# ENERGY HARVESTING FOR SELF-FOLDING MICRO DEVICES

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Abstract: The miniaturization of medical devices allows numerous new solutions in medicine including implantable devices that can diagnose, treat and monitor patients. Drug delivery systems have the potential to drastically change the drug administration and hence to improve their therapeutic efficiency. These devices can be fabricated by combining self-folding methods with the conventional multi-layer lithography. This combined lithography technique allows precise patterning of two dimensional (2D) templates that can transform into three dimensional (3D) structures with higher surface area to volume ratios. The same technique allows the incorporation of small antennas with devices and enabling wireless capabilities. An efficient wireless link between an external reader and the implanted device provides a remarkable advantage to both patients and caregivers including greater patient ease of movement, continuous data feeds, higher quality and reliability of data reporting. This paper proposes a system which is composed of a $500x500\mu m^2$ square loop antenna with 5GHz operating frequency, embedded on a SU-8 cubic container suitable for small implantable medical devices.

## 1 INTRODUCTION

Implantable biomedical devices are becoming smaller and smaller due to the availability of the high levels of miniaturization. Millimeter scale structures can work as medical tools (Randall, 2011) (Rahimi, 2011) and perform tasks that are only possible because of their miniaturized dimensions. Several miniaturized tools such as drug delivery systems (Yang, 2009), blood glucose (Ahmadi, 2009), blood pressure (Cong, 2009), ECG monitoring systems (Fu, 2011) and neural probes (Kensall, 2008) have been reported in the literature.

Implantable drug delivery systems have a variety of applications in medicine due to their efficacy to control the administration of drugs both in time and space. They have the ability to control drug release rate and to target specific organs or locations inside the body. With local precision, effective dosage and prompt drug release, these devices can reduce the negative side-effects of traditional systemic medication and significantly improve the therapeutic efficiency (Barbé, 2004). Drug release systems can be divided into two main categories: Passive and active release. Passive devices depend on the rate of diffusion for the drug release while active devices can control release by an external trigger such as a RF signal (Smith, 2007). These devices can be fabricated using standard lithographic techniques that can pattern on silicon wafer substrates at micrometer and/or nanometer scale. The main limitation of the standard lithographic fabrication technique is its two dimensional (2D) restrictions. 2D nano or micro fabrication can result in bulky devices when compared with 3D structures that have greater surface area to volume ratio allowing more usable surface and small form factors (Randall, 2007).

Self-folding of lithographically patterned structures can overcome the inherent 2D limitations, thus enabling 3D structures. Figure 1.A shows a 2D template with liquefiable hinges that folds upon heating and transforms into a 3D structure. This process enables the fabrication of containers (Figure 1.B) that can be made out of metals, oxides and polymers which are suitable for drug delivery applications. The fabrication of optically transparent polymeric containers has been reported (Azam,


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2010) where polymer panels were patterned using conventional photolithography. The reported lithographic fabrication process is also compatible with electronic components integration which represents a promising new approach in the design and fabrication of implantable devices with integrated antennas.

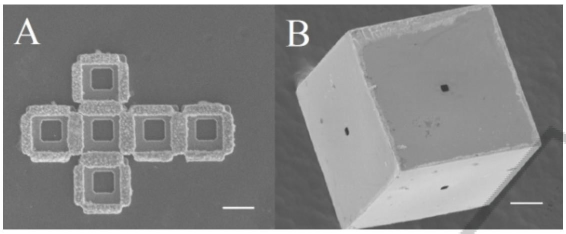


Figure 1: Fabrication of 3D structures using planar lithography. (A) SEM image of a 2D template of a cubic container. Bar scale: 10µm. (B) SEM image of a container after self-folding. Bar scale: 100µm.

Implanted medical devices with wireless capability allow efficient communications between the device and an external reader, providing a higher level of autonomy for either inpatients or outpatients and thus improving their quality of life (Fang, 2011). A small polymeric box with an embedded efficient antenna system can unveil a wireless link suitable for such purposes. As an implanted device, the described system has energy requirements that are still challenging to fulfill especially for miniaturized implants. While significant achievements in battery technology reached higher levels of energy density e.g. lithium-ion batteries, the bulky size of the batteries considerably increases the implant dimensions. Also, batteries eventually need to be replaced (Olivo, 2011) which is not desired or possible in some applications.

Transmitting power through electromagnetic waves (EM) has been proposed as a promising technology to resolve the dependency on the wired energy transfer or storage (Jabbar, 2010) (Nishimoto, 2010). However, harvesting energy from an external power source is a challenge for miniaturized devices because it requires an efficient small antenna that has to fulfill the power requirements of the device. The amount of power harvested through EM radiation depends on antenna parameters such as size, geometry, gain and efficiency plus the power loss due to tissue attenuation. The antenna plays a major role in the wireless capability, and its performance gets severely constrained due to the high degrees of miniaturization (Huang, 2011).

# 2 PROPOSED SYSTEM AND ANALYSIS

This paper proposes the integration of a square loop antenna with a polymeric container. Figure 2 shows the schematic of a 2D polymeric template where the antenna metallic structure is patterned as a common wire antenna. After the self-folding, the 2D template transforms into a cubic container with an embedded square loop antenna.

