Expansion of the band of operating frequencies for antenna radiators using impedance-matched materials

A. S. Godin
R&P Corp. "LEMZ",
Moscow, Russian Federation
andrey.godin@gmail.com,
godin@media-publisher.ru
IEEE Member

K. N. Klimov
R&P Corp. "LEMZ",
Moscow, Russian Federation,
IEEE Member

***Abstract*— A technique is proposed for using impedance-matched materials to expand the operating frequency of existing antenna radiators. The results of numerical electromagnetic modeling and experimental investigation of a waveguide slit radiator, whose operating frequency was expanding.**

Keywords*— *impedance-matched material; impedance of the medium; antenna radiators; bandwidth expansion; dielectric and magnetic permeability.

I. Introduction

The term impedance of the medium was introduced in the work of Schelkunoff [1, 2]. J.A. Stratton in his book considered the solution of the problem of matching impedances of media [3]. Stratton expanded the concept of impedance to electromagnetic fields. He solved the problem of matching impedances of media and showed that in order to avoid reflection of a plane wave from the interface between two media, it is necessary to have equal wave impedances.

Impedance-matched materials are used to decrease the working frequency of already existing patch antennas. One of these radiating elements is explored in Buell's work (2005) [4]. This element is situated in rectangular parallelepiped made of impedance matching material with different values of relative permittivity and relative permeability. Topological layout of this radiating element is shown at fig. 1

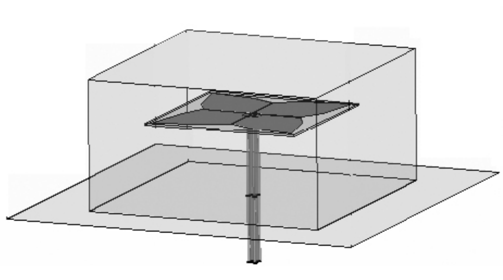

Fig.1. Topological layout of radiating element, placed into the rectangular parallelepiped made of impedance-matched material.

A possibility to narrow frequency band of meander-type radiating element using insertions made of impedance-matched material is examined in Karilainen's work (2012) [5]. The fig. 2 shows the picture of the element and impedance-matched material insertions.

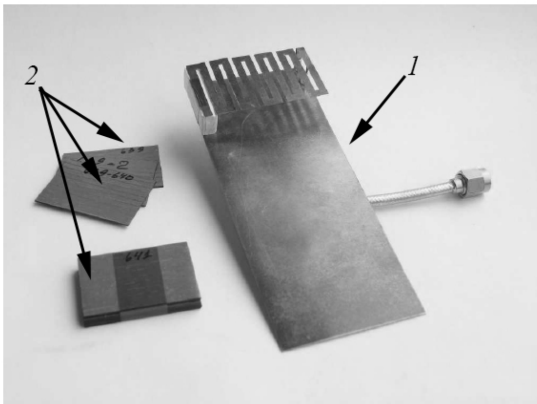

Fig. 2. The picture of meander-type radiating element *1*, impedance matching material insertions *2* change the frequency band.

Parsche's patent (2009) describes the idea of using impedance-matched material to decrease dimensions of the helix-form antenna located on sphere [6]. Fig. 3 shows the topology of Parsche's antenna: circularly polarized omnidirectional antenna *4* is placed into the ball made of impedance matching material *1*. Generator *2* feeds the element using twin-wire line *3*. The diameter of impedance-matched sphere *1* must be by 2π times smaller than the longest operating wavelength of antenna in free space [7]. Circularly polarized omnidirectional antenna *4* decreases by $\varepsilon_r = \mu_r$ times comparing to the similar radiating element developed considering the absence of impedance-matched material. Parshe suggested using Light Nickel Zinc (High Curie Temperature) Ferrite as an impedance-matched material Fig. 4 shows real parts of relative permittivity and relative permeability frequency-response plots of this material [6].

Impedance-matched materials based on spinel materials and hexaferrites are produced by Skyworks Solutions Inc. [8] and Fair-Rite Products Corp [9].

978-1-5386-6474-2/18/$31.00 ©2018 IEEE

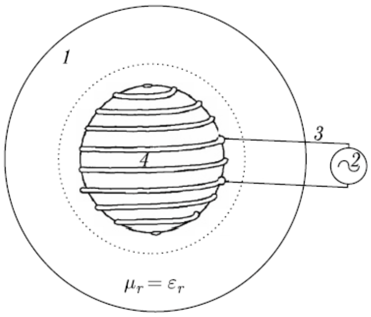

Fig. 3. Parsche's antenna topology.

