Integration of Magnetoelectric Antennas and Synthetic Biology for Advanced In-Body Sensing and Wireless Communication

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***Abstract*—This paper introduces an innovative bio-hybrid implant that merges advancements in synthetic biology for sensing and actuation with novel magnetoelectric (ME) antennas, enabling in-depth, zero-power wireless data transfer within the human body. The system utilizes synthetic biology mechanisms for molecular-level sensing, integrated with a MEMS switch to modify the impedance properties of the ME antenna. This antenna, resonating in length mode within the 60 MHz range, capitalizes on its high Q-factor to produce a significant output voltage in reception mode and signal reflection in response to the MEMS switch, controlled by muscle cell contractions. The external reader operates on an induction modulation mechanism, with a magnetic field that facilitates deep tissue penetration and minimizes biological loss. Integration of the MEMS switch, modulated by the synthetic biology sensing mechanism, allows for altering the ME antenna's impedance, which can be detected by the reader to convey binary information of the sensed molecules externally, thus obviating the need for implant batteries or electronics. This paper demonstrates the concept's viability through comprehensive COMSOL Multiphysics simulations and modeling, presenting a novel approach in the realm of in-vivo chemical monitoring and data transmission.**

***Index Terms*—Magnetoelectric (ME) Antennas, Synthetic Biology-Controlled MEMS, Inductive Modulation Communication, Bio-Hybrid Implant Technology, Passive Wireless Sensor Modules**

I. Introduction

THE field of implantable antennas and communication techniques has seen remarkable advancements, particularly in the context of biological implants and in-situ communication. The challenges posed by the asymmetric and hostile human body environment on implant antenna and communication technology, emphasizing the need for innovative designs and materials [1]. The ongoing challenges and the latest applications of implantable devices, pointing towards the evolving landscape of biomedical applications are discussed in [1]-[3], where the evolving domain of implantable antennas and communication technologies sets the stage for introducing novel integrated communication systems such as the use of Magnetoelectric (ME) antennas and induction modulation to support miniaturized battery-free connectivity via wireless energy harvesting [4] . Furthermore, advancements in reconfigurable antennas, including those with RF MEMS switches highlighting their significance in implantable communication devices and the impressive switching speeds ranging from 1–200 μsec [5], [6] reduces the energy consumption of the implant electronics sustaining the data rates.

Magnetoelectric (ME) thin film antennas, utilizing micro or millimeter-sized layers of magnetostrictive and piezoelectric materials [7], [8], resonate at significantly smaller acoustic wavelengths compared to traditional electromagnetic antennas, also are particularly effective in the MHz frequency range. Their high Q resonance, combined with the capacity to generate substantial output voltages under external magnetic fields, and their independent characteristics in the biological medium, makes them ideal for micro-size induction modulation schemes [9].

By integrating synthetic biology for precise molecular sensing with a MEMS switch connected to the ME antenna, we achieve a dynamic alteration of the antenna's RCS in response to molecular interactions. This integration enables the transmission of sensed molecular data to an external reader, circumventing the need for internal power sources or complex implant electronics. This paper introduces a groundbreaking approach: combining synthetic biology-based sensor MEMS switches with ME antennas to forge a bio-hybrid implant. This implant excels in advanced molecular sensing and efficient wireless communication, functioning as a self-activated, battery-free, mm-sized device. It is remotely accessed through an induction modulation link, triggered by alterations in the ME antenna's impedance, facilitated by an on-body driver. This novel integration signals a significant leap in self-activated, battery-free sensitive biomedical applications.

II. Synthetic Biology and Mems Integration

A bio-hybrid implant composed of genetically modified skeletal muscle tissue, a switch operated by this muscle tissue, and a magneto-electric (ME) antenna which senses the switching is proposed in this work. The muscle is going to be engineered to contract upon reception of a molecule of interest. Its contraction is going to be used for switching. The switching is going to cause a change in the transmission from the ME antenna. By this chain of events, the arrival of the molecule of interest is going to be tracked by the on-body reader antenna. Note that although we are sensing a molecule which is at micron scale, we are forming the communication link with microwaves of which wavelength is at centimeter scale.

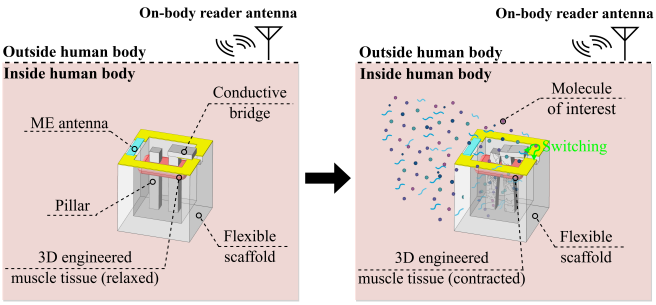

Fig. 1. The sensing system and its components.

