A Review of Various Approaches for Beam Steering in Lens Antenna

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Abstract

In this paper, we will be reviewing beam steering application using lens antenna. Various approaches are available for achieving beam steering of lens antennas for different applications and some of them will be reviewed here. In radar systems, beam steering is accomplished by switching the antenna element or changing the relative phase. Beam steering has major role for 5g due to the quasi optic layer. Beam steering can also be done by varying the refractive index. In most of these papers studies, we found out that beam steering overcomes the interference, improves gain, increases directivity and also save power. Wide angle is also achieved in lens antenna.

Keywords: lens antenna, beam steering, refraction

1 Introduction

This paper will present a systematic review of lens antennas showing beam steering and using it for various microwave applications or radar applications. Lens antenna is a device that converts the incoming divergent energy waves to plane waves with the use of accurate lens material [1]. Lens antenna is basically a device working at microwave frequencies which utilizes the principle of refraction of an optical lens to achieve the radiation of the energy incident on it into some other direction and at desired frequencies.

For the transmission and reception of signals, the lens antennas utilize the properties of a lens like divergence and convergence. A lens antenna comprises of a horn or dipole antenna and after that there is a lens. Operating frequency is decided by the size of the given lens. The refractive index as seen by the lens used is generally more than unity. For obtaining higher frequencies, the size of lens is kept small. Because of this property, they are generally used for generating at high frequencies only. If we go for lower frequencies using lens antennas, the size of the lens will increase significantly [2]. Lens antennas are designed to work at a frequency range starting from 1GHz, with its prime use being for frequencies higher than 3GHz. Lens antenna does the generation of plane wave front at its focus from an incoming spherical wave front. It also does the work of controlling aperture illumination.

The shift in direction of main lobe of radiation in the radiation pattern is known as Beam Steering. In radar systems or radio systems, to achieve beam steering, the relative phase of the signals that drive the elements of the antenna can be changed, or changing the antenna elements can also be done. Because of the near optic nature of the frequencies of 5G technology, beam steering has been playing a major role behind success of 5G communications.

In acoustics, the audio coming out of a group of loud speakers is directed to a certain spot or location by the use of beam steering only. To accomplish this, the values of phase and magnitude of the speakers that are installed in a column are altered to make the collective sound cancel out or add up in a way that maximum sound is received towards the required position.

In context of an optical system, the beam steering methods can be altering of the refractive index of the medium of beam transmission or using of mirror, lens, prism etc. Examples of optical beam steering can be seen in beam director unit, mirror based mechanical gimbal, galvanometer mechanism for the rotation

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of mirrors, micro-electro-mechanical systems, and phased array optics. Beam steering helps in saving power, reducing interference, and also increases the directivity and gain of a micro strip antenna.

