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Article

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DEVELOPMENT OF A FLEXIBLE ANTENNA-WRISTBAND FOR WEARABLE WRIST-WORN INFOCOMMUNICATION DEVICES OF THE LTE STANDARD

The object of research is the process of radiation of electromagnetic waves from a flexible antenna-wristband. The subject of research is the wave parameters and directional properties of a flexible antenna-wristband. The existing problem is that it is necessary to ensure the electromagnetic compatibility of the radio frequency units of the wrist-worn infocommunication device. This problem is due to the fact that LTE/NB-IoT, Bluetooth/Wi-Fi, and GPS antennas must be placed inside the small-sized case of the infocommunication device. To solve this problem, let's propose a simple and cheap version of a broadband flexible bracelet antenna for LTE networks, located outside the device case.

As a basis for the development of a flexible antenna-wristband, the authors chose a patch antenna, which is the base of the theory of microstrip antennas. This is due to the fact that the theoretical material is well developed for the calculation and study of the patch antenna. Structurally, a patch antenna consists of an upper metal layer that emits electromagnetic waves, a solid dielectric base, and a lower metal layer that acts as a reflector. With the classical approach to constructing a patch antenna, the width and length of its upper layer are commensurate, and its lower metal layer has geometric dimensions much larger than the upper metal layer. In contrast to the classical design, the authors proposed a new shape of the patch antenna, in which the length of the upper layer of the radiation surface is much greater than its width (5–6 times), and the lower metal layer has dimensions slightly larger than the dimensions of the upper layer.

The authors have developed a flexible antenna-wristband for the frequency range of 800–1300 MHz with a wave impedance of 50 ohms, 118.7×23 mm of the upper metal layer, and 124.7×25 mm of the lower metal layer. The length of the microstrip feed line of the antenna is 54.6 mm, its width is 2 mm, and the length of the insert is 51.6 mm. The flexible antenna-wristband is connected to the printed circuit board of the infocommunication device by soldering or using a mini-coaxial cable. The authors developed an experimental layout of a flexible antenna-wristband and studied its wave and directional properties. It has been established that in the frequency range 800–1300 MHz the voltage standing wave ratio coefficient of this antenna does not exceed 3.5. The flexible antenna-wristband has directional properties, which allows reducing the level of electromagnetic radiation in the direction of the human body.

Keywords: *flexible antenna, LTE, patch antenna, infocommunication device, VSWR (voltage standing wave ratio), radiation pattern.*

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1. Introduction

The rapid development of wireless infocommunication technologies stimulates the development, production and use of new types of LTE devices [1, 2]. Currently, new generation cellular communication systems NB-IoT, LTE-m1 [3] are widely used. All of them have a broadband unified radio access system that makes it possible to transmit information in real time [1–3].

One of the most important tasks that arise in the development of wireless infocommunication devices is the development of an antenna shape that would fit well into the design of the device. In this case, the antenna must provide the necessary gain, have the necessary wave parameters and the shape of the radiation pattern [4]. Such an antenna should provide stable reception of radio waves from any angle in urban areas. The expansion of the functional and service capabilities of infocommunication devices leads to the need to increase the number of operating frequency ranges. This greatly complicates the design of antennas. The process of calculating and modeling built-in antennas is also complicated.

To date, a number of infocommunication devices are known to be worn on the arm [5]. The design of wrist-worn devices consists of a strap or wristband and the body of the device. The most common type of antennas is printed patch antennas [6]. The classical approaches of antenna theory require that the linear dimensions of the antenna be a multiple of the operating wavelength. Designs of half-wave and quarter-wave antennas are known. Less common are 1/8-wave antennas. Changing the dimensions of the antenna affects the wave parameters and impedance.

The complexity of the design of wrist-worn infocommunication devices is in compliance with the requirements of the electromagnetic compatibility of the blocks inside the case. This is due to the fact that at least three antennas must be used in the case of modern infocommunication devices:

1) LTE and/or NB-IoT;
2) Bluetooth/Wi-Fi;
3) GPS.

