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A high-gain steerable reflective array antenna for V-band wireless communications

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Abstract

Problem statement. To fully utilize the millimeter wave spectrum in 5G systems, it is planned to adopt a heterogeneous network (HetNet) architecture, in which modern 4G Internet access technologies operating within bands below 6 GHz are integrated with new broadband communication systems of the millimeter wavelength range. However, the deployment of heterogeneous networks in urban conditions that are difficult for the propagation of millimeter-wave radio signals imposes special requirements on antenna systems. Therefore, the development of cheap millimeter-range scanning antennas with a high gain and a working frequency band of several gigahertz is an urgent task.

Objective. The main purpose of this work was to develop a scanning antenna system of the 60 GHz band with a planar reflector combined with a compact phased array antenna (PAA) module.

Results. The measurement results have shown that the developed reflective array 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 20.1–24.5 dBi and is capable of performing electronic beam scanning in the azimuthal plane in the $\pm 15^\circ$ sector. Moreover, the simulation results have shown that the full coverage sector in the azimuthal plane may potentially amount to $\pm 35^\circ$.

Practical significance. The use of such antennas at both ends of reconfigurable relay communication lines will allow data to be transmitted over a distance of 100–150 m at a speed of 2.5–4.62 Gbps.

Keywords

Reflective array antenna, phased array antenna, electronic beam scanning, millimeter wave range

For citation

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Introduction

One of the promising approaches to the construction of fifth-generation mobile communication systems (5G) is the deployment of heterogeneous networks (HetNet), in which modern 4G Internet access technologies operating within bands below 6 GHz are integrated with new broadband communication systems of the millimeter wavelength range [1–2]. It is assumed that microcells with a radius of several tens of meters will be located in the coverage areas of macrocells in the places of the largest concentration of users (hot-spots). At the same time, the transmission of a large amount of data between the basic macro and micro stations will be carried out using a reconfigurable backhauling network of small millimeter-wave relay repeaters that provide data transmission at a speed of several gigabits per second.

The deployment of heterogeneous networks in urban conditions that are difficult for the propagation of millimeter-wave radio signals imposes special requirements on antenna systems. The antennas used at base stations and access points should have a gain of at least 20 dBi so that the range of high-speed radio communication was 100–300 m. Another important requirement imposed by the developers of 5G networks for the receiving and transmitting equipment is the presence of electronic beam scanning. The ability to switch the beam quickly will allow communication systems to adapt flexibly to changing reception and transmission conditions. Therefore, the development of cheap millimeter-range scanning antennas with a high gain and a working frequency band of several gigahertz is an urgent task.

It is well known that multi-element phased array antennas have a complex structure, low radiation efficiency, and high manufacturing cost. In this regard, alternative versions for scanning antennas have been proposed for applications of 5G standards. For example, papers [3–7] present lens antennas designed for base stations [3], access points [4–5], and relay lines [6–7]. The main disadvantage of such antennas is the large weight of the lenses.

Currently, there is a growing number of studies aimed at creating scanning antennas with flat reflective arrays, which combine the advantages of conventional reflectors and multi-element PAAs. Reflective arrays manufactured on cheap PCBs are capable of creating beams of the required shape like PAAs and at the same time have a convenient contactless power supply circuit, like conventional parabolic antennas.

There are various options for beam scanning reflective array antennas (RAA). For example, antenna systems with mechanical scanning are presented in [8–10]. In the first case, the beam was controlled by rotating full-metal elementary reflectors around their own axes. In the second case, the height of the patches above the grounded plane changed, and in the third case, the irradiator shifted relative to the focus points of the printed array. However, all antenna systems with mechanical scanning have a low beam switching rate.

The known narrow-beam RAA with electronic scanning built based on pin-diodes [11], thin-film barium strontium titanate (BST technology) [12], and liquid crystals [13]. The disadvantages of such antennas include high energy losses during reflection and the high manufacturing cost.

