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Research Article

Impact of Dielectric Constant on Embedded Antenna Efficiency

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The impact of dielectric constant on radiation efficiency of embedded antenna located inside human body or another liquid environment is investigated both analytically and numerically. Our research is analysed and simulated at 403 MHz in the MedRadio band (401–406 MHz) and within a block of 2/3 human muscle phantom. Good agreement is achieved between analysis and simulation results. This work provides a guidance in selecting insulator for embedded antennas.

1. Introduction

An antenna working in a dissipative medium such as human body or other liquid environments needs to be insulated to avoid short circuit, oxidation, and corrosion caused by surrounding medium, which lead to the use of a dielectric medium that encloses the antenna. However, the question is what the rules to choose dielectric constant value for this insulator are. Previous studies have utilized different relative permittivity values for implanted antennas, for instance, $\varepsilon_r = 10.2$ [1, 2], $\varepsilon_r = 10$ [3], and $\varepsilon_r = 30$ [4]. A high dielectric constant has an advantage of reducing the size of embedded antenna, but does it impact on antenna radiation efficiency? Briefly, we are motivated to answer these questions.

Antennas employed in implantable devices should be compact, lightweight, small in size, and high in radiation efficiency. While a small size permits these devices to be inserted inside the human body, high radiation efficiency lengthens their operating time. Therefore, both size and radiation efficiency are important factors for implanted antenna. Nevertheless, in other embedded devices such as underwater applications, space limitation for antenna may not be a crucial factor; then antenna sizes can be large to have a high efficiency.

The goal of this study is to specify a dielectric constant value of insulating materials in order to maximize the radiation efficiency of embedded antennas. Our approach makes use of a foundation presented in [5] of Tai and Collin. In their inspiring work, the authors analyzed theoretically power transmission coefficient of a Hertzian dipole immersed in a dielectric medium surrounded by a dissipative medium. In this paper, the foundation is developed in the following ways:

(i) applying the theory of a Hertzian dipole in a general dissipative medium for a block of 2/3 muscle model phantom having similar characteristics to human body (this content is shown in Section 2);

(ii) using a real loop antenna in HFSS simulation to confirm the theory above since the Hertzian dipole is an unrealistic antenna (this part is presented in Section 3).

Throughout this work, the main contributions are as follows:

(i) this work proves that, for implantable devices, a vacuum insulator can maximize the antenna radiation efficiency;

(ii) for other applications (e.g., underwater applications), the antenna radiation efficiency becomes very high at some certain dielectric constant values (so-called resonant points in antenna radiation efficiency). Surprisingly, these have not been done before.

This work is performed at 403 MHz in the band of Medical Device Radio Communications Service (MedRadio,

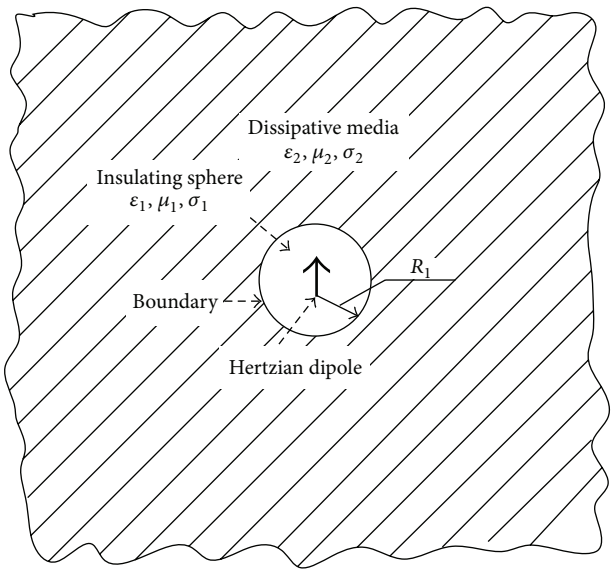

Figure 1: An insulated dipole in a lossy medium.

401–406 MHz) as required by the Federal Communication Commission (FCC). This is the operating frequency band of pacemaker. Also, the proposed method presented in this paper can be applied for other frequency bands. Limitation and some related works are going to be discussed at the end of this paper.

