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Hybrid radome lens structure for gain enhancement and angular radiation control in patch antenna arrays

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ABSTRACT

The work in this study presents the design of a hybrid radome lens structure and its analysis aimed at achieving high gain and improved angular radiation capability. Wide-angle radiation with dome structure usually results in low gain and beam distortion, making it difficult to maintain stable performance at large scan angles. In this work, a dielectric radome lens is designed to increase gain and support better radiation capability. This dome structure is compared with multilayered lens with type-C structure. This study results in improved gain stability, and radiation characteristics which is influenced by radome geometry and material parameters. The variations in geometry of radome and dielectric properties of multilayers results in gain stability and radiation pattern. The proposed dielectric radome lens structure results in scan of 60° as compared to multilayered lens C structure resulted with a scan of 45°. The outcomes indicate that dielectric radome–based lenses provide a promising approach for applications in advanced communication and radar systems with wide angular radiation.

Keywords: Patch Antenna, Array, Single Solid lens, Multilayered lens, Gain, Return Loss.

1. INTRODUCTION

The rapid advancement in wireless technologies, antenna design must keep pace by offering high gain, wide scanning capability, and while ensuring consistent stability. Antennas must work efficiently, compact and cost-effective in all types of applications like commercial communication systems, defense, radars and satellite links, surveillance platforms (Silvestri et al., 2017). Among the various antenna technologies, patch antenna arrays are the popular choice because of its low manufacturing cost, lightweight structure, simple fabrication, and its seamless integration with RF circuits (Vyavahare et al., 2007). These characteristics make patch antenna arrays highly suitable for electronically steerable phased arrays used in SATCOM terminals, weather monitoring radars, tracking systems, and intelligent defense platforms (Mahatmanto & Apriono 2020). Electronic beam steering can be achieved by phased antenna arrays. However, this scanning range is limited by increased scan loss, reduction in gain at larger angles, and degradation in radiation patterns. To overcome these challenges, dielectric lenses are widely used above the antenna aperture (Probst et al., 2020). The improvement in gain, beam shaping and enhanced directivity can be provided by dielectric lenses.

Stable return-loss characteristics and desirable side lobe behavior are resulted by thoroughly designing these lenses geometry and having material properties of various layers (Mosallaei & Rahmat-Samii, 2001). The practical realization of high-performance dielectric lens antenna is possible due to the availability of low-loss dielectric materials, such as polypropylene, PTFE, ABS, and polyethylene. The flexible and efficient implementation of these lens configurations like a single hemispherical structure, multilayer configuration and radome-C type sandwich lens are enabled by different dielectric materials. This results in improved radiation characteristics and structural versatility (Malik et al., 2019). The designed dome antenna resulted in wide scanning capability (Gandini et al., 2021). Lens antenna with microstrip array resulted in improved gain (Mahesh et al., 2009). The various configurations of these multilayered lenses offer specific advantages. Gain enhancement is provided through a single solid lens by improving wave collimation (Dos Santos et al., 2019). Wave refraction control is better in multilayer lenses resulting in improved phase correction and beam shaping (Mahesh & Jetgonda, 2021). Two circularly layered shells with different permittivity resulted in enhanced radiation characteristics by optimizing field distribution within the lens (Boriskin et al., 2010).

Alternating high and low permittivity layers are built in C-type sandwich lenses resulting in balanced trade-off between gain, bandwidth and suitable for real-world applications (Arya et al., 2021). Understanding how each lens type interacts with and modifies the radiation performance of a patch antenna array is essential for selecting the most effective configuration. Motivated by this, the present work provides a comprehensive comparison of three hemispherical dielectric lens structures—single solid, multilayered, and radome-C Type Sandwich lenses—used with a 2×2 patch antenna array. The duroid substrate is selected for antenna because of low dielectric loss and good performance at high frequency (Chepala et al., 2021). To obtain improved gain, side- lobe characteristics, half power beamwidth and scanning performance, a model of antenna-lens is developed and optimized in ANSYS HFSS.

The main goal of this work is to find best lens configuration that offer good tradeoff between wide angle beam scanning and gain performance. By analyzing and comparing these designs, this work aims to provide valuable insights for developing efficient lens-integrated phased- array antennas consisting of a conventional patch array placed beneath or inside a dielectric lens structure suitable for modern radar, tracking, and communication systems operating in the X-band frequency range (Zhang et al., 2021). The developments of high gain antennas with stable radiation characteristics are in pressing need in emerging 5G/6G communication. Though microstrip patch antennas are preferred in these applications, they come with limitation of low gain and restricted beam scanning capability.

In this work, antenna arrays with dielectric lens are investigated extensively to address these challenges. Lens antenna acts as an augment for the existing antenna arrays. Focused electromagnetic waves can be obtained by dielectric lenes, which enhances radiation performance. Antenna array configuration results in improved gain and directivity. In literature, gain improvement is resulted with homogeneous and multilayer dielectric lens structure with antenna arrays. However, these studies have not focused on radiation performance and impedance matching. Though radome structure is used for environmental protection, but its role in electromagnetic waves modification is not explored.

This work proposes a proper design of dielectric lens which is integrated to antenna and its analysis. Initially a single patch antenna integrated to lens is designed and evaluated with respect to gain and radiation performance. This is further moved to design 2X2 array, multilayer structure and the fourth type designed is radome configuration. In conventional approach any one parameter is optimized. However, in this work a gain improvement, lowered return loss and enhanced radiation characteristics are achieved. The distance between lens and antenna array is varied to obtain optimized results. The main contribution of this study is radiation of beam up to 60° with better impedance matching characteristics. In conventional lens integrated antenna array design, beam radiation is only 45° (Henry & Yang, 2020). An analysis is presented to know the interaction between dielectric lens structure and patch antenna array structure.

2. METHODOLOGY

Design of Antenna

Dielectric lens design

Transformation of spherical wavefronts to planar wavefronts is achieved by a dielectric lens. This improves gain and directivity. Snell's law is followed by electromagnetic waves refraction in dielectric medium. The change in direction of propagation is observed at material interfaces.

