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Comparison of the Parameters of Textile Antennas Manufactured Using Three Techniques: Magnetron Sputtering, Ink-Jet Printing and Embroidery

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Abstract

In this work, three textile antennas with the same geometry were produced using three different technologies: magnetron sputtering (PVD), ink-jet printing and embroidery using electroconductive yarn. In all three cases, the electrically conductive medium was the same, which was silver, known for centuries for its very good conductive properties. In order to show how the method of manufacturing antennas affects their operational parameters, the following measurements were carried out: surface resistivity, impedance, standing wave coefficient of antenna radiators, and their radiation characteristics were assessed. The surface resistivity value of the antenna paths obtained ranged from 0.05 to 1.2 Ωm/m.

Keywords

textile antenna, PVD process, ink-jet printing, embroidery, wearable antenna.

1. Introduction

Currently, BAN (Body Area Network) telecommunications networks are widely developed; these are systems that include miniature radio transmitters and receivers working in the vicinity of the human body. These systems can be used both in hospitals (monitoring of heart rate, breathing function, blood pressure), in everyday life (holters for athletes, sleep monitoring for infants) and in the design of clothing for uniformed and rescue services. An important element of a BAN is a properly constructed antenna called a body worn antenna. Antennas of this type are designed in such a way that the interaction of the antenna radiation with the human body does not significantly deteriorate the operating parameters of the antenna. A subclass of wearable antennas are textile antennas, which have small dimensions, are flexible and their placement in smart clothing is much easier than classic antennas. Textile antennas are flat, with a certain flexibility, of small size and can be mounted in clothing in such a way as not to restrict the user's movements. When designing such an antenna, it is necessary to take into account the complex interaction between the electromagnetic wave and the human body [1-5].

There are known solutions in the literature for the production of textile antennas [6-18], however, the authors decided to make three antennas with the same geometry using different methods and compare their parameters, thus showing a new approach to the subject of textile antennas.

2. Antenna's Project

Out of the many antenna designs that can be made in textile technology, the one that requires the implementation of appropriately shaped conductive paths (radiators) was chosen. In the experiments described below, the base structure of the textile antenna was a modified Vee antenna, which has two symmetrical arms made of electrically conductive elements and has already been described in the literature [2, 19-22]. This antenna has good resistance to impedance detuning in relation to the proximity of the human body and to deformations caused by the flexibility of the antenna substrate, although it is very sensitive to changes in the distance between the arms, has been designed to operate in the unlicensed ISM 2.4 GHz band, and is, by definition, intended for scientific applications (ISM – Industrial Scientific Medical – industrial, scientific, medical purposes). This choice was made in such a way that the emission necessary to measure the radiation characteristics would not interfere with the functioning of other radio communication systems. It is assumed that the output impedance of the radio module, to which the antenna will be connected via a coaxial cable, is 50 Ω. The design of the antenna (Figure 1) was made using Remcom's XFDTD software, which enables the analysis of electromagnetic phenomena using the finite difference method in the time domain.

3. Manufacture of antenna radiators

In order to determine the impact of the method of manufacturing on the operating parameters of textile antennas, prototype textile antennas with a single, fixed geometry were made, changing only the production technique. Three antenna radiators with the same geometry were produced using three different techniques: magnetron sputtering (as a new technique in the textile field), ink-jet printing, and embroidery with the use of electrically conductive yarn. The electroconductive agent in all structures

