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Proposing and Modeling a 2.4 GHz Antenna for the Endoscopic Capsule Reader

D.M. Mikhaylov[1], A.V. Averin[2], A.V. Starikovskiy[3], V.N. Konev[4] and O.K. Kurysheva[5]

National Research Nuclear University "MEPhI" (Moscow Engineering Physics Institute), Kashirskoe highway, 31, 115409, Moscow, Russian Federation.

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A miniature reader is used for reading information from capsules in wireless capsule endoscopy. One of the key elements of this reader is an antenna. This antenna must be powerful and have low power consumption to ensure that the reader works throughout patient's gastrointestinal tract examination procedure. This article is devoted to the development of a specialized 2.4GHz-antenna for the reader. It considers types of antennas used for reading data, simulation results of patterns for rectangular and circular antennas and antennas in the form of an Archimedean spiral. It describes the specification of the antenna for readers of the renowned manufacturers of capsule endoscopy complexes, the requirements to develop the antenna are listed, and the development process of the "radiating cable" type 2.4 GHz-antenna and the simulation results are described.

Key words: Antenna for capsule endoscopic complex reader, Radiating cable, Antenna pattern, amplification.

Currently, endoscopic technological progress greatly enhances possibilities of gastrointestinal tract diseases diagnosis and treatment. The procedure of digestive tract examination using an endoscopic capsule is as follows: the patient swallows a tiny capsule the size of a tablet, which is due to peristaltic contractions slowly passes through the gastrointestinal tract, capturing images. The capsule is equipped with an auxiliary lighting that produces images of the gastrointestinal tract of sufficient quality[1-3] The recorded images are transmitted to the portable reader, positioned on the patient's belt. The reader uses special systems and protocols to transfer images from the endoscopic capsule. Further, images are sent from the reader to the doctor's personal computer for automated processing and analysis[4-5, 6]

A miniature reader for reading information from wireless capsule is used in capsule endoscopy. One of the key elements of such reader is an antenna, through which the exchange of information between the capsule and the reader is done. Note that specification of the antenna directly affects the quality of images, which are transmitted from the capsule to the reader. This antenna must be, on the one hand, powerful, and on the other hand, have low power consumption to ensure that the reader functions throughout the examination procedures[7]

Antenna is one of the most important elements of the reader that provides timely data

* To whom all correspondence should be addressed.
Tel: +79153539285
E-mail: polynna@yandex.ru

transfer from the capsule to the reader and vice versa. Antenna should be powerful enough to ensure that signal stably passed through a human body, miniature to fit in a small reader as well as to consume a minimum of energy[8]

A lot of scientific papers are devoted to the development of antennas for capsule endoscopy complexes[9-11]. For example, in[12] the authors write about the design of antenna for the endoscopic capsule transceiver. See et al. describe implantable and external antennas with circular polarization for the external base station operating in the frequency range of 915 MHz (920-925 MG)[13].

Manufacturers of capsule endoscopy complexes develop their own antennas for readers or use already existing components. Existing solutions have their advantages and disadvantages[6]. The latter include large size and considerable power consumption. Therefore, in the case of the capsule endoscopic system "Landish" it was decided to develop a special antenna, which would meet the requirements of the complex for the duration of the operation (at least 8 hours), be of a miniature size and have high sensitivity.

MATERIAL AND METHODS

Antenna type choice
Types of antennas

A strip line antenna is known to be a simple cavity. The antenna includes a substrate of certain thickness, a screen and a metal strip. The screen and the metal strip are set as the boundary of a perfect electric wall. The screen is the lower part of the substrate and the metal strip is a rectangle, placed on a level with the upper face of the substrate[14, 15].

The antennas discussed below are powered according to the coaxial line scheme, with the resistance of 50 Ohms[16]. Note that a more significant complication of excitation scheme was not carried out due to lack of information about the internal structure of the radio frequency (RF) connector used. However, it did not prevent us from obtaining good enough electrodynamic parameters of planar antennas.

Figure 1 shows schemes of the two most widespread strip line antennas, rectangular and round, with excitation of the strip and coaxial lines. In order to reconcile the point of excitation is shifted from the edge of the antenna (figure 1, dimensions C_0 and $Á_0$)[14, 17].

