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# Estimation of the Parameters of Focused Beams at Short Distances for Antennas of Diffraction Radiation at the Millimeter-Wave Band

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**Abstract:** The article considers the results of experimental studies of the parameters of focused beams formed in W-band planar antennas of diffraction radiation using an axial dielectric lens and at focal lengths from tens of centimeters to several meters. The focusing of the beam was carried out utilizing a set of replaceable dielectric lenses with a calculated focusing distance of 1,5 m, 3 m, and 6 m. The focusing mode was also considered with two lenses installed in series, jointly providing focusing of the beam at a distance of about 0,8 m. Evaluation of the operating parameters of an electrodynamic system consisting of a planar dielectric waveguide and a planar diffraction grating both located near an inhomogeneity in the form of a dielectric layer with a variable profile (thickness), which is an axial dielectric lens, was the main aim of the researches, as well as the effect of this inhomogeneity on the quality of the formed focused beams under conditions of changes in the distance (depth of field) in the imaging mode, when the beam is inflected from the lens axis, as well as when the operating frequency changes over a wide range of values. In the course of the research, it was found that dielectric lenses with an axial profile made of high-quality polystyrene or PTFE provide the parameters of focusing antenna beams for the developed antennas of diffraction radiation following theoretical calculations, both in the focusing depth and in the mode of beam inflection from the lens axis up to  $\pm 9^\circ$  while changing the frequency in the range of 84÷100 GHz. In this case, the level of the measured side lobes in the generated beams practically did not differ from the similar values obtained for these antennas during their measurement in the open space (in the far-field zone). At a focal length of 75 cm, the transverse dimension of the focused beam was estimated as 3÷5 mm, which approximately corresponds to the radiation wavelength and demonstrates a high focusing quality approaching the theoretically possible diffraction limit and also indicates a weak influence of the inhomogeneity in the form of a dielectric lens on the electrodynamic properties of the antenna of diffraction radiation.

**Keywords:** Millimeter Wavelength Antenna, Antenna of Diffraction Radiation, Antenna Focusing Beam, Antenna Radiation Pattern, Millimeter Wave Measurements

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## 1. Introduction

Antenna systems in the millimeter-wave (MMW) band due to a number of their advantages (namely, relatively small dimensions, high directivity, a wide operating frequency band and the possibility of implementing fast observation modes) have attracted much attention from developers in recent years. MMW antennas of various types are used in

telecommunications, active and passive radars, radio vision, remote sensing, defense, security, etc. [1-5]. A promising field of application for MMW sensors and, accordingly, antennas of this band is an observation of objects located at a short distance - from tens centimeters to several meters from the antenna that corresponds to their location in the near-field zone or at the border of the transition between the near-field and far-field zones of radiation. Such a mode of

operation is necessary, for example, when solving problems of non-destructive technological control, when measuring the parameters of various materials, during medical diagnostics, when creating security systems, etc. All these areas utilize imaging with a high spatial resolution at short distances to an object. These conditions require the antenna to form focused beams with a field spot size in the caustic in the scope of  $2\div 10$  wavelengths of radiation. For example, such beams can be formed when implementing a circular flat focused aperture with a diameter of at least  $130\div 150$  wavelengths.

When solving this circle of problems, a responsible stage is a selection of the MMW antenna type. The horn or the mirror-type structures are unacceptable for imaging tasks at short distances for several criteria. The phased antenna arrays (PAA) can provide the required characteristics since they have a flat surface of the emitting aperture and a small depth, which depends on the construction scheme and the set and arrangement of functional elements. Considering the electrodynamic characteristics of an antenna array, that is important to note the ability to realize electrical control of the location of the antenna pattern (AP) in space or frequency scanning of the AP in a broad sector of observation angles [2, 5].

Until now development of highly efficient PAA of MMW (up to 100 GHz) and sub-millimeter (from 100 to 300 GHz) frequency bands has been a rather complicated task. Elements used in the PAA (controlled phase shifters and attenuators, microstrip or waveguide transmission lines and their connections) have significant losses, amounting to several dB per element, instability of characteristics, etc.

The class of leaky wave antennas [5], as well as the Antennas of Diffraction Radiation (ADR) close to them in terms of physical principles of operation [6, 7] should also be classified as MMW antennas with the properties necessary for forming images at short distances. These antennas have a flat configuration of the emitting / receiving aperture and small depth, providing the possibility of frequency control of the position of the beam pattern in space and allowing, based on these properties, to form multi-beam patterns [8].

