Optimized Polygonal Slit Rectangular Patch Antenna with Defective Ground Structure for Wireless Applications

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Abstract **─** A novel triple-band polygonal shaped slit rectangular patch antenna with defective ground structure (DGS) is proposed for WLAN and WiMAX applications. The proposed probe-fed antenna consists of a rectangular patch, zig-zag shaped slit, dual T-shaped slits on both sides and circular dumbbell shaped defected ground. The designed antenna can generate three separate resonant frequencies to cover both the 2.45/5.28 GHz WLAN bands and the 3.5 GHz WiMAX bands while maintaining a small overall size of 40 mm x 28 mm x 3.175 mm. The location and dimension of loaded polygonal slit is obtained with the aid of interfacing a genetic algorithm (GA) model with an IE3D simulator. The results obtained from simulated antenna show 5.23% impedance matching bandwidth at 2.29 GHz, 1.14% at 3.5 GHz, 5.17% at 4.64 GHz. The antenna is experimentally tested, which gives good radiation patterns and sufficient antenna gains over the operating bands.

Index Terms **─** Defective ground structure, polygonal slit, radiation pattern.

I. INTRODUCTION

Multiband antennas play a vital role in integrating more than one communication applications on a single compact size structure. The desired characteristics of the multiband antenna are wide impedance bandwidth over the resonant frequency, better gain and good radiation properties [1]. Numerous antenna designs for tri-bands have been recently investigated employing various shapes of defective ground planes [2], [3]. Applying defective ground structures is found to be simple and effective method in size reduction as well as excite additional resonant modes [4].

Wang et al. proposed a monopole antenna with DGS which excites for triple resonant frequencies [5]. For obtaining triple resonant frequencies a DGS unit cell is etched out as a single defect on the ground plane of PCB. The single defect radiates over the desired frequency range by stopping wave propagation through the substrate. Cap et al. highlights about the compact design with slits introduced into a conventional patch antenna for dual-band operation [6]. The attractive feature of genetic algorithm (GA) is its ability to achieve the desired performance by using a single, unique patch shape. Johnson et al. [7] designed a dual-band microstrip antenna on air substrate using GA approach. Proper selection of the microstrip patch antenna parameters such as length, thickness, shape, feed point position and method will excite the desired bands. Paitoon et al. [8] demonstrated slot cuts at radiating edges add a reactive load which alters the equivalent circuit of loaded patch, and hence adjust the dual frequency operation. Reactive loads added to the basic patch will change surface current distribution, which ultimately changes the excited resonance modes.

Guha et al. discussed about reducing interference effects with metallic backing to the patch. Metallic backing behind the defective ground structure is done to suppress leakage which reduces mutual coupling for microstrip antenna arrays [9]. A defect changes the current distribution in the ground plane of the patch antenna, giving rise to an equivalent inductance and capacitance. Hence, the DGS behaves like a LC resonator. When RF signal is transmitted to the patch antenna, strong coupling occurs between the top surface of the patch and DGS around the resonant frequency. LC parameters are determined by the shape and size of the defect geometry [10-14].

In this paper, a novel multiband planar antenna with defective ground structure is proposed. The antenna consists of a zig-zag shaped slit inserted on the radiating rectangular patch, dual T-shaped slits on either side of the patch and the ground plane modified by loading it with a circular shaped dumbbell as shown in Fig. 1. By properly selecting and varying the dimensions through implementation of GA for proposed structure, it can provide operating frequencies of interest, improve impedance bandwidths, and simultaneously work at multibands.

The effect of key structure parameters on the antenna performance are also analyzed and discussed in Sections II and III.

