

# Characteristic Mode Analysis Based X-Band Defected Dodecagonal Patch Antenna

Bharath Ganji, Riyaz Hussain Shaik

**Abstract:** A defected dodecagonal microstrip antenna fed through co-planar waveguide and operating in X-band frequency range(8-12 GHz) is proposed. Characteristic mode analysis is employed in examining the impact of defects on the resonant frequencies and return loss. Contrast in return loss for the suggested antenna with and without defects is dealt through Characteristic mode Analysis. Geometrical aspects of the proposed antenna are 40 mm × 35.5 mm × 0.1 mm. Substrate material used in design is FR4 with a dielectric constant ( $\epsilon_r$ ) = 4.4 and height ( $h$ ) = 0.1m. CST Microwave Studio is used to simulate antenna parameters and Characteristic mode analysis. A return loss of -49.5dB at center frequency of 10.12GHz is observed with a fractional bandwidth of 47.6%. Gain of the antenna peaks at 4 dBi in the band of operation.

**Index Terms:** CPW, Characteristic modal analysis(CMA) , X-band, Microstrip patch ,CST.

## I. INTRODUCTION

Microstrip antennas are influential in the proliferation of compact wireless systems and RF integrated circuit technologies. Planar characterization along with the ease of fabrication through printed circuit board technology makes microstrip antennas more appealing for integration into innumerable industrial applications. Nonetheless, an improper feeding scenario leads to narrow impedance bandwidth. Growing demand for broad frequency bandwidth in both defense and commercial application makes it challenging for microstrip antenna designer.

A range of 8 GHz to 12 GHz on the electromagnetic spectrum is allocated as X-band by IEEE Standard. Typically applications in this band include radar, terrestrial and satellite communications[1], remote sensing, surveillance, and telemetry. Some of the antenna designs in X-band include tracking based Radar systems, microwave linear accelerators design used for medical purposes like radiation therapy[2], Low-Power High-Sensitivity SAR Imaging System[3], dual-polarized arrays for Airborne applications like air traffic control [4,5], surface water and ocean topography satellite antennas [6], rosetta(deployed to study comet Churyumov-Gerasimenko)space probe's deep-space communication antenna [7]. The proposed antenna uses a dodecagonal shaped patch with adjoining defects. Dodecagon is a twelve-sided polygon with twelfth order rotational symmetry. Dodecagonal shaped microstrip patch with fractals fed through microstrip line is proposed in[8] for

ultra-wideband(UWB) applications. In[9] RFID with circular polarization using a slotted dodecagonal patch fed coaxially is proposed. Our proposed antenna uses a coplanar waveguide feeding technique. Out of the copious methods for feeding patch antenna [10], coplanar waveguide(CPW) feeding is applied to the design because of its easy integration into front end rf circuits and nominal radiation loss. For the CPW feed to be consonant with radiating structure a compatible and decent transition between the feed and radiating patch must be formulated. A CPW feed antennas in X-band are proposed in[11,12,13] either with a nominal impedance matching or less X-band purity.

In this paper, antenna with wide bandwidth spanning X-band is proposed. To enhance the performance of feed though good impedance matching defects [14] are introduced in the dodecagonal patch surface. Defected ground structures (DGS) are sequenced defects on a ground conductor engraved either with recurrent or non-recurrent planar cuts which alter properties of the line such as line inductance and capacitance because of the effect of defects on distribution of current. Diverse DGSs have been proposed substantially in microwave circuits[15]. Antenna design with defects on the patch surface to reduce cross-polarization is proposed in [16]. To achieve optimal coupling placement and shape of the defects are analyzed through characteristic mode analysis(CMA). CMA provides perspective into the placement and design of the antenna. This technique is formulated through the evaluation of fundamental resonant characteristics of antenna structures. Coupling of energy between a given eigenmode and source is accounted for by the position and orientation of the excitation source. Insight into characteristics of individual eigenmodes enables an antenna designer to model desired characteristics by exciting a linear summation of the calculated eigenmodes. Though cavity model is usually used for analyzing microstrip structures it doesn't account for any internal coupling whereas CMA derived from Method of moment architecture accounts for internal coupling making it expedient for antenna design[17]. Method of moments(MoM) based simulators or MoM impedance matrix is used for analysis of CMA.

