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MODELLING OF THE METAL CORRUGATED-ROD ANTENNA WITH TRANSVERSE RADIATION

The question connected with construction of corrugated-rod antennas, that are proportionate with wavelength with transverse radiation to the main antenna axis are considered in this paper. These issues involve selection of impulse function's width and its period, that especially effects on radiation pattern. Features and operation modes of metal corrugated-rod antenna of length 4λ have been researched by using numerical method. Synphase radiation of two surface waves is appearing when the ratio of impulse function period to λ is in the range from 0.697 to 0.742. In this case the first surface wave spreads in forward direction and the second one propagates in the reverse direction due to reflection from the end of antenna structure and as a result disk radiation pattern has been emerged. Relative geometric design parameters of corrugated-rod antenna are presented. The author has achieved radiation patterns by using computer program MATLAB, three-dimensional modelling of corrugated-rod antenna based on finite element method in HFSS technology and by doing experiment. The comparison of the resulted radiation patterns which have been obtained by using numerical methods and by experiment shows a good correspondence between them.

Keywords: surface wave antenna, radiation pattern, surface electromagnetic wave.

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МОДЕЛЮВАННЯ МЕТАЛЕВОЇ РЕБРИСТО-СТЕРЖНЕВОЇ АНТЕНИ З ПОПЕРЕЧНИМ ВИПРОМІНЮВАННЯМ

У даній роботі розглянуто питання побудови ребристо-стрижневих антен, співрозмірних із довжиною хвилі, які мають випромінювання, поперечне до осі структури. Вони стосуються вибору ширини імпульсної функції та її періоду, що особливо впливає на вигляд діаграми спрямованості. За допомогою чисельного моделювання вивчалися особливості та режими роботи металевої ребристо- стержневої антени довжиною 4λ, отримані розподіли просторового поля в смузі частот. При відношенні періоду імпульсної функції до λ у межах від 0,697 до 0,742 проявляється синфазність випромінювання двох біжучих хвиль, які розповсюджуються в прямому й у зворотному, відбитої від кінця структури, напрямку, що призводить до формування дископодібної діаграми спрямованості. Наведено відносні геометричні конструктивні параметри моделі ребристо-стрержневої антени. Діаграми спрямованості отримані за допомогою комп'ютерного середовища MATLAB, тривимірного моделювання ребристо-стрижневої антени методом скінчених елементів в технології HFSS та в ході експерименту. Порівняння результатів розрахованих діаграм спрямованості з отриманими експериментально показує гарну відповідність одне одному.

Ключові слова: антена поверхневої хвилі, діаграма спрямованості, поверхнева електромагнітна хвиля.

Introduction. Surface wave antennas (SWA) play an important part in the modern radio engineering means of microwave range. The interaction effect of surface electromagnetic wave and structure is existed in SWA which appears in slowing down the electromagnetic wave spreading in it. SWA can be a periodically modulated metal structure or combination of two materials: metal and dielectric. Using slowing down directed structure made of dielectric has several disadvantages: considerable losses, weight and cost increase during growth of wavelength and antenna's size. These disadvantages don`t exist in SWAs in which periodical metal corrugated structure is used instead of dielectric [1, 2]. The explanation of the interaction effect between surface electromagnetic wave and periodical corrugated structure has been presented in the works [3–7]. Metal corrugated rod antennas (CRA) depending on geometrical form are divided into rod, disk and plane ones. The results of modelling infinite periodical corrugated metal structures are known in the literature [7].

The research problem of SWA radiation diagram in microwave and terahertz ranges has significant scientific and practice importance [1,7]. Relatively high level of side lobes is the peculiar feature of these structures. However, the transverse radiation problem of corrugated structures is remained insufficiently researched. One of the ways to make an impact on phase velocity in the structure and on its radiation pattern for acquire transverse radiation is impedance variation along the structure. Mathematical model [7] that adequately describes electromagnetic field distribution of metal-dielectric endless size structures is well-known. In this work the author considers the issues of verifying adequacy of such a mathematical model for radiate structure commensurate with *λ*, in which the emission effect is observed with the propagation wave that is being spread in forward direction and also the wave which is being reflected from the end of the structure. There is a way to reduce the effect of the surface wave reflected from the end of the structure on the radiation pattern, which consists in placing an absorbing matched load at the end of the structure. In this case efficiency coefficient is being decreased due to the part of useful energy is being consumed by load.

