Design of High-Gain Lens Antenna Using Pixelated Phase Gradient Metasurface

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Abstract*— In this paper a novel systematic design method based on Genetic Algorithm (GA) for transmitting lens antenna design is introduced. The antenna consists of a dual-layer phase-gradient metasurface (PGMS). GA has been used to design the unit cells configurations incorporating in the cost function the performances of the main parameters of an antenna such as gain, bandwidth and side lobe level. To design a set of pixilation-based unit cells, a single bit with a binary value of 0 or 1 that indicates the presence or absence of copper at the pixel level, respectively, has been considered for each pixel. By setting the dimensions of each unit cell with a value of 0.4λ×0.4λ (λ being the wavelength at 12 GHz) and with binary optimization based on GA, appropriate transmission coefficient with suitable transmission phase in the range of [0, 2π] has been achieved. The proposed PGMS antenna uses a 1.58 mm thick, RO4003C (lossy) transmission lens with a dimension of 110×110×35 mm^3 and a microstrip patch antenna acts as a radiation source. The proposed PGMS antenna has a 20.3 dB realized gain which is 13.5 dB greater than the single patch antenna one (6.8dB) and exhibits -15.5 dB side lobe level (SLL) at 12 GHz. Simulation results of the proposed PGMS antenna verify the validity of the design method.

Keywords*— *lens antenna, phase gradient metasurface, unit cell, optimization

I. Introduction (*Heading 1*)

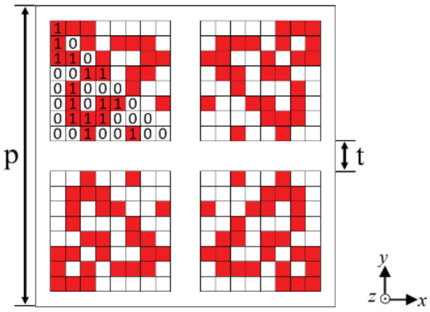
In today's world of communication, high gain antennas are in great demand and the request for this type of transmitter/receiver is continuously increasing. Waveguide antennas [1], microstrip antenna arrays [2] and three-dimensional (3-D) lens antennas [3], are some of the most popular high-gain antennas which are widely used in different communication systems. Waveguide antennas and (3-D) lens antennas have large volumes that limit their use in commercial applications. In addition, (3-D) lens antennas present a variety of problems due to their volumetric structure. Microstrip antennas overcome some of these challenges, but present high dielectric losses in the higher frequency bands and are less efficient in high power applications. On the other hand, metasurfaces, 2D metamaterials, exhibit interesting and unusual electromagnetic properties allowing controling of transmission and reflection. Therefore, a suitable alternative solution for transmission or reflective antennas is to use metasurface in their structure to manipulate the antenna pattern [4].

In recent years, considerable research has been done to achieve a high gain, efficient and applicable antenna. A suitable solution for this application is a phase gradient metasurface (PGMS) lens antenna. Planar PGMS antenna is a convenient, low-cost, lightweight, ease of fabrication and simple solution for high-gain applications [5]. The structure of these antennas consists of a PGMS and a feeding antenna. This latter should be located in the focal length of the PGMS to convert of the spherical wave to plane wave that led to gain enhancement. This antenna was first introduced in 2015 by Li et al. [6]. By applying three layers of dielectric, unit cells with a transmission coefficient above 0.8 and covering the phase range from 0 to 360, 18.5 dB realized gain were reported. In [7], PGMS with one-layer dielectric was presented which uses unit cells with a transmission coefficient larger than 0.7. This solution allows achieving a maximum gain of 16.5 dB. Another single layer lens antenna with 19.5 dB gain was proposed in [8]. PGMS are designed based on optimization that provides phase compensation of between 0-360° across the metasurface. The automatic design procedure of unit cell is based on GA optimization in such a way that the shape of the unit cell (the metal layer on the dielectric) is optimized to achieve the best possible performance. Moreover metasurfaces are widely used in high impedance surface structures [8], frequency-selective surfaces [9], polarization converters [10], absorbers [11], electromagnetic sensor [12] and radar cross-section reducers [13].

In this letter, a novel PGMS lens antenna based on the GA design method is presented that has a 20.3dB gain at 12 GHz. Proposed PGMS consists of six approximate transparent unit cells with a transmission coefficient larger than 0.9 and can assure a phase difference up to 360° between cells. These six unit cells have been placed in 2D configuration with suitable phase gradient that satisfies a gain enhancement condition. Based on GA the unit cells are designed such that 13.5 dB gain enhancement compared with the microstrip patch antenna is accomplished. The proposed PGMS lens antenna has a dimension of 110×110×35mm^3 and shows -15.5 dB SLL. The proposed PGMS lens antenna has a suitable radiation performance which is presented and validated by numerical simulations.

