CHARACTERISTIC MODE ANALYSIS OF A STEPPED GRADIENT PLANAR ANTENNA FOR UWB APPLICATION

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ABSTRACT

Characteristic mode technique is employed to gain a physical insight and also to find out the dominant mode of stepped gradient planar antenna without considering the feeding port. The rational of the model further implies that we can consider antenna's shape and feed design as independent steps. The stepped gradient planar antenna is constructed and measured, in which both the measured and simulated agreed on each other in terms of reflection coefficient and voltage standing wave ratio. The miniature stepped gradient planar antenna is appropriate for numerous applications in ultra-wideband (UWB) communication systems from 2.7 to 12GHz and stable radiation pattern at both E and H-fields were attained over the operating frequency band which is suitable for use in UWB systems.

1. INTRODUCTION

Nowadays, designing a planar antenna system that support high data rate and multiple wireless metric capabilities with effective electromagnetic spectrum is needed. The low power requirements of the UWB system has earned important attention in wireless high data rate usage [1] – [4]. In perspective on that, the federal communication commission has administered an unlicensed frequency range of 3.1 - 10.6GHz for ultra-wideband frameworks [5]. UWB technology have been proved to enhance wireless system performance in environment where interference, fading and multipath tends to degrades the signal quality, reduce effective data rate and large number of subscribers in the cell [6]. The need for antennas that support UWB application can never be over emphasized. Previously, conical antennas, horn antennas, and log-periodic antennas were used in UWB applications. But, the present day wireless and compact framework, these traditional receiving wires are not suitable. Therefore, with the ultimate objective of this application, printed planar antennas are highly preferred due to their advantages like little size, light weight, low cost, simplicity of joining with planar structure, and simplicity of fabrication. Large variation in group delay is an important factor that need proper attention when designing planar antennas for UWB application because group delay may distort UWB signals. Sometimes strong resonance at any frequency can cause large group delay variation [7], [8]. In this way, to the extent pulse constancy is concerned, the group delay must be steady over the whole range of UWB. For the most part, a reception apparatus gain plot without a nulls cause a linear phase response that lead to a steady group delay. To provide insights in planar antenna working mechanism, the theory of characteristic mode is applied in the planar antenna research. In [9] – [11]. Modal analysis also provides guidance for the research of planar antennas [12] – [17]. The use of empirical formulas was investigated in [18], where a feed independent was used. Chassis mode reception apparatus are designed based on the theory of modal analysis [19], [20]. All these research work has significantly advanced the capability and application of characteristic mode theory. The linearity and orthogonality of the characteristic mode are potentially useful for planar antenna design. Different modes can be sorted differently, in which each mode can be excited as a channel resulting into very low mutual coupling between different ports [21]. This accounted our employment of characteristic mode theory for planar antenna design. Most of the literatures mentioned above used theory of characteristic mode, employing rectangular chassis which represents the ground plane, they also rely on the chassis as the main emanating component. The main reason of using the chassis modes was the ease in the excitation of such modes through an inductive coupling element or capacitive coupling element. In this work, none of these techniques is used rather employing a multilayer solver which require only the structure without the feeding port and the substrate material should be loss free.

In this study, characteristic mode analysis is employed for a stepped gradient planar antenna for UWB application. We utilized both the time domain solver and multilayer solver in which the time domain solver is responsible for the reflection coefficient and voltage standing wave ratio of the antenna whereas the multilayer solver is responsible for the modal significance, characteristic angle, eigenvalues, modal surface current, and modal far field radiation properties of the antenna. The design and analysis was carried out using CST version 2017. The simulated results are affirmed by the exploratory measurements. The theory behind the design and analysis of the antenna is presented in segment II, the system framework is displayed in segment III, while results and discussion are exhibited in segment IV, and finally followed by conclusion in segment V.

