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Wide Beam Steerable High Gain Antenna Using Graded Index Metasurface Lens

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Abstract

In this paper, the design of an ultrathin highly transmissive angular graded-index metasurface (AGIMS) lens is proposed and a beam steerable high gain low profile lens antenna is designed using AGIMS lens and microstrip patch antenna (MPA) radiator operating at 10.10 GHz. An ultrathin graded-index metasurface lens is designed by using fundamental unit cell and its modulated form. The direction and gain control of the microwave radiator's beam using designed modulated metasurface lens having doubled sided double circular ring resonator as a fundamental unit cell is presented. The uniform radial and linear movement of AGIMS in step of 12 mm steers the radiated main beam of MPA continuously in a conical plane from -40° to +40° with a maximum measured broadside gain of 13.15 dBi and minimum broadside gain of 11.80 dBi at 10.10 GHz frequency indicating maximum and minimum gain enhancement of 8.40 dB and 7.0 dB in -40° and 0° direction respectively. Using AGIMS lens, stable broadside radiation characteristic with beam steering and continuous gain enhancement is achieved. The measured and simulated results are in good agreement.

1 Introduction

Metasurface is a two dimensional artificially engineered surface made up of array of sub-wavelength metamaterial unit cells having controlled material properties. These surfaces act like a beam director in several cases where gain and direction of radiated beam of radiator can be tailored.

The beam steering of antenna is achieved by using electronically tunable surface in [1] and beam forming with gain enhancement by using metasurface is achieved in [2]. Using the similar approach a non uniform dielectric lens is designed to enhance the antenna characteristics and a wide band high gain antenna is designed in [3]. The dielectric lens characteristic used in [3] is modified by using unit cells and a non uniform metasurface lens is designed to achieve beam steering and gain enhancement of millimetre wave antenna in [4] and [5] respectively. To achieve better beam steering a phase modulated metasurface on the top of low loss substrate is designed in [6]. To achieve multi band operation by using metasurface lens a multilayer double mode metasurface is designed and gain enhancement with good aperture efficiency is achieved in [7] [8]. A huygens metasurface lens is designed to achieve reconfigurable polarization and direction control of beam in [9] by placing the lens on the top of horn antenna radiator. Further modifying the metasurface with uniform amplitude and phase distribution unit cells, a metasurface lens aperture is designed and gain enhancement with aperture efficiency enhancement is achieved in [10].

In this paper, a high gain low profile beam steering antenna is designed by using graded index metasurface (GIMS) lens. A highly transmissive sub wavelength unit cell is designed first and a modulated metasurface is designed by using modulated unit cells. The movement of GIMS lens in linear and angular manner over microstrip radiator causes gain enhancement with beam steering in wide range. The designed AGIMS lens antenna is novel in terms of mechanism of achieving gain enhancement with wide beam steering, stable broadside radiation characteristic and compactness of the antenna design.

2 Designing of Angular Graded Index Metasurface Lens

The configuration of proposed lens antenna consist of a microstrip patch antenna (MPA) radiator acting as a microwave source and a graded index metasurface (GIMS) acting as a lens placed over microwave radiator as shown in Figure 1.

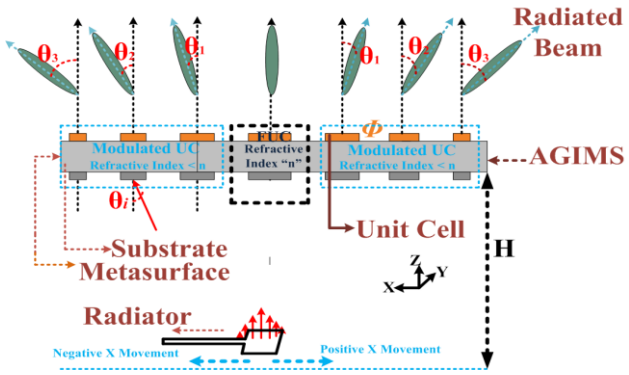


Figure 1. Working principle of AGIMS lens over electromagnetic radiator.

The arrangement of GIMS consist of group of modified double sided double circular ring resonator (DSDCRR) unit cell in a nearly circular uniform phase profile on the top surface of lens as shown in Figure1. The DSDCRR unit cell

is modulated by changing its radial dimension parameters. The modulated DSDCRR causes change in transmission magnitude and transmission phase due to change in surface current distribution, resulting in to progressive change in refractive index profile. The metasurface (MS) is designed by using double sided double circular ring resonator (DSDCRR) as sub wavelength unit cell. The DSDCRR unit cell consists of two circular ring resonators (CRR) printed on both sides of substrate. The geometrical parameters of fundamental unit cell are calculated to provide optimum equivalent inductance and capacitance to achieve maximum transmission at 10.10 GHz with wide 3 dB transmission band. Due to the additional geometries of unit cell, compactness of 26 % as compared to conventional CRR's electrical dimensions operating at 10.10 GHz is achieved. The geometry of top and bottom surface of DSDCRR with dimensions is shown in Figure 2(a) top layer and Figure 2(b) bottom layer respectively. The DSDCRR unit cell is simulated by using perfect electric condition (PEC), perfect magnetic condition (PMC) boundary and two waveguide ports by using CST microwave studio software as in [10].