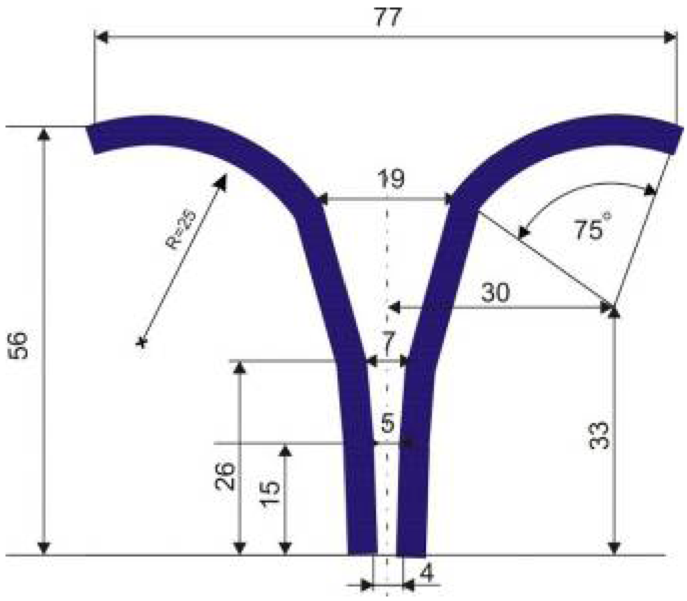

Fig.1. Project of textile antenna

was silver. The process of imparting local electrical conductivity to textile products is not easy, and each of the technologies presented requires a corresponding optimization process. The authors wanted to attain the lowest possible value of surface resistivity of the antenna radiators obtained.

In connection with the potential use of a textile antenna produced at work as an antenna in tectonic clothing, e.g. for a firefighter, it was decided that the antenna substrate must be a non-flammable substrate.

To produce a textile antenna radiator using the magnetron sputtering method, an MK-50 magnetron was used, which was placed in the chamber of a Classic 500 Pfeiffer Vacuum sputtering machine from Softrade. A sample of the polypropylene spun-boned nonwoven fabric was purified by extraction in ethanol alcohol, acetone, and sonication. A dried 12×15 cm textile substrate was placed on a metal operating table and fixed. A foil mask with profiled holes was applied to the surface of the sample, which was used to map the geometry of the antenna on the textile substrate. The stage with the sample was placed on a rack in the vacuum chamber directly above the source of the sprayed metal in the form of a target. Ag was sprayed at a pressure of 2.0×10^{-3} Torr in an argon atmosphere (99.999 % purity argon was used). The distance between the textile material and the sputtering source was 10 cm. The process of deposition of the y-layer was carried out with a variable power supply, the maximum value of which is 1.1 kW. The time of magnetron sputtering lasted 180 minutes; the magnetron operation was cyclical. The process of deposition of electroconductive layers on textile substrates with the use of a magnetron launcher has been described in more detail by the authors in the literature [23,24].

The radiator of the printed textile antenna was manufactured with the use of printer sand LP-50 from PixDro designed for ink-jet printing. The printing process was carried out at room temperature (approx. 25°C). The textile substrate of para-aramid fabric was placed on the printer's power table, attached to it by means of a vacuum pump, and additionally covered with adhesive tape all around to prevent it from moving. Prior to the printing process, the textile substrate was washed in accordance with ISO 105-C06:1996 and purified by ethanol extraction. The traces printed in the form of antenna arms were applied to a Kevlar substrate using Suntonic EMD5603 silver nanoparticle ink. The Spectra SL print head was used, which has 128 piezoelectric printing nozzles with a diameter of 8 μm and is recommended by the manufacturer as the best for the production of printed electronics. In order to produce a suitable printout, Corel Draw 9 prepared templates containing the geometry of the path of the electrically conductive cable,; 15 layers were applied consecutively, and the printing speed was 200 mm/min. The samples were then tumble dried for 60 minutes to solidify the layer.

The antenna embroidered on the spun-bonded non-woven fabric substrate was manufactured using a Kornelia 2004 machine from Łucznik with the use of a silver-coated polyamide thread called X-Static. The yarn, purchased directly from the manufacturer, had good electrically conductive properties, but it was not suitable for machine sewing, as its specific strength was too low and there were frequent spurts during the sewing process, and possible joints disturbed the flow of current in the path produced. Therefore, 2 yarns were joined by twisting (they were given a twist of 350 twist/m) and a thread with a linear density of 49 tex was obtained, the breaking force of which was 1177.5 cN/tex. During the sewing process, the length of the stitch was 2 mm, and each antenna arm was stitched 25 times to fill the path of the 4 mm wide antenna cable with an electrically conductive agent.

The first two technologies for the production of antenna radiators are thin-film technologies; the resulting pattern is obtained by applying metallic particles to the structure of a textile product, with the use of specialized equipment. As a result of the deposition process, an electrically conductive path is created on one side of the fibrous substrate, according to the shape imposed by the producer; although the operation of the path-producing equipment requires appropriate knowledge and experience from the operator. Embroidery technology with the use of electrically conductive yarns allows to obtain a path on both sides of the textile substrate, and the radiant obtained as a result of embroidery has the largest thickness.

