# A Systematic Design Method of Miniaturizing Microstrip Patch Antenna using Theory of Characteristic Modes

ECE I

***Abstract*—A systematic crostrip patch antenna u presented. The TCM is a currents to excite the low patch. The first current r distribution, and J2 show direction of the width of been done to procure th modes. The slot etching w first in vertical and then of the patch. The success mode, i.e., J1, was achie direction of J1. After opti % miniaturization than th no significant deterioratio**

***Index Terms*—antennas,**

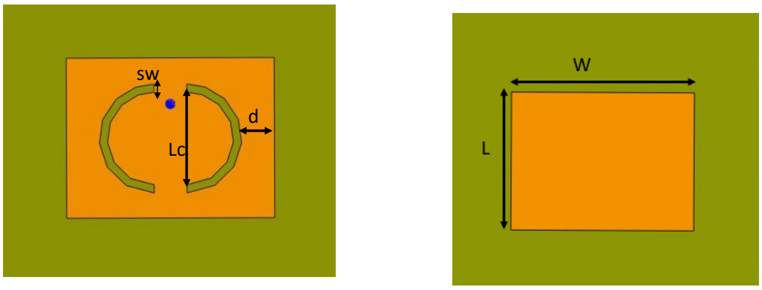



Fig. 1. Geometry of rectangular patch antenna

## I. Introduction

Antennas are a critical part of modern low profile wireless sensing devices and must be compact for easy integration. Therefore, patch antennas are a popular solution for many wireless applications [1]- [3]. Various miniaturization methods have been reported in the literature, e.g., bending the branches of the monopole antenna and etching the slots on the conducting patch [4]- [5].In [6], By etching a series of slots with various shapes on the antenna, the size of the antenna was reduced effectively. Alternatively, as proposed in [7], the meandering line and shorting strips are used for miniaturization. However, most of these methods do not follow systematic design procedure and they depend on several iterations for optimization.

The theory of characteristic modes(TCM) is widely used for optimizing the antenna structure via efficient excitation or current manipulation of the modes [8]- [10]. Using TCM, The antenna structure can be fully characterized by a finite number of orthogonal current modes, which gives insight into the antenna structure and helps in systematic analysis and design of antenna structure. In [5], the antenna was miniaturized systematically using edge curving, stub loading, and aperture etching with the help of TCM. In [9], The characteristic mode analysis (CMA) method was used to explore the operating mechanism of the CP radiation to miniaturize the antenna.

In this paper, the information on the direction of modal current of the lowest resonating mode was used to miniaturize the antenna. In this design process, the patch was analyzed to find the optimum slot etching method to excite the lowest resonant mode, thus finding the limit of miniaturization. Compared to the original rectangular patch operating at the same frequency, the miniaturized antenna has a 60% miniaturization in the size of the antenna.

## II. Conventional Microstrip Patch

The configuration of the conventional antenna is shown in Fig1. The antenna was designed on an FR4($\epsilon_r$=4.3) substrate with a 1.6mm thickness, dimensions 29.39mm in length, and 37.93mm in width. The antenna's return loss is shown in Fig.9. The antenna resonates at 2.4 GHz with peak gain of 5.9 dBi and directional pattern as shown in Fig.13. The dimensions of the microstrip patch antenna, including its length and width, are typically designed to achieve resonance at a specific frequency. The resonance frequency of a microstrip patch antenna is primarily determined by the effective electrical length of the patch, which is influenced by both the physical length and the electrical properties of the substrate.

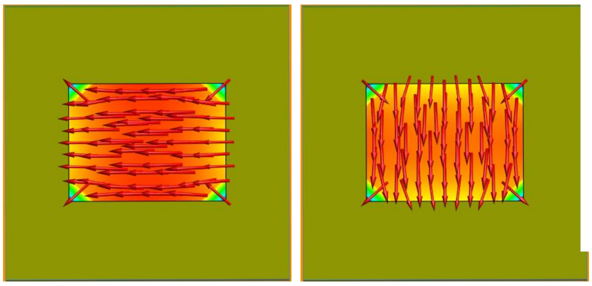
## III. CMA and Miniaturization

When the current path length of a microstrip patch antenna is increased, it alters the effective electrical length of the patch, thereby shifting its resonant frequency. As a result, the wavelength at which the antenna resonates also changes. Increasing or manipulating the current' path length using slots enables the formation of larger wavelength. Hence, it is an effective technique to lower the frequency or miniaturize the antenna. In order to determine the appropriate modification to the path length, the Characteristic Modal Analysis (CMA) was applied. The total current J of the antenna structure can be