The main purpose of this work was to develop a scanning antenna system of the 60 GHz band with a planar reflector combined with a compact PAA. The possibility of electronic beam scanning in the azimuthal plane is implemented in the claimed antenna using PAA and a special configuration of the reflective array, which has the shape of a rectangular matrix with identical columns. The results of experimental studies have shown that the main advantages of the presented antenna are a wide operating band of 57.24–65.88 GHz (8.64 GHz band), a high gain up to 24.5 dBi, as well as the possibility of electronic beam scanning in the azimuthal sector $\pm 15^\circ$. Moreover, the simulation results have shown that the full coverage sector in the azimuthal plane may potentially amount to $\pm 35^\circ$. Therefore, the claimed solution may find its use in the new 5G applications.

Unit cell design and analysis

A typical planar reflector is an array of elementary reflectors printed on a dielectric substrate. Each elementary reflector (unit cell) consists of one or several thin metal plates (microstrip patches) located at a small distance from the screening plane [14–15].

An irradiator (primary radiation source) is an integral part of such antennas, as well as classical reflectors. However, unlike parabolic antennas, which transform the incident wave front due to the special shape of the reflector, the correction of the electromagnetic field phase in flat arrays is conditioned by the reflective properties of printed elements. The value of the phase correction depends on a large number of parameters, particularly, on the size and shape of the patch, the number of metallization layers used, as well as on the material and thickness of the dielectric substrate. Each elementary reflector should have a certain value of the complex reflection factor so that an amplitude-phase distribution corresponding to the radiation pattern of a given shape is generated throughout the entire aperture of the flat array. Therefore, the study of the reflective properties of a layered printed structure takes an important place in the design process of flat antenna arrays.

In this paper, the study of the reflective properties of flat printed structures with two, three, and four copper layers with a thickness of 0.018 mm (see Fig. 1) was carried out in the CST Microwave Studio software package at a frequency of 60 GHz for cells with transverse dimensions of 2.5×2.5 mm ($0.5\lambda \times 0.5\lambda$) and square patches.

Examples of the obtained dependences of the reflected wave phase on the size of the printed element (1st patch) are shown in Fig. 2.

According to the results of electromagnetic modeling of a two-layer cell (blue line in Fig. 2,*a*), with a decrease in the thickness of the dielectric substrate, on the one hand, the phase range of the reflected wave increases, on the other hand, the phase-dimensional specification becomes non-linear. In practice, this means that a minor change in the patch geometry will lead to a significant phase jump. The latter circumstance increases the requirements for the precision of manufacturing printed elements and makes the simplest single-layer structure unsuitable for antenna arrays in the 60 GHz band.

