Beam Diversity Analysis of Compact Microstrip Antenna with Suspended Superstrate: An Experimental Study

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Abstract

A multi-functional microstrip compact antenna capable of steering the main beam to eight different directions in the elevation plane is conferred in this study. The compact antenna consists of a driven patch of $28 \times 28\,mm^2$ to bring in the resonance to $2.8\,GHz$, for achieving enormous application in european radar service under Wi-MAX band. The conductive layer on the superstrate deflect the beam with an angle corresponding to the position of superstrate on parasitic layer, without considering complex phase shifters and associated circuits. Proper alignment of superstrate results maximum scanning angle of $139\,°$ with $59°$ of deflection angle. The directivity of the antenna is enhanced by manipulating the parameters of the superstrate. The gain of the antenna was improved up to $\sim 6\,dBi$ and the efficiency is improved up to $16\,\%$ using engineered superstrate. The full-wave simulation as well as analytical study was done using the IE3D EM simulator.

Keywords: Microstrip Antenna; EM Beam Manipulation; Engineered Superstrate; Gain Enhancement; Beam diversity

1. Introduction

In recent electromagnetic research, design of steerable antenna is frequently studied. Microstrip printed antenna (MSAs) are preferred among other type of antenna, because the MSAs are offering very high operating frequency with a more compact structure which can be fabricated easily and economically low cost [1] -[3]. Recently the application of high efficient MSAs in modern microwave communication has made the device more compact [4]. Steering the main beam of the MSAs are inevitable in recent electromagnetic studies. Steering of the main beam studied using mechanically as well as electronically beam steering. Among which electronically beam steering is well suited and somewhat easy to steer the beam with improved scanning or tilting angle [5]. The electronic beam steering has widely used, many of the wireless communication systems, especially in a mobile satellite communication and microwave radar communication [6] - [7].

The addition of high refractive surface at a suitable distance from the radiating patch has been reported for antenna radiation efficiency and enhancement of the antenna gain in [8]. Rather than this, this configuration using high refractive surface called superstrate will protect the MSAs from hazards caused by environment, when the MSAs are proposed for satellite, aircraft, missiles and other exterior communication [9]. In earlier electromagnetic research it has been demonstrated that addition of superstrate layer in $z-plane$ of the microstrip patch antennas having a better steering angle instead of referring array structure [10], leaky wave model [11], phase shifter [12] and other models reported, in fact these techniques are increasing the complexity, design cost and somewhat difficult to analysis and manipulating [13].

The MSAs configured in several techniques with engineered superstrate to enhance the radiation efficiency and directivity, such as highly refractive surface, artificial magnetic superstrate , electromagnetic band gap (EBG), and some design uses dielectric slabs [14]- [16]. Use of magneto-dielectric materials having high permittivity instead of dielectric material improves the gain of the MSAs. For this operation the thickness of the superstrate should be half of the wavelength [17]. The multi-layer antenna structure is analyzed using the transverse equivalent model [18], when the source is a Hertzian dipole. The transverse equivalent network model was modified to arbitrarily orient multi-layer dielectric structure, with respect to the arbitrary feeding source. In which the antenna feeding sources are replaced by the hertzian dipoles, these Hertzain dipoles replicate the far-field properties of the designed antenna. The far-field properties are analyzed [19] – [20].

This work investigates the beam steering operation of a planar antenna using an engineered superstrate. The suggested antenna operating at 2.8 GHz has an inevitable application in European aeronautical radar service. The said Resonance with RF band ranging from 2.7-2.9 GHz massively used for sharing the spectrum with other communication service as well as between other radars. In addition to that the discussed RF band can be used for Wi-MAX application [21]. A high-refractive superstrate is placed at the top of the patch with suitable z height. The antenna directivity, gain and radiation efficiency can be enhanced by manipulating the refractive index (r_i) of the engineered superstrate. Control on the beam deflection in $E-Plane$ and $H-Plane$ of the radiating electromagnetic wave is realized using this multi-layer dielectric-superstrate structure. In this proposed structure the superstrate is shifted along the $x - y\,plane$ in order to achieve the control on beam deflection. Artificial magnetic superstrate model is also investigated in this work. From the simulation study it is observed that the antenna exhibits $59°$ of beam tilting and $139°$ of maximum scanning angle. The directivity of the antenna is also enhanced with improved gain up to 6 dBi. The composite structure of the MSAs with engineered superstrate is analyzed in full wave electromagnetic (EM) simulation tools by Mentor graphics, which follows advance methods to analyze the iterative computational task.