Let us consider the formulas for a rectangular antenna presented in[14], for rational selection of dimensions.

The input resistance at the point of resonance is purely resistive and is equal to:

$$R_{вх} = \frac{\cos^2(\frac{\pi}{b}y)}{2G_{\Sigma}} \quad \text{... (1)}$$

where G_{Σ} is the conductivity of the end face of the resonator emission:

$$G_{\Sigma} = \frac{\pi}{377}\cdot\frac{a}{\lambda} \quad \text{...(2)}$$

The resonant length of the antenna is calculated according to the formula (3):

$$l_{рез} = 0.48\cdot\frac{\lambda_0}{\sqrt{\varepsilon_r}} \quad \text{...(3)}$$

where ε_r is the relative dielectric conductivity of the substrate material.

The recommended dimensions *a* derive

0.3λ $J_1(x)$

from to .

The input resistance of a circular disk antenna at the point of resonance equals to:

$$R_{вх} = \frac{\left[\dfrac{J_1\left(\dfrac{1.84\rho_0}{a}\right)}{1.84J_1\left(\dfrac{\rho_0}{a}\right)}\right]^2}{G_{\Sigma}} \quad \text{...(4)}$$

where is the Bessel function of the first order.

The resonant frequency for the main type of the disk-strip antenna oscillations can be defined by the formula (5):

$$f_{рез} = \frac{1.84c}{2\pi a_{эф}}\cdot\frac{1}{\sqrt{\varepsilon_r}} \quad \text{...(5)}$$

where:

$$a_{эф} = a\sqrt{1+\frac{2d}{\pi a\varepsilon_r}\left(\ln\left(\frac{\pi a}{2d}\right)+1.772\right)}. \quad \text{...(6)}$$

Rectangular and circular strip line antennas operating in the main oscillation mode radiate a field of linear polarization (vector YOZ) with a high degree of cross-polarization component suppression.

Archimedean spiral is a spiral, flat curve, the trajectory of the point M (figure 2) moving uniformly along the beam OV beginning with O, while the OV beam rotates uniformly around O. [18, 19]

According to [18], Archimedean spiral equation in polar coordinate system takes the form:

$\rho=\kappa\phi(1)$, ...(7)

where k is the shift of the point M along the beam r while rotating by an angle equal to one radian.

Rotation of the line by 2À corresponds to the shift:

$a = |BM| = |MA| = 2k\pi$ ...(8)

The value a in (8) is the pitch of the spiral. Therefore, Archimedean spiral equation can be represented as[18]:

$$\rho = \frac{a}{2\pi}\varphi. \qquad ...(9)$$

Given the experimental selection of the partitioning grid and convergence region of decision that affect the simulation result, boundaries of the linear dimensions of the antenna presented above, and estimates of the input resistance can be partly taken into account when designing a scheme in the HFSS program [20]. At the first stage of modeling this will help to fix one or more parameters and to optimize the rest.

The antennas radiation patterns simulation

The simulation results of the radiation patterns for rectangular, circular antennas and antenna in the form of an Archimedean spiral are presented below (figures 3-5).

Figures 6-8 show the simulation results of the voltage standing-wave ratio (VSWR) of the considered types of antennas.

Comparative analysis of the main parameters of antennas according to figures 3-11 showed that the spiral antenna has a purely resistive input resistance at the operating frequencies of the receiver in the reader.

Thus, the location of antennas on a dielectric substrate reduces the input resistance of the antenna $\sqrt{\varepsilon_r}$ times. In turn, this allows to simplify the design and construction of the matching elements. However, only the spiral antenna has a purely resistive resistance at the operating frequencies of the receiver in the reader and requires only the presence of a quarter-wave transformer, the design of which is simpler than the compensation of the reactive resistances of the rectangular and circular antennas.

Despite the lower gain, the spiral antenna, however, has a lower VSWR on the working range of frequencies in comparison to the other types of antennas. Archimedean spiral turns increase leads to the broadening of the main lobe of the pattern and, accordingly, improves the quality of the reader receiving signal from an endoscopic capsule, and also reduces the dimensions of the antenna.

