



RF Telemetry System for an Implantable Bio-MEMS Sensor

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Abstract — In this paper, a novel miniature inductor and a pick-up antenna for contact less powering and RF telemetry from implantable bio-MEMS sensors are presented. The design of the inductor and the pick-up antenna are discussed. In addition, the measured characteristics at the design frequency of 330 MHz have been shown.

I. INTRODUCTION

The biological and physical sciences program at the National Aeronautics and Space Administration (NASA) seeks to develop telemetry based implantable sensing systems to monitor the physiological parameters of humans during space flights [1]. This focus is rather unique when compared to efforts by other investigators, which have been mainly in the area of RF/microwave applications in medicine and biological effects [2]. Conventional sensors that are used in biomedical implants require powering through batteries and lead wires. The disadvantage of this approach is that it restricts mobility, requires shielding from moisture, potential for malfunctioning and may also cause infection. This also limits the life span of the sensor.

In this paper, we present the development of micro inductor/antennas for contact less powering and RF telemetry to acquire data from implantable bio-microelectromechanical systems (bio-MEMS) based capacitive pressure sensors. Our approach relies on active inductive coupling between the implanted sensor and the printed antenna in the interrogating/receiving hand-held unit. RF telemetry reception from implanted sensors has been demonstrated by several researchers in the past [3–6], and Table I summarizes the dimensions of the implanted inductor as well as the distance over which they communicated. However, our approach has the following unique features: first, the size of our inductor/antenna is significantly smaller (1×1 mm) resulting in smaller implant size. Second, an MMIC amplifier has been integrated with the pick-up antenna in the hand held unit to enable communications across larger implant depths. When compared with conventional sensors, the sensors with telemetry have the following advantages: first, the size of the inductor/antenna is very small which allows the device to be integrated into miniature MEMS pressure sensors in bio-implants. Second, eliminates the need to implant

batteries and thus reduces the possibility of infection. Third, the circuit operates only when interrogated by an external hand held unit and hence minimizes power dissipation in the biological tissue, which avoids local heating and extends the life span of the sensor. Fourth, eliminates feed-through wires for powering and telemetry thus greatly enhancing mobility and reducing the risk of infection.

TABLE I
SUMMARY OF IMPLANTABLE INDUCTOR DIMENSIONS AND
DISTANCE OVER WHICH TELEMETRY SIGNALS ARE
TRANSMITTED

On-Chip Inductor Dimensions (mm)	Wireless Link Distance (mm)	Reference
2×10	30	Von Arx and Najafi [3]
5×5	5	Eggers et al. [4]
10.3 diameter	30	Ullerich et al. [5] Mokwa and Schnakenberg [6]
1×1	100	This paper

II. OPERATING PRINCIPLE

The contact-less powering and telemetry concept, including the miniature square spiral inductor/antenna circuit intended for integration with a MEMS pressure sensor, is illustrated in Fig. 1(a). The pressure sensor is of the capacitive type and is located in the annular region of the inductor. The inductor behaves both as an inductance as well as an antenna thereby allowing the sensor to receive as well as radiate out energy. In the receive mode, the inductance picks up energy and charges the MEMS pressure sensor diaphragm capacitance. In the transmit mode, the above inductance and capacitance form a parallel resonant circuit and radiate energy through the inductor which now behaves as a planar spiral antenna. To obtain a pressure reading, a pulse emitted by the hand held unit initially interrogates the sensor. At the rising and the falling edges of this pulse a voltage is induced in the spiral inductor thus implementing contact less powering. The waveform of this induced voltage is a decaying sine wave. These oscillations also cause the inductor to radiate energy that is picked up as a telemetry signal by the receiving antenna in the hand held unit. Since the inductance of the implanted sensor circuit is fixed, the frequency of the decaying sine wave is mainly determined by the capacitance introduced by the pressure

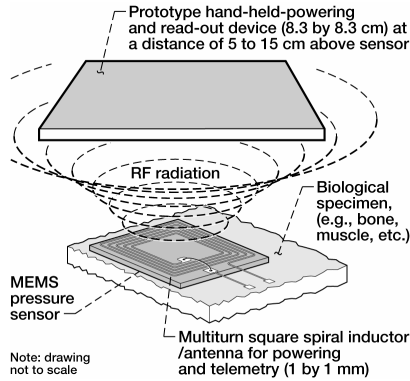


Fig. 1(a) Contact-less powering and telemetry concept.