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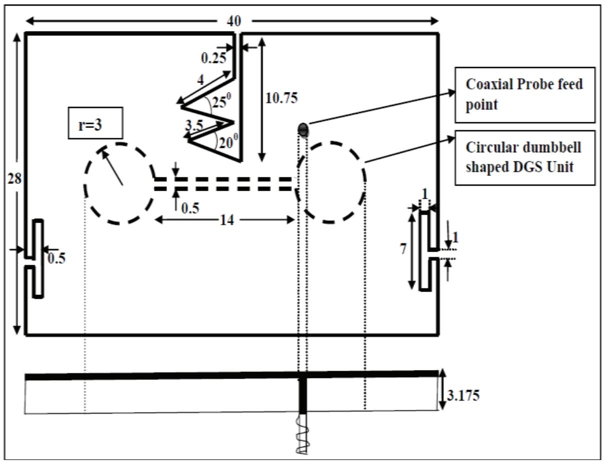


Fig. 1. Geometry of proposed antenna structure (dimensions are in mm).

II. DESIGN OF PROPOSED ANTENNA

A. Zig zag shaped polygonal slit and T-shaped slits

The conventional rectangular patch antenna is chosen with dimensions L x W:

$$L=\frac{c}{2f_r\sqrt{\varepsilon_e}}-2\Delta L,\;\; W=\frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}, \tag{1}$$

$$\Delta L=\frac{0.412h(\varepsilon_e+0.3)(W/h+0.264)}{(\varepsilon_e-0.258)(W/h+0.8)}, \tag{2}$$

$$\varepsilon_e=\frac{(\varepsilon_r+1)}{2}+\frac{(\varepsilon_r-1)}{2}\left[1+\frac{12h}{W}\right]^{-1/2}, \tag{3}$$

where ε_r is the substrate permittivity, f_r is the resonant frequency and h is the substrate thickness.

In the first part of work, an extensive search of changing the shapes with different iterations is fixed for the conventional design in order to approach near desired frequencies. Several geometries of reactive loads were analyzed using IE3D tool solver. During the process, a linear T-shaped rectangular slits are placed on either side of the radiating patch, the antenna resonates at multibands. The lengths of the slits can be varied to get dual- or tri-band operation. In the present paper after optimizing the lengths, dual-band is obtained with reasonable bandwidth. The resonant bands can be increased by introducing additional slits. In the present antenna, a zig-zag polygonal slit is selected. The dimensions of the slit are varied to get a third resonant band. The placements of the slits are selected to get better radiation patterns and return loss characteristic. However, manually finding the accurate desired frequencies for the problem was difficult and selected the approach of optimization tool.

B. Optimization process using genetic algorithm

In the second part, GA tool is used as an optimization tool to find the desired frequency response. GA keeps the fit solution to an optimization problem. This is done by converting optimized parameters to genes; these genes form chromosomes to the optimization problem. GA evaluates the fitness of the solution and keeps ones that most fit. GA main program is interpreted by MATLAB and Fig. 2 shows the flow chart of GA and IE3D interaction. During the GA approach, twenty chromosomes in each generation are evaluated, cost is computed for each individual as sum of return losses at desired frequencies and the fitness is to minimize the cost:

$$\text{Cost function} = \sum_{m=1}^{3} S_{11}(f_m), \tag{4}$$

where S_{11} is the return loss, f_m is the m_{th} desired resonance frequency. Mutation rate is selected to be 5%, pairing chromosomes is done using cost weighting. The resultant antenna with the optimized parameters (in mm) as follows: L=38.5, W=25.6, probe feed position (5, 4.5), the length and width of DGS slot dimensions respectively (13.7, 0.47).

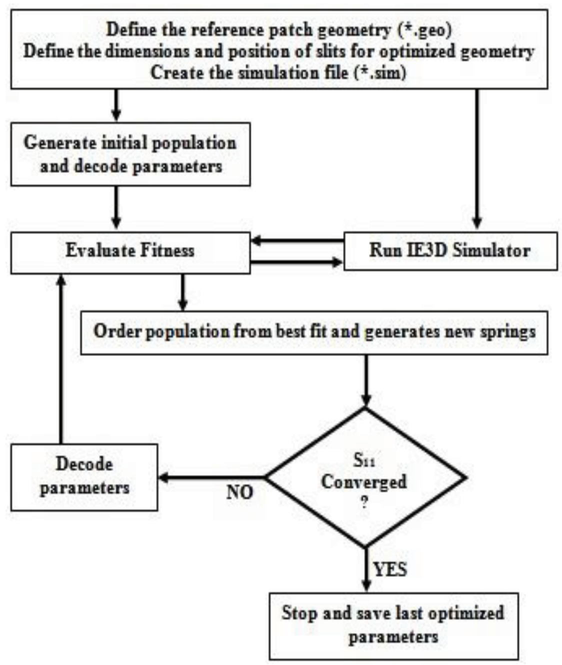


Fig. 2. Flow chart of genetic search with IE3D simulator.