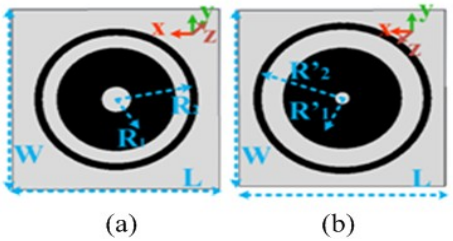


Figure 2. The Dimensions of Fundamental Unit Cell (FUC) (a) The Top View, (b) The Back View. Dimensions are R_1= 2.25 mm, R'_1= 2.00 mm, R_2= 4.75 mm, R'_2= 5.00 mm and L= 12 mm and W = 12 mm.

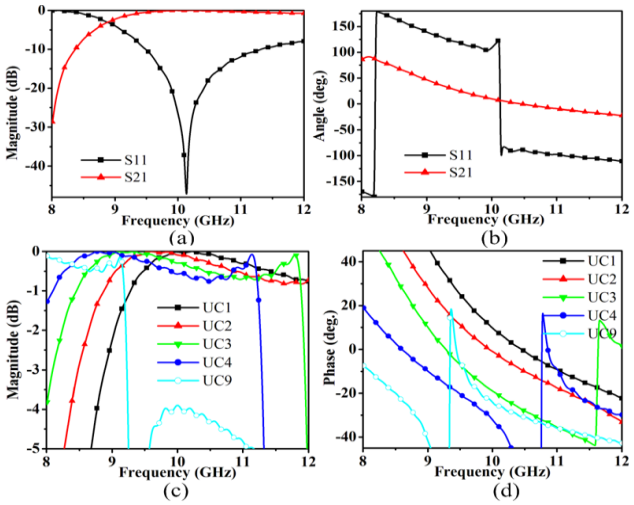


Figure 3. The transmission and the reflection coefficient (a) Simulated Magnitude plot (b) Simulated Phase Plot (c) The transmission coefficient of the modulated unit cell for negative "ΔR" , The Magnitude Plot and (d) Negative "ΔR" The Phase Plot.

The simulated transmission and reflection characteristic with magnitude plot and phase plot of unit cell is plotted in Figure 3(a) and Figure 3(b) respectively. The simulated 3 dB transmission band of more than 3.50 GHz from 8.80 GHz to more than 12 GHz is obtained. Other modulated unit cells is generated from this DSDCRR (Figure 2) by changing critical inner and outer radial dimensions hence this unit cell is considered as fundamental unit cell (FUC). The modulated unit cells are designed by a radial dimension change factor "ΔR". The quantity "ΔR" ($\Delta R = 0.2\ mm$) is a changing factor in the dimensions of simultaneous ring resonators of the outer and the inner ring radius ("R_2 and R'_2" and "R_1 and R'_1" respectively) for next modulated FUC. It can be observed that the negative change factor "ΔR" causes negative change in corresponding refractive index profile. Several optimum negatively modulated unit cells with wide transmission magnitude plot and wide transmission phase plot is selected and their corresponding transmission magnitude and transmission phase is plotted in Figure 3(c) and Figure 3(d) respectively. It is observed that negative "ΔR" causes slowly decreasing transmission magnitude change and fast decreasing transmission phase change. The gradual radial dimension changes of unit cells cause change in surface current density resulting in changing gradual the transmission magnitude and the transmission phase.

The arrangement of modulated FUCs UC1, UC2, UC3 and UC4 are shown in Figure 4 (a). These modulated unit cells are arranged as shown in Figure 4 (b) In a uniform circular phase distribution profile. Here 1 = FUC, 2 = UC1, 3 = UC2 and 4 = UC3 are the modulated unit cells. This arrangement results into change in the refractive index profile in graded manner along the radius/ angle of circular plane ($\frac{dn}{dx}$ *or* $\frac{dn}{dy}$). Due to this arrangement the designed MS is called as angular graded index metasurface (AGIMS). The AGIMS is fabricated on the top of RT/duroide 5880 substrate of dimension 120 mm × 120 mm with permittivity 2.2 and thickness 0.762 mm (0.025 λ) by photolithography making AGIMS ultrathin. The fabricated AGIMS front and back view surface is shown in Figure 4 (c) and Figure 4 (d) respectively.

