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Broadband scanning integrated lens antenna for 5G millimeter-wave applications

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Abstract

Problem statement. One of the promising approaches to the construction of fifth-generation mobile communication systems (5G) is the deployment of heterogeneous networks (HetNet), in which millimeter-wave small cells are placed in "hotspots" and overlaid on conventional macro-cells operating in frequency bands below 6 GHz. At the same time, the deployment of such heterogeneous networks in an urban environment imposes special requirements on the receiving and transmitting antenna equipment. Particularly, the antennas used in radio relay stations should have a wide operating band, a high gain, as well as the possibility of electronic beam scanning.

Objective. The purpose of this paper was to develop a scanning antenna system of the 60 GHz band containing a toroidal-elliptical lens made of high-density polyethylene (HDPE) integrated with an irradiator in the form of a compact phased array antenna (PAA) module. This paper focuses mainly on the study of the frequency properties of a toroidal-elliptical lens antenna since this is of particular practical interest for broadband applications of the IEEE 802.11ad and IEEE 802.11ay standards.

Results. The results of experimental studies have shown that the developed lens antenna within the band of 57.24-65.88 GHz, divided in accordance with IEEE 802.11ad and IEEE 802.11ay standards into four channels with a bandwidth of 2.16 GHz, has a high gain of 21.8-24.8 dBi and is capable of performing electronic beam scanning in the azimuthal plane in the ±35° sector.

Practical significance. The claimed lens antenna can be used in reconfigurable backhauling networks of millimeter-wave relay stations transmitting data over distances of 100-150 m at a speed of 2.5-4.62 Gbps.

Keywords

Integrated lens antenna (ILA), phased array antenna (PAA), electronic scanning, millimeter range

For citation

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Introduction

An important element of the future 5th generation cellular heterogeneous networks (HetNet) [1–2] should be small millimeter-range relay stations providing the transmission of a large amount of data between basic macro- and micro-stations with speeds up to several tens of gigabits per second. Such speeds are common for Wi-Fi systems of IEEE 802.11ad and IEEE 802.11ay standards operating within the 57–71 GHz band. However, the deployment of millimeter-wave wireless mobile networks in an urban environment imposes special requirements on the receiving and transmitting antenna equipment. The antennas used in radio relay stations should have a high gain and include the electronic beam scanning function.

There are various options for scanning antennas in applications of the new 5G standards. For example, [3, 4] present lens antennas made of a homogeneous dielectric, in which the beam is controlled by switching between elements of the antenna array located on the back surface of the lens. The direction of radiation, in this case, depends on the displacement of the active element relative to the focus of the lens. It should be noted that as such displacement increases, not only does the angle of deviation of the main beam from the central position increase but also the level of internal reflections in the lens increases and, as a result, the antenna's gain decreases.

Luneburg lens antennas have a wide scanning sector [5–6]. However, despite the significant progress in the field of materials science and the improvement of 3D printing technologies, the mass production of Luneburg lenses for mobile millimeter-range communication systems still remains a difficult task.

An alternative direction of research is the development of antennas with passive flat reflective arrays [7–9]. The main disadvantage of such antennas is the narrow bandwidth.

Currently, controlled antennas based on complex composite materials (metamaterials) [10–12] and tunable elements such as varactors [13], pin-diodes [14], and liquid crystals [15] are being intensively developed. However, such promising technologies are at an early stage of development and it will take time for cheap and reliable solutions that can be applied practically in 5G networks to emerge.

The purpose of this paper was to develop a scanning antenna of the 60 GHz band, in which a lens made of a homogeneous dielectric is integrated with an irradiator in the form of a compact PAA. It is known that such antennas are capable of focusing the radiation and performing wide-angle beam scanning in the azimuthal plane [16–18]. This paper focuses mainly on the study of the frequency properties of a toroidal-elliptical lens antenna since this is of particular practical interest for broadband applications of the IEEE 802.11ad and IEEE 802.11ay standards. The results of electromagnetic modeling and experimental studies have shown that the developed antenna within the band of 57.24-65.88 GHz has a high gain of up to 24.8 dBi and is capable of performing electronic beam scanning in the azimuthal plane in the ±35° sector. Therefore, the claimed solution can be applied in millimeter-wave relay stations.

The development of an integrated toroidal-elliptical lens antenna

The lens profile in this paper was calculated in the approximation of geometric optics. The lens was considered as a continuous radio-transparent body with a refractive index of $n > 1$ and the irradiator as a spot source of spherical waves.

It is well known that the focusing properties of a homogeneous dielectric lens are determined by the shape of its refractive surface [19]. Particularly, the profile of the refractive surface of the lens that transforms a spherical wave into a flat one can be described using the following equation written in the Cartesian coordinate system:

$$y^2 + x^2\left(1-\frac{n_2^2}{n_1^2}\right) - 2xf\frac{n_2}{n_1}\left(1-\frac{n_2}{n_1}\right) - \left(1-\frac{n_2}{n_1}\right)^2 f^2 = 0, \quad (1)$$

where n_1 and n_2 are the refractive indices of the media, in which the electromagnetic wave propagates, f is the distance between the irradiator and the refractive surface. Depending on the n_2/n_1 ratio, equation (1) changes its type. In the case of $n_2/n_1>1$, the profile of the refractive surface will be hyperbolic, and in the case of $n_2/n_1<1$, elliptical.

However, the lenses have two surfaces (internal, which faces the irradiator, and external), through which electromagnetic radiation passes. In this paper, it was decided to integrate an irradiator (PAA) on the inner non-refractive side of the lens in order to prevent distortions of the plane wavefront formed by the surface described by equation (1). Since HDPE was used as the lens material, it can be assumed that $n_1 = n_{lens} = \sqrt{\varepsilon} \approx 1.53$ and $n_2 = 1$ (air). In this case, equation (1) describes an ellipse with an eccentricity of $1/n_{lens}$.