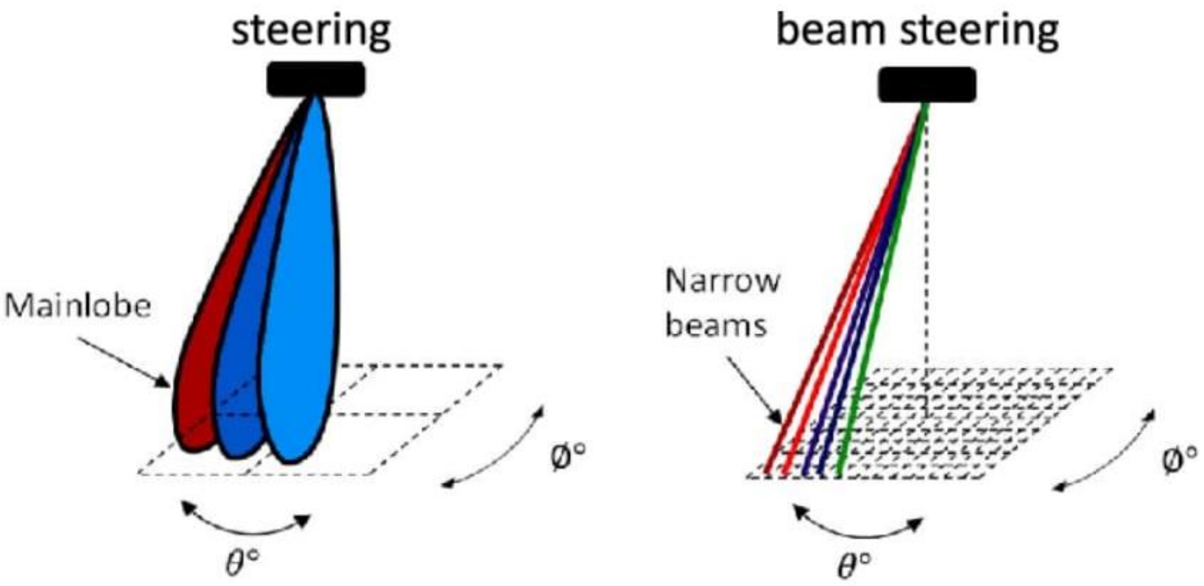
2 Lens Antenna

A Lens antenna is a very popular and useful device used in various microwave applications for its usability benefits and its capabilities. It is a device working at microwave frequencies which utilizes the principle of refraction of an optical lens to achieve the radiation of the energy incident on it into some other direction and at desired frequencies. The lens antenna's frequency depends upon the size of the lens antenna used.[3] If we go for lower frequencies using lens antennas, the size of the lens will increase significantly. Beam steering of the radiation of lens antenna focuses the beam and hence makes it very useful for even 5g applications.

Lens Antenna [1]

3 beam steering

In the radiation pattern of any antenna, the resultant beam may be focused or scattered. More focussed beam will mean higher directivity. We can focus the beam towards a particular direction [2] to get better results and for that we can do beam steering. The shift in direction of main lobe of the radiation pattern is known as Beam Steering. In 5g technologies, beam steering has been playing a very major role. Beam steering is very useful as it helps in saving power, reducing interference, and also increases[5] the directivity and gain of a micro strip antenna. In the review papers below, we will be seeing beam steering in lens antennas for different applications.



Beam Steering

4 Studies Reviewed

Marin et. al. [3] in their research designed a novel lens antenna for applications of beam steering for a wide angle. They have designed a very simple and cost effective planar feed technology. For that, they made use of transformation optics in order to change the 2d lens permittivity profile of the lens in accordance with Luneburg and hence achieving a focal surface that is plain. To get the beam steering in the plane that has the slice of lens, the slice is used to form a parallel plate transmission line by keeping the slice in between the two metallic surfaces. To obtain a more focused beam, stacking of beam was done. 2d Beam steering was possible because of that much focused beam showing the lesser $\pm 15°$ steering range in one plane, whereas the wider $\pm 60°$ range in the orthogonal plane[12]. The material used for making of lens was not homogeneous, having 4 different dielectric materials showing different permittivity. But they had a pattern of holes drilled in them for different diameters, which tends to provide a smooth gradient of the effective value of permittivity of the lens material. It was evident from the results obtained from performance analysis of the designed antenna prototype that a 17.2dB of maximum directivity could be obtained while operating at 10GHz of frequency, with a scan loss of just above 0.8dB, side, aperture efficiency 74%, side lobe level better than 11dB. Hence, it performed better than any other beam steering antennas having plane focal surface.

Design approach used in the proposed lens antenna system for beam steering presented by Z. Zhang et. al. [4] utilizes phase-shifting surfaces (PSSs) having circular aperture with 11.5λ0 diameter that are rotatable mechanically. The two PSSs act as a pair of Risley prisms leading to beam scanning operation at X-band. Very less phase errors and high transmission characteristics were obtained through codesigning the unit cells containing two PSSs, optimally determining spacing between two PSSs and at the same time varying the spacing between them. The proposed design showed steering of main beam in between ±60° range from the broadside direction in the[11] upper hemisphere at 10 GHz with less than -13.1dB side lobe level. The gain variation was less than 3.6dB. The design has the advantages of providing quality beam steering results with high efficiency and minimal complexity, making it an affordable choice for phased- array antenna for communication applications.