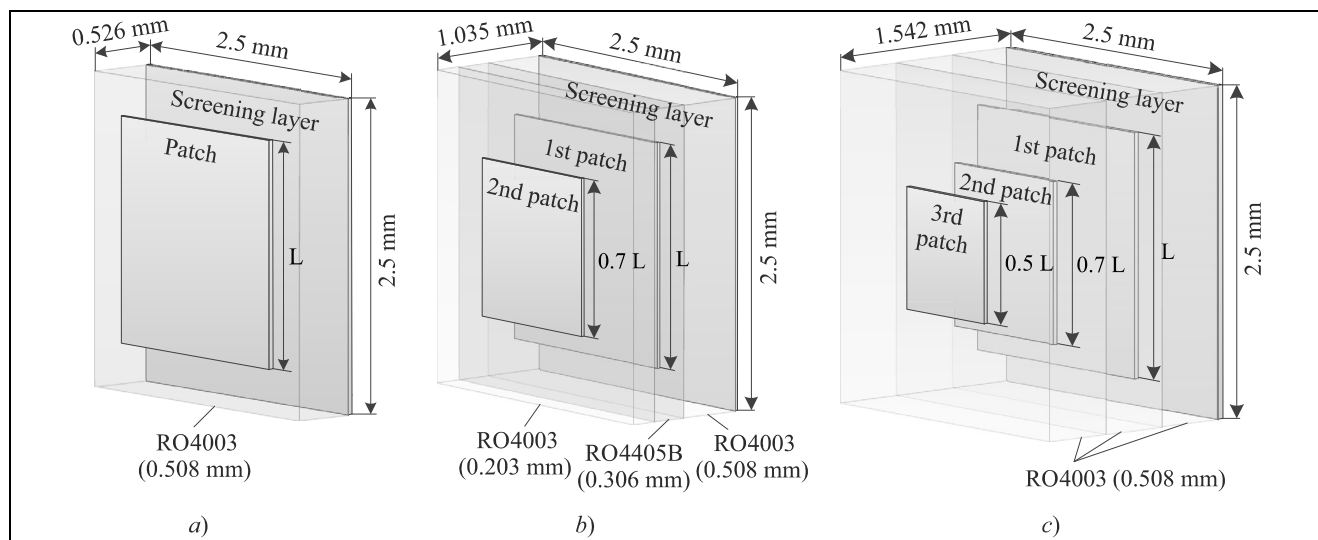


Fig. 1. Structures of the studied reflective cells: *a* – two-layer; *b* – three-layer; *c* – four-layer

Рис. 1. Структуры исследованных отражательных ячеек: *a* – двухслойная; *b* – трехслойная; *c* – четырехслойная

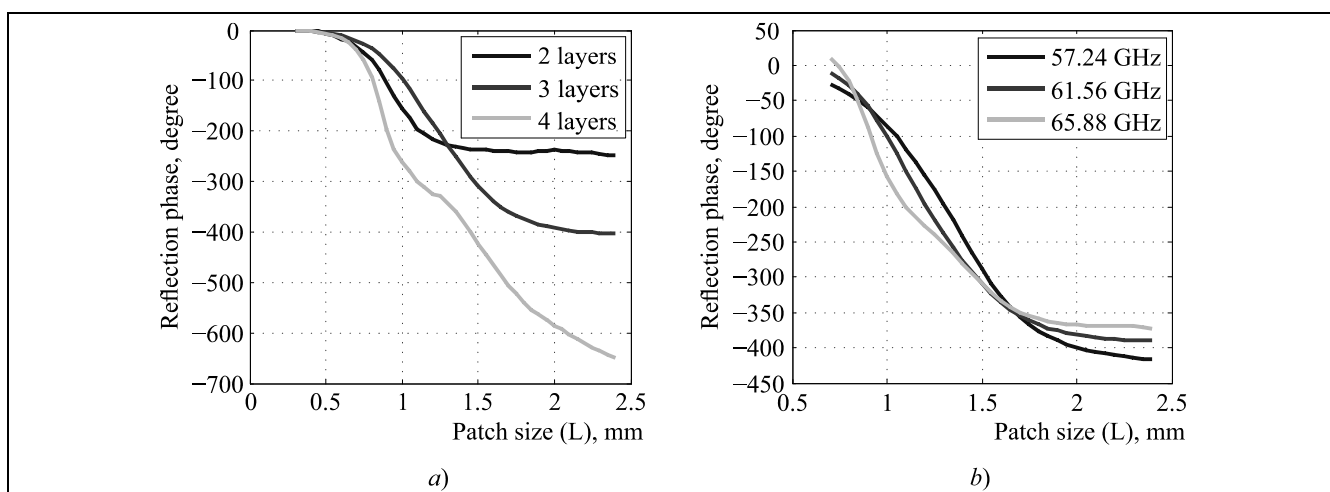


Fig. 2. Phase-dimensional dependences calculated for: *a* – cells with a different number of metalized layers; *b* – three-layer cell at different frequencies

Рис. 2. Фазоразмерные зависимости, рассчитанные для: *a* – ячеек с различным числом металлизированных слоев; *b* – трехслойной ячейки при различных частотах

One of the possible solutions to this problem is associated with an increase in the number of metalized layers in the reflective cell (see Fig. 1, *b* and 1, *c*). Typically, it is possible in this case to expand the phase range of reflection factors to values exceeding 360° , to obtain a relatively smooth phase distribution, and to increase the operating band of the antenna array [14]. Examples of phase-dimensional dependences obtained as a result of modeling for three- and four-layer structures are shown in Fig. 2, *a* with red and green lines, respective. Ideal specifications were obtained for a three-layer cell, in which the side ratio of the upper patch to the lower one is 0.7 (red line in Fig. 2, *a*).