In connection with the increase of the interest to plasma antennas in the last years, the author believes that the using of plasma as rod of CRA is possible and relevant. It allows to obtain principally new elements of infocommunication means, e.g. interferometers, collimators and radiation means for using in the hidden radar systems [8-11]. It has been analysed to research the possibility of the electric contact influence between metal radial rings and metal rod of CRA on the radiation.

The goal and the problems of this research. The goal of this work is the research of CRA far-field pattern with transverse radiation using MATLAB and development three dimensional model of such a structure in HFSS technology. It is necessary to examine experimentally the acquired results based on theoretical investigations.

The goal can be achieved in two ways. The resolving of this problem by using mathematical model which describes far-field pattern of periodically modulated metal-dielectric structure has been shown in the first chapter. The resulting radiation patterns indicate efficiency of such a structure while giving constructed parameters. The solution of the problem has been obtained in the second chapter by using software Ansoft HFSS. This technology gives effectively sufficient opportunity to resolve electrodynamics problems for objects that are characterized by complex structure and geometrical shape using the finite element method. The metal CRA model has been developed and the field distribution has been calculated for such an antenna. The comparative analysis of the acquired results points in similarity of character of radiation patterns, which have been received by two methods. The author has made experimental investigation of CRA for verifying the numerical result adequacies.

Modelling of metal corrugated-rod antenna. The strict solution results of electrodynamics problem of excitement of MDS by outside field source has been used as mathematical model and presented in the papers [12, 13]. Such a mathematical model correctly describes MDS on the basic of what it is possible to construct SWAs and CRAs. The results of the field distribution calculation of MDS of infinite sizes based on rectangle impulsive functions shown in the work [7].

Problem formulation of excitement of metal-dielectric structure by the outside field source. Let the infinite plane, which is boundary section of two environment 1 and 2, be characterized by impedance boundary condition [7, 14, 15]:

$$Z_{E(y)} = \frac{E_{y(y)z=0}}{H_{x(x)z=0}}, \tag{1}$$

where E_y and H_x – components of the electric and, respectively, magnetic fields.

Let accept that distribution of the outside sources of field is located in the volume V' with transverse section square $S(y', z')$ and surface impedance value $Z_{E(y)}$ don't depend on coordinate x. It allows to use representation of the field in the upper half space ($z \geq 0$) in the form of an overlay of two-dimensional electric and magnetic waves [7].

Consider the field of electric waves (E-waves). We write impedance bound condition (1) for total E-waves field which consists of the outside sources field and field reflected from plane (fig. 1) as an initial relationship in such a view [7, 12]:

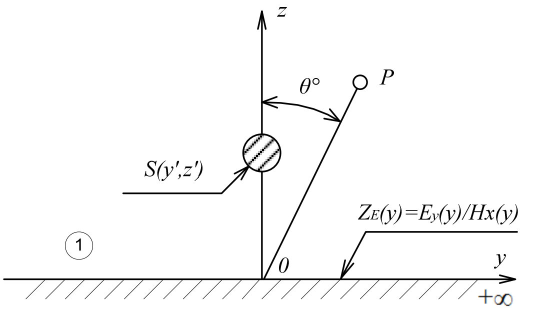

Fig. 1. Modulated impedance plane

$$Z_E(y) = \frac{i}{\omega\varepsilon_a'} \frac{\int_{-\infty}^{+\infty}\left[f_1(\chi) - F^e(\chi)\right]\frac{e^{-i\chi y}}{\chi}d\chi}{\int_{-\infty}^{+\infty}\left[f_1(\chi) - F^e(\chi)\right]\frac{e^{-i\chi y}}{\chi\sqrt{\chi^2 - k^2}}d\chi}, \tag{2}$$