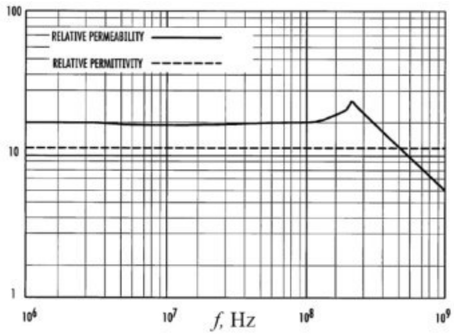

Fig. 4. Frequency-response plots of real parts of relative permittivity and relative permeability of Light Nickel Zinc (High Curie Temperature) Ferrite of Parsche antenna.

II. METHODS OF USING IMPEDANCE-MATCHED MATERIALS TO INCREASE OPERATING WAVELENGHT OF EXISTING RADIATING ELEMENTS

Operating frequencies of radiating elements that had already been produced can be transferred to the bands with greater wavelengths [10, 11]. There are two main requirements to impedance-matched materials to accomplish that:

1) low loss level;
2) ratio of relative permittivity to relative permeability should be within the range from 0.5 to 2.

These properties allow keeping efficiency and VSWR at the desired levels.

The use of impedance-matched materials allows decreasing operating frequency f_0 of existing antennas without changing their dimensions. This effect can be achieved due to the use of impedance-matched material. The radiating element is placed to the sphere made of this material. Its relative permittivity real part is by ε_r bigger than permittivity of vacuum and its relative permittivity real part is by μ_r times bigger than permeability of vacuum. According to the electromagnetic similarity principle [12, 13], because of the wavelength reduction in the impedance matching material by $\sqrt{\varepsilon_r \cdot \mu_r}$ times, working frequency f_0 reduction by $\sqrt{\varepsilon_r \cdot \mu_r}$ times also occurs without changing the dimensions of radiating element. In addition to that, relative frequency Bandwidth $\frac{2\Delta f}{f_0}$ does not change.

Fig. 5 shows topological layout of radiating element *1* in vacuum. This antenna has operating frequencies band $f_0 \pm \Delta f$ and dimensions $a \times b \times c$. The radiating element can be of any type: dipole, slot, horn, parabolic, helical, Vivaldi and etc.

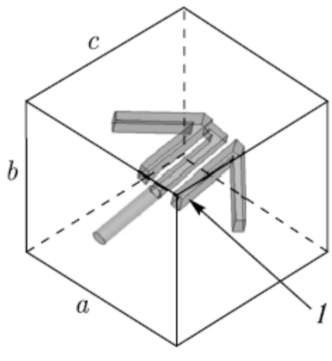

Fig. 5. Topology of the antenna with dimensions $a \times b \times c$.

The chosen radiating element *1* with dimensions $a \times b \times c$ is placed into the ball *2* made of impedance-matched to vacuum material with radius *R* (fig. 6). This impedance-matched material should have the following properties:

1) ratio of real parts of relative permittivity to relative permeability should be within the range from 0.5 to 2;
2) dielectric and magnetic loss tangent should be less than 0.1;
3) Relative permittivity real part is by ε_r bigger than permittivity of vacuum and its relative permittivity real part is by μ_r times bigger than permeability of vacuum.

Radius *R* should be chosen using the following ratio:

$$R \geq \frac{c}{4 \cdot \pi \cdot (f_0 - \Delta f)}, \qquad (1)$$

here: *c* – speed of light in vacuum, $f_0 - \Delta f$ - lower border of the band.

Bandwidth of this radiating element with impedance matching ball is $\frac{f_0 \pm \Delta f}{\sqrt{\varepsilon_r \cdot \mu_r}}$.

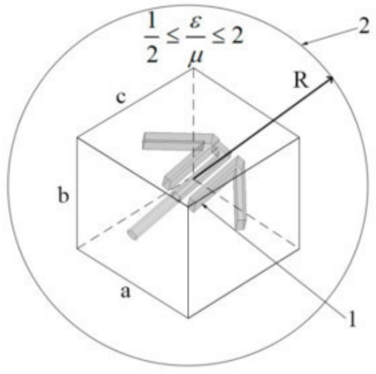

Fig. 6. Topological layout of the radiating element with dimensions $a \times b \times c$, placed into the ball made of impedance-matched material.