2. CHARACTERISTIC MODE ANALYSIS

Characteristic mode analysis is a numerical computation of a loaded set of rectangular current modes that is supported by a conducting body, originally developed by Garbacz in 1968 [22] and then revised by Harrington [23]. Using the characteristic mode analysis (CMA) the Eigen responses of an antenna can be realized, in which previously the information was only available to closed waveguide and resonant cavities. The access to these Eigen responses will offer new physical insight regarding antenna operating principles. Characteristic mode is realized by solving the eigenvalues which is derive from the method of moment matrix assorted into real and imaginary components as shown in the following equations.

$$[X]I_n = \lambda_n [R] I_n \quad [23] \tag{1}$$

From (1) X and R represents the real and imaginary part of the method of moment impedance matrix, λ_n and I_n are the Eigen value and Eigen current of the n^{th} mode. The Eigen value equation can be solved using Matlab at any frequency to get a series of characteristic modes. In this work, the Characteristic mode was connected utilizing multilayer solver in CST version 2017. The orthogonality property of characteristic modes makes them a useful set of basis for antenna response expansion. Given the characteristic modal response, we can expand the antenna response for an arbitrary excitation in terms of the modal response. The resulted response of a given antenna can be expanded in terms of its characteristic modal responses as

$$\vec{J} = \sum_{n=1}^{N} C_n J_n \tag{2}$$

$$E = \sum_{n=1}^{N} C_n E_n \tag{3}$$

where $C_n = \frac{(E^{'}, J_n)}{1 + j\lambda_n}$ is the n^{th} mode coefficient and represents how strongly a mode is excited, and $\langle E^{'}, J_n \rangle = \iiint E.J_n dv$ is the symmetrical product of the excitation field and the modal current. Apart from the current and radiation pattern, some other parameters like impedance Z, quality factor Q, admittance Y and radiation efficiency have also been evaluated in terms of characteristics modes. Example in [24]. The characteristic mode Q factors are studied and found useful for input port Q factor expansion. Characteristic modal efficiency is determined by utilizing or acquainting loss to the characteristic modal solution of the perfect electric conductor reception apparatus. Assuming a 1V gap voltage source at certain feed position (hub i), the total admittance of the feed can be expressed as:

$$Y_{ii} = \frac{J_{tot}(i)}{1V} = \sum_n \alpha n J_n(i) = \sum_n \frac{\langle E^i, J_n \rangle}{1 + j\lambda_n} J_n(i) = \sum_n \frac{J_n(i)}{1 + j\lambda_n} J_n(i) \tag{4}$$

Similarly, the mutual admittance between port j and excitation port i can be expressed as

$$Y_{ji} = \frac{J_{tot}(i)}{1V} = \sum_n \alpha n J_n(j) = \sum_n \frac{\langle E^i, J_n \rangle}{1 + j\lambda_n} J_n(j) = \sum_n \frac{J_n(i)}{1 + j\lambda_n} J_n(j) \tag{5}$$

3. ANTENNA GEOMETRY AND DESIGN

The proposed step-shaped UWB antenna as shown in figure 1 consist of two rectangular ground plane and stepped-gradient structure as the main radiating element. FR4 substrate is used in which the height is 1.6mm with a 4.3 dielectric constant. The coplanar-waveguide feed line is designed by utilizing a rectangular patch associated with the fundamental radiator. The two structures (patch and the ground) are placed on top of the substrate. the CPW-feed line is fed by 50Ω impedance. The width of the feeding line is 2.8mm while the ground gap that is, a space between the feeding line and the two ground plane is 0.3mm. The parameters mentioned was calculated based on the frequency from 1 GHz to 12GHz in order to realize an UWB frequency range. The optimal dimensions for the antenna are listed in table 1. Modifying the coplanar waveguide on top of the antenna using some steps near the feeding line control the bandwidth of the antenna for the fact that the current distribution on that plane influence the behavior of the antenna and in this situation the rectangular coplanar waveguide serve as the ground plane of the antenna.