where $F^e(\chi)$ – spectral density of distribution function of extraneous sources for E-waves; $f1(\chi)$ – spectral density of reflected field; k – free space wavenumber; $k = 2\pi/\lambda_0$; λ_0 – free space wavelength; $k^2 = \omega_2 * \varepsilon_a * \mu_a$; χ – generalized space-number (rad/m); ω – angular frequency (rad/s); $\omega = 2\pi/T$; T – period of electromagnetic source`s oscillations; ε_a, μ_a – permittivity and permeability of environment; the outside source field defines $F^e(\chi)$, that occupies volume V' [15]:

$$F^e(\chi) = \frac{1}{4\pi}\oint\left[\frac{\chi^2}{i\omega\varepsilon_a'}\dot{j}_z^E - i\chi\left(\frac{\pm\sqrt{\chi^2 - k^2}}{i\omega\varepsilon_a'}\dot{j}_z^E + \dot{j}_x^M\right)\right]e^{i\chi y' * \sqrt{x^2 - k^2}z'}dy'dz', \tag{3}$$

where $\dot{j}_z^E, \dot{j}_y^E, \dot{j}_x^M$ – given outside electric and magnetic current distribution.

We formulate the problem of analysis in such a setting.

Let the surface impedance distribution $Z_{E(y)}$ to be described by mathematical model:

$$Z_{E(y)} = Z_0 + Z_{M1}\sum rect\left(\frac{y - n * d_1}{\Delta}\right), \tag{4}$$

where Δ – impulse function`s width; $d_1$ – period of subsequence of impulse function ($d_1 = 2\lambda$, $3\lambda$, $5\lambda$, $10\lambda$); $n$ – infinite subsequence of integers; $Z_{M1}$ – amplitude of rectangular impulse function; $Z_0$ – surface impedance`s direct component; $rect$ – operator which gives the shape of impulse rectangular functions. The law of surface impedance distribution is shown in the graphical view on fig. 2.

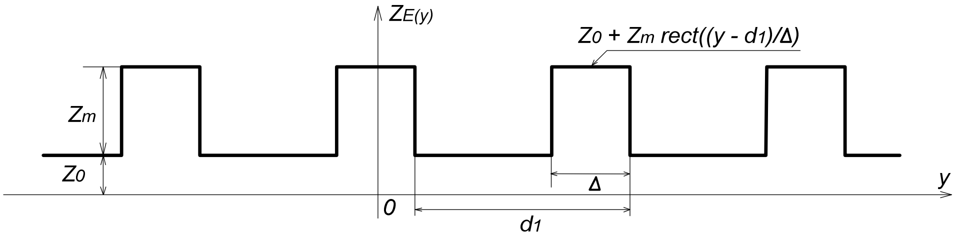

Fig. 2. The law of surface impedance distribution

It is necessary to find the E-waves field in the upper half-space of plane ($z \geq 0$), that satisfies impedance boundary condition (2).

Problem solving of the metal-dielectric structure`s excitation by the outside field source as a magnetic current ring. Let MDS has been excited by the outside field source as a magnetic current ring that lies on the structure perpendicularly to modulation direction of structure by periodical inhomogeneouses as the impulse rectangular functions. Such an outside field source is convenient to implement technically in the microwave and terahertz wavelength ranges based on MDS. The magnetic current ring is convenient to implement as slot transmission line by using dielectric lining which relative permittivity is ε_a. We have substituted spectral density of magnetic current density in the relation (2), according to the problem solving method that is presented in the paper [15].

The problem solving of excited periodically inhomogeneous MDS by the arbitrary outside source field has been obtained in the work [13] in the next view:

$$\xi_1(\chi) \cong \xi_0(\chi) - G(\chi) * \frac{Z_{M1}\frac{\Delta}{2d_1}\sum_{n=-N}^{N}\xi_0(\chi - n_1T_1)\,sinc\left(\frac{n_1\pi\Delta}{2d_1}\right)}{D_{1,\Delta}(\chi)}. \tag{5}$$

The first expression describes spectral density of field which has been reflected from the plane with direct impedance (5). The second expression describes the field spectral density that is emerged due to impact of periodical modulation to main surface wave field.