The body size of the wrist-worn device is small. Therefore, the problem of ensuring electromagnetic compatibility can be solved in two ways. The first way is the use of specialized chip antennas and multilayer patch antennas that receive radio signals of different standards. Now the world is mass-producing LTE, Bluetooth/Wi-Fi/Zibbee chip antennas in case and SMD versions. Their disadvantages are the high cost and the need to design electronic circuits for broadband matching of chip antennas or multilayer patch antennas with device stages. The second way to solve the problem of electromagnetic compatibility is to develop a special-shaped LTE antenna design for use outside the case. The best option is to use a flexible LTE antenna as a wrist-worn device strap [7, 8].

Today, the flexible electronics industry is rapidly developing. This is due to the high demand for flexible electronic components for IoT devices [9, 10]. Flexible electronic devices are lighter, simpler and cheaper [2]. The global market for flexible electronics is growing rapidly [2]. Therefore, the development and research of flexible electronics devices is a relevant and modern direction.

So, *the object of research* is the process of radiation of electromagnetic waves from a flexible bracelet antenna. *The subject of research* is the wave parameters and directional properties of a flexible bracelet antenna. *The aim of research* is to develop and study a flexible wristband antenna for wrist-worn infocommunication devices for a wide range of LTE frequencies from 800 MHz to 1300 MHz.

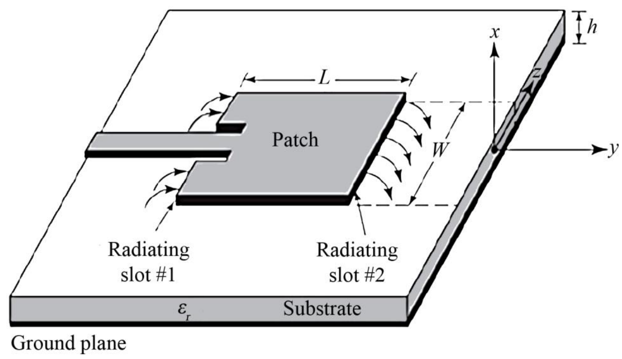
2. Research methodology

The rapid growth of radio technologies for Internet access to things has led to the rapid development of antenna technology. The main direction of research is the miniaturization of antennas for wearable infocommunication devices [7, 8]. The main task is to reduce the geometric dimensions of the antenna when operating at a given operating length of the electromagnetic wave. One of the options for solving this problem is the use of flexible antennas [2, 4]. Flexible antennas are widely used in Internet devices [3, 5]. Also, flexible antennas are widely used in devices of 4G and 5G infocommunication networks [7–9]. Recently, flexible antennas have been used in wireless sensor networks [2, 4, 6]. The use of wireless medical networks, such as WBAN (Wireless Body Area Networks), encourages the creation of new flexible antennas for telemedicine [1, 4, 9]. The purpose of the calculation is to develop a flexible antenna design with a characteristic impedance of 50 ohms for the frequency range of 900–1300 MHz with the following electrical parameters: peak radiation power 23 dBm, standing wave ratio $VSWR \leq 3.5$.

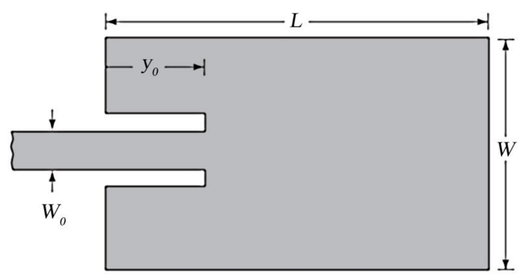
The simplest embodiment of a flexible antenna is to use a microstrip patch antenna design. The design of the microstrip patch antenna is shown in Fig. 1, *a* [11, Fig. 14.1]. For the satisfactory functioning of the patch antenna, it is necessary that its geometric dimensions satisfy the following relations [11]:

$$\begin{cases} \frac{\lambda_0}{3} < L < \frac{\lambda_0}{3}, \\ 0.003\lambda_0 \leq h \leq 0.05\lambda_0, \\ 2.2 \leq \varepsilon_r \leq 12, \end{cases} \quad (1)$$

where λ_0 – the wavelength of the middle frequency of the operating frequency range; L – the length of the radiating part of the patch antenna; h – the thickness of the dielectric substrate; ε_r – the relative permittivity of the substrate (Fig. 1, *a*).