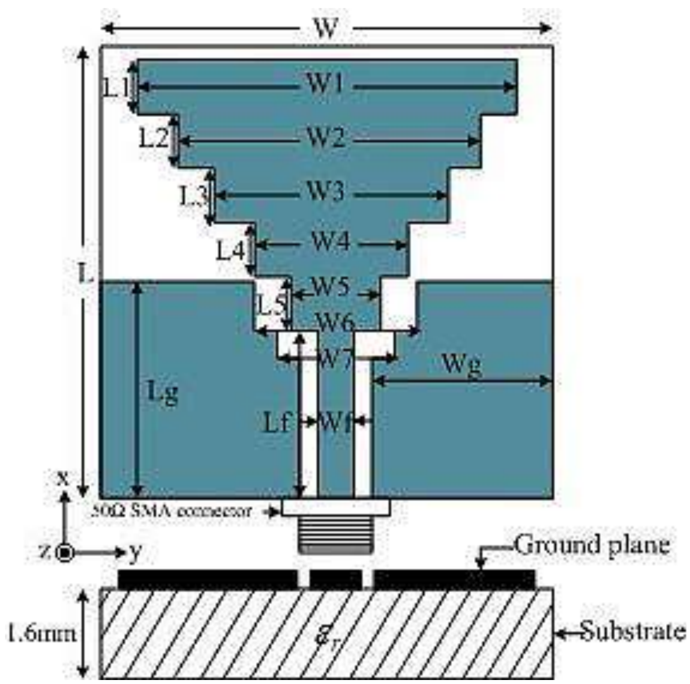


Fig. 1. Configuration of the antenna.

Table 1 Basic parameters of the stepped gradient antenna

Optimized Antenna parameters			
Parameter	***Size (mm)***	***Parameter***	***Size (mm)***
L	32	W1	23
L1	8	W2	17
L2	4	W3	12
L3	2.5	W4	9
L4	2.5	W5	6
L5	2	W6	10
Lf	11	W7	8
Lg	12.5	Wf	2.8
W	26	Wg	11.3

4. RESULTS AND DISCUSSION

The theory of modal analysis was employed to the rectangular plate planar antenna without feeding port using a multilayer solver in CST version 2017. It represents the normalized amplitude of the current modes. This normalized amplitude does not rely upon feeding port but rather just relies upon the shape and size of the conducting object. The transient solver is likewise employed for the s-parameters of the reception apparatus. Figure 2 depicted the S_{11} of the antenna while figure 3 presents the voltage standing wave ratio of the rectangular plate. From the outcome it demonstrates that the reception apparatus is working at an UWB frequency from 2.7-12GHz. There is a little discrepancy between the measured and simulated result as can be seen from the S_{11}, these accredited to environmental effect and construction tolerances. The VSWR is less than 2 but greater than 1 as presented in figure 3. For the modal analysis, we have used a frequency band of 2.7GHz to gain the physical insight in to the antenna properties being the fact that the antenna is an UWB antenna.

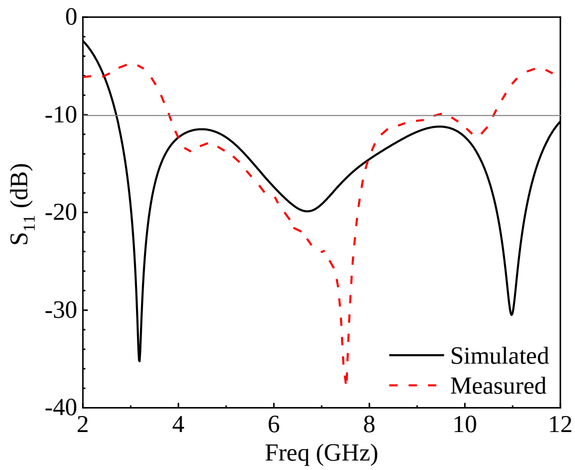


Fig. 2. Simulated and measured S_{11}.

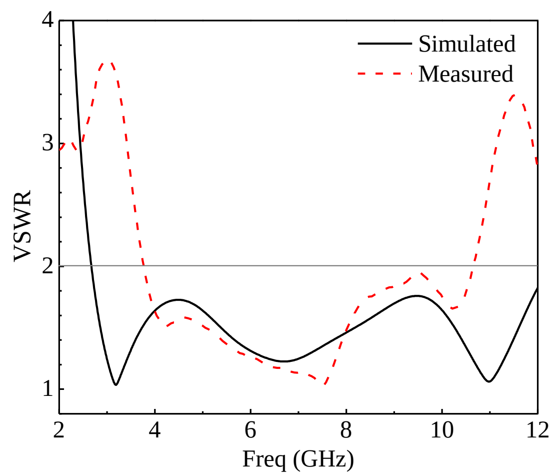


Fig. 3. Measured and simulated VSWR.

As we said earlier, we can access the resonant frequency of each characteristic mode without even exciting the antenna with physical feeds and it is also independent of antenna feed positions in general. Figure 4 depicts the eigenvalues of 5 different modes at 2.7GHz of a rectangular patch antenna. As can be observed from the figure only mode 1 that is at 0 level or closer to zero, the remaining modes are very far from the value of zero, so it signifies that mode 1 remains the prevailing mode in the framework.