For a flat antenna, the mode of a beam focusing at a small distance can be reached by quasi-optical methods by installing a focusing lens in the near zone of the antenna or electro-dynamically by forming the required phase distribution of the electromagnetic field in the antenna aperture [1, 9].

The first method is the most frequently utilized because it is simple, cheap, and makes it easy to adjust and change the focal length depending on the needs. At the same time, the focusing lens introduces additional energy losses, which reduces the efficiency (potential) of the system, and also, when operating in the sector of angles and frequency band, can introduce unaccounted phase distortions that cause additional aberrations that degrade the quality of the focused beam.

New low-loss dielectric materials and modern technologies of fabrication expand the fields of application of focusing lens antennas and can improve their electrodynamic characteristics. These, first of all, include the technology for focusing lenses manufacturing using 3-D printing that allows making a prototype of a lens with any geometric profile using

one technological operation, which significantly reduces the cost of the antenna system [10-12]. All these increase interests in the creation of new antenna structures that include dielectric lenses and stimulate their use in solving a wide range of practical tasks [9].

In the order of R&D of the MMW antennas in recent years, devices that allow combining various technical solutions have been of great interest. Suchlike antennas include the ADR for which the receiving area is forming due to a two-dimensional electrodynamic system of leaky surface waves based on a diffraction grating [7]. The advantage of such antennas is the small thickness of the receiving or emitting electrodynamic system, which makes them similar to flat antenna arrays. With that, the distribution of energy over the aperture provided using quasi-optical methods that, in comparison to the phased arrays, reduce losses notably in the feeder path and reduce the complexity and cost of the antenna.

ADR initially uses the effects of scattering of electromagnetic waves and the subsequent phase superposition of the components of the scattered field in a dielectric waveguide associated with a diffraction grating. These features potentially affect the phase distribution of the electromagnetic field. As a sequence, that depends on the side lobes level, when the observation angle change, and when the operating frequency change. The phase distribution of the field inside the aperture may be disturbing because the structural elements of the antenna placing near the specified electrodynamic system. Some distortions in the generated amplitude-phase distribution (APhD) can introduce inhomogeneity present as a dielectric layer with a variable profile, which forms a focusing dielectric lens. Therefore, assessments of the quality of the generated APhD for ADR are of significant interest, based on the influence of scattering effects on the main parameters of the ADR and the need to assess the possibilities of using such antennas in the beam-focusing mode when creating imaging systems.

The article discusses the results of experimental studies and the evaluation of the geometric parameters of focused beams for broadband highly directional W-band ADR created in the development of radio vision systems.

## 2. Brief Overview of the Theoretical Issues Connected with Antenna Beam Focusing Mode

The theory and methods for calculating focused apertures are well-developed at the present [13-15]. They are based on the postulates of geometric and physical optics on changing the orientation of the front of an electromagnetic wave at the interface between two media with different refractive indices using direct and indirect methods for solving boundary problems.

Two directions in the design of focused antenna systems there are in general.

The first direction is based on the introduction of lenses directly into the emitting/receiving structure to form the

required APhD, both for the feeds of reflector antennas and antenna arrays [16-18]. Electromagnetic modeling and optimization of such structures using the well-established software packages CST MWS, and HFSS, as well as the recently created software product for calculations, optimization, and analysis of integrated lens antennas ILASH can nowadays be performed. The HSRT program, based on hybrid spectral ray tracing, can also be referred to as an effective development tool. For all these software products, a characteristic feature is the discretization of the designed structures on the assumption that the electromagnetic radiation wave is comparable with the geometric dimensions of the emitter/receiver and the lens built into it.

The second direction refers to the cases of calculating lens antennas that form narrow beams, which corresponds to the need to build quasi-optical lens antenna systems of large electrical size in which the geometric dimensions of the lens are hundreds or more times greater than the wavelength. Quasi-optical millimeter wave systems are usually designed based on Gaussian beam and thin lens approximations. Such lenses have the capability of angular scanning and achievable small transverse dimensions of a beam in the focal plane, which determines the spatial resolution of the antenna. The main characteristics of the lens objective should also include losses in the lens, which affect the radar sensitivity, especially if it is of a passive type, as well as the depth of field, which is crucial for obtaining high-quality images in MMW imaging systems.

For this direction, when modeling, approaches based on classical concepts are used with the method of moments, diffraction theory, and the finite element method. An example of such an approach can be the program for electrodynamic modeling of antenna systems FEKO, based on the symbiosis of several calculation methods. The methods of moments and geometric and physical optics, together with a new technique for solving systems of linear equations using block selection based on this program.

