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Abstract

This paper reports a metamaterial inspired combined inductive-capacitive sensing method for detecting and distinguishing metallic and non-metallic objects. Metallic and non-metallic objects can be distinguished by measuring both of their inductive and capacitive responses based on the fact that they respond differently to inductive and capacitive sensing. The proposed method is inspired by metamaterial structures. Both inductive and capacitive sensing are simultaneously realized when the sensor is operating at off-resonant frequencies. The proposed method is demonstrated with typical printed circuit board (PCB) technology. The designed sensor can distinguish the metallic and dielectric objects with a sensing range about 10 mm, showing a competitive performance compared with commercially available proximity sensors.

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A Metamaterial-Inspired Combined Inductive-Capacitive Sensor

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ABSTRACT

This paper reports a metamaterial inspired combined inductive-capacitive sensing method for detecting and distinguishing metallic and non-metallic objects. Metallic and non-metallic objects can be distinguished by measuring both of their inductive and capacitive responses based on the fact that they respond differently to inductive and capacitive sensing. The proposed method is inspired by metamaterial structures. Both inductive and capacitive sensing are simultaneously realized when the sensor is operating at off-resonant frequencies. The proposed method is demonstrated with typical printed circuit board (PCB) technology. The designed sensor can distinguish the metallic and dielectric objects with a sensing range about 10 mm, showing a competitive performance compared with commercially available proximity sensors.

Keywords: proximity sensor, metamaterials, combined sensing.

1. INTRODUCTION

Proximity sensing is important in many industrial applications. Various types of proximity sensors have been developed including inductive, capacitive, optical, ultrasonic. Key criteria of a sensor include the sensitivity, sensing range, and functionality. Researches have been done on improving the sensitivity and sensing range, by improving the sensor structure or the detecting methods ,[1–4] and on developing novel sensors with special functionalities .[5–9]

In this paper, we focus on the design of an electromagnetic (EM) proximity sensor with special functionality of detecting and distinguishing metallic or non-metallic objects. Such functionality can be useful in numerous applications. Automatic drilling machine uses proximity sensor to detect if a target is approaching it. It is desirable to know whether the object uder the drilling bit is metal or not, so that the system can do better to protect unexpected damage. Such sensors can be installed in car seats[6,7,10,11] so that the car can determine if there is anything on the seat, and distinguish if it is a human or some other types of cargo. Robots can become smarter if they can distinguish different types of object before even touching them.

Proximity sensor that is able to distinguish metallic objects and non-metallic counterparts can be realized by sensing in both inductive and capacitive modes. Metal objects respond to both inductive and capacitive sensors, while dielectric objects respond only to capacitive sensors. Authors in Ref.[7,10] proposed to use alternating even and odd modes to excite a coil, so that the sensor works as inductive sensor and capacitive sensor alternatively. However, the proposed method needs two sets of coils, one for excitation and the other for signal reception. Besides, frequent switching for excitation and detection system was required to work on the two different modes, which complicates the detection circuity.

Recently, metamaterial structures have been applied for sensing applications .[1,5,8,9,12–14] Compared with the conventional proximity sensing structures ,[3,6,7,10,15–17] those metamaterial structures typically have strong resonant features. Sensors based on such metamaterial structures detect nearby objects based on those resonances, typically at much higher frequencies than the operating frequency of conventional sensors. An intruding object disturbs the EM fields surrounding the sensor, leading to a detuned resonance, which is captured by the detection circuit of the sensor. However, existing metamaterial sensors based on resonance detection do not have the capability of distinguishing metallic or non-metallic objects.

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In this paper, we propose a method of combining the inductive sensing and capacitive sensing together with a metamaterial inspired structure. The structure has a resonant frequency, and presents either inductive or capacitive property at different sides of its resonance. Instead of working at resonant frequency, the response at off-resonant frequencies is utilized for object detection. It thus provides a method of realizing both inductive and capacitive sensing simultaneously so that the metallic and non-metallic object can be distinguished. Comparing with ,[7,10] only a single sensing unit is needed, so the sensor is much simplified. The proposed sensor is fabricated with typical low-cost printed circuit board (PCB) technology and tested with aluminum and wood objects. Reflection phase of the sensing structure is measured with different objects at different positions. Experiment results show that the sensor is capable of distinguishing metallic and dielectric objects.

2. PRINCIPLE OF OPERATION

Metamaterials are composed of artificial particles that are designed to have unique responses to external electromagnetic waves. Many of the artificial particle designs have strong resonances at certain frequencies in order to achieve many of the intriguing properties such as negative refractive index. One example of resonant particle design in metamaterials is the Ω particle,[18,19] as shown in Fig. 1. The structure is a metallic inclusion of Ω shape. This structure can be simply modeled as a L-C shunt resonant circuit, in which the inductance L is mainly determined by the long arc-shape line on the top and the capacitance C is mainly contributed by the two horizontal bars at the bottom, as illustrated in Fig. 1. Its resonant frequency is determined by the effective inductance and capacitance. When operating at off-resonant frequencies, the particle presents either capacitive or inductive properties.