III. Numerical Electromagnetic Simulation of Waveguiding Slot Radiator

We are going to carry out electromagnetic simulation of radiating element using program complex ANSYS HFSS v.18.2 to prove the validity of the suggested method [14].

As an example, consider an antenna constructed on the basis of a slot radiator element by a rectangular metal waveguide, in which the lower frequency of the operating frequency range has the value f_0. Topology of waveguiding slot radiating element (WSRA) is shown at fig. 7 [15-21].

Fig. 7 shows WSRA that is situated in the metal sheet *B*. Slot's dimensions are: width $a_1 = \frac{7}{15}\lambda_0$, height $b_1 = \frac{95}{355}\lambda_0$ (fig. 7 a), length $k_1 = \frac{1}{150}\lambda_0$ (fig. 7 b), where λ_0 - the wavelength in free space for a given f_0 - the lower frequency of the operating frequency range of the antenna. The slot is fed by rectangle metal waveguide *A*. Waveguide's dimensions are: width $a = \frac{7}{15}\lambda_0$, height $b = \frac{1}{5}\lambda_0$, length $k = \frac{7}{15}\lambda_0$ (fig. 8).

WSRA is in the vacuum box *C*. Its dimensions are: $a_2 = 2.8\lambda_0$, $b_2 = 2.8\lambda_0$ and $k_2 = 4\lambda_0$ (fig. 9).

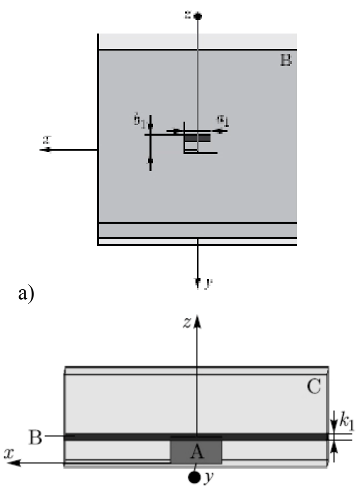

Fig. 7. Topology of waveguiding slot radiating element. Top view.

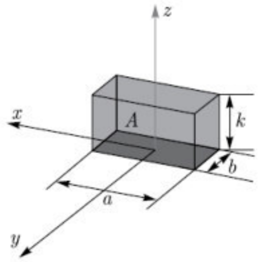

Fig. 8. Topology of rectangle metal waveguide *A*.

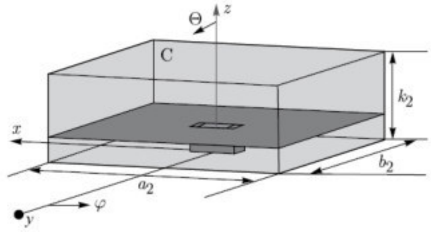

Fig. 9. WSRA topology inside the vacuum box *C*.

Radiation condition is set on the sides of the box [14]. Therefore, WSRA radiation to free space is simulated. On fig. 10 is shown the manufactured WSRA.

Fig. 110. The manufactured WSRA.

On fig. 11 is shown the manufactured and calculated VSWR frequency dependence of WSRA. On fig. 12 is shown the manufactured and calculated Gain frequency dependence of WSRA.

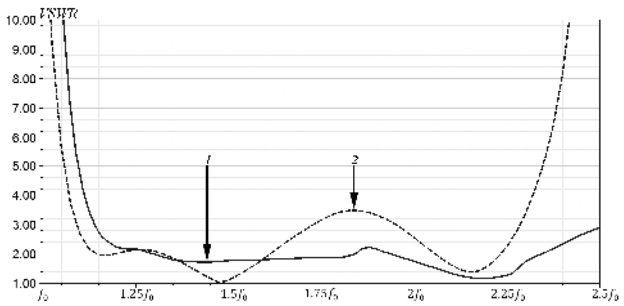

Fig. 11. Experimental (curve *1*) and calculated (curve 2) VSWR frequency dependence of WSRA for frequencies from f_0 to $0.75 f_0$.