The refractive index of dielectric medium is represented as in equation (1).

$$n = \sqrt{\mathcal{E}_r} \qquad (1)$$

Where, n is refractive index and $\mathcal{E}_r$ is the relative permittivity of material. Constant distance from optical path length to feed of the aperture must be maintained for proper focusing. This can be expressed as depicted in equation (2).

$$d+nt= \text{constant} \qquad (2)$$

Where, d is the free space distance and t is the distance travelled in dielectric material.

d is the distance of lens location from patch antenna structure, such that the feed is placed near the focal region. This results in illumination of lens aperture efficiently, reduced spillover losses and improved radiation efficiency. Fig 1 (a) shows lens integrated with patch antenna array.

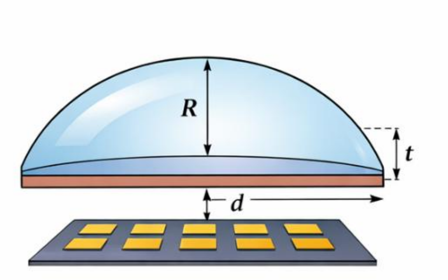

Fig. 1. (a): Dielectric lens integrated with antenna array

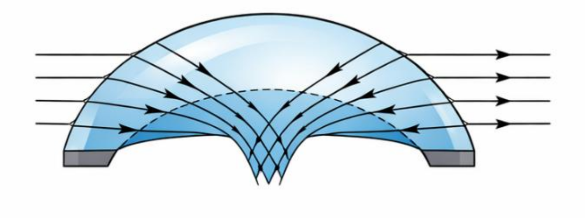

Fig. 1. (b): Refraction and focused electromagnetic waves through the dielectric lens

In this contribution, multilayer dielectric surfaces are considered to approximate a graded refractive index, which enables smooth wave bending and reduces phase errors (Figure 1b). Fig 2 (a) shows multilayer dielectric lens configuration to approximate graded refractive index. The radial variation of the refractive index is expressed as depicted in equation (3).

$$n(R) = n_0 - kR^2 \qquad (3)$$

Where, n_0 represents refractive index at the center, R represents the radial distance from lens axis and k is a design constant. The focus efficiency is enhanced and thereby improves aperture field uniformity.

Further, a radome structure is introduced to modify electromagnetic wave propagation characteristics. This proposed structure contributes to beam shaping and stabilizes angular propagation. Results in enhanced radiation characteristics. Beam propagation with and without radome is shown in Fig 2 (b).

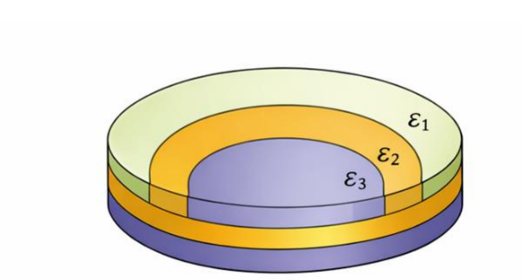

Fig. 2. (a): Multilayer dielectric lens configuration

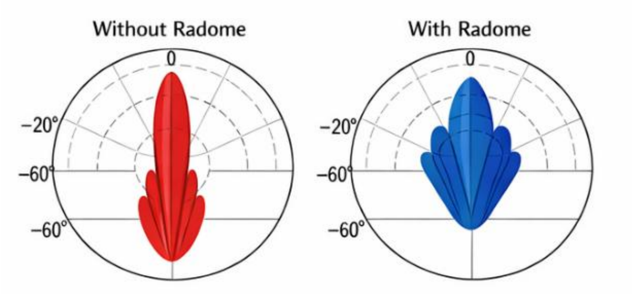

Fig. 2. (b): Beam propagation with radome and radomeless structure

A. Single Patch Antenna

A patch antenna is designed and simulated in ANSYS HFSS as a first case. The patch antenna designed here has a measurement of 2.4 cm x 1.9 cm. This designed antenna resonates at 5 GHz frequency. The dielectric material utilized in this antenna structure as a substrate is Duroid having a subH of 62 mil (1.57 mm). The substrate lateral dimension is 3.9 cm x 3.3 cm. The substrate gives mechanical support and controls the fringing fields around the patch edges. This results in stable radiation performance. To obtain a good radiation with proper impedance characteristics, a ground plane is kept on the other side of the substrate. Microstrip feed line is used to excite the antenna. This feed is designed carefully to obtain good impedance matching and in turn to reduce return loss. The antenna structure is thoroughly optimized to enhance gain, to obtain stable radiation patterns, and to reach efficient performance within the desired wavelength.

B. Design of 2x2 Array

A 2 × 2 microstrip patch antenna array depicted in Fig. 3(a) is designed which operates over a 5 GHz frequency applied with a low-loss Duroid substrate. The inter-element distance between adjacent, patches is maintained at about 0.5λ to reduce mutual coupling and ensure good array performance. The optimized inter element spacing improves the array to result in improved gain and provides stable radiation characteristics compared to a single patch antenna structure. This design resulted in improved operation at the 5 GHz frequency band.

C. A Single Lens with a Patch Antenna Design

The Fig 3 (b) illustrates a sold lens structure kept over a 2x2 patch array. This is designed to achieve a increased gain and improved radiation capability at 5 GHz frequency. The directivity and radiation performance are improved as the lens focuses on radiated waves. The substrate in patch is Duroid. The lens is made of polyethylene. The dielectric constant of polyethylene is 2.25. This offer low loss performance and it is good in focusing electromagnetic waves. A hemispherical lens with a 3.5 cm radius is selected to provide effective beam focusing. The lens is placed 1.5 cm above the patch, determined as the optimum spacing for improved performance. The spacing kept in this design resulted in optimum focusing of electromagnetic waves. The effective phase transformation of signals is also obtained. Enhanced radiation characteristics and increased gain are resulted in lens integrated structure. This is an improvement over a single patch antenna structure. The implemented lens structure gives a focused phase compensation and also works on wavefront collimation.

