A 2D Reflective Metasurface Augmented Luneburg Lens Antenna for 5G Communications

Alali, B., Zelenchuk, D., & Fusco, V. (2022). A 2D Reflective Metasurface Augmented Luneburg Lens Antenna for 5G Communications. In *2022 International Workshop on Antenna Technology (iWAT 2022): Proceedings* (pp. 136-138). (International Workshop on Antenna Technology, iWAT 2022: Proceedings). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/iWAT54881.2022.9811041

Published in:
2022 International Workshop on Antenna Technology (iWAT 2022): Proceedings

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
© 2022 IEEE.
This work is made available online in accordance with the publisher’s policies. Please refer to any applicable terms of use of the publisher.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access
This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: http://go.qub.ac.uk/oa-feedback

Download date:13. Apr. 2024

A 2D Reflective Metasurface Augmented Luneburg Lens Antenna for 5G Communications

Bader Alali
Center for Wireless Communications,
CWI, The Institute of Electronics,
Communications and Information
Technology Queens University Belfast,
Northern Ireland Science Park, Queen's
Road, Queen's Island, Belfast,
Northern Ireland, UK, BT3 9DT
balali01@qub.ac.uk

Dmitry Zelenchuk
Center for Wireless Communications,
CWI, The Institute of Electronics,
Communications and Information
Technology Queens University Belfast,
Northern Ireland Science Park, Queen's
Road, Queen's Island, Belfast,
Northern Ireland, UK, BT3 9DT
d.zelenchuk@qub.ac.uk

Vincent Fusco
Center for Wireless Communications,
CWI, The Institute of Electronics,
Communications and Information
Technology Queens University Belfast,
Northern Ireland Science Park, Queen's
Road, Queen's Island, Belfast,
Northern Ireland, UK, BT3 9DT
v.fusco@ecit.qub.ac.uk

Abstract— **In this paper, we show a new two-dimensional reflective metasurface augmented Luneburg lens antenna to operate at the Ka frequency band for 5G wireless communication systems. It consists of a half-circle 2D Luneburg lens and a 40-element microstrip patch reflective metasurface. The simulation results of the metasurface augmented Luneburg lens antenna illustrate its capability for beam-steering towards chosen directions by changing the distribution of the microstrip patches on the surface of the reflective metasurface which makes it a suitable application for beam-steering that may operate within the 5G communication frequency bands at 28 GHz.**

Keywords— Reflectarrays, Luneburg Lenses, Metasurface, 5G Communication systems.

I. INTRODUCTION

In recent years, the development in the microwave and mm-wave communications has led to a significant interest in beam-steering, and high-gain antennas [1]. Such requirements could be realized by phased array antennas [2]. Nevertheless, phased array antennas suffer from a complex design, a high cost, a large structure, a complex feeding mechanism, and a high loss, particularly at mm-wave bands. To address this, various solutions have been proposed such as reflectarray antennas [3] and lens antennas [4].

Reflectarray antennas can indeed adopt beam-steering techniques using several approaches such as mechanically rotating elements [5], patch elements with variable size [6], patch elements with variable-length stubs [7], etc. Further control flexibility can be achieved by employing electronically reconfigurable elements at unit cells of the reflectarrays including PIN diodes [8], microelectromechanical MEMS phase switching [9], and varactors [10]. All of these approaches suffer from the potential for intermodulation distortion (IMD) on transmit of complex and high power waveforms.

Besides reflectarray antennas, lens antennas can be also used for beam-steering and multibeam applications including the ultra-wide half Maxwell Fisheye lens [11] as well as the SIW Rotman lens [12].

In this paper, we provide a design of an entirely passive (hence IMD free) 2D reflective metasurface augmented Luneburg lens antenna applicable at the Ka frequency band for the 5G wireless systems. This 2D reflective metasurface augmented Luneburg lens antenna has a lightweight and compact structure. It also can control the directions of the beam, thus, it is a promising candidate for beam-steering applications for 5G communications.