In cases where the quasi-optical focusing system is sufficiently large compared to the wavelength, good simulation results give optical system design tools such as ZEMAX® [19], CODE -V, and FDTD in combination with various numerical methods for calculations of the near and far fields [20-22].

### 3. Results of Electrodynamic Simulation of the ADR-Lens System in the Beam Focusing Mode

When using a lens focusing system in conjunction with ADR, an essential condition is the formation of a plane wavefront in the ADR at any frequency of the operating band and in the entire sector of viewing angles. The features of the operation of open electrodynamic systems used in ADR and the principles of formation of a given APhD of an electromagnetic field in an ADR aperture have already been considered earlier [6, 7].

The task of the research was to assess the achievable quality

of focusing of an electromagnetic wave formed in the ADR aperture using an extra lens and taking into account the dispersion properties of the ADR and the influence of the mutual orientation of the ADR and the focusing system.

As already noted, the initial condition for good focusing is the presence of a flat phase front at the ADR output. Carrying out direct measurements of the phase distribution in the MMW band is a non-trivial task. On the other hand, in the presence of an “ideal” lens that doesn’t introduce phase distortion the achievable transverse size of the focused beam can indirectly serve as a criterion for the correspondence of the phase front formed in ADR to a given linear distribution.

A singlet lens system with a plano-convex lens with one refractive surface was used during the research to form focused beams. Such a lens system is simple, and its operation is well studied; thus, extra errors could be minimized when estimating the phase distribution of the field in the ADR aperture.

In the process of frequency scanning, the wavefront falls on the lens surface at different angles due to the dispersion properties of ADR. In this case, the problem arises of determining the possible deviation of the focused beam from the optical axes of the system with simultaneous deterioration of its focusing at a given distance. In this regard, the optimizing function of the parameters was applied to the focused lens model when calculating the lens profile according to the criterion of minimizing focusing losses and wavefront distortion in the paraxial focus (PF) region. The ZEMAX® software package provided the calculations. Figure 1 shows the scheme of a planar ADR with an axial focusing dielectric lens.

The analysis showed that a plano-convex dielectric lens with one refractive surface in the working sector of observation angles  $\pm 9^\circ$  from its axis forms a focused wave beam at a given focusing distance in the selected frequency band with low distortion and deformation of the wavefront in the field spot region.

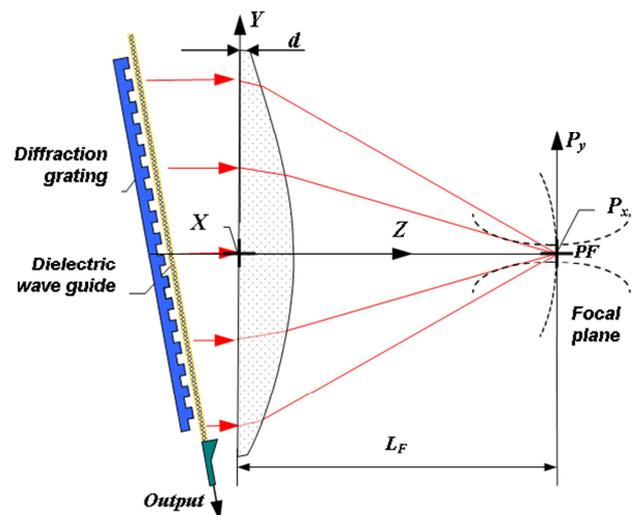
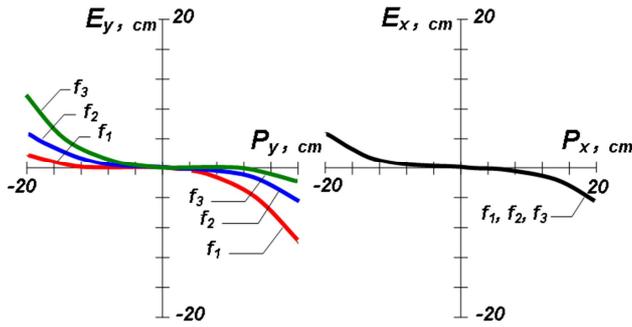


Figure 1. The main elements of an ADR in the focusing mode realized with an axial dielectric lens;  $X$ ,  $Y$ , and  $P_x$ ,  $P_y$ , correspondently, coordinate axes in the aperture plane and the focal plane;  $L_F$  – focal distance,  $d$  – “edge thickness”.