1.1 Importance of Control Beam Direction and Improve Directivity.

Enhancing the beam directivity towards a particular direction is essential in microwave radar and satellite communication including base station. In fact increase in antenna directivity increases the sensing range of the radar which is an essential and important parameter for realizing maximum coverage. Control on radiated electromagnetic (EM) beam deflection is a novel mechanism to direct the radiated wave in the required direction with a deflection angle (θ_t). In steerable MSAs, higher the deflection angle (θ_t), higher will be the scanning angle (θ_s). This work is proposed for enhancing the directivity and realizing improved scanning angle (θ_s) [19]. The designed MSA is proposed for modern microwave radar communication as well as for satellite communication with improved gain and radiation efficiency.

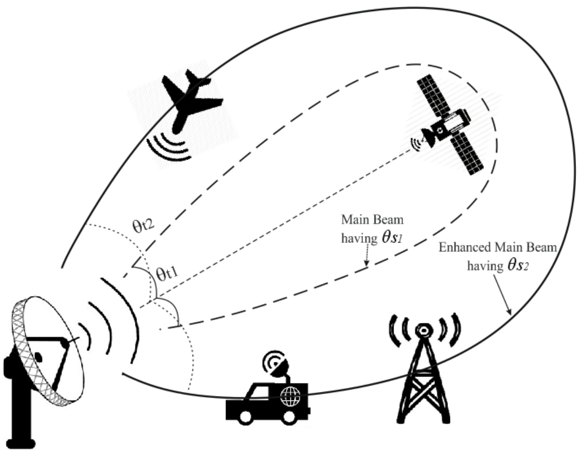


Figure 1. Enhanced performance of aeronautical Radar service using a steerable antenna.

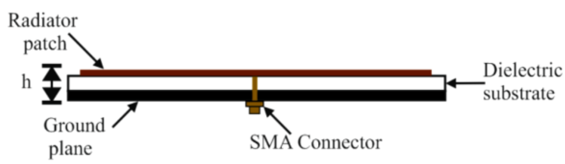
Figure 1 illustrates the advantages of using proposed steerable antenna in base stations and microwave radar terminal, which clearly demonstrates that the steerable antenna captured maximum signals from the communication devices. In case of radar it propagates electromagnetic (EM) waves to long distance without any loss and able to cover up maximum area. Consistently the antenna having a deflection angle of θ_{t1} which commits a scanning angle of θ_{s1}. The illustration indicates adopting of steerable antenna enhances the deflection angle (θ_{t1}). However, this technique provides a wide range of scanning angle (θ_{s1}) which in turn improves the coverage angle of the radar service. In the present scenario, rigorous investigation on directivity enhancement as well as improving the coverage area. Use of the proposed structure reduces the number of base station, which enables it to provide economically low cost communication and avoids the use of number of communication device in specific regions.

2. Design and Analysis of Antenna Structure

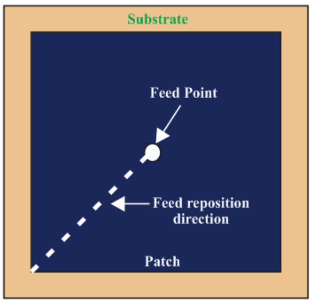
A novel printed antenna is suggested for beam steering with high refractive index engineered superstrate. The engineered superstrate is shifted and arranged in eight different positions above the radiator patch in $xy-plane$ along with the $E - Plane\ and\ H - Plane$ for realizing the maximum tilting angle. The detail antenna configuration is discussed in below section.