Further, the frequency properties of a three-layer cell were studied. The results of electromagnetic modeling in CST Microwave Studio have shown (see Fig. 2, *b*) that the phase-dimensional dependence varies slightly within the band of 57.24–65.88 GHz, as envisaged by the IEEE 802.11ad and IEEE 802.11ay standards. For patches 0.7 to 2.4 mm in size, the maximum deviation of the phase value from the central curve calculated at a frequency of 61.56 GHz (red line in Fig. 2, *b*) does not exceed 60° . Therefore, a three-layer printed structure based on substrates RO4003 ($\epsilon = 3.55$, $\text{tg}(\delta) = 0.0027$) and prepreg RO4450B ($\epsilon = 3.3$, $\text{tg}(\delta) = 0.004$), as shown in Fig. 1, *b*, formed the base of a flat reflective array presented in the next section of this paper.

The prototype of the scanning RAA and measurement setup

The manufactured prototype of the scanning reflective antenna array of the 57.24–65.88 GHz band, as shown in Fig. 3, included a flat reflector in the shape of a printed circuit board (1), PAA (2) with a heat sink radiator (3), as well as various fasteners (4). An antenna module (chip) developed by Intel was used as the PAA [16]. This chip contained 2×8 active patches that formed main lobes with a half power beam width (HPBW) of 40°–60° in the elevation plane YOZ and 13°–15° in the azimuthal plane XOZ. The total azimuthal scanning sector was ±40°, and the maximum gain was about 15 dBi. Moreover, the entire operating band of the antenna module of 57.24–65.88 GHz in accordance with the IEEE 802.11ad standard was divided into four 2.16 GHz channels. During the measurements, a specific frequency channel and the spatial-angular sector of radiation were set using specialized software installed on a portable personal computer (PC).

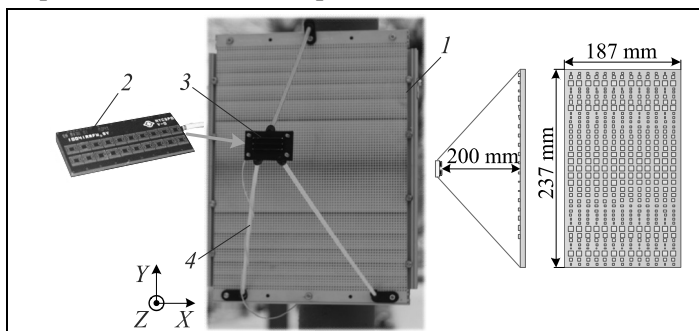


Fig. 3. Beam scanning RAA prototype: 1 – flat reflector, 2 – PAA, 3 – heat sink radiator, 4 – fasteners

Рис. 3. Прототип сканирующей антенны с плоским отражателем: 1 – плоский отражатель, 2 – ФАР, 3 – теплоотводящий радиатор, 4 – крепежные элементы

To preserve the scanning properties of PAA (2), an array of passive reflectors on the printed circuit board (1) was formed in the shape of a rectangular matrix with identical columns (see Fig. 3). Such a structure can be considered an analog of a classical cylindrical reflector that focuses the radiation of PAA in the elevation plane YOZ, without significantly distorting the shape of the beam in the azimuthal plane XOZ.

In this case, the configuration of all columns of the matrix was based on the principle of linear arrays. First of all, the phase distribution on the array elements required for the formation of a flat phase front in the elevation plane YOZ was calculated. In this case, the focal length was chosen to be 200 mm. Further, the sizes of patches were determined depending on their position within the vertical aperture of the columns, using a known phase-dimensional specification (red line in Fig. 2,a). The dimensions of the printed circuit board, the structure of which is shown in Fig. 1b, were limited by the process capabilities of the manufacturer and amounted to 187×237 mm.

