# Micro Antennas for Implantable Medical Devices

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*Abstract*—**Implantable devices are becoming smaller and smaller, making possible new solutions for the current challenges in medical diagnosis, treatment and monitoring. These implantable solutions may rely on miniaturized devices that can be controlled and powered via wireless communications. Due to the high degree of system miniaturization very small antennas are required pushing the communication range to the high frequencies domain. Nevertheless, since human body tissue attenuation increases with frequency it is challenging to obtain an efficient wireless link. This paper reports the design of micro-device integrated antennas suitable for energy harvesting applications. These devices, and integrated antennas, can be fabricated by combining self-folding methods with conventional multi-layer lithography, allowing precise patterning of two dimensional templates that can transform into three dimensional antennawith wireless capabilites.**

***Keywords—micro antenna; small antenna;medical device; implantable device; energy harvesting; self-folding***

## I. INTRODUCTION

A vast number of implantable medical technologies have been reported in the literature [1-4] and this rising interest in research and development of implantable solutions naturally follows the growing trend of the implantable medical devices market, predicted to grow 7.7% anually trought 2015 in the United States alone [5]. The market demands forces technology to evolve faster than ever before, and “small”, “efficient”, “less power”, “more complex”, and “wireless” are common words and expressions when discussing new implantable technologies.Wireless medical implants represent a portion of this fast growing market. Their remarkable feature is the bidirectional link between the implant and an external receiver, enabling medically usefull data to be transmitted both ways providing physicians with instant and more accurate diagnosis [6], and hence playing a key role in the in patient care and quality of lifeimprovement.

In this paper we discuss the design and fabrication technique of a miniaturized antenna, suitable for an energy harvesting application, integrated in a small 500 x 500 x 500 $\mu m^3$ implantable microdevice. A discussion on human tissue properties and signal losses as well as an antenna efficiency discussion are provided in order to clarify the antenna energy harvesting performance when implanted in the human body.

## II. IMPLANTED MEDICALMICRO DEVICES

The proposed antennas are designed to be integrated into self-folding microdevices [7]. These devices are fabricated using standard lithographic techniques that can pattern on silicon substrates at micro and/or nano scale. Self-folding of lithographically patterned templates overcome the two dimensional restrictions of standard lithographic fabrication and thus enabling three dimensional structures.

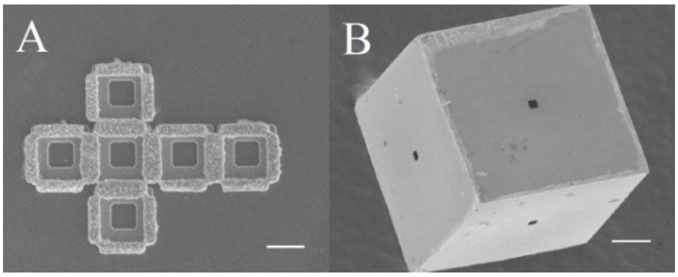

Figure 1. Fabrication of 3D structures using planar lithography. (A) SEM image of a 2D template of a cubic container. Bar scale: 10µm. (B) SEM image of a container after self-folding. Bar scale: 100µm [21].

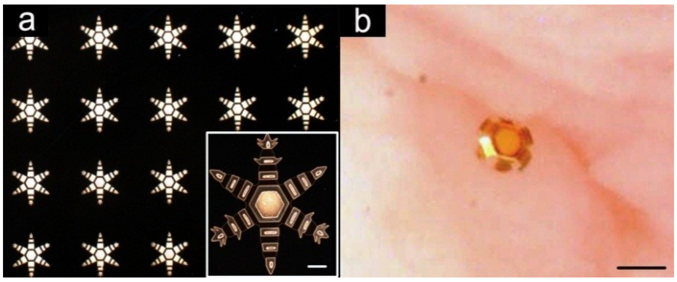

Figure 2. Optical images of microgrippers (a) on the silicon substrate before lift off, the inset shows the higher magnification, scale bar shows 100µm and (b) attached to the tissue, scale bar shows 500 µm [12].