2.1. Antenna design

The proposed antenna patch is designed on an FR4 dielectric substrate having dielectric constant (ε_r) of 3.48, height (h) of 0.762, and loss tangent of $\tan\delta = 0.0018$. The antenna configuration is like single layer, single element model. The radiator patch of the proposed antenna is placed at the top of the substrate and the ground plane is placed at the bottom of the dielectric substrate. The cross sectional view of the proposed antenna is shown in Figure 1. The radiator patch is a continuous square patch with length (L_{Patch}), the physical dimension of the radiator patch is determined by using the formula given in Equ. 1 and the corresponding effective dielectric constant $(\varepsilon_{eff.})$ is determined from Equ. 2. A $50\,\Omega$ coaxial probe is connected to the patch through an SMA connector to excite the radiator patch. The feed point is initially placed at the center of the radiator patch $(x = 0, y = 0)$ and later the position of feeding point has been changed in order to get optimum impedance matching, gain and efficiency. From the observational study it was found that optimum result is achieved when the antenna is placed on the diagonal line with $45\,°$ angle to the previous feed point, as illustrated in figure 2. The length of the proposed antenna for $f_r = 2.8\,GHz$ is determined by equation 1. The relationship between patch length and design frequency is derived in the section below.



(a) Cross sectional view



(b) Top view

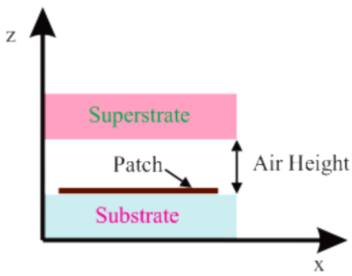
Figure 2. Conventional structures of the proposed antenna.

$$L_{Patch} = \left\{ \left(\frac{1}{f_r} \right) \times \left(\frac{c}{\sqrt{\varepsilon_{eff.}}} \right) \right\} \qquad \dots (1)$$

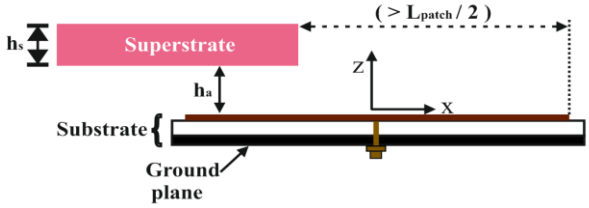
The effective dielectric constant of the proposed antenna structure is determined by the specified formula [1].

2.2. Formation of Engineered Superstrate or Magnetic superstrate

The designed radiator patch is introduced with a high refractive engineered superstrate for beam diversity operation. The superstrate was placed at the top of the proposed antenna architecture in $Z - Plane$ with specific Electromagnetic Band Gap (EBG). The formulation of the steerable antenna structure is demonstrated in figure 3 (a). Here the square type structure is used as superstrate having dielectric constant of $\varepsilon_s = 7$, and thickness of $h_s = 5\, mm$ and physical dimension of $(L_{SS} \times L_{SS} \times hs \quad mm3$. An Air layer is placed in between the radiator patch and superstrate layer with layer height of h_a . The cross sectional view of the proposed steerable antenna with high refractive superstrate is shown in figure 3 (b). The position of the high refractive superstrate is repeatedly rearranged in $E - Plane$ along with the $xy\, direction$ for observing the characteristics of the electromagnetic wave radiation from the radiator patch. The effect of high refractive superstrate also studied by changing the superstrate parameter $(\varepsilon_r \; and \; \mu_r)$. In fact, change in $\varepsilon_r \; and \; \mu_r$ parameter gives a remarkable impact on the steering operation. By increasing the refractive index (r_i) of the superstrate maximum scanning angle can be achieved. The details antenna parameter and its actual values are recorded in table 1.



(a) Formulation of Engineered superstrate



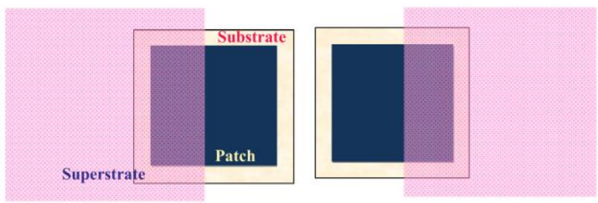
(b) Cross-view of the steerable antenna using superstrate.

Figure 3. Proposed antenna structure for Beam diversity.