To obtain a high gain and to implement the scanning capabilities of the PAA, a lens was developed of the toroidal shape, which is formed by rotating an elliptical profile with a linear aperture of 70 mm (minor axis of the ellipse) around a vertical axis passing through the focus point, near which the irradiator is located.

The characteristics of the designed toroidal-elliptical lens antenna were evaluated using electromagnetic modeling in CST Microwave Studio, where an equivalent PAA horn antenna was used as an irradiator. Particularly, Fig. 1 shows the profile of the designed lens against the background of a **E**-field slice, in the elevation plane. It can be seen that process thickenings in the upper and lower parts of the lens do not actually affect the formation of a flat wavefront in the antenna aperture.

Fig. 2 shows gain patterns in the elevation plane, calculated at various frequencies. According to the data presented the gain of the toroidal-elliptical lens antenna amounts to 25.8 ± 0.3 dBi.

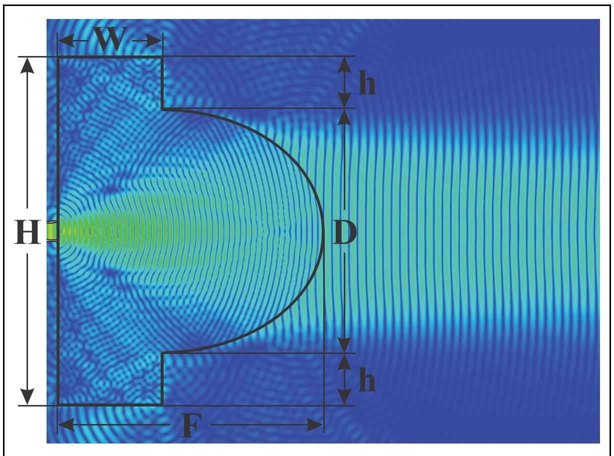

Fig. 1. The profile of the designed lens against the background of a E-field slice in the elevation plane (H = 100 mm, D = 70 mm, F = 76.3 mm, W = 30.1 mm, h = 15 mm)

Рис. 1. Профиль спроектированной линзы на фоне среза E-поля в плоскости угла места (H = 100 мм, D = 70 мм, F = 73,6 мм, W = 30,1 мм, h = 15 мм)

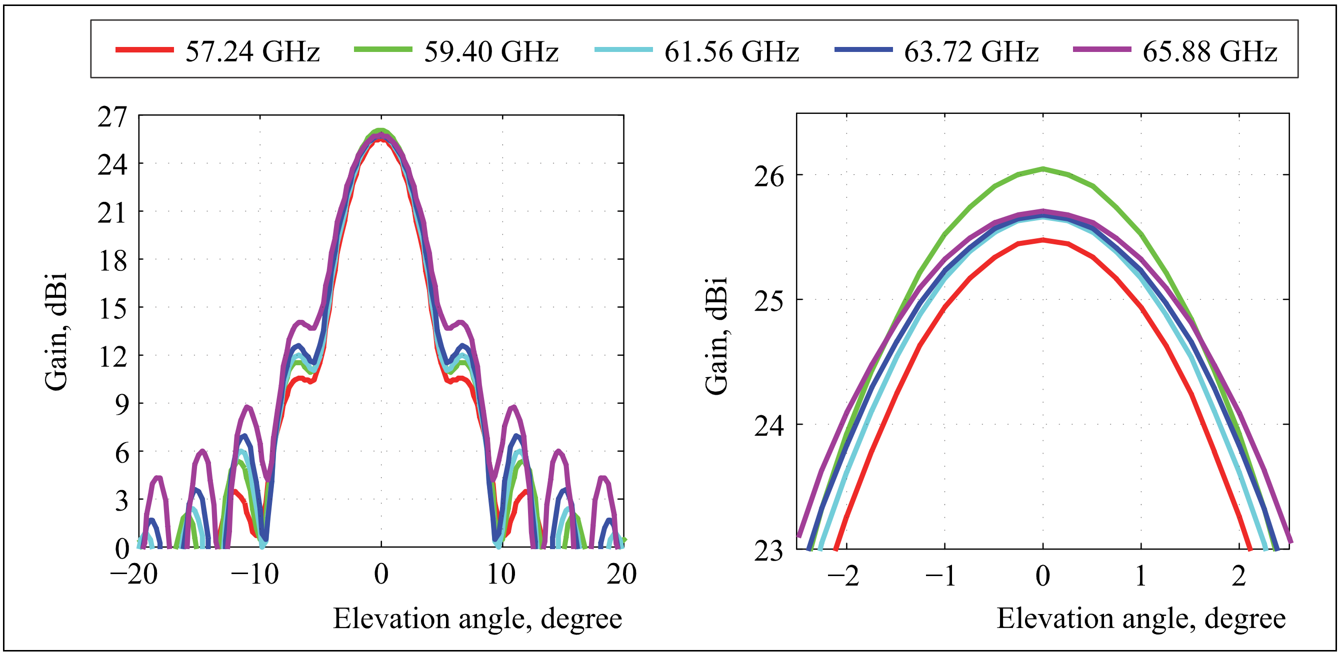

Fig. 2. Gain patterns in the elevation plane, calculated at various frequencies
Рис. 2. Зависимости КУ от угла места, рассчитанные на различных частотах

