
Compact MMW-band Planar Diffraction Type Antennas for Various Applications

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Abstract: The principles of formation of antennas of diffraction radiation with flat surface in the millimeter wave radio band are considered. Such kinds of antennas are based on the effect of the conversion of volumetric electromagnetic waves into surface waves of a dielectric waveguide in an open electrodynamic structure. A brief description of the theoretical basis for the calculations and examples of the technical implementation of flat (2D) antennas of diffraction radiation in the W-band and Ka-band are presented; their parameters and areas of possible use are discussed. In the *E*-plane angle-to-frequency dependence of beam position is realized with coefficient near 0,9°/1% of frequency change. That makes it possible effective control of beam position in space (beam scanning along 1, or even along 2 axes). There was estimated that total active loss in such kind antennas is related to dielectric losses in the material of planar dielectric waveguide and to active losses at the elements of internal waveguide transitions in the ratio near (2: 1). Losses of first kind may be reduced due to implementation of novel dielectric materials providing the smallest dielectric loss (near as for the PTFE material) and appropriate mechanical rigidity at the same time. Active losses of the second kind may be reduced due to implementation of transitions on the base of super-size waveguides.

Keywords: Physical Theory of Diffraction, Millimeter Wave Technology, Antenna of Diffraction Radiation, Leaky-wave Antenna

1. Introduction

One well-studied and widely used class of antennas related to leaky-wave antennas of various types are described in references [1-5]. Compared to mirror and lens type antennas their advantage is the absence of a forward protruding feeder, which makes it possible to create emitting structures with very thin dimensions. Compared with antenna arrays, this class of antenna does not require formation of a feeding waveguide network that can introduce significant energy losses, especially large array sizes, if their implementation is in the millimeter and sub-millimeter wavebands. The phase constant of a leaky wave antenna is usually a function of the operating frequency. This fact can be used to control antenna beam direction by means of a sweeping operating frequency.

At the end of the 1970's, using the technique of leaky wave

antennas, a separate subclass of electrodynamic structures with specific characteristics had appeared. They consisted of open electrodynamic structures based on a dielectric waveguide and a diffraction grating spatially spaced, but interconnected by an electromagnetic field. In a number of publications such kind of electrodynamic structures were named Antennas of Diffraction Radiation (ADR), which some researchers still consider as a sub-class of leaky-wave antennas, and some distinguish this as a separate class of antennas [6, 7]. Without going into details of terminology, it may be noted that the main difference of ADR is in spatial separation of the dielectric waveguide and diffraction grating in the combined electrodynamic structure with their interaction due to appearance of external surface waves of the dielectric waveguide, which have specific properties affecting characteristics of the antenna. Due to the fact that the diffraction grating and dielectric waveguide, in this case, are

separate structural elements, their spatial position (namely the air gap between them) may be changed at the course of antenna tuning in order to ensure optimal electromagnetic coupling between these elements. This parameter allows the generation of the desired amplitude-phase distribution of the field in the plane of the antenna's aperture.

When discussing electrodynamic properties of open diffractive electrodynamic systems it should be noted that during the past 40 years the effect of transformation of surface electromagnetic waves into volume electromagnetic waves using periodic structures has been proven for creation of effective radiators in the millimeter (MM) and Sub-millimeter (Sub-MM) wave bands [8, 6, 9]. These results were preceded by theoretical and experimental studies of transformation of energy of surface waves into energy of diffraction radiation by various periodic structures (ribbon gratings, gratings of bars with rectangular cross-section, reflecting gratings in the form of combs, echelette with rectangular combs, grids from circular half-cylinders lying on a metal surface, etc.). The main results of studies covering MM, Sub-MM and optical wave bands are given in [6, 10, 11]. It was established that only ribbon gratings, a grid of bars with rectangular cross-section and combs have significant vertical radiation. Energy characteristics of electromagnetic fields scattered by a grating in the form of combs indicate expediency of using such kind of diffusers both in generators of diffraction radiation and in radiators that convert surface electromagnetic waves into volumetric waves. These kinds of emitters are included in the theory and techniques of Antennas of Diffraction Radiation (ADR). During research in this technical area different types of ADR in MM and Sub-MM wave bands were developed on the basis of linear (one-dimensional) and planar (two-dimensional) "open" electromagnetic structures, and their characteristics were described in [7, 12-14].

This paper presents a review of the results of theoretical studies and technical and technological experiments conducted during recent years at the O. Ya. Usikov Institute of Radiophysics and Electronics National Academy of Sciences of Ukraine in creation of planar ADR in MM wave band

2. Principles of Operation and Structure of Antennas of Diffraction Radiation

Principals of operation of ADR pertain to the conversion of volume electromagnetic waves, which are distributed from the observing object, into directed waves of a restricted waveguide using the process of diffraction of electromagnetic waves on an open connected structure: diffraction grating - dielectric waveguide. In the case of creation of this kind of electrodynamic system, in the form of a two-dimensional planar structure, a planar antenna with small depth is formed, which is determined by the total thickness of a diffraction grating and dielectric waveguide. Dispersion properties of such kind "open electrodynamic system" depend on relative orientation of the E vector of

falling electromagnetic field and direction of orientation of the bars of a diffraction grating, and allow the wave at the selected frequency band to be converted effectively from different directions in space. Thus, when changing the antenna operating frequency and/or changing location of the bars of the grating, a certain sector of viewing angles may be formed and different schemes of space observation (beam scanning) may be realized with a single-beam or multi-beam directional pattern of the antenna. Figure 1 presents the structure of an ADR as a cross-section of a two-dimensional planar electromagnetic structure shown in direction transverse to the profile of the combs for a variant of grating from combs.

