Bandwidth Enhancement of Microstrip Antennas using Crossing Avoidance of Characteristic Modes

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***Abstract*—In this paper, a method of designing antennas by avoiding crossing between the modes is presented. This is aimed at enhancing antenna bandwidth using ground fragmentation techniques based on the characteristic modes analysis (CMA) approach. A compact and flexible Saxophone antenna and a conventional rectangular microstrip antenna both dimensioned at 30 × 30 mm^2 (0.66λ_g × 0.66λ_g) are designed to operate at 5.8 GHz to validate the proposed method. The proposed saxophone structure with a full ground enhances the bandwidth up to 170 MHz (2.97%) relative to the conventional antenna. This is then improved up to 890 MHz (14.67%) and 794 MHz (13.58%) when integrated with a fragmented and a partial ground plane, respectively. In comparison, the conventional antenna exhibited a bandwidth of 360 MHz (6.38%) and 410 MHz (7.25%) for these cases. Modeling is performed using FEKO software based on two approaches: the method of moments (MoM) and CMA. Results show a satisfactory agreement of the predicted resonant frequencies from simulations and measurements.**

***Index Terms*—Crossing avoidance, ground fragmentation, CMA, antenna.**

I. Introduction

Patch antennas are commonly used in wireless communication systems due to their benefits - low cost, thin profile configuration, compact size and ease of manufacturing and integration into microwave circuits [1]. They are generally capable of working in wide and multiple band frequencies when integrated with various broadbanding techniques. These includes increasing the substrate thickness, defected ground structures, introducing parasitic elements, introducing slots, and modifying the shape of patches [2-3].

Several recent bandwidth enhancement methods for wearable antennas have been proposed [4]. They include an antenna in [5] with full ground plane based on polydimethylsiloxane (PDMS)-embedded conductive fabric, which increased its bandwidth by more than 6 GHz and operated between 3.68 to 10.1 GHz on the human body. Next, the research in [6] implemented a simple slot in the radiating patch to operate with a bandwidth of up to 1200 MHz in free space and 1300 MHz on body. Besides that, a new wideband topology is presented in [7], consisting of a system of two coupled miniaturized eighth-mode resonant radiating cavities with a low-complexity feeding network.

The theory of characteristic modes (TCM) is another efficient method for designing antennas, as it can provide direct insight into the radiating phenomena of an antenna. TCM was first proposed by [9], before being refined by [10-11]. Characteristic mode analysis (CMA), which is derived from TCM enables a more systematic design procedure rather than a brute force approach [8]. This technique is gaining popularity due to its independence from the need of analyzing feeds and excitation. In addition to that, the substrate and the ground plane do not need to be included in the analysis [12]. Its minimal post-processing requirements in solving method of moments (MoM) surface integral equations reduces memory needs and CPU time overhead. Also, it allows the original MoM software architecture to be retained, and only the strong-matrix subroutines are changed.

The main focus of this study is to define a procedure for antenna bandwidth enhancement using crossing avoidances of the characteristic modes [13-14]. This method is applied onto two microstrip antennas: a conventional rectangular microstrip antenna and a saxophone-shaped patch antenna. CMA and MoM simulations are performed over broad frequency ranges using fragmentation/partial ground techniques. The use of the fragmentation technique enables the antenna to operate with different characteristic modes and with closely operating resonant frequencies. The relation between the number of crossing modes and the bandwidth improvement is studied in detail for each design step. As an innovative step, this paper applies the crossing avoidance method of characteristic modes to enhance the impedance bandwidth in a more complex radiator structure and compares its performance with a conventional rectangular antenna.

The paper is organized as follows. The detailed description of the proposed antenna is first presented in the next section, followed by the results and discussion in Section III. Finally, Section IV summarizes this paper.

