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Synthesis of Plasma Corrugated-Rod Antenna for Multi-Gigabit Wireless Technology

Ivan Teplyakov [1,a,*], Viktor Hoblyk [1,b], Oleksiy Liske [1,c], Irina Gado [1,d], Serhiy Maslakov [1] and Ivan Pylypiak [1]

[1]*Department of Electronics and Information Technology, Lviv Polytechnic National University, Lviv, Ukraine*

*a. teplyakov.iu@gmail.com, b. vhoblyk@gmail.com, c. liske2017@gmail.com, d. ira_nychai@i.ua, *corresponding author*

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Abstract: This paper deals with synthesis problem of corrugated rod-antenna by induced electromotive force method for using in gigabit wireless technology. The authors have interpreted survey corrugated rod-antenna as isotropic dipole system and open interpreted programming language «Python» has been used for automatic synthesis of corrugated-rod antenna. Normalized amplitude radiation patterns for different supply voltage of dipoles have been calculated in polar coordinate system. The authors executed experimental investigation of field distribution of corrugated rod-antenna length $4\lambda_0$ in which plasma discharge is used as the component of the structure. Adequacy of implemented numerical model has been verified using the comparative analysis method.

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1. Introduction

Recently, Internet of Things (IoT) has emerged as the promising concept, which can improve the living experience of people in nearly every aspect. It is defined as a global network, which connects billions of things to the Internet. IoT is expected to leverage the future self-configuring infrastructure based on 5G, all-optical networks and mobile cloud computing [1-5].

Nowadays there exists a possibility to develop wireless systems for multi-gigabit technologies based on Wi-Gig standard. Multi-gigabit wireless means contain plasma antenna systems as network components for the 4G/5G mobile infrastructure, operating in the 2.4, 5 and 60 GHz bands [6]. Antenna systems based on plasma can provide a faster rate of data transmission, e.g. networks that consists of plasma antennas can transmit data at speeds from 1 to 7 gigabits per second [7]. It is known that the solid state plasma antennas can be used in multi-gigabit technologies. But there is not enough knowledge about using of similar plasma antennas which characterized by complex form of surface impedance. The results of numerical simulation and experimental investigations of plasma antennas in which propagation of surface electromagnetic waves happens in smooth dielectric tube that contain mercury, surface impedance of which is unchangeable along the whole structure, is good known in the literature [8-12]. Instead, there are not enough researches of plasma antennas which has complex design of surface impedance. Corrugated-rod antennas (CRA) can serve as such antenna prototype in which surface impedance varies according to the pulsed law and metal rod is replaced by plasma.

The class of surface wave antennas (SWA) includes dielectric rod antennas, spiral antennas, impedance antennas, planar antennas and Uda-Yagi antennas, among which the CRA occupy a special place [13]. Such antennas are characterized by design simplicity, small cross-sectional dimensions and dielectric absence facilitates high energy conversion efficiency, small weight and low loss. The unique properties allow to use CRA on the upside of flying spaceships, which need to provide directional radio link with Earth [14, 15].

Currently SWA simulation methods based on solving of Fredholm integral equation of the second kind have been developed in antenna theory. The results of distribution field modeling of SWA were shown in the papers [16-18], where mathematical models (MMs) in the form of continued fraction had been obtained. The main disadvantage of such MMs is that the high calculation accuracy of field distribution will be provided in case the length of the structure is much longer than the wavelength. The reason is that MMs describe field distributions of infinite long structures in which reflected surface electromagnetic waves don`t exist. Instead computer-aided design (CAD) of high frequency structures, e.g. CST Microwave Studio, Ansoft HFSS, COMSOL Multiphysics, AWR Microwave Office, EMpro etc. have become widely used in industry. The work [19] has presented comparative analysis of modeling results of plane antennas which had been obtained in different CAD. As can be seen, the main disadvantages of these CAD are connected with considerable time loss for electromagnetic characteristic calculation of microwaves devices, requirement of license and high computer efficiency. In this case, investigate necessity of new mathematical methods which are available for effective calculations of field distribution of finite size SWA arises.