**Figure 2.** The distribution of transverse aberrations relative to the main beam for three frequencies in the sector of observation angles  $\pm 9^\circ$ , where  $E_y$  and  $E_x$  are aberrations in the meridional and sagittal plane, respectively, and  $P_y$  and  $P_x$  are the coordinates of the observation point in the corresponding plane in the region of the paraxial focus;  $f_1, f_2, f_3$  - frequency values, respectively, 84 GHz ( $-9^\circ$ ), 92 GHz ( $0^\circ$ ) and 100 GHz ( $+9^\circ$ ).

As an illustration, Figure 2 shows the results of calculating the aberration values for a model of a focusing lens made of

polystyrene with a diameter of 650 mm and a focal length of 1500 mm.

Table 1 shows the simulation results for focusing lenses made of polystyrene with a permeability  $\epsilon = 2,56$  and one refractive surface when operating in the frequency band 84÷100 GHz.

#### 4. The Main Types of the Tested ADR and Some Their Constructive Features

During the research, antenna characteristics were tested and measured for various types and design options of ADR.

Earlier publications present their structure, composition, and principles of function [7, 8, 23]. Most measurements of the focused beam parameters correspond for the planar W-band ADRs with an aperture size of 40 cm × 42 cm ( $\vec{H} \times \vec{E}$ ).

**Table 1.** Results of calculations of the lens system parameters for three selected focal distances.

$L_F$ , cm	PFД, %	DPFES in the XoZ plane, mm	DPFES in the YoZ plane, mm
150	-0,1	-52,7	-24,6
300	-0,02	-104,2	-47,9
600	-0,007	-206,9	-94,9

PFД - Paraxial Focus Distortion;

DPFES - Displacement of the Paraxial Focus along the main beam at the Edge of the viewing angle Sector

This ADR has a two-tier design; in the down tier, there was a horn-parabolic transition, which excites a planar dielectric waveguide of ADR [7].

Somewhat earlier, successively in different years, measurements of the parameters of focused beams were also carried out for one-tier W-band ADR with a turntable diffraction grating in the form of a disk mounted on the axis of rotation with all other elements of the ADR stationary. Due to the change in the phase distribution of the electromagnetic field as a result of the turning of the diffraction grating, electromechanical scanning of the antenna pattern in space was carried out [24].

When designing focusing lenses, polystyrene was chosen for large apertures and PTFE (Teflon™) for relatively small versions of ADRs. The polystyrene material selection for

large-size lenses was because of smaller weight and the inability of manufacturers to supply PTFE slabs of the required size.

The total thickness of the lens along its central axis depends on the calculated profile and the “edge thickness” (parameter  $d$  in Figure 1), which was established by the ZEMAX® program to reduce the reflection of the electromagnetic wave from the dielectric layer and optimized for the minimum distortion values at the paraxial focus. During the research, lenses with a calculated focal length of 150 cm, 300 cm, and 600 cm were developed and manufactured. Figure 3 shows a focusing lens made of polystyrene with a diameter of 65 cm and a focal length of  $L_F = 300$  cm. Table 2 assumes the main parameters of the developed ADR [23].

**Table 2.** Parameters of the developed planar ADR.

Parameter	ADR sample #				
	1	2	3	4	5
Antenna aperture size, $\vec{H} \times \vec{E}$	400 mm × 420 mm			∅350 mm	∅280 mm
Operational frequency band	84,0÷100,0 GHz			86,0÷100,0 GHz	
Beam width at far field zone ( $\vec{H} \times \vec{E}$ ) (-3 dB, 91 GHz)	0,35°×0,4°			0,4°×0,42°	0,6°×0,8°
A sector of viewing angles (from the normal to the aperture plane)	0,5°÷19° ( $\vec{E}$ )			(0,5°÷17°)×(±17°) ( $\vec{H} \times \vec{E}$ )	
Beam inclination from frequency	±0,1° ((from normal to aperture plane, $\vec{H}$ -plane)				
VSWR (output flange, at the band)	better 1,25				
Focus distance, cm	300			350	
Focus lens material	polystyrene			PTFE (Teflon®)	
Focused beam waist size $\vec{H} \times \vec{E}$ , mm × mm :	f = 91 GHz			f = 95 GHz	
- 3 dB	26×33	35×31	35×34	34×32	46×60
-20 dB	60×90	59×85	59×86	65×90	90×120
Worst first side lobe level at $\vec{H}$ and $\vec{E}$ planes at the band, dB	-18	-19	-19	-18	-18