a



b

Fig. 1. Ordinary micro-location patch antenna: *a* – design [11, Fig. 14.1]; *b* – geometric dimensions of its shape for calculation [11, Fig. 14.11]: *L* and *W* – the length and width of the radiating surface, respectively; *h* – the thickness of the dielectric substrate material; y_0 – the length of the tie-in; W_0 – power strip width

The width of the patch antenna W is selected for reasons of providing the required impedance at the resonant frequency [11]:

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{c_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}, \quad (2)$$

where c_0 – the speed of light in vacuum; f_r – the resonance frequency.

The effective permittivity of the substrate material is calculated by the formula [11]:

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\frac{h}{W}}}. \qquad (3)$$

Effective patch antenna length [11]:

$$L_{eff}=L+\Delta L, \qquad (4)$$

where

$$\Delta L=0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)}. \qquad (5)$$

Resonance frequency for the main mode TM_{010} [11]:

$$f_{r_{010}}=\frac{1}{2L\sqrt{\varepsilon_r}\sqrt{\mu_0\varepsilon_0}}=\frac{c_0}{2L\sqrt{\varepsilon_r}}. \qquad (6)$$

Taking into account the effective length of the patch antenna, its resonant frequency is defined as [11]:

$$f_{rc_{010}}=\frac{1}{2L_{eff}\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}}=q\frac{c_0}{2L\sqrt{\varepsilon_r}}, \qquad (7)$$

where

$$q=\frac{f_{rc_{010}}}{f_{r_{010}}}. \qquad (8)$$

The conductivity and input impedance of a rectangular patch antenna are calculated using the formulas [11]:

$$\begin{aligned}&Y_1=G_1+jB_1,\\&G_1=\frac{W}{120\lambda_0}\left[1-\frac{1}{24}(k_0h)^2\right],\ \frac{h}{\lambda_0}<\frac{1}{10},\\&B_1=\frac{W}{120\lambda_0}\left[1-0.636\ln(k_0h)\right],\ \frac{h}{\lambda_0}<\frac{1}{10},\end{aligned} \qquad (9)$$

where

$$k_0=\frac{2\pi}{\lambda_0}.$$

The input impedance of a microstrip patch antenna is calculated by the formula [11]:

$$R_{in}=\frac{1}{2(G_1+G_{12})}, \qquad (10)$$

where conductivity G_{12} [11]:

$$G_{12}=\frac{1}{120\pi^2}\int_0^{\pi}\left[\frac{\sin\left(\frac{k_0W}{2}\cos(\theta)\right)}{\cos(\theta)}\right]^2 J_0\left(k_0L\sin(\theta)\right)\sin^3(\theta)d\theta,$$

where J_0 – the zero-order Bessel function of the first kind [11].

Reducing the input resistance relative to the feed point is achieved by cutting the length y_0 into the rectangle of the microstrip patch antenna (Fig. 1, *b*) [11, Fig. 14.11]. In this case, the input resistance [11]:

$$R_{in(y=y_0)}=R_{in(y=0)}=\cos\left(\frac{\pi}{L}y_0\right). \qquad (11)$$

The wave impedance of a microstrip power line with a width W_0 (Fig. 1, *b*):

$$Z_c=\begin{cases}\frac{60}{\sqrt{\varepsilon_{reff}}}\ln\left[\frac{8h}{W_0}+\frac{W_0}{4h}\right], & \frac{W_0}{4}\le 1,\\ \frac{120\pi}{\sqrt{\varepsilon_{reff}}\left[\frac{W_0}{h}+1.393+0.667\ln\left(\frac{W_0}{h}+1.444\right)\right]}, & \frac{W_0}{h}>1.\end{cases} \qquad (12)$$

The equations for the radiation pattern of a patch antenna look like this [11]:

