A Wideband Miniaturized Implantable Antenna for Biomedical Application at HBC Band

Xin Wang
Sino-Dutch Biomedical and Information Engineering School
Northeastern University
Shenyang, China

Jingjing Shi
Sino-Dutch Biomedical and Information Engineering School
Northeastern University
Shenyang, China
shijj@bmie.neu.edu.cn

Lisheng Xu
Sino-Dutch Biomedical and Information Engineering School
Northeastern University
Shenyang, China

Jianqing Wang
Graduate School of Engineering
Nagoya Institute of Technology
Nagoya, Japan

***Abstract*—In this study, a wideband implantable antenna with a small size of 3 cm is designed to operate at Human Body Communication (HBC) band. The proposed implant antenna is realized with two layer of non-equally spaced helical copper foil for dual-resonance frequency band in which -10 dB impedance bandwidth is 15.66 MHz (48.21%). The miniaturization of the antenna is realized by forming the copper radiation element on two layers of flexible magnetic sheet. Simulation results in a cubic tissue-equivalent phantom demonstrates that the proposed wideband antenna is a useful and capable candidate for high-speed transmission in implant biomedical applications at HBC band.**

Keywords—HBC; Implant antenna; Wideband; Dual-resonance frequency

I. INTRODUCTION

With the increasing growth of aging population, the study of wireless body area communication has become a new hot topic in medical, health care, and monitoring supports [1]. Wireless body area communication applications require either wearable devices or implantable devices based on the device-operation environments. Particularly for an implantable medical device, it is confronted with many technical challenges such as biocompatibility inside human tissue, swallowable miniaturized size with high-quality transmission performance, low power consumption, and wireless charging from outside terminals. Wireless capsule endoscope (WCE), a typical implantable biomedical application for intestine endoscopic examination, is an intelligent system that integrates electronic engineering, image processing, information communication and biomedical technologies, which has brought new options for the diagnosis and treatments of internal diseases due to its non-invasive and painless diagnostic technology [2, 3].

In general, WCE utilizes medical implant communication service (MICS) band at 400 MHz, and the available transmission speed is at the order of several hundred kbps because of the limited frequency regulation and narrow-band modulation schemes in this band. However, a very high data rate up to 10 Mbps should be required for WCE in order to realize real-time image transmission. To increase the data rate, applying ultra-wideband (UWB) technology for communication was considered as a solution [4], but trade off the penetration distance of human body. Because the human body is a lossy dielectric medium, the penetration depth is affected by the wavelength of the frequency. As compared to a penetration depth of 5.3 cm at 400 MHz and 1.7 cm at 4.1 GHz in muscle tissue, the penetration depth is as large as 8 cm at 30 MHz in HBC band. In view of the significant improvement on transmission distance in the human body, as well as the ultra-wideband communication for high data rate requirements, we tried to apply HBC band from 10 to 50 MHz for implantable biomedical applications. According to our previous study [5], a wideband HBC transceiver with impulse radio pulse position modulation (IR-PPM) scheme has been manufactured and evaluated to possess good performance on high transmission speed at the order of Mbps. Since a narrow bandwidth antenna connected with our wideband HBC transceiver will degrade the transceiver performance, an antenna with -10 dB impedance bandwidth as large as possible is in urgent demand for high data rate achievement. On the other hand, due to the fact that physical size of antenna depends on the operating frequency, HBC band antenna faces a more difficult problem for the miniaturization design.

As a result, in this study, we aim to develop a miniaturized implantable wideband antenna at HBC band. The wide bandwidth is realized with two layers of non-equally spaced helical copper foil for dual-resonance frequency band, and the miniaturization of the antenna is realized by forming the copper radiation element on two layers of flexible magnetic sheet. Performance evaluation in a cubic tissue-equivalent phantom is conducted to reveal its possibility for high-speed transmission in implant biomedical applications at HBC band.

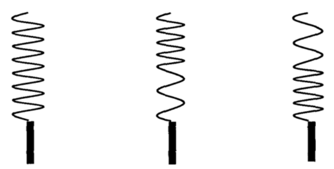
II. ANTENNA DESIGN

In order to design a wideband antenna in this study, we tried to adopt a helix structure with non-uniform pitch angle. It also means a non-equally spaced helical foil structure which can make dual-band antenna. As long as the dual-band resonance frequencies are combined together and close enough, it can eventually make a broadband effect. In [6], a non-uninform dual-band helix antenna with single wire element for cellular phones have been presented. The lower resonance frequency is determined by total length of the wire or copper foil, and the second resonance frequency is determined by different pitch angle or different turn radii. Therefore, a desired dual-band operation can be achieved if the pitch angle is modified in a suitable manner with constraint wire length [6]. As can be seen in Fig. 1, three models of helical antenna with uniform pitch angle (a), decreasing pitch angle (b), increasing pitch angle (c). The helix with decreasing pitch angle will move the second resonance closer to the first one, while the helix with increasing pitch angle will move the second resonance away from the first one [7]. It was expected that using the helix antenna with decreasing pitch to bring two frequency bands closer to form a wider frequency band.