Specification of the designed antenna

Let us consider the specification of antennas of the renowned manufacturers of endoscopic capsules: IntroMedic[21], Given Imaging[22] and Olympus [23] (table 1).

Based on the Table 1 and the “Antenna type choice” section, performance requirements of the antenna for reader of complex “Landish” were specified as follows:

→ The frequency range of 2.4-2.5 GHz, at this frequency the antenna receives and transmits the signal with the greatest efficiency;

→ The pattern should be circular, because it suggests that the antenna radiates the signal equally in all directions;

→ The standing wave ratio d” 3.0;

→ The input resistance is 50 Ohms.

The antenna is designed to have the maximum gain value. The challenge of building the antenna corresponding to these requirements is the need to ensure the small size of the device. The size of the device is ten times less than the wave length of the waves it emits.

RESULTS

Development of a “radiating cable” type 2.4 GHz-antenna

Radiating cable

Let us consider in detail the process of developing a “radiating cable” type 2.4 GHz-antenna.

According to the patent RU 2265923 radiating cable is a coaxial RF cable used for wireless communication. Figures 12 and 13 show a radiating cable, which contains a segment of coaxial cable (1) made of the inner conductor (2) surrounded by a dielectric layer (4) and four radiating elements (3); (5) is a hole which is designed for branching electromagnetic energy. There are holes made in the outer conductor, the dielectric layer and the inner conductor of the coaxial cable segment in order to branch electromagnetic energy by inserting radiating elements. The number of radiating elements depends on the length of the coaxial cable segment. The outer surface of the cable is excited by a magnetic field, covering a cross-section of the cable. Electromagnetic wave, which propagates in the segment of coaxial cable, excites in the pictes corresponding to a quarter-wave vibrators, high frequency currents, which lead to the emission of electromagnetic waves to the environment. In this segment there is a mode of traveling waves, but the current distribution on the surface of the cable jacket is uneven and depends on the interaction of two waves with different distribution constants[24]

The more holes there are and the larger they are, the more energy is radiated. At the same time both rate and quantity of the reflected waves increases. Reflected waves, while propagating towards the initial wave radiated from the holes of the emitter, break the uniformity of the radiation field of the initial wave. Due to the fact that the conductive radial inserts are capacitive inhomogeneities with parallel connection to the equivalent electric circuit, it is possible, in case of appropriate choice of the capacity values !$_{M,}$ to compensate for the heterogeneity of holes and

Table 1. Comparative table of the characteristics of the antenna devices of other manufacturers.

	MiroCam (IntroMedic)	PillCam (Given Imaging)	EndoCapsule (Olympus)
Frequency range	e”2,4 ÃÃö	e”2,4 ÃÃö	e”2,4 ÃÃö
Antenna pattern	Circular	Lobes (the direction of the primary radiation)	Lobes (the direction of the primary radiation)
The standing wave ratio	e”3.0	e”3.0	e”3.0
Input resistance	50 Îì	50 Îì	50 Îì

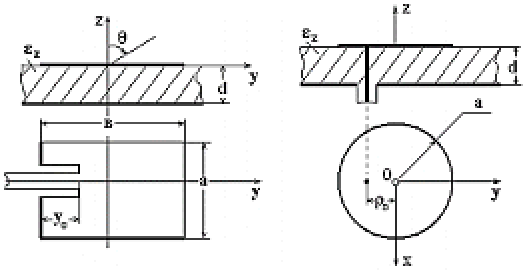

Fig. 1. Types of stripline resonators

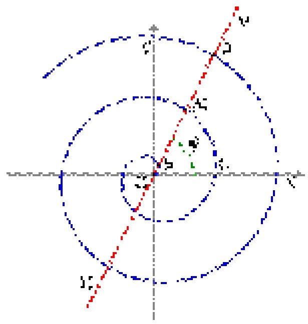

Fig. 2. Archimedean spiral in the polar coordinate system[18]