Characteristic Modes analysis was beneficial in the evaluation and synthesis of numerous antennas, like electrically small antennas, linear wire antennas, mobile handset planar antennas[18].CMA is employed in various planar antenna of which few include estimation of the resonance, excitation of circular polarization and location of feed[19], mode excitation in metasurface antenna[20], effects of ground plane dimensions[21], Placement and dimensional analysis of slot [22], wideband

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omnidirectional antenna[23].

II. ANTENNA DESIGN USING CMA

A. CMA Formulation

Characteristic modal analysis(CMA) as suggested by Harrington and Mautz [24] provides a numerical framework for calculating Eigen current on a metallic structure. CMA design approach yield physical insight into the resonant frequency and optimum feeding arrangements of these orthogonal modes. Calculation of eigen currents is done through eigen equation as stated in equation(1). This equation includes the real part of MoM matrix and the intended eigen currents are independent of any source excitation

$$[Z]\vec{J}_n = \lambda_n [R]\vec{J}_n \tag{1}$$

Where  $[Z]=[R]+j[X]$  and  $J_n$  are the characteristic Eigen currents, and  $\lambda_n$  are the corresponding eigenvalues that are dependent on geometry and shape of the structure

Eigenvalue  $\lambda_n$  is the ratio of energy stored near the structure to the radiated energy. Modes with

- $\lambda_n = 0$  Mode at resonance and all energy radiated
- $\lambda_n < 0$  Stored energy is dominated by electric energy, a capacitive mode
- $\lambda_n > 0$  an inductive mode

Orthogonality properties of modes enable expansion of any unknown currents on the antenna surface as a sum of basis set of characteristic eigenmodes on the surface[25].

$$J = \sum_n \frac{V_n^i J_n}{1 + j\lambda_n} \tag{2}$$

Total current contribution to each mode can be delineated from the magnitude, position, and phase of excitation field ( $E^i$ ) through modal excitation coefficient ( $V_n$ ) as given in the equation (3)

$$V_n^i = \langle J_n, E^i \rangle = \iint \vec{J}_n \cdot \vec{E}^i ds \tag{3}$$

Instead of the eigenvalue ( $\lambda_n$ ) more insightful parameters like modal significance of an eigen modes (MS) and characteristic angle (CA) of an eigen modes are used to study the resonant properties of the structure. Modal significance (MS) characterize amplitude of modal currents and is formulated as[26]

$$MS = \left| \frac{1}{1 + j\lambda_n} \right| \tag{4}$$

As observed from equation (2) modal expansion of the current is inversely dependent inversely on the eigenvalues, so rather than using isolated eigenvalues we can use MS for more variational analysis for a given structure. MS is independent of the excitation but depends only on the geometry of the conducting object. The value of modal significance(MS) lies between one and zero. If the value of MS is close to the maximum value it accounts for the resonating condition of the associated mode. Width of frequency on the model significance curve around the maximum value determines the radiation bandwidth of a particular mode.

Characteristic angles(CA) of an eigenmode is defined as[26]

$$\alpha_n = 180^\circ - \tan^{-1}(\lambda_n) \tag{5}$$

CA of a particular mode accounts for the phase difference between eigen currents, and their associated electric field.CA value near  $180^\circ$  implies a good radiator whereas CA near to

$90^\circ$  or  $270^\circ$  indicates that mode is associated with stored energy.