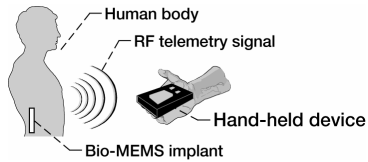


Fig. 1(b) Contact-less powering and telemetry application in biosensors.

sensor. Thus, the larger the pressure difference, the larger the frequency offset between the received telemetry in the two pressure states. The implanted bio-MEMS sensor and the hand held unit together form the wireless RF telemetry system [7] as illustrated in Fig. 1(b).

III. PRESSURE SENSOR

The pressure sensor consists of a diaphragm suspended over a cavity micromachined from a silicon wafer and is of the capacitive type. A tri-layer of silicon dioxide and silicon nitride is used to realize the diaphragm. The diaphragm moves up and down in response to mechanical pressure. Thin gold films on the diaphragm and on the lower surface of the cavity together form a parallel plate capacitor whose capacitance changes with pressure. For our application, we need a sensor with capacitance change in the range of 0.3 to 4 pF. A schematic rendition of this pressure sensor is shown in Fig. 2(a).

IV. SQUARE SPIRAL INDUCTOR/ANTENNA

Figure 2(b) shows a schematic of the miniature square spiral inductor/antenna. The strip and separation or gap widths are indicated as W and G , respectively. The outer dimensions of the inductor are about 1×1 mm, and the inductor is fabricated on a high resistivity silicon (HR-Si) wafer to reduce the attenuation of the signals. The above dimensions and substrate material are typical for an implantable sensor. An initial estimate based on the capacitance values of the pressure sensor show that an inductance (L) with a quality

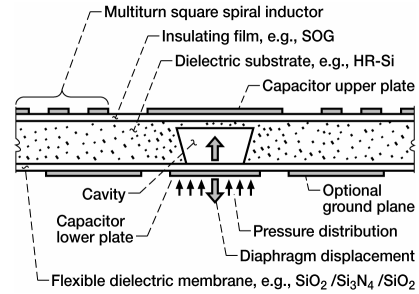


Fig. 2(a) Schematic of a capacitive pressure sensor.

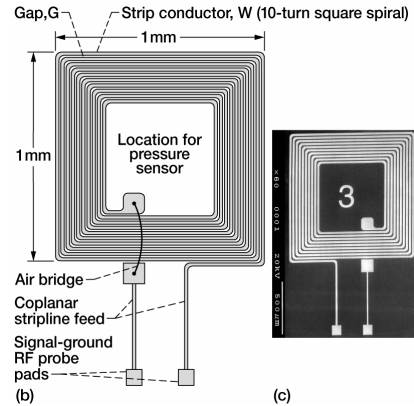


Fig. 2(b) Schematic of miniature spiral inductor on SOG/HR-Si wafer. (c) Photomicrograph of inductor/antenna.

factor (Q) of about 150 nH and 10 respectively, are adequate for the application described above. The frequency range over which this device will operate is 200 to 700 MHz. To facilitate characterization using signal-ground RF probe, the inductors are excited by a short length of coplanar stripline (CPS). Figure 2(c) shows a SEM picture of a typical inductor/antenna circuit. It is well known that the inductance and quality factor are dependent on the strip and separation or gap dimensions. In addition, elevating the inductor by introducing an insulating layer such as spin-on-glass (SOG) also improves performance. Hence to carryout a parametric study several inductors with strip and gap dimensions in the range of 10 to 15 μ m were fabricated on HR-Si wafers with a SOG layer.

V. PICK-UP ANTENNA

The pick-up antenna in the hand held device is a printed multi-turn loop antenna [8], which is also excited by a CPS. For high sensitivity, the input impedance of the loop antenna at about 330 MHz is matched to the 50 Ω input impedance of the MMIC low noise amplifier (LNA) chip in the receiver. The impedance matching is accomplished by a lumped element PI-network. The antenna as well as the conductor traces for surface mounting of the matching

network components and the LNA chip are printed on a dielectric substrate. The complete pick-up antenna assembly is schematically illustrated in Fig. 3. The circuit diagram of the assembly including the loop antenna, matching network, MMIC amplifier, and bias supply is shown in Fig. 4.