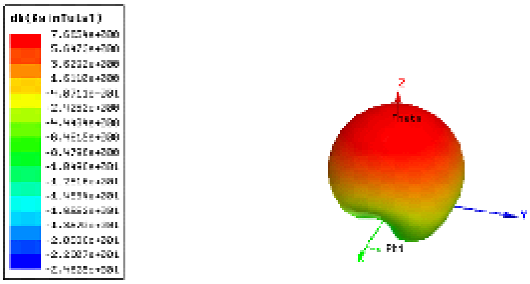

Fig. 3. Pattern of a rectangular antenna

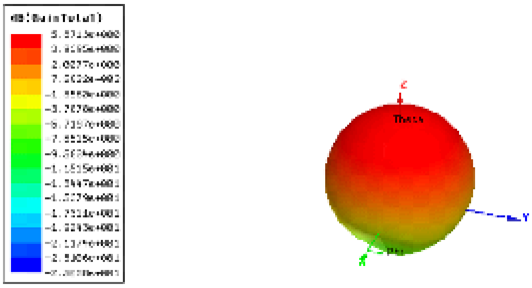

Fig. 4. Pattern of a circular antenna

virtually eliminate the occurrence of reflected waves, thereby reducing the standing wave ratio. Introduction of conductive inserts can improve the radiation of the cable, since the high frequency current flowing on the surface of the conductive insert approaches the hole, increasing field intensity around proportionally to the height of the conductive insert. The location of the conductive inserts between the inner and outer conductors coaxial with holes, allows to compensate for the inhomogeneity introduced by the holes most efficiently[25].

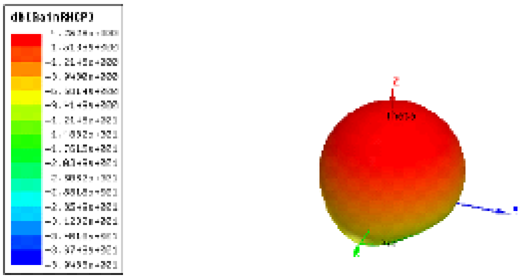

Fig. 5. Pattern of an antenna in the form of an Archimedean spiral

While analyzing the field, the radiating cable can be considered as a thread with current, devided into discrete elementary electric radiators ”l<<» long with current I_n, where n is the ordinal number of the element. Then all subsequent calculations can be performed according to the expressions known for such emitters[26,27].

In the radiation field electromagnetic field components would look as follows[27]:

$$H_\phi = \frac{ikI_0^Э L}{4\pi}\sin\theta\frac{\exp(-ikR)}{R},$$

$$E_\theta = WH_\phi, E_R = \frac{I_0^Э LW}{2\pi}\cos\theta\frac{\exp(-ikR)}{R^2},$$