A planar ADR includes the following functional elements:

- 1) A Planar Dielectric Waveguide (PDW), which is made from high-quality dielectric material. The main requirements for this are low dielectric loss and mechanical stiffness, which ensures immutability of geometrical dimensions and distance between the PDW and the PDG during operation.
- 2) Planar Diffraction Grating (PDG), which should be made from high conductivity material (metal) and may be implemented in two possible variants: i) planar lattice from strips placed between the PDW and the object of observation (path-through operation), and ii) a reflecting grating from combs placed on the opposite side of the PDW, as shown in Figure 1.
- 3) Waveguide transition from PDW to PDG. This transition may be formed according to different schemes of the horn, horn-lens, or horn-parabolic antenna with the standard operation mode (i.e. single-mode field structure), or on the basis of a super-dimensional waveguide transition with a multimode structure of the electromagnetic field, including E -type waveguide angular turns of 90 or 180 degrees, which allow optimized dimensions of the entire structure.

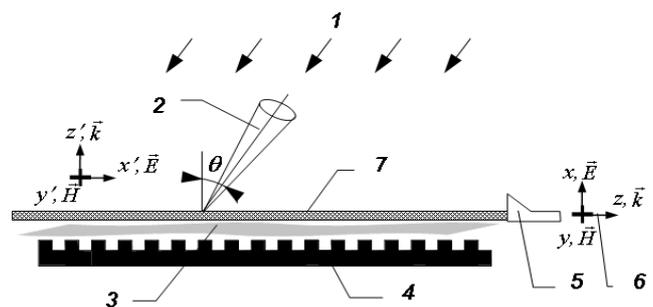


Figure 1. The main elements of planar ADR; 1 - incoming radiation; 2 - antenna beam; 3 - surface wave; 4 - diffraction grating; 5 - waveguide transducer; 6 - antenna output signal; 7 - dielectric wave guide.

Polarization of the received signal is linear in relation to the surface of observation. The antenna has a high-frequency output with a standard waveguide flange and the H_{01} wave mode propagates in the waveguide channel.

3. Theoretical Basis of Design of the Antenna of Diffraction Radiation

3.1. Planar Dielectric Waveguide and Diffraction Grating

Spatial distribution of beams in the ADR is provided by dispersion properties of the PDW and diffraction elements. During the course of the ADR development and the electrodynamic problem solving of volume electromagnetic wave transformation into the PDW surface wave a small-dimensional approximation was used. This assumption is fully justified due to the small distance of the PDW from the PDG utilized in the construction, which make up the order of a half a wavelength of the receiving signal, and because interaction of the PDW surface wave with PDG elements occurs throughout whole PDG length. At the heart of the mechanism of the transformation of the volumetric wave into the PDW surface wave, there is a phase synchronism between the PDG diffraction field and the PDW's peculiar field. The problem of electromagnetic wave diffraction on the PDW-PDG electrodynamic system should be solved with the aim this field seeks out. In the accepted theoretical model the beam was taken as a bounded space electromagnetic wave with field intensity distribution in the form of the Gauss-Hermite function in two reciprocally orthogonal planes. The role of a phase matching element performs a strip diffraction grating. The considered scheme of an open electrodynamic system is shown in Figure 2. Here the coordinate system is chosen conveniently for studying the propagation of waves in the PDW, in which the z coordinate indicates the direction of propagation.

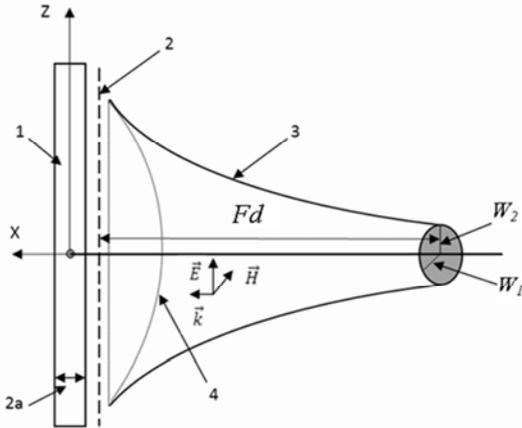


Figure 2. The contours of the electrodynamic structure in the beam diffraction problem on the PDW-PDG system; 1 - PDW with thickness $2a$; 2 - PDG; 3 - an outline of the antenna beam; 4 - focused lens (in the case of forming focused beam at small distance from the antenna); $W1$ and $W2$ - the widths of the beam in mutually perpendicular y and z directions, Fd - focal distance.

Solution of the boundary diffraction problem for the Helmholtz equation, with corresponding boundary conditions on the PDW and PDG planes, is aimed on searching the diffraction fields attendant to each considered spatial domain, as well as the falling field, and conveniently may be represented in the form of Fourier integrals by wave numbers, as:

$$U^0(x, y, z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F^0(\eta, \zeta) \exp(-j(\eta y + \zeta z)) \times \exp(-jk_x(x_1 + x_2)) d\eta d\zeta, \quad (1)$$

$$U_i^{Dif}(x, y, z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F^0(\eta, \zeta) \psi_i(\eta, \zeta, x, z) \times \exp(-j(\eta y + \zeta z)) d\eta d\zeta, \quad (2)$$

where, $U^0(x, y, z, t)$ $U_i^{Dif}(x, y, z, t)$ – are the falling and diffraction fields, respectively; the function $\psi_i(\eta, \zeta, x, z)$ must be determined from the solution of boundary value problem for the spectrum of partial Fourier waves in each of the regions represented on Figure 1; x, y, z – are spatial and temporal coordinates, η, ζ – are spatial variables of integration and are projections of the wave vectors on y - and z -axes, $k_x = \sqrt{k^2 - \eta^2 - \zeta^2}$ – is the wave number according to each of the boundary domains, the index i defines the region of space where the corresponding diffraction field is (i.e. (1) - outside PDW in the open space, (2) - between PDG and PDW, and (3) - inside PDW). The distribution function of the incident beam has the form:

$$F^0(\eta, \zeta) = \frac{1}{2\pi} \sqrt{\left(\frac{W_2}{W_2(c)}\right)} \times \exp\left(j\left(\omega t - k_0 \frac{c}{2} + \left(n + \frac{1}{2}\right) \Phi_2(c)\right)\right) J_1 J_2, \quad (3)$$

where: c – is the value of displacement between the necks of the beam in the planes $z = \text{const}$ and $y = \text{const}$; $W2, W2(c)$ – are, correspondently, the width of the beam in the focal plane, and the width of the beam for selected displacement (c) between the necks, ω – circular frequency of the incident spatially bounded field; k_0 – is the dimensionless wave number, $\Phi_2(c)$ – determines the phase distribution taking into account the displacement between the necks of the beam, functions:

$$J_1^m = \int_{-\infty}^{\infty} H_m\left(\frac{\sqrt{2}}{W_1} y\right) \exp\left(-\frac{y^2}{W_1^2}\right) \exp\left(-i \frac{k_0 y^2}{2R_2(c)}\right) \exp(i\eta y) dy; \quad (4)$$

$$J_2^n = \int_{-\infty}^{\infty} H_n\left(\frac{\sqrt{2}}{W_2} z\right) \exp\left(-\frac{z^2}{W_2^2}\right) \exp\left(-i \frac{k_0 z^2}{2R_2(c)}\right) \exp(i\zeta z) dz; \quad (5)$$

determine the spatial distribution of the beam, where $W1, W2, R1(c), R2(c)$ are the beam widths and the radii of curvature of the phase edges along y - and z - axes; $H_m(\sqrt{2}y/W_1), H_n(\sqrt{2}z/W_2)$ – the Hermite polynomials that determine distribution of field's amplitude in the cross-section, and m and n – the number of variations of the field along y - and z - axes.

The function $U_i^{Dif}(x, y, z, t)$ means the E , or H component of the electromagnetic field depending on the chosen polarization of the incident electromagnetic wave on the diffraction structure.

Based on the shape of the falling field it follows that the forming wave is a continuous spectrum of partial plane waves incident on a PDW-PDG system at arbitrary angles relative to

the normal to the aperture plane of the antenna. Due to the periodicity property of restriction each partial plane-wave generates an infinite spectrum of spatial harmonics of the scattered field. The desired fields and, consequently, the function $\psi_i(\eta, \zeta, x, z)$ must also satisfy the Helmholtz equation with boundary conditions on the grating and on the dielectric layer, the Sommerfeld condition and the condition of finite energy. Therefore the spectral functions for the scattered field in each domain may be represented as Fourier series with unknown coefficients. The boundary conditions on the lens's surface were not taken into account because it could be fabricated from dielectric material with a very small reflection coefficient (for example, from polystyrene foam).

At the next stages the main interest is related to the diffractive field existing at the area occupied by the dielectric waveguide. According to the definition of the function $\psi_i(\eta, \zeta, x, z)$ given in (2), the field in this area is described by the following expression:

$$\begin{aligned} \psi_3(\eta, \zeta, x, z) = & \sum_{s=-\infty}^{\infty} \{d_s \exp[-ip_s(\frac{x_1+x_2}{2}-b)] + \\ & e_s \exp[-ip_s(\frac{x_1+x_2}{2}-b-2a)]\} \times \exp(i\frac{2\pi s}{l}z), \end{aligned} \quad (6)$$

where: d_s, e_s – the unknown Fourier coefficients of the partial waves, which are determined from system (9) taking into account (10-19), values, p_s, q_s – are propagation constants of the Fourier harmonics of the diffraction grating, which are determined from the following relationships:

$$p_s = \sqrt{k^2 \varepsilon - \eta^2 + (\zeta - \frac{2\pi s}{l})^2}; \quad (7)$$

$$q_s = \sqrt{k^2 - \eta^2 + (\zeta - \frac{2\pi s}{l})^2}, \quad (8)$$

where: l – period of diffraction gratings, ε – dielectric constant of the PDW, $k = 2\pi/\lambda$ – wave number, λ – wavelength in free space. The same formats have expressions of diffraction fields for other regions.

Submission of the fields to boundary conditions leads to a system of paired summarized equations for desired functions $\psi_i(\eta, \zeta, x, z)$ with unknown coefficients. This system is poorly conditioned and does not allow for obtaining stable solutions under a wide range of parameter variations. In solving the problem its regularization is made by means of the Riemann-Hilbert method [15]. Due to the cumbersome nature of necessary transformations the final form of the system of linear algebraic equations of the second kind may be obtained with rapid convergence of elements, which allows to obtain a solution of the boundary value problem and hence the solution of the problem of a focused beam formation by the PDW-PDG structure:

$$\begin{cases} x_n = Q_0 V_n^0 + 2 \sum_{s=0}^j x_s V_n^s + \sum_{s=-\infty}^{\infty} x_s \frac{|s-v|}{s-v} \Omega_s V_n^s + 2cR_n; \\ 0 = Q_0 V_\sigma^0 + 2 \sum_{s=0}^j x_s V_\sigma^s + \sum_{s=-\infty}^{\infty} x_s \frac{|s-v|}{s-v} \Omega_s V_\sigma^s + 2cR_\sigma; \end{cases} \quad (9)$$

$$Q_0 = -q_0 \frac{l}{2\pi} \exp\left\{-iq_0\left(L + \frac{C}{2}\right)\right\}; \quad (10)$$

$$R_\sigma = \sum_{n=-\infty}^{\infty} (-1)^n \frac{R_n}{n+v} P_{-v-1}(u); \quad (11)$$

