RADIATION CHARACTERISTICS OF LOOP ANTENNAS FOR BIOMEDICAL IMPLANTS

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ABSTRACT

Designing efficient in-body antennas is a key requirement towards the realization of reliable biomedical implanted communications systems. This work investigates the use of loop antennas for these applications. Here, loop antennas have been characterized in terms of their radiation resistance, transmitting bandwidth and biocompatibility at an operating frequency of 405 MHz. The designed miniature loop antenna has a differential input resistance of $110\,\Omega$, a transmitting bandwidth of 15 MHz and a specific absorption rate (SAR) well below the safety limits. With this performance, loop antennas prove to be good candidates for use in biomedical implanted systems.

I. INTRODUCTION

Recently, there has been a strong trend in medicine to use implanted electronic devices for therapeutical and/or diagnostic purposes. Recent advances in wireless communication techniques and material sciences, along with the miniaturization of wireless communication devices have allowed for the vast evolution of biomedical implanted transceiver systems. These systems usually involve a one- or two-way communication link, with the associated necessary radio frequency (RF) blocks, allowing communication with the implant.

Research studies on RF and microwave hazards have allowed international organizations to develop safety standards to be followed by the RF design engineers involved in building the implanted RF front-end. This is to ensure that the in-body radiation by these devices is not harmful to the human body and that they can be used by physicians safely.

Organizations responsible for frequency spectrum allocations have dedicated the frequency band from 402-405 MHz for biomedical implants. These are the FCC's MICS in North America and the ERC for ULP AMI in Europe. Choosing this band for this particular application resulted from studies on the RF effects on the human safety and electromagnetic interference (EMI) issues.

In order to actually build a reliable communication link through the human body, the body has to be characterized as a medium for wave propagation. According to the data given in the literature, the electrical properties of the body tissues [1] show that the biological tissues are strongly dissipative within the biomedical frequency band. Thus, the high body losses and the practical constraint on the size of the implant together with the complexity of the radiation environment make the design of antennas for biomedical implants a challenging task. One way to overcome the body losses is to use an efficient transmitting antenna. However, the practical constraint on the size of the implant forces the antenna to be very small, in the order of a few millimeters.

This work investigates the performance of loop antennas operating deep inside the human body for the use in biotelemetry. Performance characteristics are evaluated in terms of the radiation resistance, transmitting bandwidth (BW) and compliance with the human safety standards in terms of the specific absorption rate (SAR). The characteristics of loop antennas are evaluated at the biomedical frequency band (402-405 MHz). Electrically small loops radiating in free space are known for their very small radiation resistance. But this work shows that the high permittivity and conductivity of the biological tissues in the MICS band make the electrical size of the loop large enough to achieve a reasonable radiation resistance. In addition, it will be shown that loop antennas have decent transmitting bandwidths allowing reliable communication and that with a few mW power-feed, the 1-g average SAR is well below the safety threshold (1.6 W/kg) given in the safety standards. Consequently, this work shows that loop antennas perform well as implanted antennas and can be used reliably in implanted transceiver systems.

This paper is organized as follows. Section II lists the performance characteristics that are used to evaluate the loop performance when used in biomedical implants. Section III gives the dimensions of the designed loop antenna and presents its resulting in-body performance. Finally, the conclusion is given in Section IV.

II. DESIGN AND OPTIMIZATION OF LOOP ANTENNAS IMPLANTED IN THE HUMAN BODY

The first step in designing an in-body radiating antenna is to characterize the human body as a medium for RF wave propagation and accordingly model the radiation environment. The electrical properties of the body tissues are frequency-dependent and should be identified for the frequency of interest. Table I lists the conductivities, the dielectric constants and the penetration depths of muscle, fat, and skin tissue at 405 MHz [1]. In addition to the high losses that the transmitted RF wave will face, the composition of the biological tissues inside the human body is very complex and varies from one person to another. Thus, numerical models, no matter how complex, will serve only as best estimates and an accurate solution to the problem of wave propagation in the human body can hardly be found. As previously mentioned, the loop antenna will be characterized in terms of its radiation resistance, voltage standing wave ratio (VSWR) bandwidth and its compliance with the human safety standards.

Table I. The electrical properties of some typical body tissues at 405 MHz [1].