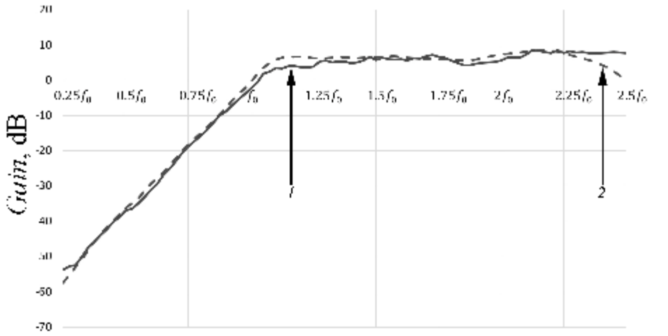

Fig. 12. Experimental (curve *1*) and calculated (curve 2) Gain frequency dependence of WSRA for frequencies from f_0 to $0.75f_0$.

The differences in the experimental characteristics of VSWR and Gain from those calculated are related to the following factors:

- inaccuracy in the manufacture of geometric dimensions of WSRA;
- methodical error of the finite element method in calculating the VSWR characteristic.

As show's from fig. 11 and 12 the value of the frequency characteristic of the VSWR of the experimental WSRA is less than 3 since the frequency $1.14f_0$, a Gain increase from 3.3 dB on frequency $1.13f_0$ to 7.67 dB on frequency $2.5f_0$. The operating frequency range of the described antenna is $1.14f_0$ - $2.5f_0$.

IV. Numerical Electromagnetic Simulation of Waveguiding Slot Radiator and Expanding of Operating Frequency From f_0 To $0.75f_0$

We are going to examine the topology of antenna that is built on the base of the radiating element that was examined before. The original radiator is put into the hemisphere with radius *R* that is made of material whose relative permittivity and permeability are equal 1.5. The options of antenna for $R = 0.4\lambda_0$ will be explored.

Fig. 13 shows the topology of WSRA with hemisphere made of the impedance-matched material. This type of radiator was called «Godin's radiator» [10-11].

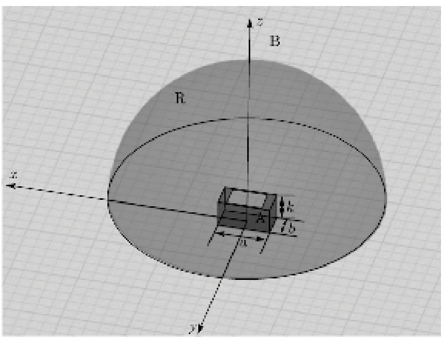

Fig. 13. The topology of «Godin's radiator».

«Godin's radiator» is a radiating element installed in the hemisphere with radius $R = 0.4\lambda_0$ made of material whose relative permittivity and permeability are equal 1.5. The center of this impedance matching hemisphere is united with phase center of radiating element. Operating wavelength of WSRA increases by 1.5 times. Dimensions of the waveguide that excites the slotted radiator remain the same. The material whose relative permittivity and permeability are equal 1.5 also fills this waveguide.

«Godin's radiator» is in the vacuum box *C*. Dimensions of the box are: $a_2 = 2.8\lambda_0$, $b_2 = 2.8\lambda_0$ and $k_2 = 4\lambda_0$.

Boundaries of the vacuum box *C* are signed as radiation so «Godin's radiator» can radiate to free space. On fig. 14 is shown the manufactured «Godin's radiator».

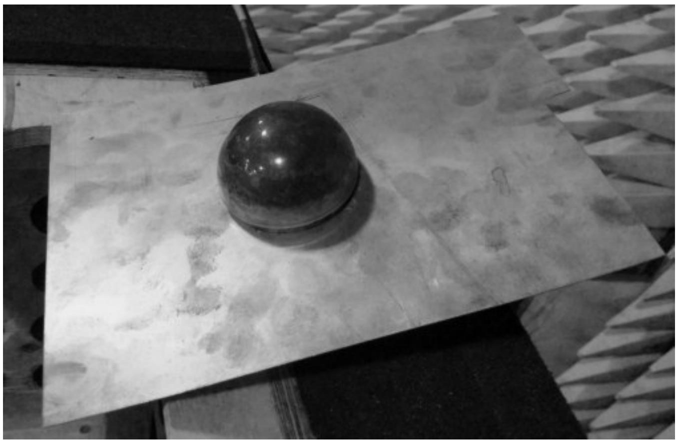

Fig. 14 The manufactured ESA.

On fig. 15 is shown the manufactured and calculated VSWR frequency dependence of «Godin's radiator». On fig. 16 is shown the manufactured and calculated Gain frequency dependence of «Godin's radiator».