Literature analysis has revealed that the questions which are associated with using of induced electromotive force (EMF) method for calculation of field distribution of SWA are insufficiently studied. This method is efficient for planar, Uda-Yagi, array antenna synthesis and calculation results are close to experimental [19-23]. It is known that SWA is similar to Uda-Yagi antennas in the form of field distribution, thereby metal ring system, which are connected to central rod, can be interpreted as dipole system [15]. Then two paths can be used to calculate the radiation pattern (RP) of CRA: 1) use the approximate theory of symmetric dipole; 2) the metal ring system with central rod can be interpreted as cylindrical impedance slow structure.

Summing up what has been said, the main task of this paper is the development of plasma CRA model using induced EMF method and result adequacy will be verified experimentally. This task is actual because it has important practical meaning for development of gigabit wireless technology based on WiGig standard and efficiency improvement of existent radio hidden appliances.

2. Synthesis of Plasma Corrugated-Rod Antenna

The basic mathematical relations that had been used for field distribution calculation by induced EMF method have been presented in this chapter. The authors have chosen CRA of length $4\lambda_0$ for numerical modeling and experimental research. Structural model of investigated CRA, which consists of metal rod (1), fourteen plane ring (2) that are used as artificial dielectric for slowing surface electromagnetic wave and four metal radial heterogeneities (3), is shown on fig.1a in coordinate system XYZ. Metal radial heterogeneities were interpreted as system which consists of N isotropic dipoles of length l_i and radius $a \ll \lambda_0$ (fig.1b).

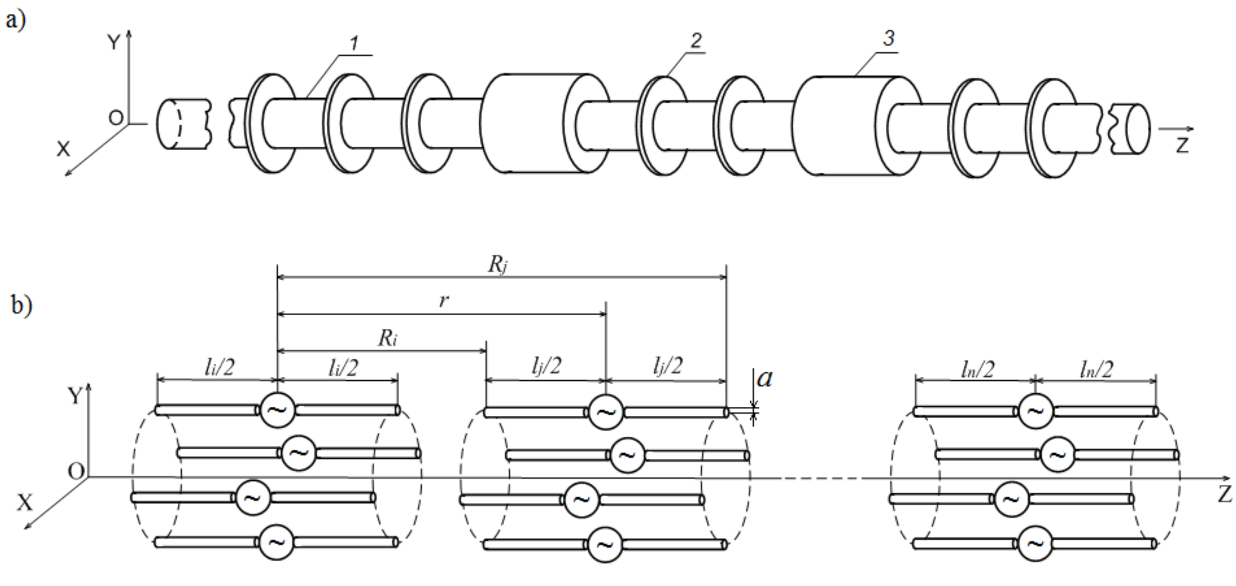

Figure 1: Structural (a) and calculative (b) models of corrugated-rod antenna

2.1. The basic mathematical relations

According to the principle of pattern multiplication, electric far field $E(\theta)$ in CRA can be defined in the form of vector complex radiation pattern multiplication of one element and scalar directional multiplier. In this article CRA synthesis has been fulfilled by the general algorithm, which is described in the works [15, 21, 23]:

1. If the dipole is thin and its length is approximated to half-wave dipole, current will be submitted in the form:

$$I = I_n * \sin(k * (l_n - |z|)), \tag{1}$$

where: I_n – unknown current amplitude on n-th dipole; l_n – half of dipole length; $k = 2\pi/\lambda$ – wave number of medium which surrounds the radiator the radiator.