B. Antenna design

The geometric depiction of the suggested antenna is shown in fig.1. A dodecagonal shape patch is infused with defects and fed though coplanar waveguides. The antenna is designed with a substrate material (FR4) having relative permittivity  $\epsilon_r= 4.4$  , loss tangent  $\tan\delta=0.02$  . The substrate used for antenna design is 0.1 mm thick, as proposed in [26]. These kind of thin substrates are flexible and have significant applications in flexible electronics[27]. The dimensions of the CPW feeding is taken in a way to ensure a line impedance of 50 ohms [26]. The dimensions of the substrate are 35mm x 35mm x 0.1mm. Dodecagon is designed with a circumradius(R) of 10mm.Circumradius(R) and side length(a) of dodecagon are related as

$$a = 2R \tan\left(\frac{\pi}{12}\right) \tag{6}$$

Defects with length and width of 8.8mm and 1mm are taken respectively. These defects are placed symmetrically about the feed with distance(d) between them. This distance is taken between the edges of the defects. All parameters mentioned are tabulated below in the table

TABLE 1. Antenna Design Parameters

Substrate Length (L)	40 mm
Substrate Width (W)	35.5 mm
Substrate thickness (H)	0.1 mm
Length of Ground plane(L <sub>G</sub> )	8 mm
Width of Ground plane(W <sub>G</sub> )	0.1 mm
Gap between the ground plane and feed(W <sub>GAP</sub> )	0.5 mm
Feed Width (W <sub>F</sub> )	1.5 mm
Length of Feed(L <sub>F</sub> )	9.54 mm
Length of Defect(L <sub>D</sub> )	8.8 mm
Width of Defect(W <sub>D</sub> )	1 mm
Distance between defects(d)	5 mm
Circumradius of dodecagon(R)	10mm

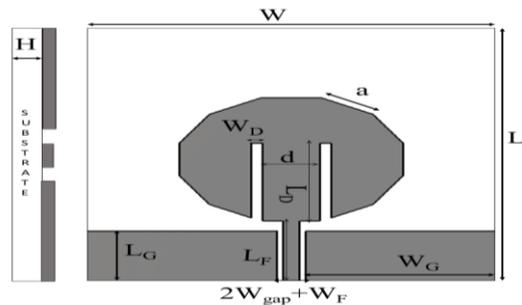


Fig 1 : Geometry of the proposed antenna.

III. RESULTS AND DISCUSSIONS

Antenna design parameters are optimized using CMA as discussed earlier. Dodecagonal shape's resonant frequency is similar to the circular patch which enables us to guess the circumradius for our initial design. But the formulated analysis to calculate frequency of resonance to a circular shaped patch is done with the assumption of an infinite ground



plane and by applying cavity analysis. To analyze the resonant behavior dodecagonal patch with 10mm circumradius and without the ground plane and on an FR4 substrate of thickness 0.1mm is simulated in multilayer solver of CST microwave studio for CMA. Modal significance plots obtained from simulation dodecagon shown in fig 2.

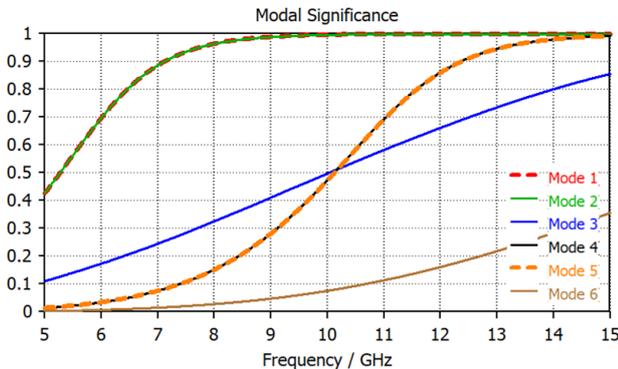


Fig 2: Modal significance of Eigen modes on Defected dodecagonal shaped patch.