– in space:

$$f(\theta,\varphi)=\frac{\sin\left[\frac{kW}{2}\sin(\theta)\sin(\varphi)\right]}{\frac{kW}{2}\sin(\theta)\sin(\varphi)}\cos\left(\frac{kL}{2}\sin(\theta)\cos(\varphi)\right), \qquad (13)$$

– in the plane E ($\varphi=0°$):

$$F_E(\theta)=\cos\left(\frac{kL}{2}\sin(\theta)\right), \qquad (14)$$

– the equations for the radiation pattern of a patch antenna look like this [11]:

– in space: H ($\varphi=90°$):

$$F_H(\theta)=\cos(\theta)\frac{\sin\left(\frac{kW}{2}\sin(\theta)\right)}{\frac{kW}{2}\sin(\theta)}. \qquad (15)$$

The directional action coefficient for the case $k_0h\ll 1$ is calculated by the formula [11]:

$$D_0=\frac{U_{max}}{U_0}=\frac{4\pi U_{max}}{P_{rad}}, \qquad (16)$$

where

$$U_{max}=\frac{|V_0|^2}{2\eta_0\pi^2}\left(\frac{\pi W}{\lambda_0}\right)^2, \qquad (17)$$

$$P_{rad}=\frac{|V_0|^2}{2\eta_0\pi^2}\int_0^{\pi}\left[\frac{\sin\left(\frac{k_0W}{2}\cos(\theta)\right)}{\cos(\theta)}\right]^2\sin^3(\theta)d\theta. \qquad (18)$$

The total quality factor of the patch antenna is determined by the total losses [11]:

$$\frac{1}{Q_t}=\frac{1}{Q_{rad}}+\frac{1}{Q_c}+\frac{1}{Q_d}+\frac{1}{Q_{sw}}, \qquad (19)$$

where Q_t – the total quality factor; Q_{rad} – the quality factor taking into account radiation losses; Q_c – the quality factor based on conduction losses (ohmic losses); Q_d – the quality factor, taking into account losses in the dielectric; Q_{sw} – the quality factor, taking into account losses due to surface electromagnetic waves (taking into account surface conduction currents and the skin effect). Under the condition $k_0 \ll h$, the components of the total quality factor are calculated in accordance with the formulas [11]:

$$Q_c = h\sqrt{\pi f \mu\sigma},\ Q_d = \frac{1}{\tan(\delta)},\ Q_{rad} = \frac{2\omega\varepsilon_r}{hG_t/l}K,$$

where for the electromagnetic wave mode TM_{010} [11]:

$$K = \frac{L}{4},\ G_t = G_{rad}\frac{l}{W}.$$

The value of the total quality factor of the patch antenna has a significant impact on its bandwidth. Relative bandwidth of the patch antenna [11]:

$$\frac{\Delta f}{f_0} = \frac{f_{\max} - f_{\min}}{f_0},$$

is calculated by the formula [11]:

$$\frac{\Delta f}{f_0} = \frac{1}{Q_t}, \tag{20}$$

where $f_{\max}$ and $f_{\min}$ are the maximum and minimum frequencies of the operating range, respectively; f_0 is the average frequency of the operating range [11]:

$$f_0 = \frac{f_{\max} - f_{\min}}{2},$$

$$\frac{\Delta f}{f_0} = \frac{VSWR - 1}{Q_t\sqrt{VSWR}}. \tag{21}$$

Approximate capacity equation at $VSWR \leq 2$, $|\Gamma| \leq 1/3$ [11]:

$$\Delta f = 3.771\left[\frac{\varepsilon_r - 1}{(\varepsilon_r)^2}\right]\frac{h}{\lambda_0}\left(\frac{W}{L}\right). \tag{22}$$

According to the above formulas (1)–(22), electrical calculations were made. A sketch of a drawing of a flexible bracelet antenna with calculated geometric dimensions in millimeters is shown in Fig. 2.