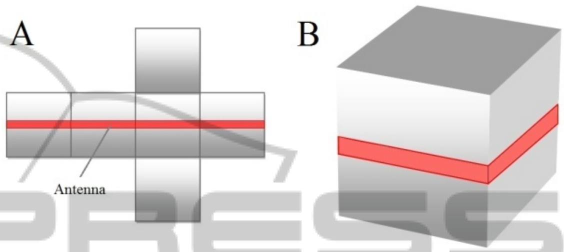


Figure 2: The schematic of the proposed system. A) 2D template of the container with an antenna (red) patterned onto polymeric panels. B) The polymeric cube and embedded antenna after folding.

The proposed system was simulated and analyzed with AnSoft HFSS v.12 which utilizes finite element technique for electromagnetic computation. The model is composed of a cubic box layer ($5x5x5mm^3$) whose dielectric properties are similar to those of real human tissues and the proposed system is in the centre of the box. In order to study the antenna properties when implanted in human tissue, cubic tissue samples of skin, fat and muscle were individually tested. Since the human body can be considered as a non-uniform dielectric with frequency dependent conductivity and permittivity all tissues were programmed with their specific dielectric properties for the tested frequencies (values taken from (Gabriel, 1996)).

The simulated antenna design (Figure 3) has a total length of 1.98mm (with a lumped port of $20x20\mu m^2$), with a $0.2x10^2\mu m$ cross section (200nm thick and 10µm wide). Gold and SU-8 were chosen as the antenna and the cube material respectively. Among the possible antenna geometries, a loop antenna was chosen since its square geometry is suitable for this specific application. The loop antenna efficiently utilizes the container's cubic shape while maximizing the antenna electrical size and it is compatible with the container’s fabrication process.

As a result of the physical size of the antenna which is inversely proportional to the frequency, the proposed antenna has a resonant operating central frequency of 163 GHz. At this frequency severe tissue attenuation occurs and virtually no power can be transmitted to the implant. Thus, the antenna was matched to operate at lower frequencies between 5 to 20 GHz by changing its feeding source resistance and capacitance.

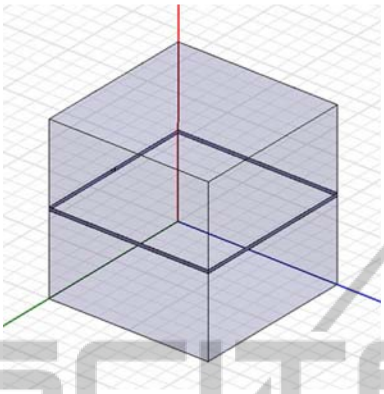

Figure 3: HFSS design of proposed antenna and SU8 cube.

The HFSS radiation efficiency was the chosen antenna parameter to evaluate the efficiency of the wireless link since it reflects not only the antenna's efficiency but also the tissue attenuation losses. The simulations results reveal that each tissue has an optimal frequency that maximizes the antenna radiation efficiency. As it can be seen in Table.1, muscle tissue and skin tissue share the same optimum 5 GHz because of their similar dielectric properties with radiation efficiencies of -24.8 dB and -25.45 dB respectively. For fat tissue, the optimal frequency centers around 20 GHz with -23.81 dB radiation efficiency.

Table 1: Antenna radiation efficiency of tested tissues at their optimum frequencies.

| Tissue | Optimum Frequency (GHz) | Radiation Efficiency (dB) |
|---|---|---|
| Fat | 20 | -23.81 |
| Muscle | 5 | -24.8 |
| Skin | 5 | -25.45 |

## 3 ANTENNA PERFORMANCE FOR ENERGY HARVESTING

The device should be fed by a RF signal provided by an external source. Assuming 1µW as the device's power requirement, one can calculate the required incoming power by using the radiation efficiency (Table 2). For example, considering a muscle tissue box of 5x5x5 $mm^3$ and the referred 1µW power requirement, the external RF signal generator should provide 264µW to fulfill 1 µW requirement. Increasing the size to a 10x10x10 $mm^3$ box inevitably decreases the radiation efficiency due to tissues losses and a signal of 776µW would be needed to power the device.

Table 2: Antenna and radiation efficiency at 5GHz for different tissues types and thicknesses.

| Tissue | Tissue Box $mm^3$ | Radiation Efficiency (dB) |
|---|---|---|
| Fat | 5x5x5 | -25.98 |
| | 10x10x10 | -31.73 |
| Muscle | 5x5x5 | -24.23 |
| | 10x10x10 | -28.90 |
| Skin | 5x5x5 | -25.29 |
| | 10x10x10 | -30.82 |

The simulations and the power calculations suggest that, for the chosen operating frequency, an energy harvesting application is possible for the proposed system even though the antenna efficiency is severely constrained due to tissue losses. Nevertheless, several improvements can be achieved, using self-folding techniques, in order to maximize the antenna efficiency by exploring different 3D antenna profiles that would increase the antenna electrical size and thus its efficiency.

## 4 CONCLUSIONS

Incorporating an electrically small antenna into a miniaturized polymeric cube using self-folding fabrication techniques could unveil new applications such as implanted active drug delivery systems. In this paper we showed that wireless energy harvesting can be explored using relatively low frequencies (5GHz) and thus diminishing tissue losses that occur at higher frequencies. We showed by computational simulations that it is possible to supply 1µW power to a miniaturized device integrated with a square loop antenna through an exterior RF source of several hundreds of microwatts.

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