2. Theory of a Hertzian Dipole in a Dissipative Medium

Here, t Hertzian dipole with a dipole moment "p" is inserted in a dissipative medium of infinite extent and is insulated by a dielectric sphere, radius of R_1 as shown in Figure 1.

In Figure 1, a block of 2/3 human muscle phantom is selected to model the biological media of the human body. Therefore, the parameters of this medium (medium 2) are absolute permittivity $\varepsilon_2 = \varepsilon_{r2}\varepsilon_0 = 42.807\varepsilon_0$, absolute permeability $\mu_2 = \mu_0$, and conductivity $\sigma_2 = 0.6463$ S/m [2]. The parameters of the insulating media (medium 1) are $\varepsilon_1 = \varepsilon_{r1}\varepsilon_0$, $\mu_1 = \mu_0$, and $\tan\delta_1 = 0.0023$. The goal here is to specify the value ε_{r1} that produces the highest radiation efficiency of the dipole. According to [5], the authors used method of the Hertzian potential function Π to calculate $\mathbf{E}$ and $\mathbf{H}$ field. The radiated power obtained at the surface of insulating sphere can be computed through Poynting vector $\mathbf{S}$ by

$$P = \text{real}\left\{\int_0^{2\pi}\int_0^{\pi}\mathbf{S}d\mathbf{s}\right\} = \frac{1}{2}\text{real}\left\{\int_0^{2\pi}\int_0^{\pi}\mathbf{E}\times\mathbf{H}^{*}d\mathbf{s}\right\}. \quad (1)$$

This integration is taken over the sphere surface on which the power radiates outwardly. Finally, the authors found out a general formula for radiated power generated by the Hertzian dipole as shown in following equation (2),

$$\begin{aligned} P = \Big[& \left(k_1^3 D^3 p^2 b\right) \\ & \times \Big(3\pi\varepsilon_1 \left[(1+b)^2 + a^2\right] \\ & \times \left[1 + r_1^2 + r_2^2 + 2\left(r_1 \cos 2k_1R_1 + r_2 \sin 2k_1R_1\right)\right]\Big)^{-1}\Big] \\ & \times \Big(\Big[2a + 4a^2D + 2a\left(a^2+b^2\right)D^2 \\ & + \left(a^2+b^2\right)^2 D^2 + \left(a^2+b^2\right)^2 D^3\Big]\Big) \\ & \times \Big(\Big[A_0 + A_1D + A_2D^2 + A_3D^3 \\ & + A_4D^4 + A_5D^5 + A_6D^6\Big]\Big)^{-1}, \end{aligned} \quad (2)$$

where

(i) p is dipole moment,

(ii) $k_1 = \omega(\varepsilon_1\mu_1)^{1/2}$ is propagation constant in medium 1,

(iii) $D = k_1R_1$,

(iv) r_1, r_2, a, b, and A_i ($i = 1 \rightarrow 6$) are constants derived from medium 1's and medium 2's parameters.

Once parameters of media 1 and 2 are determined, it is straightforward to calculate the radiated power as a function of dipole moment "p." The normalized radiated power (reference power P_1 with $\varepsilon_{r1} = 1$) is displayed in Figures 2 and 3 for small and large radii R_1 of dielectric sphere, respectively. The dielectric constant ε_{r1} runs from 1 to 500.

When radius R_1 is small, for example, $R_1 = 3, 5, 7, 9$ mm, Figure 2 shows that P_i/P_1 ratio achieves the highest value of unity with $\varepsilon_{r1} = 1$ and decreases when the dielectric constant increases. It demonstrates that vacuum insulator is able to result in the highest radiation efficiency. This case is equivalent to implanted devices since the size of device must be small to embed in human body.

Oppositely, when radius R_1 of the insulating sphere becomes greater, P_i/P_1 ratio can be very high at some certain values of dielectric constant, so-called resonance points in radiated power which change when R_1 changes as shown in Figure 3. The resonance occurs when radius R_1 of insulating sphere is approximately an integer of half-wavelength in medium 1 [5].

So far, the theory of the Hertzian dipole immersed in a lossy medium has been analyzed and discussed. In the next section, HFSS simulation is adopted to confirm the results above.