II. DESIGN OF THE 2D REFLECTIVE METASURFACE AUGMENTED LUNEBURG LENS ANTENNA

A. Luneburg lens antenna

Luneburg lens ideally follows the following refractive index formula [13]:

$$\epsilon_r = 2 - \left(\frac{r}{a}\right)^2$$

where ϵ_r represents a dielectric permittivity, a represents the most outer circular ring radius, and $0 \leq r \leq a$ is measured from the center of the concentric rings. The permittivity equals 1 at the lens edges and gradually increases to equal 2 at the center. A multi-shell Luneburg lens antenna design, e.g. [14], is utilized in this paper. More highly graded refractive index values often lead to more efficient designs as it gets closer to the ideal model. Numerical optimization of radiation and dielectric permittivity for a cylindrical Luneburg lens is provided in [15].

In this paper, the 2D Luneburg lens antenna is composed of 5 dielectric rings\shells where the overall radius of the lens is 100 mm, and the inner radius values are increased at an equal interval of 20 mm for each ring. The values of the refractive indices corresponding to the 5 shells are approximated following the Luneburg lens refractive index formula and are equal to 1.19, 1.51, 1.75, 1.91, and 1.99. The lens thickness is 6 mm and is uniform for all five rings. Two metallic parallel plates are placed to cover the top and bottom of the lens. The proposed 2D Luneburg lens and the half-circle Luneburg lens are illustrated in Figure 1.

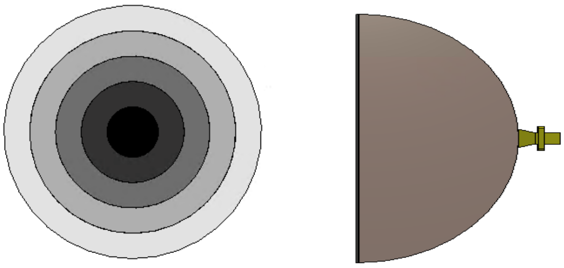
(a) (b)

Figure 1. (a) view of cross section for the 2D lens (b) model of proposed 2D half-circle Luneburg lens antenna with a PEC reflector

B. *Reflective Luneburg lens antenna*

The half-circle 2D Luneburg lens antenna with a full reflector attached in the middle of the lens is excited using a horn antenna, and the beam can be reflected in various angles by moving the horn feed around the 2D half-circle Luneburg lens structure as will be discussed in *Section III*.

Alternative to steering the beam by moving the feed around the half-circle 2D Luneburg lens, a reflective metasurface can be introduced for the beam scanning, which is explored in this paper. In comparison to normal reflectarray studies where the incident waves come from the air, the unit cell here is analyzed by assuming that the incident waves are coming from different dielectrics ranging from 1 to 2. The single unit cell behavior is studied for each layer of each dielectric. The single unit cell is 6 mm X 5 mm composed of RO3003 material of 0.020 inches as a standard thickness and a permittivity of 3.

In this procedure, the phases needed for a single unit cell excited by an external feed to collimate a beam is realized by changing the medium's permittivity between the single unit cell and the external feed with respect to the composed half-circle 2D Luneburg lens antenna of five layers having the dielectrics of 1.19, 1.51, 1.75, 1.91, and 1.99. The phase behavior corresponding to the change of square patch dimensions for the single unit is demonstrated in Figure 2.

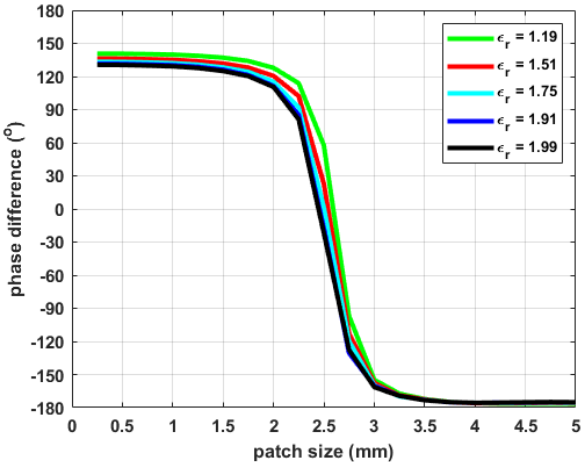

Figure 2. The phase behavior with the change of square patch dimensions of the single unit cell for dielectrics 1.19, 1.51, 1.75, 1.91, and 1.99