The prototype of an integrated toroidal-elliptical lens antenna

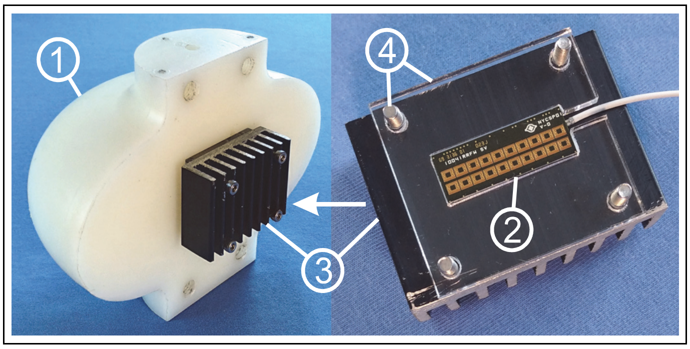

Fig. 3. Prototype of an integrated lens antenna: *1* – toroidal-elliptical lens, *2* – PAA, *3* – heat sink radiator, *4* – fasteners
Рис. 3. Прототип интегрированной линзовой антенны (ИЛА): *1* – тороидально-эллиптическая линза, *2* – ФАР, *3* – теплоотводящий радиатор, *4* – крепежные элементы

The manufactured prototype of the scanning lens antenna of the 57.24-65.88 GHz band, as shown in Fig. 3, included a lens (1) turned on a CNC machine, an active PAA module (2) with a heat sink radiator (3), as well as various fasteners (4). The PAA was inserted into a plexiglass housing with the lens closely adjacent to one side and a heat sink radiator adjacent to the other one. All the listed elements were fastened into a single structure. The total weight of the lens antenna was 650 g.

The antenna module (chip) of the 57.24-65.88 GHz band, developed by Intel, was used as the PAA [20]. The radiating elements of this module are slotted holes (slots) in the form of closed loops etched on the upper surface of the PCB.

The total contour length of each loop is equivalent to the wavelength λ, corresponding to the central frequency of 60 GHz. In total, the antenna array has 20 (2×10) elements located at a distance of 0.5λ from each other. At the same time, only 16 of them (the central ones) are excited by microstrip lines located in the lower layers of the PCB. The four extreme elements are a dummy extension of the antenna array and are required to minimize parasitic edge effects.

The chip shown in Fig. 3 is a full-fledged receiving and transmitting module, in which the antenna array is integrated with a radio frequency part manufactured using CMOS technology. This module has a maximum gain of 15 dBi and is capable of forming beams with a half power beam width (HPBW) of 40–50° in the elevation plane and 12–14° in the azimuthal plane. Moreover, the entire operating band of the chip of 57.24-65.88 GHz in accordance with the IEEE 802.11ad standard is divided into four channels with a bandwidth of 2.16 GHz. During the measurements, a specific frequency channel and radiation sector in the azimuthal plane were set using specialized software installed on a laptop.