3. Simulation Results

Because of the unrealistic property of the Hertzian dipole a simple loop antenna is adopted in HFSS simulation to validate the results shown in Figures 2 and 3. Simulation will

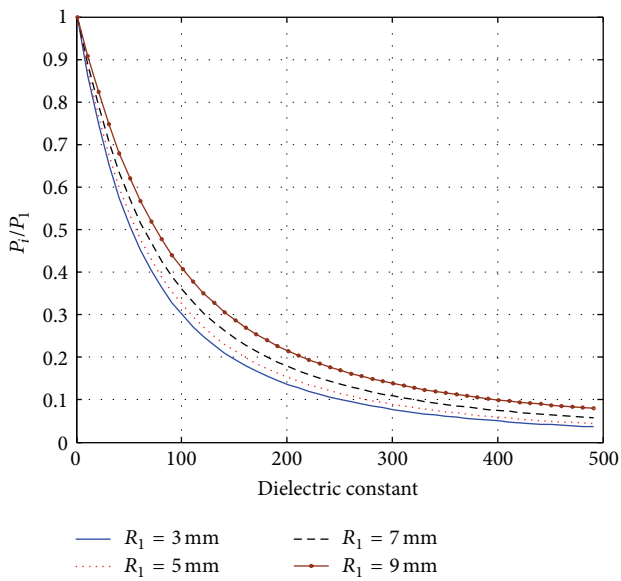

Figure 2: Normalized radiated power versus dielectric constant with small R_1 at 403 MHz.

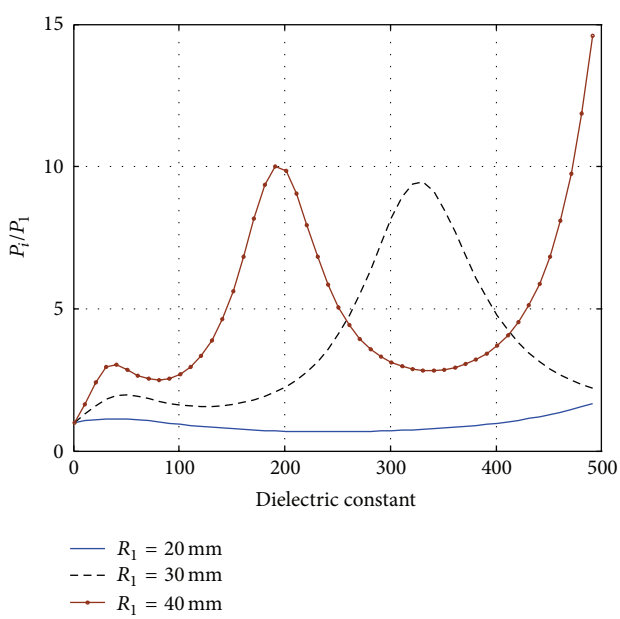

Figure 3: Normalized radiated power versus dielectric constant with large R_1 at 403 MHz.

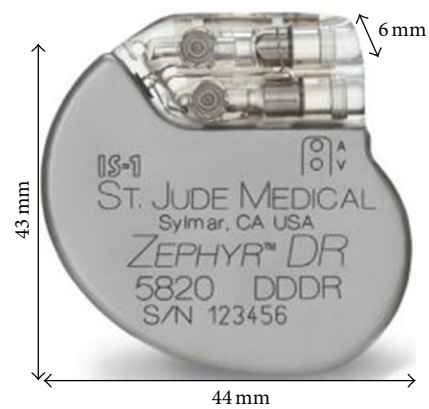

Figure 4: Typical sizes of a cardiac pacemaker.

