A Compact Ultra-Wideband Spiral Helix Antenna for In-Body Communications

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Abstract—An ultra-wideband and compact spiral helix antenna is designed for transmitting or receiving signals to or from human body. The antenna in free space covers the frequency band of 3-10 GHz with input impedance of 200 ohms. The designed antenna is embedded in a high dielectric material of distilled water to provide wave impedance matching to human body tissues. The frequency band is adjusted to 300-1000MHz. The embedded antenna is optimized with 30 ohms input impedance in the proximity of 4-5 cm to the chest of a human body model. Electromagnetic computation is conducted by including frequency dependent dispersive materials of human tissues. Due to the directive radiation pattern of the antenna, the wave penetration inside human body is improved. The embedded antenna provided almost circular polar pattern for whole operating bandwidth. The average energy of the penetrated wave in different depths inside the chest are presented.

Keywords- On Body antenna, Spiral Helix, Wire Antenna, Medical application, Ultra-wideband

I. INTRODUCTION

Design of a compact size antenna inside high permittivity dielectric material to provide efficient wave impedance matching with human body tissues for medical applications is a demanding task [1]. An appropriate antenna can transfer significant part of radio frequency (RF) energy to implanted devices or to the internal organs of human body for the potential RF diagnostic or treatment. Therefore, the link quality of in-body to outside body communication system can be improved and a radar or tomography imaging system can operate efficiently. Using ultra-wideband the data rate of an in-body communication system can be increased, a microwave hyperthermia applicator can focus tightly and a microwave imaging radar can provide high quality images.

By using a compact antenna, it is possible to provide sufficient space to install several antennas on the body surface and bring the opportunity of communication diversity or phased array antennas. Ultra-wideband is also desired for the medical applications [2] that requires optimized antenna. Thus an embedded compact and wideband antenna in required for the medical applications.

Different frequency bands defined as Industrial, Scientific and Medicine (ISM) were assigned for the medical applications. However, there is a great potential for ultra-wideband frequency, especially for the range of 300-1000MHz. Some frequencies in this range are assigned for medical usage, but still there are good potential for several other frequencies in the range. In addition, we have shown that by using matching layers on the human body surface, the plane wave penetration inside body can be improved by a factor of 5-10 depending on the matching material properties [1]. Using a permittivity of 10-20 improves the wave penetration significantly, and by applying higher permittivity values the penetration of EM wave is improved slightly [1]. Therefore, in this paper a new design of an ultra-wideband wire antenna which implemented inside high permittivity dielectric material of distilled water is presented for 300-1000MHz. The antenna is optimized near the body surface to benefit from the near-field components of electromagnetic (EM) waves [3]. The designed embedded antenna has an impedance of 30ohms and covers, at least, the frequency band of 300-1000MHz. The radiation pattern of the dielectric embedded antenna is directive in free space that guarantee high field intensity in its aperture. The antenna has circular polarization at the main beam direction. Using the antenna inside distilled water and close proximity of human body model can provide good wave penetration to the body.

The paper is organized as follows. In section II, antenna design and simulation parameters are described in free space and high permittivity material. In section III, the optimized antenna is placed on the chest of an electromagnetic modeled human body. Different field probes are implanted inside the model to study the wave penetration phenomenon. Section IV concludes the paper.

II. ANTENNA DESIGN AND SIMULATION RESULTS

The initial prototype of the antenna was a three dimensional helical Archimedes antenna on top of a circular ground plane of diameter 50 mm, Fig. 1a. The antenna is fed through a coaxial cable. The antenna opening curve is modified to increase the bandwidth and provide more constant radiation pattern with frequency, Fig. 1b. The parametric equation of the modified antenna is,

$$
\begin{align}
\bar{x}(t) &= 0.00175 \times t^2 \cos(\omega t) \\
\bar{y}(t) &= 0.00175 \times t^2 \sin(\omega t) \\
\bar{z}(t) &= 1 + \frac{t}{5} \quad 0 \leq t < 30\pi
\end{align}
$$

where \( t \) is the variable parameter and \( \omega = 0.75 \) is the frequency of dimension variation. This antenna is called T-square spiral helix. The final aperture of the two antennas are 30mm with the
maximum height of 19mm on the ground plane. First, the antennas are modeled in free space with a wire diameter of 0.25 mm. The wire diameter can be used to adjust the input impedance of the antennas. The impedance of Archimedes and T-square antennas are shown in Fig. 2. An average impedance of 200 ohms in the frequency range of 3-10GHz can be observed. The antenna impedance reduces if embedded inside high permittivity ($\varepsilon_r$) material with a factor of about $1/\sqrt{\varepsilon_r}$. The antenna return loss in free space is depicted in Fig. 3, for the port impedance of 200 ohms. The return loss of the T-square antenna is well below 10 dB for the frequency band of 3-10 GHz. Thus, this antenna is selected for the on-body studies.