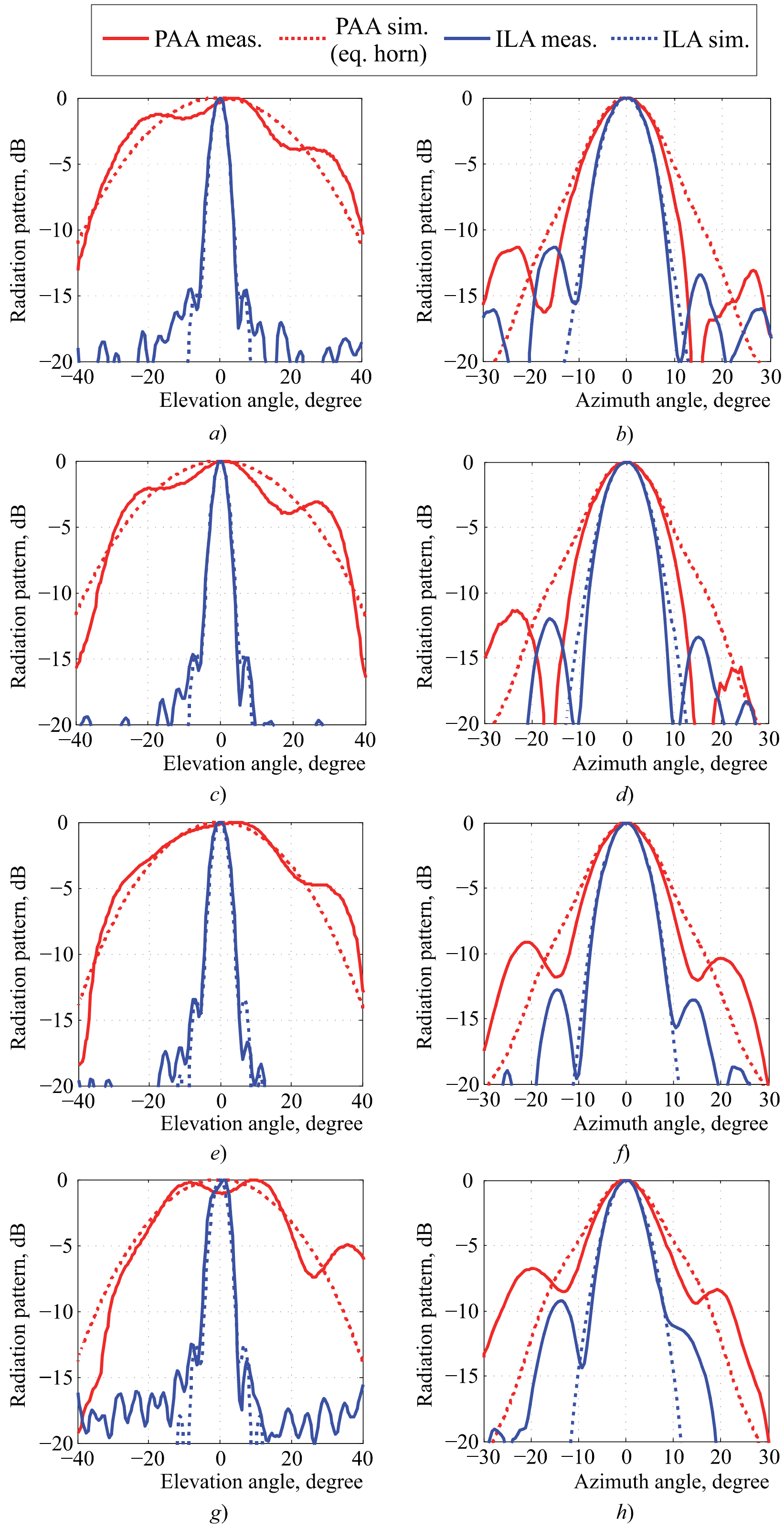

Fig. 4. RPs in the elevation (left) and azimuthal (right) planes, measured in four frequency channels of the single PAA and ILA: *a*, *b* – channel 1 (57.24 – 59.40 GHz); *c*, *d* – channel 2 (59.40 – 61.56 GHz); *e*, *f* – channel 3 (61.56 – 63.72 GHz); *g*, *h* – channel 4 (63.72 – 65.88 GHz)

Рис. 4. ДН в угломестной (слева) и азимутальной (справа) плоскости, измеренные в четырех частотных каналах ФАР и ИЛА: *а*, *б* – канал 1 (57.24–59.40 ГГц); *в*, *г* – канал 2 (59.40–61.56 ГГц); *д*, *е* – канал 3 (61.56–63.72 ГГц); *ж*, *з* – канал 4 (63.72–65.88 ГГц)

Experimental studies were carried out in the far zone of the test antenna using a fixture that included a pivoting device (positioner), a receiving lens antenna with an 34 dBi gain, a 11970V frequency converter, and an E4407B universal spectrum analyzer (both manufactured by Agilent Technologies). The operation principle of the measuring unit is described in the paper [18].

Experimental results

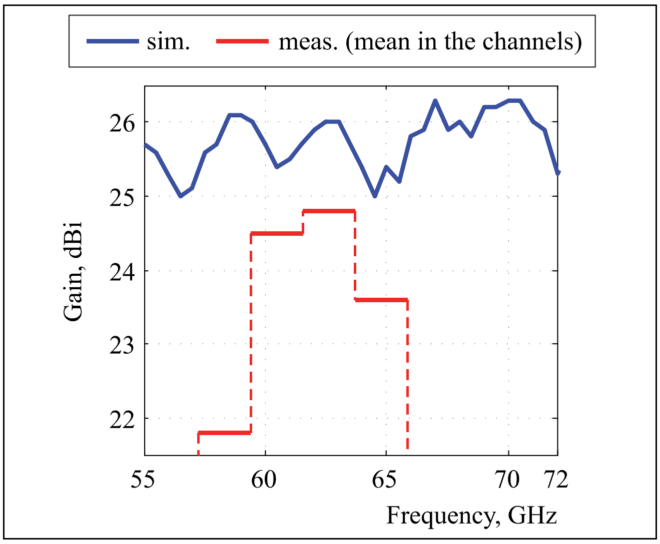

Fig. 5. The dependence of the gain on frequency
Рис. 5. Зависимость КУ от частоты

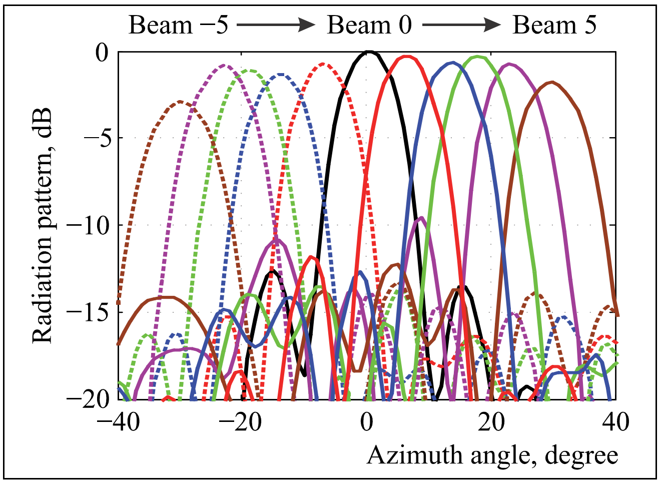

Fig. 6. RPs measured at different positions of the main beam of the ILA in the azimuthal plane
Рис. 6. ДН, измеренные при различном положении главного луча ИЛА в азимутальной плоскости

In the course of experimental studies, radiation patterns (RP) of the single PAA and the proposed integrated lens antenna were obtained in two orthogonal planes, in each of the four frequency channels of the IEEE 802.11ad standard. Fig. 4 shows the measured characteristics in solid lines and the simulation results in dotted ones. According to the data obtained, the toroidal-elliptical lens antenna focuses radiation well in the elevation plane, in all four frequency channels (total band of 57.24–65.88 GHz). A slight narrowing of the beam in the azimuthal plane by 2–4° is due to the fact that the PAA has a width (25 mm) comparable to the curvature radius (76 mm) of the outer surface of the lens (the wavefront incident on the interface is not straightly spherical). As the calculations have shown, the operating frequency range of the antenna is not limited to the 57.24–65.88 GHz band and may potentially amount to 55–72 GHz (see Fig. 5).

