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A NOVEL ELECTROMECHANICAL INTERROGATION SCHEME FOR IMPLANTABLE PASSIVE TRANSPONDERS
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ABSTRACT
This paper presents design, fabrication, and implementation of a novel electromechanical energy scavenging and wireless interrogation scheme using low frequency components of mechanical vibrations to overcome challenges associated with previously reported passive transponders such as: short transmission range, misalignment sensitivity, and complicated receiver circuitry. The transponder has two phases of operation: 1) mechanical vibration phase, in which an acoustic receiver (a piezoelectric cantilever) converts the sound vibration into electrical power and charges a capacitor; and 2) electrical radiation phase, in which the stored charge is dumped into an LC tank, forcing it to oscillate at its natural resonance frequency and emitting the energy to an outside receiver. In a pressure sensing configuration, the distance between a planar coil and a ferrite core is modulated by the pressure, thus changing the inductance and in turn inducing a change in the frequency of the emitted signal. A prototype transponder was built and tested using a PZT cantilever with a mechanical resonant frequency of 435 Hz encapsulated in a glass capsule (length=40 mm, diameter=8 mm) along with a rectifier circuitry and a storage capacitor. The inductive pressure sensor located outside the capsule had a sensitivity of 2.5k Hz/kPa. We were able to easily pick up the transmitted RF pulses at distances of up to 7 cm without the tight requirement on alignment between the receiver and the transponder coils.

INTRODUCTION
Implantable wireless devices for measurement of physiological parameters have a long and celebrated history [1]. Recently, advances in low-power interface and RF electronics, micromachined transducers, and miniature power sources have provided unique opportunities for design and development of much more sophisticated systems [2]. A good example of such systems is the Pill-Cam, which is a high-tech version of earlier single transistor radio-pills that includes advanced imaging system (white LED, micro-lens, CCD camera) and state of the art interface and wireless electronics [3].

An elegant and simple method to measure pressure and other physical parameters (and even chemical ones if they can be converted to a pressure signal) is resonant passive transponders [1, 4]. In these devices, the pressure change is coupled to the movable plate of a capacitive sensor (or an inductive one in which a ferrite core moves in and out of a coil’s flux field) which is connected to an inductor forming a passive LC resonant circuit. Although, from a manufacturing point of view, passive transponders are easy to fabricate, their interrogation at a distance poses severe challenges. This has been one of the main reasons that so far very few of such systems have been commercialized (an exception being CardioMEMS pulmonary and aortic aneurysm transponders [5]). The standard readout scheme uses an interrogating coil brought in close proximity of the implanted transponder. Once within a few cm (depending on the diameter of the inductor in the LC tank), the input impedance of the interrogating coil is measured at different frequencies. At the resonant frequency of the implanted sensor, the phase of the impedance exhibits a dip, offering a remote measurement technique to interrogate the transponder. The difficulty with such systems is the cost and complicated instrumentation required to scan the frequency, identify the dip, and make an accurate measurement. In this paper, we report on a novel electromechanical interrogation scheme for implantable passive transponders that overcome many of the aforementioned shortcomings, i.e., short interrogation range, misalignment sensitivity, and complicated readout circuitry.

DESIGN
Figure 1-a shows a schematic of the transponder (in this case an inductive pressure sensor) implanted in human body.

Figure 1: (a) Implanted transponder scavenging musical sound and radiating an RF pulse at passive sensor resonant frequency; (b) detailed schematic of the inductive pressure sensor with acoustic scavenging.
Detailed structure of the microdevice is illustrated in Figure 1-b. As depicted, it incorporates a piezoelectric cantilever beam that converts the acoustic vibrations into electric power; rectifying circuitry; a storage capacitor; a single turn loop of wire that acts both as the coil of the inductive sensor and the transmitter antenna; and a ferrite core. The ferrite core is attached to a PDMS membrane separated from the coil by a PDMS ring thus modulating the resonant frequency of the LC tank upon applying the pressure.

Figure 2-a shows a block diagram illustrating the operation principle of the wireless transponder. Musical sound from a loudspeaker induces vibrations in the piezoelectric cantilever at harmonics, which match its mechanical resonant frequency. This, in turn generates a voltage that is rectified and stored in the capacitor. At non-resonant harmonics, the supply is interrupted, causing the stored charge to be dumped into the sensing LC tank. This makes the tank oscillates at its resonant frequency and radiate an RF pulse which is picked up externally with a receiver coil. Applying pressure reduces the distance between the ferrite core and the coil, changing the inductance and hence modulating the resonance frequency of the radiated signal.

When the acoustic power is below this threshold, cantilever stops resonating, hence powering is interrupted and LC tank radiates the stored energy at natural electrical resonance frequency (radiation mode).