where ”$_D$ and ¸ are the electromagnetic field components,

W is the wave resistance of the medium,

$I_0^Э L$ is the electric moment of the vibrator,

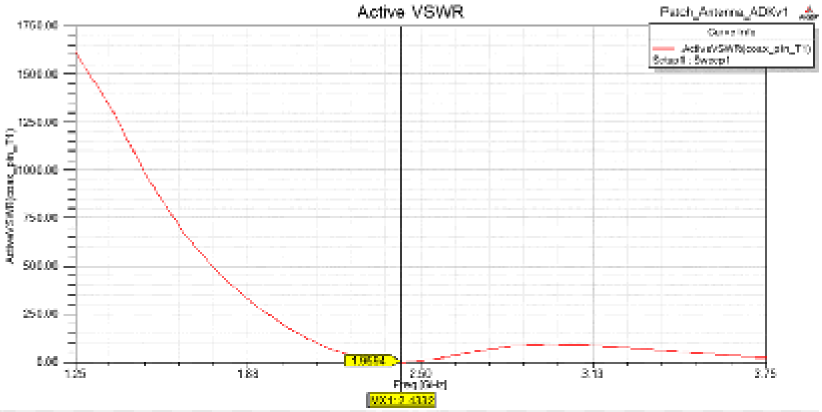

Fig. 6. Rectangular antenna VSWR

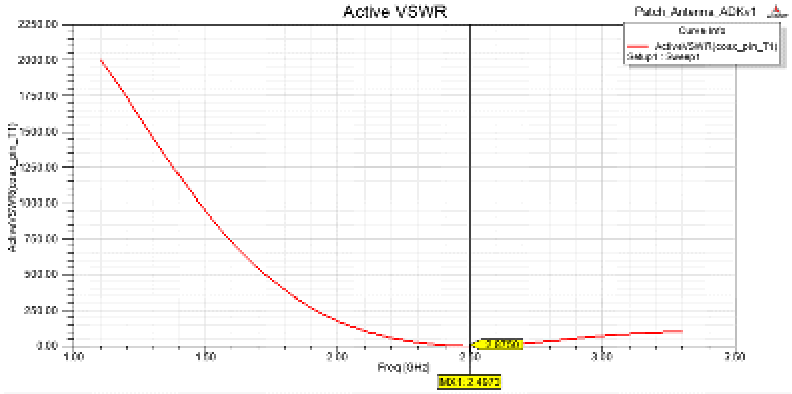

Fig. 7. Circular antenna VSWR

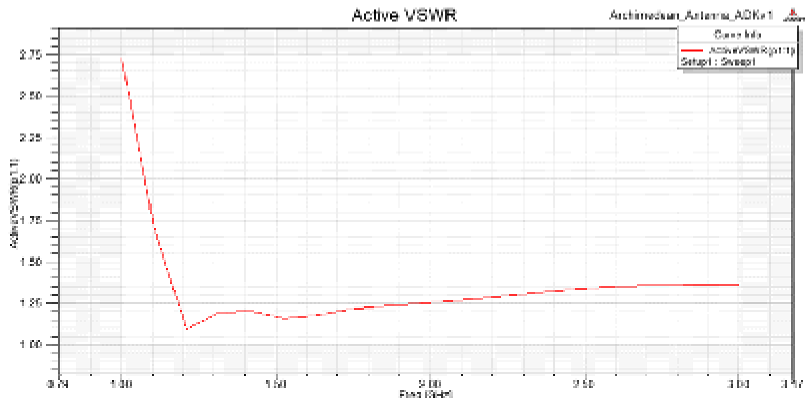

Fig. 8. Antenna in the form of an Archimedean spiral VSWR

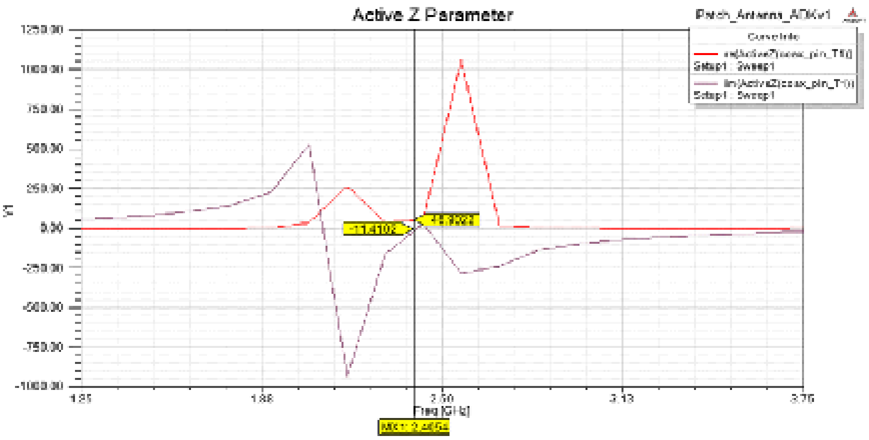

Fig. 9. Input resistance of a rectangular antenna

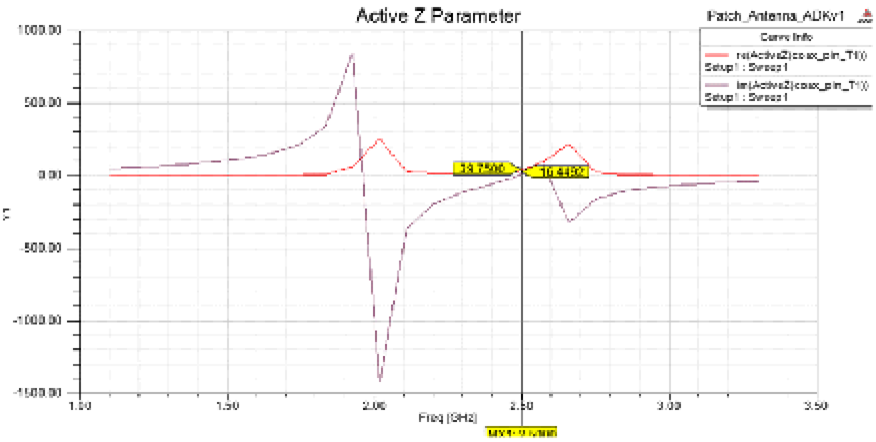

Fig. 10. Input resistance of a circular antenna

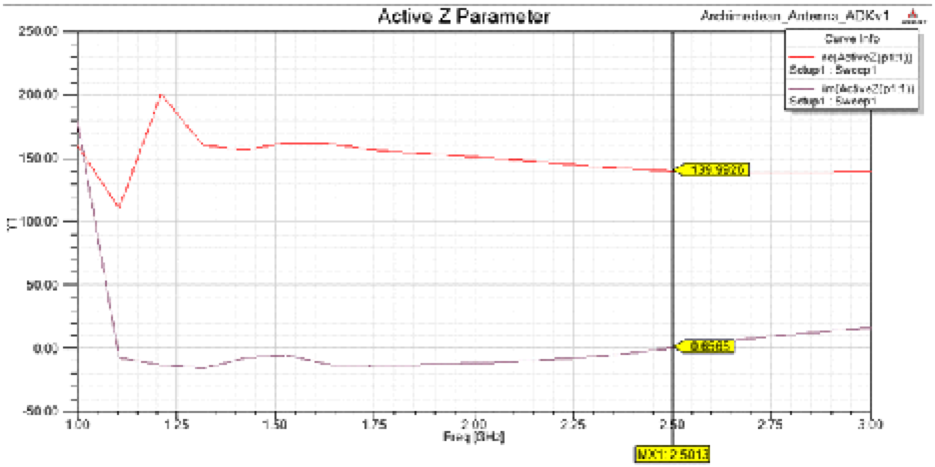

Fig. 11. Input resistance of the antenna in the form of an Archimedean spiral

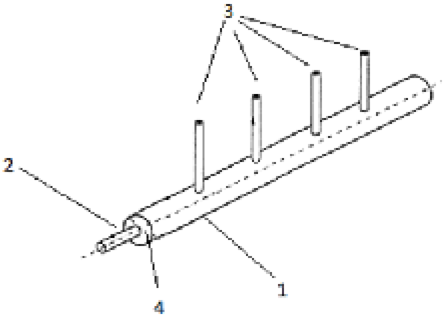

Fig. 12. General view of the "radiating cable" type antenna

k is the wave vector,

R is the distance to the radiation source,

