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Magnetoelectric (ME) Antenna for On-chip Implantable Energy Harvesting

Mehdi Nasrollahpour, Mohsen Zaeimbashi, Adam Khalifa, Xianfeng Liang, Huaihao Chen, Neville Sun, Seyed Mahdi Seyed Abrishami, Isabel Martos-Repath, Shadi Emam, *Student Member, IEEE*, Sydney Cash, Nian Xiang Sun, *Fellow, IEEE*

***Abstract*— A novel magnetoelectric (ME) antenna is fabricated to be integrated to the on-chip energy harvesting circuit for brain-computer interface applications. The proposed ME antenna resonates at the frequency of 2.57 GHz while providing a bandwidth of 3.37 MHz. The proposed rectangular ME antenna wireless power transfer efficiency is 0.304 %, which is considerably higher than that of micro-coils.**

***Clinical Relevance*— This provides a suitable energy harvesting efficiency for wirelessly powering up the brain implant devices.**

I. Introduction

Robust and powerful wireless power energy harvesting systems are an integral part of implantable medical devices (IMDs). Evolution of implant devices provide the paths to the new approaches for new treatments, medicines, neural stimulation and recording while designing mm-scale power harvesting systems has always been a key challenge in implantable devices. Therefore, it is required to reduce the size of the implant devices and make them operate wirelessly to reduce the chance of infection, damage to the issue and periodic invasive surgeries [1].

Electromagnetic wave and ultra-sound are two main approaches to wirelessly power the implant devices [2]. Investigation of the acoustic waves for power delivery to the implants is also increasing considerably [3, 4]. Traditionally, the reported designs utilize low-frequency electromagnetic waves for power delivery systems which require large receiving coils on the implant devices [5-7]. Large form factor of these bulky coils makes them impractical for implant devices although they provide high power transfer efficiency. It is shown in [8] that low GHz frequencies are the optimum frequency for energy harvesting in body tissues. Therefore, increasing the frequency of carrier signal shrinks the size of receiver coil or antenna to overcome the miniaturization challenges of the mm-sized implant devices [9-12]. On the contrary, the frequency increase is also limited since the EM loss enhances significantly in higher frequencies.

This paper is presenting a novel magnetoelectric (ME) antenna suitable for power harvesting applications in implant devices due to the compatibility to silicon and smaller size in compare to the state-of-the-arts micro-coils at lower GHz frequencies. In summary, the ME antenna provides better power transfer efficiency than the state-of-the-art coils. This paper is organized as follows: Section I explains the proposed ME antenna fabrication and performance and the energy harvesting measurement results are presented in Section III. Finally, the paper is concluded in Section IV.

II. PROPOSED MAGNETOELECTRIC ANTENNA

Miniaturization of antennas is one of the main challenges in state-of-the-art antenna technologies. EM wave resonance theory leads to the antenna size of at least one-tenth of the EM wavelength ($\lambda 0$). Therefore, achieving smaller antenna for low and mid frequency applications and the need for antenna arrays are challenging. Mechanical resonance of antennas based on the magnetoelectric heterostructures is a novel approach proposed by Lin, H., et al. [13, 14]. The effect of strong ME coupling of multiferroic materials, such as FeGaB [15] and FeGaC [16], has demonstrated practical energy conversion between electric and magnetic fields, allowing for multiferroic devices such as sensors, tunable RF/microwave devices, etc. A layer of piezoelectric material and magnetostrictive material (FeGAB/AlN) are the main consisting layers of the ME antenna which based on the bulk acoustic wave (BAW) resonator transfers the dynamic strain across different layers. Mechanical resonance of the NEMS resonator due to applying RF electric field in the transmitting mode induces alternating strain wave/acoustic wave which will be transferred to the ferromagnetic thin film. Therefore, magnetic currents are generated owing to the dynamic change of the magnetization caused by the strong piezomagnetic constant; Reciprocally, the ferromagnetic layer detects RF magnetic field component of the electromagnetic wave and induce an acoustic wave on that layer in the receiving mode. The dynamic voltage/charge or RF signal would be generated due to the direct piezoelectric coupling when this acoustic wave transfers to the piezoelectric thin-film. ME antennas provide hundreds to thousands of times smaller size at the same frequency of operation by using acoustic waves instead of electromagnetic waves [17, 18]. The fabrication process with 5-masks is explained comprehensively in [13].