The measured gain of the PAA and lens antenna in the four frequency channels was 12.1, 14.2, 15.0, and 14.6 dBi and 21.8, 24.5, 24.8, and 23.6 dBi, respectively. Therefore, the greater variation in the values of the lens antenna gain in comparison with the simulation results can be explained by the deviation of the PAA gain.

Fig. 6 shows the RPs measured in the second frequency channel at various positions of the main PAA beam in the azimuthal plane. It follows from the above dependencies that the toroidal-elliptical lens antenna reliably covers the ±35° sector. At the same time, the scan loss does not exceed 3 dB. According to previously obtained experimental assessments [16], if using such antennas at both ends of reconfigurable relay communication lines, it is possible to transmit data over a distance of 100–150 m at a speed of 2.5–4.62 Gbps.

Comparison and discussion

In the last three years, a lot of work has been devoted to the development of scanning lens antennas. Table 1 shows the specification of some of these antennas.

Particularly, the letter [4] presents a dual-spherical lens antenna with a rather wide operating band of 71–76 GHz and a scanning sector of ±40°. The beam here was controlled by switching between the 16 Vivaldi antennas, which were located on the back surface of the lens. To power all 16 Vivaldi antennas, long transmission lines were required, which eventually generated a huge loss, significantly reduced the antenna's gain, and increased scan loss.

Table 1. ***Comparison of the specifications of the manufactured ILA prototype with analogs***

Ref.	Freq. range, GHz	Max. gain, dBi	Scan sector in E/A-plane	Scan loss, dB	Side lobe level, dB	Size in E/A-plane, mm
[4]	71–76	19.6	±40° A	3.9	–12	75/75
[13]	27–28	15.8	±30°/±50°	~6	–10	45/90
[17]	26.5–28.2	15.3	±52° A	2.39	–4.78	82/180
[18]	58–62	27.5	±45° A	4	–15	190/220
[21]	30–32	18	±14° A	0.8	–10	10/80
[22]	29–30.3	18.5	±60°/±60°	3.7	–12	105/105
[23]	73.5–81	31.0	±30°/±30°	3.8 in A–plane 6.2 in E–plane	–15	65.3/65.3
This work	**57.24–65.88**	**24.8**	**±35° A**	**2.9**	**–10**	**70/152**

The antennas presented in [13, 22] have an impressive scanning sector. A feature of the claimed solutions is that the lenses are made in the form of printed circuit boards with ordered sets of strip elements that transformed the phase front of the incident electromagnetic wave. The dimensions of the printed elements and the distances between them are determined by the working wavelength, which makes it difficult to provide broadband in such antennas. Moreover, in the mentioned article [13], electronic scanning was performed using varactors integrated with strip elements. However, the loss in the cells during phase rearrangement was 1.17–6.5 dB. In turn, electronic scanning was not implemented in the paper [22]. The beam was controlled here by mechanical displacement of the feed (horn) along the lens plane.

The paper [17] presents a cascaded Fresnel lens antenna with the declared scanning sector of ±52°. According to the data presented, the main beam was split at the joints of adjacent cascade lenses. The authors tried to solve this problem by implementing a special amplitude and phase distribution on the illuminating PAA. Despite this fact, the gain deviation in the ±52° sector exceeded 5 dB. Moreover, this antenna has a narrow working band (< 2 GHz) and a high side lobe level.

The letter [18] presents a toroidal lens-array antenna with a zoned profile, a high gain of 27.5 dBi, and a wide ±45° scanning sector. However, the profiles of zoned lenses are calculated taking into account the operating wavelength, which significantly limits the bandwidth of such antennas.

The paper [21] reports a compact lens antenna based on corrupted parallel-plate waveguides with a low scan loss. The disadvantages of this solution are a narrow operating frequency band and a small ±14° scanning sector.

Finally, [23] presents an integrated metal-lens antenna (IMLA) with a high gain of 31 dBi. Since, the effective permittivity of the metal-plate lens is a function of frequency, the operation bandwidth of the IMLA is limited.

Therefore, a comprehensive comparative analysis has shown that the integrated toroidal-elliptical lens antenna presented in this paper combines many advantages. The claimed solution has a simple, cheap, and ergonomic design. However, the main advantages of this antenna are a wide operating frequency range of 57.24–65.88 GHz (8.64 GHz band), high gain of up to 24.8 dBi, and a moderately wide ±35° scanning sector, the loss in which does not exceed 3 dB.

Conclusion

This paper presents the results of the development and experimental studies of the characteristics of a prototype of a scanning toroidal-elliptical lens antenna of the 57.24-65.88 GHz band with an irradiator in the form of a compact PAA. It is established that the measured characteristics generally correspond to the simulation results. The achieved high values of the 21.8-24.8 dBi gain and the possibility of electronic scanning in the azimuthal plane within the ±35° sector make the claimed antenna an attractive solution for small relay stations operating within the band of 57.24-65.88 GHz at distances of 100–150 m.

References

1. *Okasaka S.* et al. Proof-of-Concept of a Millimeter-Wave Integrated Heterogeneous Network for 5G Cellular. Sensors. 2016. DOI: 10.3390/s16091362.
2. *Sakaguchi K.* et al. Where, When, and How mmWave is Used in 5G and Beyond. IEICE Transactions on Electronics. 2017. V. E100.C, № 10. P. 790–808. DOI: 10.1587/transele.E100.C.790.

