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STEERABLE TOROIDAL BIFOCAL LENS-ARRAY ANTENNA IN 57–64 GHZ RANGE

Abstract

Introduction. *Currently, one of the most promising approaches to the development of 5th generation mobile wireless systems is the deployment of heterogeneous networks based on existing LTE cellular systems having both large and small cells. Small, low-cost relay stations equipped with highly directional steerable antenna systems to connect small cells with LTE base station serving macrocell can comprise the main elements of such networks.*

Objective. *Since existing solutions are either too expensive or do not allow the flexible rearrangement of current information transmission lines, the objective of this work is to develop antenna equipment for low-cost relay stations based on simple, steerable antenna systems of millimetre wavelength (57-64 GHz), which allow beamsteering on both azimuth and elevation planes.*

Methods and materials. *The developed steerable, bifocal lens antenna system comprises a specially-shaped lens made of high-molecular-weight polyethylene and integrated with a phased array antenna. A key feature of its design is a wide-angle beamsteering in the azimuth plane and ability to adjust the beam in the elevation plane. The calculation of the lens profiles was carried out by means of an approximation of geometrical optics in Matlab, while the main technical characteristics of the lens antenna system were obtained by direct electromagnetic modelling in CST Microwave Studio.*

Results. *A prototype steerable, bifocal lens-array antenna system has been developed and its characteristics studied. The following technical characteristics are achieved in the 57–64 GHz range: beamsteering in the elevation plane – ±3°; beamsteering in the azimuth plane – ±40°; antenna gain – from 20 to 27.5 dBi for all angles.*

Conclusion. *It is shown that the developed antenna system can be successfully used as a component of the receiving and transmission equipment of small relay stations that transmit information in the frequency range of 57-64 GHz over a distance of 100-300 m.*

Keywords: bifocal lens antenna, millimetre band, phased array, scanning, radiation pattern

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СКАНИРУЮЩАЯ ТОРОИДАЛЬНО-БИФОКАЛЬНАЯ ЛИНЗОВАЯ АНТЕННАЯ СИСТЕМА ДИАПАЗОНА 57–64 ГГЦ

Аннотация.
Введение. *В настоящее время одним из перспективных подходов к построению систем мобильной радиосвязи пятого поколения является развертывание неоднородных сетей на основе существующих систем сотовой связи LTE с большими и малыми сотами. Основными элементами таких сетей могут стать небольшие дешевые релейные станции, оснащенные высоконаправленными сканирующими антенными системами для связи малых сот с базовой станцией LTE, обслуживающей макросоту. Существующие решения во многом слишком дороги или не позволяют гибко перестраивать используемые линии передачи информации.*
Цель работы. *Разработка антенного оборудования для дешевых релейных станций на основе простых сканирующих антенных систем миллиметрового диапазона длин волн (57…64 ГГц), позволяющих управлять главным лучом в двух плоскостях: азимутальной и угломестной.*
Материалы и методы. *Профиль линзы из высокомолекулярного полиэтилена был рассчитан в приближении геометрической оптики в MATLAB. Основные технические характеристики линзовой антенной системы получены прямым электромагнитным моделированием в CST Microwave Studio, а также в ходе экспериментальных исследований с помощью вспомогательной антенны с высоким коэффициентом усиления, расположенной в дальней зоне.*
Результаты. *Разработан и создан прототип сканирующей бифокальной линзовой антенной системы, представляющий собой линзу специальной формы из высокомолекулярного полиэтилена, интегрированную с плоской фазированной антенной решеткой. В диапазоне рабочих частот 57…64 ГГц достигнуты следующие технические показатели: углы сканирования в угломестной плоскости ±3°, в азимутальной плоскости ±40°, коэффициент усиления антенной системы для всех углов сканирования находится в пределах 20…27.5 дБи.*
Заключение. *Разработанная линзовая антенная система может найти практическое применение в качестве приемо-передающего антенного оборудования небольших релейных станций, осуществляющих передачу информации в частотном диапазоне 57…64 ГГц на расстояния 100…300 м.*

Ключевые слова: бифокальная линзовая антенна, миллиметровый диапазон, фазированная антенная решетка, сканирование, диаграмма направленности

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Источник финансирования. Инициативная работа.

