magnetic modal analysis to develop a H-shaped slot antenna in a systematic way. The features of the work lie in the direct characteristic mode analysis on the slot itself and proposing a systematic method for dual-polarized slot antenna designs with improved performance. The effectiveness of the proposed design method is validated through experiment.

II. MODAL ANALYSIS OF SLOT ANTENNAS

As a duality problem of the electric modal analysis for PEC structures, the TCM for aperture problems is developed from the admittance operator and solves the characteristic magnetic currents $M_n$. The characteristic magnetic currents could be solved from the following generalized eigenvalue equation:

$$BM_n = b_n GM_n$$

(1)

where $b_n$ is the eigenvalue of the nth characteristic mode, $n$ is the index of the order of each mode. $G$ and $B$ are the real and imaginary parts of the admittance matrix $Y:

$$Y = G + jB$$

(2)

To illustrate the potential radiation capability of each mode in the case ideal external source is applied, the modal significance (MS) is defined as follows,

$$MS = \frac{1}{1 + jb_n}$$

(3)

As can be observed, the modal significance lies in the range of [0, 1]. To provide a criterion to measure the bandwidth (BW) of each mode, a half-power BW is defined as follows [13],

$$BW = \frac{f_{H} - f_{L}}{f_{res}}$$

(4)

where $f_{res}$, $f_H$, and $f_L$ are the central resonant frequency, high end and low end of the frequency band with MS ≥ 0.707, respectively. A mode is considered to be significant and in the resonant state within the frequency range $[f_L, f_H]$. This information is helpful in the initial design stage when a feeding structure is not yet available.

A. Modal Analysis of an H-Shaped Slot in an Infinite Plane

To illustrate the design process of the final wideband antenna demonstrated in Fig. 1, an H-shaped slot antenna printed on a 1.5 mm-thick substrate with $\epsilon_r = 2.2$, as shown in Fig. 2(a), is taken as the initial structure for further optimization. This structure has also been discussed in [9]. To understand the resonant behavior of the H-shaped slot, modal analysis is conducted first. The modes are solved through an in-house MATLAB code based on the impedance matrices extracted from FEKO [14]. Fig. 3 shows the modal significance obtained from the magnetic modal analysis and the normalized radiation patterns of the first four dominant characteristic modes of the slot antenna at 2.5 GHz. For practical applications, it is reasonable to excite the first two modes simultaneously as both of the two modes radiate in the broadside direction. On the other hand, investigations on the $E_0$ and $E_\theta$ components of the modal fields of the two modes find that the two modes have orthogonal polarizations. From Fig. 4, we could also observe the orthogonality of the two modes from the magnetic current distributions over the slot aperture. Specifically, magnetic characteristic currents for mode 1 mainly distribute along the main slot. Currents in the upper and lower half segments of each side slot flow in the opposite directions. Magnetic characteristic currents for mode 2 mainly focus on the two side slots. As a result, far-fields contributed by characteristic currents of mode 1 and mode 2 are in perpendicular direction. Based on the modal analysis of the slot, we can easily come to a conclusion that the H-shaped slot is suitable for dual-polarized antenna. It can be achieved by exciting the first two modes.

B. Bandwidth Enhancement of the Slot Antennas

An investigation to the modal significance of the H-shaped slot antenna as shown in Fig. 3 finds that the mode 1 and mode 2 do not resonant exactly at the same frequency. Based on the magnetic current path for each mode shown in Fig. 4, shape of the slot are modified. Evolution of the slot antenna is presented in Fig. 2 and can be divided into two steps.

a) Shift the resonant frequencies of the selected modes into the operation band. It can be done by altering electric length of the current path or reactive loading. As indicated in Fig. 2(a) and Fig. 4(a), length of the magnetic current...
A symmetrical ridge suitable for slot. This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2018.2828881, IEEE Antennas and Wireless Propagation Letters

...path for mode 1 is \( L_{m1} + (W_{m1}) \). To increase the resonant frequency of mode 1, a modified H-shaped slot, shown in Fig. 2(b), is employed. The equality of the dimensions is defined such that resonant frequencies of the first two modes would be close to each other.

b) Enhance common bandwidth of the modes. To fully explore the useful bandwidth of each mode, it is ideally to move the two modes in the same band. A symmetrical structure modified from Design 2 is thus implemented. Comparison among the modal significances of the first two modes for the three slots are shown in Fig. 5. As can be observed, BWs of the proposed slot are greatly enhanced for both modes as compared with the initial H-shaped slot. Moreover, the common BW of the two modes are improved from 0%, 33.3% to 43.4% in the slot shape evolutions. As compared with the conventional antenna design and performance optimization method, magnetic modal analysis provides a convenient excitation-independent approach for slot antenna designs. This design procedure also removes the additional computation burden resulted from feedings.

