Design and SAR Reduction of the Vest Antenna using Metamaterial for Broadband Applications

M. Fallah[1], A. A. Heydari[2], A. R. Mallahzadeh[2], and F. H. Kashani[1]

[1]Faculty of Electrical Engineering
Iran University of Science and Technology, Tehran, Iran

[2]Faculty of Engineering
Shahed University, Tehran, Iran
mohsen_fallah@ee.iust.ac.ir, amirabbas.heydari@gmail.com, mallahzadeh@shahed.ac.ir, kashani@iust.ac.ir

Abstract **─** One of the most important obstacles that portable antennas are facing is their harmful effect on the user's body. In this paper, besides proposing a UWB vest antenna with a bandwidth of at least 500MHz, we try to reduce the specific absorption ratio (SAR) due to the proposed antenna on the human body. In order to achieve the mentioned goal, we modeled the human body after designing the antenna. In order to have simulation results closer to reality, we have used a 3-layer model of the human body instead of the 1-layer model. In our model of the human body, all of the body parts, except the torso, are modeled with three layers of bone, fat, and muscle. Since the torso has a different structure from other body parts and is close to the place of the antenna feed, we modeled it using four layers of air, bone, fat and muscle. As the next step in our simulation process, the antenna was installed on the human body and then the antenna parameters and its SAR were obtained again. In the last stage, SAR due to the proposed antenna is reduced using metamaterial.

Index Terms **─** Meta material antenna, SAR reduction, vest antenna.

I. INTRODUCTION

Soldiers, police officers, firefighters, forest workers, etc. need "hands free" operation for their wireless equipment. A solution is to use antennas borne or worn on their helmet (as a helmet antenna) or on their upper torso (as a vest antenna) [1, 2]. The process of designing the RF vest antenna started with the analysis of ultra wideband antenna concepts, followed by computer simulation of potential designs. An optimum design was chosen based on the input impedance and voltage standing wave ratio (VSWR). In [3], an antenna with a bandwidth of 360MHz was designed; in [4], the design of a vest antenna with a VSWR less than 3.1 for the 100 to 500 MHz frequency band is shown; design of an ultra wideband vest antenna with a VSWR less than 3 for frequencies 31 to 475 MHz can be found in [5]; also, a ZERO VISUAL SIGNATURE vest antenna with VSWR<3 for the frequency range of 50 and 500 MHz is reported in [6].

Ongoing work includes the improvement of the computer model, design optimization, fabrication, and SAR reduction [6].

Natural low-frequency EM fields come from two main sources: the sun and thunderstorm activities. But in the last 100 years, man-made fields at much higher intensities and with a very different spectral distribution have altered this natural EM background in ways that are not yet fully understood. For example, in the design of the combat wear integration (COMWIN) RF vest antenna in addition to providing appropriate frequency range to establish wireless communication, we need to protect the health of the men that use and carry the antenna. There is strong challenge in designing body worn antennas

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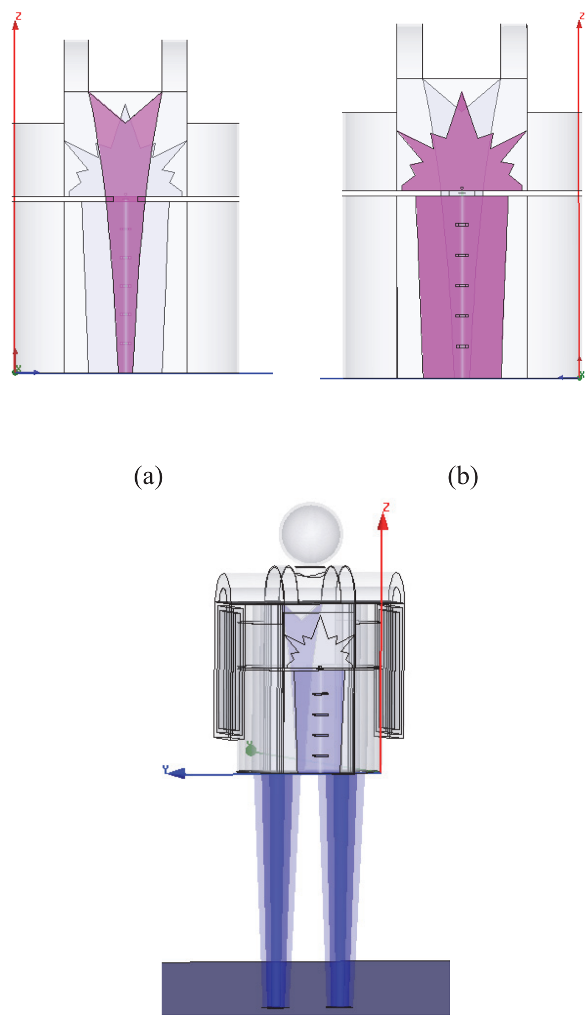
with the appropriate frequency range and at the same time protecting the human body from harmful effects.