2. The unknown amplitude values of current can be calculated using matrix equations for voltages and currents if dipoles will be in the fixed state:

$$\begin{pmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{pmatrix} * \begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{pmatrix} = \begin{pmatrix} U_1 \\ U_2 \\ \vdots \\ U_n \end{pmatrix}, \tag{2}$$

where: $Z_{nn} = R_{nn} + jX_{nn}$ – self impedance; $Z_{mn} = R_{mn} + jX_{mn}$ – mutual impedance.

3. Next equations can be used for calculation unknown real and imaginary parts of self and mutual impedances:

$$R_{ii} = \frac{\eta}{2\pi}\{C - \ln(kl_{ii}) - C_i(kl_{ii}) + 0.5\sin(kl_{ii}) * [S_i(2kl_{ii}) - 2S_i(kl_{ii})] + \\ +0.5\cos(kl_{ii}) * [C + \ln(kl_{ii}/2) + C_i(2kl_{ii}) - 2C_i(kl_{ii})]\}, \quad (3)$$

$$X_{ii} = \frac{\eta}{4\pi}\{2S_i(kl_{ii}) + \cos(kl_{ii}) * [2S_i(kl_{ii}) - S_i(2kl_{ii})] + \\ + \sin(kl_{ii}) * [2C_i(kl_{ii}) - C_i(2kl_{ii}) - C_i(2ka^2/l_{ii})]\}, \quad (4)$$

$$Z_{ij} = Z_{ij\ in}\sin\left(\frac{kl_i}{2}\right)\sin\left(\frac{kl_j}{2}\right), \quad (5)$$

where S_i, C_i – sine and cosine integrals; C = 0.5772 – Euler's constant; $\eta = 120\pi$ wave impedance of the medium; $Z_{ij\ in}$ – input impedance which is determined by the following ratio:

$$Z_{ij\ in} = j\frac{30}{\sin\left(\frac{kl_i}{2}\right)\sin\left(\frac{kl_j}{2}\right)}\int_{-\frac{l_j}{2}}^{\frac{l_j}{2}}\sin\left[k\left(\frac{l_j}{2}\right) - |z|\right] *$$

$$* \left[\frac{\exp(-jkR_i)}{R_i} + \frac{\exp(-jkR_j)}{R_j} - 2\cos\left(k\frac{l_i}{2}\right)\frac{\exp(-jkr)}{r}\right]dz.$$

4. Unknown current amplitudes on each dipole during solving of matrix equations were being found. Then system multiplier will be found from the next ratio:

$$f_{\Sigma}(\theta,\varphi) = \sum_{n=1}^{N} A_n exp(j * (\Phi_n + k * R_n\,cos\,\alpha_n)), \quad (6)$$

where R_n – the line segment which connects origin of coordinate system XYZ with the n-th dipole input; α_n – the angle between origin to n-th dipole and direction from origin to observation point; A_n and Φ_n – accordingly amplitude and phase distribution.

Voltage along CRA structure are given by the next expression:

$$U(z) = U_0[exp(-\gamma z) + \rho * exp(\gamma z)], \quad (7)$$

where U_0 – voltage amplitude which is conditionally accepted 1 volt; γ = α + jβ – complex propagation constant; α – attenuation coefficient; β – wave number; ρ – reflection coefficient.

Such mathematical representation of voltage along the CRA structure allows to consider return surface wave that has reflected from the end of the structure. It provides the phase difference of additional dipole power taking into account.

2.2. The results of numerical research

Calculative CRA's model is shown on fig.1b and it has been developed in the 2.4 GHz frequency range. The program has been developed on «Python» software for automated calculation self and mutual dipole impedances (3-5), matrix equation solving (2) and result RP calculation of CRA.

As a result, self and mutual impedances have been calculated and presented in table 1 for 16 isotropic dipoles.