Proposed ME antenna S_{11} measurement is presented in Fig. 1, showing the resonance frequency of 2.57 GHz while the optical microscope image of the fabricated ME antenna is shown in Fig. 2.

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M. Nasrollahpour, M. Zaeimbashi, X. Liang, H. Chen, N. Sun, S. M. S. Abrishami, I. Martos-Repath, S. Emam and N. Sun are with Department of Electrical Engineering, Northeastern University, MA 02115, USA (phone: 617-373-3351; e-mail: n.sun@northeastern.edu).

A. Khalifa and S. Cash are with Department of Neuroscience, Massachusetts General Hospital, Harvard Medical School, MA 02115, USA.

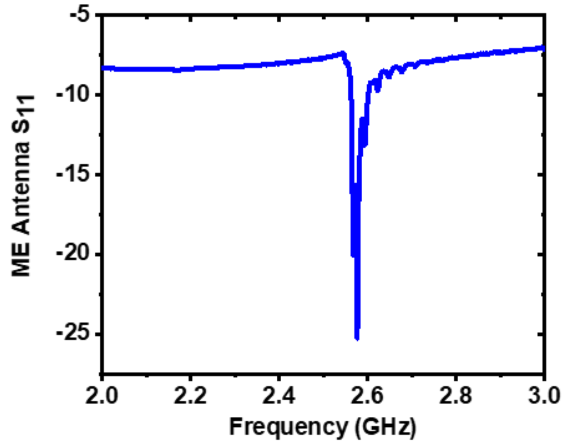


Fig. 1. S_{11} measurement of the fabricated ME antenna

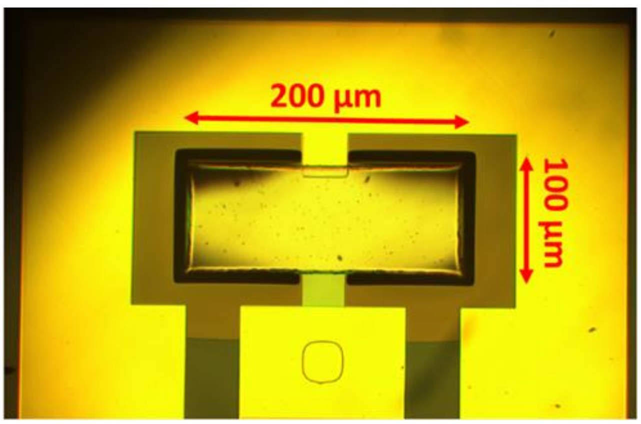
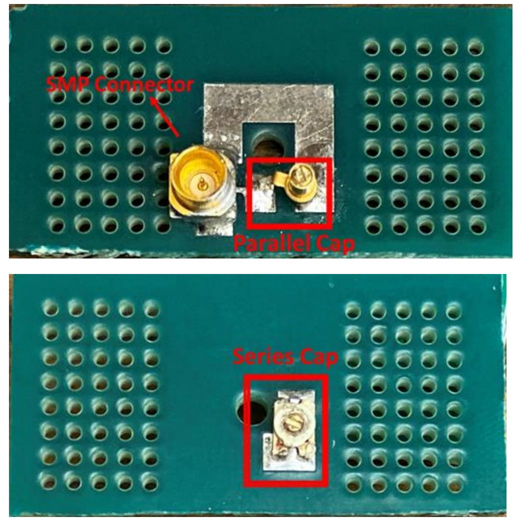