$$V_\sigma^s = \sum_{n=-\infty}^{\infty} (-1)^n \frac{V_n^s}{n-v}; \quad (12)$$

$$\begin{aligned} \alpha_s = & \frac{1}{4q_s p_s} \{[(q_s + p_s)^2 \exp(i2ap_s) - (q_s - p_s)^2 \times \\ & \exp(-i2ap_s)] \exp(ibq_s) + [(q_s^2 - p_s^2) \exp(i2ap_s) - \\ & (q_s^2 - p_s^2) \exp(-i2ap_s)] \exp(-ibq_s)\}; \end{aligned} \quad (13)$$

$$\begin{aligned} \beta_s = & \frac{1}{4q_s p_s} \{[(q_s + p_s)^2 \exp(i2ap_s) - (q_s - p_s)^2 \times \\ & \exp(-i2ap_s)] \exp(ibq_s) - [(q_s^2 - p_s^2) \exp(i2ap_s) - \\ & (q_s^2 - p_s^2) \exp(-i2ap_s)] \exp(-ibq_s)\}; \end{aligned} \quad (14)$$

$$\Omega_s = 1 + i \sqrt{\frac{\chi^2 - \mu^2}{(s+v)^2}} - 1 \frac{\alpha_s + \beta_s}{2\alpha_s}; \quad (15)$$

$$d_s = \frac{p_s + q_s}{2p_s(s+v)\alpha_s} x_s \exp(ip_s(2a + L + \frac{c}{2})); \quad (16)$$

$$e_s = \frac{p_s + q_s}{2p_s(s+v)\alpha_s} x_s \exp(-ip_s(L + \frac{c}{2})); \quad (17)$$

$$\mu = \frac{\eta l}{2\pi}; \quad (18)$$

$$\chi = \frac{kl}{2\pi}; \quad (19)$$

where: $L = Fd$ – is distance between paraxial focus and the PDG surface, u – coefficient of filling of the grating's period by metal, $P_{-v-1}(u)$ – function of Legendre, R_n, V_{ns} – combinations of polynomials and functions of Legendre and defined in [15].

By determining the unknown values x_n from the system of equations (9) through accounting (10)-(19) a solution of the diffraction problem may be founded after integration with the substitution in (2), and the field inside dielectric waveguide may be calculated, which is excited by the focused wave beam.

On the base of the theoretical formulations all corresponded numerical calculations have been secured on the base of original specially developed software. Some results obtained at the course of investigations are presented below.

A transverse distribution of amplitude of electromagnetic wave excited in the PDW is presented in Figure 3 and illustrates some forms of distribution when the phase synchronism for the basic wave has happened, or wasn't obtained. By choosing dielectric and geometric parameters of

PDW and PDG a fully symmetrical transverse distribution of intensity could be obtained.

Such kind of distribution corresponds to the propagation of the main wave mode inside the PDW [12, 16].

The peculiarity of such kind of electrodynamic system is the ability to convert a volumetric electromagnetic wave into a surface wave of a dielectric waveguide and vice versa in a wide frequency band [9, 12].

In this case the dependence of frequency for the receiving/transmitting angle is occurred for the direction, from which such kind of transformation is occurring with maximal efficiency. Figure 4 shows an example of calculated and measured data presenting angular position of the main lobe in the pattern from the frequency for an electromagnetic system constructed in the W-band of spectrum.

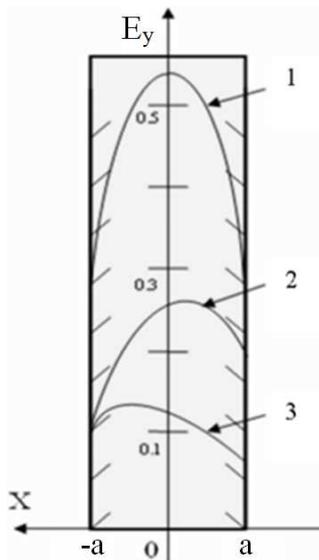


Figure 3. Transverse distribution of the electrical component of the electromagnetic wave exciting inside the PDW at the cases of different periods of combs of the PDG; 1 - the effect of phase synchronization, 2, 3 - the absence of phase synchronization with less (2) and greater (3) phase velocity of the diffraction wave; a - half-thickness of PDW.

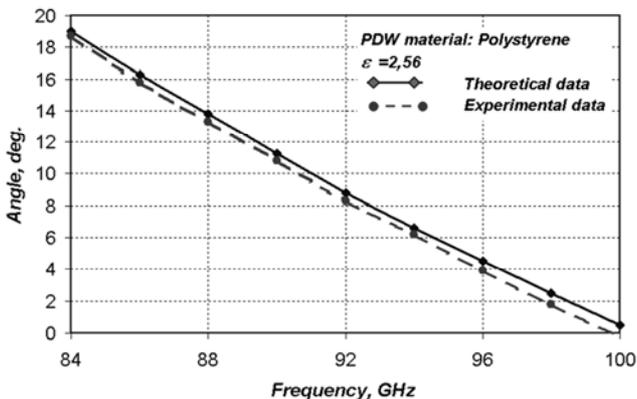


Figure 4. Calculated dispersion characteristic of W-band ADR; reception angle is deduced from the normal to the PDW plane.

It should be noted also that insertion of a mutual angle α between the direction of propagation of the surface wave of PDW (z - axis) and the direction of the location of the PDG tapes

leads to an additional deviation of the beam in the XOY plane according to the law, $\sin(\phi) = \text{tg}(\alpha) \cdot \lambda/l$, where ϕ - is the angle of deflection of the antenna beam in the XOY - plane, l - is period of tapes, and this effect generates abilities for the ADR beam control due to variation of the PDG parameters, for example, to organize the antenna beam scanning along y - axis in slight nonlinear manner when the PDG is forming as a moveable disk having ability to oscillate around its central axis [6].