Let MDS is described by relationship (1) and is excited by current source as a magnetic current ring with coordinates:

$$z = 0,\ y = 0;$$

$$J_x^M(x, y) = I_{x_0}^M rect\left(\frac{x}{b}\right)\delta(y - 0). \tag{6}$$

Substitution (6) to (3) has given an expression for spectral density of the outside field sources` function of distribution as:

$$\Phi(\chi_1) = \Phi(\chi_1 - n_1T_1) = -i\left(\frac{I_{x_0}^M}{4\pi}\right) = \Phi_0;\ \Phi(\chi_2) = \Phi_0 sinc(b * \chi_2). \tag{7}$$

It is proved in the work [12] that in case spectral density of direct field source is immutable, the spectral density $\xi_1(\chi)$ is described by expression:

$$\xi_1(\chi) \cong \Phi_0\varphi_0(\chi)\varphi_{1,\Delta}(\chi), \tag{8}$$

where:

$$\varphi_0(\chi) = \frac{2}{\beta_0(\chi)};\varphi_0(\chi) = \frac{1}{D_{1,\Delta}(\chi)};\Delta \ll \lambda. \tag{9}$$

Substitution $\chi = k\cdot\sin(\theta^\circ)$ to (7) gives the next analytical expression for space field distribution calculation of MDS:

$$\hat{E}(\theta^\circ) = \frac{\cos(\theta^\circ)}{\left[\cos(\theta^\circ) - \hat{Z}_0\right](1 - \hat{Z}_1\frac{\Delta}{2d_1} * \sum_{n=-N}^{N}\frac{sinc(\frac{n\pi\Delta}{2d_1})}{\sqrt{(\sin(\theta^\circ) - \frac{n\lambda}{d_1})^2 - 1 - \hat{Z}_0}})}, \tag{10}$$

$$E(\varphi^\circ) = \Phi_0\left|sinc(\sin(\varphi^\circ) * \frac{b}{\lambda)}\right|, \tag{11}$$

where λ – free space wavelength;

Δ – impulse function`s width (fig. 2);

d_1 – period of impulse function`s subsequence (fig. 2);

$\hat{Z}_0$ and $\hat{Z}_1$ – normalized values of surface impedance which is determined by permittivity`s magnitude of plate and its thickness, that is varying with periodical law along MDS.

The mathematical model (10) is an analytical functional dependency that describes normalized value of the electric field E depending on the angle of observation θ° for given parameters of MDS's construction. The mathematical model (11) – depending on angle φ°. Computer model has been developed on MATLAB software based on mathematical model (10).

The main advantage of this mathematical model is that it has been obtained in analytical view. It has simplified the development of computer model.

The author has researched an impact of MDS's parameters: width and period of impulse function on SWA's field distribution. Radiation patterns of MDS are shown on fig. 3 and fig. 4. Radiation patterns have been acquired with $d_1/\lambda = 0.712$ on fig. 3.

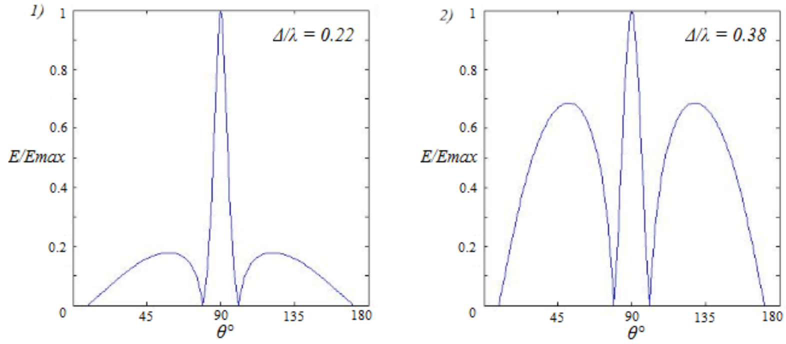

Fig. 3. Radiation patterns with $d_1/\lambda = 0.712$

The analysis of fig. 3 allows making the conclusion that impulse function's width has an effect on radiation pattern of SWA, which is revealing itself in growth of side lobe levels during ratio increasing of the impulse function's width in λ.