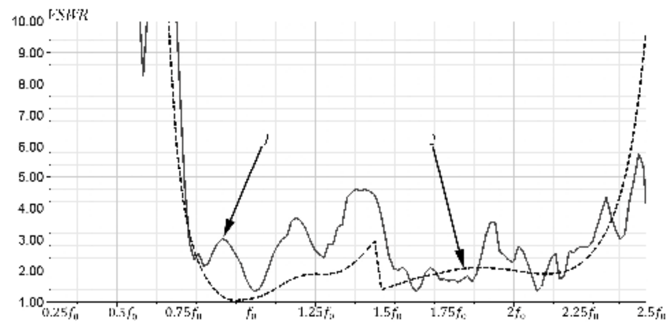

Fig. 15. Experimental (curve *1*) and calculated (curve 2) VSWR frequency dependence of «Godin's radiator» for frequencies from $0.25f_0$ to $2.5f_0$.

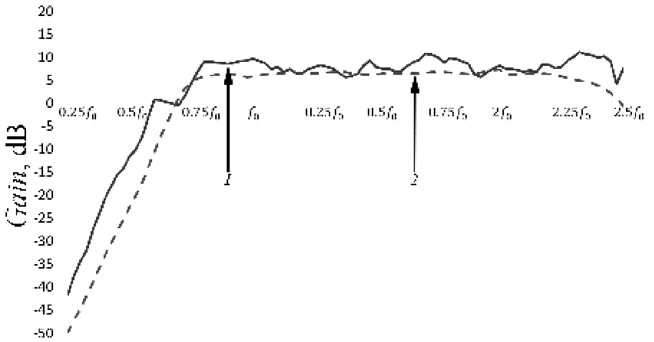

Fig. 16. Experimental (curve *1*) and calculated (curve 2) Gain frequency dependence of «Godin's radiator» for frequencies from $0.25 f_0$ to $2.5 f_0$.

The differences in the experimental characteristics of VSWR and Gain from those calculated are related to the following factors:

- inaccuracy in the manufacture of geometric dimensions of «Godin's radiator»;
- methodical error of the finite element method in calculating the VSWR characteristic.
- inaccuracy in setting the values of the relative permittivity and permeability.

As show's from fig. 15 and 16 the value of the frequency characteristic of the VSWR of the experimental «Godin's radiator» is less than 3 since the frequencies: $0.77 f_0 - 1.12 f_0$; $1.13 f_0 - 1.32 f_0$; $1.52 f_0 - 1.89 f_0$; $1.94 f_0 - 2.3 f_0$. In the whole frequency range from $0.75 f_0$ up to $2.5 f_0$ the value of the Gain exceeds 5 dB. The operating frequency range of the described antenna is $0.77 f_0$ - $2.5 f_0$.

In Fig. 17, we compare the frequency characteristics of the Gain of the «Godin's radiator» (curve 1) and the initial WSRA (curve 2).

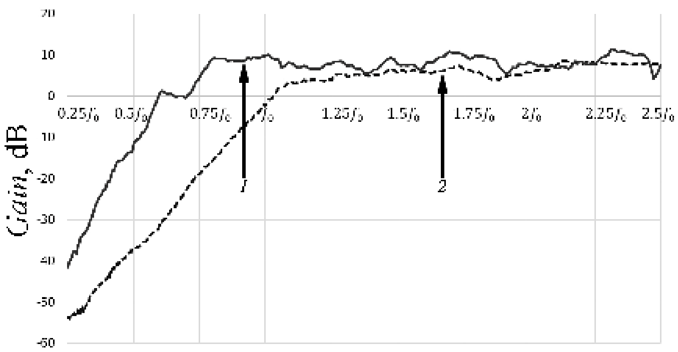

Fig. 17. A comparison the frequency characteristics of the Gain of the «Godin's radiator» (curve 1) and the initial WSRA (curve 2).

As can be seen from Fig. 17, the frequency at which the value of the Gain is zero, has shifted from frequency f_0 to frequency $0.6 f_0$. In the -3 dB level, the Gain value shifted from frequency $0.98 f_0$ to frequency $0.57 f_0$. In the 3 dB level, the Gain value shifted from frequency $1.09 f_0$ to frequency $0.73 f_0$. In the 5 dB level, the Gain value shifted from frequency $1.26 f_0$ to frequency $0.75 f_0$. Almost in the entire frequency range up to $2.5 f_0$, the Gain of the «Godin's radiator» is greater than the Gain of the original WSRA. Thus, the «Godin's radiator» in comparison with the original WSRA not only shifts the operating frequencies, but also increases the value of the Gain.