3.2. Waveguide Transition from PDW to the Standard Rectangular Waveguide

Peculiarities of the development of planar ADRs are connected with solution of a number of complex electrodynamic problems. The task of matching the standard rectangular waveguide with the PDW is related to the problem of plane wave diffraction on unclosed screens with complex geometry.

Calculations were carried out mathematically by the methods of the theory of diffraction and propagation of electromagnetic waves. In the first instance that is due to the fact that dimensions of individual elements of the antenna (waveguide horn transition, elements of waveguide turns (if any), etc.) are compatible with the wavelength in the selected frequency band. In such electrodynamic conditions, different types of resonance effects could occur that may negatively affect some characteristics of the antenna system. In addition, optimization of all these elements should form robust and mathematically grounded solutions of the boundary problems in a wide range of electrodynamic parameters.

From the point of view of achieving both high-grade technical characteristics and compactness of the ADR overall design, the most suitable variant of the transition from the PDW to standard rectangular waveguide is the horn-parabolic transition (HPT) as a one-dimensional version of the well-known horn-parabolic antenna. Interaction of E -polarized electromagnetic waves with the system of surfaces inside HPT is described by the two-dimensional boundary problem for the Helmholtz equation.

The task is an electromagnetic wave reproduction in the receiving horn of the HPT, which occurs when the plane wave falls on a one-dimensional parabolic mirror. The solution of the boundary problem has many stages, is rather cumbersome and already has been described in details [17-21]. The calculations carried out in wide range of variations of parameters allowed to determine the optimal geometry of one-dimensional HPT in terms of the efficiency of excitation of an electromagnetic wave in the receiving horn, which provides suitable field distribution at the PDW side-face.

When high directivity antennas are constructed, corresponding increase of the PDW size in the (y) coordinate needs to be realized. As a result, the geometric dimensions of the HPT increase also, that leads to increasing the length of wave's guide and, consequently, to increase the level of loss of electromagnetic energy due to its absorption in the walls of the waveguides. This is significant in the MMW bands; therefore, with the aim of reducing the total loss of the antenna, the HPT may be designed with super-dimensional distance between the forming planes. This requires the introduction into the

structure of the HPT of linear waveguide transitions from the standard size to the super-dimensional waveguides, including planar ones. In simulation, the approximation of linear transitions in N stairs may be chosen as a mathematical model. Using this approach, a numerical algorithm for analysis of the transitions was implemented, based on the method of partial regions for calculating the full-wave scattering matrices of individual stairs and the method of generalized scattering matrices for their integration [22].

When choosing optimized parameters of the HPT, the amplitude distribution of field close to a cosine shape with homogeneous phase distribution could be obtained at the output section of HPT, which is in close proximity to the PDW.

In the course of development of the HPT in W-band with super-dimensional internal area, the H_{30} -wave excitation level at the output broad waveguide was better than -30 dB.

4. Variants of Realization for Planar Antenna of Diffraction Radiation

Based on the considered theoretical principles of formation of diffraction type open electrodynamic structures, different types of ADR were developed and their parameters were measured for Ka- and W-bands of spectrum. Several schemes of open electrodynamic structures were used, several types of dielectric and metal materials and technological approaches to their processing and coating were tested, several design solutions for PDWs were developed, which provided possibility of precise adjusting and mutual arrangement of the PDW and PDG and preserving such settings in time for heavy operating conditions of the antennas.

Traditionally, PDGs and HPTs are made from metal with high electrical conductivity, such as copper, brass, and aluminum alloys. As a coating for the PDG and internal surfaces of the HPT silver plating is most often used by means of galvanic deposition. But with this approach, the total weight of the design elements of the antennas in the planar version of their construction could be significant. In the course of experiments, a technique of manufacturing of structural elements of the HPT and PDG from plastic materials with subsequent coating by copper in the installation of plasma pollution was tested. Figure 5 shows the ADR construction for two-tier waveguide circuit.

In this case the HPT is located in the lower tier of the design - such a scheme can significantly reduce dimensions of the antenna, but requires installation of additional wideband planar angular turns, which should ensure immutability of characteristics throughout the operating frequency band.

A photograph of the body of W-band ADR in a two-tier variant of construction is presented in Figure 6 with organic glass as a constructive material followed by application of copper film on all surfaces.

Figure 7 shows the ADR in the assembly built according to the two-tier scheme and installed on the rotating platform. Such an antenna in the 64-beam forming mode was used in the W-band passive imaging system when rotated around its

central axis at a speed up to 8 revolutions per second [23, 24].

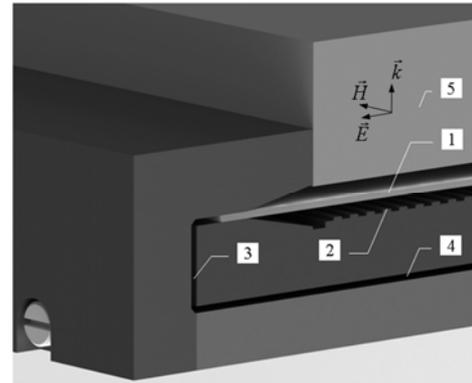


Figure 5. Variant of development of planar ADR with two-tier layout of PDG and HPT (in partial cross-section); 1 - PDW; 2 - PDG; 3 - waveguide turn 180°; 4 - HPT; 5 - radio transparent supporting layer.

