

# Enhancing LC Sensor Telemetry via Magnetic Resonance Coupling

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**Abstract**—Inductor-capacitor (LC) passive wireless sensors have been widely used in a variety of applications, ranging from medical diagnosis to industrial and environmental monitoring. In some certain circumstance, the sensors are required to be scaled down to small dimensions, which results in the limited readout distance. Here, a resonant reader is proposed to enhance signal strength and quality factor. The resonant frequency of the reader is changed by controlling varactor. An LC humidity sensor, as an example, is detected both with and without the proposed reader. Experimental results display that the signal strength get greatly enhanced and reflection coefficient S11 is enhanced to -43dB compared with the conventional -0.33 dB, at the same detection distance 1.2cm. Our results may have an impact on wireless sensing, particularly benefiting the emerging micro-machined sensors, and so on.

**Keywords**—adaptive reader; coupled magnetic resonances; passive wireless sensor; readout enhancement

## I. INTRODUCTION

LC passive wireless sensors can obtain a continuous and real-time monitoring for the variable parameters of interest in situations where wired connection is difficult or even impossible [1], [2]. At the same time, they need no power supply and have small size and long lifetime advantages, which makes them superior in some certain circumstances such as biomedical implants, etc. Up to now, a great number of LC wireless sensors have been proposed to monitor various parameters, such as pressure, strain, temperature, humidity and PH value, etc. The change of the parameter to be measured results in the variation of the sensor capacitance, which leads to a resonance frequency shift. Conventionally, a readout coil is used to measure the sensor frequency through the inductive coupling, as shown in Fig.1a. However, the very limited readout distance is proved to be a serious problem for these conventional LC sensors when their sizes become smaller. A passive wireless adaptive repeater is proposed to enhance the readout distance of LC sensors [3]. However, it requires an additional repeater between the sensor and the reader. The concept “PT symmetry” is applied to wireless power transfer in recent years. Then a MEMS-based (intraocular pressure) IOP sensor based on PT symmetry is proposed in [4], while it needs to convert complicated active components as negative resistances.

This paper shows an adaptive reader which with adjustable resonant frequency is magnetically coupled to the passive wireless LC sensor. When the resonant frequency of the reader becomes consistent with that of the sensor, the magnetic

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resonance coupling occurs, then the signal strength is greatly increased.

## II. MAGNETIC RESONANCE COUPLED WIRELESS SENSOR SYSTEM

An equivalent circuit of the passive wireless LC sensor system with the resonant reader is shown in Fig. 1(b).  $L_s$ ,  $C_s$ ,  $R_s$ ,  $L_r$ ,  $C_r$ , represent the inductance, capacitance, and resistance of sensor(s) and reader (r), respectively.  $M$  is the mutual inductance between the readout coil and sensor,  $k = \frac{M}{\sqrt{L_r L_s}}$ . The reader and the LC sensor are not in magnetic resonance until their resonant frequencies become the same. To avoid the frequency splitting, which would cause the failure of capturing the sensor frequency precisely and the reduction of magnetic coupling, the coupling coefficient  $k$  between the reader and the sensor has to satisfy the following relations [5]:

$$k \leq k_c = \frac{1}{\sqrt{Q_s Q_r}} \quad (1)$$

Here  $k_c$  is the critical coupling coefficient, and

$$Q_s = \frac{1}{R_s} \sqrt{\frac{L_s}{C_s}} \quad (2a)$$

$$Q_r = \frac{1}{R_r} \sqrt{\frac{L_r}{C_r}} \quad (2b)$$

In the reader closed-loop analysis, the external Network Analyzer (PNA) with characteristic impedance  $Z_0 = 50\Omega$  can be attached to  $L_r$  and  $C_r$  in the form of a resistance  $Rr = Z_0$  in series with a variable frequency voltage source [6].

When  $k = k_c$ , the reader and the LC sensor are in the state of critical coupling, and the magnetic coupling and the power transmission reach the maximum. As a result, at the same detection distance, the signal strength increases comparing with the conventional reader, in other words, the readout distance would be extended. When  $k > k_c$ , the system is in strong coupling, and the coupling efficiency is reduced and the frequency splitting would happen, which make it impossible to identify the sensor frequency. When  $k < k_c$ , the coupling efficiency is also reduced. In this state, the sensor frequency can be exactly captured with the signal intensity decreased. In conclusion, only when  $k = k_c$ , the sensor frequency can be detected precisely, and the signal is strongest.