II. Unit Cell Design

In last year's pattern optimization has become one of the well-known design methods that has been widely used in the design of metasurfaces [14]. Even though this kind of optimization could hardly meet the challenges of design but it is a powerful tool for the enhancement of PGMS antenna performances. The GA used in this paper is such that it considers a basic 2D binary cell and then mirror it in both X and Y directions to achieve a unit cell with two symmetry axes. The 2D binary matrix of the main unit cell is the unknown variable of GA. On the other hand, transmission coefficients of larger than 0.9 and transmission phase according to equation (1) are two desired parameters from the GA method. The considered geometry of the unit cell is shown in Fig. 1. It uses two substrate sheets and a total of three metallic layers. The unit cell is printed on a RO4003C (*lossy*) substrate with a relative permittivity (ε_r) of 3.55, loss tangent (*tan δ*) of 0.0035, and 1.58 mm of thickness (*d*). The period is p =10 mm corresponding to $0.4\lambda_0$, where λ_0 is the wavelength of the center frequency of 12 GHz. Moreover t=1mm is the distance between inter-cells of the unit cell.



(a)

(b)

Fig. 1. (a) Top view of unit cell, (b) Side view of unit cell

Using GA linked with a commercial software (Microwave Studio), each unit cell was designed with properly set boundary conditions. To design of unit cells, as shown in Fig. 1, the surface of a single cell is divided into small squares (called pixels) with dimension of 0.5×0.5 mm^2. In this case, 36 pixels have been considered. Each of them can take values of 0 or 1. The goal of optimization is to reach six unit cells with different phases that cover the range from 0 to 360° and have a high transmission coefficient. Flowchart of GA procedure is shown in Fig. 2. In GA design procedure, first, an initial binary population is formed in MATLAB and then this binary matrix is used to define the pixeled pattern within the unit cell. This configuration is numerically analyzed in the full-wave simulator. The resulting S-matrix is reloaded in MATLAB, to be considered in the next step of the GA optimization process generating a new population of a 2D binary matrix. This process continues until GA reaches the unit cells with the desired amplitude and phase response. Finally, the algorithm delivers the required six unit cells that exhibit the desired transfer amplitude (larger than 0.9) and phase (according to equation (1) for each unit cell). The transmission amplitude and phase of each unit cell are reported in Fig.3. It is shown that all of the six unit cells have a transmission coefficient of larger than 0.9 that is suitable for this type of lens antenna. In the same manner transmission phase of unit cells is in good agreement with eq. (1) which leads to the best performance of lens antenna.

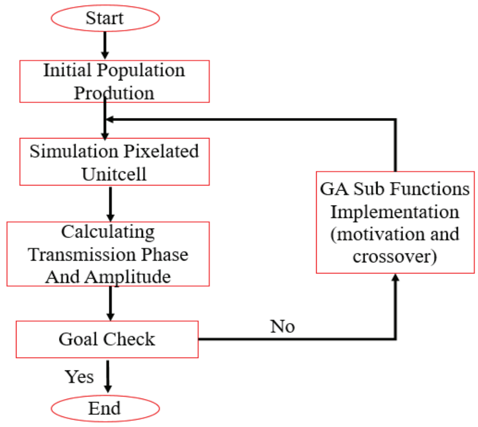


Fig. 2. The flowchart of the GA procedure for design of PGMS unit cells

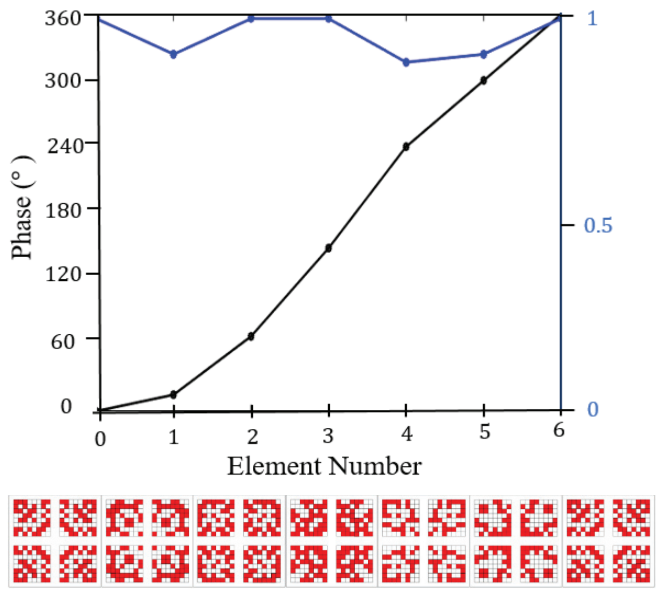


Fig. 3. Transmission phase and amplitudes of six unit cells in the 2-D supercell

III. PGMS LENS STRUCTURE

A center frequency of 12 GHz, a focal length ratio of 0.31 was set constructing a 2D focusing square metasurface lens with 11×11 unit cells. Therefore the total dimension of PGMS lens antenna is $D \times D \times H$=110×110×35 mm^3. It is noteworthy that H=35 mm is the distance between PGMS and microstrip patch antenna. Phase compensation distribution of unit cells on the focusing metasurface is a basic requirement for conversion of spherical wave of the source antenna to plan wave. The phase calculation formula for each unit cell on metasurface is given by [7]