TABLE I
DESIGN VALUES OF ALL VERSIONS OF ANTENNAS

| Parameters(mm) | L | W | sw | d1 | d2 | Lc | sh |
|---|---|---|---|---|---|---|---|
| rect[a] | 29.39 | 37.93 | - | - | - | - | - |
| DM[b] | 29.39 | 37.93 | 1.55 | - | - | 16.9 | - |
| SM[c] | 29.39 | 37.93 | 3.5 | 12 | 13 | 16 | - |
| SMwithslot | 29.39 | 37.93 | 6 | - | 12 | 10.5 | 9 |

[a]rect=Rectangular patch,
[b]DM=Double Moon,
[c]SM=Single Moon



(a) J1@1.89GHz (b) J2@2.4GHz

Fig. 2. Surface current distribution of the rectangular patch

decomposed into finite set of orthognal characteristic modes as follows:

$$J_{tot} = \sum_{n=1}^{N} \alpha_n J_n \tag{1}$$

Where $\alpha_n$ is the modal weighting coefficient (MWC) that determines contribution of n[th] characteristic mode to the total surface current J upon excitation. Another important parameter to analyse the resonant behavior of modes is modal significance

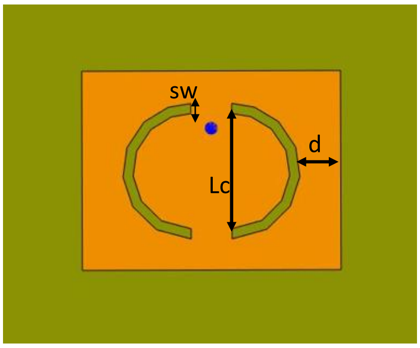
$$MS = \frac{1}{|1 + j\lambda_n|} \tag{2}$$

Its value shows the resonance potential of particular mode at that frequency. CMA illustrates the direction of surface currents of characteristic modes. Upon examination of the surface current plot in Fig.2, it can be seen that the first two modes, J1 and J2, are characterized as horizontal and vertical current modes respectively. The remaining modes are more intricate and complex. J1 resonates at 1.89 GHz and J2 resonates at 2.4 GHz as shown in modal significance plot in Fig.10.It can also be observed from modal weighting coefficient plot in Fig.11 that a rectangular patch resonates at 2.4 GHz due to the J2 i.e., vertical current mode being excited. After analyzing the characteristic modes, two ways of miniaturization were selected that describes as follows

1) Elongate the current path length using slots that excite J2 at a lower frequency.
2) Excite J1 that resonates at more lower frequency i.e., 1.87 GHz.

### *A. Vertical Moon-shaped Slot*

To further investigate that concept, The patch was manipulated by introducing two symmetrical vertical arcs or moon-shaped slots on the patch as shown in Fig.3; the resonating



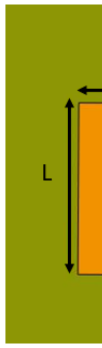
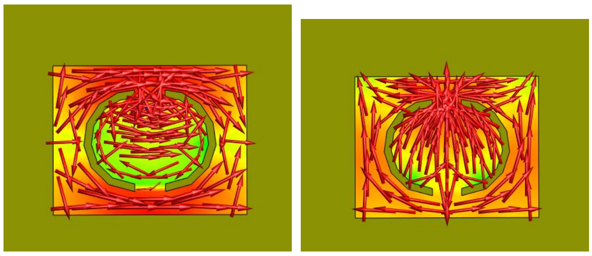
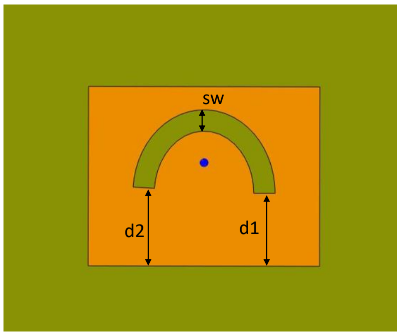




Fig. 3. Geometry of Double moon vertical patch antenna





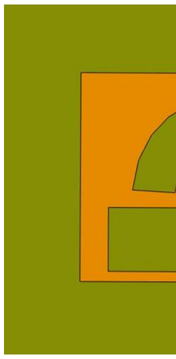
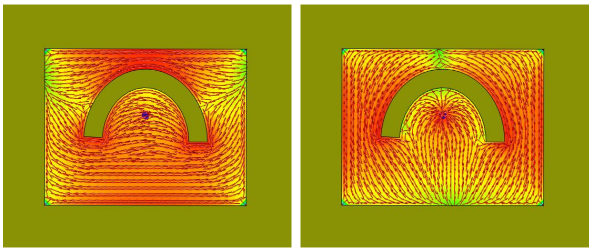



Fig. 5. Geomtery Single moon horizontal patch antenna

frequency was shifted to 2.1GHz. The design values are given in TableI.The modal significance showed that the introduction of moon-shaped slots moved the resonant frequency of J1 and J2 to 1.467 GHz and 2.1 GHz. The surface current plot showed that vertical arcs elongates the current path for J2 more effectively than J1 and J1 showed null in the middle ( See Fig.4). It can also be observed from the modal weighting coefficient plot that the antenna is resonating due to the excitation of J2 at 2.1 GHz. Several optimization attempts of feed location and slot position and slot width did not help excite the lowest resonant mode, i.e., J1. Another drawback of the vertical moon was that it showed null at 2 GHz, as shown in the plot of boresight gain.