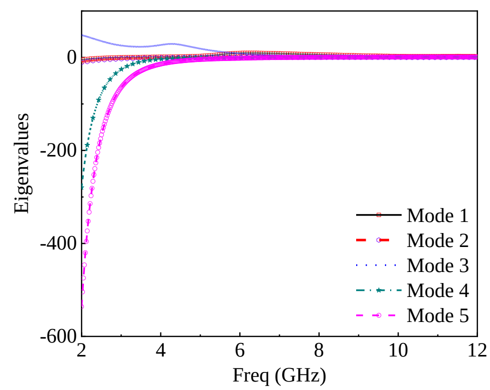


Fig. 4. Eigenvalues of a stepped gradient antenna at 2.7 GHz.

Another important parameter that we can also derive from the Eigen values is modal significance which is defined as

$$Ms_n = \frac{1}{|1 + j\lambda_n|} \tag{6}$$

Modal significance shows clearly how each mode is close to resonance at each frequency. It achieves the maximum value of 1 at its resonant frequency (when $\lambda_n = 0$) and falls off when Eigen values are large. Figure 5 depicted the modal significance of the antenna. From the figure, we have 5 modes at 2.7GHz but only mode 1 has a high value of 1 or closer to one that is at 0.88 as depicted from the figure. Mode 2 is at 0.26, mode 3 is at 0.03, mode 4 is at 0.02 and finally mode 5 is at 0.009. It clearly shows that mode 1 which has a higher value closer to one will remain the dominant in that reception apparatus, this remains the essential point of utilizing the modal analysis. The modal significance is feed independent. A large modal significance is needed, equivalent to one or nearer to one. Figure 6 shows the characteristic angle of the antenna where a 5 modes was employed at 2.7GHz, mode 1 is near a resonance at 180 degrees but the remaining modes are not close to resonance. Figure 7 presents the modal surface current distribution and modal 3D radiation pattern of mode 1 to mode 3 at 2.7GHz.

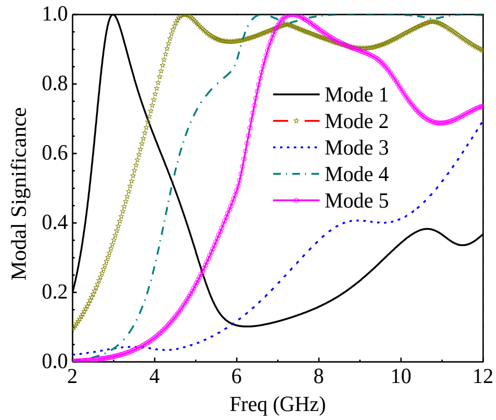


Fig. 5. Modal Significance of stepped gradient antenna at 2.7 GHz

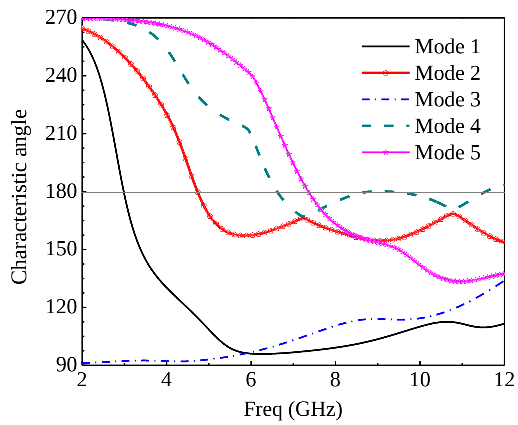
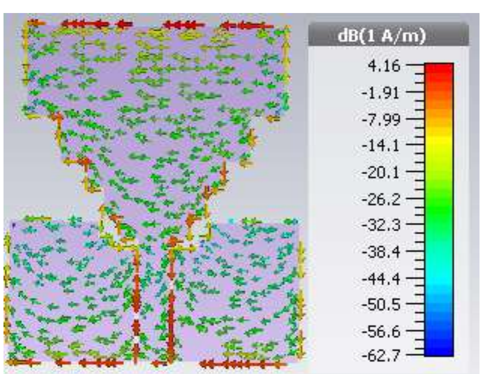
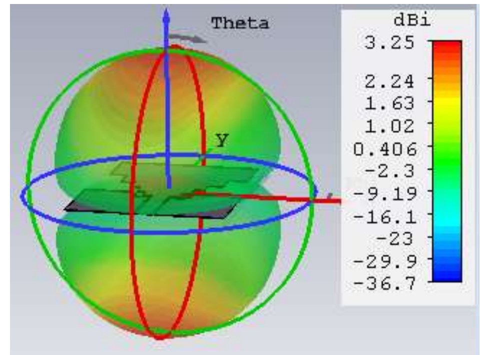