3. *Artemenko A., Mozharovskiy A., Maltsev A., Maslennikov R., Sevastyanov A., Ssorin V.* Experimental Characterization of E-Band Two-Dimensional Electronically Beam-Steerable Integrated Lens Antennas. IEEE Antennas and Wireless Propagation Letters. 2013. V. 12. P. 1188–1191. DOI: 10.1109/LAWP.2013.2282212.
4. *Lamminen A.E.I.* et al. Beam-Switching Dual-Spherical Lens Antenna with Low Scan Loss at 71–76 GHz. IEEE Antennas and Wireless Propagation Letters. 2018. V. 17. № 10. P. 1871–1875. DOI: 10.1109/LAWP.2018.2868543.
5. *Saleem M.K., Vettikaladi H., Alkanhal M.A.S., Himdi M.* Lens Antenna for Wide Angle Beam Scanning at 79 GHz for Automotive Short Range Radar Applications. IEEE Transactions on Antennas and Propagation. 2017. V. 65. № 4. P. 2041–2046. DOI: 10.1109/TAP.2017.2669726.
6. *Li Y., Ge L., Chen M., Zhang Z., Li Z., Wang J.* Multibeam 3-D-Printed Luneburg Lens Fed by Magnetoelectric Dipole Antennas for Millimeter-Wave MIMO Applications. IEEE Transactions on Antennas and Propagation. 2019. V. 67. № 5. P. 2923–2933. DOI: 10.1109/TAP.2019.2899013.
7. *Nayeri P., Yang F., Elsherbeni A.Z.* Bifocal Design and Aperture Phase Optimizations of Reflectarray Antennas for Wide-Angle Beam Scanning Performance. IEEE Transactions on Antennas and Propagation. 2013. V. 61. № 9. P. 4588–4597. DOI: 10.1109/TAP.2013.2264795.
8. *Visentin T., Keusgen W., Weiler R.* Dual-Polarized Square-Shaped Offset-Fed Reflectarray Antenna with High Gain and High Bandwidth in the 60 GHz Domain. In 2015 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal. 2015. P. 1–5.
9. *Yang J., Shen Y., Wang L., Meng H., Dou W., Hu S.* 2-D Scannable 40-GHz Folded Reflectarray Fed by SIW Slot Antenna in Single-Layered PCB. IEEE Transactions on Microwave Theory and Techniques. 2018. V. 66. № 6. P. 3129–3135. DOI: 10.1109/TMTT.2018.2818698.
10. *Nikfalazar M., et al.* Beam Steering Phased Array Antenna with Fully Printed Phase Shifters Based on Low-Temperature Sintered BST-Composite Thick Films. IEEE Microwave and Wireless Components Letters. 2016. V. 26. № 1. P. 70–72. DOI: 10.1109/LMWC.2015.2505633.
11. *Zhang W., Liu Y., Jia Y.* Circularly Polarized Antenna Array with Low RCS Using Metasurface-Inspired Antenna Units. IEEE Antennas and Wireless Propagation Letters. 2019. V. 18. № 7. P. 1453–1457. DOI: 10.1109/LAWP.2019.2919716.
12. *Jafargholi A., Jafargholi A., Choi J.H.* Mutual Coupling Reduction in an Array of Patch Antennas Using CLL Metamaterial Superstrate for MIMO Applications. IEEE Transactions on Antennas and Propagation. 2019. V. 67. № 1. P. 179–189. DOI: 10.1109/TAP.2018.2874747.
13. *Xi Q., Ma C., Li H., Zhang B., Li C., Ran L.* A Reconfigurable Planar Fresnel Lens for Millimeter-Wave 5G Frontends. IEEE Transactions on Microwave Theory and Techniques. 2020. V. 68. № 11. P. 4579–4588, DOI: 10.1109/TMTT.2020.3025337.
14. *Tang X.L., Zhang Q., Chen Y., Liu H.* Single-Layer Fixed-Frequency Beam-Scanning Goubau-Line Antenna Using Switched PIN Diodes. IEEE Microwave and Wireless Components Letters. 2019. V. 29. № 6. P. 430–432. DOI: 10.1109/LMWC.2019.2913779.
15. *Li X.*, et al. Broadband Electronically Scanned Reflectarray Antenna with Liquid Crystals. IEEE Antennas and Wireless Propagation Letters. 2021. V. 20. № 3. P. 396–400. DOI: 10.1109/LAWP.2021.3051797.
16. *Maltsev A., Lomayev A., Pudeyev A., Bolotin I., Bolkhovskaya O., Seleznev V.* Millimeter-wave Toroidal Lens-Array Antennas Experimental Measurements. In 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Boston, MA, USA. 2018. P. 607–608. DOI: 10.1109/APUSNCURSINRSM.2018.8608633.
17. *Hill T.A., Kelly J.R., Khalily M., Brown T.W.C.* Cascaded Fresnel Lens Antenna for Scan Loss Mitigation in Millimeter Wave Access Points. IEEE Transactions on Antennas and Propagation. 2020. V. 68. № 10. P. 6879–6892. DOI: 10.1109/TAP.2020.2992837.
18. *Maltsev A., Bolkhovskaya O., Seleznev V.* Scanning Toroidal Lens-Array Antenna with a Zoned Profile for 60 GHz Band. IEEE Antennas and Wireless Propagation Letters. 2021. V. 20. № 7. P. 1150–1154. DOI: 10.1109/LAWP.2021.3073913.
19. *Milligan T.A.* Modern Antenna Design. 2nd ed., Wiley-IEEE Press. 2005. 633 p.
20. *Pan H.K., Horine B.D., Ruberto M., Ravid S.* Mm-wave Phased Array Antenna and System Integration on Semi-Flex Packaging. IEEE International Symposium on Antennas and Propagation (APSURSI). Spokane. WA, USA. 2011. P. 2059–2062. DOI: 10.1109/APS.2011.5996913.
21. *Yang F., Wu X., Zhou J., Shao H.* Beam-Scanning Lens Antenna Based on Corrugated Parallel-Plate Waveguides. IEEE Antennas and Wireless Propagation Letters. 2018. V. 17. № 7. P. 1296–1299. DOI: 10.1109/LAWP.2018.2842742.
22. *Wang H.-F., Wang Z.-B., Wu Z.-H., Zhang Y.-R.* Beam-Scanning Lens Antenna Based on Elliptical Paraboloid Phase Distribution Metasurfaces. IEEE Antennas and Wireless Propagation Letters. 2019. V. 18. № 8. P. 1562–1566. DOI: 10.1109/LAWP.2019.2922695.
23. *Karki S.K., Ala-Laurinaho J., Viikari V.* Low-Profile Scanloss-Reduced Integrated Metal-Lens Antenna // IEEE Transactions on Antennas and Propagation. Feb. 2022. V. 70. № 2. P. 876–887. DOI: 10.1109/TAP.2021.3111192.