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Introduction. Current 4th generation broadband high-speed cellular network (WiMAX-Advanced IEEE802.16m [1], [2], LTE-Advanced 3GPP LTE Rel.10 [3]) systems, as well as wireless Internet access Wi-Fi (IEEE 802.11 ac [4], [5] and IEEE 802.11ad [6]) standards, use highly efficient noise immunity coding methods, new types of broadband modulation (OFDM, OFDMA, MIMO-OFDM, etc. [7]) and various space-time signal processing algorithms to fully utilise channel capacity. However, even when fully deployed, these modern mobile wireless systems cannot meet rapidly growing user demand. Therefore, finding new ways of increasing the capacity of existing mobile terrestrial radio systems becomes a very important task [8].

One of the most promising approaches in the development of 5th generation mobile wireless systems is the deployment of heterogeneous networks based on existing LTE cellular systems. Here it is assumed that small cells with coverage of several tens of metres will be additionally placed in LTE macrocell coverage areas having a high concentration of users (hotspots) [8]. In this case, the ability to transfer a large amount of data from base stations serving small cells to macrostations is carried out by means of a reconfigurable backbone network of small relay stations providing a data transfer rate up to several tens of gigabits per second.

New millimetre wave Wi-Fi systems support these data transfer rates [9], [10]. However, in order to use these standards in relay stations, it is necessary to increase the transmission distance up to 100…300 m. Thus, one of the key elements of future heterogeneous 5th generation cellular backbone networks is small low-cost relay stations equipped with highly directional steerable antenna systems.

Existing solutions based on multi-element phased array antennas (PAA) are expensive [11], and commonly used parabolic antennas and reflective array antennas [12] require precise installation and not allowing flexible rearrangement of current information transmission lines. In the present work authors propose to use toroidal bifocal lens antennas for such relay stations, since they have a sufficiently high gain and allow wide-angle beamsteering in the azimuth plane [13], [14]. However, their application is limited to relay stations with antennas of approximately the same height due to their inability to adjust the beam in the elevation plane.

The objective of this work is to develop steerable toroidal bifocal lens-array antenna integrated with a primary radiation source in a form of a small planar phased array antenna, which elements form separate PAA subarrays (modules). Measurements showed that the developed lens-array antenna can be successfully used as receiving and transmission antenna equipment of small relay stations that transmit information between backbone network nodes of heterogeneous cellular systems over a distance up to 300 m.

Development of a dielectric toroidal bifocal lens for a steerable antenna. The main requirements for the developed lens antenna system are high gain, allowing data transmission over a distance of several hundred meters in the millimetre wavelength range, and wide-angle beamsteering in the azimuth plane and ability to adjust the beam in the elevation plane.

The solution of the task is achieved by combining a primary radiation source in a form of a small planar PAA with a passive focusing system in a form of a dielectric lens having a special toroidal bifocal shape. PAA consists of several horizontal modules, allowing wide-angle beamsteering in the azimuth plane. In order to preserve this property of the designed antenna system, the lens shape was formed by rotating its bifocal geometric profile around a vertical axis located near the radiation source. As a result, the lens has a toroidal shape.

A distinctive feature of bifocal lenses is a presence of two refracting surfaces and two perfect focus points [9]. When placing the phase centre of a radiation source in such a lens, a flat phase front forms having a certain inclination angle relative to the vertical plane. Thus, the desired beamsteering angle in the azimuth plane can be achieved by switching the PAA horizontal modules.

In the present work, calculations of a vertical bifocal lens profile were carried out analytically by means of geometrical optics approximation using the Gent-Sternberg method [9]–[12]. Radiation patterns (RP) of the developed lens antenna were calculated by direct electromagnetic modelling in CST Microwave Studio. For the purposes of the modelling, a horn antenna having an aperture size close to the size of the PAA subarrays was substituted for the radiation source in order to simplify the simulation and reduce the time requirement.

A high molecular weight polyethylene material was used in the production of the lens due to its availability, low cost and appropriate dielectric parameters. This material has a dielectric constant of $\varepsilon = 2.35$ and a low loss tangent $\operatorname{tg}\delta = 0.0006$. The other lens parameters were determined by the technical requirements for antenna gain and scanning angles. Thus, in order to provide antenna gain of about 25 dB and beamsteering in the elevation plane within ± 3° simultaneously with wide-angle beamsteering in the azimuth plane within ± 40°, the elevation aperture was set at 130 mm and the distance between foci was 10 mm. According to preliminary calculations, these lens antenna parameters should provide a stable connection to users at a distance of 100…300 m and precise RP main lobe electronic adjustment to receiving antenna heights in the elevation plane of the order of ±10...15 m.