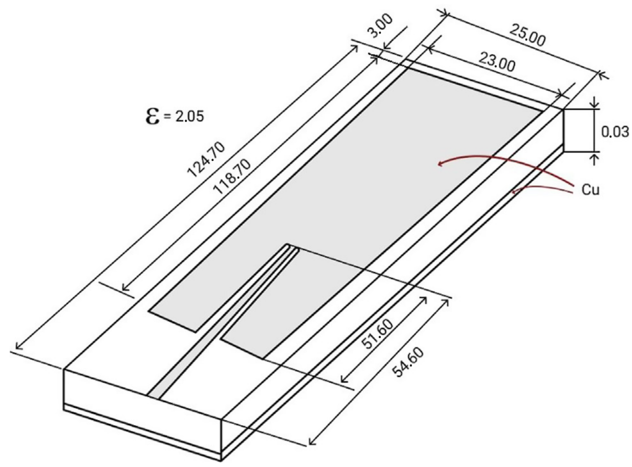


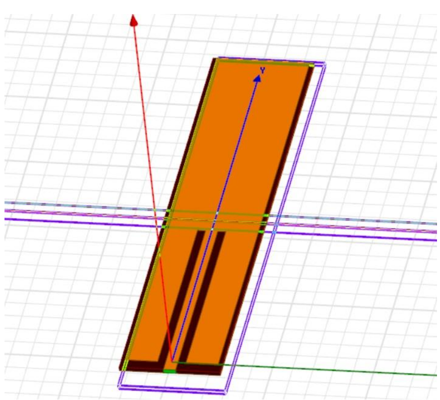
Fig. 2. Design of a flexible bracelet antenna with calculated geometric parameters in millimeters

Computer modeling of a flexible bracelet antenna was carried out by the authors using the ANSYS HFFS software package. Electrodynamic modeling in HFSS is based on the Finite Element Method (FEM). The solution of the limit task is sought in the frequency domain. The use of the finite element method provides a high level of universality of numerous algorithms, which are very effective for a wide range of electrodynamic problems.

3. Research results and discussion

The creation of a flexible bracelet antenna project in the ANSYS HFFS software package is shown in Fig. 3. The introduction of a coordinate system into a flexible bracelet antenna for studying the directional properties of radiation in space is shown in Fig. 4. As a result of the simulation, the spatial radiation pattern of the flexible bracelet antenna was studied in the operating frequency range. Fig. 5 shows the spatial radiation pattern of a flexible bracelet antenna at a frequency of 800 MHz (Fig. 5, *a*) and at a frequency of 1300 MHz (Fig. 1, *b*). Fig. 6 shows the result of modeling the frequency dependence of the voltage standing wave ratio (VSWR) of a flexible bracelet antenna.

The authors made a model of a flexible bracelet antenna (Fig. 7). A metal foil 50 μm thick was used as the material of the metal surface. A polyethylene film 30 μm thick with a relative dielectric constant of 2.05 was used as a flexible dielectric material.



a

b

Fig. 3. Creation of a project of a flexible bracelet antenna in the ANSYS HFFS software package: *a* – in a flat position; *b* – in a curved position in the form of a wrist

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A photo of connecting a flexible bracelet antenna to equipment for measuring the frequency dependence of VSWR is shown in Fig. 8, *a*.

A photo of connecting a flexible bracelet antenna to equipment for measuring the spatial radiation pattern is shown in Fig. 8, *b*.