III. DUAL-POLARIZED SLOT ANTENNA DESIGN

A. Feeding Network Design for the Proposed Antenna

To realize wideband dual-polarized antennas, we employ differentially-fed capacitive coupling elements (CCE) to excite the first two modes of the slots shown in Fig. 2. Geometries and S parameters of the antennas are shown in Fig. 6. With ideal 3 dB power divider and 180° phase shifter, CCE 1 and CCE 3 are combined to get port 1, and CCE 2 and CCE 4 are assembled to form port 2. As we can see, bandwidth of the resultant slot antenna is gradually enhanced during the slot evolution. The proposed slot antenna design method is quite suitable for slot etched on relatively large metallic ground. For antennas with compact sizes, impact of edge length of the square-shaped ground on the bandwidth is also investigated in Fig. 7. A 48% relative bandwidth is still achieved with much reduced size of 70 mm×70 mm, while the bandwidth for the initial H-shaped slot antenna is 13.6% with a ground size of 150 mm×150 mm and 17% with a ground size of 101 mm×80 mm in [9].

...
B. Measurement Results

According to the antenna structure illustrated in Fig. 1, a prototype antenna is manufactured. For RF-35 substrate of thickness 0.787 mm, permittivity 3.5, and loss tangent 0.0018, the optimized antenna dimensions are listed in Table I.

Fig. 8 compares the simulated and measured reflection coefficient for the proposed dual-polarized slot antenna. Measurements are performed with PNA-N5244A network. As can be observed, measured bandwidth from 1.86 to 2.97 GHz is obtained for $|S_1| < -10$ dB with a relative bandwidth of 46%, and good agreement is achieved between simulated and measured results. The bandwidth of the proposed antenna is compared to previous works in Table II. The proposed dual-polarized slot antenna achieves a considerable wide impedance bandwidth and smaller aperture size as compared with the H-shaped slot antenna [9], the triangular slot antenna [16], and the rectangular slot antenna [17].

Considering the reciprocity of a two port network, only the coupling coefficient $S_{11}$ is presented in Fig. 8. We can observe that the isolation between two ports is larger than 25 dB across the operation frequency band. Simulated and measured radiation patterns in both of the E- and H-planes at 1.95 and 2.95 GHz for port 1 are shown in Fig. 9. Due to the symmetry of the dual-polarized slot antenna, only the results for port 1 are shown. As can be observed, the measurement cross-polarization levels in both of the E- and H-planes are less than 28 dB as compared with the co-polarizations. Radiation patterns are quite stable over the operation frequency band. The measurement gain for port 1 at 1.95 GHz is about 4.5 dBi.

![Fig. 8. Simulated and measured S-parameters of the proposed slot antenna.](image)

<table>
<thead>
<tr>
<th>Refs.</th>
<th>Aperture size (λ^2)</th>
<th>Port 1</th>
<th>Port 2</th>
<th>Common BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>0.42 × 0.31</td>
<td>2.24–2.66 GHz</td>
<td>2.11–2.72 GHz</td>
<td>2.24–2.66 GHz</td>
</tr>
<tr>
<td>[16]</td>
<td>0.38 × 0.33</td>
<td>4.83–6.28 GHz</td>
<td>4.99–6.08 GHz</td>
<td>4.99–6.08 GHz</td>
</tr>
<tr>
<td>[17]</td>
<td>0.34 × 0.33</td>
<td>1.96–2.63 GHz</td>
<td>1.93–2.75 GHz</td>
<td>1.96–2.63 GHz</td>
</tr>
<tr>
<td>This work</td>
<td>0.29 × 0.29</td>
<td>1.86–2.97 GHz</td>
<td>1.86–2.97 GHz</td>
<td></td>
</tr>
</tbody>
</table>

* $\lambda$ is calculated at the frequency of the lower common BW limit.

IV. CONCLUSION

TCM has been applied to an H-shaped slot antenna in an infinite ground plane. Unlike the traditional electric modal analysis, magnetic modal analysis clearly shows the resonant behavior of the slot itself. The resonant frequency, magnetic current distribution, and radiation pattern of the CM of the slot are then solved. These information is then used to provide guidelines for the modification of slot shape in a systematic way to enhance antenna performance. Symmetric feeding structures are employed and wideband baluns are used to form the feeding networks. A prototype of the antenna has been fabricated. S-parameters and radiation patterns have been measured to validate the design. Owing to the wide bandwidth, high isolation, and pure polarization, the proposed antenna find wide applications in GSM1900, CDMA2000, WLAN/WMAX, and LTE communication systems.

REFERENCES