Table 1: Self and mutual impedances of 16 isotropic dipoles

№	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	3.9-189.2j	0.7-1.9j	-2.9+3.8j	-0.2 -0.2j	2.1-3.9j	3.0+2.8j	-2.6+3.1j	0.3-0.3j	4.2-3.9j	2.7-2.1j	-16.5 -1.4j	3.4-4.4j	24.4-19.1j	6.5-3.6j	-16.5-1.4j	3.4-4.4j
2	0.7-1.9j	13.2-216.2j	1.5-4.4j	1.0-0.2j	-0.1+1.7j	6.5-11.7j	-0.3+3.6j	-0.2+2j	-0.3-1.7j	12.9-11.0j	3.4-4.4j	-12.1-1.0j	-0.3-1.7j	12.9-11.0j	3.4-4.4j	-12.1-1j
3	-2.9+3.8j	1.5-4.4j	28.3-180j	-3.5-3.8j	0.2-0.1j	-4.5+3.6j	12.2-21.7j	-3.4+2.9j	-6-2.1j	-3.9-3.7j	24.4-19.1j	-4.4-2.4j	-6.1-2.1j	-3.9-3.7j	24.4-19.1j	-4.4-2.4j
4	-0.2-0.2j	1.0-0.2j	-3.5-3.8j	5.8-197.6j	0.3-0.1j	-1.3+0.4j	1.1+5.3j	3.1-5.6j	-8.7-5.5j	-15.6-0.9j	6.5-3.6j	6.1-5.6j	-8.7-5.5j	-15.6-0.9j	6.5-3.6j	6.1-5.6j
5	2.1-3.9j	-0.1+1.7j	0.2-0.1j	0.3 -0.1j	3.9-189.2j	0.7-1.9j	-2.9+3.8j	-0.2-0.2j	4.2-3.9j	2.7-2.1j	-16.5-1.4j	-9.8-6.9j	4.2-3.9j	2.7-2.1j	-16.5-1.4j	-9.8-6.9j
6	3.0+2.8j	6.5-11.7j	-4.5+3.6j	-1.3+0.4j	0.7-1.9j	13.2-216.2j	1.5-4.4j	1.0-0.2j	-0.3-1.7j	12.9-11.0j	3.4-4.4j	-12.1-1.0j	-0.3-1.7j	12.9-11.0j	3.4-4.4j	-12.1-1.0j
7	-2.6+3.1j	-0.3+3.6j	12.2-21.7j	1.1+5.3j	-2.9+3.9j	1.5-4.4j	28.3-180j	-3.5-3.8j	-6.1-2.1j	-3.9-3.7j	24.4-19.1j	-4.4-2.4j	-6.1-2.1j	-3.9-3.7j	24.4-19.1j	-4.4-2.4j
8	0.3-0.3j	-0.2+2.0j	-3.4+2.9j	3.1-5.6j	-0.2-0.2j	1.0-0.2j	-3.5-3.8j	5.8-197.6j	-8.7-5.5j	-15.6-0.9j	6.5-3.6j	6.1-5.6j	-8.0-5.1j	-15.6-0.9j	6.5-3.6j	6.1-5.6j
9	4.2-3.9j	-0.3-1.7j	-6.1-2.1j	-8.7-5.5j	4.2-3.9j	-0.3-1.7j	-6.1-2.1j	-8.7-5.5j	3.9-189.2j	0.7-1.9j	-2.9+3.8j	-0.2-0.2j	2.1-3.9j	3.0+2.8j	-2.6+3.1j	0.3-0.3j
10	2.7-2.1j	12.9-11.0j	-3.9-3.7j	-15.6-0.9j	2.7-2.1j	12.9-11.0j	-3.9-3.7j	-15.6-0.9j	0.7-1.9j	13.2-216.2j	1. 5-4.4j	1.0-0.2j	-0.1+1.7j	6.5-11.7j	-0.3+3.6j	-0.1+2.0j
11	-16.5-1.5j	3.4-4.4j	24.4-19.1j	6.5-3.6j	-16.5-1.4j	3.4-4.4j	24.4-19.1j	6.5-3.6j	-2.9+3.8j	1. 5-4.4j	28.6-180.0j	-3.5-3.8j	0.2-0.1j	-4.5+3.6j	12.2-21.7j	-3.4+2.9j
12	-9.8-6.9j	-12.1-1.0j	-4.4-2.4j	6.1-5.6j	-9.8-6.9j	-12.1-1.0j	-4.4-2.4j	6.1-5.6j	-0.2-0.2j	1.0-0.2j	-3.5-3.8j	5.8-197.6j	0. 3-0.1j	-1. 3+0.4j	1.1+5.3j	3.1-5.6j
13	4.2-3.9j	-0.3-1.7j	-6.1-2.1j	-8.7-5.5j	4.2-3.9j	-0.3-1.7j	-6.1-2.1j	-8.0-5.1j	2.1-3.9j	-0.1+1.7j	0.2-0.1j	0. 3-0.1j	3.9-189.2j	0.7-1.9j	-2.9+3.8j	-0.2-0.2j
14	2.7-2.1j	12.9-11.0j	-3.9-3.7j	-15.6-0.9j	2.7-2.1j	12.9-11.0j	-3.9-3.7j	-15.6-0.9j	3.0+2.8j	6.5-11.7j	-4.5+3.6j	-1.3+0.4j	0.7-1.9j	13.2-216.2j	1. 5-4.4j	1.0-0.2j
15	-16.5-1.4j	3.4-4.4j	24.4-19.1j	6.5-3.6j	-16.5-1.4j	3.4-4.4j	24.4-19.1j	6.5-3.6j	-2.6+3.1j	-0.3+3.6j	12.2-21.j	1.1+5.3j	-2.9+3.8j	1. 5-4.4j	28.3-180.0j	-3.5-3.8j
16	-9.8-6.9j	-12.1-1.0j	-4.4-2.4j	6.1-5.4j	-9.8-6.9j	-12.1-1.0j	-4.4-2.4j	6.1-5.6j	0.3-0.3j	-0.2+2.0j	-3.4+2.9j	3.1-5.6j	-0.2-0.2j	1.0-0.2j	-3.5-3.8j	5.8-197.6j