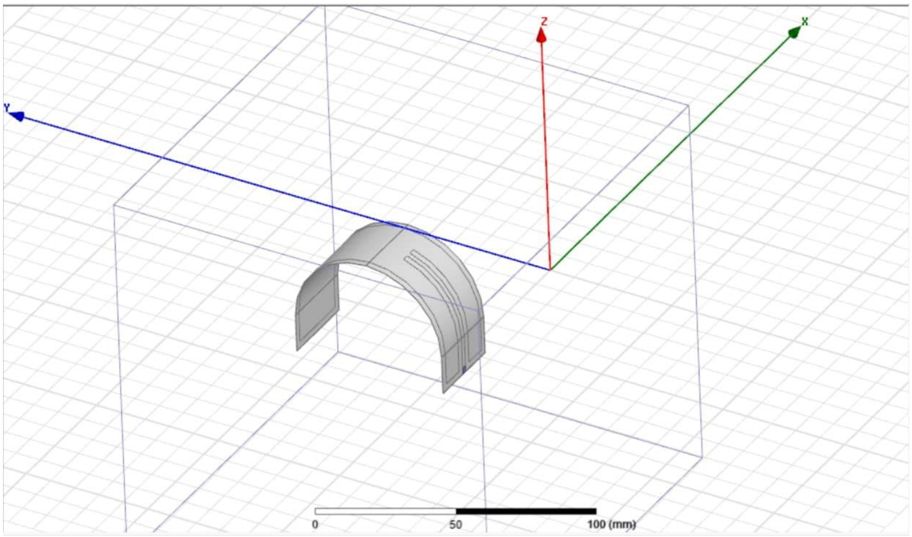

Fig. 4. Introduction of a coordinate system into a flexible bracelet antenna for studying the directional properties of radiation in space

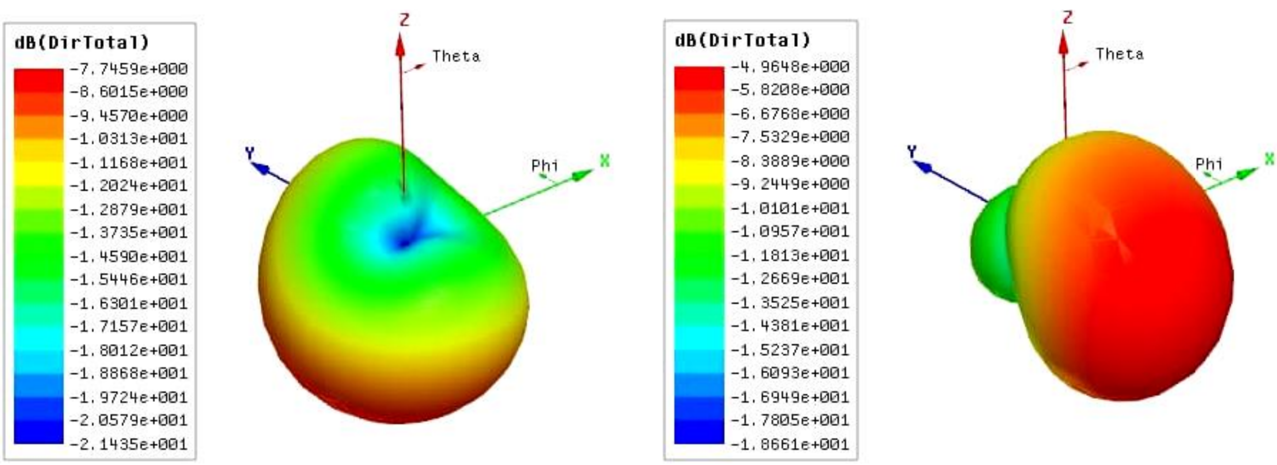

Fig. 5. Spatial radiation pattern of a flexible bracelet antenna at a frequency: *a* – 800 MHz; *b* – 1300 MHz