	Dielectric constant ε	Conductivity σ [S/m]	Penetration depth δ [m]
Muscle tissue	57.088	0.79759	0.052464
Fat tissue	5.5777	0.41199	0.30828
Skin tissue	46.672	0.6902	0.55064

Radiation Resistance and Input Impedance:

To estimate the radiation resistance of small implanted loops, the analytical formulation given in [2] was used. This formulation assumes the antenna to be radiating in an infinite lossy medium, whereas in practice, the antenna is to be radiating inside the finite human body, which is surrounded by free space. Therefore, this model is more suitable for designing loop antennas implanted deep inside the human body (e.g. small intestine). The formulas of the radiation resistance and reactance assume a medium with a complex propagation constant $\gamma = \alpha + j\beta$, where α and β depend on the electrical parameters σ and ε. Fig. 1(a) shows the geometry of the loop. Here, *a* is the wire radius, *b* is the loop radius and *c* is half the spacing between the turns. The loop can be represented by the equivalent circuit shown in Fig. 1(b) including the matching network.

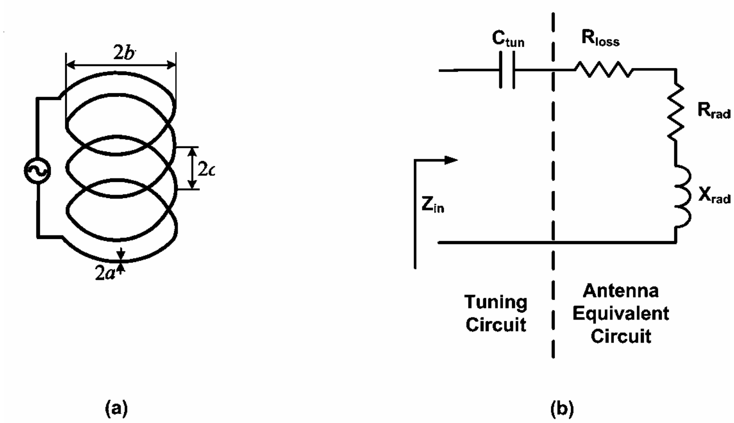

Fig. 1. (a) The geometrical dimensions of the loop antenna. (b) The equivalent circuit of the loop antenna including the tuning network.

Transmitting Bandwidth:

In the design, we seek a tuned loop matched to the preceding RF stage, which is usually a power amplifier or a filter stage with 50-Ω resistive output impedance. The input reactance of the loop at RF frequencies is inductive. For a zero-Ω input reactance, a tuning capacitor C_{tun} is added in series to the loop. Now, the fractional bandwidth (BW/ω_0) can be calculated for a maximum allowable VSWR *R* as [3]

$$BW = \frac{1}{2\pi} \cdot \frac{2 \cdot (R-1) \cdot \mathrm{Re}(Z_{in}(\omega_0))}{\sqrt{R} \cdot \omega_0 \cdot |Z'_{in}(\omega_0)|} \quad \text{[Hz]}.$$

Here, Z_{in} is the input impedance as shown in Fig. 1(b) and Z_{in}' is its derivative with respect to the radian frequency ω. The bandwidth of the RF antenna should be large enough to allow reliable communication.

SAR and Safety Issues:

In-body radiation is restricted to certain levels for human safety purposes. These limits can be found in international and regional safety codes. According to the definitions given in the IEEE C95.1 standard [4], body exposure to radiation from implanted medical devices is considered as "partial-body" exposure in an "uncontrolled environment". In such a case, limits are specified in terms of a maximum limit on the SAR. Whole-body average SAR is to be below 0.08 W/kg and spatial peak SAR, averaged over any 1-g of tissue, is to be less than 1.6 W/kg across the body. To evaluate the average 1-g SAR distribution in the close proximity of the radiating loop, numerical simulations were performed using the method of moments (MoM) antenna simulator FEKO [5]. In the simulations, the human body was modeled as a finite dielectric cylinder built of dielectric cuboids of electrical parameters similar to those of real body tissues.

III. RESULTS AND DISCUSSION

Having the previous design specifications, the geometrical parameters of the small loop were optimized targeting a 100-Ω differential radiation resistance R_{rad}, minimum wire losses R_{loss}, maximum BW and minimum SAR in the proximity of the loop. By building the loop with a high conductivity metal and making its turns far enough from each other, the skin and proximity effects can be minimized and high radiation efficiency can be achieved. Optimization resulted in a 6-turns loop with a 2 mm loop radius, a 0.25 mm wire radius and 2 mm spacing between the turns. These dimensions result in an antenna of a realistic size suitable for our application.