Based on the calculated values of self and mutual impedances, series of radiation pattern has been computed in the polarized plane of electric field and it had been normalized to the amplitude in a polar coordinate system. As a result, impact of CRA relative length and supply voltage parameters (α and ρ) on field distribution form has been explored.

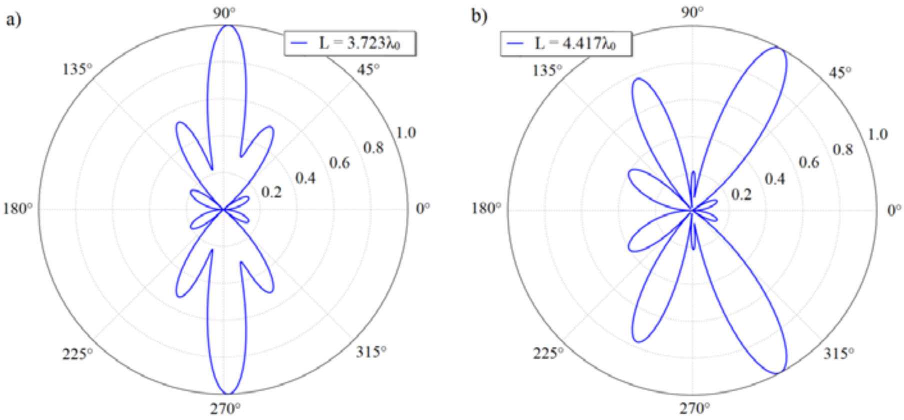

Figure 2: Dependence of field distribution form on relative length of corrugated-rod antenna

Fig.2 has presented investigated influence of CRA relative length on field distribution form. When value of CRA relative length is shorter than $4\lambda_0$ the main lobe is being directed almost perpendicular to the antenna axis. This radiation form is close to discoid form (fig.2a). In the case when value of CRA relative length is longer than $4\lambda_0$ the radiation pattern is being approximated to funnel form and side lobe number and values are being increased simultaneously (fig.2b).