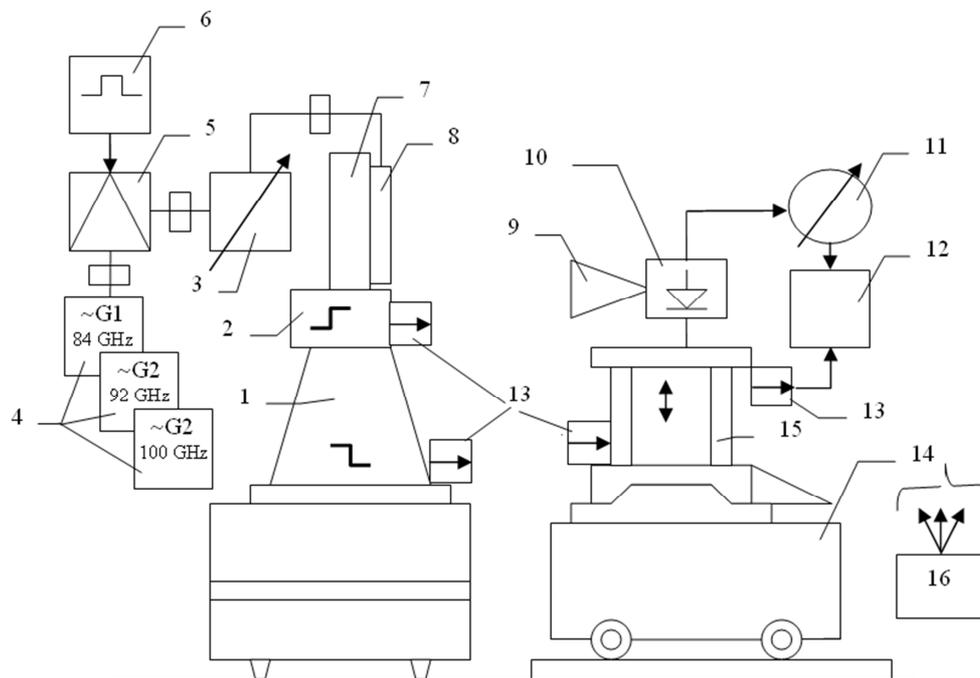
**Figure 3.** The main view of a focusing dielectric lens  $\varnothing 650$  mm made from polystyrene.

## 5. Experimental Measurements of the Focused Beam Parameters for ADR in Laboratory Conditions

The purpose of the experimental research was to assess the quality of focusing antenna beams at a given focal distance using calculated and manufactured dielectric lenses joint to

study the dependence of the focusing parameters with distance, frequency, observation angle, and polarization of the electromagnetic field. The spatial structure of the electromagnetic field and the transverse distribution of the beam energy in the caustic were estimated while simultaneously fixing the spatial coordinates, amplitude, and polarization of radiation using calibrated waveguide detector as a power meter. Synchronous alignments of optical, geometric, and electrical axes of the combined antenna system were performed as an additional task during measurements. The measuring facility consisted of standard hardware components during the experiments in laboratory conditions. Figure 4 presents the block diagram of the stand, and Figure 5 depicts its general view.

This stand included a stationary transmitting station and a movable receiving station placed on a rail carriage. The distance between the points could vary from 0,5 m to 8 m. The transmitting station included a support-rotary device, on which the measured ADR was located together with a replaceable focusing lens. A replaceable waveguide module based on a Gunn generator operating in the pulse modulation mode was utilized as a W-band radiation source. There were three generating modules with operating frequencies of 86 GHz, 93 GHz, and 98 GHz. Emitting power was controlled through a precision waveguide attenuator.



**Figure 4.** Functional diagram of the measuring laboratory stand: 1 - Support-Rotating Device (SRD) azimuth drive; 2 - SRD elevation drive; 3 - Precision measurement attenuator; 4 - High-frequency generator; 5 - Waveguide modulator; 6 - Modulating pulses generator; 7 - Platform of the SRD; 8 - ADR under test together with a lens; 9 - Measuring antenna; 10 - Waveguide detector; 11 - Measuring logarithmic amplifier; 12 - Recorder; 13 - Mechanical movement sensor; 14 - Horizontal displacement system; 15 - Vertical displacement system; 16 - Source power for sensors of moving.

The receiving station locates on a rail carriage containing a receiving antenna in the form of a probe 9 (open end of the W-band waveguide), a square-law detector with an amplifier, and

a recording module. The positioning device mounted on the carriage made it possible to change the probe position horizontally, vertically, and in angular coordinates. A two-coordinate recorder

was used as a registration device. The measuring stand made it possible to record signals in a dynamic range of 50 dB.