D. Multilayered Lens Structure with a Patch Antenna Design

A multilayered lens structure consists of four material layers: inner vacuum region surrounded by successive layers of ABS, polyethylene, polypropylene, and PTFE, and is used with patch antenna. Several layers are designed to obtain a decreasing refractive index profile. This arrangement is kept to enable smooth transformation in phase, minimized reflections, enhanced gain and improved scanning performance. The dielectric materials applied on various layers are outlined in Table 1. The separation of patch as in vacuum is of radius 3 cm. The next four outer layers have radii of 3.3 cm, 3.6 cm, 3.9 cm, and 4.2 cm. The inner shell uses a higher dielectric constant material, and the outermost shell uses a lower dielectric constant which results in gradual refractive profile. This improves the overall gain performance and increases the radiation characteristics. The distance between patch antenna and lens structure is 5 cm. This optimized distance results in enhanced antenna performance. In turn gives less return loss with high gain.

Table 1. Dielectric material specification

Dielectric Sphere	Used Material	Dielectric Constant
Sphere 5	PTFE	2.1
Sphere 4	Polypropylene	2.2
Sphere 3	Polyethylene	2.25
Sphere 2	ABS	3
Sphere 1	Vacuum	--

Design of multilayered lens with array

A multilayered dielectric lens integrated with a 2×2 patch antenna array is shown in Fig 3 (c). It is designed to enhance gain and improve wide-angle scanning performance. The lens consists of multiple dielectric layers, including an inner vacuum region followed by successive layers of ABS, polyethylene, polypropylene, and PTFE. Each layer has a different radius, with r = 6.7 cm for the vacuum region and r_1= 4.9 cm, r_2= 5.2 cm, r_3 = 5.5 cm, r_4= 5.8 cm, and r_5 = 6.1 cm for the outer layers. The inner layers use higher dielectric constant materials, while the outer layers are designed with materials of low dielectric constant. The smoothed wave refraction and efficient beam focusing are achieved because of this gradual transition. The gain is enhanced by lens structure. This is achieved at a 6 cm optimum distance. The collimated radiated waves are achieved by lens structure. Hence, it improves antenna capability in scanning.

E. Array Antenna Design with Structure of RADOME-C

Fig. 3(d) illustrates a radome-C structure with array antenna design. A gradual refractive profile is achieved in this design. The structure is arranged in such a way that inner shell as high dielectric constant, where as it is decreased towards outer shell. The high dielectric material is used in the inner layers with ABS ($\varepsilon_r \approx 3$). Next, outer layer to this inner layer is designed with polypropylene material having $\varepsilon_r \approx 2.2$, which is of low dielectric. This arrangement is done to achieve a gradual (decreasing) refractive index profile. This alternating refractive index arrangement provides good wave propagation, which is smooth. In turn, results in enhanced bending and concentrated radiation of electromagnetic waves. The graded dielectric profile reduces impedance discontinuities and reflection losses, thereby resulted in increased gain and improved beam-scanning capability. The radome-C structure is made of multiple spherical shells. The radius of inner most sphere is 6.7 cm, the next few shells radii from inner to outer are 7.0 cm, 7.3 cm, 7.6 cm, 7.9 cm, and 8.2 cm. The distance between antenna and lens is 5 cm. The proper phase alignment between lens and radiated fields is obtained with optimum distance. This results in reduced return loss and improved gain.

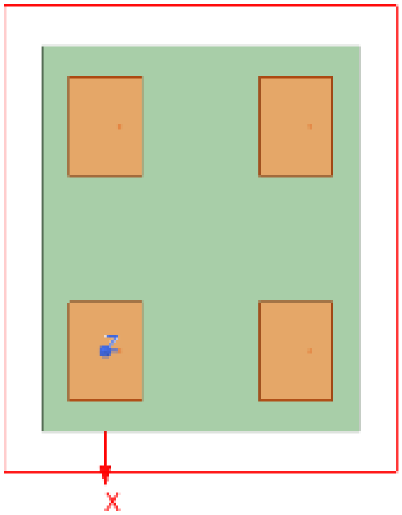

Fig. 3. (a): Patch 2X2 array antenna

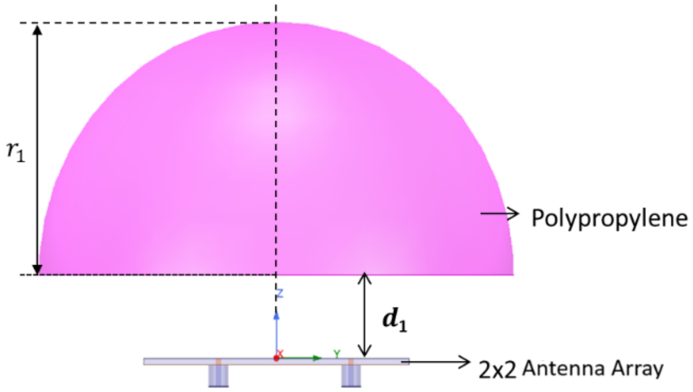

Fig. 3. (b): Single lens structure with patch 2x2 array antenna

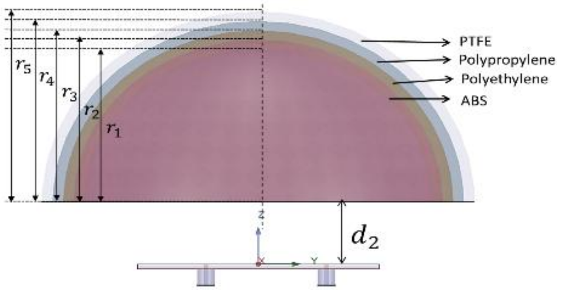

Fig. 3. (c): Multilayered lens structure with patch 2x2 array antenna

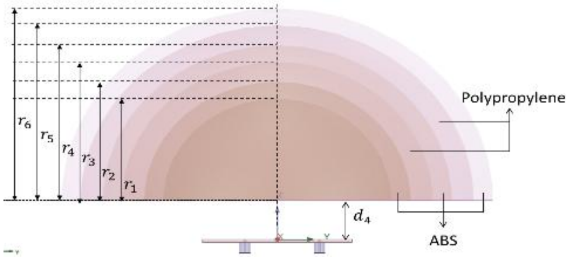

Fig. 3. (d): Radome-C with patch 2x2 array antenna

3. RESULTS & DISCUSSIONS

A structured study is carried out in this work to determine the influence of key design parameters such as radius of lens, spacing between lens to antenna, dielectric constant of substrate, and number of layers considered. The effect of beam collimation and gain is evaluated by varying lens radius. An optimized distance is achieved between antenna and dielectric lens structure. This enables to improve gain and thorough impedance matching. The various dielectric materials are considered in this work to understand the effect on wave refraction and resonant frequency. The enhancement of graded refractive index profile is examined by considering number of layers variation. This analysis results in choosing optimal parameter values. This includes improved gain, stable impedance characteristics, and enhanced radiation capability.