### *B. Horizontal Moon-shaped Slot*

To excite the lowest resonant modes, a moon-shaped slot was etched in perpendifular to the direction of vertical slot



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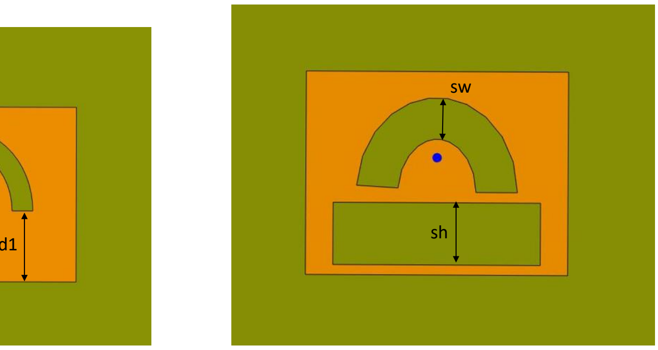
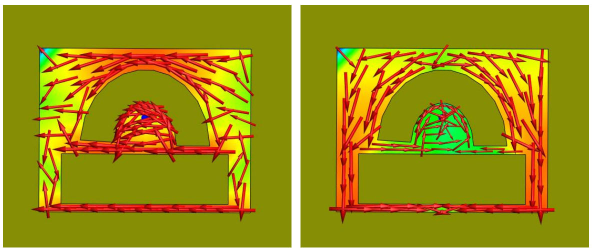



Fig. 7. Geometry of Single moon horizontal patch antenna with slot



(a) J1@1.5GHz (b) J2@1.71GHz

Fig. 8. Surface currents of single moon horizontal patch antenna with slot

and in parallel to the direction of horizontal currentmode i.e., J1. The surface current plot in Fig.6 shows that the moon-shaped slot causes the elongation of the current path length in J1. The current mode J1 resonated at 1.67 GHz, and J2 resonated at 1.925 GHz . After examination of the modal weighting coefficient and return loss, it was concluded that J1 can be excited after optimization. After parametric study and optimization of slot width, arc radius, and feed location optimization, the antenna resonates at 1.67 GHz, causing 43.7%miniaturization. It can be seen from the normalized modal weighting coefficient plot, too, that J1, i.e., the horizontal current mode, was excited(See Fig.11). It can also be observed that the moon shape also helped in stabilizing the boresight gain for a wide frequency range as shown in Fig.12, and the null at 2 GHz was disappeared.

### *C. Horizontal Moon-shaped Slot with Horizontal slot*

To further miniaturize the antenna, another slot was etched parallel to the direction of surface currents beneath the moon-