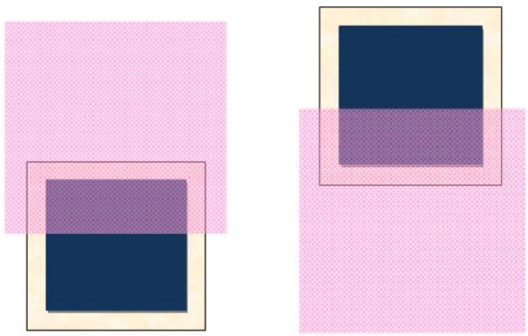
Table 1: Physical dimensions of the suggested antenna.

Parameters	Value
Dielectric constant (ε_s)	3.48
Substrate height (h)	0.762 mm
L_{patch}	28 mm
Dielectric constant of Superstrate (ε_r)	7
Superstrate height (h_s)	5 mm
L_{ss}	56 mm
Air gap (h_a)	5 mm

The Engineered superstrate is periodically shifted along the $xy - direction$ to achieve beam steering operation in desired angle. However the radiated beam is deflected with an angle (θ_t) in the elevation plane with respect to the shifting position of the engineered superstrate meanwhile all other parameters should have to be kept as previous. This operation also yields better coverage in terms of scanning angle, the scanning angle (θ_s) is primarily depends on the angle of tilting (θ_t). In each step we have observed different beam pattern with improved $\theta_t \; and \; \theta_s$.



(a) Left; (b) Right



(c) Top (d) Bottom

Figure 4. Manipulation of radiation pattern in different direction with superstrate at different position.

2.3. Antenna far field Analysis with Engineered Superstrate:

The MSA was printed on the grounded substrate having relative permeability of μ_r , relative permittivity of ε_r and thickness of h . The superstrate above the MSA layer with a suitable distance h_a from substrate layer in free space covers the radiating patch. The superstrate layer is having relative permeability of μ_{rs} , relative permittivity of ε_{rs} , and layer thickness of h_s . The far-field analysis of the MSA structure can be done using several ways like, dielectric cavity model, applying reciprocity theorem, and transmission line analogy of the whole structure. In this work the far-field of proposed MSA is analyzed by the help of the transmission line model.

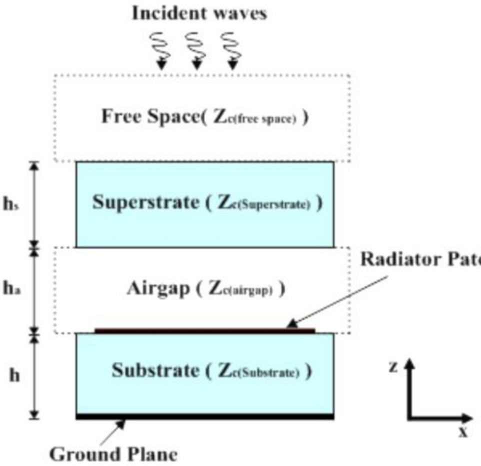


Figure 5. Equivalent Transmission line model of the suggested antenna structure (fig. 3)

The transmission line model of the proposed antenna structure with superstrate layer is shown in fig. 5. In which all the layers are replaced by its own reactance value multiple of a constant and the air layers also replaced with its reactance value multiple of a constant. The reactance values for each layer, in case of perpendicular polarization $(TE\ wave)$ is determined from the [equ. 2] – [equ. 5] and in case of parallel polarization $(TM\ wave)$ is determined from [equ. 6] – [equ. 9].

Derivation of the reactance value for each layer in case of perpendicular polarization;

$$Z_{c(substrate)} = (\eta_0\ \mu_r) \times \left(\frac{1}{\sqrt{\mu_r\ \varepsilon_r - \sin^2\theta}}\right) \quad ...(2)$$

$$Z_{c(air\ gap)} = (\eta_0\ ) \times \left(\frac{1}{\cos\theta}\right) \quad ...(3)$$

$$Z_{c(superstrate)} = (\eta_0\ \mu_{rs}) \times \left(\frac{1}{\sqrt{\mu_{rs}\ \varepsilon_{rs} - \sin^2\theta}}\right) \quad ...(4)$$

$$Z_{c(free\ space)} = (\eta_0\ ) \times \left(\frac{1}{\cos\theta}\right) \quad ...(5)$$