Figure 2 shows 2D templates with liquefiable hinges that fold upon heating and transform into a 3D structures. This process enables the fabrication of devices such as theterless microgrippers [8] and micro containers suitable for implantable drug delivery systems [9]. The folding process is driven by residual stress on the flexible hinges allowing these devices to reconfigure themselves.

This composition obviates the need forwireless communications enabling remote manipulationofthese microscale structures suggesting an approach for the development of smart implantable devices.The reported tools dimensionsand fabrication process nature suggest that miniaturized antennas can be either integrated into these micro structures by lithography patterning of the antenna structure into 2D templates (Figure 4A), or beingthe micro device structure itself acting as an antenna (Figure 4B).With the fabrication process flexibility to accomodate proper electronics [10],wireless communications with and exterior base station and harvesting energy from an exterior radiofrequency (RF) sourcecan be explored.Due to the host size restraints, havesting energy from electromagnetic wavesrepresents a strong adavantage since it eliminates the needforbulky batteries that considerably increase the device dimensions.

In the next section a discussion on the wireless link losses is provided. Some insights on human tissue attenuation and antenna design for maximized efficiency will be given.

## III. WIRELESS LINK LOSSES ON IMPLANTABLE DEVICES

Signal losses are an undesirable and inevitableaspect of electromagnetic wave propagation. They occur in free space according to Friss transmission equation but become even more severely in lossy mediums such as the human tissues.

A medical implant can be placed either transdermally or embedded several centimeters deep in the human tissue. In both cases it is imperative to evaluate the power lost in the path between the external radiofrenquency source and the implanted device. The device received power ($P_r$) is a small fraction of the RF source transmitted power ($P_t$) due to the losses occuring in the path between them. The received power can be calculated:

$$P_r = P_t \times FSPL \times TL \times \eta \qquad (1)$$

The external RF source transmitted power is first reduced in the free space path (FSP) between the source and the first tissue layer. The power losses increase inside the tissues (TL) until the remaining signal reaches the implant where all the mentioned losses are multiplied by the antenna efficiency $\eta$.

### A. *Tissue Losses*

The human body is not the ideal medium for RF signal propagation since electromagnetic radiation propagation depends heavily on the tissues water concentration due to the water poor conductivity ($\sim 5.5\times10^{-6}$ S/m). Nevertheless, biological tissues have high conductivities when compared with air and thus higher losses due attenuation. The human body behaves as a dielectric with frequency dependent electrical permittivity ($\varepsilon$) and conductivity ($\sigma$) and its electric field distribution depending on the body physiological parameters and geometry as well as the incident electromagnetic wave frequency and polarization [11].

The power loss in a specific medium can be calculated using its frequency specific permittivity and conductivity to compute the attenuation factor ($\alpha$) according to [12]. The power loss, as a function of frequency, has been calculated for human skin, fat and muscle for frequencies up tu 100 GHz, where it was concluded that tissue attenuation increases with frequency.

### B. *Antenna Efficiency*

Due to the host system size limitsthe antenna has to be small and, as seen in (1), with an efficient antenna playing a major role in determining the implant received power. Thus a miniaturized and efficient antenna is required. It is known that the antenna size with respect to the wavelength is the most important parameter influencing the antenna's radiation [13]. In fact, the first works on the limits of electrically small antennas conducted by Chu [14],Wheeler [15] and Harrington [16], reported a relation between antenna size and its radiation characteristics. Harrington demonstrated that the antenna efficiency is directly proportional to its electrical size and thus high operating frequencies are required for geometrically small but efficient antennas. Hence, based on this theory and the dimensional limits of the proposed medical implanted tools, the antenna efficiency significantly decreases if lower operating frequencies are used.