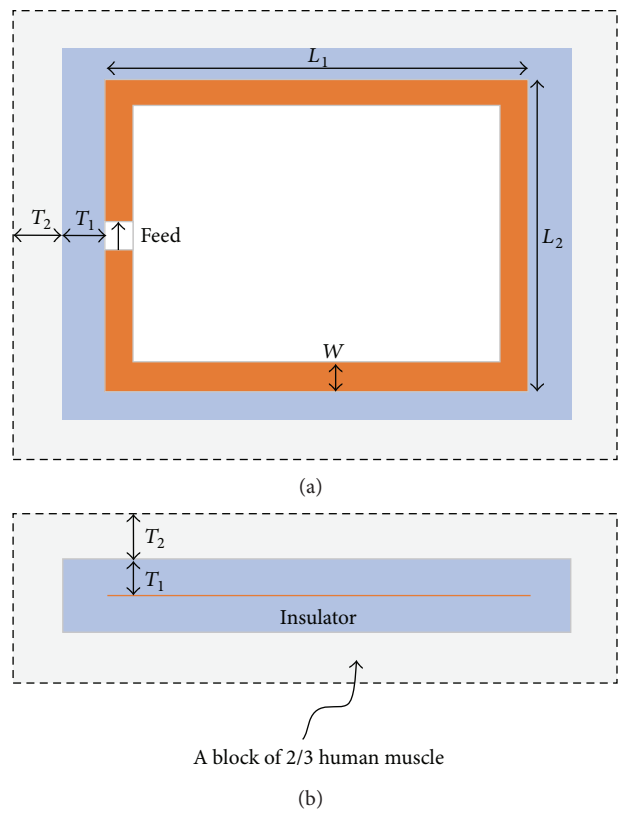

Figure 5: Geometry of embedded loop antenna: (a) top view; (b) side view.

be divided into two cases, one for implanted devices and one for other applications.

Case 1 (implanted devices). To illustrate the impact of dielectric constant, a cardiac pacemaker is selected as an example for an implanted device. The typical size of a pacemaker is shown in Figure 4 [6]. An embedded loop antenna is designed as depicted in Figure 5.

In this simulation model, the thickness of the insulator fixed at 6 mm (T_1 = 3 mm) is the same as the thickness of the pacemaker in Figure 4. The thickness of muscle layer T_2 is fixed at 7 mm as done in [7]. The loop antenna located in the center of the insulator has dimensions of $L_1 \times L_2 \times W$ = 69.1 mm × 50 mm × 5 mm. These dimensions of antenna are designed to resonate at 403 MHz with dielectric constant ε_{r1} = 42 since a high dielectric constant similar to that of dissipative media can widen antenna bandwidth as proved in [8].

To study the effect of dielectric constant on the antenna radiation efficiency, dielectric constant is changed from 1 to 300, keeping loss tangent of insulator unchanged ($\tan\delta_1$ = 0.0023) as in Section 2. When changing the dielectric constant, impedance mismatch of the antenna

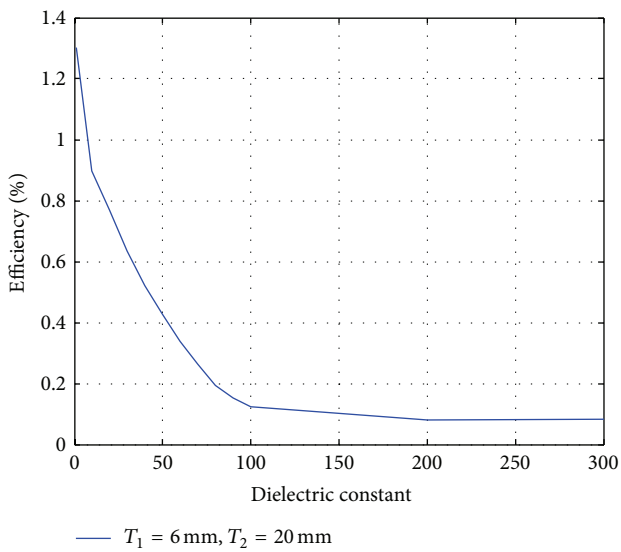

Figure 6: Antenna efficiency versus dielectric constant (ε_{r1}) at 403 MHz.