θ is the angle between the axis of the vibrator and the observation point.

Antenna simulation

Let us simulate an individual radiating element in the HFSS program. HFSS finds the electromagnetic field on the surface of the radiation and calculates the electric field in the far zone using equation, which is a form of the theorem of equivalence known in electrodynamics as:

$$E(x,y,z)=\iint_s \left((i\omega\mu_0 H_t)G+(E_t\times\nabla G)+(E_n\nabla G)\right)ds \quad ,$$

where s is radiation surface,

i is imaginary unit number,

is angular frequency,

is the absolute magnetic permeance,

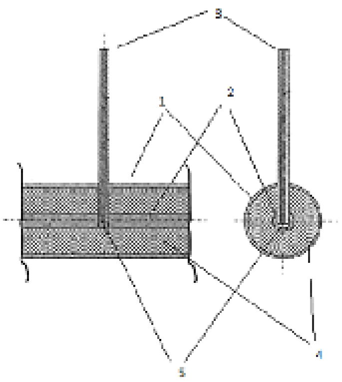

Fig. 13. Longitudinal and cross section of the "radiating cable" type antenna

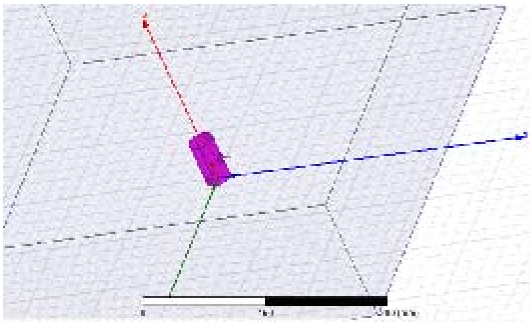

Fig. 14. A three-dimensional model of a segment of coaxial cable with a single radiating element.