It is shown in a previous study [12] that,accordingly to the works of Chu [14] and Harrington [16] for electrically small antennas, an antenna confined within a 500 x 500 x 500 $\mu m^3$ volume is expected to operate in the range of tenths to hundreads of gigahertz where efficiency increases with frequency.

### C. *Tissue Attenuation and Antenna Efficiency Tradeoff*

The analysis of the power loss due to tissue attenuation shows [12] that extremely intense signal attenuation occurs when high frequencies are used to the point that virtually no power can be tranfered to the device. On the other hand, the antenna efficiency analysis shows that the efficiency of a miniaturized antenna confined in a 500 x 500 x 500 $\mu m^3$ volume increases when exploiting higher frequencies. The results suggest that the tradeoff between tissue attenuation and antenna efficiency which can be controlled by the selection the a proper frequency. Works on optimal frequency for energy harvesting have been presented [12][17], showing that a frequencies in the low gigahertz range are more suitable such applications.

## IV. HFSS MODEL

The proposed antennaswere designed and simulated with Ansoft HFSS v.12 [18],which utilizes the finite element technique for electromagnetic computation.

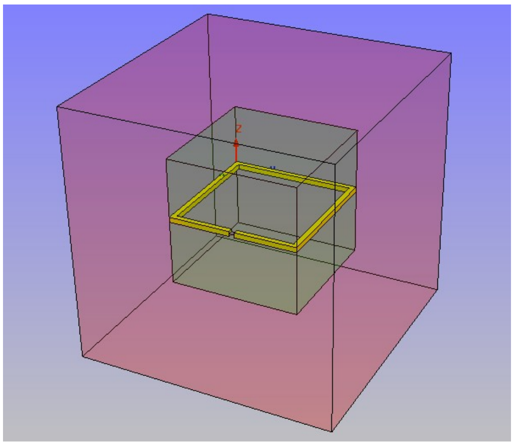

Figure 3. HFSS Model of a square loop antenna within the a $500 \times 500 \times 500\ \mu m^3$ air box representing a micro device volume surrounded by a human tissue layer [20].