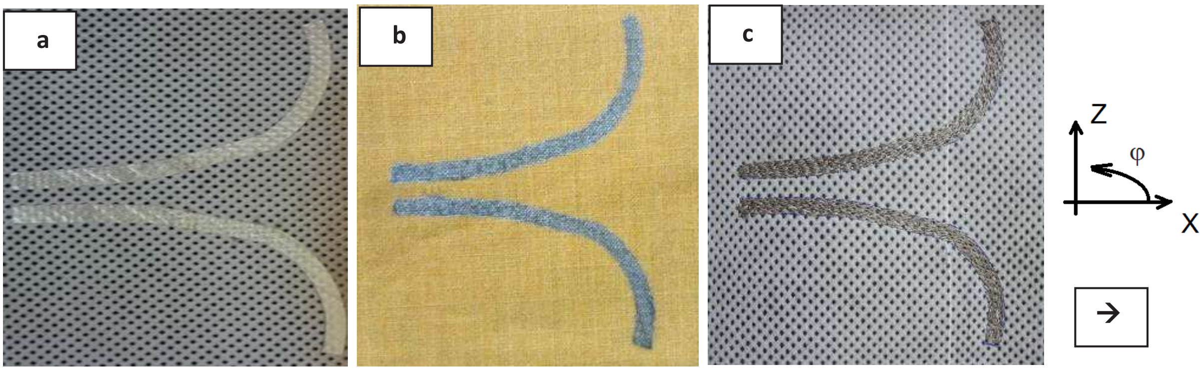

Fig. 2. Textile antennas with radiation: a)sputtered, b)printed, c)embroidered

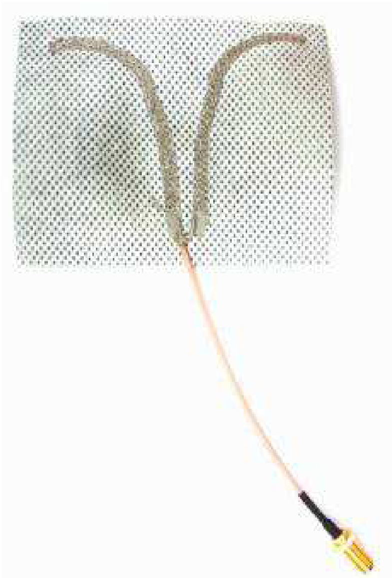

Fig.3. Embroidered antenna connected to coaxial cable

Method of production	***Magnetron sputtering***	***Ink-jet printing***	***Embroidery***
Electroconductive factor	Ag	Ag nanoparticles	Yarn with Ag
Surface resistivity r_S, Ωm/m	0,05	2,83	1,20

Table 1. Comparison of r_S electroconductive paths

Initially, the authors wanted to obtain electrically conductive paths produced by different methods on the same textile substrate (spun-bonded non-woven fabric), but unfortunately this was not possible in the case of printed traces, because the ink after application to the substrate must be placed in an environment of elevated temperature for a certain period of time in order to carry out the sintering process. The polypropylene substrate is thermoplastic and changed its properties after the annealing process. The printed antenna radiators were therefore made on a substrate of para-aramid fabric (which, in turn, did not work well as a substrate for spraying). The substrates selected in the work had a similar value of the dielectric constant. Photos of antenna radiators and the direction of their examination are shown in Figure 2.

The antenna radiators were connected to the coaxial cable by means of embroidery and soldering. An example picture of an antenna connected to a coaxial cable and a protected antenna is shown in Figure 3.

4. Testing methodology

Electroconductive properties of the transmission paths formed were evaluated by measuring surface electrical resistivity according to Standard PN-EN 1149:2008. The samples were conditioned for 24 hours and tested at 23°C and relative humidity of 25 %. The study was performed for a 2-electrode system, using an Extech EX570 multimeter, electrometer Rigol DM3052 and stabilized power supply.