Derivation of the reactance value for each layer in case of parallel polarization;

$$Z_{c(substrate)} = \frac{1}{\varepsilon_r} \times \left(\eta_0\sqrt{\mu_r\ \varepsilon_r - \sin^2\theta}\right) \quad ...(6)$$

$$Z_{c(air\ gap)} = (\eta_0\ \cos\theta\ ) \quad ...(7)$$

$$Z_{c(substrate)} = \frac{1}{\varepsilon_{rs}} \times \left(\eta_0\sqrt{\mu_{rs}\ \varepsilon_{rs} - \sin^2\theta}\right) \quad ...(8)$$

$$Z_{c(free\ space)} = (\eta_0\ \cos\theta\ ) \quad ...(9)$$

Where, $\eta_0 = \left(\sqrt{\mu_0/\varepsilon_0}\right)$

The far-field of the designed MSA covered by the engineering superstrate is obtained by adding the field due to the radiating slots. The complete far field analysis of the steerable antenna is well investigated by Attia, et.all in [22].

2.4. Artificial Magnetic Sources.

Further analysis of the steerable antenna is carried out using the artificial magnetic source representation of the radiator patch. This mechanism is well studied in this section. The radiating patch of the proposed antenna is logically divided into four magnetic sources. The four magnetic source representation of the designed radiator patch is shown in figure 6. However the effect of the artificial magnetic source of the radiator patch is analyzed by representing these magnetic sources as radiating slot. The beam steering operation is observed by covering one magnetic source at a time and observing the corresponding radiation pattern. In this way the engineered superstrate is shifted above the radiator patch to cover the each magnetic source individually as shown in figure 7 and observe the corresponding beam tilting / scanning.

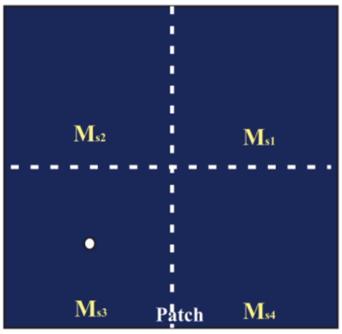
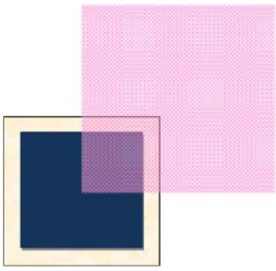
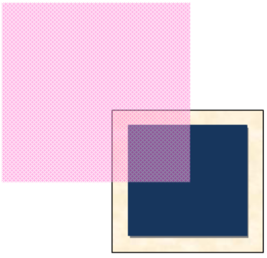


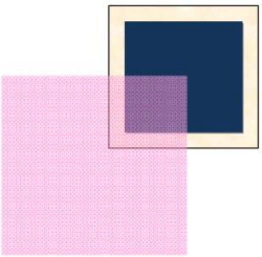
Figure 6. Analyzing the radiating patch as four magnetic sources.



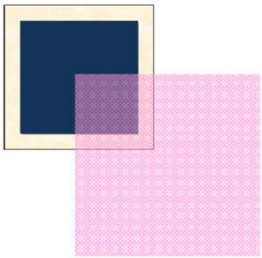
(a) Covering Ms_1



(b) Covering Ms_2



(c) Covering Ms_3



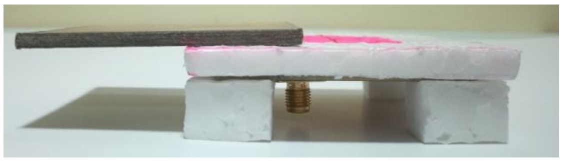
(d) Covering Ms_4

Figure 7. Manipulation of radiation pattern by covering Magnetic Sources.

