J-5-01 (Invited) Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp577-578

Wireless interface in biomedical applications

Sanghoek Kim[1] and Ada S. Y. Poon[2]

[1] Kyung Hee University
Yongin, 17104, South Korea
E-mail: sanghoek@khu.ac.kr
[2] Stanford University
California, 94305, USA
E-mail: adapoon@stanford.edu

Abstract

Recent development of wireless interfaces in biomedical applications using electromagnetic wave are reviewed. First, the paper introduces the analytical bound on the efficiency of wireless power transfer to a miniature implant and its implementation. The optimal source is physically synthesized using a slot array structure whose performance is very close to the theoretical bound. The development of highly efficient power delivery system miniaturizes a cardiac neuro-stimulator to a millimeter scale, removing energy storage from the device. The neuro-stimulator is demonstrated on a rabbit. As a second example of wireless interfaces for biomedical applications, this paper demonstrates a method to assess ones abdominal fatness using electromagnetic waves. The thickness of the fat can be estimated by measuring the frequency where the wave reflection is minimized.

1. Introduction

Wireless technology enables the wireless network connection of various mobile devices such as laptops, smartphones, tablets, and smart watches. Recently, mature wireless technology is actively deployed in biomedical applications. This paper will introduce two applications of those.

Efficient wireless power transferring to medical implantable devices is highly desirable to remove bulky energy storage and miniaturize the devices. There are various modalities to deliver power wirelessly, such as ultrasound, optical, piezoelectric, and biological sources. Among those, wireless powering through radio-frequency (RF) electromagnetic waves is the most established. While most studies for powering implantable devices utilizes inductive coupling, the power transfer is not efficient when the receiver size is much smaller than the distance. Recently, optimization of power links for a millimeter-sized implantable device was performed based on full-wave analysis [1, 2]. The first part of the paper reviews the recent progress of these findings. Based on the analytical derivation of the upper-bound of the powering efficiency, we design and implement the overall powering system to achieve maximum efficiency. This power delivery system is equipped in a millimeter-sized cardiac neuro-stimulator and tested in a rabbit [3].

The second part of the paper demonstrates a methodology to measure the abdominal fat thickness by measuring the reflected electromagnetic wave from a body [4]. The dangers of obesity-related health risks have been escalating recently. To assess obesity, patients can self-monitor their fatness, especially in the abdomen, in a private setting. There are many methods used to measure the degree of central obesity, but all suffer from drawbacks in self-assessment. Imaging equipment such as Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) yield accurate results for fat thickness, but is prohibitively expensive. Ultrasound imaging requires specialized skills to analyze [5]. Body mass index (BMI), probably the most common parameter to represent obesity, does not provide any information about the regional distribution of fat in the abdomen. We report that the input impedance of an antenna changes depending on the thickness of fat beneath the skin. The phenomenon can be explained by the principle of Salisbury screen. This new method allows us to measure the abdominal fatness with reasonable accuracy and greater availability than other established methods.

2. Wireless power transfer to a mm-sized pacemaker

When we model the inhomogeneity of the tissue as a planar multi-layered medium, the upper-bound of power transfer efficiency can be analytically obtained [1, 2]. Specifically, we consider multilayered tissue composed of skin, fat, muscle, and heart tissue (with thickness 2, 10, 8, 16 mm, and ∞, respectively). When a receiver coil has a diameter of 800 um on the surface of heart, the upper-bound of efficiency can be obtained as the black curve in Fig. 1 (a) [2]. Moreover, from the theoretical study in [2], the current density solution that maximizes the efficiency can be found in a closed-form. Based on identified features on the optimal current density solution, the source to power a mm-sized pacemaker is implemented using a slot array Fig. 1 (b). The structure consists of a 2 by 2 array of cross slots. By exciting the structure at the indicated ports [Fig. 1(b), red dots], important features of the optimal current density are reproduced [2]. As a result, the efficiency of the slot array approaches very close to the theoretical bound. Fig. 1 (a) also shows the efficiency of conventional coil sources of which the diameter varies from 0.6 to 6 cm, serving as reference structures. The efficiency of the proposed slot array structure exceeds that of coil sources by far.

Another benefit of using an array system is that the powering system can be more tolerable to the displacement of implantable devices. By adjusting the phase of excitation, the efficiency degradation by the displacement can be mitigated. The blue curve and the dashed red curve in the inset of Fig.1(a) show the efficiencies of coil and unadjusted slot array, respectively. Both degrade rapidly according to the displacement of implant Δx. On the other hand, the efficiency of adjusted source is more robust to the displacement (the solid red curve in the same plot).

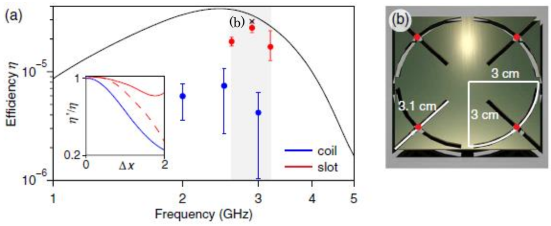

Fig. 1. (a) Theoretical upper bound on efficiency (black curve) with efficiencies of the slot array (red) and the coil sources (blue) (b) physical dimension of the slot array.