Over the last fifteen years, many authors have investigated the SAR with human head due to the complexity and large scale involved in such kinds



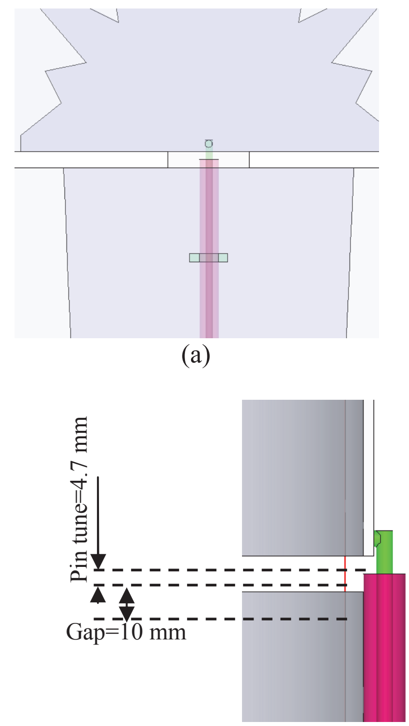
(a) (b)

(c)

Fig. 1. Schematic of the vest antenna (a) front view, (b) back view, and (c) 3D view.

of problems [11-19]. Recently, lots of attention has been paid to the reduction of peak SAR within materials and metamaterials. In [12], a ferrite sheet was adopted as a protection attachment between the antenna and the human head. A reduction over 13% for the spatial peak SAR over 1 gm averaging was achieved. Study on the effects of attaching materials and metamaterials for SAR reduction is presented in [19], and it was concluded that the position of shielding played an important role in the reduction effectiveness.

Recently, metamaterials have inspired great interests due to their unique physical properties and novel application [20, 21]. Metamaterials denote artificially constructed materials having



(a)

(b)

Fig. 2. The configuration of the feed region (a) side view and (b) front view.

electromagnetic properties not generally found in nature. Two important parameters, electric permittivity and magnetic permeability, determine the response of the materials to the electromagnetic propagation. Mediums with negative permittivity can be obtained by arranging the metallic thin wires periodically [7, 22-31]. On the other hand, an array of split ring resonators (SRRs) can exhibit negative effective permeability [32]. Metallic thin wires and SRRs are narrow-banded and lossy materials. When one of the effective medium parameters is negative and the other is positive, the medium will display as stop band. The metamaterials is on a scale less than the wavelength of radiation and use slow density of metal. The structures are resonant due to internal capacitance and inductance. The stop band of metamaterials can be designed as operation bands of cellular phone while the size of metamaterials is similar to that of a cellular phone. Metamaterials are designed on circuit boards so it may be easily integrated to the cellular phone [33]. Simulation of

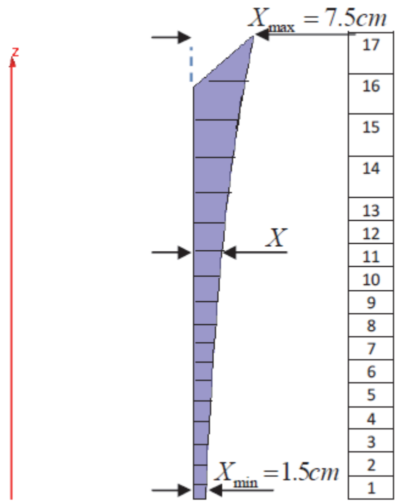


Fig. 3. Schematic of the strip in front side of the vest antenna.

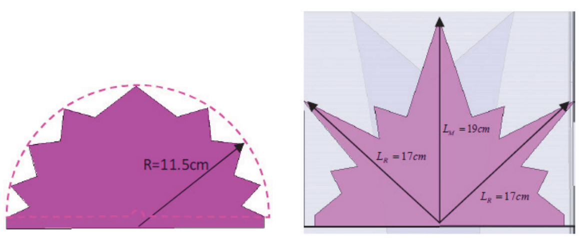


Fig. 4. The initial pattern (a) upper part of the vest antenna and (b) final pattern.

wave propagation into metamaterials was proposed in [34].