A conceptual phase profile for a particular direction of the beam was fulfilled by simulation of the phase distribution across the diameter of the full Luneburg lens, presented in Figure 1(a). A difference between the phase distributions for the normal incidence and the specific selected direction of the beam provides the phase profile to be synthesized at the metasurface. Following the above-mentioned procedure for 5 dielectric constant values, which corresponds to the 5 layers Luneburg lens. A phase profile for the single unit cell for varied-size patches was obtained and implemented to physically mimic the patches spread across the surface of the reflective metasurface such that these match the conceptual arrangement.

The proposed reflective metasurface is established by spreading 40 square patches of various sizes across its surface that reproduces the conceptual phase profile. Since the periodicity for the single unit cell is 5 mm, and the radius of the 2D half Luneburg lens is 100 mm, the reflective metasurface, operated at 28 GHz, consists of 40-element unit cells. Thus, the reflective metasurface is 6 mm X 200 mm.

Then, the 2D reflective metasurface augmented Luneburg lens has been developed by attaching the 40-element microstrip patch reflective metasurface to the half-circle 2D Luneburg lens antenna along the diameter segment. The 2D reflective metasurface augmented Luneburg lens is demonstrated in Figure 3.

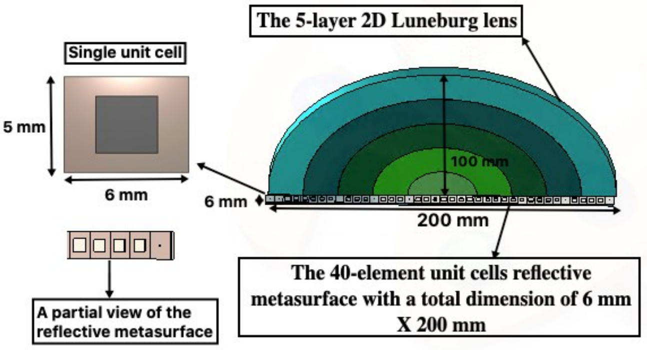

Figure 3. The 2D reflective metasurface augmented Luneburg lens

III. RESULTS AND DISCUSSION

A horn feed of opening dimensions 14 mm X 11 mm oriented at the rim of the lens is utilized to illuminate this 2D reflective Luneburg lens antenna by using the numerical simulations CST Microwave Studio® [16].

Firstly, our 2D Luneburg lens antenna was designed to have a full PEC reflector to act as a mirror instead of the metasurface, and it is fed by the horn antenna at the normal incidence (0°) and an offset position (-30°) to the lens structure. Simulated results show that the beam was reflected towards angle 0° in the light of the normal incidence and towards angle $+30^{\circ}$ in the light of the offset position as expected and shown in Figure 4.

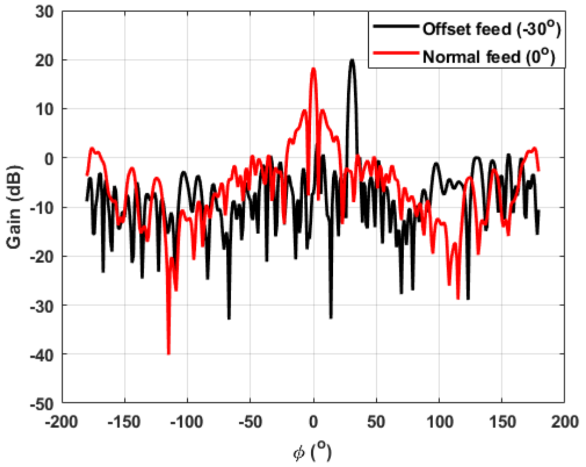

Figure 4. Radiation patterns gain at 28 GHz for a normal incidence feed and $-\mathbf{30}^{\circ}$ offset feed for a 2D half-circle Luneburg lens antenna with a PEC reflector

Then, the PEC reflector was replaced by a 40-element reflective metasurface to steer the beam by changing the patch distribution on the surface of the reflective metasurface while the feed is kept at an offset position (-30°) for all designs presented in this paper. The beams were steered for angles 45°

and 75° with taking into consideration the position of the feed (i.e., from -30° to $+15^{\circ}$ and from -30° to $+45^{\circ}$) as shown in Figure 5.