The radiation patterns of the T-square antenna are shown in Fig. 4 at $\phi=0$ and 90 degree. As shown, the radiation pattern is toward the main axis of the antenna for all frequency range. Thus the near field of the antenna is intense at the aperture. The antenna shows a circular polarization with the axial ratio shown in Fig. 5, except for 5GHz where the axial ratio is increased to 8.

![Figure 1. Antenna model. a)T-square helix b) Archimedes helix](image1)

![Figure 2. Antenna impedance in free space for two spiral helix antennas](image2)

![Figure 3. Return loss versus frequency for two spiral helix antennas](image3)

![Figure 4. T-square antenna pattern at different frequencies. a) $\phi = 0$ b) $\phi = 90$](image4)
III. EMBEDDED ANTENNA CLOSE TO BODY

The designed antenna is embedded in distilled water in 37 degree Celsius with average $\varepsilon_r = 74$ due to simple accessibility. The material properties of water is frequency dependent that is included in the EM simulations. The embedded antenna is placed in 4-5 cm from human body chest. The body model is obtained from U.S. National Laboratory of Medicine (NLM). The model includes different human body tissues with 32 assigned different EM material properties. The material properties are frequency dependent and can be modelled with Cole-Cole model based on Gabriel [4]. Simpler model based on the second order equation approximation can also be applied, for the frequency range of 300-1000MHz [5]. This frequency dependency can distort the shape of a pulse propagating through a frequency-selective attenuating channel, and UWB signals are particularly prone to suffer from this effect [1].

The simulation model is shown in Fig. 6. The human torso with 1mm Voxel resolution are considered and 850 field probes for every components of $E_x$, $E_z$, $H_x$ and $H_z$ fields are used outside and inside human model in 10 different depth planes from the antenna aperture with a resolution of 20 mm in depth. 85 probes in each surface is considered containing 17 probes in x-direction and 5 probes for z-axis direction with a resolution of 10 mm for each field component. CST microwave studio is used for the simulations and time domain solver is applied. A Gaussian pulse is radiated and the field components are computed. The simulation contains 120e6 meshes run on a fast PC with 36GB of RAM.

Fig. 7 shows the return loss versus frequency of the embedded antenna inside water and the embedded antenna close to the human body. As shown, the embedded antenna can be operated in the frequency band of 300-1000 MHz with the port impedance of 30 ohms and return loss of less than 10 dB. The impedance can be adjusted to 50 ohms if a thinner wire is used. Due to the selected matching layer and the high field intensity at the antenna aperture we expect significant energy penetration into the body. The farfield radiation pattern of the water embedded antenna is more or less similar to the pattern in free space with a small squint angles. Certainly, the antenna close to the body surface shows different farfield because the human body and the antenna will act as radiators.

\[
S(t) = E(t) \times H(t) \quad \text{W/m}^2
\]

where $E(t)$ and $H(t)$ are the electric and magnetic field components, respectively. Due to the fact that the antenna has two major polarizations for $E_x$ and $E_z$, thus the magnetic field for $H_x$ and $H_z$ are calculated. The other field components are negligible. The power flow toward the body is computed from the field components. The UWB signal energy density, which was received inside the body at different depths from the body surface, was calculated by integrating the power density over the whole observation time; this time interval was sufficiently large to include 99% of the signal energy. Hence, the signal energy is obtained for each probe location as,
\[ e_s(x,y,z) = |\mathcal{S}_s(x,y,z;\tau)| \text{J/m}^2 \] \( \tau_0 < \tau < \tau_{\text{max}} \) (3)

where \( \tau_0 \) and \( \tau_{\text{max}} \) delimit the time window of the received signal energy for the selected channels inside the chest. The average energy for each depth is computed by spatially averaging the energy of the probes for each plane. Thus a unique number for every probe plans can be presented.

Fig. 8 shows space-time averaged energy density (J/m²) versus distance from the antenna. We note that the two first planes has 20 mm and 40 mm away from the antenna and are placed almost outside the body. The planes at 60 mm and further are inside the chest. As shown, the energy density close to the antenna (outside body) reduces slightly with distance and further inside the body. For the probes inside body there is about 5dB loss for every 20 mm penetration into the body. We note that the results are obtained by considering whole energy of the received signals in the probes. In addition, from Fig. 8 we can distinguish that the energy flow due to x-polar and z-polar electric field components are slightly different in low depth inside body and are almost the same for deep inside body. Thus have similar contributions for energy transfer to the body. This is the direct result of dual polarization property of the antenna.

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**REFERENCES**