H_τ is the tangential component of the magnetic field,

E_τ is the tangential component of the electric field,

E_n is the normal component of the electric field,

G is Green function of free space, equal to:

$$G = \frac{e^{-jk_0\left|\bar{r}-\bar{r}'\right|}}{\left|\bar{r}-\bar{r}'\right|},$$

where k_0 is the wave number of free space, $\bar{r}$ and $\bar{r}'$ are radius-vectors that define,

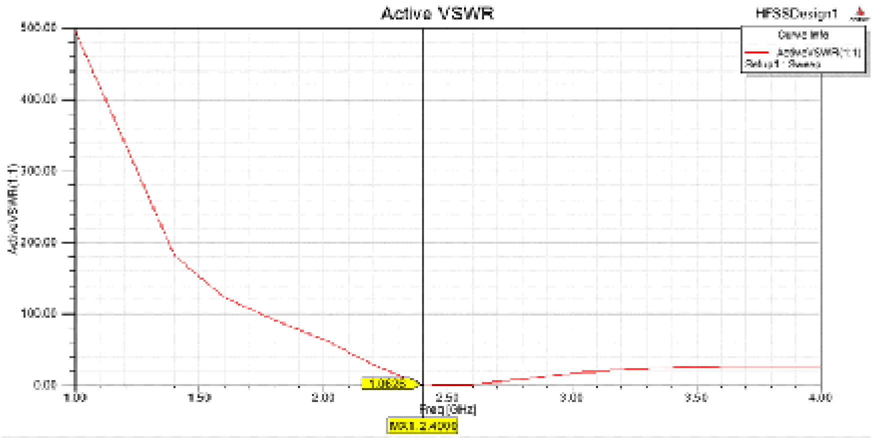

Fig. 15. VSWR of the segment of coaxial cable with a single radiant element

respectively, the observation point (r) and the point on the radiation surface ().[28]

Figure 14 represents a three-dimensional model of a segment of coaxial cable with a single radiating element.

Below are the pictures of VSWR, radiation pattern and input persistence of the segment of coaxial cable with a single radiant element (figures 15-17, respectively).

The input resistance of the segment of coaxial cable with a single radiating element at the

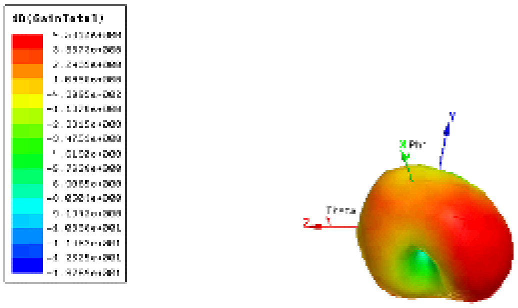

Fig. 16. A three-dimensional radiation pattern of the segment of coaxial cable with a single radiant element

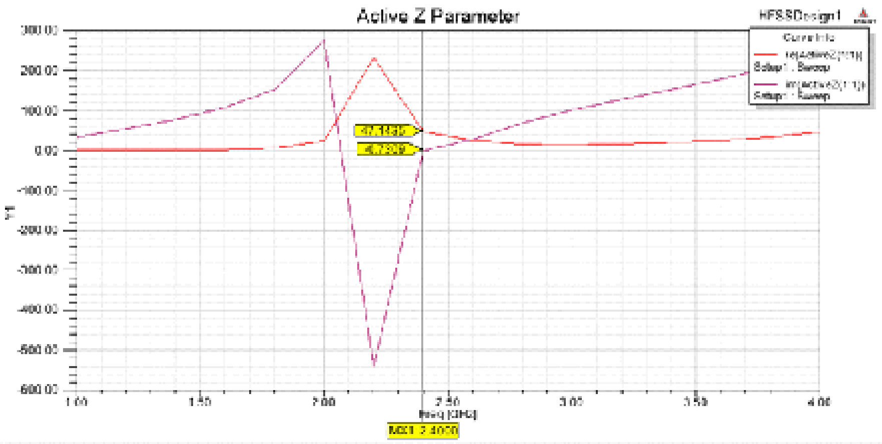

Fig. 17. Input resistance of the segment of coaxial cable with a single radiant element