In accordance with the Gent-Sternberg method [15]–[18], curves describing vertical cross sections of the external and internal refracting surfaces of the bifocal lens are approximated by following functions:

$$y(x) = (Ax + B)^k, \qquad (1)$$

where *A*, *B* and *k* are numerical coefficients depending on set parameters of the bifocal lens model (distance between foci, inclination angle of the flat phase front and the lens material). In (1), variables y and x are measured in millimetres.

Fig. 1 shows the vertical cross section of the bifocal lens with two refracting surfaces and two foci calculated in Matlab for the given set of parameters

$(n_e,\ n_l$ are refractive indices of the environment and the lens, respectively).

The external lens surface is described by a curve

$$y(x) = \pm(-730x + 85142)^{0.4}, \qquad (2)$$

and internal surface is given by an expression

$$y(x) = \pm(14124x - 984180)^{0.5}. \qquad (3)$$

Note, the presence of two refracting surfaces of the bifocal lens leads to additional reflections on the internal surface and within the lens, complicating the whole process of the lens antenna production and adjustment. It is known that when antenna elements are placed on a dielectric surface, the higher the permittivity, the more electromagnetic radiation "permeates" into the dielectric. In this case, the ratio of a radiation power directed inside the dielectric to the emitted radiation power is directly proportional to $\varepsilon^{3/2}$ [19]. This effect leads to a reflection coefficient decrease (back radiation level) in lens antennas with radiation sources located on the internal lens surface and can be successfully used in their design [20].

Fig. 1 shows that the internal surface considered lens described by Equation (3) can be approximated with high accuracy by a straight line (Fig. 1, 2). Consequently, the space between the radiation source located in $y = 5$ (upper focus) or $y = -5$ (lower focus) and the lens is filled with polyethylene so that antenna elements can be placed on the superficies of the lens. The numerical calculations showed that for this purpose a distance between the radiation source (focal axis) and lens external refracting surface described by Equation (2) should be increased by 38 mm.

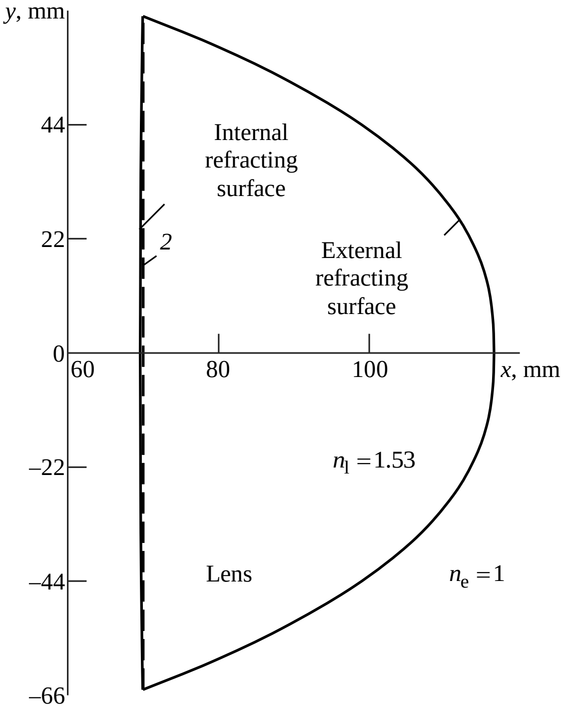

Fig. 1. Vertical cross section of a polyethylene bifocal lens calculated in MATLAB

A 3D model of the toroidal bifocal lens designed in accordance with the described methodology, along with its vertical cross section, are shown in Fig. 2 and 3, respectively.

