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Research Article

Development and construction of new scanning antennas with high remote sensing capability for wireless communication systems in the millimeter wavelength range

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ABSTRACT

In this paper, geometric methods and wave optics were used to calculate the basic profiles and characteristics of the lens antennas. The planar reflector arrays were assembled using an iterative method with multiple forward and inverse Fourier transform calculations. Three-dimensional electromagnetic modeling was performed in CST Microwave Studio software to evaluate the technical parameters of the designed antennas. Measurements of the characteristics of fabricated prototypes of far-field scanning antennas were performed using a custom-designed experimental setup. This study focuses on the analysis and development of scanning antennas for use in millimeter-wave wireless communication systems. The researchers aim to develop a lenticular antenna in the 57.24-65.88 GHz band with a high DER and a wide-angle radial scanning function in the azimuth plane and another lenticular antenna system in the 58-62 GHz band with a high DER and a wide scanning sector in the azimuth plane. The researchers also aim to develop a methodology to design flat reflective gratings to provide electron beam scanning in the azimuthal plane. The characteristics of prototypes of these antennas have been studied, and experimental tests have been conducted. The study predicts the realization of scanning antennas in the 57.24-63.72 GHz band using microstrip flat reflector grids.

1. INTRODUCTION

Nowadays, the issue of increasing the capacity of wireless communication systems is becoming more and more important due to the emergence of new multimedia services[1, 2].
The millimeter wave range (30-300 GHz) is one of the most promising areas in modern radio electronics systems [3]. Due to its unique characteristics, such as high frequency and narrow beam, millimeter waves find applications in a wide range of technologies, including next generation wireless communication systems (5G and 6G), advanced materials science and precision engineering techniques, as well as a thorough understanding of electromagnetic processes at high frequencies[4-6]. Performance and flexibility. This is particularly important in radar applications, where fast and accurate object tracking is required, and in advanced communication systems, where dynamic resource allocation is needed to increase throughput[7-9].
Key technical challenges include the development of low-noise, high-efficiency antenna systems, as well as safety and control systems [10, 11]. Antennas operating in this band play a key role in enabling the transmission and reception of electromagnetic waves, and their performance determines the efficiency and reliability of the overall system [12, 13].
Scanning antennas are able to change the direction of the beam without mechanically moving the antenna, greatly improving the ability of systems to operate at high frequencies with minimal loss [14-16]. This requires the use of advanced materials science and precision engineering techniques, as well as a thorough understanding of electromagnetic processes at high frequencies [17-19].

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Applications for these antennas range from communications and radar systems to medical and biomedical devices where millimeter waves can be used for non-invasive diagnostics [20-22]. In addition, these antennas play a key role in security systems, such as scanners for detecting hidden objects on the human body [23-25].
New fifth-generation (5G) mobile networks will need to deliver data rates of tens of gigabits per second [26]. These speeds can be achieved by moving communications systems into the millimeter-wave frequency range, using much wider-band signals (up to 8 GHz) and a special heterogeneous architecture [27-29].
The IEEE Standards Committee has already adopted the IEEE 802.11ad and IEEE 802.11ay standards for Wi-Fi systems operating in the 57 to 64 GHz and 57 to 71 GHz frequency bands, respectively [30-32].
The new approach to building LTE-Rel15 and 5G NR cellular networks involves deploying additional small cells with millimeter-wave ranges of up to 50-100 meters in microcell coverage areas located in places with high concentrations of users (hotspots)[33, 34]. [35]
However, deploying such heterogeneous networks in the challenging urban conditions of millimeter-wave radio signal propagation places special demands on antenna systems [36-38].
Antennas used in small base stations and access points should have particularly high gain and scanning power to track mobile users [39, 40].
The specific pattern and maximum coverage angle should be determined on a case-by-case basis for each network deployment [41, 42] .
Multi-element phased array antennas (PAs) in the millimeter band are known to have a complex structure, low efficiency (due to a number of technological issues in this band) and high manufacturing costs [43-45].
Therefore, alternatives to scanning antennas are proposed for use in applications of new 5G standards. For example, antennas with lenses made of monolithic dielectric materials are widely used [46, 47]. However, such high DER antennas typically have a large mass[48].
In this suggested paper, advanced lens antennas are modernized, and a new methodology for designing flat reflector networks is designed and built on advanced electromagnetic modeling that enhances the performance of advanced communication systems. In addition, experimental validation of prototypes and accurate beam scanning using flat reflector networks is achieved, which could positively impact applications such as 5G, space communications, and advanced radars.
This research is divided into several sections. Section 2 discusses previous work related to the topic, while Section 3 explains the two-part research methodology (design of scanning lens antenna systems and design of scanning antennas with planar reflector arrays). Section 4 discusses the results and analysis (prototype of manufactured lens antennas, typical scanning antennas manufactured with planar reflective arrays, and discussion of the main results of the research), while Section 5 focuses on evaluation and comparison. Finally, Section 6 presents the conclusions.