Another approach for reducing the SAR is the use of a directional or reflectional antenna [35, 36]. In [17], a perfect electric conductor (PEC) reflector was arranged between a human head and the driver of a folded loop antenna. The result showed that the radiation efficiency can be enhanced and the peak SAR value can be reduced. Metamaterial have inspired great interests due to their unique physical properties and novel applications [35, 40]. The motivation of this paper is to design metamaterial to investigate the potential reduction of the peak SAR value.

In this paper, a broadband vest antenna with a bandwidth of 160% ranging for VSWR<3 with reduced SAR on the human body by using metamaterial is proposed. In order to reduce the vest antenna SAR appropriate metamaterial namely TW type is used.

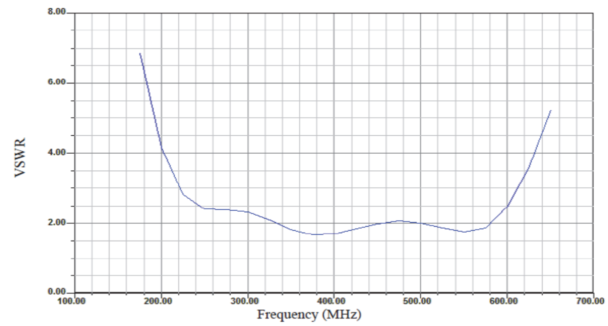


Fig. 5. Simulated VSWR of the designed vest antenna.

In section two of this paper, first we designed an ultra wideband vest antenna. In section three, we modeled the human body using four layers in the abdominal region and three layers in other parts of the body. In section four, we designed metamaterial to reduce the SAR of the antenna, and finally in section five, we measured the specific absorption ratio (SAR) of the vest antenna in the presence of the designed metamaterial.

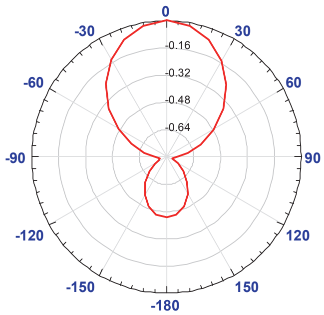
II. DESIGNING THE UWB VEST ANTENNA

For borne or worn antenna, consider the vest antenna and by shaping obtained the present structure. The antenna is installed on a polyester vest with a thickness of 5mm. It consists of two parts, the upper part and the lower part. Both of the mentioned parts are installed on the back side of the vest. There is a conductive strip in the front side of the vest.

Figure 1 shows the vest antenna from the front side and the back side. The antenna is fed through a coaxial cable in a way that the core of the cable is connected to the upper part of the antenna and the cable shield is connected to the lower part, as shown in Fig. 2.

In order to increase the antenna bandwidth, exponential equations are used in designing the lower part of the antenna and the metal strip in the front side of the antenna. Strip width in the lower part of the antenna starts from 15cm to 17.8cm.

The in front one starts from 3cm to 15cm. For example, in front strip the first 13 components are 2.95cm and the other 4 components are 3.83cm.



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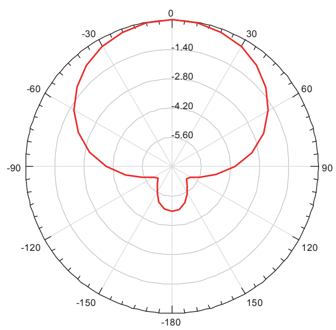

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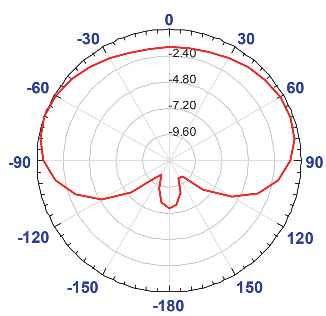


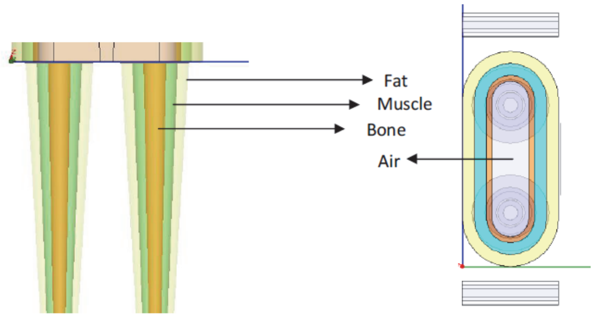
(c)

Fig. 6. Simulated radiation pattern in the horizontal plane at (a) 100MHz, (b) 350MHz, and (c) 600MHz.

$$X = \frac{X_{\min}}{2} e^{az}. \qquad (1)$$

$$a = \frac{1}{h.\ln(\frac{X_{\max}}{X_{\min}})}. \qquad (2)$$

A jagged shape with the following specifications is used in the design of the upper part of the antenna. The initial design consisted of a semicircle. The maximum point of each jag was



(a) (b)

Fig. 7. The modeled human body (a) legs and (b) torso.