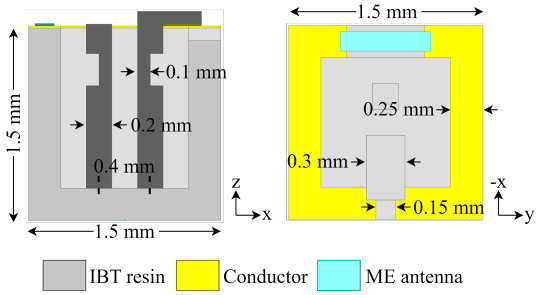

Fig. 2. The dimesions of the bio-hybrid implant. Side (left) and top (right) views.

A realization of the proposed system can be seen in Fig. 1. The principle of operation is as follows: The molecule of interest triggers the genetically modified skeletal muscle tissue. The muscle tissue is reinforced with two pillars one of which carry a conductive bridge to act as a mechanical switch. The response of the triggered muscle is contraction which toggles the state of the switch. The switching changes the response of the ME antenna which will be monitored by the wearable antenna.

To support the skeletal muscle tissue and to realize the switching mechanism, a 3D-printed flexible scaffold is proposed in this work. In the initial phases of differentiation, C2C12 myoblasts initiate the development of fiber-like structures in a two-dimensional manner. In the absence of external structural reinforcement, these tissue fibers lack the ability to orient vertically and persist in a planar configuration. To address this limitation and afford essential structural reinforcement to the two-dimensional tissue fibers, we design interfaces resembling tendons, mimicking the natural tendon and bone structures found in the musculoskeletal system. This design is embodied in our 3D-printed flexible scaffold implant. The proposed implant geometry can be seen in Fig. 2. The dimension of the implant should be as small as possible. In the literature, one of the smallest bio-robot actuated by skeletal muscle tissue has a muscle size of 700 μm $\times$ 250 μm [10]. So, the size of the well in which the skeletal muscle is placed is chosen as 1 mm $\times$ 1 mm. The total dimension of the implant is 1.5 mm $\times$ 1.5 mm $\times$ 1.5 mm as seen in Fig. 2. The upper part of pillars, which is called as handle through the rest of the paer, are designed thinner to place the 3D skeletal muscle tissue.

In order to examine the scaffold deflections against contractile forces that the skeletal muscle tissue can create, bio-hybrid

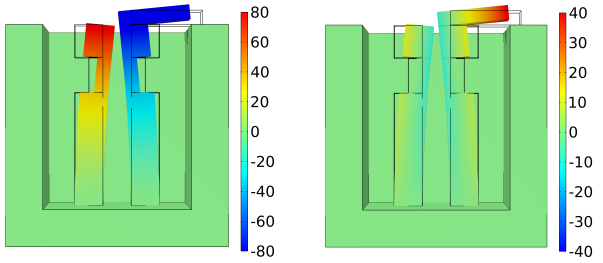

Fig. 3. The mechanical simulation results for 300 μN force. x-deflection (left) and z-deflection (right). The unit of the displacement is μm.

device design is mechanically simulated. As the material of the flexible scaffold, a biocompatible SLA-printer resin, Formlabs IBT resin, is chosen. The mechanical simulations is carried out by the physical properties of the IBT resin given in the datasheet [11]. Its Young's modulus is given as 16 MPa. In previous studies, 3D-engineered skeletal muscle tissues exhibited contraction forces ranging from 10 μN to 2.5 mN [12]. Consequently, a force of 300 μN is applied in both x and $-x$ directions to the handles. The mechanical simulation results can be seen in Fig. 3. The resulting maximum deflection of the conducting bridge is observed to be -93.2 μm and 41.2 μm in the $-x$ and z directions, respectively.