II. ANTENNA DESIGN CONSIDERATION

This study involves the design of two antenna structures, one with a conventional rectangular shape, and the other a saxophone-like patch. Both antenna structures are formed with the radiating patch positioned on the top layer;

followed by a layer of 3-mm-thick Felt substrate (dielectric constant, εr = 1.3 and a loss tangent, tanδ = 0.044). A full ground plane forms the bottom-most layer. The conductive layers of this antenna is formed using ShieldIt Super® textile. As a first step, a conventional rectangular antenna is designed, with its patch dimensioned at $Wp = 24.11 \times Lp = 19.54$ mm^2 ($0.53\lambda_g \times 0.43\lambda_g$) based on the procedure provided in [15], (see Fig. 1). Next, a Saxophone patch antenna (SPA) is then designed, as depicted in Fig. 2. This patch is chosen as it can be designed within the same substrate dimensions as the rectangular microstrip antenna and can be fed using a microstrip line. This saxophone patch consist four parts: the neck, the body, the U-shaped bow, and the round, flared bell. Next, the generated modes in terms of modal significance from both antennas are evaluated with either a full, a fragmented, and partial ground plane, as illustrated in Fig. 3. The optimized parameters of the proposed structures are listed in Table I.

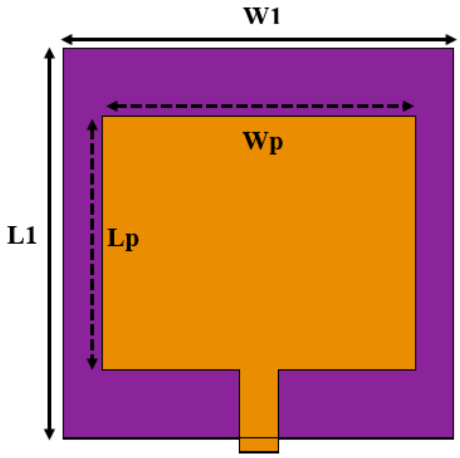


Fig. 1. Conventional patch antenna.

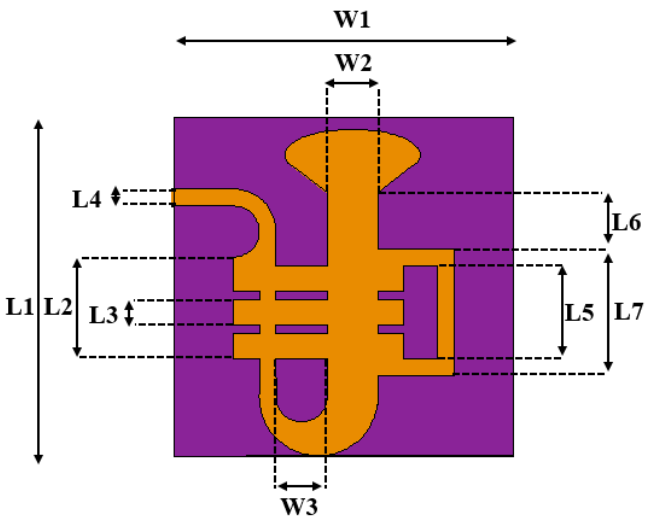


Fig. 2. Layout of the Saxophone patch antenna

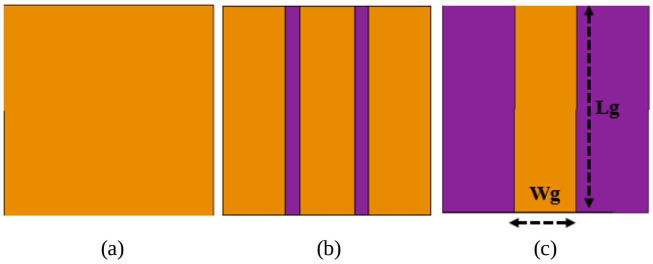


Fig. 3. (a): full ground (b): fragmented ground (c): partial ground.