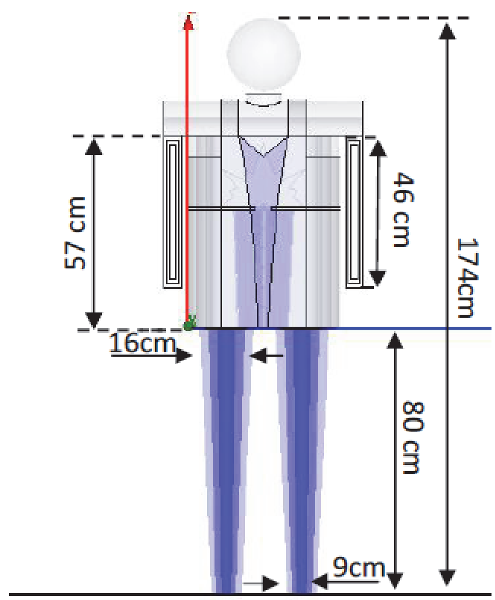


Fig. 8. The configuration of the final modeled of the human body.

located on the circumference of the semicircle. The following shape was obtained, after tuning the initial shape for having a better VSWR. The VSWR of the tuned antenna is shown in Fig. 5. As shown in Fig. 5, the antenna bandwidth is about 400MHz. The radiation pattern of the vest antenna is shown in Fig. 6. The results of the simulation and tuning of the variables are obtained by Ansoft HFSS v.11 [41].

III. SIMULATION RESULT OF THE VEST ANTENNA ON A HUMAN BODY

In this section, we are going to discuss the modeling of the human body. In order to have the closest possible results to reality, the dimensions of the modeled human body are according to the typical person.

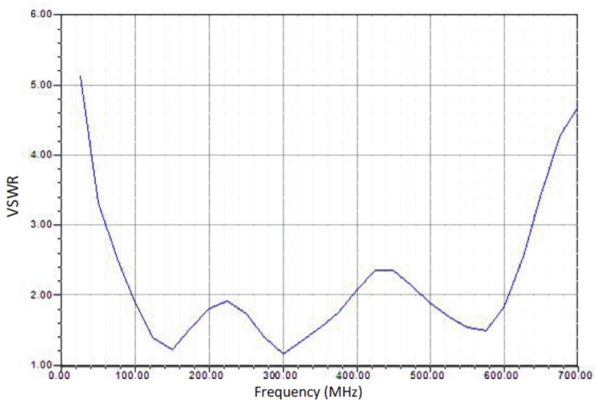


Fig. 9. Simulated VSWR of the vest antenna on the human body.

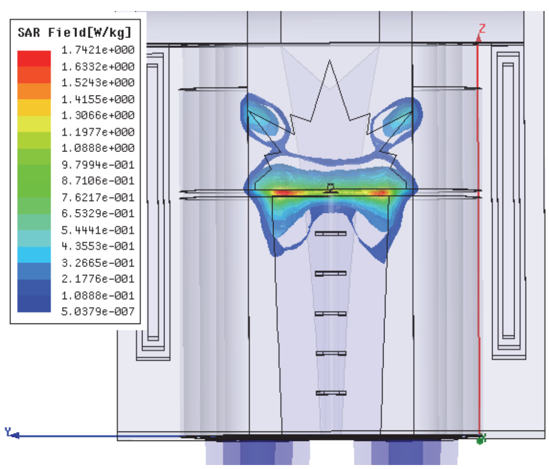
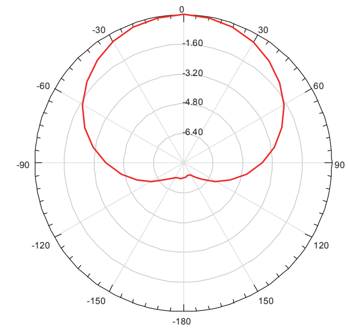


Fig. 10. The simulated average SAR on the human body at 500MHz.