Modal significance plot indicates eigenmode 1,2 and mode 4,5 have same MS indicating degeneracy of the modes. It can be observed from the plots only mode 1,2 have MS close to one in “X-band” whereas for modes 4,5 MS becomes significant after 11 GHz. Though these modes are having the same modal significance they are orthogonal surface current distributions. Surface current distributions of eigenmodes are shown fig 3

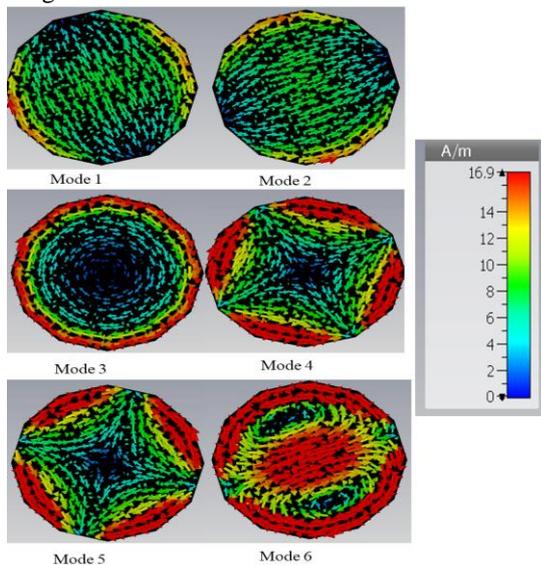


Fig 3 : Surface current of eigenmodes(CMA) R = 10 mm Dodecagonal patch on FR4 substrate of thickness 0.1 mm

From the surface currents plot it is apparent that mode 1,2 and mode 4,5 are orthogonal modes. But resonating these modes though edge feeding is inefficient in terms of impedance matching. Symmetric defected are placed at the edge of feed which are optimized for efficient impedance matching. CMA is performed on the defected dodecagonal patch and the MS is shown in fig 4.

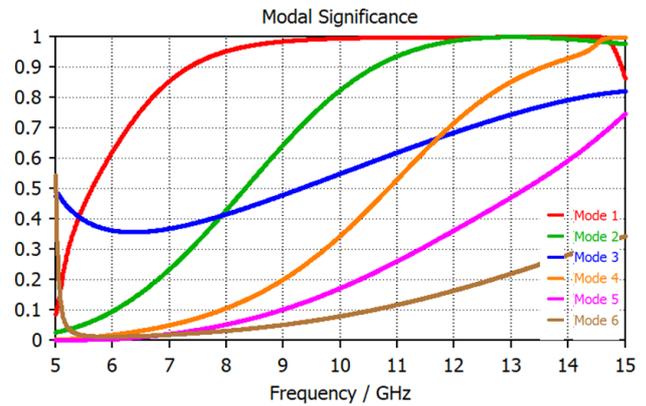


Fig 4: Modal significance of Eigen modes on Defected dodecagonal shaped patch.

Because of the defects, the degeneracy in the modes is lost and it can be observed in the MS plot that mode 1 is having a good radiating behavior compared to other modes in X-band. The distribution of currents on the dodecagonal surface with defects are simulated and displayed in fig 5. From the surface current distributions, it is perceptible that optimal coupling to feed current is possible as the characteristic mode eigen current now has the flow of currents in a direction which enables optimal coupling to the modes as understood from equation (3). Only the first six eigenmodes are computed as we can see from fig 4 modal significance of higher-order modes becomes less prominent in our desired band