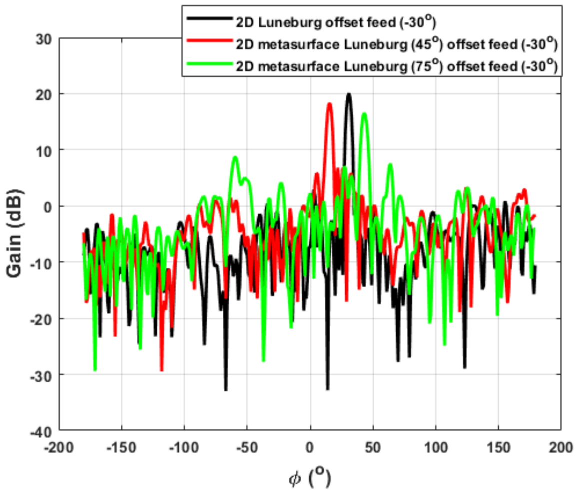

Figure 5. Radiation patterns gain at 28 GHz for angles $\mathbf{45}^{\circ}$ and $\mathbf{75}^{\circ}$ for the 2D half-circle metasurface augmented Luneburg lens and for the 2D Luneburg lens with a full PEC reflector where all feeds are at offset $-\mathbf{30}^{\circ}$

In comparison between the 2D Luneburg lens with a full PEC reflector and the 2D reflective metasurface augmented Luneburg lens, the beam can be merely reflected to a direction opposite of the incidence in the case of the 2D Luneburg lens with a full PEC reflector as a well-known property of Luneburg lens antenna while the beam can be controlled and steered to the desired angles in the case of the 2D reflective metasurface augmented Luneburg lens. The gain has dropped by 3.6 dB when the beam is steered with angle 75°, and dropped by 1.9 dB with angle 45° as highlighted in Table 1. Unfortunately, the proposed structures exhibit relatively high sidelobe levels and further investigation is required.

TABLE 1. SIMULATION RESULTS OF THE 2D LUNEBURG LENS AND THE 2D REFLECTIVE METASURFACE AUGMENTED LUNEBURG LENS FOR VARIOUS ANGLES OF BEAMSTEERING

	Main lobe direction	**Main lobe gains magnitude**	**Sidelobe levels at 28 GHz**
2D Luneburg lens with PEC reflector “Offset feed (-30.0°)”	31.0°	20.1 dB	-17.1 dB
2D metasurface Luneburg lens for beam-steering with angle 45° “Offset feed (-30.0°)”	15.0°	18.2 dB	-11.4 dB
2D metasurface Luneburg lens for beam-steering with angle 75° “Offset feed (-30.0°)”	43.0°	16.6 dB	-7.9 dB

IV. CONCLUSION

A novel half-circle 2D reflective metasurface augmented Luneburg lens antenna for mm-wave applications has been simulated and displayed in this communication. Our proposed 2D reflective metasurface augmented Luneburg lens antenna involves a reflective metasurface composed of 6 mm X 5 mm 40-element unit cells with a total dimension of 6 mm X 200 mm attached to a 2D Luneburg lens that has a diameter of 200 mm and a thickness of 6 mm. The structure can steer the beam for angles’ ranging up to 75°. Simulated results illustrate that the design has a beam-steering performance, hence, it is a good candidate for 5G communications. The design also has advantageous characteristics including portability, lightweight, as well as compact structure. In future work, the high sidelobe levels will be investigated and improved. The proposed design of this 2D reflective metasurface augmented Luneburg lens antenna will be fabricated for measurements. Furthermore, the 40-element reflective metasurface will be transformed into a reconfigurable structure using tunable components and to transmitarray.