TABLE I ANTENNA DIMENSIONS

Parameter	Value (mm)	Parameter	Value (mm)
W1	30	*L1*	30
W2	4.2	*L2*	9
W3	4.53	*L3*	2.25
Wp	24.11	*L4*	1.5
Wg	9	*L5*	8.25
L6	4.875	*Lp*	19.54
L7	11.25	*Lg*	30

III. WORKING MECHANISM AND RESULTS

The procedure to design these antennas by using the crossing avoidances of characteristic modes will be explained in this section. Crossing of these modes usually occur well above the resonant frequency of the structures. While antennas are not electrically large enough to face such phenomena, finite ground planes (e.g., mobile devices, vehicle chassis, buildings) are often large enough to cause characteristic modes to cross each other [16]. Thus, the main concept in this paper is to design antennas which modal significance avoids the crossing each other in all modes. This is aimed at obtaining an optimal (broad) impedance bandwidth. Note that the antennas used in this study are electrically small and operating near finite full ground planes.

First, the conventional antenna is analyzed using the full ground plane. It is observed that crossing of modal significance occurred in two areas between the three modes, as shown in Fig. 4. Besides that, its reflection coefficients are above -10 dB, indicating unsatisfactory bandwidth. Next, the full ground is fragmented into three partial planes. It is noticed that the resulting modes still crossed each other, as depicted in Fig. 5. On the other hand, the bandwidth is improved to 360 MHz based on a -10 dB minimum reflection coefficient. Finally, a single partial ground is used instead of three, which is centered over the radiator. One of the crossings between mode 1 and 2 is then eliminated, and a broader operating range is observed, as illustrated in Fig. 6. The impedance bandwidth is now improved to 410 MHz.

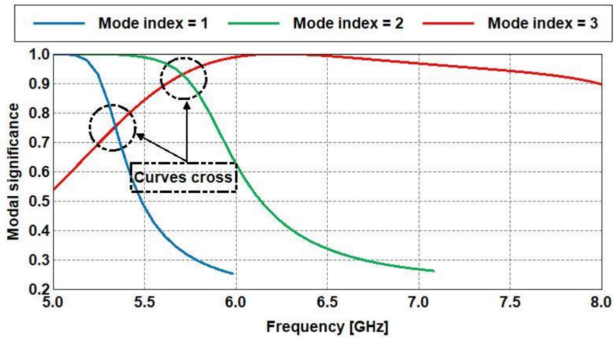


Fig. 4. Modal significance of the conventional antenna with full ground plane.

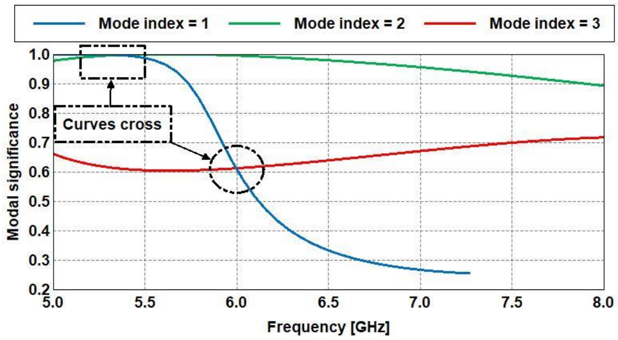


Fig. 5. Modal significance of the conventional antenna with fragmented ground plane.

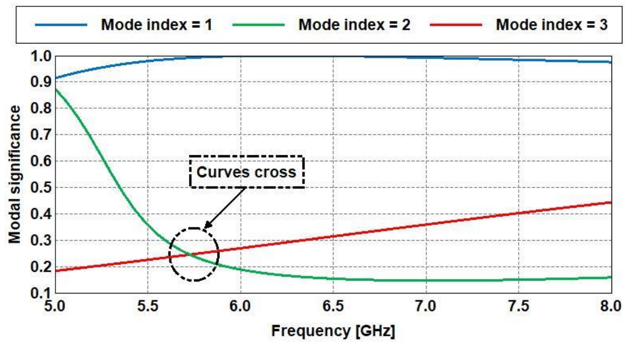


Fig. 6. Modal significance of the conventional antenna with partial ground plane.