V. Conclusion

A method is proposed for using impedance-matched materials to extend the operating frequency of existing radiators. The results of numerical electromagnetic modeling were introduced. An experimental radiator of an antenna «Godin's radiator» was made. The main result is that obtained «Godin's radiator» not only shifts the operating frequency but also increases the value of the Gain.

References

[1] K.N. Klimov, "The definition and scope of the parameters impedance matching material", *XIII International Scientific and Practical Conference «Innovation, information and communication technologies»*, 1-10 October 2016, Russia, Sochi, pp. 516-518.

[2] S.A. Schelkunoff, "The Impedance Concept and Its Application to Problems of Reflection, Refraction, Shielding and Power Absorption", *Bell System Technical Journal*, vol. 17, no. 1, pp. 17-48, January 1938.

[3] J.A. Stratton, *Electromagnetic Theory*, Mcgraw Hill Book Company, NY and London, 1941.

[4] Kevin Buell, "Development of engineered magnetic materials for antenna applications", Ph.D. dissertation, University of Michigan, USA, 2005.

[5] Antti Karilainen, "Magnetic materials and responses in antenna applications", Doctoral dissertations, Dept. of Radio Science and Eng., Aalto University, Finland, 2012.

[6] E. F. Parsche, "Broadband polarized antenna including magnetodielectric material, isoimpedance loading, and associated methods", U.S. Patent 7 573 431, August 11, 2009.

[7] H.A. Wheeler, "The Radiansphere around a Small Antenna", *in Proc. IRE*, vol. 47, no. 8, pp. 1325-1331, August 1959.

[8] http://www.skyworksinc.com/Products_TechnicalCeramics.aspx

[9] https://www.fair-rite.com

[10] K. N. Klimov, "Klimov's emitter", RU Patent 169 311, March 4, 2017.

[11] A.S. Godin, "Godin's emitter", RU Patent 170 118, April 14, 2017.

[12] N.N. Fedorov, *Fundamentals of Electromagnetics*, Moscow, , Izd-vo Vysshaya Shkola, 1980, 399 p

[13] G.T. Markov, D.M. Sazonov, *Antennas*, Moscow, Izd-vo Energy, 1975, 528 p.

[14] K.N. Klimov, D.S. Gezha, and D.O. Firsov-Shibaev, "Practical Application of Electromagnetic Modelling", Lambert Academic Publishing, Saarbrucken, 2012.

[15] A.S. Godin, M.S. Matsayan, D.S. Gezha, and K.N. Klimov, "Applying the principle of electromagnetic similarity and special materials to reduce the size of the emitter", *Science Intensive Technologies*, vol. 16, no. 4, pp. 3-13, April 2016.

[16] A.B. Tsai, A.S. Godin, K.N. Klimov, "Investigation of the problems of the overall dimensions of the Vivaldi antenna as an element of a flat antenna array", *Antennas*, vol. 2017, no. 3, pp. 37-43, March 2017.

[17] A.I. Kruglov, “Numerical electromagnetic modeling of ESA antennas using impedance matched materials using the example of an electric dipole powered by an external Huygens cube”, *XIII International Scientific and Practical Conference «Innovation, information and communication technologies»*, 1-10 October 2016, Russia, Sochi, pp. 526-529.

[18] A.S. Godin, V.V. Perfilyev, A.D. Drize, K.N. Klimov, “Using impedance matched material to measure the frequency range of radiators”, *XXIII International Scientific and Technical Conference «Radiolocation, navigation, communication»*, in 3 volumes. 18-20 april 2017, Russia, Voronesh, pp. 717-726.

[19] K.N. Klimov, I.K. Epaneshnikova, A.M. Belevtsev, A.S. Godin, A.D. Drize, “Synthesis of structures of electric small-sized radiators using impedance matching materials for millimeter waves”, *in Proc. Millimetre Wave and Terahertz Sensors and Technology X*, vol. 10439, 2017, Warsaw, Poland.

[20] K.N. Klimov, A.S. Godin, D.S. Gezha, “Electrically small antennas (part 1)”, *Achievements of Modern Radioelectronics,* Moscow, №6, 2016, pp.47-62, June 2016.

[21] K.N. Klimov, A.S. Godin, D.S. Gezha, “Electrically small antennas (part 2)”, *Achievements of Modern Radioelectronics*, Moscow, №7, 2016, pp.17-34, July 2016.