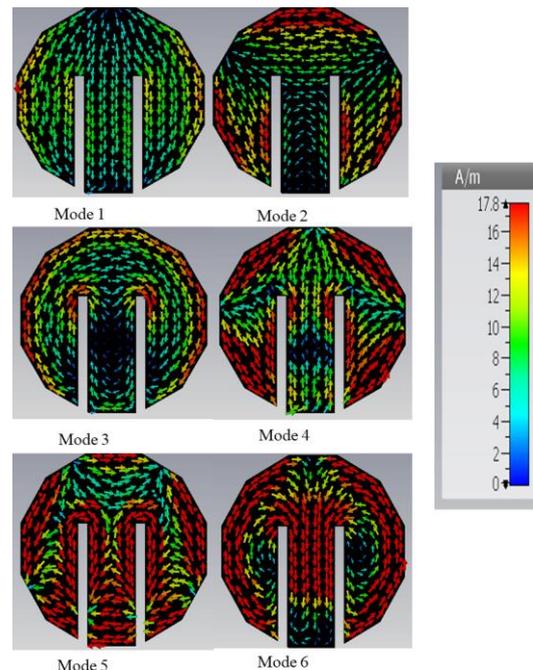


Fig 5 : Surface current of eigenmodes(CMA) R = 10 mm Defected Dodecagonal patch on FR4 substrate of thickness 0.1 mm

A CPW fed is used to feed the defected dodecagonal shaped patch as shown in figure 1. To study the characteristics of the antenna proposed structure is simulated in CST studio using transient domain solver from a frequency range of 1 to 15 GHz. Dimension of metal layer is taken to be 35µm thick. Transient solver applied to the design uses a gaussian pulse as the source of excitation whose FFT also is a gaussian. By studying the return pulse at the input port various parameters of the antenna can with studied. A

time-domain solver is more coherent and productive in connection with memory usage and speed of computation. As discussed earlier impedance match at the input port is essential for maximum power transfer to antenna. Impedance match achieved by the antenna can be analyzed through the return loss parameter, or S11 dB scale. Return loss parameter calculated at the source excitation port of the defected dodecagonal antenna is shown in fig 6. To indicate good impedance matching fig 6 is plotted in comparison with S11 dB of antenna without any defects

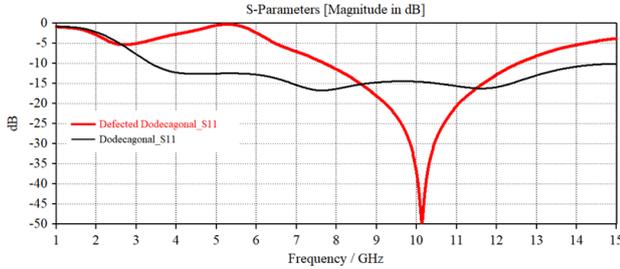


Fig 6: Comparison of Return loss vs frequency between dodecagonal patch with defects and without defects

From fig 6, suggested defected dodecagonal patch operates in the band 7.7 to 12.52 GHz with return loss below -10dB. Suggested antenna resonates at 10.12GHz with a decent return loss of -49.5dB. whereas dodecagonal antenna without defects exhibits a wide bandwidth from 3.37 to 15 GHz but simulated return loss is greater than -16 dB across an entire band which indicates a trivial performance in respect of matching input impedance and power flow into input port. Though return loss provides insight into the operating band of the proposed structure parameter radiation efficiency provides factual analysis on the fraction of power accepted at the input port to the power radiation radiated by antenna.

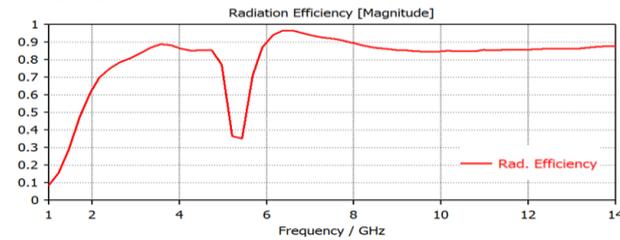


Fig 7: Radiation efficiency vs frequency for proposed antenna

Radiation efficiency simulated for suggested antenna from 1 to 14 GHz is indicated in Fig.7. If the radiation efficiency is close to one it indicates device is radiating significant ratio of power accepted. The proposed antenna has good radiation efficiency close to one in the X-Band. Along with radiation efficiency antenna gain renders a prominent role in judging the capability to radiate in a specific direction concerning an isotropic radiator. Antenna gain is usually measured in dBi which indicates decibel-isotropic which implies gain with respect to an isotropic antenna. Fig 8 is a plot between the maximum value of Gain(IEEE) at different frequencies in the band of operation. A peak gain of 4 dBi is observed for the proposed antenna