Dimensions of the piezoelectric cantilever were chosen to impart a natural mechanical resonance frequency of 435 Hz. This was the result of a compromise between the size of the implant and received acoustic power. At this resonant frequency rap music will provide the best results since it has more vibration components close to the natural mechanical resonance frequency of the cantilever. The frequency spectrums of different music are shown in Figure 3.

FABRICATION

Figure 4 shows the fabrication process for a prototype inductive pressure transponder. It starts with a 300 μm thick glass substrate. Discrete parts including: a cantilever made of PZT (20×2×0.38 mm³), Schottky barrier diodes, and 0.1 µF multilayer ceramic chip capacitor were assembled on the glass substrate using silver conductive epoxy, Figure 4-a. Next, a single circular loop transmitter/sensor coil (22AWG) was wrapped around a laser micromachined acrylic ring. Assembled discrete electronic parts and the transmitter/sensor coil connections were then coated with a droplet of PDMS to be held in place securely during packaging and operation. The PZT cantilever was inserted inside a laser micromachined acrylic mounting ring in order to clamp its base. After adding a droplet of solder on the tip of the cantilever to act as the proof mass, transponder is ready for packaging. Figure 4-b. Next, assembled structures were encapsulated in a glass tube (length = 40mm, diameter = 8mm). The acrylic ring holding the transmitter/sensor antenna resides on the outer surface of the glass capsule at one end while the other end of the capsule was enclosed by an acrylic lid, Figure 4-c. Finally, pressure sensor was formed by attaching a ferrite core on a PDMS membrane and bonding the membrane on top of the transmitter/sensing antenna through a PDMS ring, Figure 4-d. For biocompatibility assurance and protection, the whole system was coated with 10 μm thick parylene-C.
An optical image of the transponder is shown in Figures 5. The transponder dimensions and form factor allows it implantation in hollow organs such as bladder, major blood vessels, and abdominal cavity (smaller systems for tighter anatomical locations are possible through design modifications).

**EXPERIMENTAL RESULTS**

For characterization, the transponder was submerged in a water balloon to mimic the soft tissue. The acoustic excitation was provided by a 12-inch speaker connected to a power amplifier, Figure 6-a. In order to provide a uniform acoustic wave transfer to the water balloon, a thin metal sheet was attached to speaker and water balloon was pushed against the sheet. A single turn receiving coil for RF re-radiation pick-up was placed at the surface of the balloon and its output was monitored with an oscilloscope. Lower inset in Figure 6-b shows the receiver coil’s output signal re-radiated from the LC tank. The received signal shows an expected under-damped behavior with quality factor $Q \approx 15$.

Figure 7 shows the receiver output peak voltage as a function of distance between the transponder and the pickup coil while speaker to the transponder distance was kept at 1 cm. As can be seen, RF re-radiation could be picked up to 7 cm away from the transponder with a simple coil.

Figure 7: Received re-radiated RF signal vs. distance between the transponder and pickup coil for three different devices.
Sensitivity to angular misalignment between the transponder and pickup coils is depicted in Figure 8. We were able to pick up the RF signal even at 90 degree misalignment. Low sensitivity to the angular misalignment is extremely advantageous in implantable microdevices, since in many cases, after implantation the transponder coil direction cannot be ascertained.

Presented interrogating mechanism can be used with several implantable microdevices such as capacitive and inductive pressure sensors. As mentioned before, we incorporated an inductive pressure sensor into the transponder. Detected resonance frequency versus applied pressure is plotted in Figure 9. In this experiment, two different transponders with different initial inductances (519 nH and 499 nH) were implemented by changing the size of the circular loop of wire. Both sensors showed similar sensitivities of ~2.5 kHz/kPa.

CONCLUSIONS

A novel electromechanical interrogation scheme for implantable passive transponders was presented. The transponder used musical sound wave as its power source. Low frequency components of musical sound were used to excite an acoustically tuned receiver (PZT cantilever, 435Hz). The system contained a simple circuitry (full-wave bridge rectifier and inductor) to re-radiate an RF signal. Smoothing capacitor in a rectifier and integrated inductor together compose the LC tank. The electrical power converted from musical sound wave transferred to this LC tank. A simple inductive pressure sensor was constructed which was composed of a thin PDMS membrane, the coil of the LC tank, and a ferrite core. Upon pressure change, the frequency of the RF re-radiation signal was changed. This simple structure yielded a pressure sensitivity of 2.5 kHz/kPa. The overall dimension of the transponder was 40mm long, 5mm diameter (8mm diameter for PDMS membrane). We were able to track the RF signal up to 7 cm away from the transponder. Low sensitivity to angular misalignment between the transponder and the receiver coils was another advantageous of the developed transponder technology.

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REFERENCES


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