In practical applications, the coupling coefficient  $k$  is represented by the corresponding detection distance  $D$ , which is

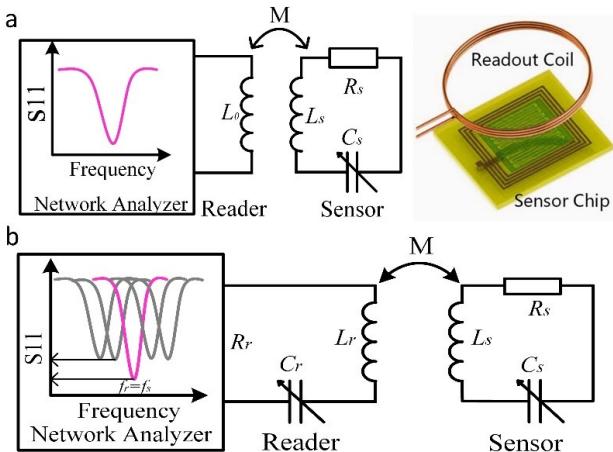


Fig. 1. Equivalent-circuit and schematic with the conventional reader (a) and with a resonant reader (b) of LC passive wireless sensing system.

more intuitive and easier to implement. The coupling coefficient  $k$  between the two inductor coils with a distance  $D$  is [7],

$$\mu = \frac{1}{\left[1 + 2^{\frac{2}{3}} \left(\frac{D}{\sqrt{r_1 r_2}}\right)^2\right]^{\frac{2}{3}}} \quad (3)$$

$r_1, r_2$  are the radius of the inductor coil. For the conventional LC interrogating system, the equivalent input impedance  $Z_{in}$  at the terminals of the readout coil is written as

$$Z_{in} = j\omega L + \frac{M^2 \omega^2}{j\omega L + \frac{1}{j\omega C} + R} \quad (4)$$

For the new system with a resonant reader as shown in Fig. 1(b), the input impedance  $Z'_{in}$  can be written as

$$Z'_{in} = j\omega L + \frac{1}{j\omega C} + \frac{M^2 \omega^2}{j\omega L + \frac{1}{j\omega C} + R} \quad (5)$$

Experimentally, for one port, the input return loss parameter S11 can be expressed as:

$$S11 = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \Big|_{Z_0=50\Omega} \quad (6)$$

The S11 has the minimum when the input impedance  $Z_{in}$  reaches its maximum due to the resonance, at the same time, the dip of the S11 parameter indicates the sensor resonant frequency  $\omega$ .

### III. CIRCUITS SIMULATIONS

Software Agilent ADS was used to conduct the simulations. The readout circuit is linked to a term with impedance normalized to  $50 \Omega$  in the schematic module. In practice, sensitive variable capacitor is connected to the sensor inductor, forming a resonant circuit. The sensitive capacitor then change the capacitance to obtain different frequency responses.

The schematic simulation of magnetic resonance coupling LC passive wireless sensor system is conducted. The readout inductor and the sensor inductor are the same  $L_s = L_r = 2.8 \mu\text{H}$ .

Here, setting sensor capacitance  $C_s = 23.5 \text{ pF}$ , the critical coupling coefficient  $k_c$  between the reader and the sensor is calculated as 0.102 by using equation (1). The resonant frequency of the reader is changed by the variable capacitor  $C_r$ . Adjusting the reader capacitance  $C_r$  from  $19.5 \text{ pF}$  to  $27.5 \text{ pF}$ , when  $C_r = 23.5 \text{ pF}$  and  $f_r = f_s$ , the system is in magnetic resonance and the  $S11 = -47.69 \text{ dB}$  is significantly enhanced at resonant frequency  $f = 19.63 \text{ MHz}$ , as the magenta line shown in Fig.2. For the very small coupling coefficient  $k = 0.102$  between the sensor and the readout coil, the signals are very weak by using conventional detection method, with  $S11 = -0.35 \text{ dB}$ , as shown in the inset of Fig. 2. This small coupling coefficient corresponds to a long readout distance in practical applications.