The meter's amplitude scale was generally non-linear. At the beginning of each cycle of measurements, and also after changing the generator based on the Gunn diode, the relative levels of the signal recording by the detector were certified using a precision waveguide polarization-type attenuator providing a relative accuracy of the power reading of the order of  $\pm 0,5$  dB.



Figure 5. The main view of the experimental apparatus of the ADR's focused beam parameters measurements in conditions of laboratory premises.

The scales of the positioning device ensured the measurement of the distance between the receiving and transmitting points with an accuracy of no worse than  $\pm 0,5$  cm, and the accuracy of the installation of the receiving probe along the vertical and horizontal axes was not worse than  $\pm 0,1$  cm and not worse than  $\pm 0,5^\circ$ .

The relative level of side echoes in the laboratory room for the sector of observation angles  $\pm 20^\circ$  from the optical axis of

the measuring device along both coordinates was estimating not worse than -55 dB at intensity for the selected range of distances between the transmitting and receiving stations.

In the course of measurements, the fixation of the transverse distributions of intensity for the investigated focused beam at a selected distance was carried out due to the automated rotation of the ADR on a rotary stand in the azimuth or elevation plane using a mechanical drive based on a stepping motor. The appropriate angular sensor of the ADR's position was connected to the longitudinal axis of movement in the two-coordinate recorder. The received signal amplitude was registered by a pen along the second coordinate of this recorder. Thus, in one cycle of measurements, the transverse distribution of the beam's intensity was recorded for a selected distance between the transmitting and receiving stations. For each point of the formed diagram at least four consecutive measurements were carried out, followed by averaging the obtained values.

### 6. Discussion of the Obtained Results

Figure 6, Figure 7, and Figure 8 show the dependences of the transverse dimensions of the neck for the focused beam on the distance and frequency in ADR with an aperture size of 40 cm  $\times$  42 cm ( $\vec{H} \times \vec{E}$ ) for the cases of using focusing lenses made of polystyrene with nominal calculated focal lengths 150 cm, 300 cm, and 600 cm.

As follow from the diagrams, the optimal focusing for lenses with prescribed focal distances of 150 cm and 300 cm occurs at distances close to the calculated ones. For a lens with a nominal calculated focal length of 600 cm, the minimal values were measured for distances shorter than expected, and no stable minimum of values was recorded in the caustic zone.

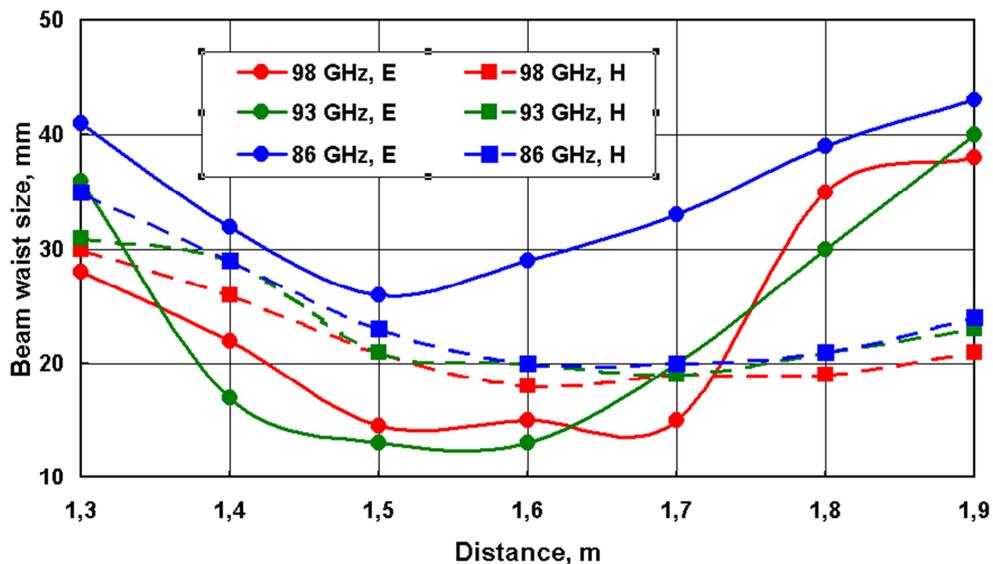


Figure 6. Experimentally measured beam waist size from distance and frequency for ADR with aperture dimensions 40x42 cm ( $\vec{H} \times \vec{E}$ ) and focusing lens distance 150 cm.