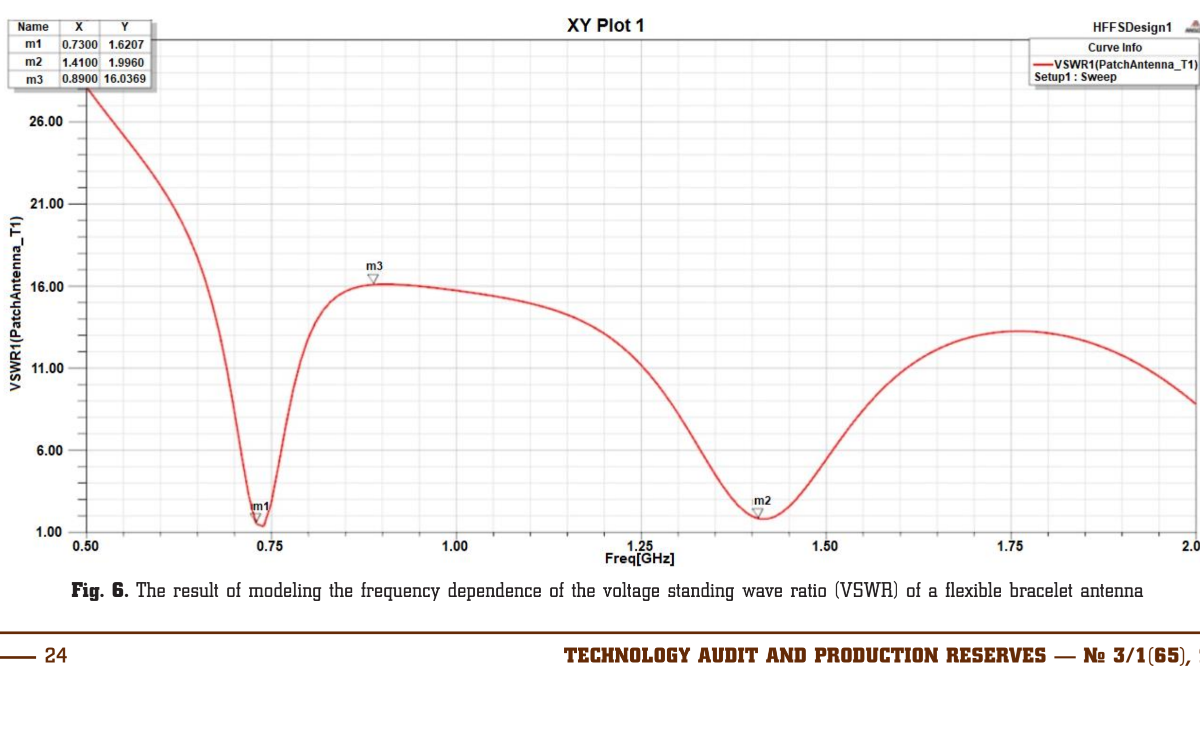

Fig. 6. The result of modeling the frequency dependence of the voltage standing wave ratio (VSWR) of a flexible bracelet antenna

a

b

Fig. 7. Flexible wristband antenna:
a – photo of the experimental layout; *b* – geometric dimensions

a *b*

Fig. 8. Photo of connecting a flexible bracelet antenna to the equipment for measuring: *a* – voltage standing wave ratio; *b* – radiation patterns

As seen in Fig. 8 during the studies, the flexible bracelet antenna was in a bent position and mounted on a Teflon glass. Studies of the wave and directional characteristics of a flexible bracelet antenna were carried out when filling a Teflon glass with air and mineral water. Filling a Teflon glass with mineral water is an imitation of putting a flexible antenna-bracelet on a person's hand. The results of experimental studies of the antenna when filling a Teflon glass with mineral water are shown in Fig. 9.

A photo of a flexible bracelet antenna in a curved position on a person's wrist is shown in Fig. 10.

The paper proposes a new design of a flexible bracelet antenna for wrist-worn infocommunication devices of the LTE standard. In the serial production of such an antenna, it will be necessary to use modern materials. Let's suggest using double-sided foil polyimide (PI) with a thickness of 50 microns or 75 microns. For comfortable wearing of the bracelet on the wrist and an aesthetic appearance, it is possible to place the bracelet antenna inside the rubber strap. Preliminary estimates of the magnitude of the downward shift in the frequency of the VSWR graph were made when using a silicone material for the strap. To apply the proposed design in practice, it will also be necessary to take into account the antenna impedance in the operating frequency range and the return loss level, the experimental graphs of which are shown in Fig. 9. This is important for the radiation efficiency of the antenna and the energy efficiency of the wrist-worn infocommunication device [12]. Also, when applying the proposed bracelet antenna in practice, it is necessary to evaluate the specific absorption rate (SAR) of the human body of electromagnetic radiation. SAR is defined as the amount of electromagnetic radiation power absorbed by the mass of the human body and is measured in watts per kilogram (W/kg). Patch antennas were chosen as the basis for the development of a flexible wristband antenna with the aim of reducing SAR. This is due to the fact that the lower metal surface of the bracelet antenna performs shielding functions. Therefore, the proposed bracelet antenna has directional properties, as can be seen from Fig. 5, in order to reduce the level of electromagnetic radiation in the direction of the human body [12].