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Широкополосная сканирующая линзовая антенна для приложений 5G миллиметрового диапазона

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Аннотация

Важными элементами будущих гетерогенных сетей (HetNet) сотовой связи 5-го поколения должны стать малогабаритные релейные станции миллиметрового диапазона, обеспечивающие передачу большого объема данных между базовыми макро- и микростанциями со скоростями до нескольких десятков гигабит в секунду. Такими скоростями обладают системы Wi-Fi стандартов IEEE 802.11ad и IEEE 802.11ay, работающие в полосе частот от 57 до 71 ГГц. Однако развертывание беспроводных мобильных сетей миллиметрового диапазона в городской среде предъявляет особые требования к приемопередающему антенному оборудованию. В частности, используемые в радиорелейных станциях антенны должны иметь высокий коэффициент усиления в широкой полосе частот и обладать функцией электронного сканирования лучом.

В работе рассматривается сканирующая антенная система диапазона 57,24…65,88 ГГц, содержащая тороидально-эллиптическую линзу из высокомолекулярного полиэтилена, интегрированную с облучателем в виде компактной фазированной антенной решетки (ФАР). Известно, что подобные антенны способны фокусировать излучение облучателя и осуществлять широкоугольное сканирование лучом в азимутальной плоскости. В данной работе основной акцент сделан на исследовании частотных свойств тороидально-эллиптической линзовой антенны, поскольку это представляет практический интерес для широкополосных приложений стандартов IEEE 802.11ad и IEEE 802.11ay.

В ходе проектирования было принято решение интегрировать облучатель (ФАР) на внутренней не преломляющей поверхности эллиптической линзы с вертикальной линейной апертурой 70 мм (малой осью эллипса). Изготовленный прототип антенны включал в себя линзу, выточенную на станке с числовым программным управлением, ФАР с теплоотводящим радиатором, а также различные крепежные элементы. Применяемая ФАР вставлялась в корпус из оргстекла, к одной стороне которого вплотную примыкала линза, а к другой – теплоотводящий радиатор. Все перечисленные элементы скреплялись в единую конструкцию.

В качестве ФАР использовался антенный модуль (чип) диапазона 57,24…65,88 ГГц, разработанный компанией Интел. Данный чип является полноценным приемопередающим модулем, в котором антенная решетка из 16 активных микрополосковых элементов интегрирована с радиочастью, изготовленной по КМОП-технологии.

Результаты экспериментальных исследований и их сравнение с аналогами показали, что представленная интегрированная тороидально-эллиптическая линзовая антенна сочетает в себе много достоинств. В частности, рассмотренное решение имеет простую, эргономичную и дешевую конструкцию. Однако главные преимущества данной антенны – широкий рабочий диапазон частот 57,24…65,88 ГГц (полоса 8,64 ГГц), высокий коэффициент усиления 21,8–24,8 дБи и умеренно широкий сектор сканирования ±35°, потери в котором не превышают 3 дБ.

Представленная линзовая антенна может применяться в реконфигурируемых транспортных сетях из релейных станций миллиметрового диапазона, передающих данные на расстояния 100–150 м со скоростью 2,5–4,62 Гбит/с.

Ключевые слова

Интегрированная линзовая антенна, фазированная антенная решетка, электронное сканирование, миллиметровый диапазон

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Список источников

1. Okasaka S., et al. Proof-of-Concept of a Millimeter-Wave Integrated Heterogeneous Network for 5G Cellular. Sensors. 2016. DOI: 10.3390/s16091362.
2. Sakaguchi K. et al. Where, When, and How mmWave is Used in 5G and Beyond. IEICE Transactions on Electronics. 2017. V. E100.C. № 10. P. 790–808. DOI: 10.1587/transele.E100.C.790.
3. Artemenko A., Mozharovskiy A., Maltsev A., Maslennikov R., Sevastyanov A., Ssorin V. Experimental Characterization of E-Band Two-Dimensional Electronically Beam-Steerable Integrated Lens Antennas. IEEE Antennas and Wireless Propagation Letters. 2013. V. 12. P. 1188–1191. DOI: 10.1109/LAWP.2013.2282212.
4. Lamminen A.E.I. et al. Beam-Switching Dual-Spherical Lens Antenna with Low Scan Loss at 71–76 GHz. IEEE Antennas and Wireless Propagation Letters. 2018. V. 17. № 10. P. 1871–1875. DOI: 10.1109/LAWP.2018.2868543.
5. Saleem M.K., Vettikaladi H., Alkanhal M.A.S., Himdi M. Lens Antenna for Wide Angle Beam Scanning at 79 GHz for Automotive Short Range Radar Applications. IEEE Transactions on Antennas and Propagation. 2017. V. 65. № 4. P. 2041–2046. DOI: 10.1109/TAP.2017.2669726.