The achieved impedance bandwidth can be increased by introducing a defect element on the ground plane. The selection of the shape and size of the DGS and analysis involved for defect element is briefly discussed in next section. A narrow length circular shaped dumbbell slot is cut on the ground plane to shift resonant frequencies with improved impedance bandwidth. The probe feed technique is chosen to have advantage of placing the feed at any desired location of the patch. This results in enhancing the gain, narrow bandwidth and impedance matching when compared with line feed [15]. The SMA connector and coaxial cable were included in all the simulations in order to fully characterize their effects on the antenna performance.

III. ANALYSIS OF DEFECTIVE GROUND STRUCTURE

Different defective ground structures are shown in Fig. 3. These DGSs are used in the design of filters, suppress unwanted surface waves, control harmonics in microstrip antennas, reduce size of microwave circuits and microwave applications. DGS are introduced to improve performance by size reduction and ease of design [16]. Circular shaped dumbbell defect element allows us to vary the resonant frequency by changing the length without affecting the dimensions of the antenna.

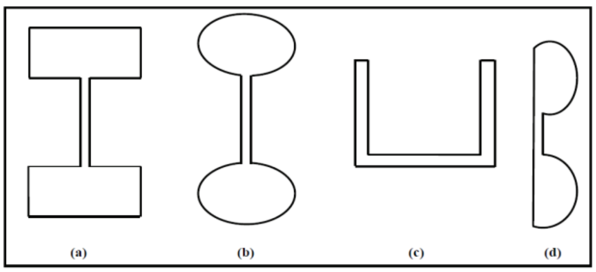


Fig. 3. Different DGS geometries: (a) rectangular dumbbell-shaped, (b) circular head dumbbell, (c) U-shaped, and (d) half-circle.

The circuit model for the DGS slot is represented in the form of a shunt capacitance C_μ and L_μ [12], and as shown in Fig. 4:

$$C_\mu = \frac{\sqrt{\varepsilon_{eff}^{slot}}}{c_0 Z_0^{slot}} \frac{l}{N_s} \text{ and } L_\mu = (Z_0^{slot})^2 C_\mu, \qquad (5)$$

where l is the length of the slot, N_s is number of slots, Z_0^{slot} is impedance of the slot and c_0 is the operating velocity. Figure 4 represents the equivalent circuit of DGS element and the values of L, C and R are determined by the slot dimension and location of the line. The change in dielectric constant changes the resonant frequency. The gain of the antenna is reduced for the antenna structure when DGS is applied to a conventional rectangular patch.

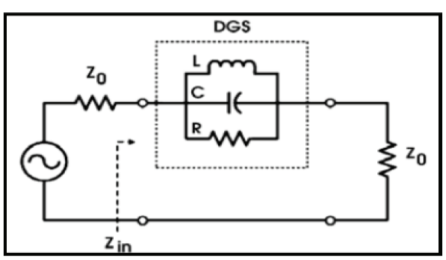


Fig. 4. Equivalent circuit of the DGS element.

IV. RESULTS AND DISCUSSION

A. Return loss and VSWR

The geometry of the proposed antenna is designed on a low-cost, RT Duriod 5880 substrate with dielectric constant εr=2.33, dielectric loss tangent tanδ=0.012 and height=3.175 mm. The probe feed position is optimized and selected at (4, 4) for better return loss characteristics and impedance variations. The measured and simulated return loss curves for the proposed structure without the defect element is represented in Fig. 5. It is observed that return loss values are 11.04 dB, 20.25 dB, 10.23 dB at 3.121 GHz, 3.677 GHz and 4.687 GHz respectively, without DGS on the ground plane.