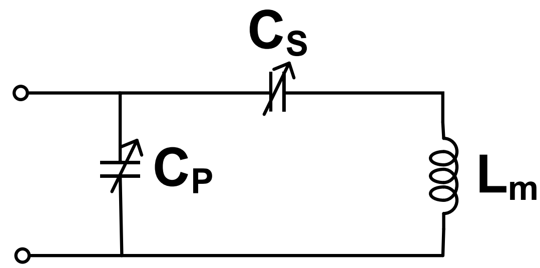
Fig. 2. ME antenna optical image

III. ENERGY HARVESTING MEASUREMENT RESULTS

A single-turn transmitter coil is designed and simulated to assess the energy harvesting capability and efficiency of the ME antenna for biomedical applications. The coil is fabricated on FR4 PCB material while the coil size is optimized to provide better quality factor, SRF, and active area. The optimized and fabricated TX coil, shown in Fig. 3 (a), has a self-resonance frequency (SRF) of 4.1 GHz, Q-factor and inductance of 110 and 10.49 nH (both @ 2.55 GHz and in air), length of 10 mm, and trace width of 3 mm. An L-match capacitive network, also displayed in Fig. 3 (b), is used to match the TX coil at 2.57 GHz for maximization of the transmitted power. SMP connector is utilized to reduce the input capacitor of the TX coil to be capable of matching at higher frequencies. Reflection coefficient (S_{11}) of the TX coil matched to 2.57 GHz frequency is shown in Fig. 4 which is equal to the resonance frequency of the proposed ME antenna, displayed in Fig. 2. It is worth mentioning that the matching of the TX coil will be a bit degraded when the ME antenna is so close due to the available magnetic materials. As mentioned earlier, an L matching network consists of two RF series and parallel capacitors are implemented to tune the matching network. RF trimmers provide the range of 0.3 pF to 1.2 pF for the parallel capacitor and 4.5 pF up to 34 pF for the series capacitor.



(a)



(b)

Fig. 3. Transmitter coil design and fabrication: (a) TX coil used for energy harvesting matched at 2.57 GHz (b) coil L-matching topology with RF trimmers

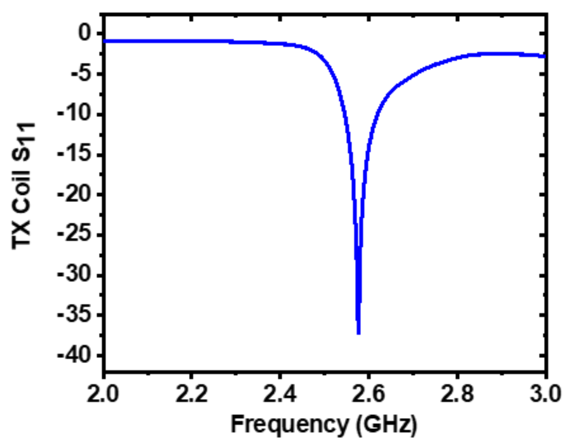


Fig. 4. TX coil reflection coefficient (S_{11})

Two 3D printed micromanipulators are utilized in the energy harvesting test setup to precisely control the distance of the ME antenna and TX coil, as shown in Fig. 5. There are a couple of advantages to using these micromanipulators: 1) the plastic material allows you to minimize the impact of the test setup on ME antenna and TX coil matching; 2) it provides the resolution of less than 200 µm; 3) adjustability along the X-Y-Z axes which gives you to investigate the link performance precisely. Power transfer efficiency is known as the ratio of the received power by ME antenna to the transmitted power is

TABLE 1. COMPARISON TABLE OF ME ANTENNA WITH STATE OF THE ARTS MICRO-COILS

Parameter	Khalifa [19]	Liuqing [20]	Nai-chung Kuo [21]	This Work
RX Area (mm^2)	0.09	0.01	0.01	0.02
RX	On chip coil	On chip coil	On chip coil	ME Antenna
Distance (mm)	6.6	0.5	2.2	10
Medium	Tissue	Air	Air	Air
PTE* (%)	0.01	0.12	0.0079	0.00764
FOM	106	12	84	2701