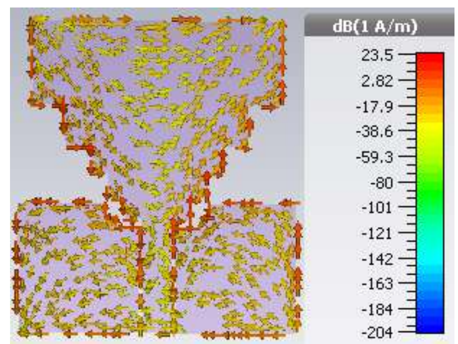
Fig. 6. Characteristic angle of stepped gradient antenna at 2.7 GHz



(a)



(b)



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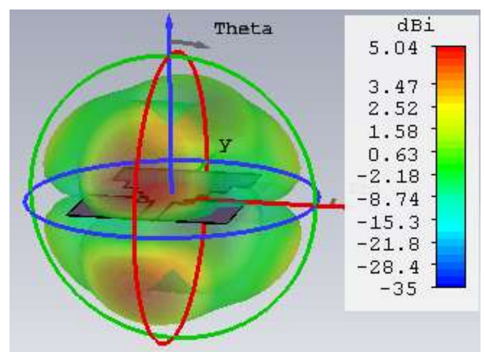
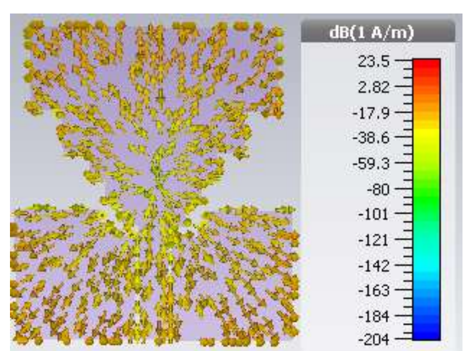
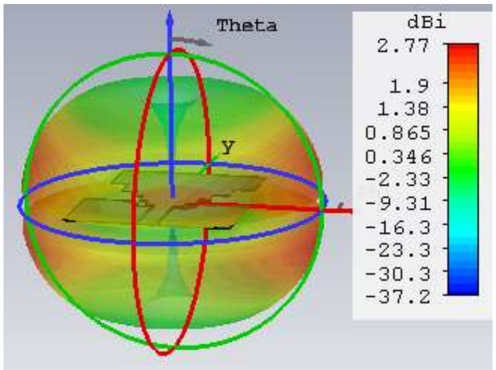


(d)



(e)

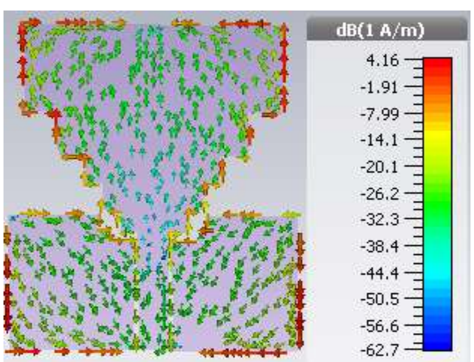


(f)

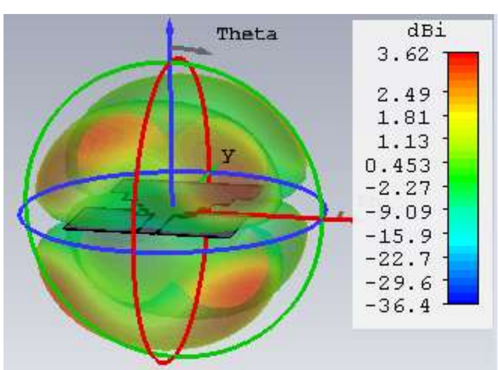
Fig. 7. Modal surface current and modal 3D radiation pattern of 3 modes at 2.7 GHz;

(a) and (b), mode 1, (c) and (d), mode 2, (e) and (f), mode 3.