Table 1: The electromagnetic characteristics of the main parts of the human body at 500MHz [8]

Material	ε	σ	***Loss tangent***
Bone	12.946	0.10047	0.27901
Fat	5.5444	0.042793	0.27748
Muscle	56.445	0.82245	0.52383
Brain Grey Matter	55.833	0.77907	0.50165
Brain White Matter	41.004	0.47391	0.41551



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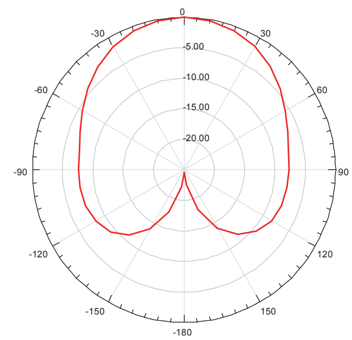

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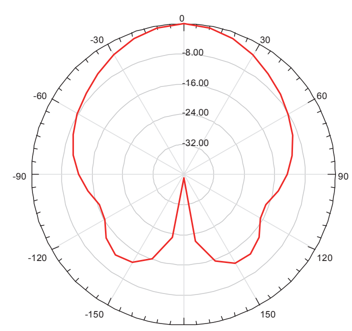
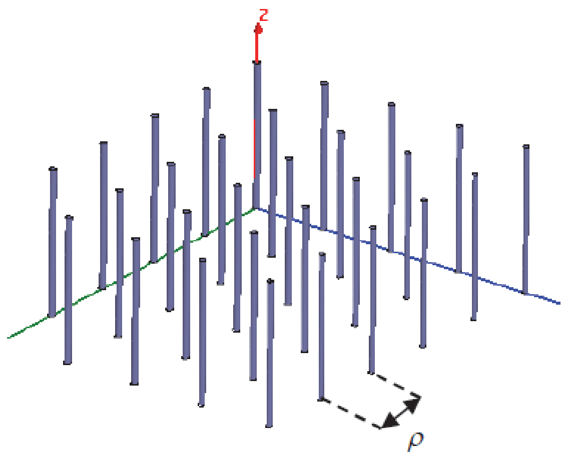


(c)

Fig. 11. Radiation pattern in the horizontal plane at (a) 100MHz, (b) 350MHz, and (c) 600MHz.

As shown in Fig. 7, the legs are constructed of three layers of bone, muscle, and fat. The height of the legs is about 80cm. In the next stage, the torso and the upper part of the shoulders are modeled. Since this part of the body is closer to the antenna and its feed, a more accurate modeling is used. Because the torso has a different structure from the rest of the body (the existence of air inside the lungs), four layers are used for modeling this part of the body as shown in Fig. 7. The final model is depicted in Fig. 8. The electromagnetic characteristics of the main parts of the human body in frequency of 500MHz are listed in Table 1. In spite of the suitable VSWR, the SAR in the body parts close to the antenna, such as the waist is much higher than the standard limits.

According to the IEEE standard, the average SAR in the human body must not be more than 0.08 W/Kg [9, 10]. But this limit is reduced to 0.02 W/Kg for the region close to the head.



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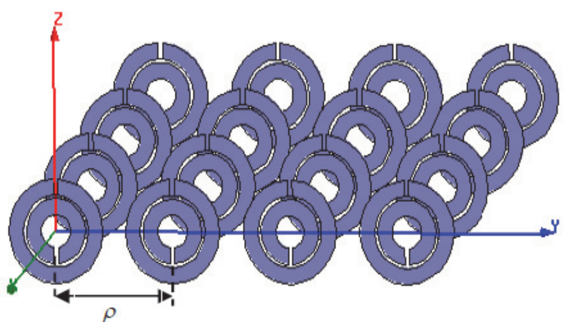


(b)

Fig. 12. Metamaterial structures, (a) TW structure and (b) SRR structure.

As shown in Fig. 10, the obtained peak SAR, due to the proposed antenna, on the human body is about 1.74 W/Kg, which is approximately 22 times the standard limit.

In the next section, we try to use metamaterial in order to reduce the SAR of the vest antenna on a human body. This method was recently used for decreasing the SAR in cell phones [19]. Radiation pattern is shown in Fig. 11 in azimuth for various frequencies.

IV. METAMATERIAL MODELING

Metamaterials are broadly defined as artificial effectively homogeneous electromagnetic structures with unusual properties not readily found in the nature. In these structures, the average cell size is much smaller than the wavelength of the operational frequency in the free space.