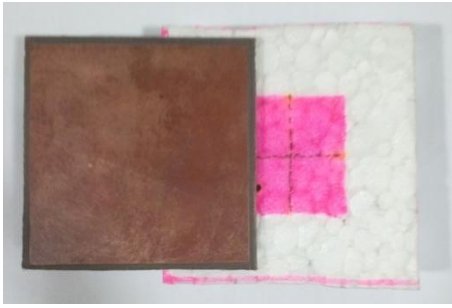
2.5. Beam tilting

The deflection angle of the main beam can be controlled in terms of changing the superstrate position over the radiator patch in $x - y\ plane$. The main radiated beam can be tilted by an angle θ_t , the tilting angle may be $+ve$ or may be $-ve$. The maximum tilting angle is due to the combined effect of superstrate parameter and its position. It has been observed that the high refractive engineered superstrate has covered only 33 % area of the radiator patch for obtaining a maximum tilting angle (θ_t) . Thereafter the high refractive superstrate is shifted along the same plane to partially cover the other parts of the radiating patch for experimental study. However the main radiated beam is steered with a desired angle by varying the high refractive index superstrate and manipulating the r_i value. With extensively study the proposed structure is logically analyzed as four equivalent magnetic sources (as demonstrated in figure 6). Each magnetic source is covered by the high refractive superstrate and the corresponding beam patterns are captured. In fact the magnetic sources are represented as radiating slots and where the beam titling is realized due to the phase imbalance between the two radiating slots. This can be mathematically calculated from the far field contribution of each radiation slot. The transverse component of the $E - field$ is obtained by incorporating the identical conditions on the transverse phase and electric field- vectors at the interface 1(area in between the radiator patch and superstrate) and interface 2 (Area above the superstrate layer). The steerable antenna also has capable of deflecting the main beam in both $E - Plane\ and\ H - Plane$ with the proper alignment of superstrate position and manipulation of superstrate components ($\mu_{rs}\ and\ \varepsilon_{rs}$) .

The antenna was fabricated using a different dielectric substrate of different parameter shown in fig. 8. A fixture of superstrate was done by considering a thermocol having same permittivity as air. The Moving of the superstrate position for covering different portions as discussed can be done using a simple mechtronics arrangement. Wherein Fig (a) illustrates the cross view and Fig. (b) illustrates the top view of the fabricated module. The driven patch is represented with pink color at the center of the thermocol, which evades the misalignment of the superstrate layer at the convenient position.



(a) Layer View



(b) Top view

Figure 8. Fabricated prototype of steerable antenna.

3. Full Wave Analysis of Steerable Antenna

The full wave analysis of the suggested steerable MSA is carried out using IE3D Electromagnetic simulator. The steerable antenna is optimized periodically to obtain better impedance matching as well as better gain response. The reflection co-efficient (│S11│) of the proposed steerable antenna is shown in figure 9. This demonstrates that the antenna exhibits a better impedance matching at 2.8 GHz with suitable impedance bandwidth.

Experimental study on │S11│parameter identifies that the reflection co-efficient of the discussed antenna experiences a negligible change with factor 0.3 and the matching is approximately equal. It has been observed that with superstrate the antenna exhibits better matching and the frequency deviation caused by the load impedance (Z_L) caused by the superstrate layer is somewhat negligible. However the measured │S11│ plot has a good agreement with the simulated │S11│ plot. The radiation pattern of the steerable antenna demonstrates the reformed beam, where the radiating beam is deflected from its original position with angle (θ_t) .The θ_t can be calculated from the radiation pattern shown in figure 10. However the radiating beam realizes a maximum tilting angle of $\theta_t = 59°$ and $\theta_s = 118°$. The experiemental evidence by using both the assumptions are exposed in figure 10. It has been observed that the each step gives an approximate equal tilting angle. But somehow the gain response and radiation efficiency are optimized.