6. Li Y., Ge L., Chen M., Zhang Z., Li Z., Wang J. Multibeam 3-D-Printed Luneburg Lens Fed by Magnetoelectric Dipole Antennas for Millimeter-Wave MIMO Applications. IEEE Transactions on Antennas and Propagation. 2019. V. 67. № 5. P. 2923–2933. DOI: 10.1109/TAP.2019.2899013.
7. Nayeri P., Yang F., Elsherbeni A.Z. Bifocal Design and Aperture Phase Optimizations of Reflectarray Antennas for Wide-Angle Beam Scanning Performance. IEEE Transactions on Antennas and Propagation. 2013. V. 61. № 9. P. 4588–4597. DOI: 10.1109/TAP.2013.2264795.
8. Visentin T., Keusgen W., Weiler R. Dual-Polarized Square-Shaped Offset-Fed Reflectarray Antenna with High Gain and High Bandwidth in the 60 GHz Domain. In 2015 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal. 2015. P. 1–5.
9. Yang J., Shen Y., Wang L., Meng H., Dou W., Hu S. 2-D Scannable 40-GHz Folded Reflectarray Fed by SIW Slot Antenna in Single-Layered PCB. IEEE Transactions on Microwave Theory and Techniques. 2018. V. 66. № 6. P. 3129–3135. DOI: 10.1109/TMTT.2018.2818698.
10. Nikfalazar M. et al. Beam Steering Phased Array Antenna With Fully Printed Phase Shifters Based on Low-Temperature Sintered BST-Composite Thick Films. IEEE Microwave and Wireless Components Letters. 2016. V. 26. № 1. P. 70–72. DOI: 10.1109/LMWC.2015.2505633.
11. Zhang W., Liu Y., Jia Y. Circularly Polarized Antenna Array with Low RCS Using Metasurface-Inspired Antenna Units. IEEE Antennas and Wireless Propagation Letters. 2019. V. 18. № 7. P. 1453–1457. DOI: 10.1109/LAWP.2019.2919716.
12. Jafargholi A., Jafargholi A., Choi J.H. Mutual Coupling Reduction in an Array of Patch Antennas Using CLL Metamaterial Superstrate for MIMO Applications. IEEE Transactions on Antennas and Propagation. 2019. V. 67. № 1. P. 179–189. DOI: 10.1109/TAP.2018.2874747.
13. Xi Q., Ma C., Li H., Zhang B., Li C., Ran L. A Reconfigurable Planar Fresnel Lens for Millimeter-Wave 5G Frontends. IEEE Transactions on Microwave Theory and Techniques. 2020. V. 68. № 11. P. 4579–4588, DOI: 10.1109/TMTT.2020.3025337.
14. Tang X.L., Zhang Q., Chen Y., Liu H. Single-Layer Fixed-Frequency Beam-Scanning Goubau-Line Antenna Using Switched PIN Diodes. IEEE Microwave and Wireless Components Letters. 2019. V. 29. № 6. P. 430–432. DOI: 10.1109/LMWC.2019.2913779.
15. Li X. et al. Broadband Electronically Scanned Reflectarray Antenna With Liquid Crystals. IEEE Antennas and Wireless Propagation Letters. 2021. V. 20. № 3. P. 396–400. DOI: 10.1109/LAWP.2021.3051797.
16. Maltsev A., Lomayev A., Pudeyev A., Bolotin I., Bolkhovskaya O., Seleznev V. Millimeter-wave Toroidal Lens-Array Antennas Experimental Measurements. In 2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Boston, MA, USA. 2018. P. 607–608. DOI: 10.1109/APUSNCURSINRSM.2018.8608633.
17. Hill T.A., Kelly J.R., Khalily M., Brown T.W.C. Cascaded Fresnel Lens Antenna for Scan Loss Mitigation in Millimeter Wave Access Points. IEEE Transactions on Antennas and Propagation. 2020. V. 68. № 10. P. 6879–6892. DOI: 10.1109/TAP.2020.2992837.
18. Maltsev A., Bolkhovskaya O., Seleznev V. Scanning Toroidal Lens-Array Antenna with a Zoned Profile for 60 GHz Band. IEEE Antennas and Wireless Propagation Letters. 2021. V. 20. № 7. P. 1150–1154. DOI: 10.1109/LAWP.2021.3073913.
19. Milligan T.A. Modern Antenna Design. 2nd ed., Wiley-IEEE Press. 2005. 633 p.
20. Pan H.K., Horine B.D., Ruberto M., Ravid S. Mm-wave Phased Array Antenna and System Integration on Semi-Flex Packaging. In 2011 IEEE International Symposium on Antennas and Propagation (APSURSI). Spokane. WA, USA. 2011. P. 2059–2062. DOI: 10.1109/APS.2011.5996913.
21. Yang F., Wu X., Zhou J., Shao H. Beam-Scanning Lens Antenna Based on Corrugated Parallel-Plate Waveguides. IEEE Antennas and Wireless Propagation Letters. 2018. V. 17. № 7. P. 1296–1299. DOI: 10.1109/LAWP.2018.2842742.
22. Wang H.-F., Wang Z.-B., Wu Z.-H., Zhang Y.-R. Beam-Scanning Lens Antenna Based on Elliptical Paraboloid Phase Distribution Metasurfaces. IEEE Antennas and Wireless Propagation Letters. 2019. V. 18. № 8. P. 1562–1566. DOI: 10.1109/LAWP.2019.2922695.
23. Karki S.K., Ala-Laurinaho J., Viikari V. Low-Profile Scanloss-Reduced Integrated Metal-Lens Antenna. IEEE Transactions on Antennas and Propagation. Feb. 2022. V. 70. № 2. P. 876–887. DOI: 10.1109/TAP.2021.3111192.

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