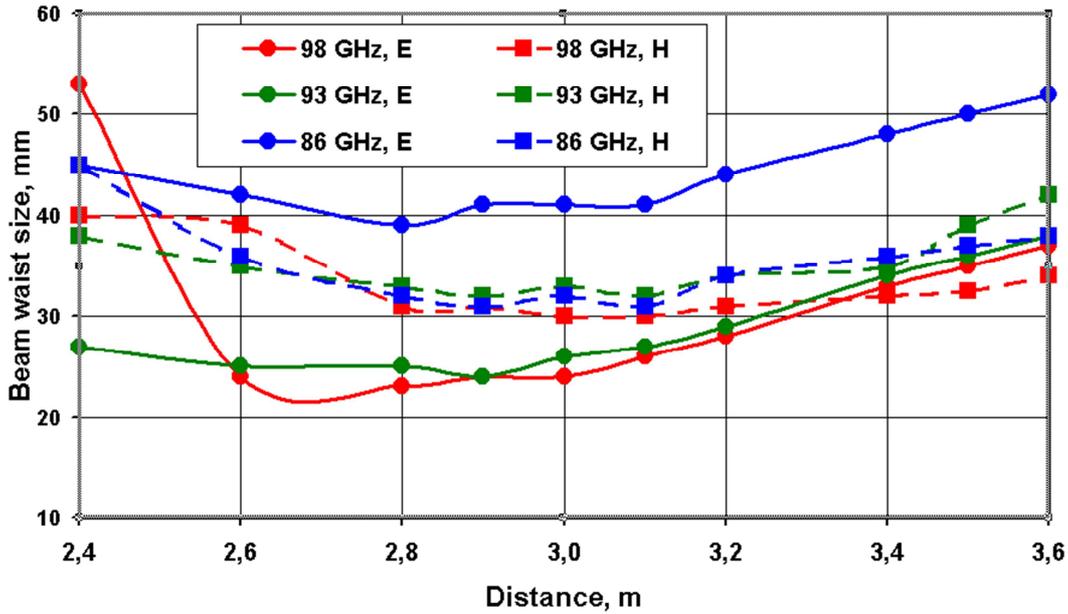


Figure 7. Experimentally measured beam waist size from distance and frequency for ADR with aperture dimensions  $40 \times 42$  cm ( $\vec{H} \times \vec{E}$ ) and focusing lens distance 300 cm.

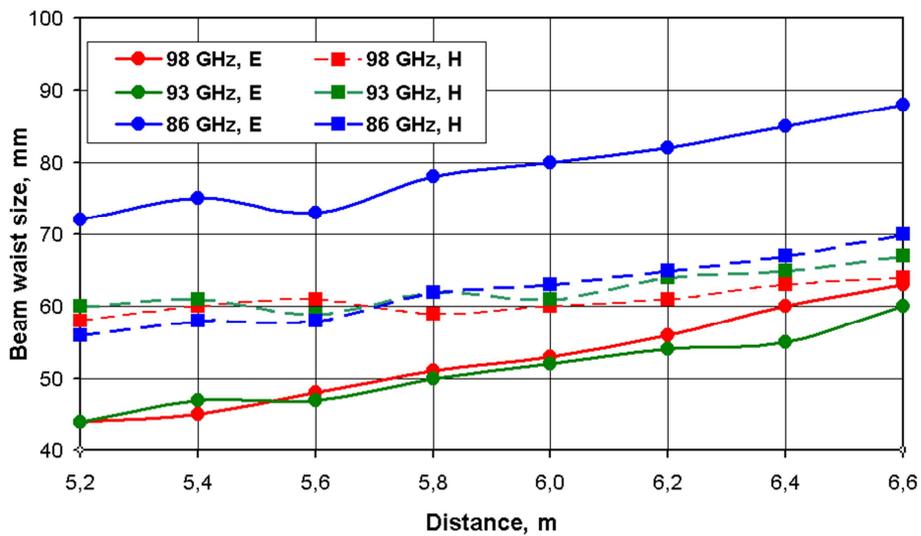
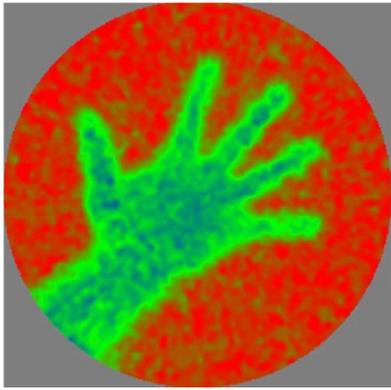


Figure 8. Experimentally measured beam waist size from distance and frequency for ADR with aperture dimensions  $40 \times 42$  cm ( $\vec{H} \times \vec{E}$ ) and focusing lens distance 600 cm.