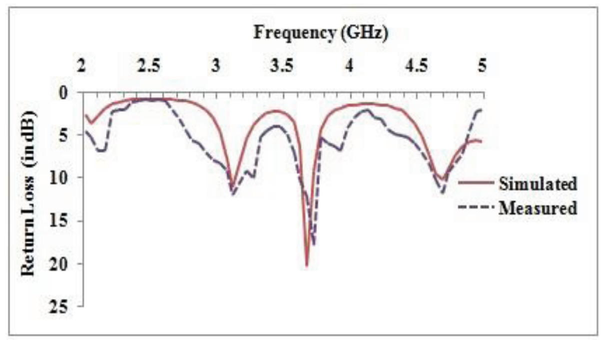


Fig. 5. Measured and simulated return loss curve for structure without DGS.

The VSWR values for the corresponding frequencies are extracted as 1.78, 1.215 and 1.89 respectively. The measured and simulated return loss curves for the proposed structure with the circular shaped single defective element is represented in Fig. 6, and noted that return loss values are 12.65 dB, 12.89 dB, 14.9 dB at 2.29 GHz, 3.5 GHz and 4.64 GHz respectively, with the DGS slot. The VSWR values for the corresponding frequencies are found to be 1.608, 1.682 and 1.5 respectively. The top layer and bottom layer of the fabricated antenna is as shown in Fig. 7.

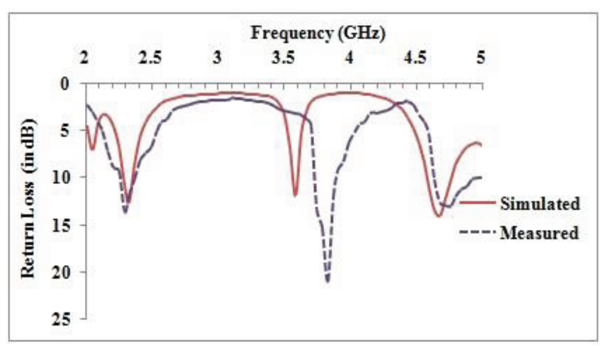


Fig. 6. Measured and simulated return loss curves for structure with DGS.

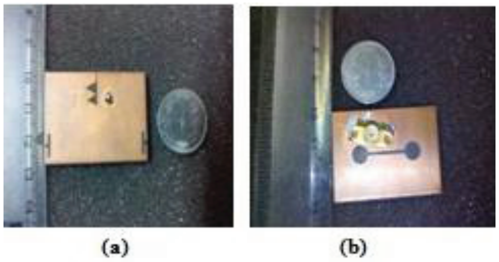
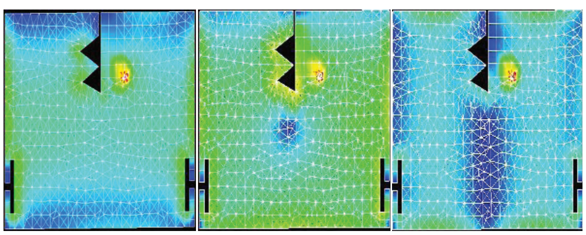


Fig. 7. Fabricated antenna: (a) top layer and (b) bottom layer.

B. Current distribution at tri-bands without DGS and with DGS

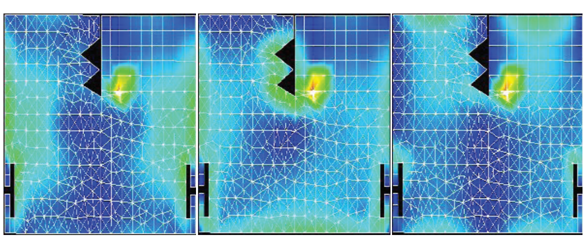
The surface current distributions of the antenna without DGS and with DGS are represented in Fig. 8 and Fig. 9 respectively, for the given frequency values.