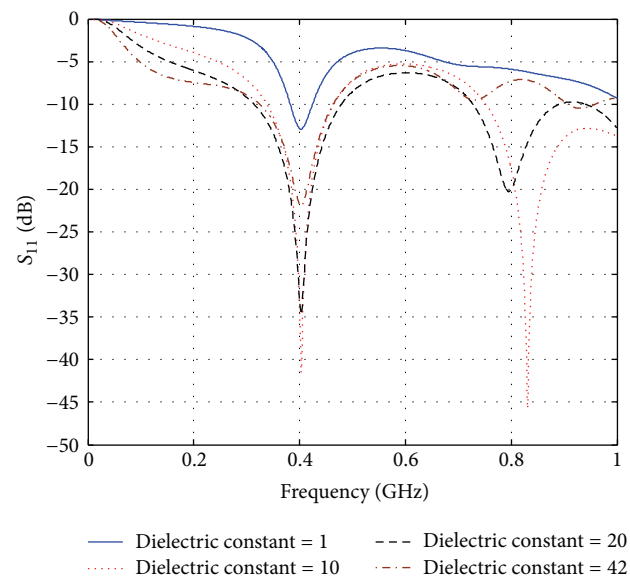

Figure 7: Return loss of antenna with different dielectric constants (1, 10, 20, and 42) at 403 MHz.

occurs, and radiation efficiency quickly degrades. For the sake of considering only the impact of the dielectric constant (ignoring mismatch loss), the radiation efficiency is given by

$$\text{Efficiency} = \frac{P_{\text{out}}}{P_{\text{in}} - P_{\text{mismatch}}} \qquad (3)$$
$$P_{\text{out}} = P_{\text{in}} - P_{\text{mismatch}} - P_{\text{diel}} - P_{\text{tissue}},$$

where P_{in} is the input power of the antenna, P_{mismatch} is the power loss due to antenna-source mismatch, P_{diel} is the dielectric loss, P_{tissue} is the loss absorbed by the tissue material, which is dominant, and P_{out} is the total power received at the outside of the tissue block. In the simulation, copper loss is neglected; a perfect electric conductor for antenna is assumed [8].

From Figure 6, it is obvious that $\varepsilon_{r1} = 1$ (vacuum) leads to the highest radiation efficiency for implantable devices and the radiation efficiency decreases when the dielectric constant value increases. This result is consistent with those of Figure 2.

When taking into account the mismatch loss in radiation efficiency that occurs in real situations, changing the sizes of the loop antenna is necessary to achieve acceptable impedance matching when ε_{r1} changes. Some examples are taken for $\varepsilon_{r1} = 1$, 10, 20, and 42 ($\tan\delta_1 = 0.0023$). Reflection coefficient, radiated power, dimensions, and radiation efficiency of the loop antennas for these four cases are shown in Figures 7 and 8 and Table 1. Evidently, even though the volume of muscle in the first case ($\varepsilon_{r1} = 1$) is the largest due to the largest dimensions of antenna (fixing T_1 and T_2), these results still show a trend that the dielectric constant $\varepsilon_{r1} = 1$ brings the highest radiation efficiency to antenna.

Briefly, in the case of implanted devices when thickness of device is thin (several millimeters), the radiation efficiency of the antenna achieves the highest value with insulator having relative permittivity of 1 (vacuum insulator).

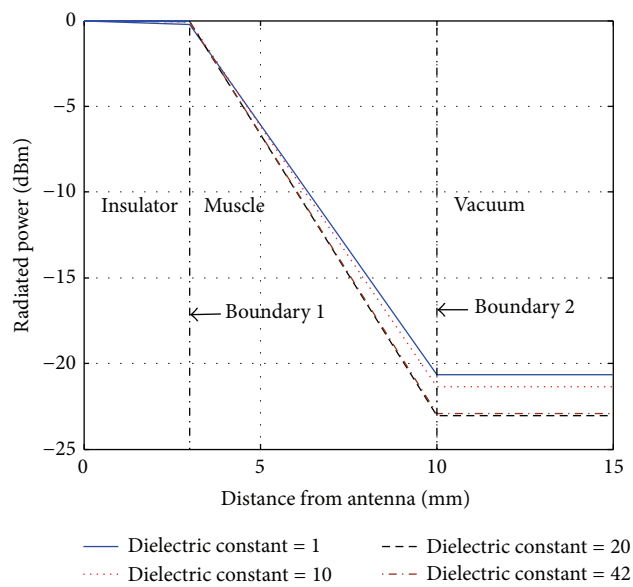

Figure 8: Radiated power (in dBm) with different dielectric constants (1, 10, 20, and 42) at 403 MHz; input power = 1 mW.

Table 1: Design parameters (in mm) of embedded loop antennas.