The design and characteristic analysis of the 2×2 array patch antenna with lens-integrated structure is performed using simulation in ANSYS HFSS tool. The patch antenna is applied with a Duroid substrate of $\varepsilon_r = 2.2$ this arrangement results in gain of 7.79 dB and a -22.8 dB reduced return loss. This minimized return loss indicates good impedance matching and improved radiation performance. These characteristic of return loss and gain is shown in Fig. 4(a) and 4(b) respectively. Fig. 5 (a) depicts return loss of 2×2 array with microstrip patch antenna. This figure indicates that the 4.88 GHz is the resonating frequency of 2x2 patch array antenna. The return loss of −29.9 dB is obtained here. Fig. 5 (b) shows achieved gain of 13.99 dB for this 2x2 antenna array structure. This shows that this array structure provides enhanced directivity through improved gain. Fig. 5(c) depicts 2x2 array antenna configuration radiation pattern.

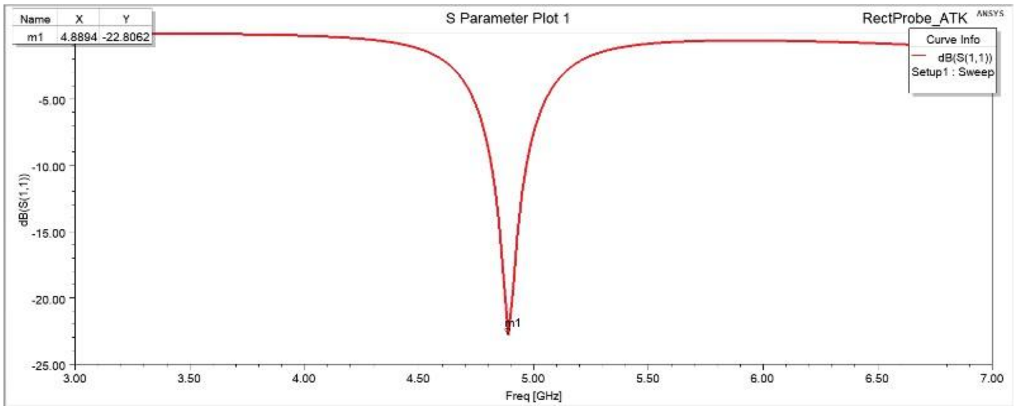

Fig. 4(a). Return loss of patch antenna

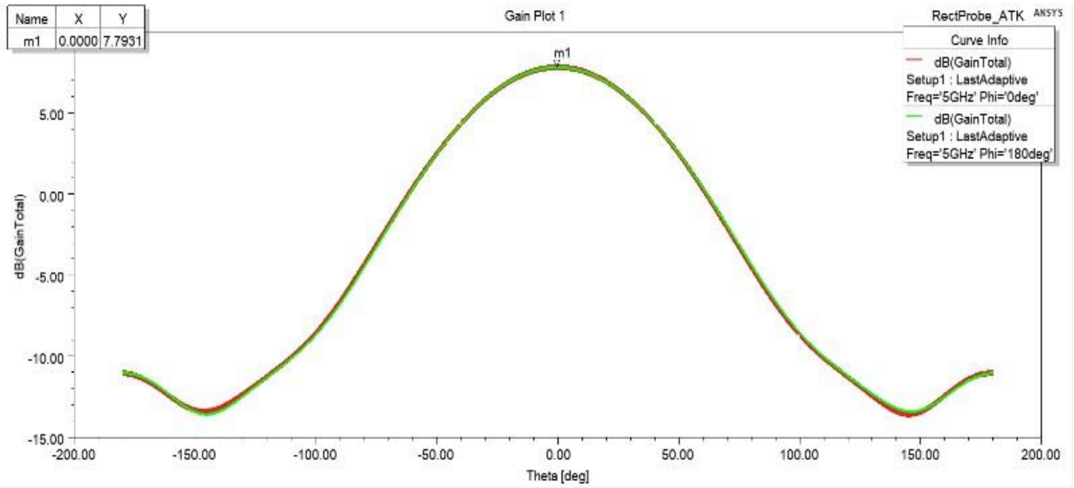

Fig. 4(b). Gain plot of patch antenna

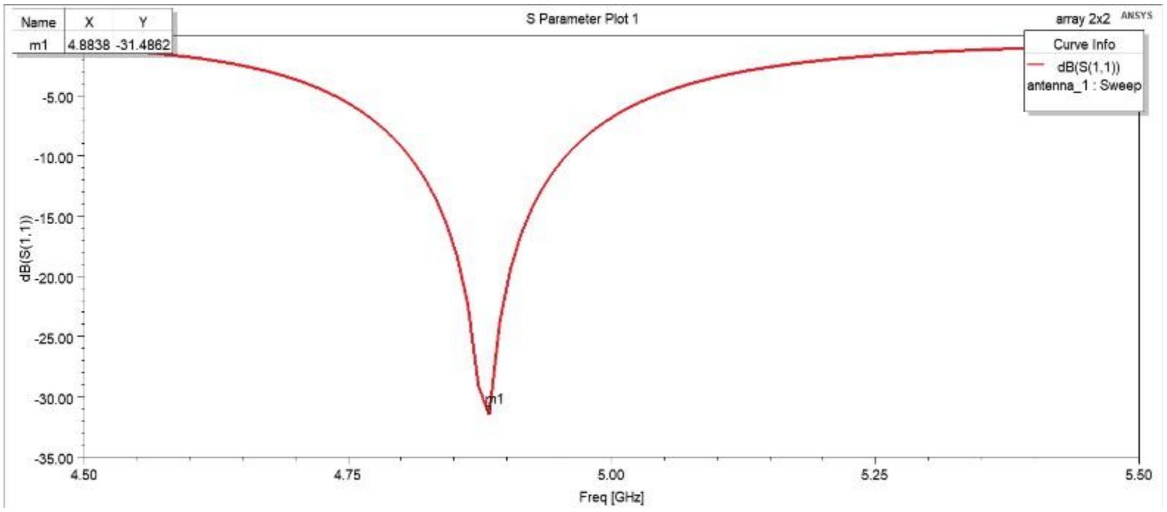

Fig. 5(a). Return Loss of 2X2 Array

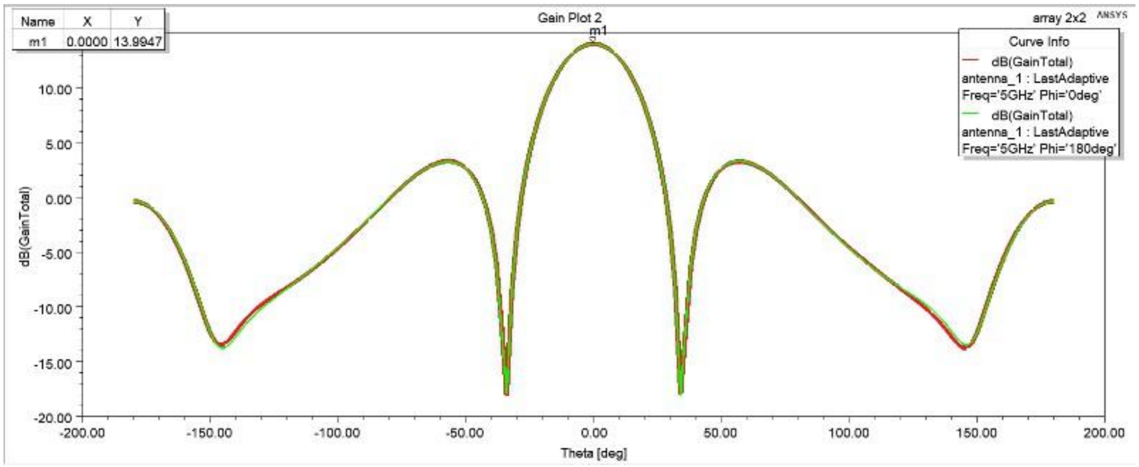

Fig. 5(b). Gain Plot of 2X2 Array

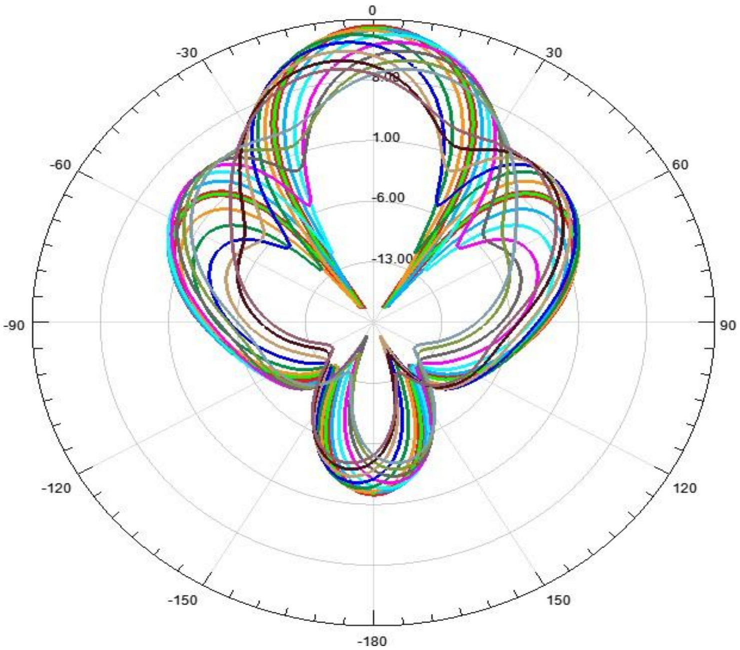

Fig. 5(c). Radiation Pattern of 2X2 array