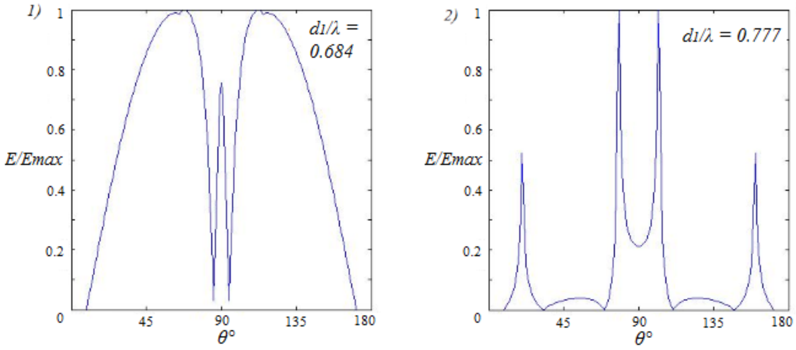

Fig. 4. Radiation patterns with Δ/λ = 0.38

As it can be seen on fig. 4 the influence of MDS's geometric sizes is appearing in splitting of the main lobe during increasing of relative period of inhomogeneouses. Narrowly focused radiation of main and side lobes of examined antenna has been appeared. This effect can be used during development of high resolution interferometers based on SWA.

The mathematical model (10) does not take into consideration reflected surface wave from the end of the structure. It is necessary to maintain synphase radiation of forward and reflected surface waves by structure during designing of finite size SWA's model. The major problem for developer is to support the radiation by elements which are also included to SWA's structure of equal amount's energy. In the next chapter the author has designed CRA's model which has taken into consideration these factors.

Modelling of metal corrugated-rod antenna with transverse radiation. Dielectric slowing structures have some disadvantages as it has been noticed earlier so as a result the author has replaced dielectric with a system of metal rings. The example of corrugated-rod construction of a surface wave structure has been shown in the work [1]. The dependence of propagated coefficient *P* from corrugated-road structure's design of a surface wave is presented in the table 1.

Corrugated surface depending on its geometrical sizes can be considered as artificial dielectric layer in which slowing of surface wave's velocity is occurred accordingly to table 1.

Table 1

Measured relative propagation constant on a corrugated-rod antenna

№ п/п	**$(D - d)/\lambda$**	**P**	**№ п/п**	**$(D - d)/\lambda$**	**P**
1	0.15	1.03	6	0.275	1.23
2	0.175	1.05	7	0.30	1.31
3	0.20	1.08	8	0.325	1.47
4	0.225	1.12	9	0.35	1.67
5	0.25	1.16	10	0.375	1.92