VI. FABRICATION

The fabrication process for the square spiral inductor/antenna commences by coating a 7.62 cm diameter HR-Si wafer ($\rho \geq 2500 \Omega\text{-cm}$, $\epsilon_{r1} = 11.7$) with a thin insulating layer such as, SOG ($\epsilon_{r2} = 3.1$). The insulating layer isolates the circuit from the substrate losses ($\tan \delta \approx 0.001$). Typically, the thickness of the insulating layer is about 1 to 2 μm . The next step is to pattern the wafer using photoresist and deposit the conductors using standard lift-off technique. The thickness of the chrome/gold metallization is chosen so as to minimize the resistive losses in the circuit and is about 20 nm and 1.5 to 2.25 μm , respectively. The multi-turn loop antenna in the hand held unit is fabricated on a 0.79 mm thick RT5880 Duroid substrate ($\epsilon_{r3} = 2.22$) using standard printed circuit fabrication techniques. The passive surface mount components forming the matching network and the MMIC amplifier chip are integrated with the loop antenna in a hybrid fashion.

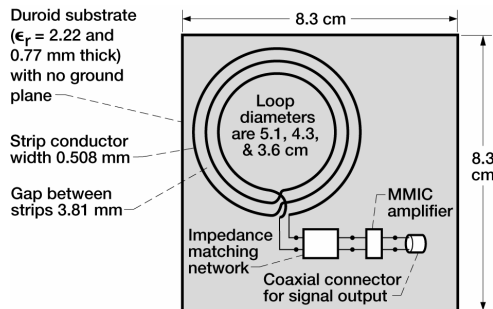


Fig. 3 Schematic of pick-up multi-turn loop active antenna for hand held unit.

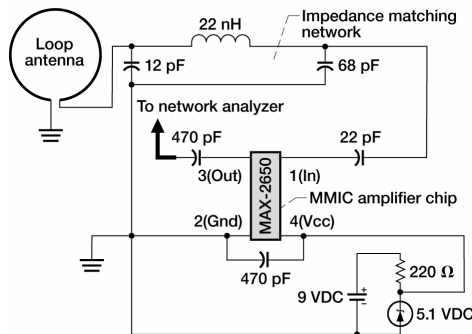


Fig. 4 Circuit diagram showing interconnection of antenna, impedance matching circuit, MMIC amplifier, and power supply in the hand held unit.

VII. EXPERIMENTAL RESULTS

A. Square Spiral Inductor

The circuits are experimentally characterized by measuring the return loss S_{11} using on-wafer RF probing techniques. From the measured S_{11} , the inductance L and the quality factor Q are analytically determined. The L , peak Q , and the frequency corresponding to the peak Q for several inductors are summarized in Table II. The results show that the highest Q value is about 10.5 and the corresponding inductance L is about 153 nH. Figure 5 shows the L and Q for this inductor as a function of the frequency. It is observed that the Q peaks at about 330 MHz. Based on the geometry of this inductor and assuming the bulk resistivity of gold as $2.2 \times 10^{-8} \Omega\text{ m}$, the calculated value for the peak Q at 330 MHz is about 11.0 using equations in [9]. The above Q and L values are adequate to perform in-vivo measurement of pressure using MEMS based sensors.

B. Pressure Sensor and Parallel Resonant Circuit

In our initial demonstration, we emulated the capacitance range of the pressure sensor by equivalent chip capacitors. In Fig. 6, the measured resonance frequency, when chip capacitors of different values are wire bonded across the inductor, is presented. The results show that for a fixed $L = 153 \text{ nH}$ and capacitance in the range of 0.3 to 4.0 pF,

TABLE II
MEASURED RF CHARACTERISTICS OF THREE SQUARE SPIRAL INDUCTOR
ON SOG COATED HR-SI WAFER WITH NO GROUND PLANE
Wafer Thickness: $\approx 325 \mu\text{m}$, Wafer Resistivity: $>2500 \Omega\text{ cm}$
SOG Thickness: $\approx 1.5 \mu\text{m}$, Metallization: Gold, Gold Thickness: $2.25 \mu\text{m}$