ε_{r1}	L_1	L_2	W	Radiation efficiency (%)
1	173.8	70	10	0.86
10	87	51	5	0.74
20	78	45.8	5	0.5
42	69	48.9	5	0.51

Case 2 (other applications). In other applications such as underwater ones, the thickness of insulator can be much greater than that in Case 1, which results in the occurrence

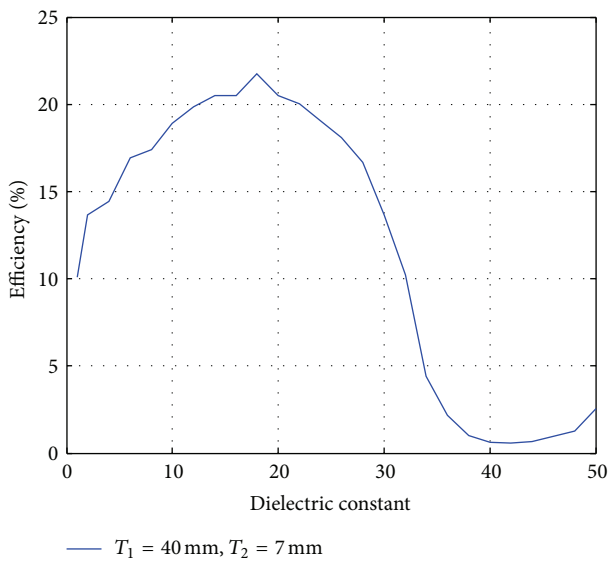

Figure 9: Antenna radiation efficiency with $T_1 = 40$ mm, $T_2 = 7$ mm at 403 MHz.

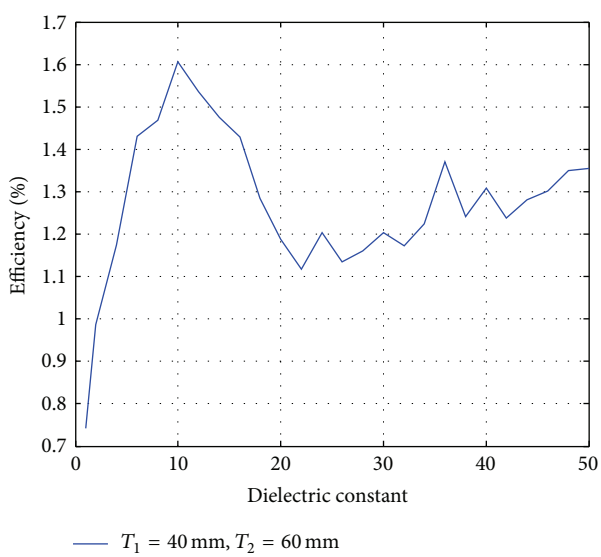

Figure 10: Antenna radiation efficiency with $T_1 = 40$ mm, $T_2 = 60$ mm at 403 MHz.

of resonant points. To this end, T_1 is set up at 40 mm and the simulation is performed for two cases: $T_2 = 7$ mm and 60 mm. Sizes of antenna are $L_1 \times L_2 \times W = 69.1$ mm$\times$50 mm$\times$ 5 mm as in Case 1. By changing the dielectric constant of the insulator from 1 to 50, step = 2, and using the efficiency definition in (3) (or ignoring impedance mismatch), the radiation efficiency of the antenna is computed and plotted in Figures 9 and 10.

As can be seen, the radiation efficiency in Figure 10 is far less than that in Figure 9 because of the thicker muscle layer ($T_2 = 60$ mm versus 7 mm). However, in both cases, the radiation efficiency with dielectric constant $\varepsilon_r = 1$ is not the highest one as in Case 1. Instead, the highest radiation