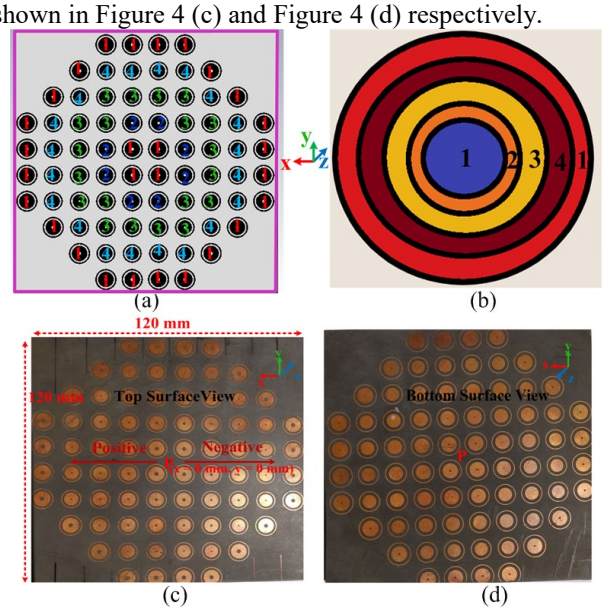


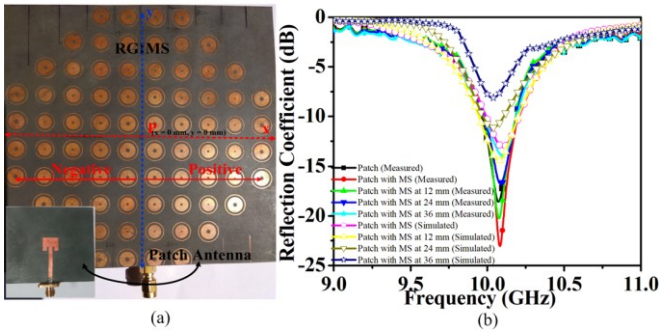
Figure 4. The modulated unit cells arrangement for designing of AGIMS (a) Unit cell arrangement, (b) Circular

phase distribution profile, (c) Fabricated AGIMS Front View and (d) Back View.

3 Lens Antenna Design and Measured Results

A microstrip patch antenna (MPA) radiator operating at 10.10 GHz of dimension 56 mm × 56 mm × 0.762 mm is used as microwave radiator as shown in the inset of Figure 5 (a). The designed metasurface lens is placed over microstrip patch antenna radiator and variations of reflection coefficient with variation of focal distance are analysed by using CST microwave studio software. The maximum reflection coefficient matching is achieved at a focal distance H= 11.25 mm. Hence the designed lens is placed over patch antenna at this optimum focal length.

The AGIMS lens antenna is measured for its reflection coefficient at its various moves of AGIMS over MPA by using vector network analyzer and plotted. The simulated and measured reflection coefficients of MPA and due to various moves of AGIMS over MPA are plotted in Figure 5 (b). A good matching between simulated and measured results of MPA and AGIMS lens antenna with various moves of AGIMS over MPA is observed in the desired band of operation.



(a) (b)

Figure 5. The prototype AGIMS lens antenna and Reflection Coefficient. (a) The Fabricated AGIMS prototype lens antenna and (b) The Measured and the simulated reflection coefficient of radiator and AGIMS lens antenna with various offset moves of AGIMS along positive x-axis.

The AGIMS lens antenna is characterized for its radiation characteristics. The H- plane radiation pattern of AGIMS lens antenna is measured in low noise closed anechoic chamber and plotted with simulated H- plane radiation characteristic in Figure 6. It is observed that placing AGIMS over MPA at optimized height of 11.25 mm results into a measured broad side gain of 11.80 dBi indicating gain enhancement of 7.0 dB as compared to MPA. The broad side gain of MPA radiator is 4.75 dBi. The movement of AGIMS along x-axis in step of 12 mm with respect to centre point P(x = 0 mm, y = 0 mm) as shown in Figure 5, causes steering of the beam radiated by MPA radiator. A good agreement between measured and simulated results is observed. The measured and simulated H- plane radiation characteristics due to movement of AGIMS lens along positive x- axis in step of 12 mm is plotted in Figure 6 (a). The main radiated beam of MPA radiator steers by 10°, 20° and 40° with measured peak gain of 12.50 dBi, 12.80 dBi and 13.00 dBi indicating gain enhancement of 7.75 dB, 8.00 dB and 8.25 dB corresponding to movement of 12 mm, 24 mm and 36 mm respectively as shown in Figure 6 (a). This steering is achieved due to positive x- axis movement of AGIMS in step of 12 mm. The H- plane radiation pattern of AGIMS lens antenna due to negative x- axis movement of AGIMS in step of 12 mm with respect to point P(x = 0 mm, y = 0 mm) as shown in Figure 5 is also measured and plotted with simulated one in Figure 6 (b).