Fig. 4 shows the antenna RP $D(\theta)$ (θ is an elevation angle) when between the radiation source located in the lower focus and the lens there is an empty space (Line 1; vertical cross section is shown in Fig. 1), as well as when the radiation source is located on the superficies of the lens (Line 2; vertical cross section is shown in Fig. 3). Fig. 4 shows that filling the space between the radiation source and the

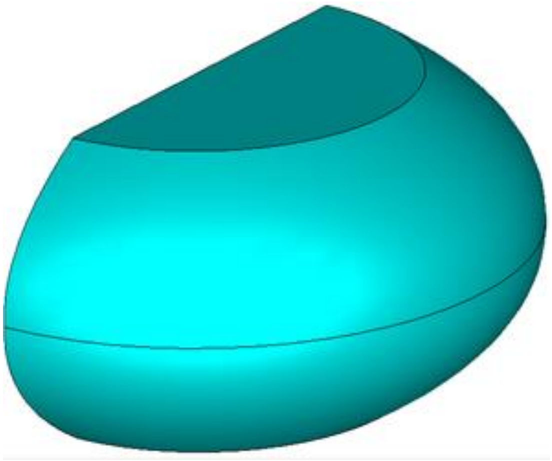

Fig. 2. 3D model of a toroidal bifocal lens

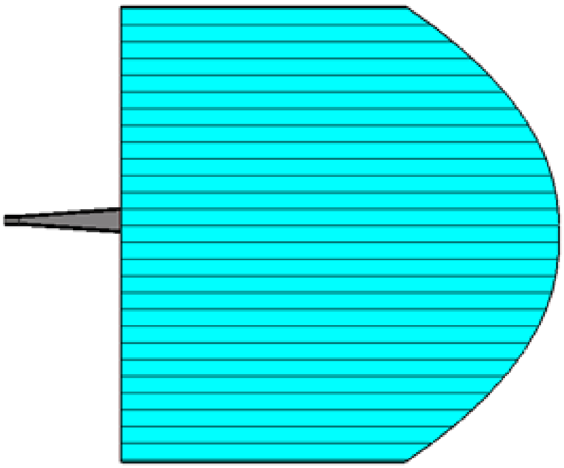

Fig. 3. Vertical cross section of a toroidal bifocal lens

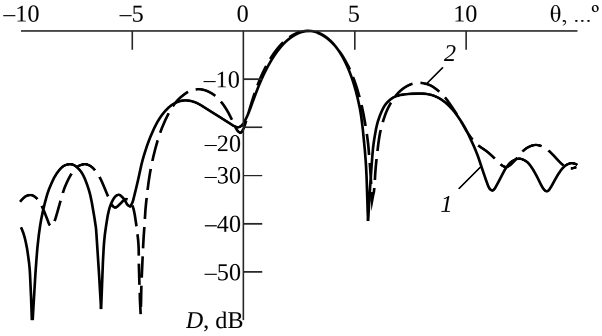

Fig. 4. Radiation patterns of a bifocal lens antenna with one and two refracting surfaces when a primary radiation source is located in the lower focus

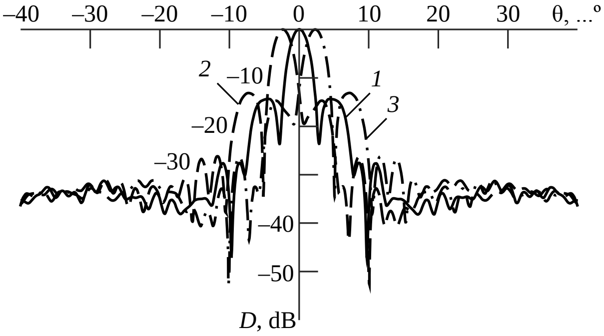

Fig. 6. Radiation patterns of a toroidal bifocal lens antenna with one refractive surface in a vertical plane (electromagnetic modelling results)

lens with polyethylene leads to a slight decrease in intensity in the side lobes without distorting the formed flat phase front, which is caused by the rather narrow RP of the used radiation source (PAA subarray) in the elevation plane (about 60...70°).

Figs. 5 and 6 show the RP of the designed 3D model of a toroidal bifocal lens antenna in horizontal (φ is an azimuth angle) and vertical planes, respectively. Radiation patterns are calculated by electromagnetic modelling in CST Microwave Studio. The RP in the horizontal plane (Fig. 5) is given for the primary radiation source location on the axis of symmetry between the foci. The RP in the vertical plane (Fig. 6) is given for the primary radiation source location in the upper (Line 2) and lower (Line 3) foci, and in the centre point between them (Line 1). As can be seen from Figs. 5 and 6, the developed model of the toroidal bifocal lens antenna is characterised not only by the formation of a narrow beam having a width of about 3° in the vertical plane, but it also exhibits some aplanatism, i.e. ability to change the direction of the emitted radiation according to the primary radiation source offset relative to the focus. In the horizontal plane, a beam having a width of about 12° is formed; its shape coincides with the RP of the primary radiation source.