On the other hand, since the antenna physical size depends directly on the frequency, the wavelength λ_0 operating in the HBC band is more than 6 meters in free space, we choose to utilize flexible magnetic sheets to shorten the wavelength for antenna miniaturization [5]. We pay attention to use a flexible magnetic sheet which has both high relative conductivity ε_r and high relative permeability μ_r as substrate on which the antenna radiation element is manufactured. Therefore, we can expect a double effect on shortening the wavelength based on the formula:

$$\lambda \cong \lambda_0 \, / \, \sqrt{\varepsilon_r \mu_r}$$

The flexible magnetic sheets also make it possible to form a cylindrical pill shape.



(a) (b) (c)

Fig. 1. (a) Helix with uniform pitch angle, (b) helix with decreasing pitch angle, (c) helix with increasingpitch angle [7].

As a result, by incorporating non-uniform pitch helix structure and double wavelength shorten effect of flexible magnetic sheets, a monopole-type helix antenna with non-equally spaced helical copper foil formed on two layers of magnetic sheet is proposed in this study. The detailed structure of our proposed implant antenna is shown in Fig. 2. The copper plane acts as the ground of antenna with a radius of a mm. The flexible magnetic sheet labeled as "layer1" is covered on the copper plane with thickness of 1 mm. Then the t-mm-thick copper foil which severs as the helical radiation element with n_1 turns and a spacing of s_1 is wrapped clockwise over "layer1". In the similar way, the first layer of copper foil is covered by the 0.5-mm-thick flexible magnetic sheet labeled as "layer2". While "layer2" is wrapped anti-clockwise by the second layer copper foil with n_2 turns and a space of s_2 . The structure of the antenna totally includes one copper, two layers of flexible magnetic sheets and two layers of copper foil. The two layers of non-equally spaced copper foil are connected by a copper wire at the top of the cylinder labeled at "A". And the feed point is on the bottom of the first copper foil.

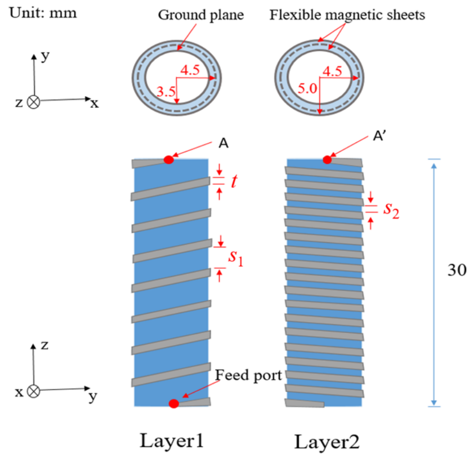
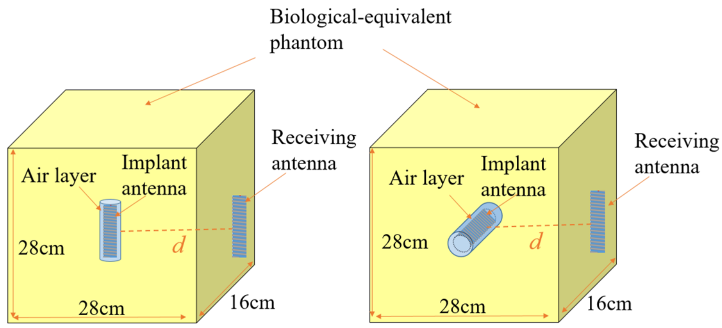


Fig. 2. Proposed antenna structure. (A monopole-type helix antenna with non-equally spaced helical coper foil formed on two layers of magnetic sheet)



(a) (b)

Fig. 3. Arrangement for antenna performance evaluation, (a) vertical implant antenna; (b) horizontal implant antenna

III. Performance Evaluation

In order to verify the performance of the proposed antenna in the human body, we inserted the antenna into a cubic muscle-equivalent phantom model in finite difference time domain (FDTD) numerical simulations. Fig. 3 shows the performance evaluation arrangements for deriving the S-parameters with two cases of antenna insert orientation, (a) vertical implant antenna; (b) horizontal implant antenna. The phantom model has a size of 28 cm$\times$16 cm$\times$28 cm, and its dielectric properties of the cubic phantom model were set to be ε_r = 56.05 and conductivity σ = 0.52 S/m at 30 MHz, nearly 2/3 times muscle's values. Assuming an actual operating environment of a specific capsule endoscope application in human body, a 1-mm-thick air layer was added around the antenna in the cubic phantom. Here we set the parameters of magnetic sheet commercially available as μ_r = 20.7, tan δ_μ = 0.12, ε_r = 13, and tan δ_ε = 0.17, where tan δ_μ and tan δ_ε are magnetic loss tangent and dielectric loss tangent, respectively.