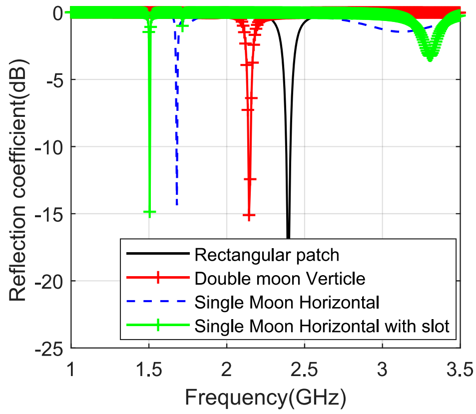



Fig. 9. Comparison of reflection coefficient of all versions of antenna

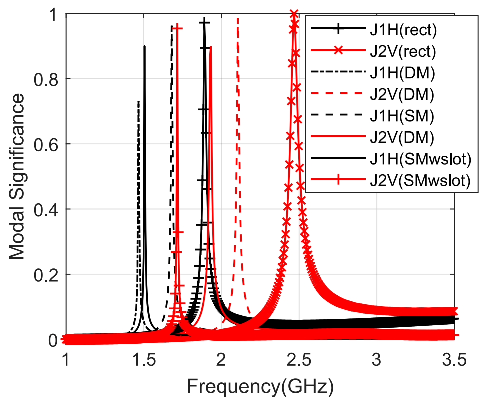



Fig. 10. Modal significance of all versions of antenna

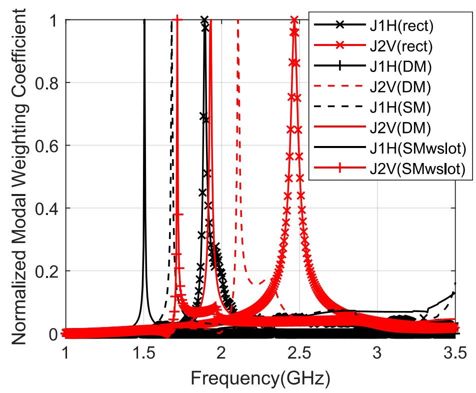



Fig. 11. Normalized weighting coefficient of all versions of antenna

shaped slot that causes further elongation of the current path, as shown in Fig.7. The characteristic mode analysis of the structure revealed that the structure has the potential of resonating at 1.5 GHz due to the resonance of J1 at 1.5 GHz(See Fig.10). After further optimization, the structure resonates at 1.5 GHz, causing 60% miniaturization. The antenna exhibited stable gain over a wide range of frequencies with a peak

TABLE II
COMPARISON OF ORIGINAL ANTENNA WITH MINIATURIZED ANTENNA

| Antenna Type | Operating Frequency(GHz) | Peak gain(dBi) | Return Loss(dB) | Area($mm^2$) |
|---|---|---|---|---|
| Original | 2.4 | 5.9 | 20 | 1114.7627 |
| Miniaturized | 2.4 | 5.8 | 22 | 461.7 |

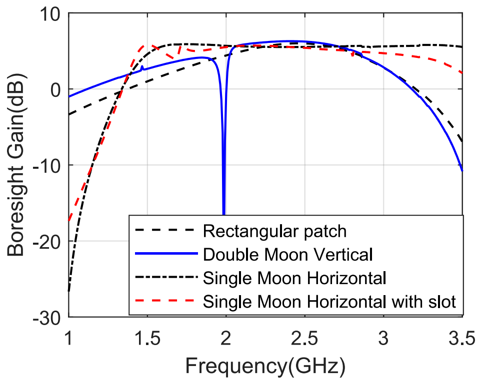
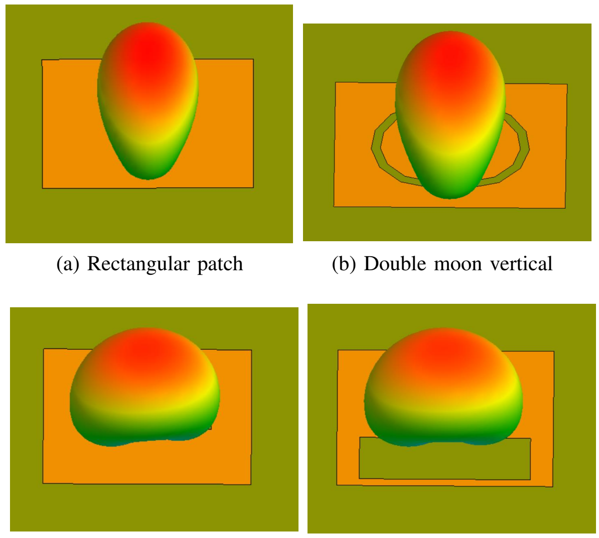



Fig. 12. Boresight gain of all versions of antenna



(a) Rectangular patch (b) Double moon vertical
(c) Single moon horizontal (d) Single moon horizontal with slot

Fig. 13. Radiation pattern of all versions of antenna at their resonance frequencies

gain of 5.8dBi at 1.5 GHz. Table I showed design values of all versions of antenna. The whole optimization procedure is not described here for brevity, but It was concluded that characteristic mode analysis provides intuitive insight for miniaturization. In the miniaturization process, the microstrip patch structure was evolved to the moon-shaped slot antenna. However, examining characteristic modes of simple structure led to a systematic miniaturization process. Slot etching is an old technique for miniaturization. However, to excite specific modes, the slot etching parallel to the direction of that particular current mode helped in antenna miniaturization up to 60%. The 3D radiation patterns of all versions are shown in Fig.13. The miniaturized design resonates at 2.4 GHz with over all dimensions $0.152\lambda_o \times 0.194\lambda_o \times 0.0128\lambda_o$. The final design showed no deterioration in its performance as shown in Table II with significant reduction in its foot print.

## IV. CONCLUSION

This paper presented a design approach to miniaturize the rectangular patch antenna using TCM. TCM gives critical insight into the direction of currents for J1 and J2, and its modal significance showed the resonant frequencies at which these modes are likely to be excited. It was observed that current path length manipulation parallel to the direction of vertical current mode excited J2, but slot etching parallel to the direction of lowest resonant mode, i.e., J1 excited J1. The excitation of J2 gives 14% miniaturization, but J1 excitation led to 60% miniaturization of the antenna.

## V. ACKNOWEDGEMENT

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