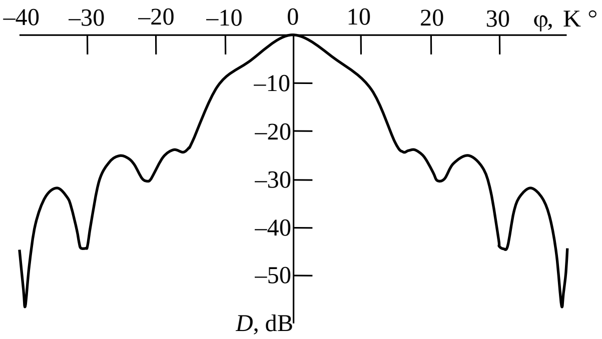

Fig. 5. Radiation pattern of a toroidal bifocal lens antenna with one refractive surface in the horizontal plane (electromagnetic modelling results)

Experimental prototype. An experimental prototype was developed (Fig. 7) for practically testing the technical characteristics of the designed lens antenna system. The prototype includes the polyethylene lens *1*, primary radiation source (PAA) *2*, metallic heatsink *3* for removing heat from the PAA and plexiglass housing *4* fixing the PAA on the back side of the lens.

The radiating PAA is inserted into the plexiglass housing with the lens tightly affixed to one side of it and the heatsink to the other. All of these elements together constitute a single structure. The sizes of the heatsink, plexiglass housing and mounting screws are reduced to minimise their impact on the characteristics of the calculated lens antenna. The lens is manufactured on a CNC machine adapted for plastics processing.

A microstrip antenna developed by Intel (Fig. 8) was used as the radiating PAA. It integrates the array antenna and radio part produced by using CMOS technology [21]. The array antenna contains 2×10 patch antennas, 16 of which are active and form the RP antenna array (2×8 patch antennas inside a dashed line in Fig. 8), while the remaining four patch

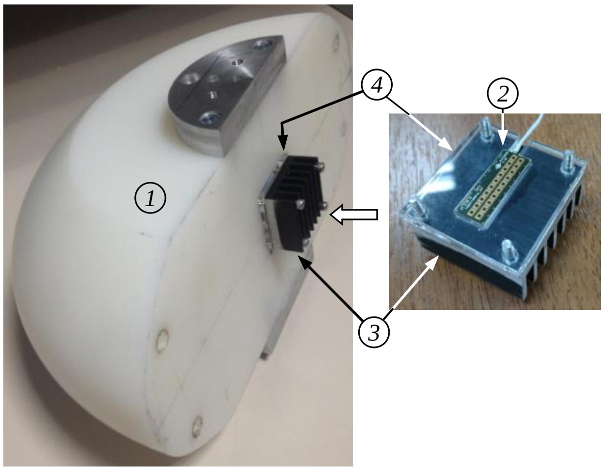

Fig 7. Experimental prototype of toroidal bifocal lens antenna system (*1* – toroidal bifocal polyethylene lens; *2* – phased array antenna; *3* – metallic heat sink; *4* – plexiglas housing)

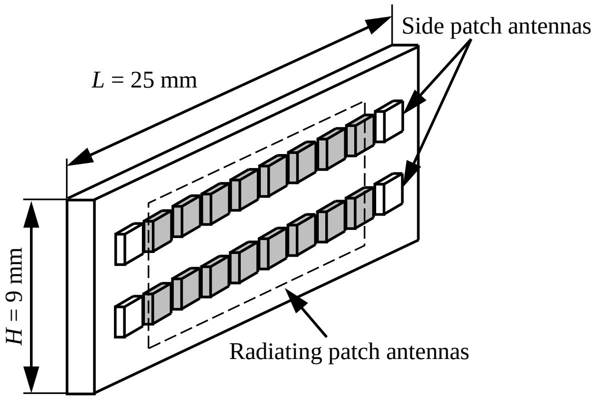

Fig 8. Radiating microstrip PAA

antennas located along the edges are passive. The radiating PAA has a linear polarisation in the vertical plane. PAA gain is about 15 dB.