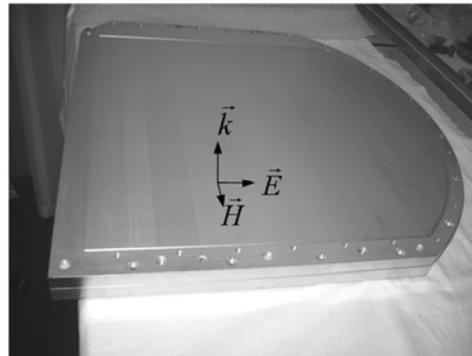


Figure 6. The body of W-band planar ADR in a two-tier variant of construction made from plastic material with a metal film coating (PDG is located on the upper side of the body; 180° turn section is not installed yet).

Figure 8 shows the main view of the W-band scanning ADR constructed with a single-tier waveguide circuit, when the PDG is performing as a metal disk, which has ability to oscillate around the rotation axis using a step-motor drive, and which provides a mode of scanning of the beam-pattern in the vertical plane. Such an antenna was tested in the 32 beam-forming mode in the W-band passive imaging system with formation of 2 images per second in the presence of only one moving element in the system - namely, the PDG in the form of a disk [25].

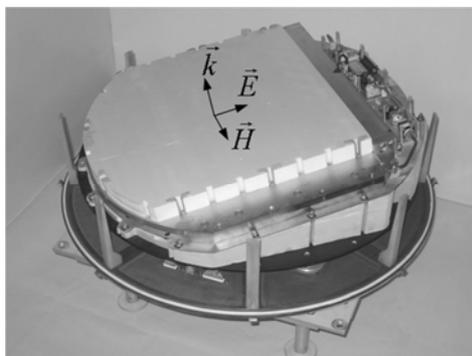


Figure 7. Total view of the W-band planar ADR built on a two-tier scheme installed on the rotating platform; aperture size 40 cm × 42 cm.

Figure 9 shows the main view of Ka-band planar ADR with aperture size $18\text{ cm} \times 200\text{ cm}$ tested as an antenna for radar station destined for airport's land area observation [26, 27].

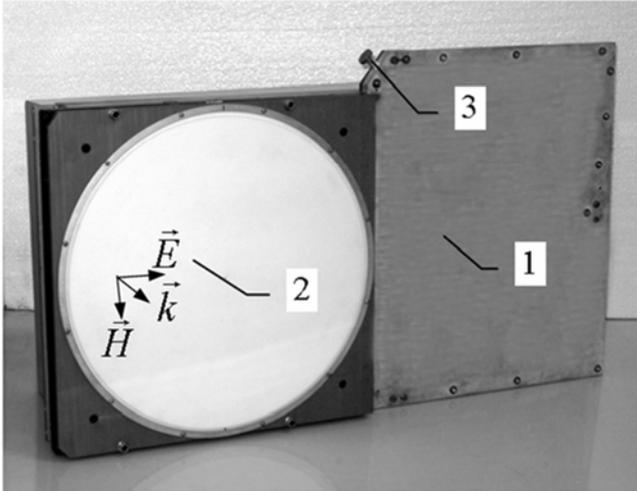


Figure 8. Variant of scanning a W-band planar ADR with one-tier placement of PDW and HPT, and PDG execution at the form of a disk; ADR also has a dielectric lens that focuses radiation at the desired distance; 1 - HPT, 2 - focused lens, 3 - output antenna flange.

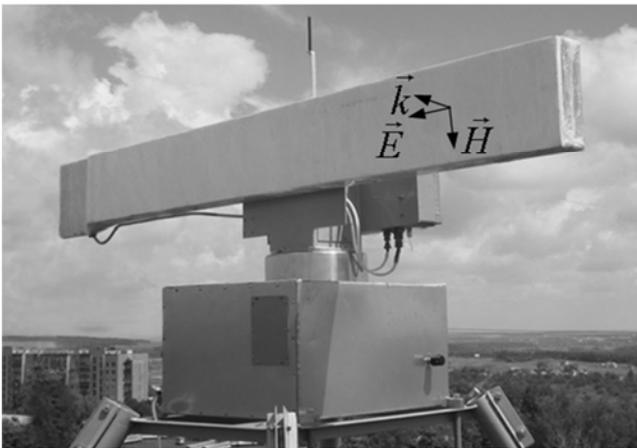


Figure 9. Ka-band planar ADR built on one-tier scheme of PDG and HPT placement with aperture size $18\text{ cm} \times 200\text{ cm}$ (radio-transparent radome is removed).

During the course of the planar ADR development both PTFE (Teflon™) and polystyrene were tested as dielectric materials for the PDW. Due to very small dielectric losses, PTFE showed good results at the case of relatively small antenna' aperture size in one or in both axes of coordinates.

However, for antennas with relatively large aperture size on both coordinates, the mechanical properties of PTFE - namely relatively low rigidity when it is used as a thin sheet, did not allow to ensure long-term stability of mutual arrangement of the PDG and PDW in adverse operating conditions, which led to selection of high quality polystyrene as the main material for the PDW. It should be noted also that due to significant progress in chemistry in the area of dielectric materials, there are rather optimistic forecasts as for abilities for creation of

new types of dielectric compounds with low dielectric losses in the millimeter-wave band, and with provision of acceptable mechanical properties for their use as a PDW units.

5. Obtained Parameters of Antennas of Diffraction Radiation

Several variants of planar ADR in W- and Ka- wave bands were developed during the research. During the process, in conditions of an anechoic chamber, many accurate measurements of electromagnetic field distribution at the main coordinate planes of the ADR were carried out, as well as parameters of the beams over a wide frequency band, active losses and their distribution by the components of the antenna. In several cases, the beam's efficiency was also measured, and the ability to focus antenna at small distances by means of dielectric lenses were tested. Additional measurements for open space allowed estimate parameters of the beams in the far field zone, ability of beam scanning by electromechanical method, etc.