It is clearly observed that the surface current density is much less at the radiating edges of the antenna without DGS. The current density of the patch at the radiating edge can be increased by introducing additional slots. Through a number of simulations the position and dimensions of the slits and slots are optimized for multibands. By introducing DGS, the current path is increased by which reduction in frequency occurs. Hence, the compact size is achieved that affects the distribution of surface current density.



(a) (b) (c)

Fig. 8. Average and vector current distributions: (a) 3.121 GHz, (b) 3.677 GHz, and (c) 4.687 GHz.

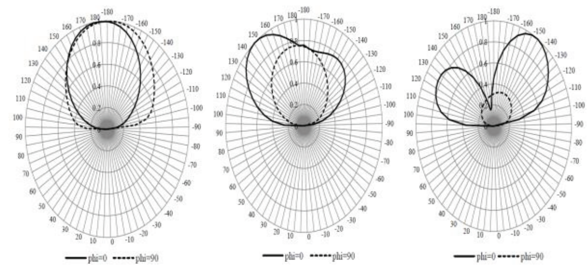


(a) (b) (c)

Fig. 9. Average and vector current distributions: (a) 2.29 GHz, (b) 3.5 GHz, and (c) 4.64 GHz.

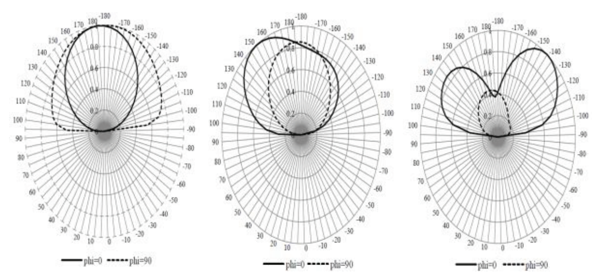
C. Radiation patterns for the structure without DGS and with DGS

Figure 10 shows the radiation pattern characteristics taken at $\phi=0^0$ and $\phi=90^0$ for the structures without DGS. Figure 11 shows the radiation pattern at $\phi=0^0$ and $\phi=90^0$ with DGS. The gain value is compromised when the DGS is placed on the ground plane and list of values are displayed in Table 1. Figure 12 shows the measured radiation patterns for multiband frequencies. The variations in the percentage impedance bandwidth value are also tabulated for the resonant frequencies. As observed, the lower frequency is shifted with an improved percentage bandwidth. This shows the impact on the size reduction capability with the applied DGS element on to the planar patch antenna. The size optimization can also be obtained placing multiple unit DGS cells on the ground plane. The gain versus frequency for the structure without DGS is as shown in the Fig. 13, and the response curve for the structure with DGS is represented by Fig. 14.



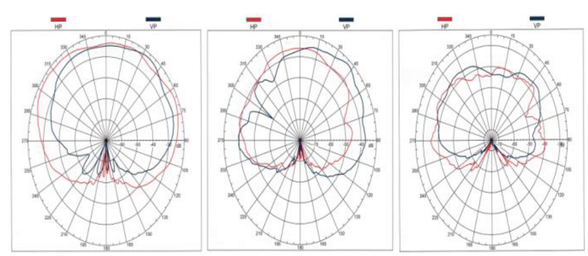
(a) 3.121 GHz (b) 3.677 GHz (c) 4.64 GHz

Fig. 10. Simulated E-plane radiation patterns without DGS: (a) 3.121 GHz, (b) 3.677 GHz, and (c) 4.687 GHz.



(a) 2.29 GHz (b) 3.5 GHz (c) 4.64 GHz

Fig. 11. Simulated E-plane radiation patterns with DGS: (a) 2.29 GHz, (b) 3.5 GHz, and (c) 4.64 GHz.



(a) (b) (c)

Fig. 12. Measured E-plane radiation patterns with DGS: (a) 2.29 GHz, (b) 3.5 GHz, and (c) 4.64 GHz.