$* \, PTE\,(\%) = \eta_{Tx} * Path\ Loss * \eta_{Rx}$

measured and the results are shown in Fig. 6. To do so, the ME antenna is connected to the power spectrum analyzer and the TX coil power is provided from the VNA to be capable of checking the matching network in each step. The left-axis in Fig. 6 shows the measured PTE versus distance between ME antenna and TX coil, and right axis shows the simulated magnetic flux density along the x-axis (Bx) generated by the TX coil versus distance from the TX coil. ME antenna sensitivity along the x-axis is defined based on the applied DC field to FeGaB material during the deposition process. Therefore, applied magnetics fluxes in the x-axis direction lead to the voltage generation in the ME antenna. Measured power transfer efficiency decreases by increasing the TX and RX distance, as shown in Fig. 6. The simulated magnetic flux of the exploited TX coil in COMSOL AC/DC module is also shown in the other Y-axis of Fig. 6 confirms the cubical reduction of the power transfer efficiency. 10mA current excitation at 2.57 GHz frequency is applied to create the same conditions as the experimental set up (7 dBm power with 50 ohms termination).

The comparison of the fabricated ME antenna energy harvesting performance with other state of the arts micro-coils is presented in Table. 1. To have a better understanding of which is system is more efficient, the following figure of merit (FoM) is used [22]:

$$\mathrm{FOM} = \frac{\eta(\%)\times d^3}{A^{1.5}} \qquad (1)$$

where η is the PTE, d is the distance of receiver and transmitter coil, and A is the receiver area in mm^2.

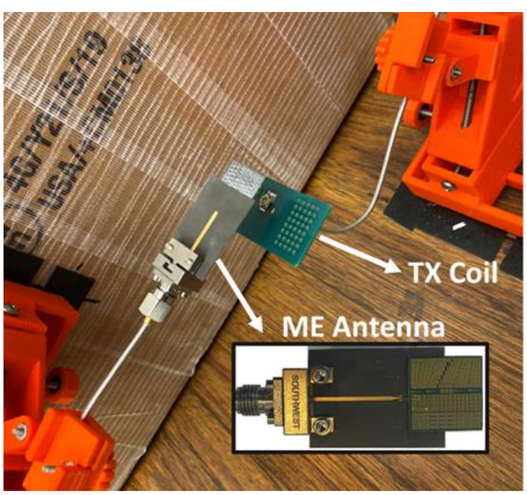


Fig. 5. Power transfer efficiency measurement setup

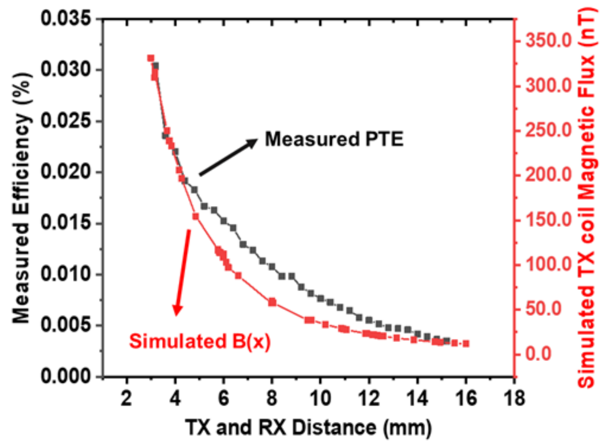


Fig. 6. Measured PTE and the TX coil simulated magnetic flux

IV. CONCLUSION

An extremely compact antenna working based on the acoustic resonance suitable for biomedical applications is presented in this paper. The proposed ME antenna with a size of 100×200 μm^2 has an acoustic resonance frequency of 2.57 GHz, which is used for wireless biomedical RF energy harvesting applications. The proposed ME antenna achieves a power transfer efficiency better than previously reported micro coils. The measured PTE shows the capability of powering energy harvesting ICs deep into the brain while meeting the FCC limits.

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