REFERENCES

[1] S. Montori et al., “A transportable reflectarray antenna for satellite ku-band emergency communications,” IEEE Trans. Antennas Propag., vol. 63, no. 4, pp. 1393–1407, Apr. 2015.

[2] R. Mailloux, Phased Array Antenna Handbook. Boston, MA, USA: Artech House, 2005.

[3] P. Nayeri, F. Yang, and A. Elsherbeni, “Beam scanning reflectarray antennas: A technical overview and state of the art,” IEEE Antennas Propag. Mag., vol. 57, no. 4, pp. 32–47, Aug. 2015.

[4] M. K. Saleem, H. Vettikaladi, M. A. S. Alkanhal and M. Himdi, "Lens Antenna for Wide Angle Beam Scanning at 79 GHz for Automotive Short Range Radar Applications," IEEE Transactions on Antennas and Propagation, vol. 65, no. 4, pp. 2041 - 2046, 2017.

[5] X. Yang et al., “A broadband high-efficiency reconfigurable reflectarray antenna using mechanically rotational elements,” IEEE Trans. Antennas Propag., vol. 65, no. 8, pp. 3959–3966, Aug. 2017.

[6] D. M. Pozar, S. D. Targonski, and H. D. Syrigos, “Design of millimeter wave microstrip reflectarrays,” IEEE Trans. Antennas Propag., vol. 45, pp. 287–296, Feb. 1997.

[7] D.-C. Chang and M.-C. Huang, “Multiple-polarization microstrip reflectarray antenna with high efficiency and low cross-polarization,” IEEE Trans. Antennas Propag., vol. 43, pp. 829–834, Aug. 1995.

[8] Q. T. Tran and B. D. Nguyen, "1-bit Reflectarray Element Based on a Single Switch for Reconfigurable Reflectarrays," 2019 Antennas Design and Measurement International Conference (ADMInC), 2019, pp. 142-145, doi: 10.1109/ADMInC47948.2019.8969403.

[9] H. Rajagopalan, Y. Rahmat-Samii, and W. A. Imbriale, “RF MEMS actuated reconfigurable reflectarray patch-slot element,” IEEE Trans. Antennas Propag., vol. 56, no. 12, pp. 3689–3699, Dec. 2008.

[10] S. V. Hum, M. Okoniewski, and R. J. Davies, “Modeling and design of electronically tunable reflectarrays," IEEE Trans. Antennas Propag., vol.55, no. 8, pp. 2200-2210, Aug. 2007.

[11] M. Huang, S. Yang, F. Gao, R. Quarfoth and D. Sievenpiper, "A 2-D Multibeam Half Maxwell Fish-Eye Lens Antenna Using High Impedance Surfaces," IEEE Antennas and Wireless Propagation Letters, vol. 13, pp. 365 - 368, 2014.

[12] J.-W. Lian, Y.-L. Ban, H. Zhu and Y. J. Guo, "Reduced-Sidelobe Multibeam Array Antenna Based on SIW Rotman Lens," IEEE Antennas and Wireless Propagation Letters, vol. 19, no. 1, pp. 188 - 192, 2020.

[13] J. Huang and J. A. Encinar, Reflectarray Antennas, Hoboken, New Jersey: John Wiley & Sons, Inc., Publication, 2007.

[14] B. Fuchs, L. L. Coq, O. Lafond, S. Rondineau and M. Himdi, "Design Optimization of Multishell Luneburg Lenses," IEEE Transactions on Antennas and Propagation, vol. 55, no. 2, pp. 283 - 289, 2007.

[15] Y.-S. C. H.-J. H. Z.-D. Y. D. T. Hsi-Tseng Chou, "Numerical Optimization of 2-D Luneburg Lens Antenna by Distorting the Permittivity Estimation to Improve the Beam Radiation," in 2019 13th European Conference on Antennas and Propagation (EuCAP), Krakow, Poland, 2019.

[16] CST-Computer Simulation Technology, Documentation. Available online: www.cst.com (Access Date November, 2021).