$$\Delta\phi(a,b) = \frac{2p}{\lambda}\left(\sqrt{(ap)^2 + (bp)^2 + L^2} - L\right) + 2n\pi \quad (1)$$

where L is the focal length of the lens, and $\Delta\phi(a,b), a, b = 0,1,\dots,6$ is the phase shift between the elements arranged at the location (a, b). It should be noted that the original element placed at the center of PGMS (a=0, b= 0) which is exist with 360° phase difference in boundary of PGMS (6$^{\text{th}}$ element number of Fig. 3). Figure 3 shows the simulated transmission phases and magnitudes of the six elements at 12 GHz. The supercell can be constructed with the elements from N = 0 to

6 along the positive x-direction. The principle to compute the required phase compensation is based on the spatial phase difference due to the the different path lengths of each unit cell from the feed of the lens array (microstrip patch antenna). The schematic of PGMS lens antenna has been shown in Fig.4. From Fig. 4 (a) it results that PGMS has a desired 2D transmission phase distribution which is satisfied by equation (1). This appropriate phase distribution of PGMS enhanced the radiation performance of the lens antenna. In Fig. 4 (b) schematic of PGMS was shown that was extracted from the GA method. By using a circular patch antenna as a source and PGMS as a lens, the 3D schematic of the high gain PGMS lens antenna has been reported in Fig.4 (c). The distance between PGMS and circular patch feed is H=35mm.

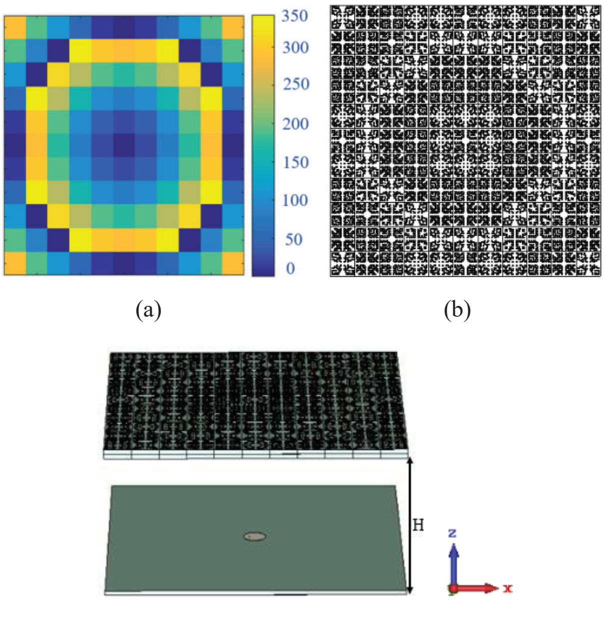


Fig. 4. PGMS lens antenna schematic and performance, (a) two-dimensional phase distribution of PGMS lens, (b) prototype of designed lens antenna, and (c) 3D schematic of PGMS lens antenna

IV. RESULTS AND DISCUSSION

Based on the two-dimensional focusing transmission lens design mentioned above, a high-efficient broadband transmission array antenna has been designed. A simple circular microstrip patch antenna is used as feed that is supported by an RT5880 (lossy) substrate, above a ground plane. The circular patch has a radius of 4.35 mm which is feed by SMA probe. The dielectric substrate has a relative dielectric constant of 2.2, a loss tangent of 0.0009, and a thickness of 1.6 mm. The proposed flat transmission PGMS lens antenna consists of 11 × 11 unit cells and circular patch with dimension of 110 ×110 × 35 mm^3. Figure 5 shows the input impedance simulation curves of the microstrip patch antenna with and without PGMS lens structure. It can be seen that the frequency deviation of S_{11} in presence of PGMS is small and $|S11| < -10$ dB in the range of 11.8-12.2 GHz with 400 MHz bandwidth. The S-parameter of the PGMS lens antenna suggests it is suitable for commercial applications.