Another work in the field of 2D beam-steering of mm-wave was depicted by K.A. Shila et. al. [5] showing an antenna system based on lens antenna subarrays which unlike previous work uses extended hemispherical dielectric lenses. The scan range has been maximized using parametric sweeps on feed antenna positions and lens geometry based on 3D simulation. Unlike conventional planar antenna system, single phase shifter is used per lens, reducing the complexity of the hardware. The antenna showed great characteristics in the frequency range of 37-40 GHz with return loss less than 10 dB, a peak antenna gain of 19.8 dB [5]. A 80° scan range and less than –9 dB SLL has been observed making this design approach best among the other subarray methods reported earlier. The lens-based approach has been proved to maximise the scan range.

Another novel design for millimeter-wave using single layer unit cell that is circularly polarised and based upon Pancharatnam-Berry (PB) phase has been propesed by S.Wang et. al. [6] for a meta-lens design. A high efficiency greater than 0.8 in the frequency range of 31-33 GHz with a size as small as 27*27 mm2 has been observed making it a low profile attractive option for wireless communication applications. The simulation results were in alignment with the theoretical analysis.

A millimetre wave lens antenna was designed by T. Elkarkraoui et. al. [7] to beam-steer radar systems at 76-81 GHz using Luneburg lens. A Luneburg lens and seven dielectric resonator elements-based design is investigated that showed a high antenna gain of 25dBi, a -30° to 30° scan angle a narrow 6-degree wide pencil beam. This design provides high gain, bandwidth and radiation properties even when it is switching among dissimilar scan angles. The proposed design is a key contender for autonomous vehicle scenarios.

Another low cost and compact solution for beam steering involved using metasurface lens array (MLA) was studied by R. Xu. et.al. [8]. The MLA is supplied by s phased array with fewer phase shifters. Dividing a large aperture lens into a number (say N) of smaller aperture lenses keeping the focus to diameter ratio unchanged reduces the thickness of the antenna by N times. This makes the antenna design compact with focal length of 1/3 and only three phase shifters are required. The beam steering is carried out in two stages, switching the direction of the main beam by moving the feeding antennas under each lens element and then steering the phased array. The proposed design works at 10 GHz with beam width span of ±30° and main beam crossing

Authors	***Method Used***	***Frequency of Operation***	***Performance Evaluation***	***Comments***
Marin et. al. [3]	It made use of transformation optics in order to change the 2d lens permittivity profile of the lens in accordance with Luneburg and hence achieving a focal surface that is plain	10 GHz	±15° steering range in one plane ±60° range in the orthogonal plane Maximum directivity of 17.2 dB scan loss of just above 0.8dB aperture efficiency of 74%	better than any other beam steering antennas having plane focal surface.

Authors	Method Used	Frequency of Operation	Performance Evaluation	Comments
			side lobe level better than 11 dB	
Z. Zhang et. al. [4]	It utilizes phase-shifting surfaces (PSSs) having circular aperture with 11.5λ0 diameter that are rotatable mechanically	10 GHz	Shows steering of main beam in between ±60° range from the broadside direction in the upper hemisphere Less than 3.6 dB gain variation less than -13.1dB side lobe level	It provides quality beam steering results with high efficiency and minimal complexity and hence is a choice for phased-array antenna for communication applications
K.A. Shila et. al. [5]	This antenna system based on lens antenna subarrays uses extended hemispherical dielectric lenses	37-40 GHz	Return loss less than 10 dB peak antenna gain of 19.8 dB A 80° scan range less than –9 dB SLL	The scan range has been maximized using parametric sweeps on feed antenna positions and lens geometry based on 3D simulation The use of single phase shifter per lens, reduced the complexity of the hardware
S.Wang et. al. [6]	This design uses single layer unit cell that is circularly polarised and based upon Pancharatnam-Berry (PB) phase to design a meta-lens	31-33 GHz	Efficiency greater than 0.8 Small size of 27*27 mm²	It is a low profile attractive option for wireless communication applications
Elkarkraoui et. al. [7]	It investigates a Luneburg lens and seven dielectric resonator elements-based design	76-81 GHz	Antenna gain of 25dBi a -30° to 30° scan angle a narrow 6-degree wide pencil beam	Preferable for autonomous vehicle scenarios.