In the most cases, in the *H*-plane the field distribution along aperture close in shape to cosine was formed due to the HPT characteristics. In the *E*-plane, the field distribution close in shape to cosine on a pedestal was realized when degree of mutual coupling for the PDG-PDW structure was tuned, but with some asymmetry related to one-sided scheme of PDW excitation. In this regard, in the *E*-plane the first side-lobe of the beam, which was measured relatively to the port of excitation (at the HPT side of the aperture) exceeds the level of the same lobe been fixed at the opposite side of the beam. As an example, Figure 10 shows the results of measurements in an anechoic chamber of directional patterns at different frequencies inside the operational band for W-band planar ADR (Figure 7).

The main technical parameters of the developed planar ADRs are given at the Table 1.

Figure 11 shows the results of measurements for beam-width in the far-field zone and in dependence from frequency for planar ADR with the two-tier scheme of placement of elements.

Beam efficiency for W-band antennas was measured by means of radiometric measurements in the anechoic chamber at the focused beam mode and on the base of the modified method known in radio astronomy as "artificial Moon" [28, 29]. A heated passive noise radiator with brightness temperature different from ambient temperature of the chamber was used. The radiation area at the measurement distance was equal to the cross-sectional area of the beam, which was determined at the level -20 dB from it maximum. Additional dielectric lens with a $\varnothing 650\text{ mm}$ and focusing distance 3 m was used at the antenna beam focusing mode.

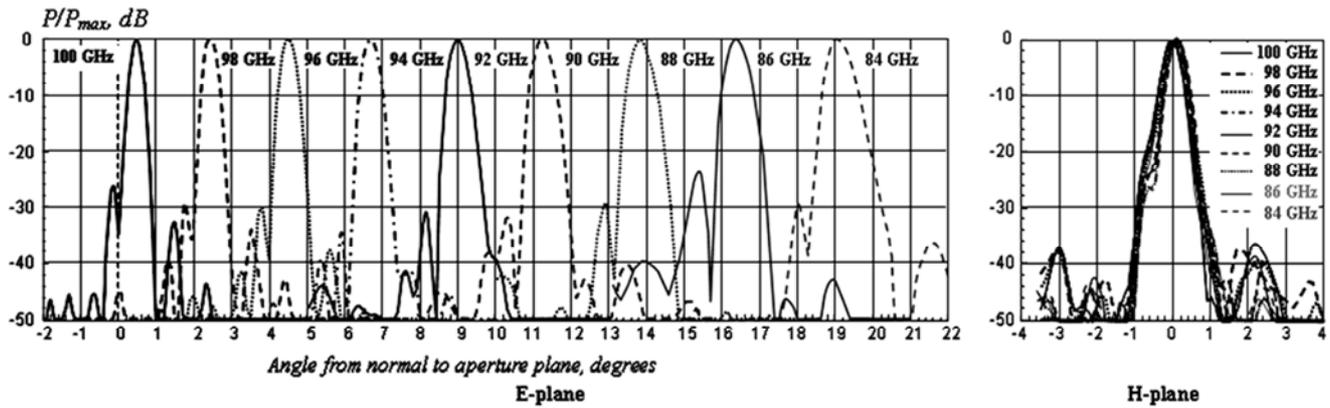


Figure 10. Directional patterns measured at different frequencies at the band for planar ADR with two-tier scheme (Figure 7).

Table 1. Parameters of the developed planar ADR.

Parameter	Value for variants		
	I (Figure 7)	II (Figure 8)	III (Figure 9)
Antenna aperture size, H×E	400 mm × 420 mm	∅280 mm	180 mm × 2000 mm
Operational frequency band	84 ÷ 100 GHz	86 ÷ 100 GHz	36 ± 0,1 GHz
Beam width at far field zone (H×E)	0,4°×0,4° (-3 dB, 91 GHz)	0,6°×0,8° (-3 dB, 91 GHz)	4°×0,25° (-3 dB)
Beam waist size at focusing mode, distance 3 m, 91 GHz: H × E, - 3 dB, (-20 dB).	26 mm × 33 mm (60 mm × 90 mm)	45 mm × 60 mm (90 mm × 120 mm)	-
First side lobe level	-23 dB (86 GHz)	-18 dB (91 GHz)	-18 dB
Antenna gain	43 dB (91 GHz)	39 dB (91 GHz)	42 dB
Active loss of antenna	3,2 dB (91 GHz)	2,6 dB (91 GHz)	3,4 dB
Beam efficiency, distance 3 m	0,71 (86 GHz) 0,68 (91 GHz) 0,64 (98 GHz)	0,81 (91 GHz)	-
Sector of viewing angles (from normal to aperture plane)	0,5°÷19° (E)	(0,5°÷17°)×(±17°) (E×H)	-
Scanning rate (revolutions/scans per second)	1÷8	2	0,5
Number of beams (receiving channels)	64	32	1

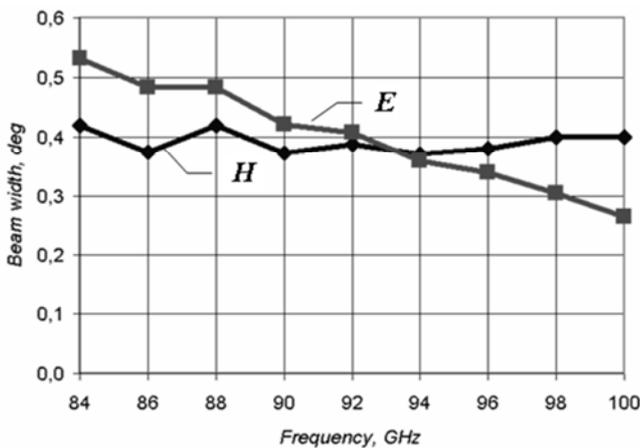


Figure 11. Dependence of beam width from frequency at far field zone (E×H) measured at -3 dB level for W-band planar ADR with two-tier scheme (Figure 7).