A. Designing the appropriate metamaterial for the proposed vest antenna

For designing the needed metamaterial, we consider the operational frequency of the vest antenna and the design formulas of metamaterial, with $\varepsilon > 0$ $\mu < 0$ for a split-ring resonator (SRR) structure and $\varepsilon < 0$ $\mu > 0$ for a thin-wire (TW) structure, we chose the second type which is TW. You can see the structures of these two types of metamaterial in Fig. 12.

B. SRR design procedure

The permeability of a SRR structure can be calculated using:

$$\mu_r(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_{0m}^2 + j\omega\zeta}$$

$$\mu_r(\omega) = 1 - \frac{F\omega^2(\omega^2 - \omega_{0m}^2)}{(\omega^2 - \omega_{0m}^2)^2 + (\omega\zeta)^2} \qquad (3)$$

$$+ j\frac{F\omega^2\zeta}{(\omega^2 - \omega_{0m}^2)^2 + (\omega\zeta)^2}.$$

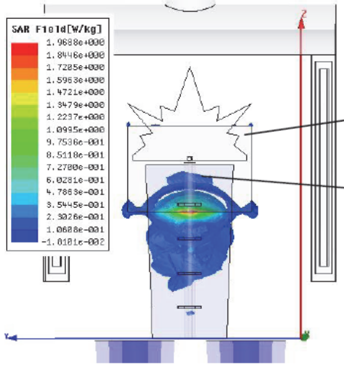


Fig. 13. Simulated average SAR in the presence of the material with a negative ε_r.

Wherein, $F = \pi(a/p)^2$, a is the inner radius of the smaller ring, $\omega_{0m} = c\sqrt{\dfrac{3p}{\pi \ln(2wa^3/\delta)}}$ is the magnetic resonance frequency in which w is the thickness of the rings and δ is the radial distance between the rings. Also, $\xi = 2pR^{/}/a\mu_0$ is the damping factor which is related to the loss in the metal, with $R^{/}$ as the metal resistance in the unit length.

For finding the frequency range in (3) in which $\mu_r < 0$, the metal loss is supposed to be small. Therefore,

$$\mu_r < 0 \;\; for \quad \omega_{0m} < \omega < \frac{\omega_{0m}}{\sqrt{1-F}} = \omega_{pm}, \tag{4}$$

where ω_{pm} is called the magnetic plasma frequency**.**

According to (4), the antenna operational frequency must be higher than ω_{0m} for having a negative μ_r, but considering the fact that for SRRs with common dimensions this frequency is about several GHz, using SRRs in our design is not feasible [42]. The attempts made in [10] for using SRR to reduce the SAR of the cell phones on the human head, show that a layer of SRR with a thickness of 25mm can reduce the SAR for only about 27% in the GSM900 frequency band, while the same SRR used in the GSM1800 frequency band can reduce the SAR up to 38%.

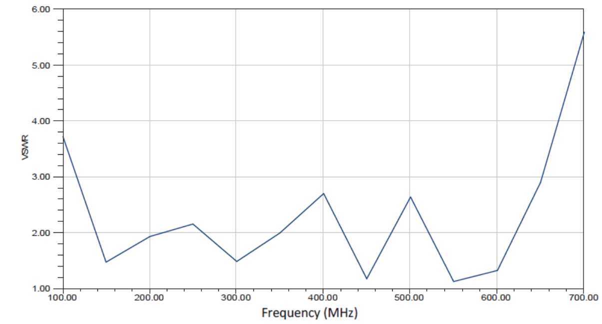


Fig. 14. Simulated VSWR of the proposed vest antenna after reduced SAR.

C. TW design procedure

The relative permittivity of the thin wire can be calculated with the following formulation:

$$\varepsilon_r(\omega) = 1 - \frac{\omega_{pe}^2}{\omega^2 + i\omega\zeta}. \tag{5}$$

In (5), $\omega_{pe} = \sqrt{\dfrac{2\pi c^2}{p^2 \ln(\frac{p}{a})}}$ is the electric plasma frequency where c is the light velocity and a is the radius of the wires. $\xi = \dfrac{\varepsilon_0 (p\omega_{pe}/a_0)^2}{\pi\sigma}$ is the damping factor with σ as the metal conductivity. From (5) we have:

$$\mathrm{Re}(\varepsilon_r) < 0 \;\; for \quad \omega^2 < \omega_{pe}^2 - \xi^2. \tag{6}$$

Equation (6) gives the frequency range for a negative permittivity. If we ignore the loss, we will have:

$$\varepsilon_r < 0 \quad for \quad \omega < \omega_{pe}. \tag{7}$$

From (6), it is evident that if the operational frequency is less than the electric plasma frequency, the ε_r will be negative [42]. The next step instead of the full modeling of the metamaterial, we used a rectangular cube with a