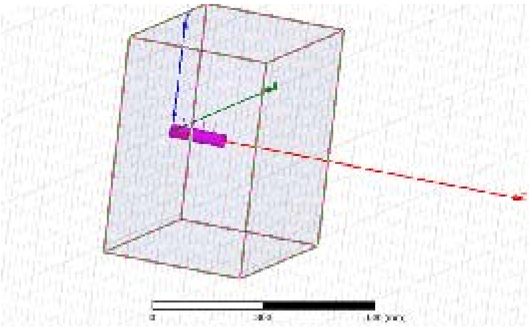

Fig. 18. A three - dimensional model of a segment of coaxial cable with four radiating elements

operation frequency of the reader of the complex "Landish" is purely resistive, and the pattern is basically circular.

Bigger number of radiating elements located at a distance of »/4 (figures 18-21) allows to obtain mainly unidirectional radiation pattern and to increase the antenna gain. The input resistance of the antenna depends primarily on the diameter of the holes in the braid of the cable. With increasing diameter of the slits active antenna resistance decreases, however, reactance of the capacitive nature increases. During the process of

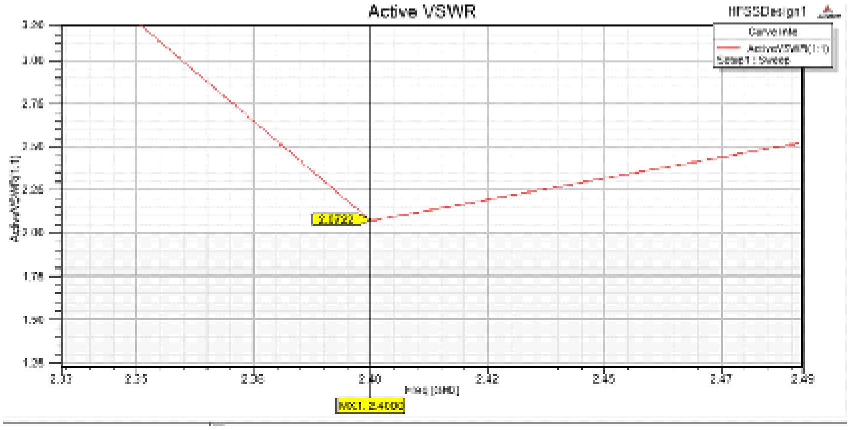

Fig. 19. VSWR of the segment of coaxial cable with four radiating elements

Fig. 20. A three - dimensional pattern of a segment of coaxial cable with four radiating elements

simulation, the optimal diameter of the slits (2.5 - 5 mm) was found; at this diameter the input antenna resistance remains purely resistive, but two times higher than the input resistance of the antenna with a single radiating element.

DISCUSSION AND CONCLUSION

Thus, the simulation of the antenna with four radiating elements showed a two-fold antenna's advantages compared to an antenna with a single radiating elements. The designed antenna has a generally unidirectional radiation pattern, a purely resistive input resistance. During simulation the boundaries for the slits diameter were found, whereby the input antenna resistance is purely resistive and is slightly higher than 100 Ohms at the resonant frequency. Therefore, a separate matching device is required, for example, a quarter-wave transformer that would allow to achieve the operation of the antenna in the RF path of the standard 50 Ohms.

In the future prototyping and testing of the antenna described above will be done, as well as its revision, increasing its gain and improving the efficiency of its functioning. It is expected that considering its specification the antenna will outperform the existing analogues due to the stable uniform strong signal and low energy consumption during the image and control commands transmission from the capsule to the reader and vice versa.

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