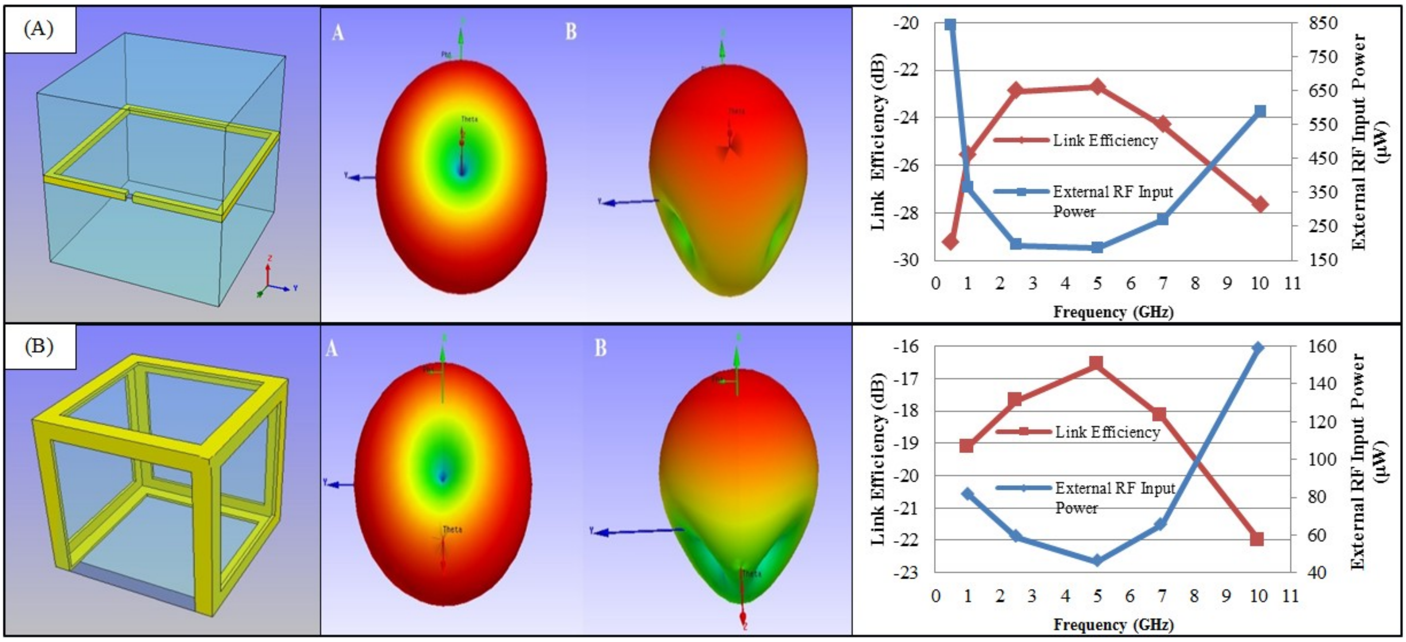

Figure 4.Proposed antennas HFSS models, radiation patterns and wireless link efficiency. **(A)** HFSS model of a square loop antenna in a 500× 500× 500 µm$^3$ box; Radiation diagram of a square loop antenna at 5 GHz;A) in free space; B) when embedded in a 5× 5 × 5 mm$^3$ human muscle tissue layer. Link efficiency of 500× 500 µm$^2$ square loop antenna embedded in 5 × 5 x × 5 mm$^3$ volume of human muscle tissue and the necessary RF input power to deliver 1 µW power to the micro-device. Figure 4.**(B)** HFSS model of a gold cubic shape antenna within a500 × 500 × 500 µm$^3$ micro-device. The missing cube edge is the antenna feeding point; Radiation diagrams of the cubic shape antenna; A) in free space;B) when embedded in a 5 × 5 × 5 mm$^3$ human muscle tissue layer; Link efficiency of the cubic antenna in 5× 5 × 5 mm$^3$ human muscle tissue and external RF input power required to transfer 1 µW power to it [20].

The model is composed of an antenna confined in a 500 × 500 × 500 µm$^3$ air box (representing the micro device volume) which is surrounded by a 5× 5 × 5 mm$^3$ box with dielectric properties similar to that of human tissue, where a radiation boundary (containing the antenna) is applied to the box surfaces. Since the human body can be seen as a non-uniform dielectric with frequency dependent permittivity and conductivity, the muscle tissue, were simulated with its specific dielectric properties (taken from [19]) for the tested frequencies. As a result of its miniaturized dimensions, the antenna maximum efficiency occursat high frequencies in the order of hundreds of GHz. However, as mentioned before, power losses due to tissue attenuation tend to be more expressive at higher frequencies. Consequently, the feeding port impedance was selected to match the antenna impedance to 50Ω in the low gigahertz range (1-10 GHz). This procedure decreases the antenna efficiency.

## V. 2D VS. 3D ANTENNA

Self-folding of lithographically patterned templates enabling the fabrication of 3D inspired structures inspired the design of a micro-device with an integrated 3D antenna. One way to make an antenna smaller and less bulky is to modify its geometry and shape [13]. With self-folding of patterned 2D structures the antenna profile can be patterned in a 2D template and then folded allowing an electrically larger antenna within the same volume. Two different antennas profiles, 2D and 3D, were designed an simulated in order to compare their energy havesting capabilities.

### *A. Square Loop Antenna*

A square loop geometry design was chosen since the 2D loop profile maximezes the antenna size within the a 500 × 500 µm$^2$surface and due to its fabrications process restrictions compability. A rectangular loop establishes a primary design as a comparison base for future designs. The antenna has a total length of 1.98 mm with a 20 × 20 µm$^2$ cross-section and itsradiation pattern is presented in Figure 4 (A).Pattern A shows the radiation pattern of a free space antenna with a commun donut shape while patter B exibits the effect of surrounding human tissue. Link efficiency results (Figure 4 (A)) point to an optimum operating frequency window between 2.5 and 5 GHz where the wireless link efficiency, and thus the power transfered, are maximized. At 5 GHz the RF source must generate 186µW to provide 1µW to the implanted micro-device.