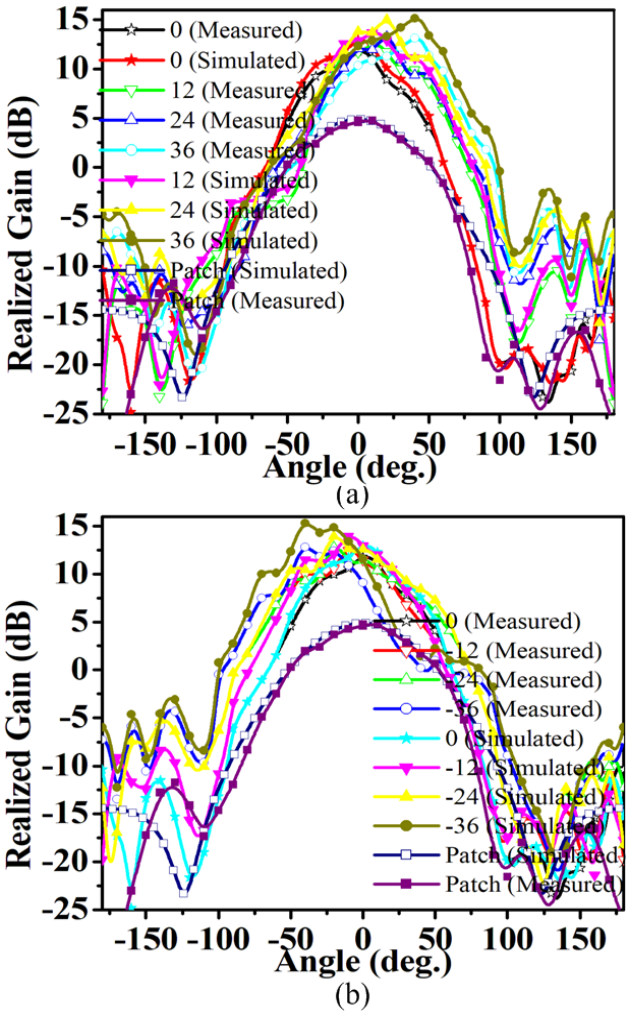


Figure 6. The radiation Characteristic of MPA and AGIMS lens antenna at 10.10 GHz. (Measured and simulated H- Plane (zx). (a) due to movements along the positive x-axis and (b) due to movement along negative x-axis.

It is observed that negative x –axis movement of AGIMS in step of 12 mm steers the main reradiated beam of MPA by -10°, -20° and -40° with measured peak gain of 12.45 dBi, 12.80 dBi and 13.15 dBi indicating gain enhancement of 7.70 dB, 8.00 dB and 8.40 dB corresponding to movement of -12 mm, -24 mm and -36

mm respectively as shown in Figure 6 (b). Similar radiation characteristics are observed for positive and negative y- axis movement of AGIMS in step of 12 mm with respect to point "P". Moving along x-axis or along y-axis in step of 12 mm on AGIMS causes maximum gradient phase change "$\frac{d\Phi}{dx}$ or $\frac{d\Phi}{dy}$" and maximum gradient index change "$\frac{dn}{dx}$ or $\frac{dn}{dy}$" resulting in wide beam steering with maximum gain variation of about 1 dB. It can also be observed from Figure 6 that AGIMS lens movement steers the main radiated beam of MPA microwave radiator in a conical plane of vertex angle about 80° from -40° to +40° with maximum gain of 13.15 dBi and maximum gain variation of about 1 dB.

4 Conclusion

A high gain low profile continuous wide beam steerable AGIMS lens antenna is successfully presented. A compact angular graded index metasurface acting as lens with modulated transmission magnitude and transmission phase characteristics is designed first. The radial movement of AGIMS in step of 12 mm steers the main radiated beam of MPA radiator continuously with vertex angle 80° in a conical plane from -40° to +40° with maximum broadside gain of 13.15 dBi and minimum broadside gain of 11.80 dBi representing maximum gain enhancement of 8.40 dB and minimum gain enhancement of 7.0 dB in -40° and 0° direction respectively. The main radiated beam of microwave MPA radiator can be steered in any direction in a conical plane of vertex angle 80° by radial movement of AGIMS in step of 12 mm. Similar type of AGIMS lens can be designed for similar type microwave radiator for high gain enhancement with wide beam steering.

5 References

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