2. RELATED WORK

1- This paper discusses the use of heterogeneous networks (HetNet) as a promising approach to building 5G mobile systems. HetNet combines existing 4G technologies with new millimeter wave (MM) broadband systems. However, in urban areas where MM-band signals are difficult to propagate, antenna systems must meet specific requirements. This paper presents a 57.24-65.88 GHz scanning antenna with a printed flat reflector array and a phased array (PA) radiator. The antenna achieves beam steering capability in the azimuthal plane through Frequency Adaptive Radar (FAR) technology and a unique reflector array configuration. The structure resembles a rectangular array of passive reflectors on a printed circuit board, acting as an analogue to a cylindrical reflector. This configuration allows the FAR radiation to be focused in the spatial angle plane without distorting the beam shape in the azimuth plane. Overall, the paper outlines a novel approach to antenna design for urban HetNet deployments in the 5G era. Intel has developed an antenna module that functions as a Far-field auto-ranging (FAR) system. This module was positioned 200 mm from the center of the reflective array and measured in the 57.24-65.88 GHz frequency range. The results showed that the Directivity Enhancement Ratio (DER) ranged from 20.1 to 24.5 dBi. The electronic beam steering capabilities of the module were assessed by switching between three azimuthal sectors (-10°, 0° and 10°). The data showed that the full coverage sector in the azimuth plane, taking into account the beamwidth at half power (-3 dB), was ±15°. However, electromagnetic modelling indicated that the potential scanning sector in the azimuthal plane could be ±35°. Experimental studies on toroidal-elliptical lens antennas with similar radiation characteristics showed that using such antennas, data rates of 2.5-4.62 Gbps could be achieved for relay stations spaced 100-150m apart in a reconfigurable transport network [49].

2- In this study, a radiator was integrated on the surface of an elliptical lens and a prototype antenna was fabricated with a FAR, a lens close to the housing and a heat sink. An Intel chip was used for the antenna and an antenna array of 16 active elements was integrated with the wireless part. Experimental studies have shown that the integrated helical lens-oval-tip antenna combines many advantages such as simple and convenient design and low cost, but the main advantages of this antenna are a wide operating frequency range of 57.24...65.88 GHz (8.64

GHz bandwidth), a high gain of 21.8-24.8 dBi and a moderately wide scanning sector of ±35° with a loss of less than 3 dB. The lenticular antenna presented can be used in reconfigurable transport networks of millimeter-band relay stations transmitting data at 2.5-4.62 Gbps over distances of 100-150 m [50].

3- 5G systems operate in millimeter waves and offer very high data rates in the multi-gigabit range. In this paper, different millimeter-wave array designs for 5G applications were presented. These designs included fixed beam antenna array designs, beam scanning in one plane only, and two-dimensional scanning array designs. The study discusses two different scanning array design strategies to achieve the required 2D scanning. The researchers point out that alternatives to conventional phase shifters are needed in the millimeter-wave range, due to their high cost and harmful effect. The study proposes two different antenna systems, which can achieve the required 2D scanning in the millimeter-wave band Overall, the research aims to improve the performance of 5G networks and provide higher communication speeds for a wide range of different applications. The paper discusses two designs for 2D scanning capabilities: Luneburg lens excited by a 2D waveguide array or microstrip patch antenna array, and phased array designs using switchable diodes or variable diodes. It also discusses methods to optimize array gain and introduces reconfigurable meta-panels.[51]

4- Multiple simultaneous characteristics are needed for dependable high data-rate transmission in millimeter wave (mmWave) 5G phased arrays. A stacked 5×5 rectangular patch stack phased array, used in a broadband process, is designed and fabricated. Multiple design strategies, such as stacked topology, electromagnetic bandgap structures, and element rotation, were used to optimize the process performance. The bandwidth is improved by 15.3% compared to a standard antenna. Unwanted mutual coupling between elements has been minimized, and a broadband beamforming network has been designed and fabricated. The proposed phased array achieves a bandwidth of 6 GHz covering 24 to 30 GHz and achieves a maximum gain of 17.5 dBi and a wide beam scanning range. The highest FoM value of 0.451 is achieved, which is better than most similar fifth-generation array designs [52].

5- Jiang et al. (2022) conducted a breakthrough study on the development of an X-band active phased array antenna using a dual-port waveguide feed. The researchers aimed to improve the performance of electronic beam steering systems through a flexible and scalable design of active antennas used in radar and communications applications. The study relied on a combination of 3D electromagnetic simulations using CST software, as well as prototype fabrication and experimental measurements to verify performance. The proposed antenna achieved a wide-area beamwidth of up to ±60°, with enhanced gain and radiation directivity. The design demonstrates high feed efficiency and phase control for each array element, making it a strong candidate for demanding military and civilian communications applications. [53]

6- Zhang and Shamim (2023) presented an advanced study on the design of integrated phased array antennas for 5G communications applications in the millimeter wave (mmWave) band. The researchers used low-temperature ceramic co-crystal (LTCC) technology to construct a 5×5 antenna array, focusing on improving radiation performance through a dual-polarization antenna design with a wide bandwidth and ±50° beam steering. A notable feature of the design is the use of a multi-layer structure based on stacked patches, in addition to the inclusion of electromagnetic blocking (EBG) structures to reduce crosstalk between the elements. The model achieved a radiation gain of up to 17.5 dB and an operational bandwidth covering 6 GHz (from 24 to 30 GHz). All design and simulation phases were performed using CST and HFSS environments, confirming the design's suitability as an antenna-in-package (AIP) component for modern communications systems [54].

3. METHODOLOGY

This paper aims to solve the design and construction of new high-performance scanning antennas for wireless communication systems in the millimeter wavelength band. This is a key requirement of the IEEE 802.11ad and IEEE 802.11ay standards for base station antennas and relay stations operating in the 60 GHz band.

In particular, it is shown that antennas under development for data transmission at distances between 100 and 300 meters must have a narrow main beamwidth of less than 20 degrees and a maximum DER of more than 20 dB.