Fig. 6(a) illustrated the obtained results of the patch antenna integrated with a single solid lens resonating at 4.93 GHz with a return loss of –30.06 dB. Fig. 6(b) shows gain increasing to 11.50 dB. Fig. 7(a) illustrates the simulation characteristic of the multilayered dielectric lens antenna structure. The antenna structure resonates at a frequency of 5.9749 GHz and achieves a return loss of -14.3945 dB. There is a shift in the resonant frequency from 5 GHz to 5.97 GHz is observed in this case. The reason behind this shifted frequency is the dielectric loading effect introduced by the multilayer lens structure. The proximity between the antenna and the lens leads to near-field coupling, which further contributes to the shift in resonance. Fig. 7(b) shows the gain plot of this configuration with a resulted gain of 10.07 dB. Fig. 8(a) shows the simulation results for the multilayered lens integrated with the 2×2 array. The antenna structure resonates at a frequency of 4.899 GHz. The Fig. 8(a) also indicates a return loss of -21.9161 dB. This shows a proper impedance matching at the resonating frequency. This enhanced characteristic is a resultant of introduced lens structure giving focused radiated electromagnetic waves. In turn results minimized phase dispersion, and improved directivity. Fig. 8 (b) depicts multilayered lens with array gain plot, achieving a gain of 15.0731 dB. This is an improvement showing higher gain than the array operating in a lens less structure. Fig 8 (c) shows scanning performance of multilayered lens structure with array antenna.