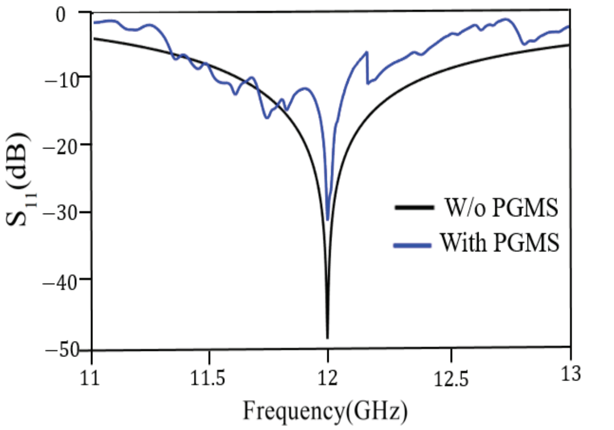


Fig. 5. Simulated input impedance of the antenna in the absence and in the presence of the PGMS layer

The simulated radiation patterns of the proposed high gain PGMS lens antenna at 12 GHz are shown in Fig. 6. The maximum simulated gain of 20.3 dB is obtained at 12 GHz. It can be seen that the maximum realized gain of the PGMS lens antenna increases with about 13.5 dB compared with the simple patch antenna with 6.8 dB at 12 GHz.

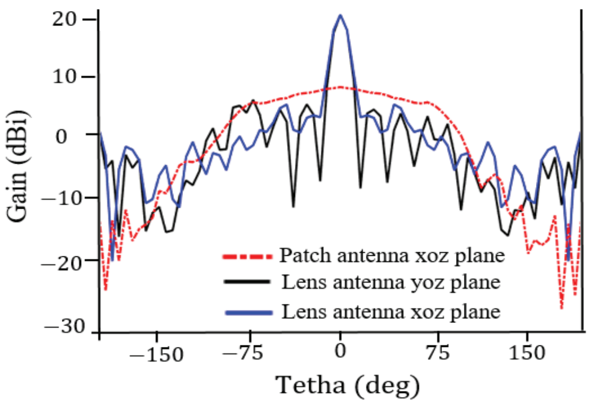


Fig. 6.Comparison of the radiation pattern for different configurations at f=12 GHz

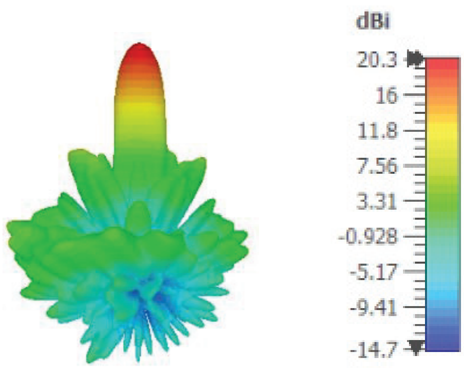


Fig. 7. 3D pattern of high gain PGMS lens antenna at 12 GHz

As it can be observed, the radiation pattern has pen beams with low SLL. The PGMS lens antenna has a 3 dB beamwidth of 10.5° and 10.1° in xoz and yoz-plane, respectively. Moreover the proposed high gain PGMS lens antenna has a -15.5 dB and -16.5 dB SLL at xoz and yoz-plane, consequently. Figure 7 gives 3-D radiation patterns of the proposed high gain

PGMS lens antenna. Low SLL, simple structure and high gain are the main advantages of proposed PGMS lens antenna. Proposed PGMS lens antenna has an aperture efficiency (AE) of 44% which demonstrate the ability of PGMS lens in focusing incident spherical wave to the pen beam. Comparison between proposed PGMS lens antenna and the state of the art is shown in Tab. I. It could be seen that the efficiency of the proposed PGMS is significantly larger than state of the arts.

TABLE I. Comparison of proposed PGMS lens antenna with the state of the art

REF.	Number of PGMS layer	substrate	AE%	SLL (dB)
[5]	3	F4B	37.8	-
[6]	3	F4B	30	-22
[7]	1	FR4	31.1	-13
[8]	1	F4B	34	-12
This work	2	RO4003	44	-15.5

V. Conclusion

In this paper, a new GA based method of phase-gradient metasurface (PGMS) design for a high-gain planar lens antenna has been proposed. To convert of spherical wave to a pencil beam (used as a lens), a patch antenna (served as a feeder) and a PGMS lens with high (larger than 0.9) transmission amplitude have been used. The proposed high gain PGMS lens antenna consists of 11 × 11 unit cells and a patch antenna with an overall size of 110×110×35 mm^3. High transmission efficiency of the unit cell and good focusing effect of the PGSM assure the good performances of the transmitting lens antenna at 12 GHz. It achieves a peak gain of 20.3dB which is 13.5 dB greater than that of the single patch antenna, SLL of -15.5 dB, aperture efficiency is found to be 44% and 400MHz bandwidth. The reported structure is a good candidate for use in commercial applications.

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