### IV. EXPERIMENTS AND RESULTS

An LC humidity sensor is detected with and without a passive wireless resonant reader respectively to verify the proposed scheme. The sensor is composed of a capacitive chip and an inductor. The humidity sensing material of the capacitive humidity sensor is the graphene oxide. A planar spiral wound inductance coil is used as the sensor inductor. The frequency response of the LC tank is detected by Agilent N5224A PNA Network Analyzer. The LC type sensor and the readout coil are attached to two moveable holders, respectively.

To clearly define the enhancement effect of magnetic resonance coupling reader compared with a conventional reader, with the same readout distance between the two inductor coils, the signal intensity can be taken as the criterion of the enhancing performance. The amplitude-frequency response curves of S11 with varying distance are obtained by two methods at room temperature  $12.7^\circ\text{C}$  and humidity  $18.8\% \text{ RH}$ . Then we find the signals strength are  $-0.33 \text{ dB}$  and  $-43 \text{ dB}$  at  $f = 19.630 \text{ MHz}$  respectively as the blue lines shown in Fig.3a,b, with the same detection distances  $D = 1.2 \text{ cm}$  which is the critical coupling distance. The experiment results display that the signal intensity of magnetic resonance coupling circuit can be 130 times as strong as conventional one, which agree well with the simulation results in Fig.2.

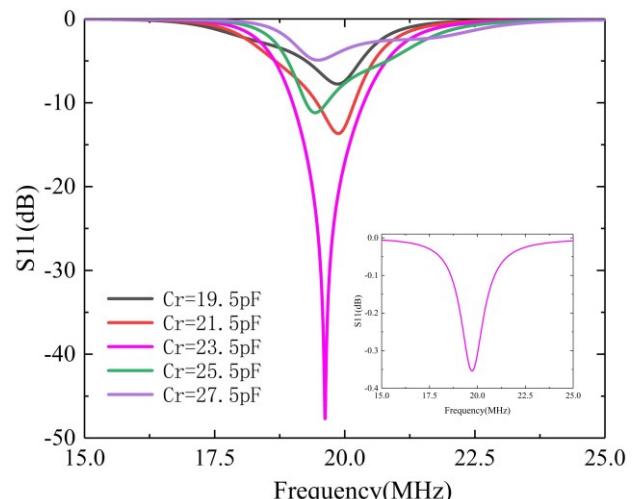


Fig. 2. Simulation results of an LC passive wireless sensing system with a resonant reader and conventional reader (inset),  $k = 0.102$ .

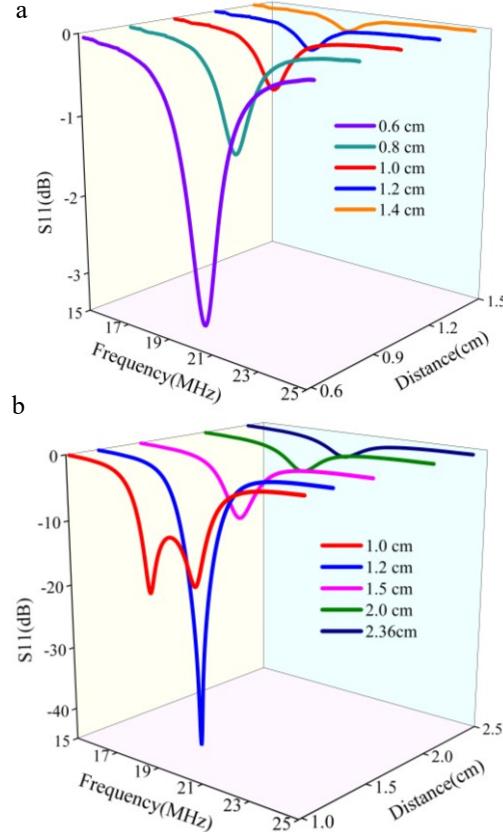


Fig. 3. Experimental results of an LC passive wireless sensing system with a conventional reader (a) and a resonant reader (b), at the relative humidity 18.8%.