In the next phase, the same ground plane variation and evaluation procedures for the conventional antennas are repeated for the SPA antenna. With a full ground plane, all modes 1, 2, and 3 crossed each other at 6.1 GHz, as shown in Fig. 7. Two operating bands are seen, each with a bandwidth of 170 MHz and 398 MHz at 5.69 GHz and 6.41 GHz, respectively. Next, when the fragmented and partial ground planes are used with the characteristic modes designed to avoid from crossing each other, as depicted in Fig. 8 and 9, respectively. It is evident that the bandwidth is significantly improved to 890 MHz and 794 MHz at 5.85 GHz and 5.8 GHz, respectively.

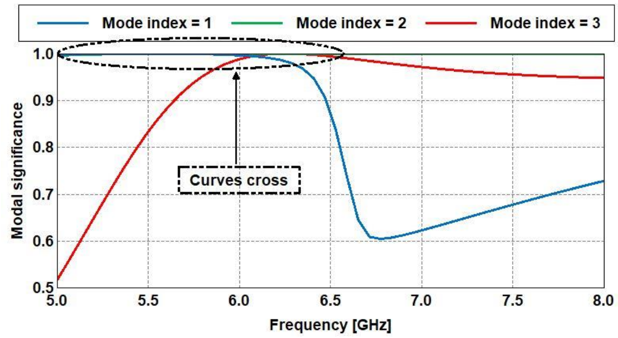


Fig. 7. Modal significance results of SPA with full ground plane.

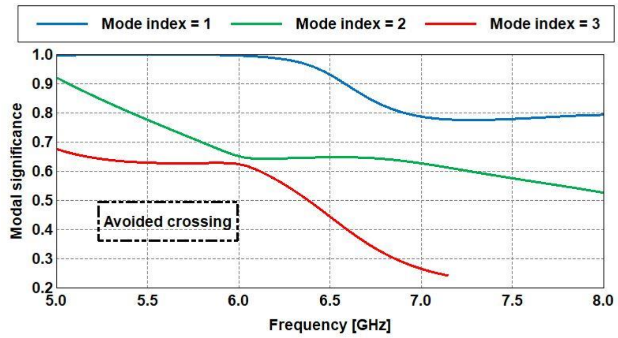


Fig. 8. Modal significance of SPA with fragmented ground plane.

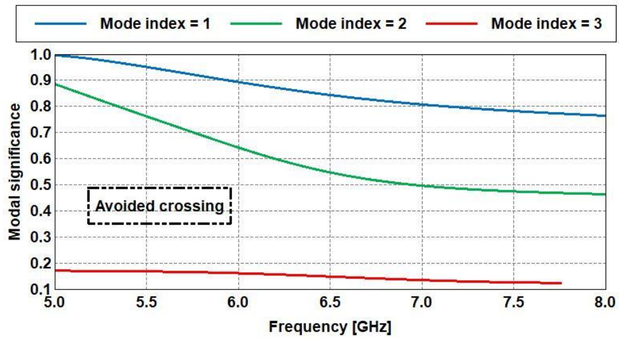


Fig. 9. Modal significance of SPA with partial ground plane.

The calculated reflection coefficient and bandwidth for the antenna are summarized in Fig. 10 and listed in Table II.