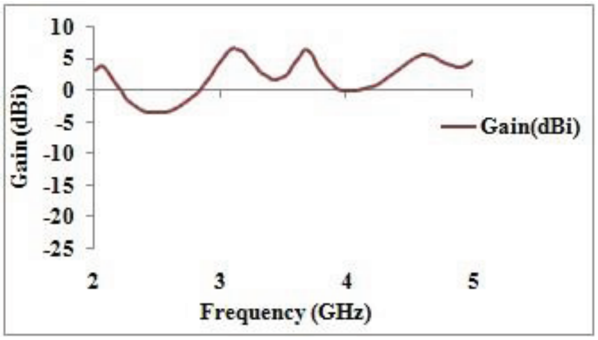


Fig. 13. Gain versus frequency for antenna without DGS.

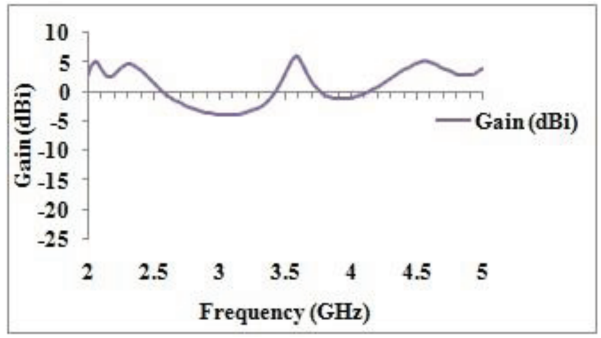


Fig. 14. Gain versus frequency for antenna with DGS.

Table 1: Value of gain and impedance bandwidth

Structures	Frequencies (GHz)	Simulated Gain (dBi)	Measured Gain (dBi)	Simulated Impedance Bandwidth	Measured Impedance Bandwidth
Without DGS	3.121	6.548	5.97	3.24%	3.96%
	3.677	6.47	6.81	2.36%	2.63%
	4.687	5.204	6.21	2.13%	3%
With DGS	2.29	4.63	5.27	5.23%	5.94%
	3.5	3.436	3.2	1.14%	3.12%
	4.64	4.67	5.78	5.17%	5.03%

D. Optimized metrics using genetic algorithm (GA)

The optimized parameters in the antenna design are position of the feed probe, length and position of the slits, length and width of the patch with minimum changes from its original dimensions of the patch. The shapes can be scaled in size to different operating frequencies of interest with minor modifications with substrate materials. The return loss values are 15.2 dB, 13 dB and 19.1 dB at respective operating resonant frequencies of 2.3, 3.4 and 4.7 GHz using GA technique. It is observed that a slight improvement is observed with the performance of the GA optimizer when compared to the simulated response curve.

The results of simulated, experimental and GA optimized responses are displayed for performance comparison. The return loss response of the GA optimizer with the best performance is represented in Fig. 15.

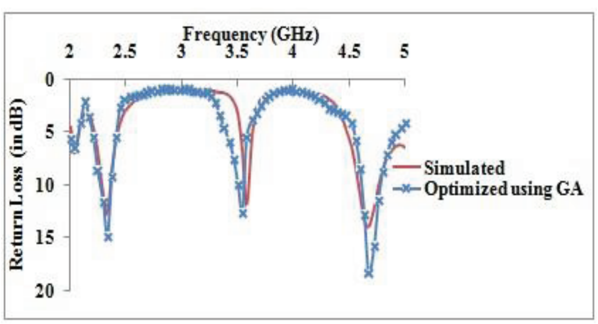


Fig. 15. Return loss response of simulated and GA optimization.

V. CONCLUSION

A novel shaped compact polygonal slit shaped planar antenna with defective ground plane is presented. The structure supports the operations for tri-band applications such as WiMax, WLAN and some bands of UWB. The major advantages of introducing DGS on metallic ground plane is to shift the resonant frequencies for different bands and also to increase the bandwidth for these bands. The optimized dimensions of the proposed patch antenna are also performed using genetic algorithm technique. The gain value decreases proportionally with the method applied for the patch antenna design. Impedance bandwidth and better radiation patterns are obtained for antennas with DGS when compared with the structure without DGS. A good agreement is obtained between simulated and measured return loss, radiation patterns and also for the gain values for this structure.

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