The electrical parameters of the textile antenna produced by digital printing were verified by measurement of the antenna's input impedance and the voltage standing wave ratio (VSWR) in relation to the impedance Z_o=50 Ω of the antenna structures produced. The measurements were made using a vector circuit analyser – Rohde & Schwarz ZVB-14. Measurements of antenna radiation characteristics were carried out in free space (open area test site) using a Rohde & Schwarz SMB 100A signal generator, a Rohde & Schwarz FSC6 spectrum analyser, and a measuring antenna – Rohde & Schwarz HF 907.

5. Results

The surface resistivity of the electroconductive paths produced by magnetron sputtering, printing and embroidery was investigated, the results of which are presented in Table 1.

Tests were carried out on antennas with magnetron-sprayed, printed and embroidered radiators. The results are summarized in Figures 4-12.

The impedance bandwidth of the sputtered antenna was determined by the condition VSWR ≤ 2, covering the range from 2300 MHz to 2580 MHz. The minimum value of the standing wave ratio is 1.16 - the value was obtained for a frequency of 2410 MHz.

The antenna tested was located on a table that rotated during the measurement. This made it possible to obtain an image of the antenna's radiation distribution in various directions on a logarithmic scale.

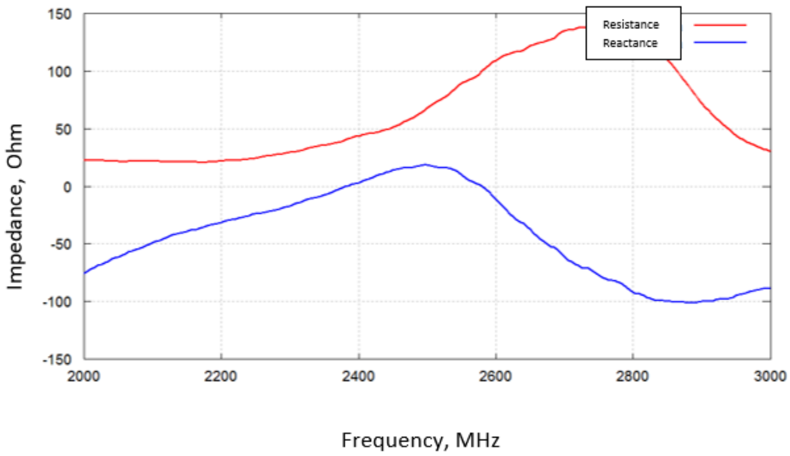

Fig.4 Impedance of textile antenna made by magnetron sputtering (reactance – blue line, resistance – red line)