The single-module PAA was used for the prototype studies allowed beamsteering to be performed in the elevation plane by mechanically moving the radiation source in the focal plane with discrete steps of 5 mm. For these purposes, additional mounting holes located 5 mm apart from each other are made in the plexiglass housing. The distance between the mounting holes is selected considering PAA size. The prototype also includes other elements necessary for its attachment to a measuring setup.

Description of the experimental setup and measurement technique. The measuring setup (Fig. 9) was developed in order to measure the characteristics of the designed steerable lens antenna system prototype (SLAS).

The measuring setup consists of the following basic units:

– positioner controlled by a personal computer (PC);

– universal spectrum analyser (SA) E4407B of the company "Agilent Technologies";

– frequency converter (FC) 11970V of the company "Agilent Technologies";

– highly directional receiving antenna (HDRA);

– specially developed software providing automatic measurements of antenna characteristics.

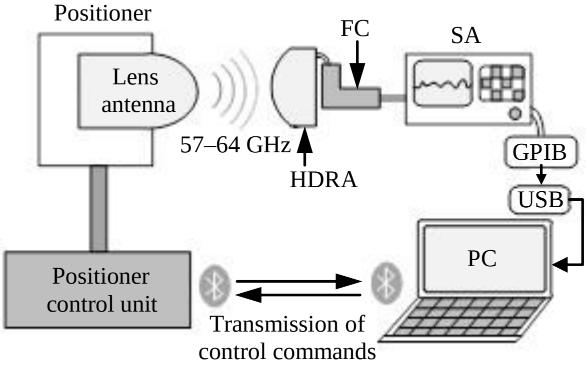

Fig 9. Block diagram of the measuring setup

The described experimental setup together with calibrated antennas allows the main characteristics of the developed SLAS prototype – i.e. two-dimensional RP, directivity, gain and frequency characteristics of the antenna – to be measured.

The operating principle of the measuring setup is described as follows. In accordance with user settings in the specially developed PC software, the positioner sequentially rotates the studied antenna in azimuth and elevation planes in angular ranges according to predetermined steps. During testing, the antenna operates in active signal transmission mode. The HDRA is used to increase the setup sensitivity and compensate for signals reflected from local objects. The signals received by HDRA in the 57…64 GHz range are converted to a frequency range suitable for the SA using a frequency controller (FC). The SA records the total power and input signal spectrum from the studied lens antenna at each measurement step. Recorded data are transmitted via GPIB-USB interface to a PC control program and stored in ROM for further processing.

Mechanical actuators of the positioner are controlled remotely by a PC program via a Bluetooth wireless channel allowing the use of the experimental setup for further field tests. Data exchange between the PC control program and the spectrum analyser is performed via the GPIB interface by using appropriate commands. The synchronisation of rotations of the studied antenna with the measuring process of the total power and spectrum of the SA input signal is provided by the algorithm of the PC control program.

Results of the experimental measurements. The measurements of the RP in the azimuth and elevation planes were carried out during the experimental study of the SLAS prototype. First of all, the measurements in two different positions of the PAA beam (two PAA sectors) were carried out in order to verify the correct lens antenna operation.

Fig. 10 and 11 show the measured RP when the PAA beam is located in the central position. The measurement results show that the RP half-power beamwidth is 2.5° in the elevation plane (Fig. 10) and 11° in the azimuth plane (Fig. 11).

Fig. 12 and 13 show the measured RP of the lens antenna system when the PAA beam is shifted at a maximum angle of –40 ° in the azimuth plane. In this case, the RP undergoes distortions leading to a widening of the main lobe. In this case, the RP half-power beamwidth is 3.8° in the elevation plane (Fig. 12) and 15° in the azimuth plane (Fig. 13).

In accordance with estimations of the RP measurements, it was found that the total gain of the developed SLAS is about 27.5 dBi when the PAA beam is located in the central position, while the radiation efficiency is about 80%. Considering that the radiating PAA gain is 15 dBi, it is possible to estimate the additional gain of the developed toroidal bifocal lens to be about 12.5 dBi.