In addition, most of the transmission networks to be deployed require the antennas to have an electronic scanning function in the azimuth plane in an angular sector between 30° (±15°) and 90° (±45°).Abbreviations and Acronyms

3.1 Design of scanning lens antenna systems.

In this section, different design concepts for millimeter-wavelength scanning antennas are presented. The analysis shows that millimeter-wave scanning antennas, lenticular antennas and planar reflector array antennas can be widely used in future heterogeneous 5G networks.

1- Calculation of lens profiles using the optical-geometrical approximation.

This geometric-optical approximation was used to calculate the profiles of elliptical, zonal and bifocal lenses. In practice, a compact FAR with an electron beam scanning function in the azimuth plane was used as the lamp. To achieve the scanning capabilities of the FAR, the annular shapes of the lenses were determined by rotating the corresponding profiles by 180° around the vertical axes passing through the foci near which the FAR is located.

Considering that some applications of fifth generation communication systems require antennas of low weight, this paper decided to make a ring lens with a custom hyperbolic segmental surface, the shape of which can be described by the following set when ($n_2/n_1 > 1$):

$$A=\left((x+\frac{m\lambda)}{n_2/n_{1-1}})^2\right)\ (n_2/n_{1-1}) \tag{1}$$

$$B=\left(L_f-\frac{m\lambda)}{(n_2/n_{1-1}}\right)\left(x+\frac{m\lambda)}{n_2/n_{1-1}}\right)(n_2/n_{1-1}) \tag{2}$$

$$A+B-Y^2=0 \tag{3}$$

where m = 0, 1, 2 ... , L_f - distance between the point of illumination and the corresponding hyperbola of m = 0, λ operating wavelength.

The designer's linear aperture is 190 mm, 20 mm thick and has a focal length of 90 mm. With these dimensions, there are eight zones (m = 0, 1, 2, ..., 7) on the aperture .

Of particular practical importance are bifocal lenses with two refractive surfaces (Fig. 1).

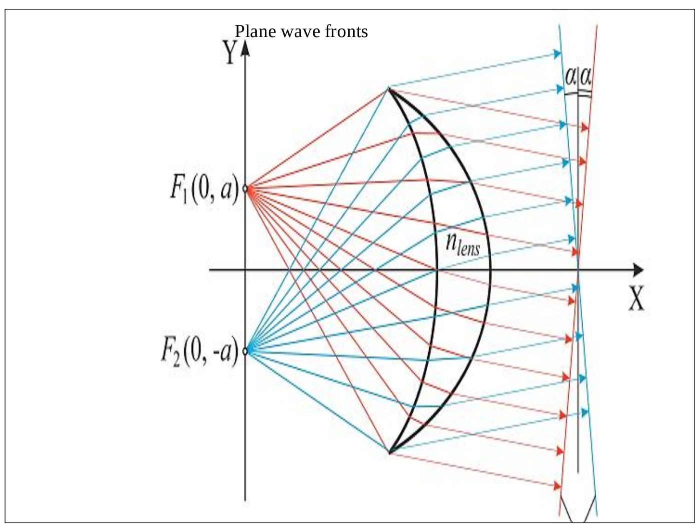


Fig. 1. Ray trajectories in a bifocal lens.

In this paper, the profile of the bifocal lens was calculated using the Jent-Sternberg method. This method was implemented in the program "Dielectric Bifocal Lens Profile Calculation," from which the profile of the bifocal lens shown in Figure 2 was obtained with the given parameters A = 5 mm, α = 3° and nlens = 1.53 (see Figure 2).

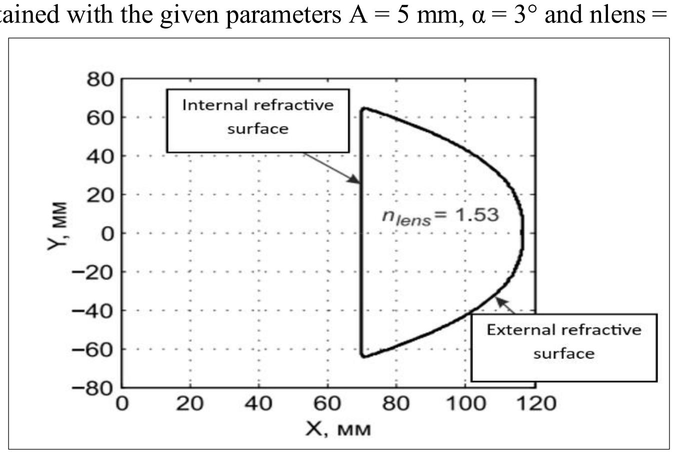


Fig. 2. Bifocal lens profile calculated for a = 5 mm, α = 3° and nlens = 1.53.

The inner and outer surfaces of the lens displayed are described by functions:

$$y_{inner}(x) = \pm(14124X - 98418)^{0.5} \tag{4}$$

$$y_{outer}(x) = \pm(-730X + 85143)^{0.4} \tag{5}$$

However, lenses with two refractive surfaces introduce additional reflections that reduce the overall efficiency of the antenna system. As can be seen in Figure 2, the profile of the inner surface of the lens can be rounded with a straight segment. It was therefore decided to fill the space between the commons and the lens with polyethylene, so that the active elements of the antenna array are located on the insulating surface.

This means that a bifocal lens actually has a single refractive surface (the outer surface). At the same time, the distance between the common and the outer surface of the lens has been increased by (35mm) in order to maintain the intra-phase field in the aperture.

2- Results of the electromagnetic modelling of lenticular antennas designed in the CST Microwave Studio software.