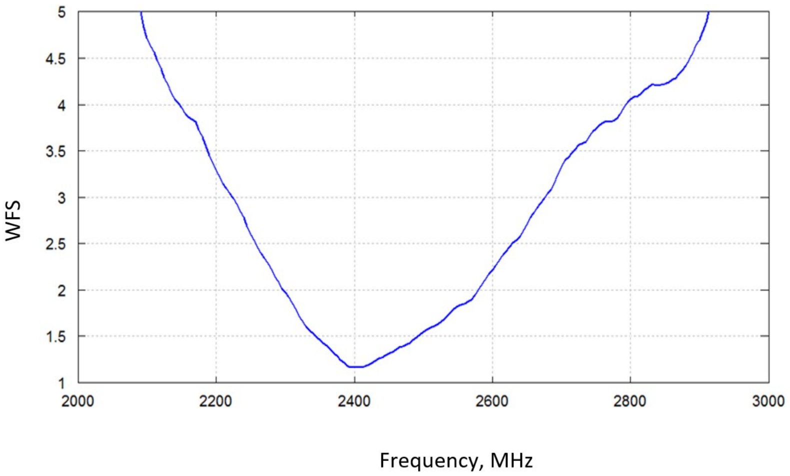

Fig.5. Voltage standing wave ratio of antenna with sputtered radiator

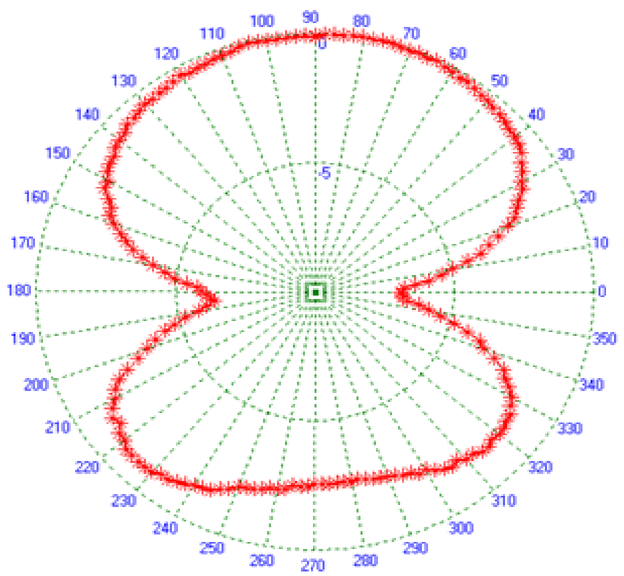

Fig.6. Radiation pattern of antenna with a sputtered radiator in free space, normalized gain of the antenna in vertical polarization $G_q(j,90)$ at a frequency of 2.4 GHz

The centre of the graph coincides with the centre of the antenna. The shape of the radiation pattern required depends on the location of the antenna in the area monitored. The radiation pattern of the magnetron-sprayed radiator antenna obtained for the Vee type antenna shows that the antenna has two main beams in the areas where it radiates most of the energy. The area limited by the red markers on the graph is the area where the antenna radiates energy; in the remaining area the antenna does not work. The antenna gain is 3.5 dBi.

The impedance bandwidth of the printed antenna was determined by the condition VSWR $\leq$ 2, covering the range from 2200 MHz to 2480 MHz. The minimum value of the standing wave ratio is 1.19 - the value was obtained for a frequency of 2300 MHz. This frequency is 100 MHz lower than that obtained in computer simulations (2400 MHz).

Figure 9 shows the radiation pattern of a fabric antenna with a printed radiator presented on a logarithmic scale. The figure shows the directivity of the antenna; the maximum gain of the antenna is 3.5 dBi.

The impedance bandwidth of the embroidered antenna was determined by the condition VSWR $\leq$ 2, covering the range from 2000 MHz to 2230 MHz. The minimum value of the standing wave ratio is 1.09 - the value was obtained for a frequency of 2085 MHz.

Figure 12 shows the radiation pattern of an antenna with a radiator embroidered on a PPT substrate presented on a logarithmic scale. The figure shows the directivity of the antenna; the maximum gain of the antenna is 4.5 dBi.

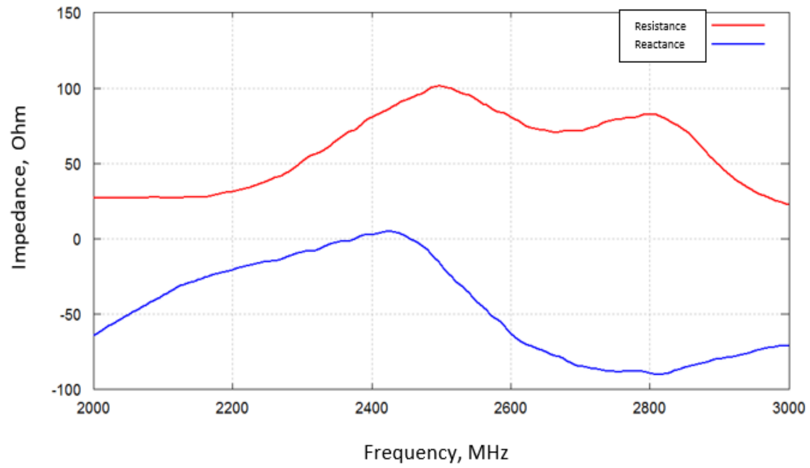

Fig.7. Impedance of textile antenna made by printing (reactance – blue line, resistance – red line)