During the next stage of the experimental studies, the specially developed software was used to switch between the spatial positions of the PAA RP main lobe in order to study the SLAS prototype beamsteering properties in the azimuth (horizontal) plane. This software allows the required angular range in the azimuth plane to be set within ±40°.

Fig. 14 shows the measured RP of the SLAS prototype in the azimuth plane for various positions of the PAA RP main lobe. It can be seen that the developed antenna system allows beamsteering in the azimuth plane with keeping the RP shape of the antenna. The gain degradation at maximum angles is about –7.5 dB compared to the antenna gain when the PAA beam is located in the central position. The maximum gain is obtained when the PAA beam is not shifted and it is 27.5 dB, and the minimum gain of the developed SLAS prototype is about 20 dB over the entire scanning range (±40°).

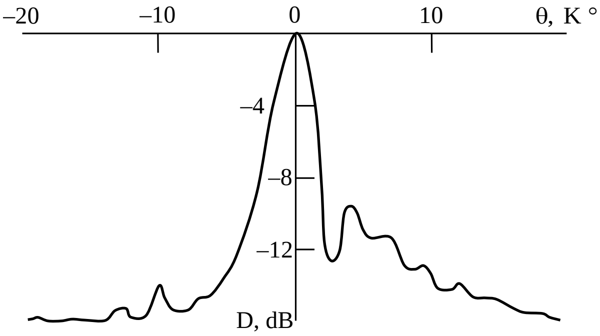

Fig. 10. Radiation pattern of the lens antenna prototype in the elevation plane when the PAA beam is located in the central position

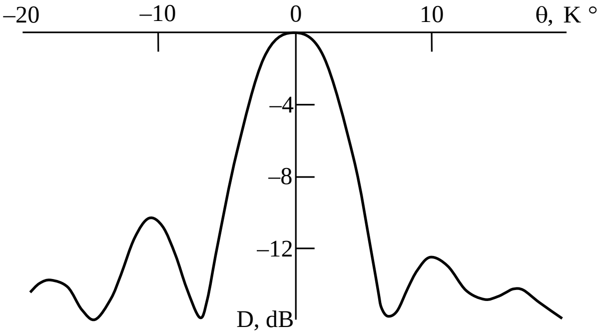

Fig. 11. Radiation pattern of the lens antenna prototype in the azimuth plane when PAA beam is located in the central position

During the next stage of the experimental investigation, the SLAS prototype beamsteering properties in the elevation (horizontal) plane were studied. In order to verify the correctness of the dielectric lens operation as a bifocal surface in a vertical plane, the radiating PAA was located in three positions: in the lower and upper foci of the dielectric lens, as well as in the centre point between them. For all three described positions of the radiating PAA, RP measurements were carried out in the elevation plane, both with a step of 0.2° and when the PAA beam was located in the central position in the azimuth plane. From the normalised RP shown in Fig. 15, it can be seen that the overlaps in the elevation plane between adjacent lobes occur at levels less than –3 dB, while the degradation of lobes does not exceed –0.6 dB when the radiating PAA is located in the lower and upper foci in contrast to the case when the PAA beam is located in the central position.

The figures also show that the beamsteering of the developed SLAS prototype in the elevation plane (at a

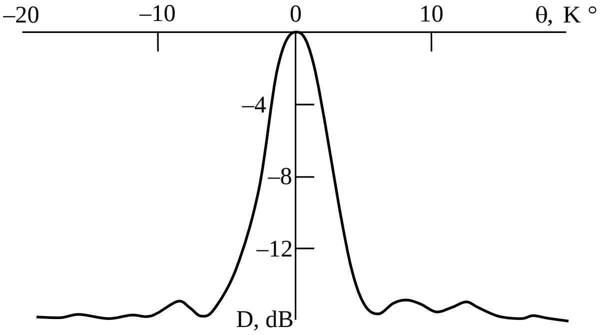

Fig. 12. Radiation pattern of the steerable lens antenna prototype when the PAA beam is shifted at an angle of –40° in the elevation plane