Authors	***Method Used***	***Frequency of Operation***	***Performance Evaluation***	***Comments***
R. Xu. et.al. [8]	It investigates metasurface lens array (MLA) supplied by s phased array with fewer phase shifters	10 GHz	Beam width span of ±30° main beam crossing level more than –3dB Maximum antenna gain of 19.1 dB gain variation of 1.6dB	It is a simpler and low-cost design with higher gain than single aperture antennas.
Y. Sun et. al. [9]	It makes use of Risley prism concept for antenna design. The design includes three lenses (one being stationary and other rotatable), three transmit-array lenses and a feed antenna.	--	Peak antenna gain of 38.1dB 80.5% aperture efficiency within the azimuth angles and elevation angles in the range (0°–360°) and 0°–45.6° respectively A gain variation of l1.7dB	The design is recommended for space applications because of its compact size, wide span and easy control.
Zhao Liuxian et. al. [10]	It uses flattened acoustic metamaterial Luneburg lens (both 2D as well as 3D) for beam steering of ultrasonic signals	Variable	beam steering at 40kHz in both near as well was far field Suitable for provides suitable flattening of the lens	This type of lens design is recommended in sonar systems and ultrasonic diagnosis

–level more than –3dB. Maximum antenna gain of 19.1 dB and gain variation of 1.6dB were observed. Thus, the proposed design has simpler and low-cost design with higher gain than single aperture antennas.

A prototype for high-power applications as high as 1GW at Ku band using Risley prism concept has been investigated by Y. Sun et. al. [9]. The various constituents of antenna include three lenses (one being stationary and other rotatable), three transmit-array lenses and a feed antenna. The two rotatable lenses aid in beam steering by rotating around the antenna axis. A peak antenna gain of 38.1dB and 80.5% aperture efficiency within the azimuth angles and elevation angles in the range (0°–360°) and 0°–45.6° respectively were reported. The gain variation was l1.7dB. This particular design because of its compact size, wide span and easy control is a prime competitor for space applications.

Another design approach utilising flattened acoustic metamaterial Luneburg lens (both 2D as well as 3D) for beam steering of ultrasonic signals was reported by Zhao Liuxian et. al. [10]. Laplace equation utilising boundary conditions along with quasi-conformal transformation technique was proved effective in providing suitable flattening of the lens. The experimental results obtained showed outstanding beam steering at 40kHz in both near as well was far field. The proposed design has the ability to be extended to different frequency operations. This type of lens design offers great potential in sonar systems and ultrasonic diagnosis.

5 Conclusions and future scope

In the studies reviewed above, beam steering is explained by the use of lens antenna. Different studies depicting various approaches for beam steering in lens antennas were studied and their respective results were depicted. For beam steering, homogeneous and in-homogeneous both types of lenses are used. In olden times, homogeneous lenses were used, now in-homogeneous lenses are being used as they are able to achieve large beam steering angles with very less distribution of shaped beam. Luneburg lenses are used as they have smooth permittivity and focusing. The permittivity of in-homogeneous lenses is modified to obtain better beam steering application. Lenses work for high frequency and we can get higher data rates, which are very useful in 5g for mm wave and sub mm wave applications. Hence, we can see how beam steering can be very useful in the coming times in 5g communications and also in other wide variety of applications.

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