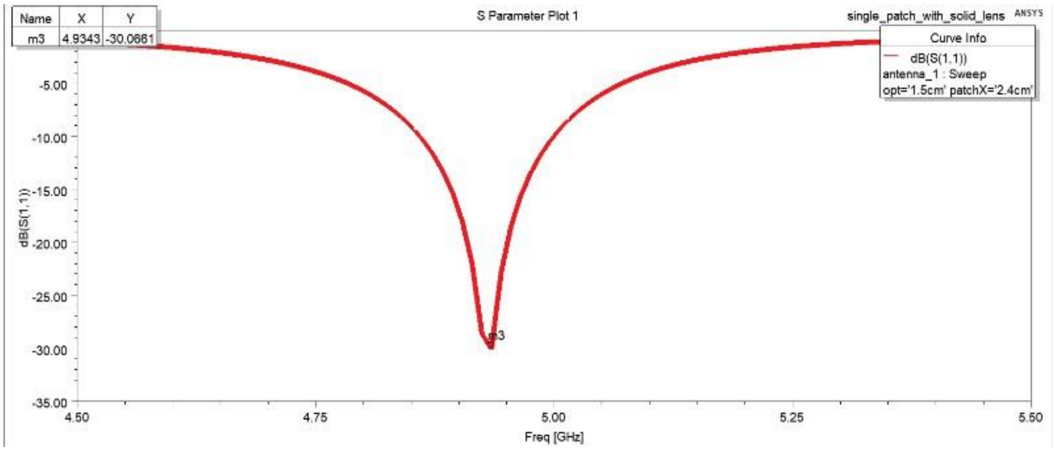

Fig. 6(a). Return Loss of Single Solid Lens

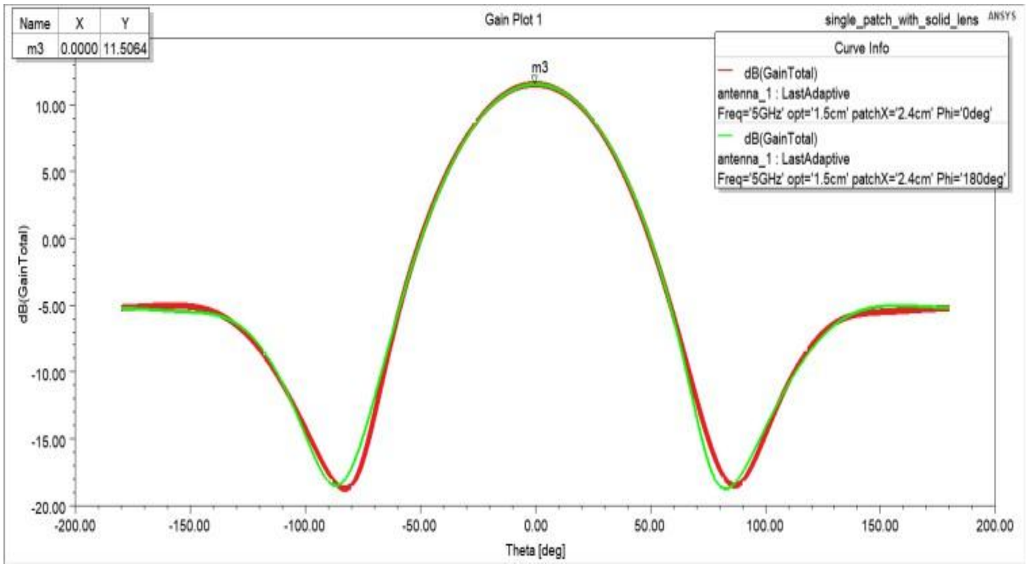

Fig. 6(b). Gain plot of a single solid lens

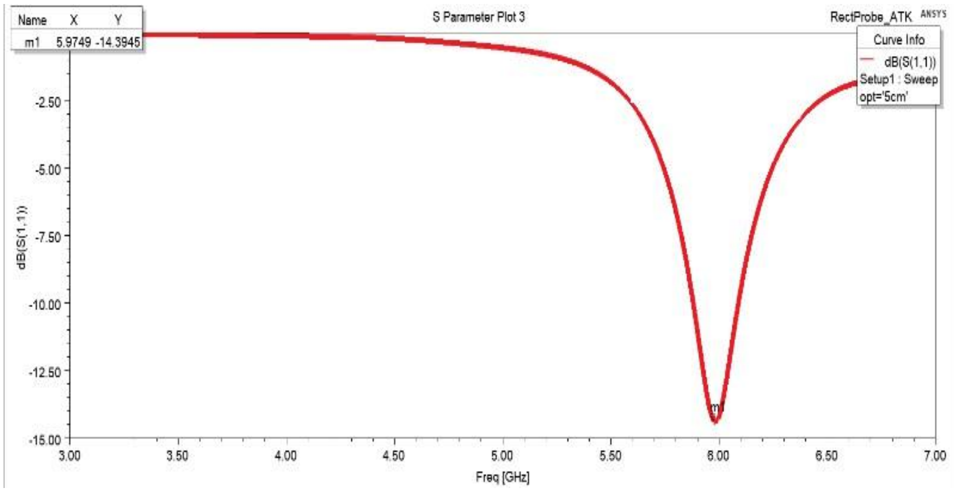

Fig. 7(a). Return loss of multilayered Lens

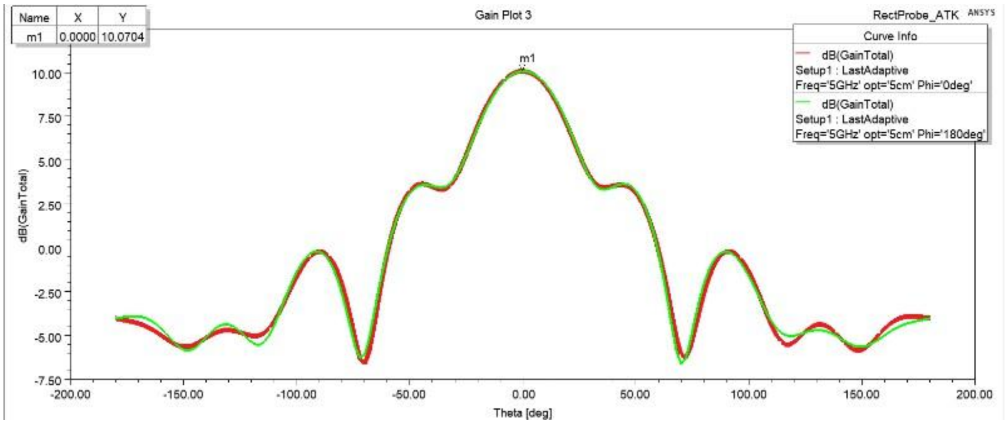

Fig. 7(b). Gain plot of multilayered lens

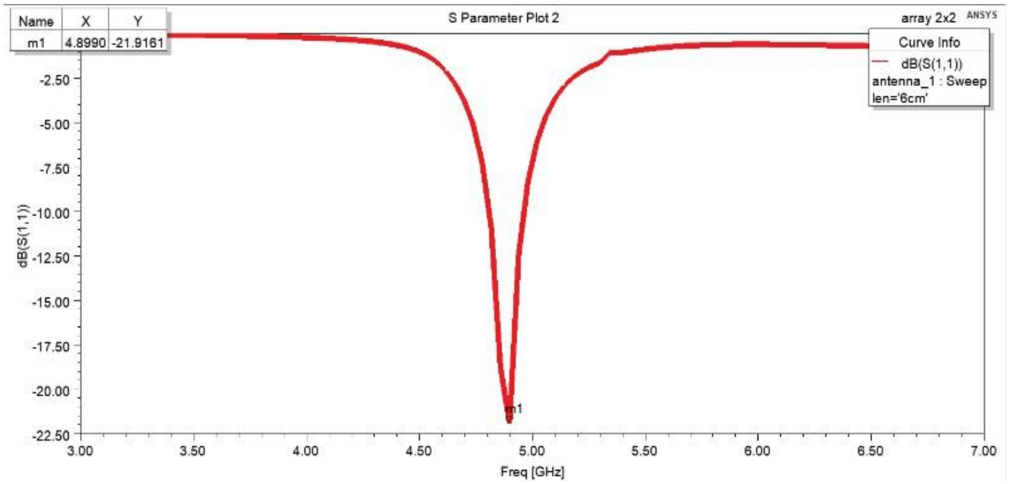

Fig. 8(a). Return loss of multilayered lens with array

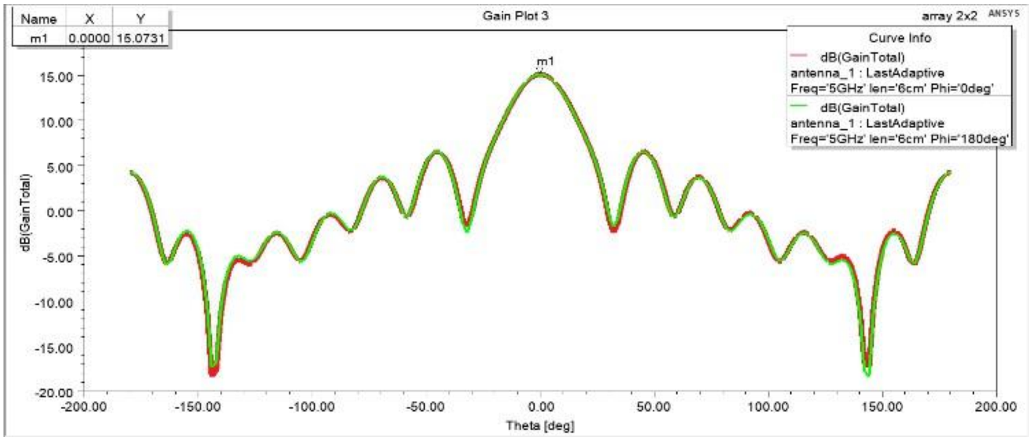

Fig. 8(b). Gain plot of multilayered lens with array

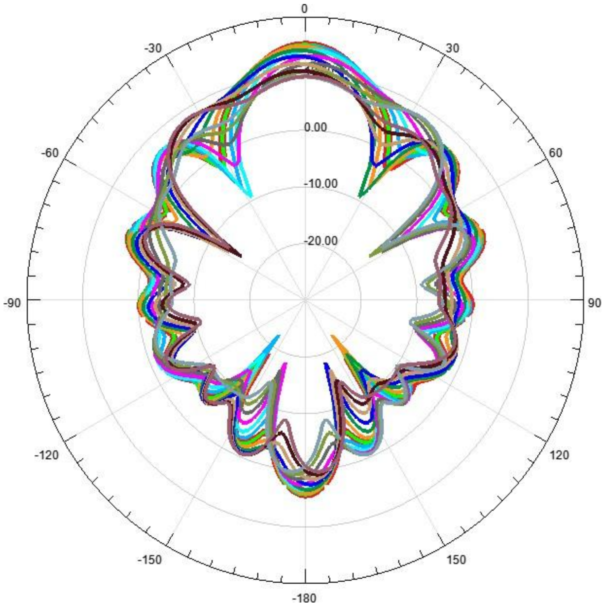

Fig. 8(c). Scanning result of multilayered lens with array

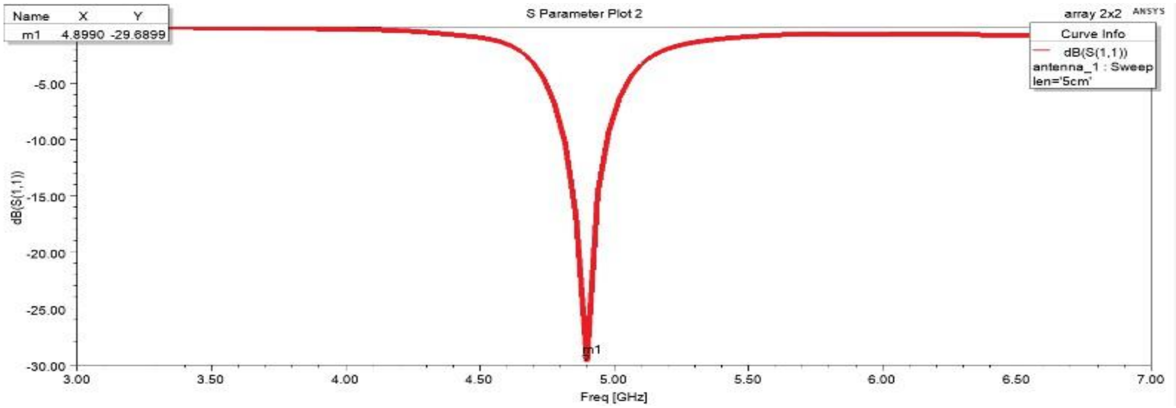

Fig. 9(a). Return loss of radome-C with 2X2 array

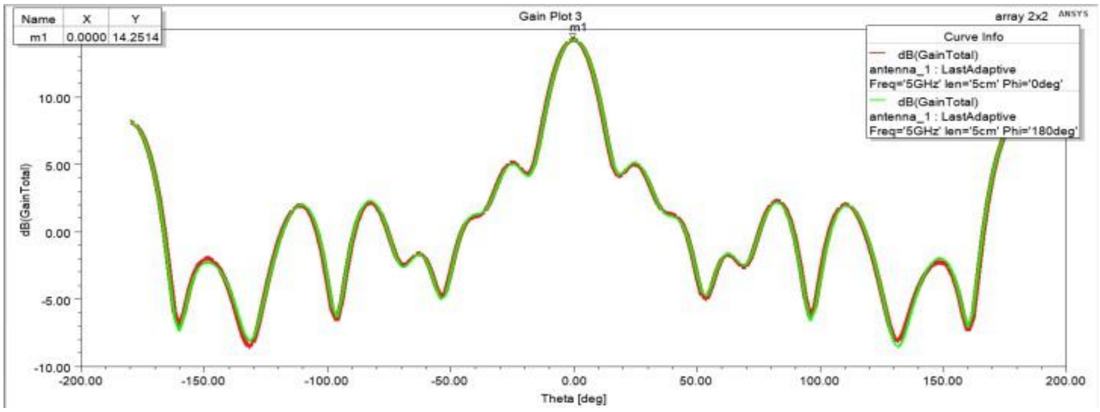

Fig. 9(b). Gain plot of radome-C with 2X2 array

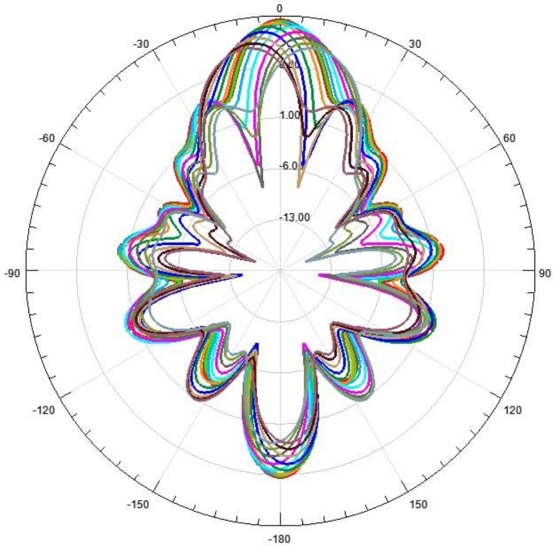

Fig. 9 (c). Radiation result of radome-C with 2X2 array

Table 2. Comparison of scanning angles results

Type	Return Loss (dB)	Gain (dB)	Scanning Angle (Degree)
Single patch	-22	7.7	--
2X2 Array	-29	13.9	45
Multilayered lens with array	-21	15	45
Radome -C	-29	14.25	60

Fig. 9(a) depicts the return loss of the radome-C dielectric lens integrated with the 2×2 antenna array structure. This figure indicates that the 4.8990 GHz is the resonating frequency of this radome-C structure. Fig. 9(b) depicts the gain this radome-C structure is 14.25 