Figure 8 presents the surface current distribution and 3D radiation pattern of mode 4 and 5 at 2.7GHz. Mode 1 being the dominant mode has a different current distribution as compared to other modes and the concentration of currents is much more in the microstrip line feeding plane as compared to mode 2, 3, 4 and 5. The red arrow signifies the current concentration.



(a)



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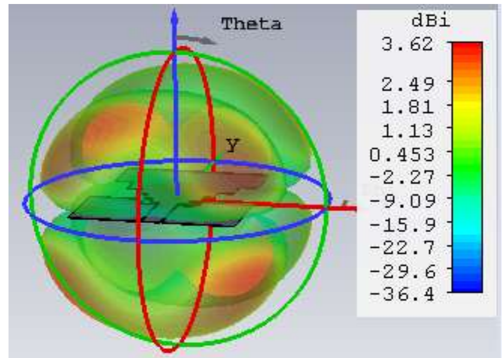

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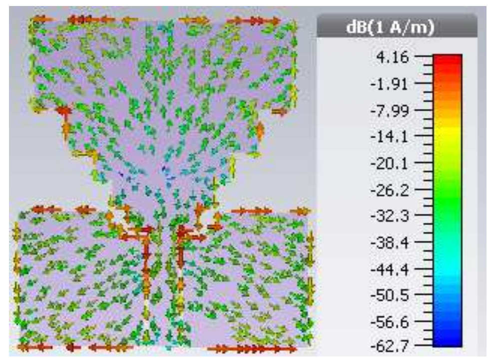
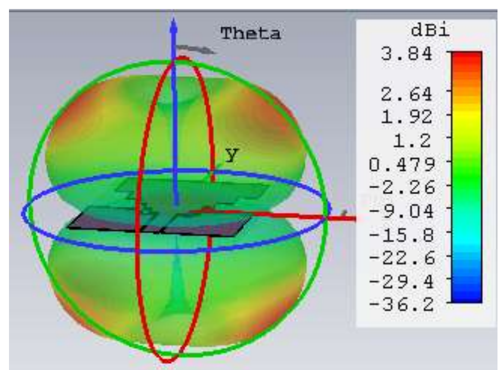


(c)



(d)

Fig. 8. Modal surface current and modal 3D radiation pattern of 2 modes at 2.7 GHz;

(a) and (b), mode 4, (c) and (d), mode 5.

Figures 9-13 are the normalized 2D radiation patterns at 2.7 GHz for mode 1, to mode 5. The pattern shows the E and H planes for the antenna element at 2.7 GHz.

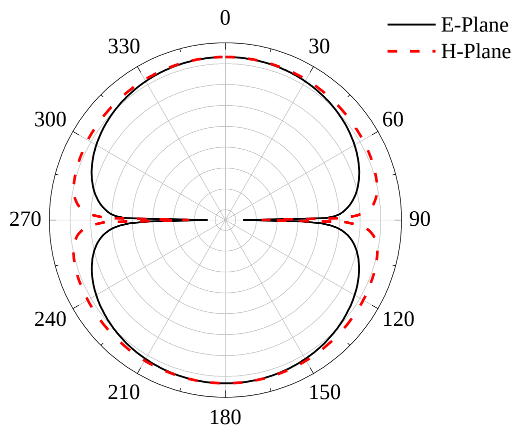


Fig. 9. Far field behavior for mode 1 at 2.7 GHz.

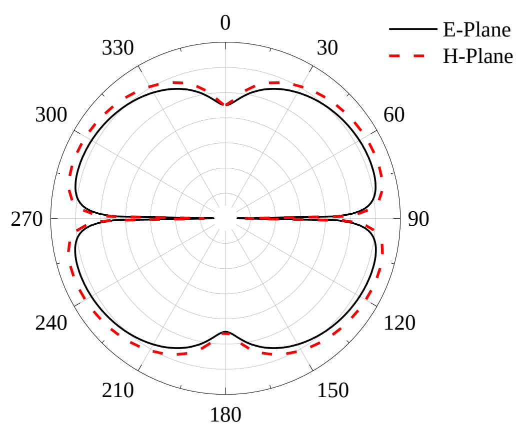


Fig. 10. Far field behavior for mode 2 at 2.7 GHz.