The characteristics of the manufactured prototype of the scanning reflective antenna were experimentally studied using the measurement setup (see Fig. 4), the main elements of which were

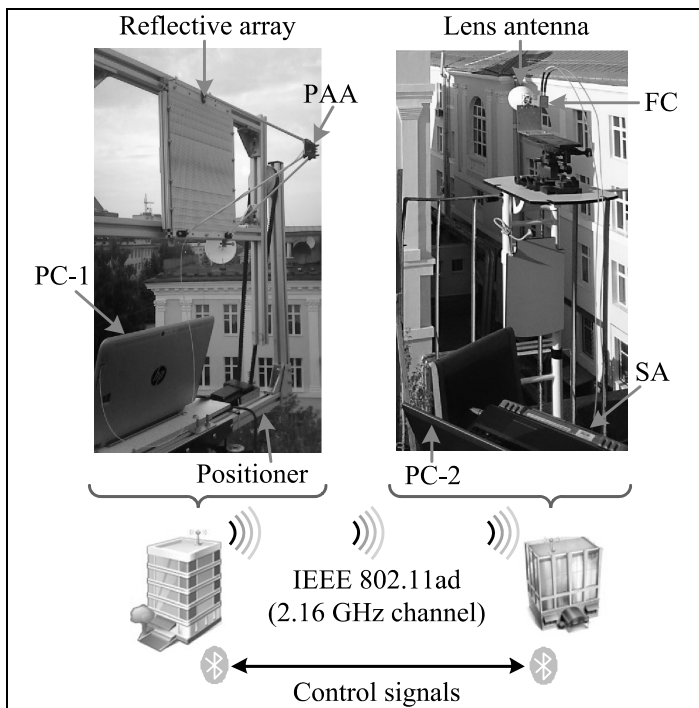


Fig. 4. Measurement setup

Рис. 4. Измерительная установка

1) tested antenna controlled by PC-1; 2) positioner controlled by PC-2; 3) receiving lens antenna with a gain of 34 dBi; 4) Agilent Technologies frequency converter (FC) 11970V; 5) Agilent Technologies universal spectrum analyzer (SA) E4407B. The operation principle of the measurement setup is given in [17].

The measurements were carried out in the far zone of the tested antenna. At the same time, the receiving and transmitting parts of the measurement setup were located at the same height but on different roofs of two neighboring buildings, the distance between which was 35 m (Fig. 4). The configuration of the communication line was selected in such a way as to avoid the occurrence of reflected signals that could have a significant impact on the experimental results.

4. Experimental results and comparison

During the measurements in each of the four frequency channels of the IEEE 802.11ad standard, radiation patterns (RP) of the single PAA and the RAA in the azimuthal and elevation planes were obtained. Fig. 5 shows the measured characteristics in solid lines and the results of electromagnetic modeling in CST Microwave Studio in dotted ones.