It should be noted that the three-dimensional electromagnetic modelling of lenticular antenna systems with a lens in explicit form required a lot of computation. Therefore, at this stage of the research it was decided to use an equivalent horn antenna instead of FAR. The effectiveness of replacing the equivalent antenna with the horn antenna in the modelling was confirmed by the results of the measurements of the characteristics of the scanning antenna prototypes.

3.2 Design of scanning antennas with planar reflector arrays

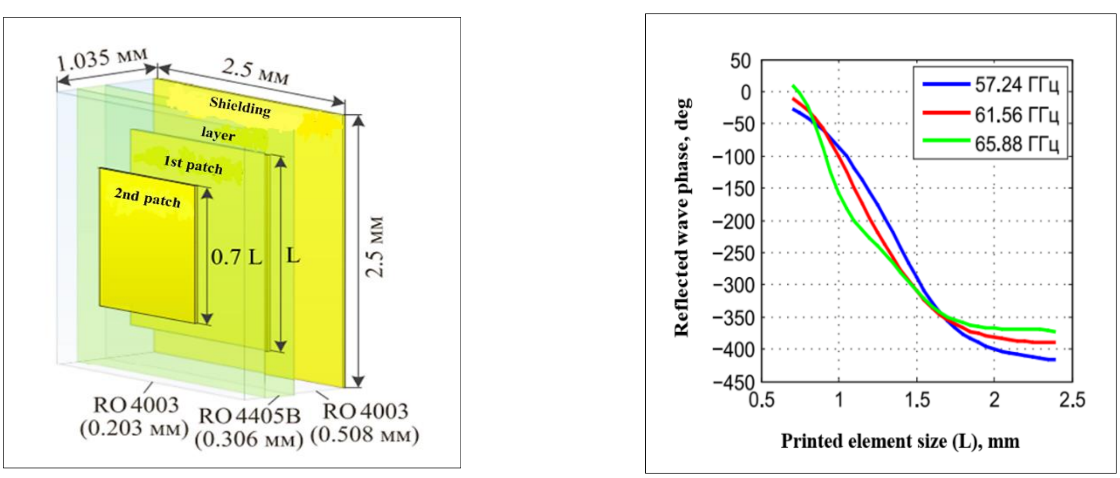
This section deals with the design of scanning antennas with planar reflector arrays forming pencil, sector and distributive reflector type planar reflector arrays.

1- Principles of operation of planar array antennas

The operation of planar reflective array antennas, consisting of several negative microscopic elements, is printed on an insulating substrate.

In this paper, the reflective properties of planar printed structures with a copper layer thickness of 2.5 × 2.5 mm (0.5λ × 0.5λ) with transverse dimensions and square patches have been studied. According to the results of the three-dimensional electromagnetic modelling presented.

Optimum performance was then obtained from a three-layer cell in which the aspect ratio of the upper to lower patch is 0.7 (see Figure 3).



(a) (b)

Fig. 3. Three-layer reflective cell: a) – geometric structure; b) – phase-size dependences calculated at different frequencies

As can be seen from Figure 3b, the phase distance dependence varies little in the frequency range 57.24 to 65.88 GHz. For patches ranging in size from 0.7 to 2.4 mm, the maximum phase deviation from the center curve calculated at 61.56 MHz does not exceed 60 degrees. Thus, the three-layer printed structure shown in Figure 3a is the basis for all designed reflectors. The basis for all designed reflective grids is therefore the three-layer printed structure shown in Figure 3a.

To explain geometric structure the flat reflector antenna construct was chosen for high-frequency communication because it provides high signal steering control and improved reflection efficiency Examined alongside conventional antennas, and compact and lightweight fabrication capabilities using microprinting techniques.

The design depends on a three-layer reflector structure, as displayed in Figure 3a. The layers are comprised of the first layer (RO 4003), the second layer (RO 4405B), and the third layer (RO 4003). The use of these varied materials achieves a balance between electromagnetic performance and manufacturing efficiency, leading to augmented reflection properties and reduced energy losses. The selection of a ratio of 0.7 between the upper and lower spots is based on simulation studies, which have shown that this ratio improves electromagnetic field distribution, reduces signal dispersion, and maintains performance across the frequency range of 57.24 - 65.88 GHz, as shown in Figure 3b.
In Figure 3b, the phase deviation at 61.56 GHz does not exceed 60 degrees, signifying stability in the reflection angle over a wide frequency range. This hybrid design has optimized antenna performance in practical applications.
When juxtaposed with conventional single- or double-layer designs, the three-layer design offers greater control over the electromagnetic wave reflection characteristics, reduces signal loss, improves bandwidth, and increases antenna efficiency in advanced wireless communications environments.

2- Reflection Array Installation Methods

In this research, a brief review of the reflection array installation methods used In this work, the reflection arrays were synthesized using an iterative method involving multiple calculations of the forward and backward Fourier transform.
In this case, exponential integer functions were used as reference amplitude plots (complex DN equations). This paper also proposes original reference functions for phase plots, which can be used to obtain a more accu
+rate approximation of the given DN schemes.
The main ideas of the iterative method are discussed and examples are given to solve the problems of one-dimensional phase synthesis of 33-element linear gratings.
Equidistant gratings forming a strip, pencil and cocoon type DNs. The DRS function (ζ) has been used as a reference capacity table for the sector type in the iterative algorithm:

$$DN_{Rs}(\zeta) = \frac{\sin \pi\zeta 36+7\zeta^2+5.5\zeta^4-0.5\zeta^6}{\pi\zeta\,(1-\zeta^2)(4-\zeta^2)(9-\zeta^2)} \tag{6}$$

$$DN_{Rs} = DN_{ref} \tag{7}$$

where ζ = 10sinθ is the generalized coordinate (θ is the location angle). The reference function of the phase diagram γref(θ) is given as a parabola:

$$\gamma_{Rs}(\theta) = \begin{cases} g^2\theta^2 & -15^\circ < \theta < 15^\circ \\ 0 & |\theta| \geq 15^\circ \end{cases} \tag{8}$$