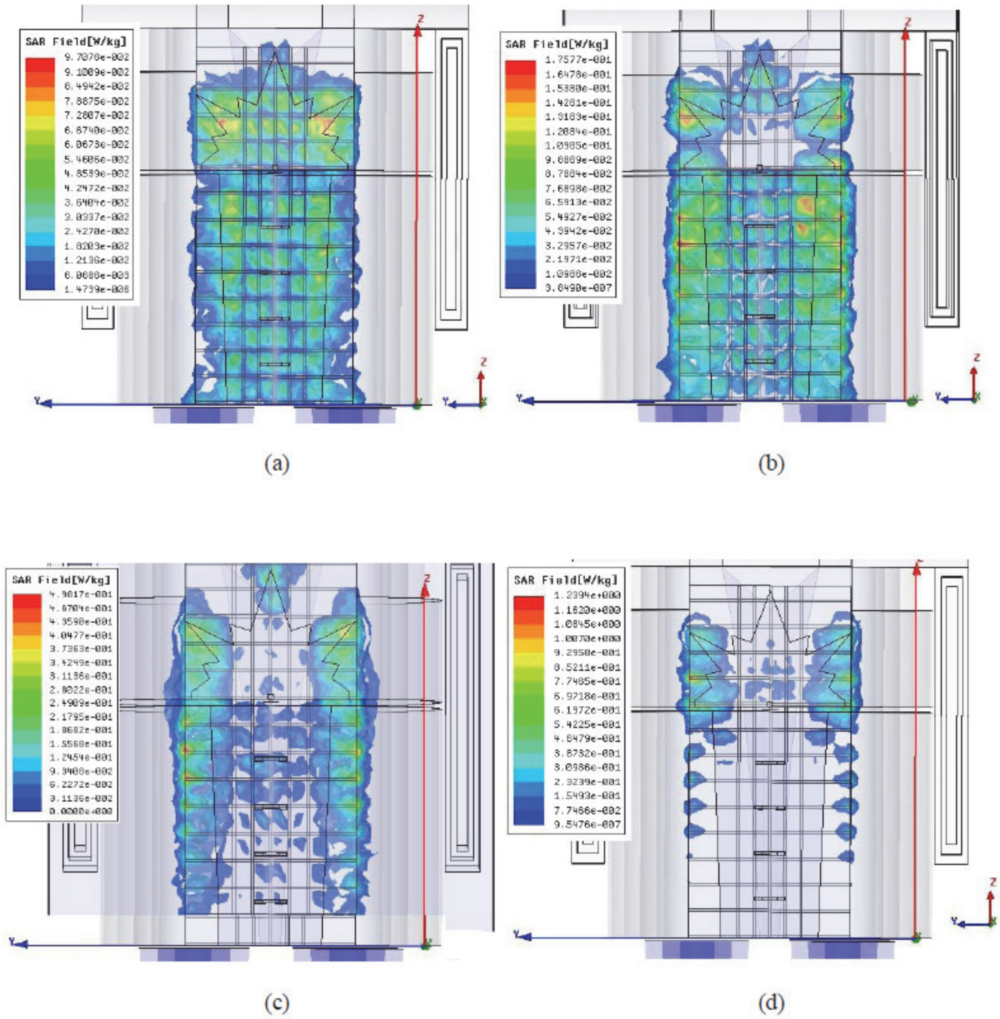


Fig. 15. Simulated SAR in the presence of the metamaterial at (a) 100MHz, (b) 350MHz, (c) 500MHz, and (d) 600MHz.

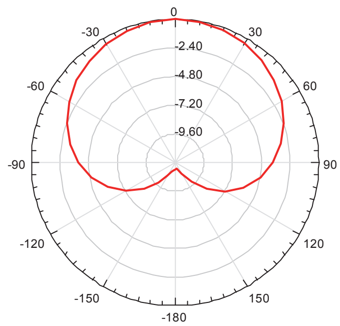
variable ε_r that it's ε_r was obtained from equation (5).

As illustrated in Fig. 13, using a material with a negative ε_r between the human body and the antenna, the SAR due to the vest antenna in the regions of the body covered with metamaterial is reduced considerably. So we will continue modeling TW metamaterial in our project.