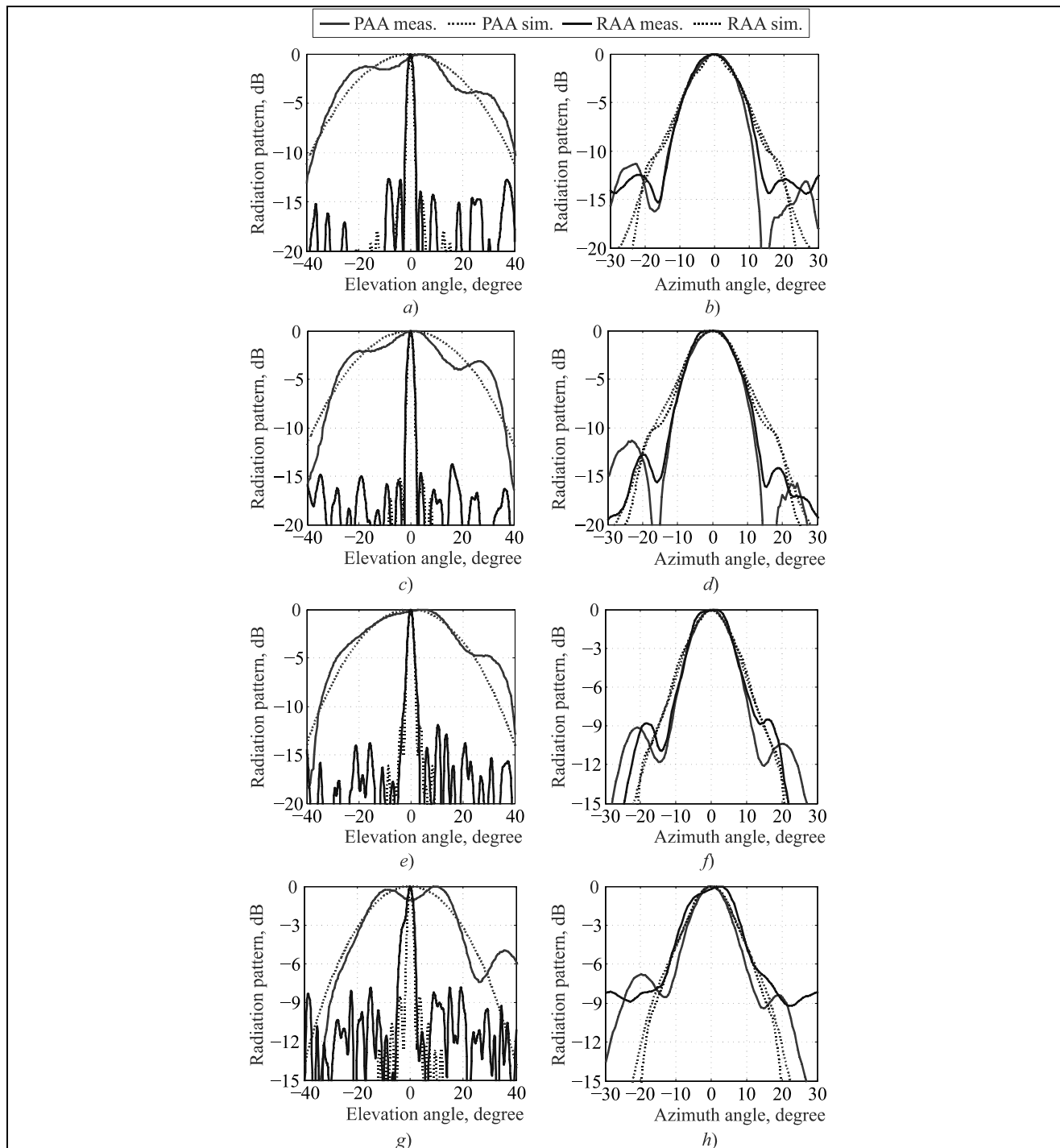


Fig. 5. RPs in the elevation (left) and azimuthal (right) planes, measured in four frequency channels of the PAA: *a, b* – channel 1 (57.24 – 59.40 GHz); *c, d* – channel 2 (59.40 – 61.56 GHz); *e, f* – channel 3 (61.56 – 63.72 GHz); *g, h* – channel 4 (63.72 – 65.88 GHz)

Рис. 5. ДН в угломерной (слева) и азимутальной (справа) плоскости, измеренные в четырех частотных каналах ФАР: *a, 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)

It should be noted that 3D electromagnetic modeling of a reflective antenna system with PAA required large computational costs, therefore, a special horn antenna with similar radiation specifications was used as an irradiator. The effectiveness of replacing PAA with a horn antenna during modeling is confirmed by the results of experimental studies of antennas previously developed by the author and presented in [6, 7].

As can be seen from the above dependencies, the reflective array focuses radiation well in the elevation plane in all four channels (the total band is 57.24-65.88 GHz). At the same time, the shape of the main beam in the azimuthal plane does not change substantially.