$\gamma_{Rs}(\theta)$: Defines the phase shift function of the system, which plays a critical role in controlling the radiation pattern.

$$\gamma_{Rs}(\theta) = \gamma_{ref}(\theta) \tag{9}$$

where θ is the location angle and g = 0.021 is the composition coefficient.
To illustrate the effectiveness of using assumed functions in the iterative algorithm, tuning of a reflective antenna array with a linear polydefinite trapezoidal (θ) DN reference was performed.
As shown in the calculation results, the relative integral errors of the approximation of the DRS(θ) and DRT(θ) functions in the angular range from θ1 = -13° to θ2 = 13° were 0.87% and 10% respectively.
Thus, using functions such as (3) and (4) in the iterative algorithm allowed us to obtain a more accurate approximation of the reference segmental DRT function. During the installation of the reflective grating with pencil D
When tuning the grating with the DR pencil, an integer exponential function (4) at = 52sinθ was used as the reference amplitude diagram DR HG(θ). Assume that the reference phase diagram is zero (γref(θ) ≡ 0).
In addition, the DN of a standard (θ) directional antenna array D HG (θ) consisting of 33 elements with the same amplitude and phase was calculated.
According to the estimates made, the equivalent DERs of the composite and standard arrays are 21.1 and 22 dB/i respectively. At the same time, the side lobe level (SLL) of the composite array did not exceed -30 dB. In contrast, the SLL of the standard array was much higher at -13.2 dB.
The DRC(ζ) function was used as the reference amplitude diagram Dref(פ) in the composition of the reflection pattern that makes up the DRC reflection scale:

$$DN_{Rc}(\zeta) = \frac{\sin \pi\zeta 585-581\zeta+187.5\zeta^2-5\zeta^3-7.5\,\zeta^4+\zeta^5}{\pi\zeta\,7.5(1-\zeta)(2-\zeta)(3-\zeta)(4-\zeta)(5-\zeta)} \tag{10}$$

Where :

- $DN_{Rc}(\zeta)$: Represents the radiation pattern function, describing the directional properties of an antenna or wave field.
- ζ = 12 sin 0: (is a generalized coordinate, defined as 12 times the sine of the location angle θ.

$$DN_{ref}(\zeta) = DN_{Rc}(\zeta) \tag{11}$$

$$\gamma_{Rc}(\theta) = \begin{cases} arctan1^{0.2}\theta - 8^{\circ} < \theta < 28^{\circ} \\ 0 \qquad\qquad |\theta| \geq (-8^{\circ}, 28^{\circ}) \end{cases} \quad (12)$$

$$\gamma_{Rc}(\theta) = \gamma_{ref}(\theta) \quad (13)$$

In order to evaluate the efficiency of using the so-called functions in the iterwswegyh46tative algorithm, a tuning of a reflective antenna array with a DN reference DRIC (θ) and oblique Multi definition (θ) is performed.
The comparative analysis of the results obtained shows that the integral relative RMS errors of the rounding are as follows of the reference functions DRC(θ) and DRIC(θ) in the angular range [-26°, 4°] were 4.7% and 9.5% respectively. Thus, the use of functions such as (5) and (6) in the iterative algorithm provided a better approximation of the reference cos angle measurement circuit.

3- Improved scanning antenna models

This section presents the improved scanning antennas, each of which has a flat reflective array and compressed radiation FAR. The azimuthal plane of the electron beam is achieved in antennas designed, thanks to the compact reflective matrix and the special configuration of the reflective matrix (see Fig. 5), as a rectangular array with identical columns composed of three-layer printed structures shown in Fig. (4).

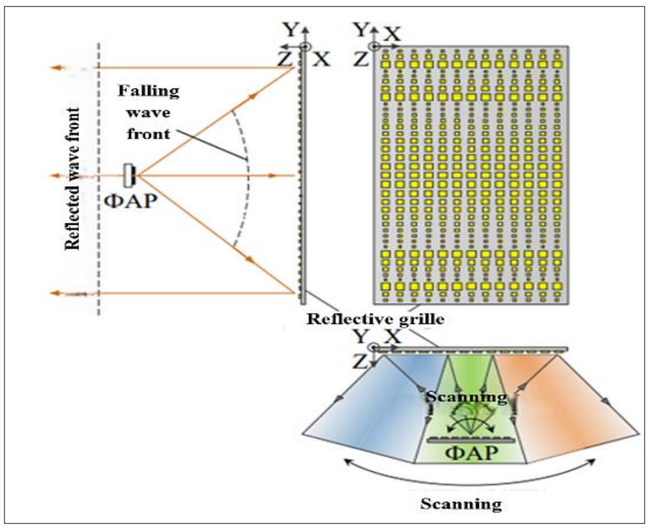


Fig 4. Configuration of a scanning antenna with a flat reflective array.