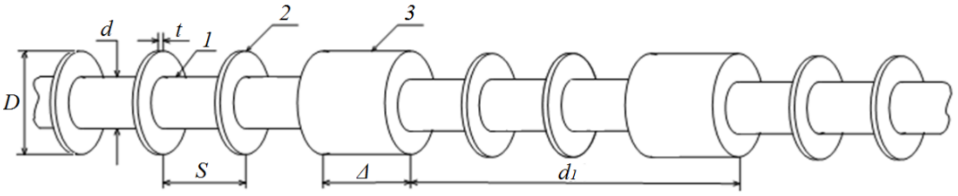

Fig. 5. Metal corrugated-rod antenna's structure

As it can be seen on fig. 5, CRA's structure consists of metal rod (1), metal radial rings (2) and radiating metal radial inhomogeneouses (3). Several examples of SWA's power supply with different design have been discussed in the work [2]. In the authors' opinion [2] it is sensible to excite rod antennas by a horn or a vibrator. In this article the CRA has been excited by the conical horn from what the wave has been transmitted to structure of cylindrical surface wave that has been directed along metal corrugated rod. The surface wave is exciting longitudinal ring magnetic currents in metal radial inhomogeneouses when they are presented along the rod. These currents cause spreading and radiating of space harmonic spectrum by CRA's structure. At the same time, the surface wave (the main space slowing harmonic of the field) is losing its energy for reradiation by metal radial inhomogeneouses during the spreading along corrugated rod of CRA. The period d_1, that is equal to distance between metal radial inhomogenouses, also equals the length of surface wave in CRA. The author has developed CRA's model of length 4λ with transverse radiation. It consists 4 metal radial inhomogenouses of length Δ_i.

The lengths of each metal radial inhomogeneous Δ_i, that have been obtained as a result of radiation pattern form's optimization, are presented in the table 2. Such lengths maintain equal energy that is radiated by each metal radial inhomogeneous.

Table 2

The lengths of each metal radial inhimogeneous

№	1	2	3	4
Δ_i/λ	0,216	0,3	0,372	0,25

The electromagnetic field distributions of CRA at different relative structure's sizes that have been obtained by finite element method in the HFSS technology have been shown on the fig. 6. The summed field in the CRA's far field is a result of outside source field`s overlaying and field of induced polarization currents in a metal radial inhomogeneouses. The radiation patterns have been computed for structure with parameter $(D - d)/\lambda = 0,31$ on fig. 6.

The radiation patterns have been obtained at length of CRA 4λ. As it can be seen on fig. 6 the direction of the main lobe ranges from 78° to 85° depending on ratio d_1/λ. The width of radiation pattern varies from 20° at $d_1/\lambda = 0,697$ to 19° at $d_1/\lambda = 0,742$. When comparing fig. 4 and fig. 6 it is seen that periodically modulated MDS of finite sizes is characterized by bigger width of radiation pattern's main lobe than MDS of finite sizes. In this case the level of side lobes is much smaller.

Experimental research of metal corrugated-rod antenna. The author has designed CRA's experimental sample of length 4λ which is supported by horn with $d_1/\lambda = 0,712$ and the dimensions of the metal radial inhomogeneouses Δ_i that are shown on table 2 for verification and correspondence of the developed numerical models.

A measuring stand has been used for experiment. It has given the opportunity to record CRA's field distribution, estimate side lobe levels, width and shape of the main lobe, fix «zeros» of radiation pattern. The measurement has been done in an anechoic chamber the walls of which are covered by radio absorbing material for impact's decreasing of external noise and reflected electromagnetic waves.

The dependence of standing wave ratio (SWR) on frequency f has being obtained during experiment (fig. 7).