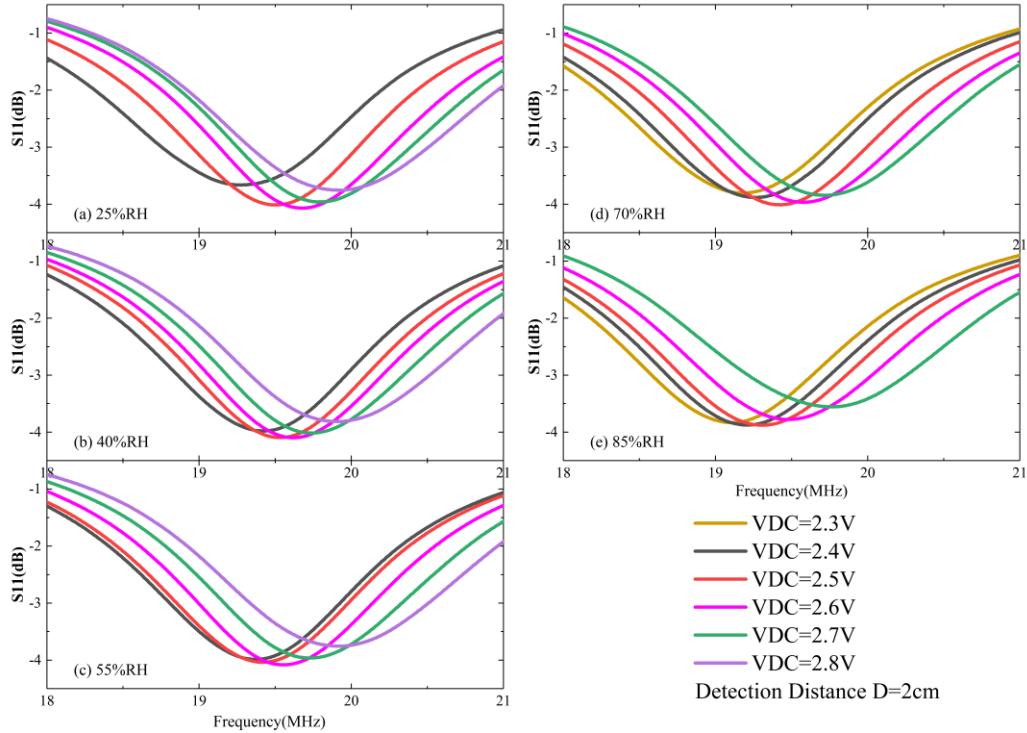


Fig. 4. Experimental results of an LC passive wireless sensing system with a resonant reader, showing a regulating process at every humidity point at Distance D=2cm.

The distance increases to 2cm, conventional reader hardly obtains the sensor signal. Then we test the sensor under different humidity levels and get S11 parameters with the proposed resonant reader, as shown in Fig.4. The PNA is connected with a  $2.8\mu\text{H}$  inductor coil and a varactor diode controlled by a DC source VDC. The voltage VDC across the varactor diode is cyclic-changing from 2.3V to 2.8V, and five curves are scanned. When  $f_r$  is coincident with  $f_s$ , in other word, the system is in magnetic resonance coupling, the signal strength increases and reaches the maximum as the middle line in each diagram. So the frequency corresponding to the strongest signal is what we want. The larger the frequency difference between  $f_r$  and  $f_s$ , the weaker the enhancement effect as the yellow and purple lines shown. In addition, the  $Q$  factor of the sensor has an obvious effect on the enhancing performance when comparing the S11 parameter from 85%RH to 25%RH. The larger  $Q$  the value, the better the enhancement effect.

## V. CONCLUSIONS

We propose a new reader with adjustable resonant frequency which is magnetic resonance coupled to the passive wireless LC sensor. We demonstrated the whole telemetry system by using simulation and experiment. Experimental results display that the signal strength S11 get greatly enhanced to -43dB comparing with the conventional -0.33 dB, at the same detection distance 1.2cm, which agree well with the simulation result. Also, there is still a signal at  $D = 2\text{cm}$  with the resonant reader. In a word, the signal strength or detection distance and quality factor are greatly enhanced. This method is the most convenient for enhancing signal strength at the moment. The only difficulty is adjusting the resonance process.

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