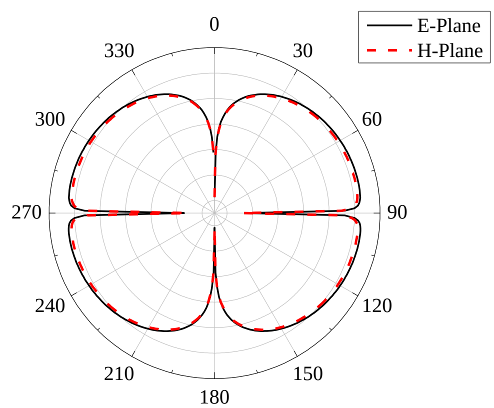


Fig. 11. Far field behavior for mode 3 at 2.7 GHz.

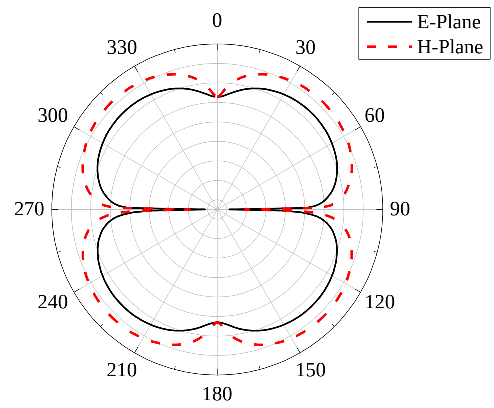


Fig. 12. Far field behavior for mode 4 at 2.7 GHz.

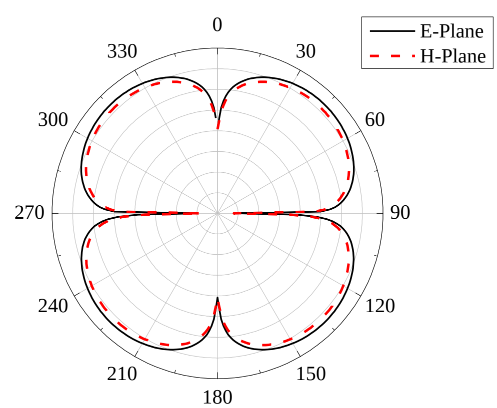


Fig. 13. Far field behavior for mode 5 at 2.7 GHz.

Figure 14 tract the antennas peak gain as a function of operating frequency from 2 to 14GHz, across the full impedance bandwidth of 2.7 to 12GHz, indicating that the antenna design is suitable for use in UWB systems. Figure 15 presented the fabricated photo of the antenna.

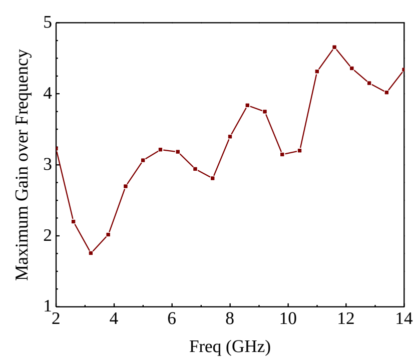


Fig. 14. Maximum gain over frequency.

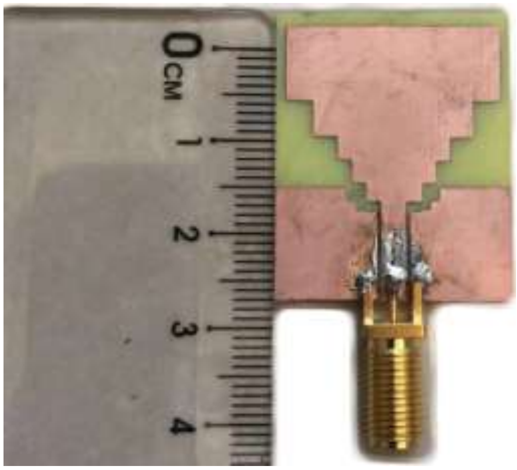


Fig. 15. Fabricated photograph for stepped gradient antenna.

5. CONCLUSION

In this study, a linearly polarized stepped gradient planar antenna is presented. Characteristic mode analysis is employed using multilayer solver without considering the feeding port. The analysis shows that mode 1 has a dominant mode. The measured and simulated results were in great concurrence with one another and showed a good performance with a maximum gain of about 5dBi.

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