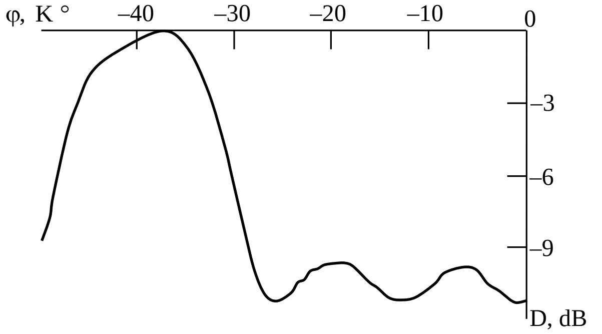

Fig. 13. Radiation pattern of the steerable lens antenna prototype when the PAA beam is shifted at an angle of –40° in the azimuth plane

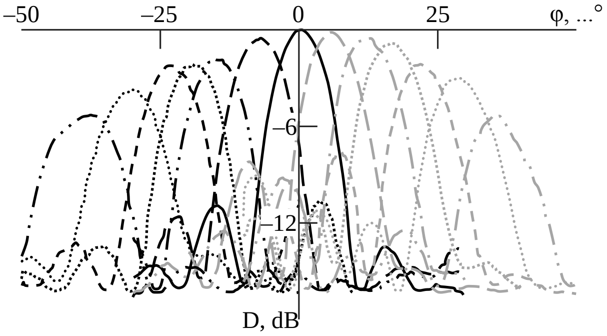

Fig 14. Radiation patterns in the azimuth plane for various PAA positions

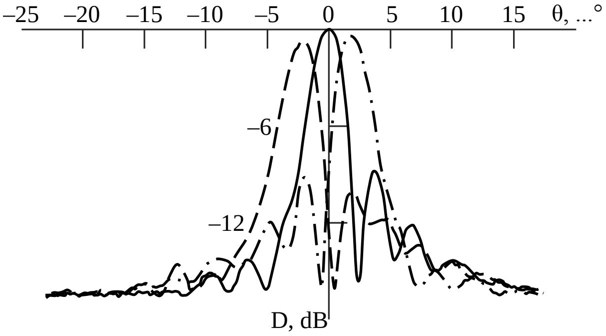

Fig 15. Radiation patterns in the elevation plane for various PAA positions

level of –3 dB) is ± 3º. The principal characteristics of the SLAS prototype are given in Table.

The main characteristics of the SLAS prototype

Characteristic	Value
Material	Polyethylene
Elevation aperture, mm	130
Azimuth aperture, mm	302 (2×151)
Distance between foci, mm	10
Gain, dB	27.5
Radiation efficiency, %	80
Directivity, dB	28.5
Main lobe width in elevation plane, ...°	3.1
Main lobe width in azimuth plane, ... °	12
Beamsteering in elevation plane, ... °	±3
Beamsteering in azimuth plane, ... °	±40
Side lobes level, dB	–8

Conclusion. In this work, we present the results of the development and experimental studies of the characteristics of a steerable bifocal lens antenna system prototype in the 57…64 GHz range. It is shown that the measured characteristics of the lens antenna prototype meet the requirements imposed on the designed antenna system and are consistent with the results of electromagnetic modelling in CST Microwave Studio. The following technical characteristics are achieved for the developed toroidal bifocal lens antenna prototype in the 57…64 GHz range: beamsteering in the elevation plane is ±3º (at a level of –3 dB), while beamsteering in the azimuth plane is ±40º. The antenna gain is from 20 to 27.5 dBi over the entire scanning range.

The achieved technical characteristics in beamsteering and antenna gain indicate the significant advantages of the proposed lens antenna system compared to existing solutions [13], [14], [20], [21]. It is demonstrated that the bifocal lens antenna system can be successfully used as receiving and transmission antenna equipment of small relay stations that operate in the frequency range of 57…64 GHz over a distance of 100…300 m.

Further research in this field should be aimed at optimising the shape of the bifocal lens in order to reduce its weight and additional losses, as well as at improving of the antenna system design as a whole to achieve better technical characteristics.

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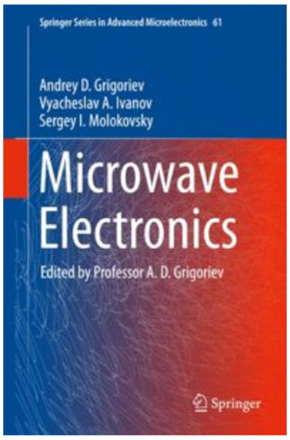

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This book describes the physical basis of microwave electronics and related topics, such as microwave vacuum and microwave semiconductor devices.

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