dB. A -29.6899 dB return loss in the figure illustrates a proper matching of impedance. Radome-C structure radiation pattern is illustrated in Fig 9 (c). The four different cases proposed in this study is depicted in Table 2, which compares the gain, return loss, and scanning angles. This compared results clearly shows that the multilayered lens provides favourable scanning performance. This structure also gives an effective 45° scan angle. An improved scan angle of 60° is resulted in the case of radome-C lens structure. A high gain of 14.25 dB is also obtained through this structure. This 60° scanning angle is better as compared to 45° in (Imran & Dragos, 2021).

4. CONCLUSION

The work presented in this paper illustrates a comparative study of three different dielectric lens configurations. It is also integrated with a 2×2 microstrip patch array antenna. The work is focused on knowing how various lens configurations affect gain performance, radiation characteristics, and electromagnetic beam shaping. The structures considered in this study are single solid lens, multilayered and radome-C. The results obtained through simulation clearly indicates that each lens configuration improves gain and enhances beam collimation. However, the improvement level varied depends on arrangement of substrate material and complexity of structure. Among the designs considered here, the multilayered lens exhibited the most enhanced radiation performance. It exhibits an improved scan range of 45°. The radome-C lens enhances a wider scan range of 60° with increased gain demonstrates best results. The work carried out clearly demonstrates selection and design of dielectric lenses for various applications with improved gain and radiation performance. This includes lens structure in applications such as air traffic control, radar surveillance, target tracking, and weather monitoring.

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Author Contributions

Conceptualization, methodology and simulation: Shruthi M; Antenna design, Result analysis, and manuscript drafting: Smitha N; Validation of results and manuscript editing: Smitha Gayathri D; Simulation: Kumar P; Methodology: Suguna Guttor Chickaramanna. All authors have read and agreed to the published version of the manuscript.

Ethical issues

Not applicable. This study does not involve any experiments on humans or animals. Hence, ethical approval was not required.

Informed consent

Not applicable.

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Conflict of Interest

The authors declare that they have no conflicts of interest, competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data and materials availability

All data associated with this study are present in the paper.

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