In the course of this work, flat reflective arrays in the form of printed circuit boards were designed to form sector, pencil and sectional scanning antennas in the plane of the Yuz site angle. Three-dimensional electromagnetic modelling was carried out in the CST Microwave Studio using a parabolic horn radiator to evaluate the characteristics of scanning antennas containing such arrays.
In all cases, the horn antenna was placed 70 mm from the center of the board, which contained 29×33 = 957 reflective cells (29 identical columns of 33 elements each). According to the modelling results, the calculated format of the main beams of the DNN networks of antenna systems generally corresponds to the specified mathematical reference models, while the operating frequency bandwidth of all the arrays studied corresponds to the main channel width of the IEEE 802.11ad and IEEE 802.11ay 2.16 GHz standards.
However, the main advantage of the presented antenna systems is the possibility of electronic scanning at the XOZ azimuth level in a sector of ± 15°.

4. RESULTS AND DISCUSSION

This section focuses on the practical application of the improved scanning antennas in the 60 GHz frequency band.

4.1 Prototype of manufactured lens antennas.

An antenna module (chip) with a frequency range of 57.24 - 65.88 GHz developed by Intel was used as a radiating antenna module (chip) FAR. This unit has a DER performance of between 12 and 15 dB per inch and is capable of scanning the electronic beam at the azimuth level in a ±50° sector.

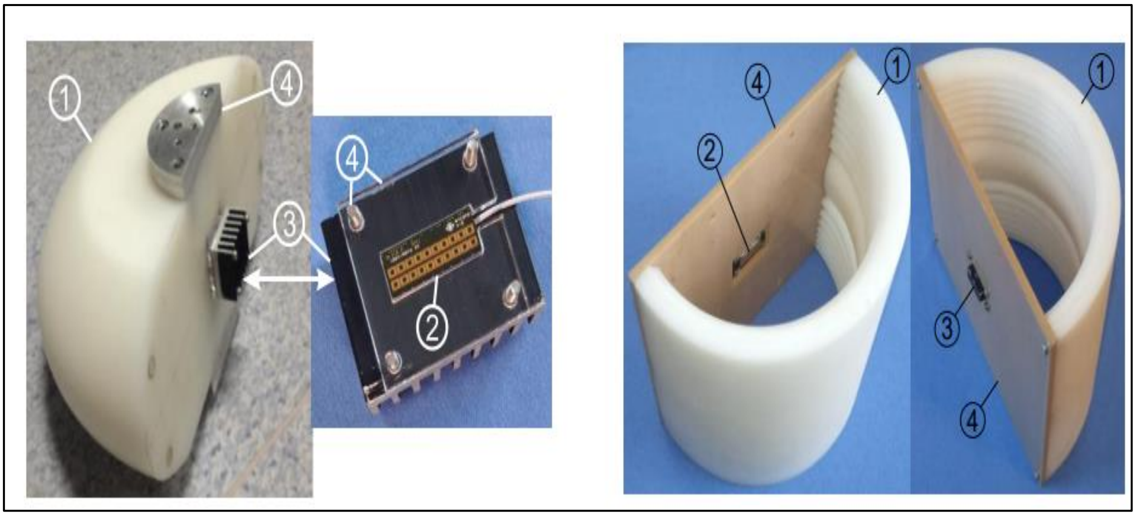
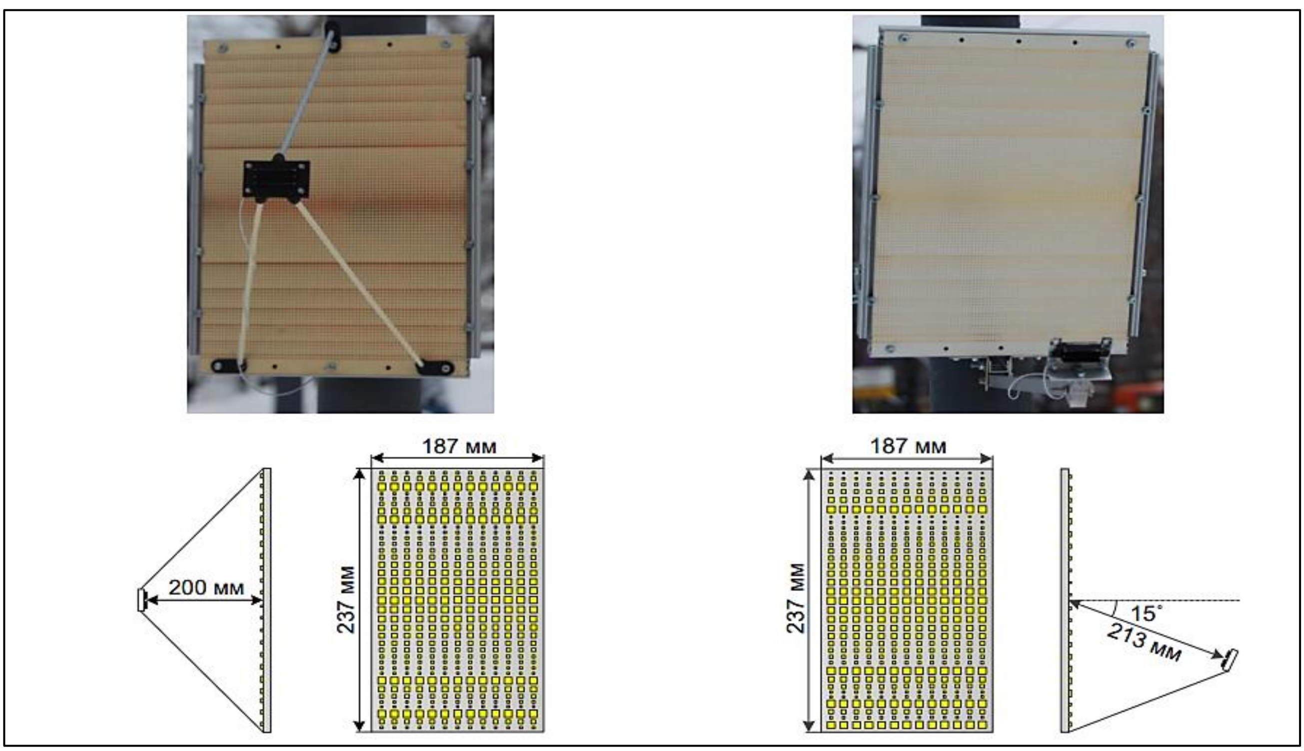