The resulting loop performance is as follows. The real and the imaginary parts of the input impedance of the loop (not tuned) at 405 MHz are $110\,\Omega$ and $667\,\Omega$, respectively. For a similar loop operating in free space, the radiation resistance is only $1.44\text{m}\,\Omega$. Thus for the same conductor, the radiation efficiency of a loop operating inside the human body is expected to be much higher than that of a similar loop radiating in free space. Since the small in-body loop antenna is inductive, a series capacitor of 0.6 pF is needed to tune the loop. Fig. 2 shows the VSWR of the tuned loop. For a maximum VSWR of 1.3, the loop transmitting bandwidth is about 15 MHz. With this bandwidth, reliable communication from the implant to the monitoring outer transceiver can be ensured. As mentioned, the local 1-g SAR distribution was calculated using FEKO numerical simulator. A feed power of 15 mW was assumed, which is a typical value for short-range low-power wireless applications. The radiation pattern of loop antennas in a uniform medium is known to be omnidirectional. The SAR distribution is accordingly also omnidirectional. Starting from a point on the periphery of the loop, the resulting distribution is shown in Fig. 3. As can be seen from the figure, the 1-g average SAR in the cuboids surrounding the loop is well below 1.6 W/kg. Thus, biocompatibility of the in-body loop antenna was assured using numerical simulations.

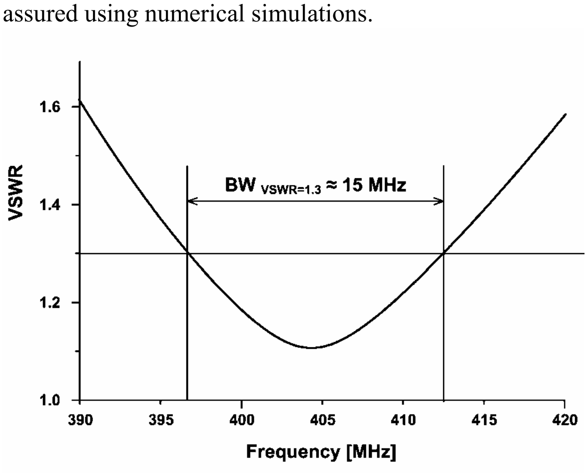

Fig. 2. The VSWR of the tuned loop versus frequency.

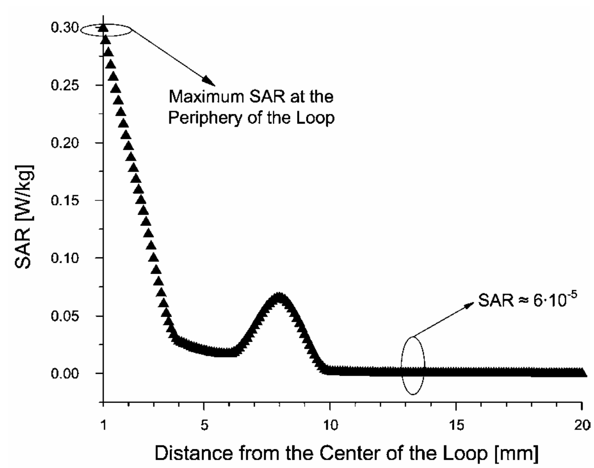

Fig. 3. The SAR distribution in the proximity of the loop, showing that the values are well below the safety threshold (variation in one direction only was assumed).

IV. CONCLUSION

The characteristics of loop antennas, in terms of their radiation resistance, transmitting bandwidths and biocompatibility have been studied at the biomedical frequency band for use in in-body telemetry systems. The radiation resistance and the VSWR bandwidth have been estimated using analytical formulations existing in the literature. It was found that, unlike in free space, small loop antennas in a highly dissipative medium like the human body, are efficient radiators and provide sufficient transmission bandwidths. Biocompatibility was assured by means of MoM numerical simulations. The SAR distribution in the body tissues surrounding the loop shows that these antennas comply well with the safety standards. Hence, it was proved that small loop antennas are well-suited for implanted medical devices. Measurements need to be carried out to confirm this fact.

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