6. Discussion of the Results

ADRs belong to the class of traveling wave antennas, the characteristic properties of which are summation of partial electromagnetic fields, which are radiated by separate elementary emitters distributed in space and having different, but rigidly specified phase shifts of the signal due to

successive excitation. Therefore, for such antennas the significant characteristic is the dependence from frequency of angular position of lobes of the directional pattern. When frequency is decreasing, then due to reduction of phase shifts between neighboring elementary emitters, the direction in which summation of partial signals in space occurring with identical phases, has the tendency to be turned to the side of the primary source of the signal.

As the result of inclination of a beam from frequency in the E-plane in accordance with the dispersion dependence (Figure 3), at low frequencies of the operational band simultaneously decreases both the relative aperture size (D/λ) with respect to the length λ of the electromagnetic wave and effective aperture size as projection on the direction of radiation. These effects lead to widening the main lobe in the directional pattern at the case of reduction of frequency of radiation in the selected frequency band. When a wideband of operating frequencies is chosen, changes of the beam's width can be substantial. For example, the frequency band of 84÷100 GHz had been chosen for Variant I of ADR (Figure 7). The change in the beam width for the boundary frequencies of the band in E- plane reaches two times (see Figure 11).

This is a penalty for the ability of electronic control of antenna beam position and for ability to scan in space by means of change of the signal frequency. For narrow band or

constant signal frequency operation it is possible to realize potential characteristics of an antenna for selected size of aperture, as was done, for example, for Variant III ADR (Figure 9).

Another distinctive feature of the traveling wave antennae relative to traditional antennas with parallel excitation (mirror, horn, etc.) is the elevated level of active losses that occur both with higher frequency operation and with aperture size enlargement. In the MMW band this could be several decibels of additional losses. During the research it was discovered that the conversion factor of a volumetric electromagnetic wave to the surface wave of the PDW may reach an index close to unity, in other words the process of transformation proceeds almost without active losses. However, there are additional losses in waveguide elements. These losses are due to energy absorption in the metal walls of the waveguide elements; for the ADR, these are metal walls of the HPT, losses at the surfaces of the PDG' combs, and losses in dielectric material of the PDW. Relative portions of absorption between these elements for the developed ADRs may be conditionally characterized by a ratio of 1: 2 (HPT to PDW), i.e. the main active loss in such kind of antenna is related to the quality of the utilized dielectric material. It is expected that with progress in this field of chemistry and the emergence of new dielectric materials with improved level of dielectric losses in the MMW band may lead to significant improvement in the overall loss of the ADR. It should be noted, that the level of active losses in the waveguide elements of the planar ADR could be compared with two-dimensional waveguide-slot antenna arrays with sequential excitation of slots. At the MMW band, due to lower losses in the dielectric material of the PDW relative to regular metal waveguides, and the absence of distributive elements, whose role in the ADR plays for both the HPT and the PDG-PDW system, the total losses of energy in planar ADRs are smaller than for 2D waveguide slot arrays with the same size of aperture.

Other factors causing energy loss in the ADR is the loss on scattering, which is indicated in the efficiency of the beam. It should be noted that in comparison to the traditional types of antennas constructed in two-mirror reflecting designs the ADR does not have both effects of energy dissipation on the second mirror supporting elements and the effects of shading, therefore the main factors influencing the scattering factor are the level of irradiation of the aperture edges and the possibility of generation of additional diffraction lobes due to the excitation of higher types of oscillations in the electrodynamic system PDG-PDW. As that was discovered during research and measurements, the beam efficiency (scattering coefficient) of the ADR may be compared with two-dimensional antenna arrays and with one-mirror and two-mirror reflection type antennas, when they are traditionally executed with non-scalar horn irradiator; achieved beam efficiency of the ADR in the total sector of viewing angles and in the full operating frequency band is at the level of $0,65 \div 0,8$. Moreover, it should be noted that due to peculiarities of construction, the level of far side-lobes and back-lobes in the directional pattern for planar ADR with reflecting PDG in the form of metal combs is

very small and that affects increases of total value of beam efficiency due to these components.

From the point of view of engineering, possibility of forming antenna surface as a plane, i.e. structure with very low depth, is very positive factor that opens abilities for using planar ADRs for number of specific tasks and for their operation in specific conditions of location. These may include the task of observation of space at limited conditions of deployment (on the board of aircraft, on the ship, on the car) and/or in necessity to ensure operation of the system in adverse operating conditions (protection against atmospheric precipitation and wind loads). In such cases, traditionally it's necessary to develop additional protective radio-transparent radomes, which in the MMW band essentially complicate the task of ensuring unchanging parameters of the antenna beam at the sector of observation angles and when operating at a wide band of frequencies. For ADRs in most cases, antennas may be designed in such a way that the PDW may perform as an external radiotransparent "window" of the radar system, which in conditions of additional forced airflow simultaneously provides protection against various atmospheric factors and minimize wind loads on the carrier and mounting elements.

7. Conclusions

Theoretical calculations, technical and technological decisions have already been proved during the development of ADRs in Ka- and W-bands and may be extended without limitations to both lower and higher frequency bands of the electromagnetic spectrum.

Further steps for planar ADRs performance improvement consist in attempts of utilization the newest dielectric materials and in improvement of the components with the aim of providing desirable field distributions across antenna's aperture and in reduction of the level of parasitic lobes in the directivity diagram that determine the overall level of beam efficiency. It may be argued that at present time, based on the existing level of technology, effective ADRs for different purposes may be developed both for active and passive radar systems and for remote sensing.

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