Fig. 5. Prototypes of assembled lens antennas: 1 – lens (bifocal on the left, zoned on the right), 2 – phased array, 3 – heat sink, 4 – fasteners.

In addition, the chip's full operating frequency range of 57.24 - 65.88 GHz is divided into four channels with a width of 2.16 GHz in accordance with the IEEE 802.11ad standard.

4.2 Typical scanning antennas manufactured with planar reflective arrays.

Typical manufactured scanning antennas are shown with planar reflective arrays. It should be noted that one of the reflective arrays is an analogue of a classical rectangular cylindrical reflector (see Fig. 6a) and the other is a reflector with a 15° beamwidth angle (see Fig. 6b).



(a) (b)

Fig. 6. Prototypes of reflective antennas: a) direct focus type b) offset type

The pilot setup used to measure the performance of the antenna prototypes built during this work and the MiWEBA (Elliptical Lens Antennas) project.

The table below shows the results of the characterization measurements of all the models of scanning antennas.

TABLE I. MEASUREMENT CHARACTERISTICS OF TYPICAL ANTENNA SYSTEMS IN MANUFACTURE.

Antenna type / Vertical linear aperture size	Operating frequency bandwidth, GHz (-3 dB level)	Maximum. CHP, E	Main beam width in azimuth/angle plane (A/U)	Azimuth/angle scanning sector (A/U)	UBL, dB
Elliptical/70mm lens	57.24 – 65.88	24.8	$9^{\circ}/5^{\circ}$	$\pm 35^{\circ}\ A$	-10
Elliptical / 90mm lens	57.24 –65.88	26.0	$9.5^{\circ}/4^{\circ}$	$\pm 40^{\circ}\ A$	-10
Elliptical / 112mm lens	57.24 –65.88	27.5	$9.5^{\circ}/3^{\circ}$	$\pm 40^{\circ}\ A$	-9
Bifocal / 130mm lens	57.24 –65.88	27.5	$9.5^{\circ}/2.5^{\circ}$	$\pm 40^{\circ}\ /\ \pm 3^{\circ}$	-8
Dedicated lens /190mm	58 – 62	27.5	$14^{\circ}/3^{\circ}$	$\pm 45^{\circ}\ A$	-10
Reflective direct focus / 237mm	57.24 – 63.72	24.5	$14^{\circ}/2^{\circ}$	$\pm 15^{\circ}\ A$	-8
Reflective displacement / 237mm	57.24 – 63.72	26.0	$14^{\circ}/2^{\circ}$	$\pm 15^{\circ}\ A$	-8

The measured characteristics of the typical antenna systems created match well with the results of the electromagnetic modelling in CST Microwave Studio and meet the requirements of the IEEE 802.11ad and IEEE 802.11ay standards for transmitting and receiving antenna equipment for small base stations (Wi-Fi access points) and relay stations operating in a 60 GHz environment at distances of 25 - 50 m and 100 - 300 m, respectively.

TABLE II. COMPARISON CURRENT STUDY WITH RECENT RELATED WORK

Aspect	Suggest Study	Jiang et al. (2022)	Zhang & Shamim (2023)
Antenna Type	Lenticular scanning antennas with planar reflector arrays	Active X-band phased array with dual-port waveguide feed	Phased array antenna-in-package on LTCC substrate
Frequency Band	57.24–65.88 GHz (mmWave, V-band)	8–12 GHz (X-band)	24–30 GHz (mmWave, 5G band)
Design Methodology	Geometrical optics, wave optics, iterative Fourier transforms, and CST 3D simulation	Waveguide-fed design with experimental prototyping and sCST modeling	Stacked patch design with EBG structures, rotated elements, HFSS/CST simulation
Key Technologies	Flat reflective microstrip gratings, 3D electromagnetic simulation	Dual-port waveguide feeding, active beamforming	LTCC multilayered packaging, wide-angle scanning, AiP concept
Scanning Capability	Radial wide-angle beam scanning in the azimuth plane	±60° beam scanning via phased control	±50° wide-angle beam steering in azimuthal plane
Innovation Focus	Hybrid optical-electromagnetic design, high DER, lens-based passive beam scanning	Compact phased array with dual-port waveguide feed and experimental validation	High-efficiency AiP phased array for wideband 5G with mutual coupling suppression
Experimental Validation	custom-built setup for real measurements	fabricated prototypes measured	design validated through simulations and measurement data
Application Context	mmWave wireless systems, potentially 5G backhaul or radar	X-band radar and communication systems	5G mobile communication systems and terminal integration

By analyzing and comparing the current study with recent related work (Jiang et al., 2022; Zhang & Shamim, 2023), it is clear that the proposed study makes an advanced scientific contribution to the design and development of directional beam scanning antennas for millimeter wave communication systems, through three main advantages:

1. Frequency range and readiness for 5G and beyond applications

While Jiang et al.'s study focused on the X-band (8–12 GHz), which is less widely used in modern 5G technologies, the current study distinguished itself by targeting the frequency range 57.24–65.88 GHz, one of the officially approved bands for 5G and 6G applications, particularly in backhaul and optical line-of-sight wireless communication. This reflects a forward-looking and strategic approach that enhances the study's practical value.