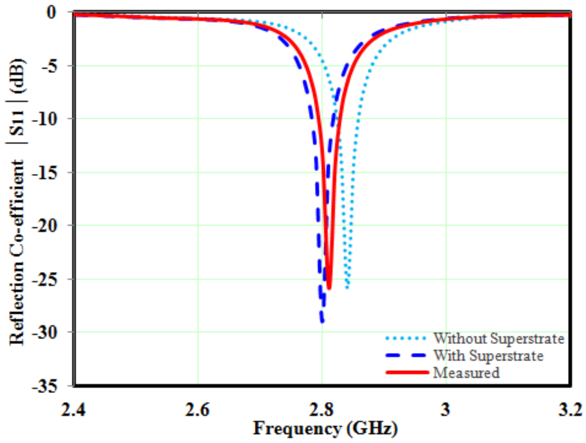
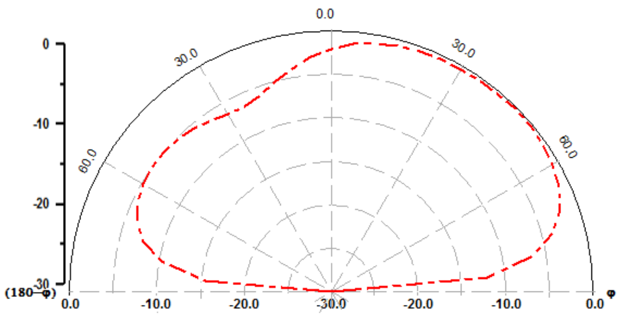
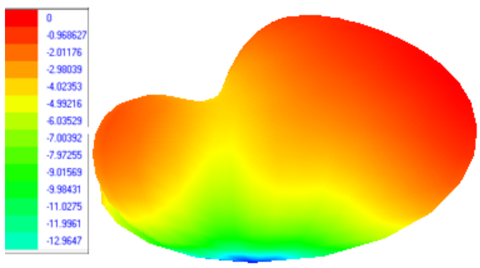


Figure 9. Return loss characteristic $|S_{11}|$ of the suggested steerable Antenna.

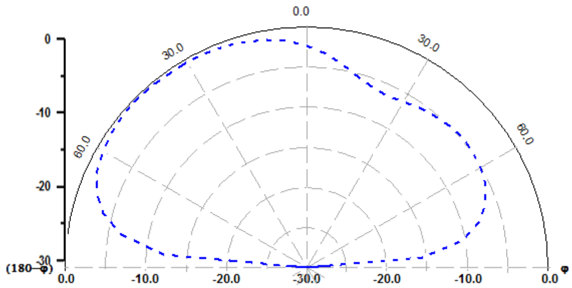


2D view

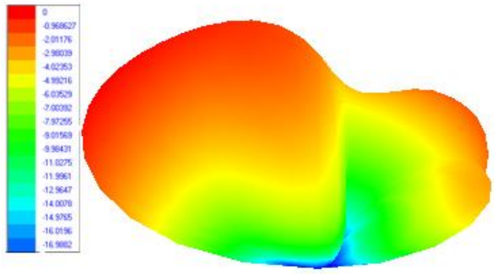


3D view

(a) Radiation Pattern with covering Left Portion

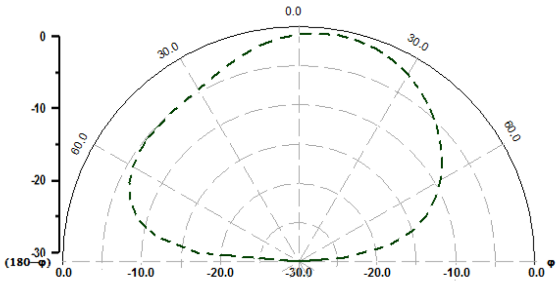


2D view

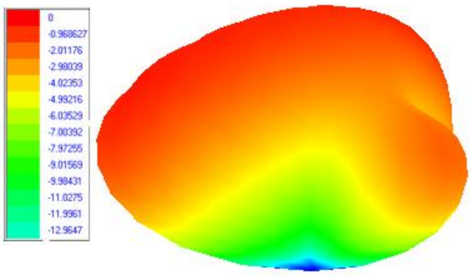


3D view

(b) Radiation Pattern with covering Right Portion.