In modeling of the TW metamaterial instead of using wires with a radius equal to a, we used strips with a width of $2a$. In order to have a better compatibility with the antenna structure and also reducing the project runtime, we used the strips in the TW structure. In this article, we used strips with a width of 4mm and the distance between strips is 24mm for the proposed antenna's operational frequency.

V. RESULTS

In this part, vest antenna simulations results are presented after modeling metamaterial. Tuned VSWR of the antenna is shown in Fig. 14. The simulation results show that the final design have the wide impedance bandwidth of approximately 160% ranging from 100MHz to 640MHz for VSWR<3. Comparing to the condition without any metamaterial, the bandwidth variation of the antenna is negligible.



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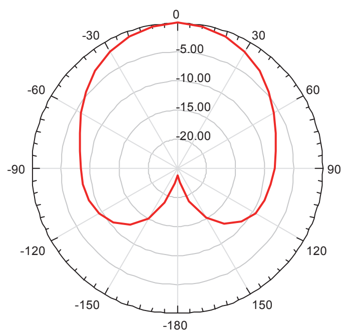

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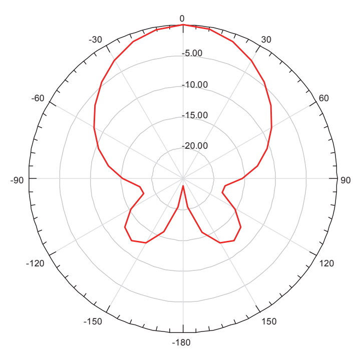

(c)

Fig. 16. Simulated radiation pattern in the horizontal plane at (a) 100MHz, (b) 400MHz, and (c) 600MHz.

Also, as it is shown in Fig. 13, the metamaterial substance prevents the waves from penetrating the human body. The parts of the body in which the SAR is higher than the standard limits are located on the ridges of the human body shape. On the other hand, the antenna VSWR is almost unaffected by the metamaterial and the antenna bandwidth is about 530MHz after implementing the SAR reduction procedure. The simulated radiation pattern of the vest antenna after the SAR reduction procedure is shown in Fig. 16.

VI. Conclusion

In this article, a broadband vest antenna with a bandwidth of 160% ranging from 110 MHz to 630 MHz for VSWR<3 is proposed. To do so, the human body was modeled after designing the antenna. To this end, a 3-layer model of the human body has been used instead of the 1-layer model. As the next step in our simulation process, the antenna was installed on the human body and then the antenna parameters and its SAR were measured again. At the last stage, in order to reduce the vest antenna SAR appropriate metamaterial namely TW type is used. It can be seen that SAR due to the vest antenna on the human body is decreased considerably to 1.2 while the VSWR bandwidth and radiation pattern of the antenna is not changed approximately.

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Mohsen Fallah was born in Kashan in 1968. He received the B.S. degree in Electrical Engineering from Isfahan University of Technology, Isfahan, Iran, in 1991, and the M.Sc. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 1997, and the Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2010. He is a member of the academic staff, Faculty of Electrical Engineering, MUT University, Tehran, Iran. His current research interests include microstrip

antennas, passive and active microwave devices, metamaterials and EBG structures, and electromagnetic theory.

Amir Abbas Heidari was born in Kashan in 1985. He received the B.S. degree in Electrical Engineering from KNT University of Technology, Tehran, Iran, in 2007 and the M.S. degree in Electrical Engineering from Shahed University, Tehran, in 2010.

Alireza Mallahzadeh was born in Bushehr in 1977. He received the B.S. degree in Electrical Engineering from Isfahan University of Technology, Isfahan, Iran, in 1999 and the M.Sc. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2001, and the Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, in 2006. He is a member of the academic staff, Faculty of Engineering, Shahed University, Tehran. He has participated in many projects relative to antenna design, which resulted in fabricating different types of antennas for various companies. Also, he is interested in numerical modeling, and microwaves.

Farokh Hojjat Kashani received his Ph.D. in Electrical Engineering specializing in Electromagnetic from the University of California at Los Angeles in 1970. From 1970 to 1971, he was an Assistant Prof. at Higher Institute of Telecommunication and the University of Tehran. From 1971 to 1976, he was an Assistant Prof. and chairman of the E. E. Dept. at IUST and from 1976 to 1977, he spent sabbatical leave in Hughes Aircraft Company, aerospace division at Canoga Park, California, US. From June 1987 to June 1988, he took one year sabbatical leave in Communication Department, New South Wales University, Sydney, Australia. He is currently a Professor of Electrical Engineering Department, Iran University of Science and Technology. In April 2002, he was selected as an outstanding professor in Iran. He has published over forty papers and ten books in Persian.