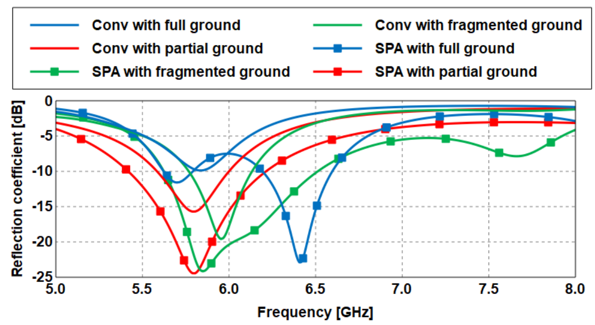
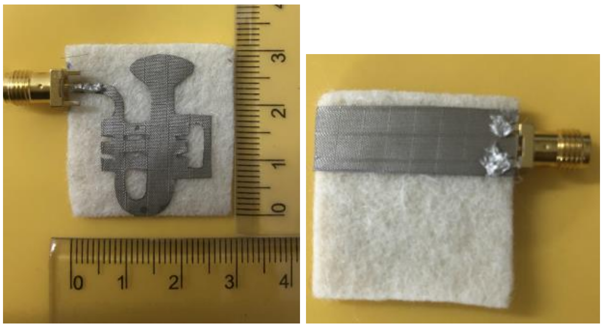


Fig. 10. Reflection coefficients for different antenna configurations.

TABLE II REFLECTION COEFFICIENTS AND BANDWIDTH FOR DIFFERENT DESIGN CASES

Cases	Resonant frequency (GHz)	Reflection coefficient (dB)	Bandwidth (MHz)
Conventional antenna + Full ground	5.83	> -10	---
Conventional antenna + Fragmented ground	5.95	-19.59	360
Conventional patch + Partial ground	5.79	-15.71	410
SPA + Full ground	5.69	-11.59	170
	6.41	-22.89	398
SPA + Fragmented ground	5.85	-24.16	890
SPA + Partial ground	5.8	-24.47	794

A prototype of the SPA was fabricated using manual cutting tools before being evaluated experimentally (see Fig. 11). The measured reflection coefficient in Fig. 12 indicates a -10 dB reflection bandwidth of about 800 MHz (from 5.48 to 6.28 GHz).



(a) (b)

Fig. 11. prototype of fabricated antenna. front view (left), back view (right).

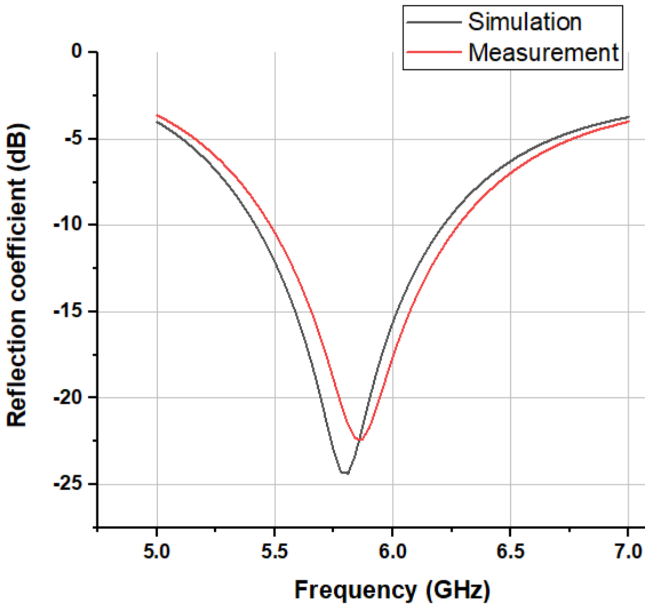


Fig. 12. Simulated and measured reflection coefficients at 5.8 GHz.

IV. CONCLUSION

This work proposes a method to enhance the impedance bandwidth of antennas by avoiding crossings between their characteristic modes. This is performed by using fragmented/partial ground planes instead of a full ground plane. A compact and flexible saxophone antenna was designed using two approaches: CMA and MoM, using the same FEKO simulator. The cross avoidance of mode method applied in its design process resulted in a maximum bandwidth of 890 MHz across the 5.8 GHz. The prototyped and measured antenna is validated to be very similar to the performance predicted by simulations.

ACKNOWLEDGMENT

This work was supported in part by the Malaysian Ministry of Higher Education (grant no: FRGS/1/2020/TK0/UNIMAP/02/19) and in part by the Academy of Finland 6Genesis Flagship (grant no. 318927).

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