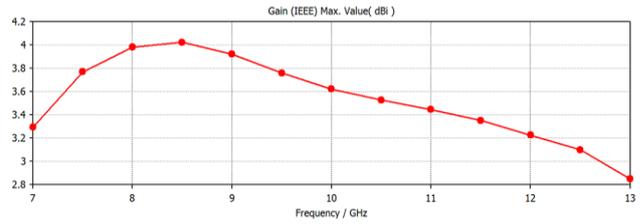


Fig 8: Gain(IEEE) vs frequency for proposed antenna

Simulated pattern for antenna in  $\phi = 0^\circ$  and  $\phi = 90^\circ$  planes to the proposed antenna at three different frequencies in the X-band antenna are shown in fig 9.

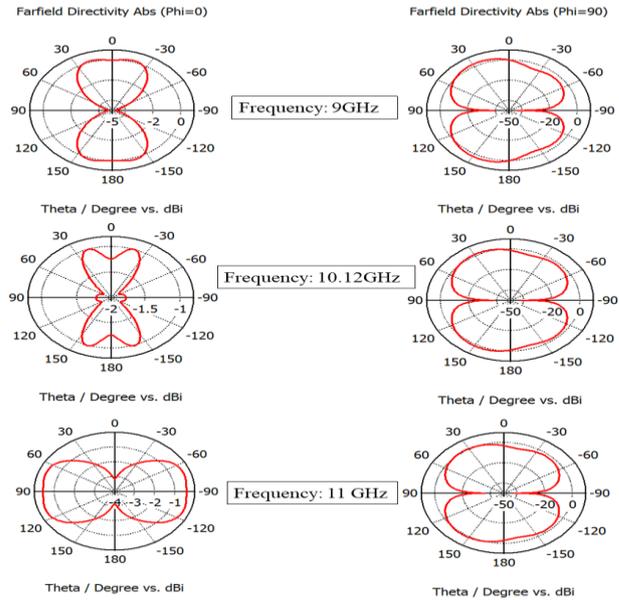


Fig 9 : Far field polar plots of proposed antenna

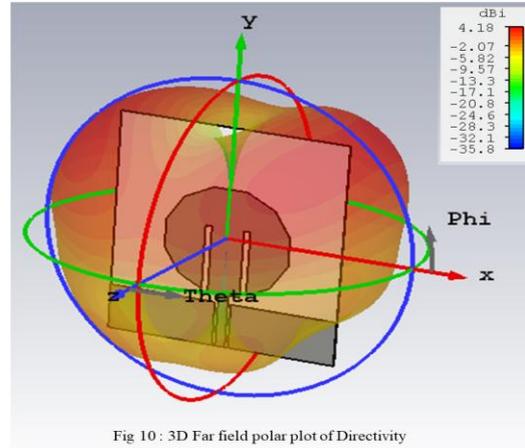


Fig 10 : 3D Far field polar plot of Directivity

The radiation patterns are taken for the designed antenna in CST in YZ plane for E field pattern and XZ plane for H field pattern at three different frequencies as mentioned above. A 3D far-field plot at 10.12 GHz is shown in fig 10.

#### IV. CONCLUSION

An X-band antenna using a defected dodecagonal patch is proposed. Good impedance matching is achieved through Coplanar waveguide feeding. The dimensions of the defects are optimized using characteristic mode analysis to achieve less return loss of -49.5dB in the band of operation. Design exhibits good radiation efficiency with a gain(IEEE) of 3dBi to 4dBi within the operating band with VSWR less than two.



Proposed antenna spans the complete X-band making it suitable for radar, satellite applications of X-band.

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