### *B. Cubic Antenna*

As seen in Figure 1, six patterned square faces can be folded originating a cube. The cubic shaped antenna (Figure 4 (B)) design makes a good use of the self-folding technique in antenna miniaturizationwhere the whole structure can act as an antenna and thus maximizing the available 500 × 500× 500 µm$^3$volume. A first set of simulations showed that, compared with the square loop geometry, a better link efficiency can be obtained by changing the antenna cross section to 50 × 10 µm$^2$ and increasing the lumped port length to 400 µm (Figure 4 (B)). The previously described tuning procedure was applied so that the antenna operates optimally in the same low gigahertz frequency range. The cubic shaped antenna radiation patternis similar to the square loop exibiting a donut shaped pattern in free space conditions and the human tissue effects when implanted. HFSS simulations show that the cubic geometry, significantly improve the wireless link efficiency when compared to the squere loop geometry. Accordingly to Wheeler [15], the antenna efficiency is directly related to the volume occupied by the antenna and thus was expected that this design would improve the antenna radiation characteristics. It is shown in (Figure 4), a 6 dB improvement in the overall wireless link efficiency at the optimal frequency of 5 GHz, which means that the external RF source must provide only 46μW to fulfill the power requirement of 1μW.

## VI. ANTENNA PROTOTYPE

The first 3D antenna prototype was fabricated combinig the surface tension driven sel-folding with the conventional multi-layer photolithography. This combined technique allowed precise patterning of 2D templates (Figure 5 A) that converted into 3D complex structures (Figure 5 B) with higher surface area to volume ratios.

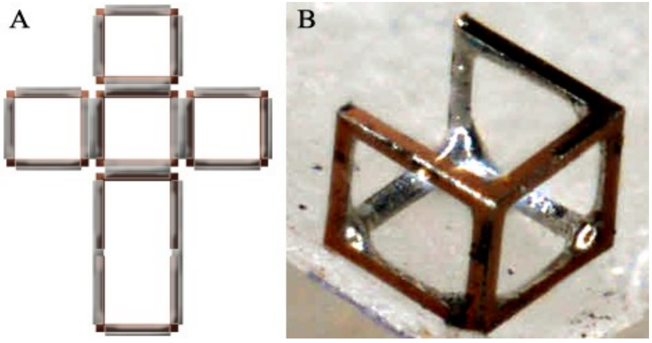

Figure 5. 3D small antenna prototype. A) Schematic of the 2D template of the small antenna before self-folding. B) The optical microscopy images of 500 × 500 × 500 $\mu m^3$ cubic shape, 3D antenna prototype [20].

## VII. CONCLUSION

Smallefficient antennas require high operating frequencies for efficient performance since antenna efficiency is directly proportional the antenna size and signal wavelength. However, in the case of an implanted antenna, severe tissue attenuation occurs when high frequencies are used.HFSS simulations suggest that wireless energy transfer is feasible for implanted micro-deviceswithenergy requirementsin microwatts range. The proposed cubic antenna showed to be able to harvest at least four times more energythan the square loop planar design within the same available volume. This achievement is made possible by using self-folding techniques with the conventional multi-layer photolithography enabling a 3D antenna with a higher surface area to volume ratio that maximizes the antenna efficiency and the harvested power.Nevertheless, further simulations and experiments are needed in order to optimize the antenna electrical size and efficiency by exploring different 3D antenna configurations.

Future workwill consider antennas measurements of the proposed prototype as well as the development of a RF-DC converter for an energy harvesting application based on schottky rectifier diodes.

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