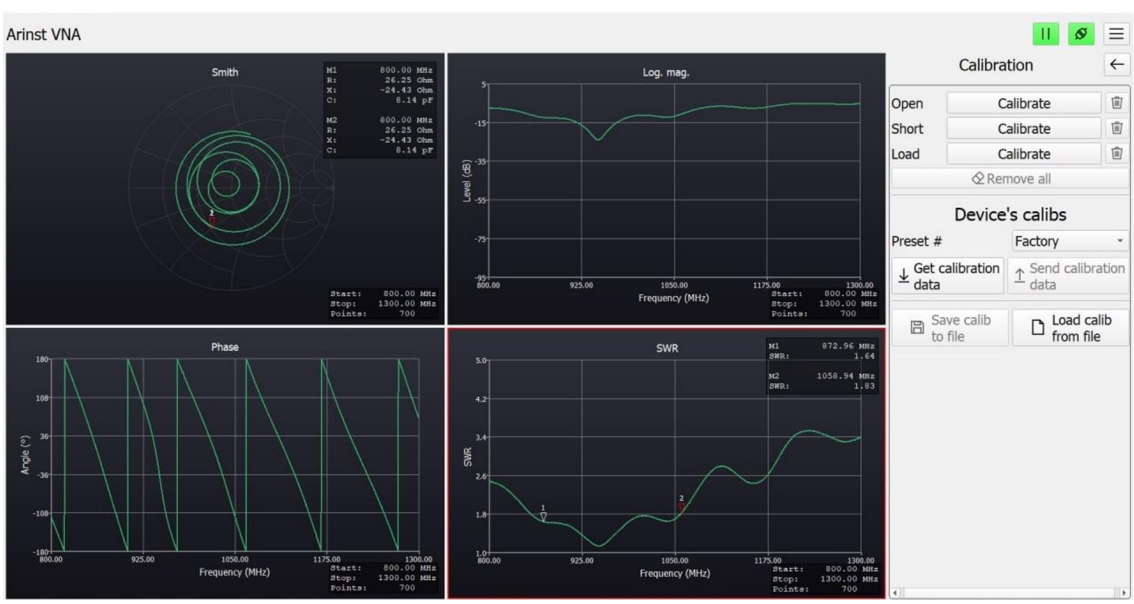

Fig. 9. Results of experimental studies of a flexible bracelet antenna when filling a Teflon glass with mineral water

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Fig. 10. Photo of a flexible bracelet antenna in a curved position on a person's wrist

4 Conclusions

In this paper, a new design of a flexible bracelet antenna for wrist-worn infocommunication devices of the LTE standard has been developed. Such an antenna can be used for use in LTE-m1 or NB-IoT networks. The proposed flexible bracelet antenna is very easy to manufacture and has the following geometric parameters of the radiating metal part: W=23.0 mm, L=121.7 mm, ε=2.05, y_0=51.6 mm, h=0.03 mm. The overall geometric dimensions of the flexible antenna of the bracelet are 124.7×25 mm. The antenna is connected to the device by soldering or using a 0.81 mini coaxial cable and has a radiation efficiency of 38.6 %. The proposed flexible bracelet antenna has directional properties in the horizontal plane and the vertical plane, which makes it possible to reduce the level of electromagnetic radiation in the direction of the human body.

The proposed flexible microlocation patch antenna can simultaneously operate in several LTE operating frequency bands and has a wide frequency band. It also significantly attenuates radio signals outside the operating frequency band. The original design of a flexible bracelet antenna and its optimal coordination with an infocommunication device worn on the arm:

– reduction of the influence of the capacitance and resistance of the antenna when putting on the bracelet on the arm;
– reduction of changes in the spatial radiation pattern of the antenna when the bracelet is bent;
– minimizing the influence of environmental parameters on the operation of a flexible broadband LTE antenna;
– ensuring reliable communication of the device in the LTE (or NB IoT) network.

The proposed flexible micro-position patch antenna is easy to manufacture and has a low cost.

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