III. Molecules For Muscle Contraction

We assume that the molecules of interest diffuse freely around the bio-hybrid implant. The molecules participate together with external receptors on the gene-modified muscle cell membrane in reversible reactions to form ligand-receptor complexes. This interaction has been vastly modeled in the molecular communications community using a second-order chemical reaction mechanism [13], characterized by forward- (binding-), backward (recycling-) and internalization-chemical reaction rate constants. It is hypothesized here that C2C12 myoblasts (or any other type of muscle cell, for example, cardiac muscle cells or smooth muscle cells) are gene-modified to express receptors that may reversibly react with the molecule of interest to form ligand-receptor complexes. The known example is engineered C2C12 murine muscle myoblasts activated with confined illumination by expressing a light-sensitive protein Channelrhodopsin-2 (ChR2) [14]. All cells, muscle cells included, use diverse signaling pathways to relay the extracellular detection of the molecule of interest to the cytosol, triggering cellular responses. Here, the contractile apparatus needs to be activated to further toggle the state of the MEMS switch. The contractile apparatus in all muscle cells consists of two proteins, actin and myosin. The activation of the contraction apparatus, however, depends on an increase in cytosolic calcium concentration. In striated muscle cells, for example, C2C12 myoblasts, increased calcium levels result after neuronal stimulus (e.g. acetylcholine release) and the activation of neurotransmitter receptors on the cell membrane. This depolarizes the cell leading to an action potential that further activates L-type calcium channels, mechanically coupled to ryanodine receptors (RyRs) of the sarcoplasmic reticulum (SR) which eventually releases calcium [15]. Spatiotemporal mathematical methods and models of calcium dynamics of different complexity help to better understand and quantify

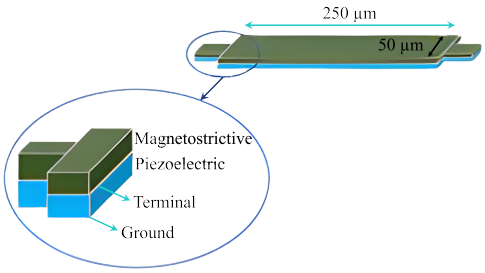

Fig. 4. ME antenna consisting of the magnetostrictive and piezoelectric. The voltage is applied to the piezoelectric terminals in transmission mode and the terminal impedance is altered in induction modulation mode.

the mechanisms involved in cellular calcium regulation [15]. Nevertheless, an integrated model of the ligand-receptor interaction, calcium dynamics, as well as the sliding filament theory and sarcomere dynamics [16] is a want to couple the molecular communication aspects of the sensed molecules with a quantitative analysis of the muscle contraction.

IV. ME Antenna And Switching With MEMS

ME antennas represent a significant innovation in the realm of antenna miniaturization [8] and specifically we intended to show its potential for inductive modulation communication systems for the implant scenario. These antennas, utilizing the magnetoelectric effect, leverage the synergistic interaction between magnetostrictive and piezoelectric materials. Their ability to operate at low frequencies and compact sizes, thanks to their acoustic resonance properties, makes ME antennas highly suitable for both wireless power transfer in the receiving mode [17], [18] and inductive modulation in communication. In inductive modulation, which is mainly defined in lower MHz range (<60 MHz), the ME antenna can efficiently absorb applied magnetic field with a coil inductor in the ME structure resonance with high Q-factor. In communication mode, the changes in the ME antenna impedance (here applied by the bio-MEMS) alters the structural mechanical resonance that consequently alter the carrier wave's characteristics for effective near-field communication. This capability to function in varying electromagnetic environments without the need for an internal power source is what sets ME antennas apart for zero-energy communication. Fig. 4 shows our thin film ME antenna design and the associated material properties are tabulated in Table I.

TABLE I
The Characteristics of the Structure

Property	**Value**
Magnetostrictive (MS) thickness	0.5 μm
Piezoelectric (PE) thickness	0.5 μm
Length of the structure (L)	250 μm
Width of the structure (W)	50 μm
Magnetic DC bias	$2-50$ mT
Mechanical damping loss η_s in the MS material	$1e-4$
Mechanical damping loss η_s in the PE material	$1e-4$
Dielectric loss $\tan\delta$ in the piezoelectric material	$1e-3$

The antenna characteristics in the biomedical environment are not affected by the biological material loading in the

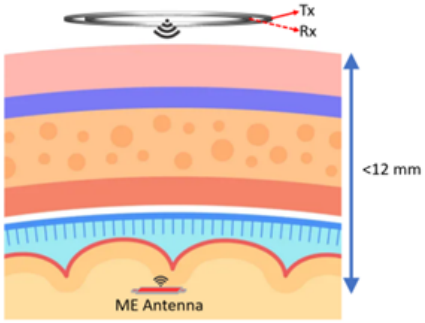

Fig. 5. The reader contains two concentric coils with an inner diameter of 9 mm and 8.5 mm with 0.25 mm thickness. The ME antenna is used as a tag and is placed in the biological medium in which the load reflection is changed by switching between open and short circuits at the piezoelectric terminals.