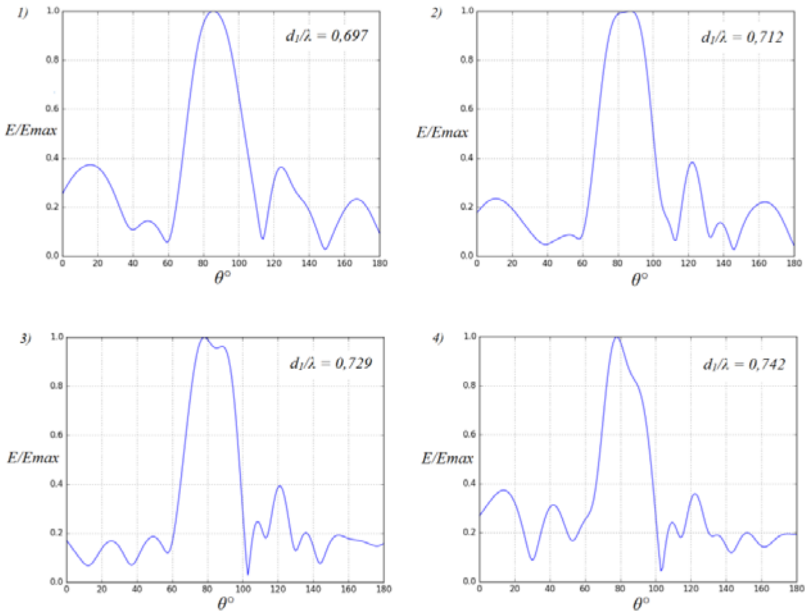

Fig. 6. Radiation patterns of corrugated-rod antenna

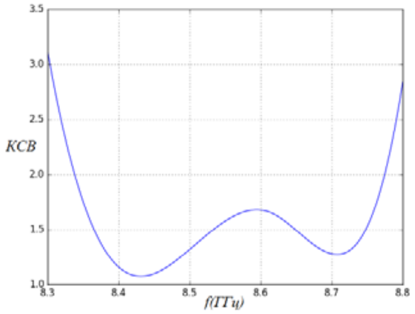

Fig. 7. The dependence of standing wave ratio on frequency

As it can be seen on fig. 7, operating wave frequency is ranged from 8.33 to 8.77 GHz on the SWR's level = 2. The author has being acquired radiation patterns (fig. 8) during experimental research.

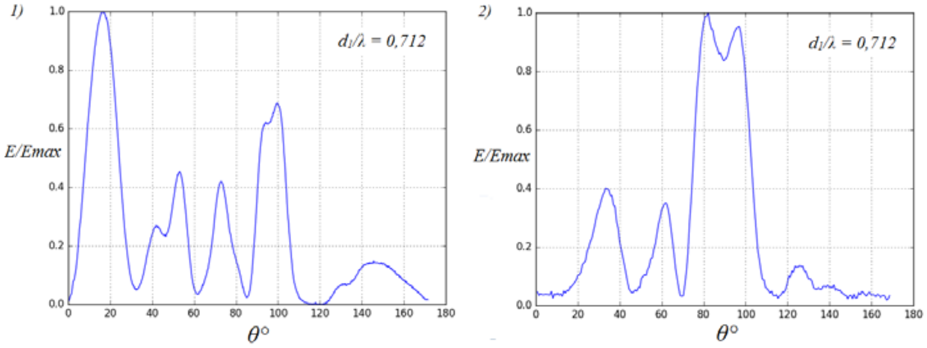

Fig. 8. Radiation patterns of metal corrugated-rod antenna:
1 – without electric contact between metal radial rings and metal rod; 2 – with electric contact between metal radial rings and metal rod

Close to transverse radiation is observed at the angle 97° on the fig. 8.1. The main lobe`s width is 16°. The considerable side lobe is appearing also at the angle 17° which is missing on the fig. 8.2. It has been established that the considerable side lobe is appearing in the case of missing electric contact between metal radial ring and metal rod. Transverse radiation to the main antenna axis at d_1/λ = 0,712 is appearing while the electric contact exists between metal radial ring and metal rod of CRA (fig. 8.2). In this case the main lobe`s width is 25°. The negligible splitting of the main lobe is observed that confirms the obtained results during computer modelling.

Summary. The author has developed numerical and computer corrugated-rod antenna's models with transverse radiation. Constructive dimensions for obtaining of transverse radiation pattern of finite length structure have been calculated in the current paper. Load`s absence in corrugated-rod antenna's construction at the end of the structure gives the opportunity to use reflected surface wave from the structure's end for its synphase radiation with propagated surface electromagnetic wave from source. It can be used for increasing of corrugated-rod antenna's energy conversion efficiency. The radiation patterns of the structure that have been calculated basing on two models are similar by form. At this time the expansion of the main lobe, which is caused by finite length of structure, has been observed. The author has examined radiation pattern during the changing of corrugated-rod antenna's constructive parameters. The amount of side lobes have being increased proportionally to increasing of impulse function's period. Experimental research of corrugated-rod antenna's sample of length 4*λ* has been done for adequacy models` confirmation. The operating frequency band of corrugated-rod antenna's sample is 5%.

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