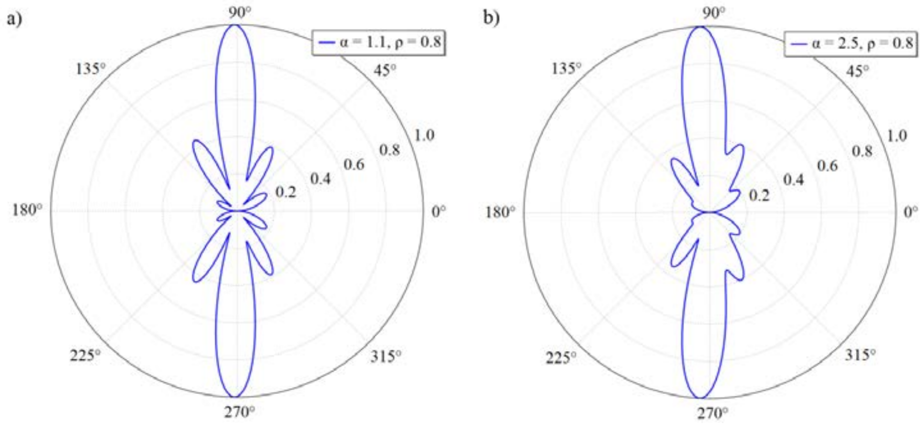

Figure 3: Dependence of field distribution form on attenuation coefficient of corrugated-rod antenna

As can be seen on fig.3, the form of RP is depended from attenuation coefficient of propagate surface wave. Analysis of obtained field distribution has been revealed that main lobes are close to discoid relative to the axis of the CRA. It is being appeared at given values of α and ρ (fig.3a), the deviation from discoid form is being discovered also with increasing the value of the attenuation coefficient (fig.3b). The slight radiation in the form of side lobes is being observed in the both cases and main lobe widths are being reached 20° and 25° accordingly at a level of 0.7.

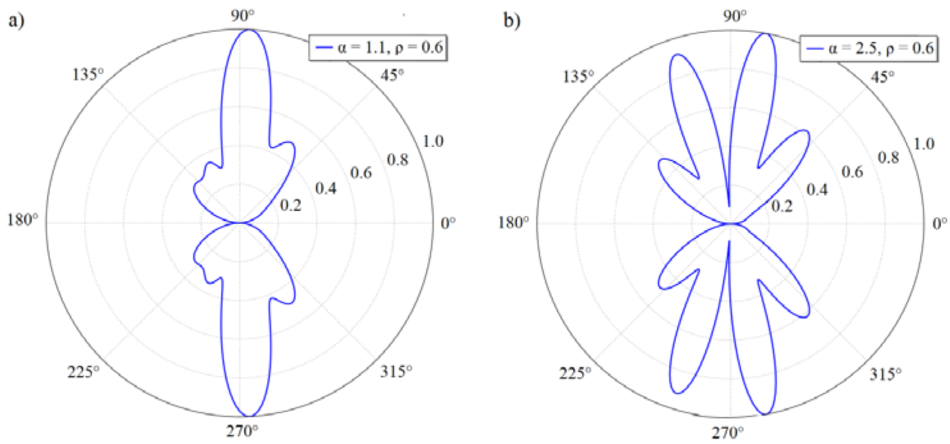

Figure 4: Dependence of field distribution form on voltage parameters of corrugated-rod antenna

Reflection coefficient impact on field distribution form has been demonstrated on fig.4 for values of coefficients which had been discussed previously. It has been discovered using the comparative analysis that direction of main lobe depends on ρ. RP form remains discoid if α is close to 1 but the main lobe angle is being changed and the main lobe's width is increased to 30° at a level of 0.7.

Comparing the numerical modeling results that had been demonstrated on fig.3b and fig.4b it has been revealed that the RP form of CRA has several lobes with a decrease of ρ. At the same time, discoid directed radiation disappears, widths and levels of side lobes significantly are being exceeded the pre-obtained.