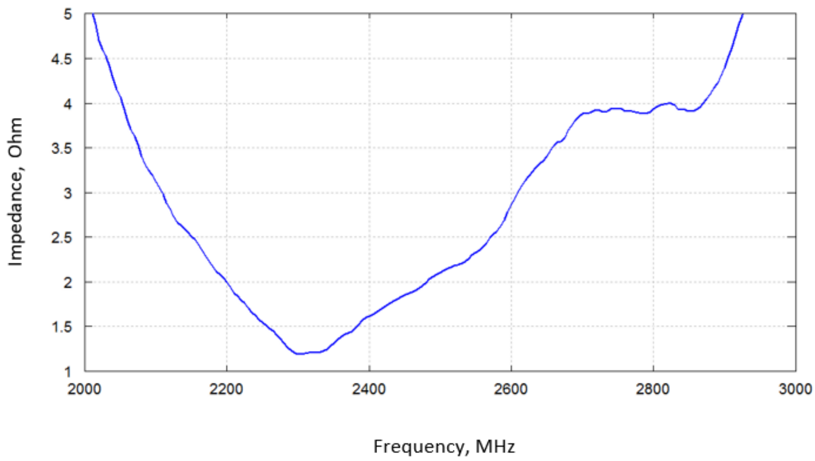

Fig.8. Voltage standing wave ratio of antenna with printed radiator

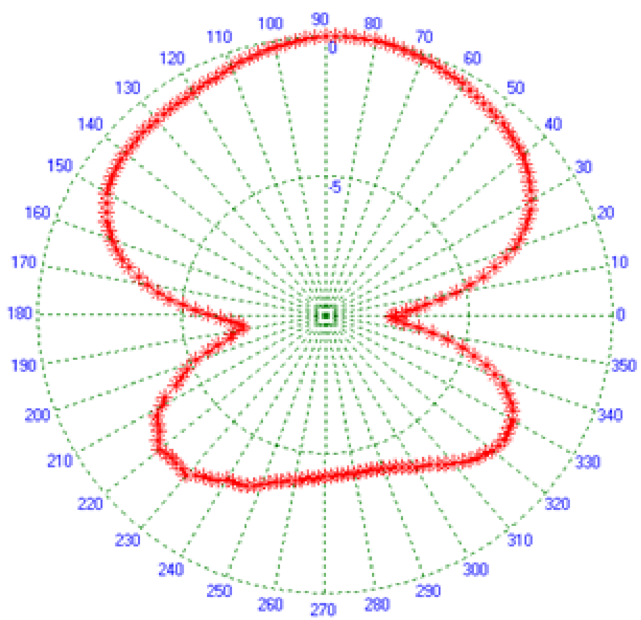

Fig.9. Radiation pattern of antenna with a printed radiator in free space, normalized gain of the antenna in vertical polarization $G_q(j,90)$ at a frequency of 2.4 GHz

6. Conclusions

The paper shows that it is possible to produce effective prototypes of textile antennas using the following technologies: magnetron sputtering, ink-jet printing and embroidery. These antennas can be used as components of smart clothing.

In all three antenna radiators, the electrically conductive agent was silver. The lowest value of surface resistivity was obtained for the magnetron sputtered path (0.05 Ωm/m), while the highest for the printed path (2.83 Ωm/m). The surface resistivity of the embroidered path was 1.2 Ωm/m.

Studies of the standing wave ratio, impedance and radiation characteristics of the textile antennas were performed. The standing wave ratio of all the antennas produced ranged from 1.09 to 1.19, which is a satisfactory result.

It has been observed that antennas made using magnetron sputtering and printing techniques have a similar impedance band.

Vee textile antennas produced at work using magnetron sputtering techniques, ink switches and handles can be found in smart devices. The highest gain identified is for the embroidered radiator antenna as it reaches a value of 4.5 dBi. At this impedance the magnetron-sprayed and printed radiator antennas achieve a higher gain than the embroidered radiator antenna; but for both radiators it is approved because its value is 3.5 dBi.

In the case of antennas with the same geometry, with an embroidered radiator, the antenna is impeded by the its input impedance towards lower frequencies. This is probably due to the fact that antennas with magnetron-sprayed and printed radiators have an electrically conductive plane only on one side of the substrate (printing and sputtering are one-sided). In the embroidery process, the electrically conductive agent is placed on both sides of the textile substrate, and this radiator has the thickest thickness of all three radiators tested.