According to the assessments made when measuring the radiation pattern, the RAA prototype gain in the first frequency channel was 22.3 dBi, 24.5 dBi in the second one, 23.9 dBi in the third one, and 20.1 dBi in the fourth one. The different values of gain can be explained not only by the limited operating band of flat reflectors but also by the features of the PAA, the radiation parameters of which change slightly when switching from one frequency channel to another.

The possibilities of electronic beam scanning were assessed by sequentially switching the PAA between three azimuthal sectors, 0°, 10°, and -10° [17] (see Fig. 6).

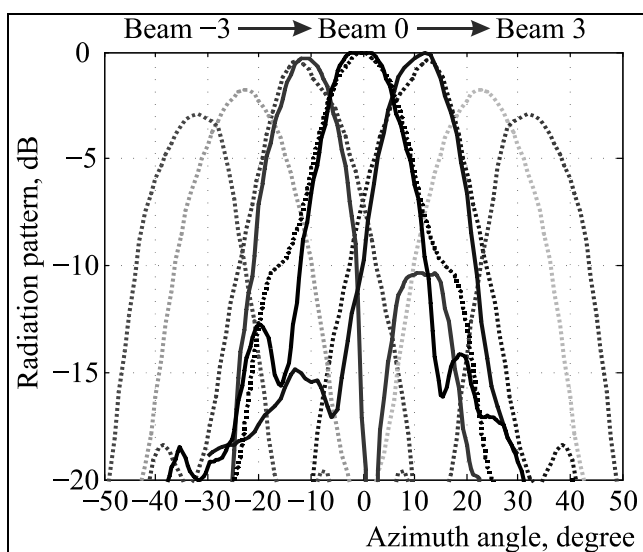


Fig. 6. RPs simulated and measured at different positions of the main beam of the RAA in the azimuthal plane.

Рис. 6. ДН, рассчитанные и измеренные при различном положении главного луча ФАР в азимутальной плоскости

According to the data obtained, the antenna gain was 24.2 – 24.5 dBi (measurements were carried out in the second frequency channel), and the full coverage sector in the azimuthal plane was ±15° (solid lines in Fig. 6).

At larger deviation angles of the main beam from the central position, rapid degradation of the gain was observed conditioned by the small width of the reflective array. This drawback will be eliminated in the next generation of prototypes. The results of electromagnetic modeling in CST Microwave Studio have shown (dotted lines in Fig. 6) that the coverage sector of the RAA may potentially amount to ±35°.

As can be seen from comparative Table, the proposed RAA combines many advantages. Particularly, the claimed solution has a simple design and low manufacturing cost. 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 24.5 dBi, and a moderately wide ±35° scanning sector.

Table. Comparison of the specifications of the manufactured RAA prototype with analogs

Specification	[8] ¹	[10]	[12]	[13]	[18]	This paper
Technology	Passive patches	Full-Metal elements	Barium strontium titanate	Liquid crystals	Passive patches	Passive patches
Aperture, mm ²	≈ 20000 ²	70×70	≈ 700 ³	75×75	93×93	187×237
Focal length, mm	≈ 115	40	≈ 70	75	46	200
Freq. band, GHz	31.63 – 33.17	24.7 – 30.0	31.5 – 32.5	22.1 – 26.1	40.0 – 41.5	57.24 – 65.88
Max. gain, dBi	30.71	18.9	8.3	20.2	27.4	24.5
Scan type	Mech.	Mech.	Elec.	Elec.	Mech.	Elec.
Scan range in A/E plane	±30°A	±60°/±60°	0° → +25°A	±45°/ ±45°	±7°/±7°	±15°A (±35°A) ⁴
Side lobe level, dB	-15	-8	-7	-3	-9	-8

Notes: ¹ – data is given for a quadrofocal antenna; ² – round aperture with a diameter of 17λ₀, where λ₀ ≈ 9.37 mm; ³ – rectangular aperture with a size of 3.8λ₀×2.1λ₀, where λ₀ ≈ 9.37 mm; ⁴ – simulation results