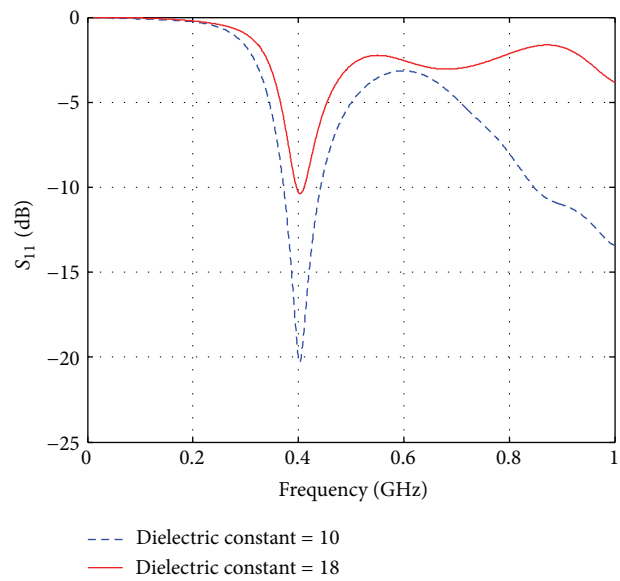

Figure 11: Reflection coefficient for two resonant points with dielectric constants 10 and 18 at 403 MHz.

Table 2: Design parameters (in mm) of embedded loop antennas with dielectric constants 18 and 10 at 403 MHz.

ε_{r1}	L_1	L_2	W	T_2	Radiation efficiency (%)
18	15	66.5	5	7	32.12
10	40	74.5	5	60	1.58

efficiencies occur at $\varepsilon_r = 18$ and 10 with $T_2 = 7$ mm and 60 mm, respectively. These results coincide well with the trend shown in Figure 3.

Next, in order to have acceptable impedance matching at $\varepsilon_{r1} = 18$ and 10 in Figures 9 and 10 when taking into account mismatch loss in real situations, the sizes of the antenna are varied to have the designed resonant frequency. The reflection coefficient, sizes of antennas, and radiation efficiency are shown in Figure 11 and Table 2. As shown in Table 2, at $\varepsilon_{r1} = 18$, although the thickness of the muscle layer is the same as in Case 1 ($T_2 = 7$ mm), the efficiency is far greater (32.12% versus 0.86%; maximal efficiency with $\varepsilon_r = 1$). Similarly, at $\varepsilon_{r1} = 10$, even though the muscle layer is much thicker ($T_2 = 60$ mm versus $T_2 = 7$ mm at Case 1), efficiency is still greater (1.58% versus 0.86%). Radiated power received at the outside of muscle block is −4.93 dBm and −18 dBm with $T_2 = 7$ mm and 60 mm, respectively (input power = 1 mW). Again, both cases demonstrate the existence of resonant points when the size of the insulator is large enough.

4. Limitation and Related Works

This paper has been proving that the highest radiation efficiency of implanted antennas can be obtained with dielectric constant $\varepsilon_{r1} = 1$ (vacuum). Yet, a lower dielectric constant leads to larger dimensions of antennas. Therefore, in antenna design, it is necessary to perform miniaturization techniques

and/or have a compromise between the dielectric constant, antenna sizes, radiation efficiency, and bandwidth.

In the literature, there are several works solving the impact of insulating material on implanted antennas. For example, authors in [8] used a high dielectric constant ($\varepsilon_{r1} = 50$) for insulating material in order to widen the bandwidth of designed antenna. However, as shown above, this choice can lower the antenna radiation efficiency.

In [9], the authors presented an interesting analysis about "the effect of insulating layers on the performance of implanted antennas." In [9], the authors computed the impact of insulating materials on radiated power of implanted ideal antennas (infinitesimal dipoles), where the authors made use of 2 insulating layers with the first layer being vacuum. However, they did not explain or demonstrate clearly the reason for using air layer as the first insulation. The current work employed a real loop antenna in HFSS simulation and provided another approach for this issue.

In [10], the authors analyzed different aspects of the design of implanted antenna including impact of relative permittivity on antenna radiation efficiency. Our work's result coincides well with the result presented in [10] (Figure 2(b) [10]).

5. Conclusions

The impact of dielectric constant on radiation efficiency of embedded antenna has been investigated both analytically and numerically. The result shows that, for implanted antennas, vacuum insulation is capable of high radiation efficiency. In contrast, for other applications such as underwater ones where size of device can be large, there exist resonant points in radiation efficiency at a certain dielectric constant. This research is analysed and simulated at 403 MHz within a block of 2/3 human muscle phantom. Good agreement is achieved between analysis and simulation results.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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