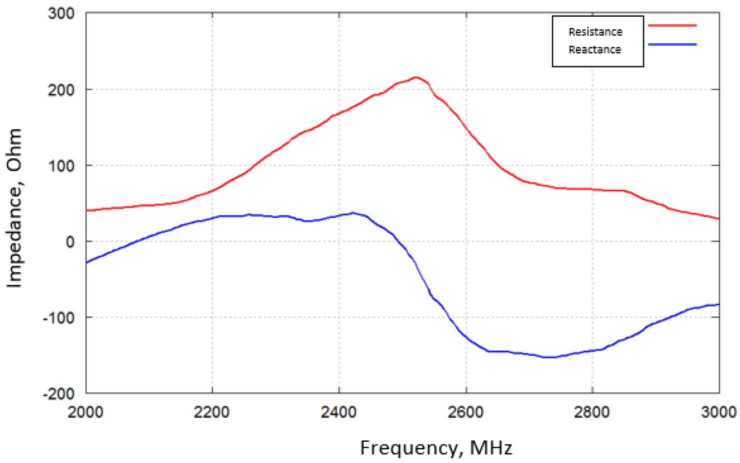

Fig.10. Impedance of textile antenna made by embroidery (reactance – blue line, resistance – red line)

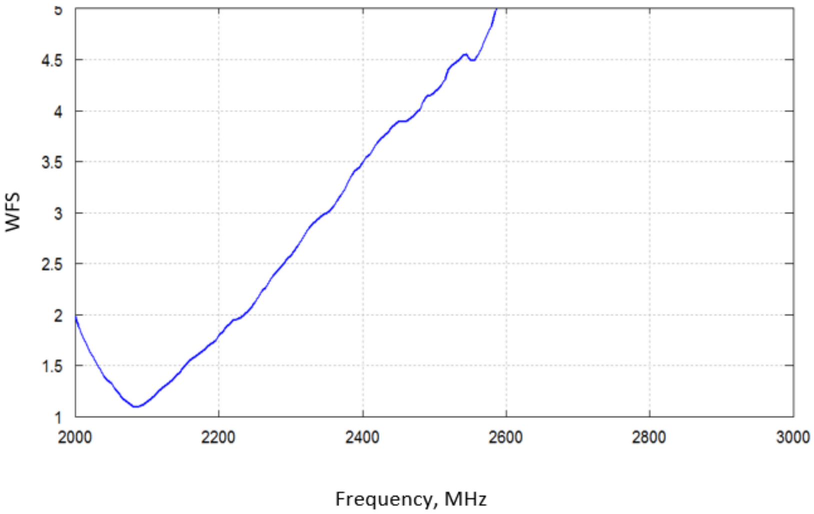

Fig.11. Voltage standing wave ratio of antenna with embroidered radiator

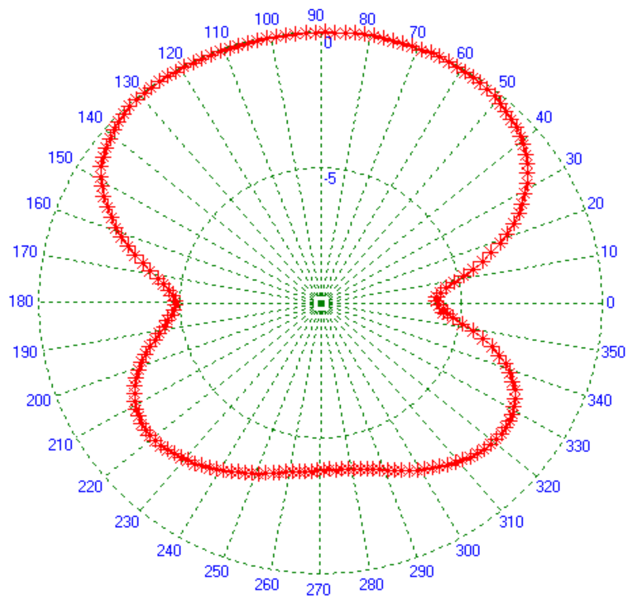

Fig.12. Radiation pattern of antenna with a embroidered radiator in free space, normalized gain of the antenna in vertical polarization $G_q(j,90)$ at a frequency of 2.4 GHz

Therefore, it can be argued that the method of manufacturing an antenna radiator has an impact on the parameters of the antenna produced.

A textile antenna was manufactured using PVD technology, which is a new solution. This technology allows for the production of antenna radiators with the lowest surface resistivity value, but requires the use of modern and expensive equipment.

The simplest and cheapest technique for producing a textile antenna is the embroidery technique, which is recommended for industrial applications.

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