vicinity of the antenna because the antenna impedance is governed by the piezo layer size, which is mainly sensitive to pressure rather than the electric properties of the tissues. Additionally, the low-frequency magnetic field applied with a coil antenna primarily generates a magnetic field where the tissues, being non-magnetic materials, only slightly influence the magnetic field penetration. To demonstrate the inductive modulation using an implanted ME antenna, we have conducted COMSOL simulations. We note that the energy source for altering the antenna impedance is obtained from biological muscle tissues that are synthetically sensitive to the target molecules. Detailed design and modeling of the ME antenna in COMSOL Multiphysics finite element method (FEM) have been presented in [9], [19] while in this section we present the antenna in the induction modulation mode, in the implant scenario. The ME antenna structure is designed using thin film layers of Aluminum Nitride (AlN) and Iron-Gallium-Boron (FeGaB) heterostructures. These layers are suspended in air, with AlN functioning as the piezoelectric element and FeGaB serving as the magnetostrictive component (see Fig. 4). Later, this antenna is integrated with the sensor structure and a metal line to interconnect the antenna to the MEMS switch sensor structure. The ME antenna is reciprocal, meaning that in the transmitting mode, the voltage applied to the piezoelectric terminals generates a strain wave in the AlN layer. This strain wave is then transferred to the FeGaB layer, causing a dynamic change in its magnetization and consequently producing an electromagnetic field. Conversely, in the receiving mode, a time-varying magnetic field induces a strain wave in the FeGaB layer, which is then transferred back to the AlN layer, generating a voltage at the piezoelectric terminals. This bi-directional functionality allows the ME antenna to effectively operate as a tag in modulation schemes, interacting with magnetic fields produced by external reader coils. Fig. 5 shows the antenna system model in COMSOL, where the ME antenna is at a distance of d from two co-centered loop antennas used as the exciter and receiver inductor coils in the induction modulation mode.

The ME antenna exhibits resonance at 62.45 MHz, where the width resonance mode of its planar thin-film structure becomes operational. The impedance of the ME antenna at this resonance is $31.33 + j36.75$. Altering the port impedance of the ME antenna allows the absorbed magnetic energy to

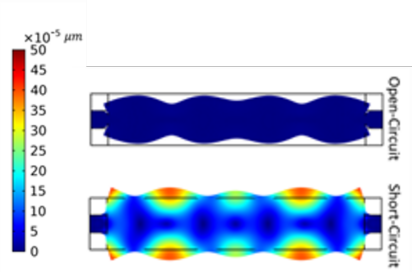

Fig. 6. The displacement of the magnetostrictive material open circuit and short circuit. The different strain between the open circuit and short circuit cases creates different magnetic intensities for inductive modulation.

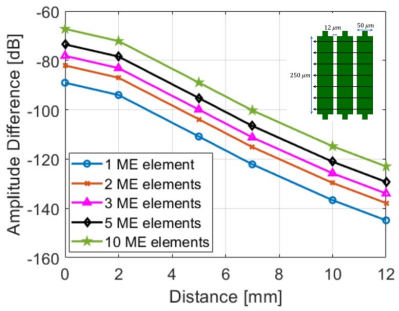

Fig. 7. Z_{12} amplitude difference versus distance between RX and TX coils, where ME is short and open circuit.

be either reflected back to the structure in short-circuit mode or dissipated within the structure in open-circuit condition. Fig. 6 illustrates the mechanical displacement of the antenna structure in both modes. Utilizing an array of ME elements can create a larger differential RCS in induction modulation. This scenario has been simulated for various numbers of elements and distances from the reader antenna within a biological medium. Fig. 7 presents the computed mutual impedance difference between the reader coils versus antenna depth in biological tissues and for N-parallel ME elements. This indicates that the data transfer can be further secured by increasing the number of elements.

V. Conclusion

The integration of the magnetoelectric (ME) antenna with MEMS switch technology, controlled by genetically modified muscle tissue, marks a significant advancement in the field implantable zero-power and electronics free sensor-communication module. The use of inductive modulation eliminates the circuits for energy harvesting and the application of muscle contraction removes the needs for controlling the MEMS switch control circuits. Genetic modification of the muscle pushes the signal processing for sensing towards the living tissue. This novel approach enables the realization of a fully passive, reconfigurable, miniaturized Bio-MEMS-ME sensor communication module. Here the switching action with the engineered muscle tissue is demonstrated through COMSOL Multiphysics simulations as well as the effect of switching on the ME antenna and how the data is going to be wirelessly linked to the off-body station. This work paves the way for innovative, efficient, and highly effective communication modules, particularly suited for passive, miniaturized biomedical devices.

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