3. Experimental research of field distribution of corrugated-rod antenna

Synthesis of CRA by induced EMF method is giving possibility to predict form of field distribution when frequency or voltage parameters are changed but the question about numerical model adequacy to physical situation has been arisen. The authors have developed physical model of CRA with relative length 4λ0 which corresponds to structural model on fig.1a for verification of numerical model adequacy. Excitation of the CRA has been done via cylindrical horn at the input of which an electromagnetic wave of type H_{10} had been supplied from a rectangular waveguide. Implementation of experiment in the isolated camera from external noise provided minimal interference influence closed by electromagnetic wave reflections from the walls. Novelty of development CRA model is that the metal rod had been changed by gas-discharge lamp that is generating plasma while enabled mode.

Fig.5 presents RPs that had been calculated as a result of numerical modelling and experimental research. Electromagnetic field distributions as normalized amplitude of RPs have been computed for values of θ = 0°..180° in the YOZ plane of rectangular coordinate system. Adequacy of numerical model to physical situation has been discussed using comparative analysis method.

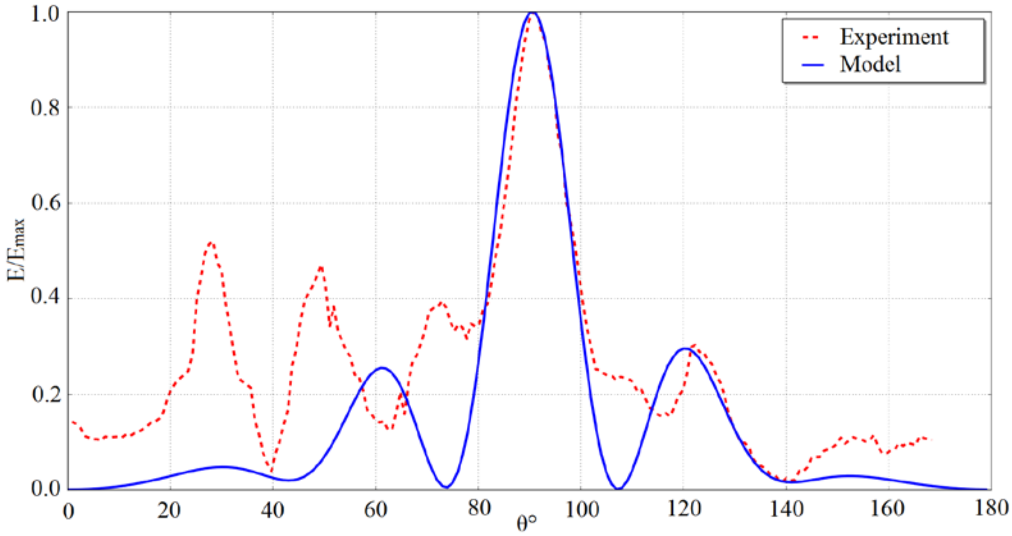

Figure 5: Comparison of experimental and modeling results of field distribution forms

As a result of numerical modeling and experimental research the authors have obtained RPs of CRA. As can be seen on fig.5, RP which was calculated during numerical modeling is represented main lobe that is characterized by perpendicular direction and 15° width at a level of 0.7. Two side lobes are characterized this RP also and side lobe levels don`t overstate 0.3 value at angles of 62° and 120°.

As can been seen on fig.5, the experimental RP is similar to model RP. The main analogy explains by the same direction of main lobes relative to the axis of the RSA and general low level of side lobes. The high levels of side lobes at 28° and 48° degrees can be explained due to interference which appears due to impact of metal horn in CRA structure. The width of experimental main lobe of RP is 13° a level of 0.7.

4. Conclusions

The authors have carried out literature review of modern method of antennas synthesis based on surface waves. As a result it has been researched that induced EMF method for distribution field calculation of corrugated-rod antennas had been unexplored.

This paper has presented structural model of corrugated-rod antenna and developed numerical model which consists of N isotropic dipoles. Basic mathematical relations with calculation algorithm based on induced electromotive force method have been shown. As a result of numerical modeling, normalized radiation patterns have been computed in polar coordinate system and influence of CRA relative length and supply voltage parameters on field distribution form have also been investigated.

The authors have researched possibility of using a plasma discharge as a structural component of a corrugated-rod antenna for the development of new and improvement of the existing telecommunication means.

Open interpreted programming language «Python» that is characterized by convenience, high-speed and the availability of large number of mathematical libraries for the needs of a wide range of applied problems has been used for automatic synthesis of corrugated-rod antenna.

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