The significant differences, relative to other plots, should be noted in the spatial dimensions of the beams measured along the  $\vec{E}$  coordinate on the lower edge of the operating frequency band. A reason for broadening the beams in the far-field zone was considered in [7]. On the one hand, this effect for ADR is associated with frequency dependence of the angular position of a beam along the  $\vec{E}$  coordinate of the field. Therefore, at the lowest frequency of the band, the beam is deflected near  $\sim 18$  degrees from the normal to the planar dielectric waveguide. That geometrically reduces the “effective” size of the aperture in this plane. On the other hand, with frequency decreasing, the relative size of the ADR aperture, expressed in wavelengths, also decreases. These physical effects lead to a corresponding broadening of the ADR beam in the  $\vec{E}$  plane both in the far-field zone and at the focus mode on short distances.

As a supplementary experiment in the course of the research, the parameters of the focused beams were estimated for the developed ADR with an aperture of  $40 \text{ cm} \times 42 \text{ cm}$  ( $\vec{H} \times \vec{E}$ ) at the focusing mode of operation and with the simultaneous use of two identical lenses - sequentially placed and axially aligned lenses with a focal length of 1,5 m. In this case, the obtained distance with the best focusing of the beams was found approximately 75 cm. The realized spatial resolution, based on the spatial dimensions of the imaged object, was estimated to be no worse than  $3 \div 5$  mm, which is close to the diffractive limit of a half wavelength of radiation. Figure 9 shows a radiometric image of a human palm obtained using a W-band multi-beam radiometric system as an example of the operation of such a focusing system [8]. The actual width of the fingers in their middle part, in this example, was on the order of  $18 \div 21$  mm.



**Figure 9.** Sample of an image of a man's hand palm in the passive (radiometric) mode of operation for a W-band imaging system on the base of ADR.

For the developed lenses made of polystyrene with a diameter of 650 mm, active losses in the dielectric material of the lenses were measured by the radiometric method at a frequency of 95 GHz. The total loss in the lenses was fixed as 0,5 dB ( $L_F = 600$  cm); 1 dB ( $L_F = 300$  cm); 1,5 dB ( $L_F = 150$  cm) [23]. Due to the significant thickness, the weight of the lens with  $L_F = 150$  cm was found more than 5 kg.

The obtained values of loss and mass are admissible for prototype lens samples during experimental studies of wave beams; however, they may not be acceptable for solving practical problems, especially in the case of creating passive focused systems. In the next stages of research, it is planned to evaluate the possibility of using a singlet lens system with convex-concave refractive surfaces, which will reduce the thickness (material consumption) and weight of the lens, as well as the use of dielectric materials that provide minimal active losses in the W frequency band. These materials include PTFE (Teflon™) and TOPAZ™. Both of these factors will help to reduce signal losses in the ADR focusing system.

## 7. Conclusions

During the research, it was affirmed that dielectric lenses with an axial profile made of high-quality polystyrene provide the parameters of focusing beams for the developed antennas of diffraction radiation accordantly to theoretical calculations. These features were confirmed: i) for the focusing beam waist size; ii) for the depth of focusing, iii) for distortion of the paraxial focus during beam deflection from the axis of a lens up to  $\pm 9^\circ$ , and iv) while changing the frequency in the range of 84÷100 GHz. At the same time, the level of the measured side lobes in the formed beams practically did not differ from the comparable values obtained for these antennas during measurements in the open area on large distances (in the far-field zone). When using a combined focusing system consisting of two identical lenses and the resulting focal length of 0,8 m, the transverse size of the focused beams was estimated at 3÷5 mm. In the relative units, that is close to the values  $(1\pm 1,5)\lambda$  and demonstrates a high focusing quality approaching the theoretically possible diffraction limit, and also indicates a weak influence of inhomogeneity in the form

of a dielectric lens on the electrodynamic properties of the antenna of diffraction radiation.

The results obtained in the course of experimental measurements of the parameters of focused beams for the developed W-band ADRs indirectly confirm the conclusions of model theoretical calculations on the possibility of forming a plane waveguide front in ADR with high linearity of the phase characteristic in a wide frequency band.

The ensuing steps in research may be aimed at improving the technical and technological performance of ADR focusing system associated with a decrease in the weight (material consumption) of lenses and a decrease in active signal losses. Both problems potentially can be solved by moving from lenses with a single arcuate refractive surface to more complex lenses with convex-concave refractive surfaces using dielectric materials with minimal dielectric losses.

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