As a result of the numerical simulation design, we determined the radius of the copper plane as a = 3.5 mm, the thickness of the copper foil t =1 mm, the turns of the first layer copper foil n_1 = 8 and the pitch interval s_1 = 2.75 mm, the turns of the second layer copper foil n_2 = 18 and the pitch interval s_2

= 0.67 mm. This makes a compact-size antenna with radius of 1 cm and height of 3 cm.

Fig. 4 shows the S-parameters results based on above parameters setting. In this case, the distance between the transmitting and receiving antenna was set as 6 cm. The receiving antenna has the same geometrical parameters as the transmitting one. It can be observed from the S_{11} results that dual resonance frequencies appear at 27.30 MHz with reflection coefficient of -21.82 dB, and 35.81 MHz with reflection coefficient of -26.89 dB, respectively for both the cases of vertical and horizontal implant antenna orientation. There is a little shift of second resonant frequency for S_{22} due to the different surrounding environments of free space for receiving antenna. This makes -10 dB impedance bandwidth of 15.66 MHz (48.21%) achieved, which covers from 24.65 MHz to 40.30 MHz. From the S_{21} results in this figure, we can see that a maximum coupling strength of -58.1 dB at 35.1 MHz and -58.6 dB at 30.4 MHz is achieved, respectively, for two cases of implant antenna orientation. A -70 dB bandwidth of S_{21} is around 28.4 MHz (68.6%) which covers from 27.2 MHz to 55. 6 MHz for vertical implant antenna, while for the case of horizontal implant antenna, -70 dB bandwidth is around 16 MHz (47.6%) which covers from 24.1 MHz to 40.1 MHz.

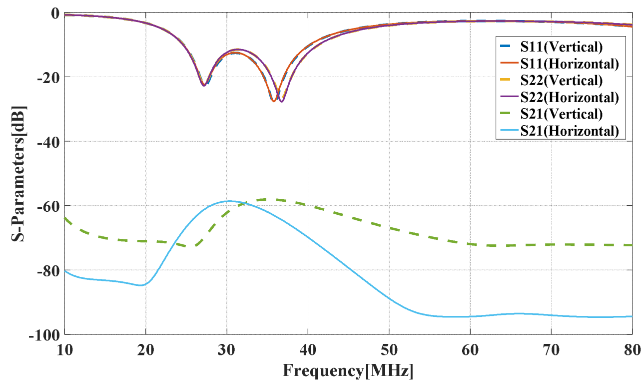


Fig. 4. Simulated S-Parameters in biological-equivalent phantom model with different placement of implant antenna.

Moreover, to evaluate the coupling strength with possible penetrate distance inside human body, we tried to plot the relationship between S_{21} and transmission distance using this antenna pair at different representative frequencies. Fixed the receiving antenna on the surface of phantom model, we gradually increased the distance between the two antennas from 2 cm to 18 cm. With an increasing distance, transmission coefficient degrades gradually. For example, the transmission loss will be approximately -80 dB at a distance of 10 cm. It should be noted that the transmission loss contains not only the path loss of the biological-equivalent phantom but also the transmitting and receiving antenna gains. The gain of the antenna in the direction of maximum radiation is approximately -67 dBi due to the lossy characteristics of magnetic sheet and dielectric phantom. If we utilize a high-gain wearable antenna as a reference receiving antenna, the improvement of penetration distance and transmission characteristics will be predicted.

In a word, the aforementioned transmission characteristics exhibit sufficient capacity for high-speed transmission in a HBC communication link. Therefore, it also can be expected that, high reliable data rate up to several Mbps by using such a wideband compact antenna will be a good candidate for implant biomedical applications.

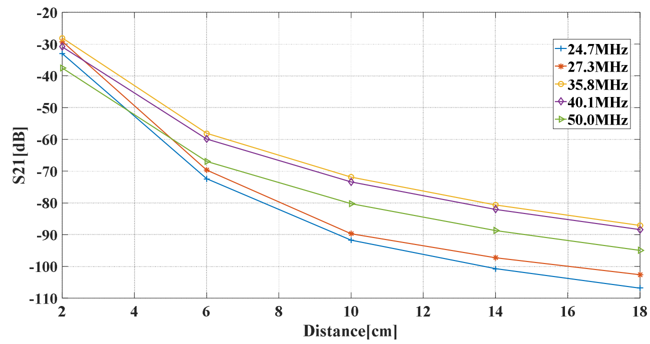


Fig. 5. Simulated transmission coefficient S_{21} as a function of transimission distance.

IV. CONCLUSION

In this paper, a wideband implantable antenna with non-equally spaced pitch foil formed on magnetic sheet has been proposed for biomedical applications at HBC band. It has a compact cylinder shape with radius of 1 cm and height of 3 cm. Non-equally spaced helical copper foil, or non-uniform pitch has been used to produce dual-resonance frequency band and then form a wide bandwidth eventually. -10 dB impedance bandwidth of 48.91 % has been realized to show good suitability for a wideband HBC transceiver. High data rate up to several Mbps for an in-body communication link can be expected by using such a wideband implantable antenna.

The future work is to further improve the antenna gain.

ACKNOLEDGEMENT

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