	Inductor Dimensions (μm)		
	15 (10)	15 (10)	12 (10)
Inner Strip (Gap) Width	15 (15)	15 (10)	13 (15)
Outer Strip (Gap) Width	5 (5)	5 (5)	6 (5)
Number of Inner (Outer) Turns	Measured Characteristics		
Peak Quality Factor (Q)	10.5	9.9	8.3
Corresponding Freq. (MHz)	330	330	330
Inductance at Peak Q (nH)	153	175	205
Calculated Values			
Quality Factor at 330 MHz	11.0	11.8	10.0

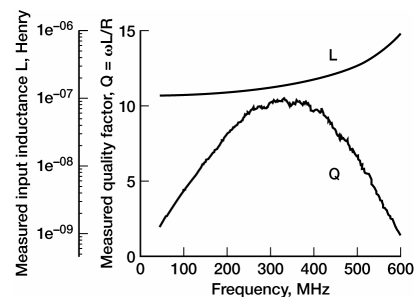


Fig. 5 Measured inductance and quality factor for inductor on SOG/HR-Si wafer.

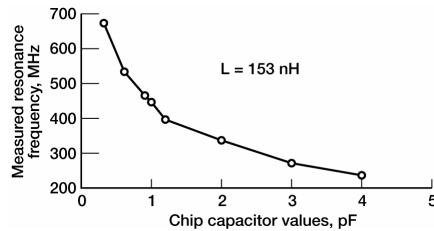


Fig. 6 Measured resonance frequency versus chip capacitor capacitance.

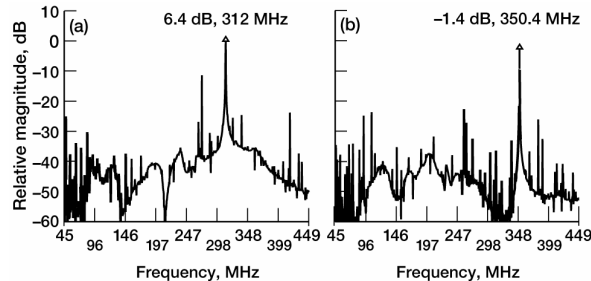


Fig. 7 Measured received relative signal strength as a function of frequency. (a) Pick-up antenna at a height of 5 cm. (b) Pick-up antenna at a height of 10 cm.

the resonance frequency falls within 670 to 230 MHz which spans the frequency range established by the Federal Communications Commission (FCC) for medical telemetry services [10].

C. Pick-up Antenna

To simulate a typical operating condition in a medical diagnostic application, the pick-up antenna assembly is held at a fixed height and coaxial with the inductor. The inductor with its parallel chip capacitor is configured to resonate at about 330 MHz. When coupled to a signal source and the frequency is swept, the inductor radiates energy. The received power as measured at the coaxial connector port of the pick-up antenna for heights of 5 and 10 cm is shown in Figs. 7(a) and 7(b), respectively. These figures indicate that maximum coupling occurs at the desired frequency of about 330 MHz and that the received intensity drops as the separation is increased. The extraneous lines at other frequencies are attributed to the vibration of the probe station and stray RF signals in the laboratory. It is important to note that this demonstration was performed without the need for laboratory animals with implanted sensors, thereby resulting in significant cost savings. A more detailed study demonstrating coupling between the inductor and pick-up antenna through stratified media (i.e., biological phantoms) will be subject matter of a follow-up paper.

VIII. CONCLUSIONS AND DISCUSSIONS

The development of a miniature square spiral inductor/antenna, which operates in tandem with a capacitive pressure sensor and a multi-turn loop pick-up antenna are presented. Measurements show that the highest quality factor Q and inductance L of the inductor are about 10.5 and 153 nH, respectively. In addition, when this inductor resonates with the capacitance of the pressure sensor, which is in the range of about 0.3 to 4 pF, it generates a telemetry signal in the range of 230 to 670 MHz. The multi-turn loop pick-up antenna with impedance matching network and a MMIC amplifier, when held at a distance of about 10 cm from the inductor, picks up the RF telemetry with better than 20 dB signal-to-noise ratio. Lastly, the safety factor of this scheme is excellent because of low RF power (typically few mW), which ensures minimum local tissue heating and absorption by body parts such as, eyes or brain.

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