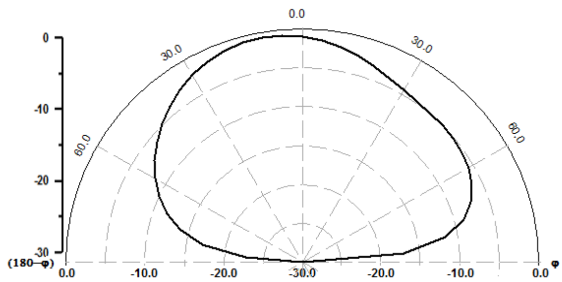


2D view

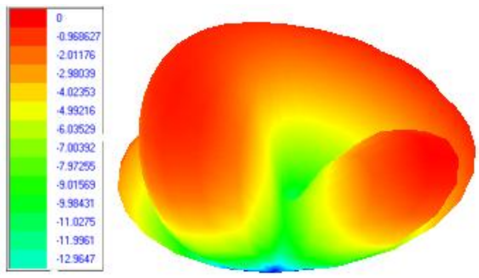


3D view

(c) Radiation Pattern with covering M2.



2D view



3D view

(d) Radiation Pattern with covering M4.

Figure 10. Radiation pattern of the suggested steerable antenna.

NOTE: In the radiation pattern, some beam patterns are unable to show the deflection angle due to its 2-dimensional representation. In fact, each step exhibits an improved θ_t.
It has been observed that the conductive plane at the top of the superstrate layer causes beam diversity of the radiating EM wave. The experimental consequence validates that the antenna exhibits maximum scanning angle with partially covering left side and right side. Coverage of Magnetic sources M_2 and M_4 provides somewhat poor deflection angle compare to left side and right side covering. Beam diversity also occurred due to partial coverage of top, bottom side, M_1 and M_3, but the patterns are best viewed in 360° angle which is not depicted here.

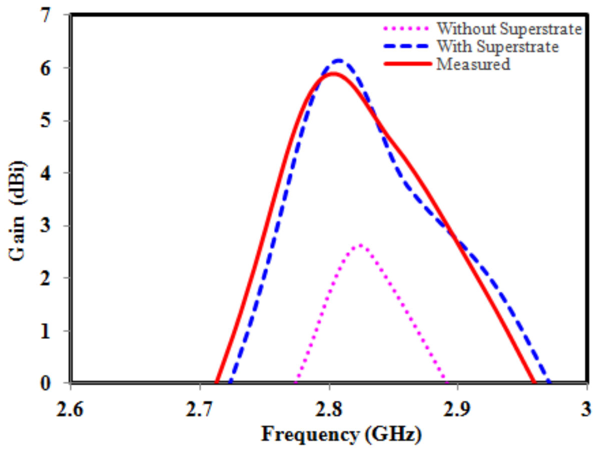


Figure 11. Gain of the suggested steerable antenna.

NOTE: Solid blue color line indicates the simulated gain response of the suggested steerable antenna and dotted red color line indicates the measured gain response.

The steerable antenna showing better gain response is plotted in figure 11. The proposed MSA has the maximum gain response of 5.5 dBi. Also the measured results are having good agreement with the simulated gain.

Table 2. Experimental Study by shifting the superstrate above the driven patch.

Superstrate Position	Scanning Angle	Deflection Angle	Gain (dBi)	Radiation Efficiency
Left	138°	58°	3.9	80 %
Right	139°	59°	3.85	76 %
Top	123°	57°	3.8	75 %
Bottom	122°	57°	3.82	76 %
Covering M1	85°	17°	0.5	69 %
Covering M2	105°	27°	5.5	82 %
Covering M3	90°	19°	0.4	69 %
Covering M4	121°	26°	5.2	81 %

4. Conclusions

A novel compact MSA is designed to analyze the deflection of the radiation field and enhance the directivity using engineered superstrate. The suggested antenna has enormous application in the S-band radar communication service, more ever to European aeronautical radar service. The analysis of the antenna is based on artificial engineered superstrate and magnetic source representation of radiating patch. The direction of radiated electromagnetic wave is controlled by shifting the superstrate. The maximum tilting angle is realized by manipulating the refractive index of the engineered superstrate. For magnetic source analysis of the radiating patch give extensive observational study. In which the beam tilting is achieved in both $E - Plane\ and\ H - Plane$. The suggested patch gives a maximum tilting angle of 59° at 2.8 GHz. It has been observed that this MSA structure can give maximum scanning up to 139° with enhanced directivity. This is very much essential for radar, communication and satellite communication. The antenna shows maximum gain response of 6.3 dBi, which is an added advantage of this model.

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