2. Innovation in Design Methodology

Unlike other studies that relied on either traditional waveguide designs or LTCC techniques, the current study used a combination of wave optics and Fourier transform spectroscopy to develop fine-scale planar reflector gratings. This approach provides higher accuracy in radiation distribution, while reducing loss and achieving more consistent beam performance across different angles, a feat not achieved to the same degree by other studies.

3. Accurate Modeling and Experimental Validation

The current study performed advanced 3D electromagnetic modeling using CST Microwave Studio, followed by practical realization through the fabrication and testing of prototypes using a dedicated experimental setup. This complete design-simulation-fabrication-testing cycle confirms the reliability of the results and their superiority over some studies that relied solely on theoretical simulations or did not include full experimental validation.

4. Practicality and Flexibility

The proposed antenna system is capable of achieving wide-angle radial scanning without the need for active feed systems or moving elements, making it ideal in terms of energy efficiency and manufacturing simplicity. In contrast, active phased antennas, as in Jiang's study, require complex feed systems and precise control electronics, which increase cost, size, and heat loss

4.3 Discussion of the main results of the research

1) Different design concepts and technologies of modern scanning antennas designed for operation in millimeter-wave mobile communication systems are analyzed. The requirements for such antennas have been formulated. It was found that for new base stations and relay stations operating in accordance with the IEEE 802.11ad and IEEE 802.11ay standards, the visible variants are antennas with lenses made of homogeneous reflective flat reflective arrays and passive dissolve.
2) The calculation of the focal lens profiles was carried out using the geometric optics zoom. Using this approximation, original polyethylene lenses with bifocal optical sections (made of hyperbolic clips) and bifocal sections were developed. An annular bifocal lens with a single refractive surface was first proposed. As shown by the results of electromagnetic modelling, an antenna with this lens has a side lobe level 2-2.5 dB lower than a similar bifocal antenna with a bifocal lens with two refractive surfaces.
3) A prototype of a bifocal ring lens antenna with a frequency range of 57.24 - 65.88 GHz was designed and manufactured. The results obtained from electromagnetic modelling and measurements indicate that the use of this antenna in small relay stations located at a distance of 100-300 meters and at an altitude of 10-30 meters will improve the quality and reliability of data transmission in reconfigurable transport networks at speeds between 2.5 and 4.6 Gbps.
4) A prototype of a lenticular antenna intended for the 58–62 GHz band has been designed and manufactured. The results of electromagnetic modelling and experimental property studies have demonstrated that this FAR-shaped lenticular lens cooler exhibits a high capacity for wide-angle electronic scanning at the azimuth plane in a ±45° sector, with a weight of 900 grams, which is 2-2.4 times less than antennas with smooth (unallocated) lenses made of the same material and with similar lens capability. It can therefore be concluded that the utilisation of a lens antenna with specific lenses will permit the reduction in weight of 60 GHz relay stations transmitting data at speeds between 2.5 and 4.6 Gbit/s at distances between 100 and 300 metres, while maintaining the quality and stability of wireless communication between nodes of reconfigurable transport networks.
5) Native models of negative planar reflective gratings forming sector, pencil and Cosinean type DNs have been developed. The synthesis of reflection networks was conducted using an enhanced iterative method, wherein the reference amplitude DN belongs to the class of integer functions of the exponential type. Concurrently, the initial reference functions of phase diagrams were employed in the configuration of reflection networks for the first time in this study, enabling a more precise approximation of the intended shape of the primary beam. As demonstrated by the results of electromagnetic modelling in CST Microwave Studio, the main beam forms of antennas containing such reflective networks typically align with the specified reference mathematical models, thereby substantiating the efficacy of the proposed iterative method. Based on the developed models of planar reflective arrays, prototypes of scanning antennas for Internet access points and small relay stations for heterogeneous fifth-generation networks have been constructed and deployed, in particular, in large social infrastructure facilities.
6) Two prototypes of two scanning antennas with original planar reflective arrays were designed and constructed. One prototype was an analogue of a straight-focus mirror antenna, while the other was an offset antenna. As evidenced by the outcomes of electromagnetic modelling and measurements, these antennas are suitable for deployment in fifth-generation reconfigurable transport network applications, which necessitate the utilisation of cost-effective antennas with minimal mass and a planar form factor. This is particularly pertinent in the context of small 60 GHz relay stations, which facilitate the transmission of data at speeds between 2.5 and 4.6 Gbit/s over distances between 100 and 150 meters.

5. CONCLUSION

The scanning antenna prototypes produced in the course of the work meet the requirements of the IEEE 802.11ad and IEEE 802.11ay standards for transmit antenna equipment for base stations and relay stations in the 60 GHz band. The results obtained can be used in the design of integrated lenticular antennas as well as antennas with planar reflector arrays. The potential applications of the scanning antenna systems proposed in this work include base stations and relay stations in the 60 GHz band for high-speed data transmission over distances of 25-50 m and 100-300 m, respectively.

Conflicts Of Interest

The author's affiliations, financial relationships, or personal interests do not present any conflicts in the research.

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