Based on this finding, a millimeter-sized cardiac stimulator is implemented and powered by the proposed slot array [3]. The device is only 2 mm in diameter [Fig. 2(a)], consisting of a coil and a capacitor for the powering and the matching purpose [Fig. 2(b)]. The epoxy encapsulated device is then inserted in the lower epicardium of a rabbit via open-chest surgery [Fig. 2(c)]. After the implantation, the chest was closed and a portable, battery-powered source was positioned ~4.5cm above the device. When the operating frequency of the source is adjusted to the estimated resonant frequency of the circuit, the cardiac activity of the rabbit in the bottom of Fig. 2(d) shows that the heart rate becomes regular as enough power is provided to the stimulator. The autocorrelation function in the bottom of Fig. 2(d) demonstrates the regularity of the heart beat in the resonant section (blue) compared to the off-resonant section (black).

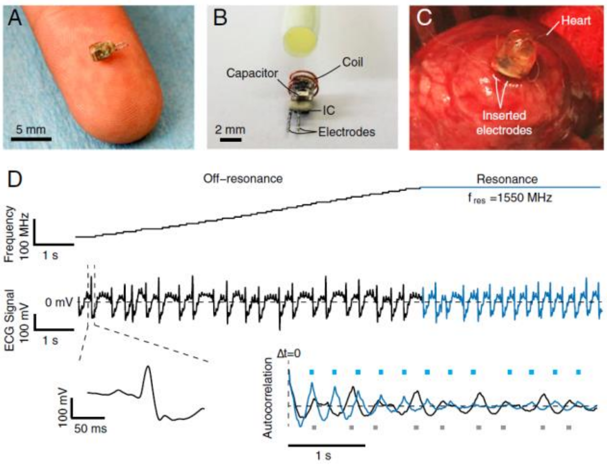

Fig. 2. (a) Electro-stimulator on a finger (b) Zoomed-in view of the device (c) device implanted on the heart of a rabbit (d) Operating frequency variation from the off-resonance to the resonant frequency (top). Measured ECG of the rabbit corresponding to the operating frequency variation (middle). The autocorrelation (bottom) shows that the neuro-stimulator makes the heart beat regular when enough power is wirelessly supplied.

3. Wireless assessment of fat thickness

Biomedical applications of electromagnetic waves are not limited to the wireless powering of implantable devices. It is already widely applied in most imaging modalities, such as MRI and CT scans. But both modalities have problems for daily self-monitoring. MRI is prohibitively expensive and CT has a danger of ionization. Compared to those, microwave imaging using RF wave has a potential for daily self-usages.

Recently, the Salisbury-screen characteristics of the human abdomen was demonstrated [4]. The Salisbury screen is one kind of electromagnetic wave absorber, consisting of a thin resistive sheet, a dielectric slab, and a conduction plane. The screen absorbs the wave of which the quarter-wavelength matches the thickness of the dielectric slab. The skin-fat-muscle structure in the human abdomen resembles that of the Salisbury screen. Therefore, wave with a particular wavelength related to the thickness of fat may show selective absorption by the abdomen.

The reflection coefficient against the abdomen is calculated and shown in Fig. 3. In calculation, the body is modelled as a planar model, where the skin is 2-mm thick and the thickness of fat changes from 8 to 40 mm. Note that the reflection sharply decreases at a certain frequency. This validates our theory that the abdominal structure can work as a Salisbury screen. Moreover, the resonance frequency, where the notch response appears, decreases with fat thickness. This is also an expected result based on the principles of the Salisbury screen. Therefore, this study shows the feasibility that observation of frequency with minimum reflection can provide the information about fat thickness.

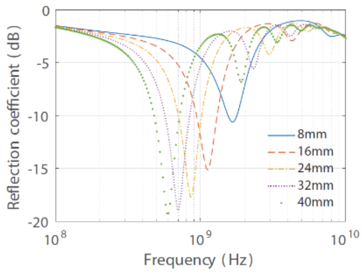

Fig. 3. Relation of frequency and the reflection coefficient when the thickness of the fat is between 8 mm and 40 mm.

4. Conclusion

Among countless applications of electromagnetics in biomedicine, two applications are introduced in this paper. The first is the wireless powering of small implantable devices. The optimal source developed based on theoretical study could be used to build a mm-sized, wirelessly powered cardiac neuro-stimulator. The second application is non-invasive assessment of fat thickness in the abdomen. This work demonstrates the feasibility of a very inexpensive and convenient method of assessing abdominal fatness compared to other established methods.

References

[1] S. Kim, J. Ho, and A. S. Y. Poon, IEEE Trans. Ant. Prop., **60** (2012) 10.

[2] S. Kim, J. Ho, and A. S. Y. Poon, Phys. Rev. Letters, 110, (2013) 20.

[3] J. Ho, et. al., PNAS, 111, (2014) 22.

[4] J. Park, e. al., Elec. Letters, 54, (2017), 14.

[5] Abe, T. et. al., Med Sci Sports Exercise, 28, (1996), pp. 908-912.