Conclusion

This paper presents an antenna system of the 57.24–65.88 GHz band with a high gain and an electronically controlled beam in the azimuthal plane, containing a reflective array and a compact PAA as an irradiator. The scanning properties of the PAA are implemented in the claimed antenna due to a special configuration of the reflective array that focuses the radiation in the elevation plane without significantly distorting the shape of the beam in the azimuthal plane. The simulation results and direct prototyping have proven the efficiency of such a solution. According to assessments obtained during experimental studies of lens antennas with similar radiation specifications [6], the data transmission rate in a reconfigurable network of relay stations located at a distance of 100–150 m from each other and containing proposed antennas can be 2.5–4.62 Gbps.

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Сканирующая антенна с плоской отражательной решеткой, предназначенная для беспроводных систем связи V-диапазона

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Аннотация

Один из наиболее перспективных подходов к построению систем мобильной связи 5-го поколения (5G) – развертывание гетерогенных сетей (HetNet), в котором современные 4G-технологии доступа в Интернет, работающие в диапазонах частот ниже 6 ГГц, интегрированы с новыми широкополосными системами связи миллиметрового (ММ) диапазона длин волн. Однако такой подход в городских условиях, сложных для распространения сигналов ММ-диапазона, предъявляет особые требования к антенным системам: антенны, используемые на базовых станциях и точках доступа, должны иметь высокий коэффициент усиления (КУ) в широкой полосе частот и обладать функцией электронного сканирования лучом.

В работе представлена сканирующая антенна диапазона 57,24–65,88 ГГц, содержащая плоскую отражательную решетку, изготовленную по печатной технологии, и облучатель в виде компактной фазированной антенной решетки (ФАР). Возможность электронного управления лучом в азимутальной плоскости реализуются в представленной антенне благодаря ФАР и особой конфигурации отражательной решетки. Массив пассивных отражателей на плоской печатной плате сформирован в виде прямоугольной матрицы с одинаковыми столбцами. Такую структуру можно считать аналогом классического цилиндрического отражателя, фокусирующего излучение ФАР в плоскости угла места без существенного искажения формы луча в азимутальной плоскости. Прототип антенны включает в себя плоский отражатель в виде печатной платы размером 187×237 мм (Ш×В), ФАР с теплоотводящим радиатором, а также различные крепежные элементы. В качестве ФАР, располагавшейся на расстоянии 200 мм от центра отражательной решетки, использован антенный модуль (чип), разработанный компанией Интел.

Проведенные измерения в рабочем диапазоне частот 57,24–65,88 ГГц, разделенном в соответствии со стандартами IEEE 802.11ad и IEEE 802.11ay на четыре канала шириной 2,16 ГГц каждый показали, что КУ изменялся от 20,1 до 24,5 дБи.

Возможности электронного управления лучом оценивались путем последовательного переключения ФАР между тремя азимутальными секторами 0, 10° и –10°. Согласно полученным данным полный сектор покрытия в азимутальной плоскости с учетом ширины лучей по уровню половинной мощности (–3 дБ) составил ±15°. При больших углах отклонения главного луча от центрального положения наблюдалась быстрая деградация КУ, которая обусловлена малой шириной отражательной решетки из-за ограничений по технологическим возможностям фабрики-изготовителя. Однако с помощью электромагнитного моделирования в программе CST Microwave studio установлено, что сектор сканирования спроектированной антенны в азимутальной плоскости потенциально может составлять ±35°.

Согласно оценкам, полученным в ходе экспериментальных исследований тороидально-эллиптических линзовых антенн со схожими характеристиками излучения, скорость передачи данных в реконфигурируемой транспортной сети из релейных станций, расположенных друг от друга на расстоянии 100–150 м и содержащих антенны предложенного типа, может составлять 2,5–4,62 Гбит/с.

Ключевые слова

Плоская отражательная решетка, фазированная антенная решетка, электронное сканирование, миллиметровый диапазон

Для цитирования

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