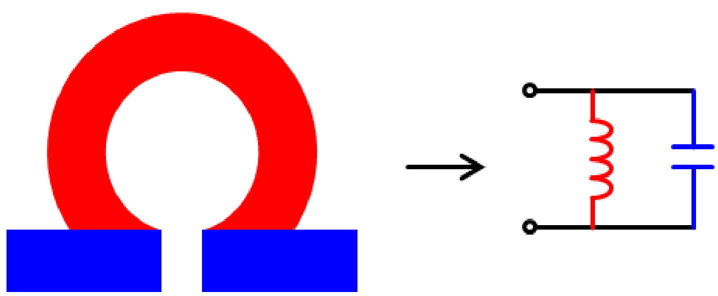


Figure 1. Ω-shape metamaterial and its equivalent circuit around resonance

Its input admittance can be obtained as

$$Y_{in} = j(\omega C - \frac{1}{\omega L}). \tag{1}$$

The associated reflection coefficient, S_{11}, and its phase can be calculated accordingly.

$$S_{11} = \frac{Y_0 - Y_{in}}{Y_0 + Y_{in}} = \frac{0.02 - j(\omega C - \frac{1}{\omega L})}{0.02 + j(\omega C - \frac{1}{\omega L})}, \tag{2}$$

$$\angle S_{11} = -2\arctan(\frac{\omega C - \frac{1}{\omega L}}{0.02}). \tag{3}$$

As can be seen from Eq.(1), the capacitance C and inductance L are proportional and inversely proportional to the admittance respectively. Their contributions to the input admittance are different. Based on the fact the metallic and dielectric objects have different impact on the capacitive and inductive components of the particle, a combined sensor can be designed. When a metallic object approaches to the structure, it affects both capacitance C and inductance L; when a dielectric object approaches, it does not affect the inductance L because no eddy current is induced. Consequently, only capacitive change can be found. Therefore, the metallic and non-metallic objects cause input admittance change differently. Thus, by calculating the input admittance or the phase of S_{11}, whether it is a metallic or non-metallic object can be determined.

More specifically, inductive and capacitive properties dominate at different sides of the resonant frequency. For instance of Ω-shape structure shown in Fig. 1, the sensor is dominated by long arc-shape line below the resonant frequency, and by two horizontal bars above it. Therefore, when a metallic object approaches, the phase of S_{11} increases due to decrease in inductance below the resonant frequency, and decreases due to increase in capacitance above resonant frequency. The proximity of a dielectric material does not change the phase of S_{11} of the sensor at low frequency, and decreases the phase at high frequency. Thus, only two frequency points are needed in order to measure in both inductive and capacitive modes. This provides an easier way to distinguish metallic and non-metallic objects.

3. STRUCTURE DESIGN & SIMULATION

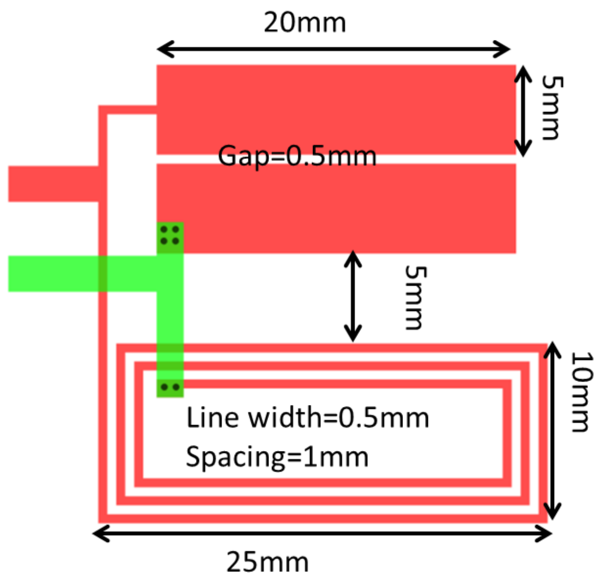


Figure 2. The proposed sensing structure with dimensions.

Different resonant structures can be designed based on the metamaterial particles in order to modify the resonant frequency while maintaining the physical size of a structure. The effective capacitance and inductance can also be tuned by using different geometrical designs. Identifying the inductive and capacitive contributions of a resonant structure is helpful as it not only explains the principle of combined sensing but also important in manipulating the operating frequency and the geometry of the sensor. A sensing structure can be developed by modifying an Ω structure. The arc-shape inductive part can be replaced with spiral structure so that the inductance is increased and the resonant frequency is decreased. The two short bars in the Ω structure, which form the capacitor, are extended in order to increase the capacitance. As the two parts contribute to inductance and capacitance respectively, they can be modified separately and arranged in a manner based on the geometrical requirements of the sensing application. As an example, we designed a sensing structure as shown in Fig. 2. The inductive part is composed of a square spiral with a dimension of 25 mm $\times$ 10 mm, a wire width of 0.5 mm, and a spacing between wires of 1 mm. The capacitive part is formed by a coplanar capacitor, composed of two rectangular patches of 20 mm $\times$ 5 mm each, with a gap of 0.5 mm between them. The two parts are placed in parallel with a spacing of 5 mm. The overall size that the whole sensor is about 30 mm $\times$ 30mm.

The structure is modeled with COMSOL Multiphyics, as shown in Fig. 3. FR4 is used as substrate. A lumped port is used to provide excitation for the sensor. A spherical perfect matched layer surrounds the whole

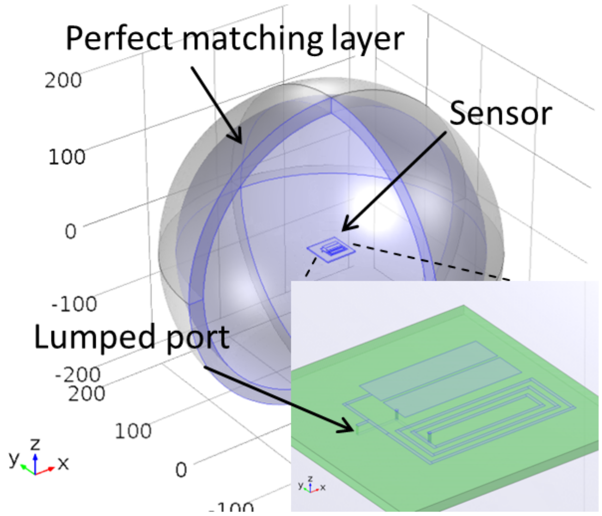
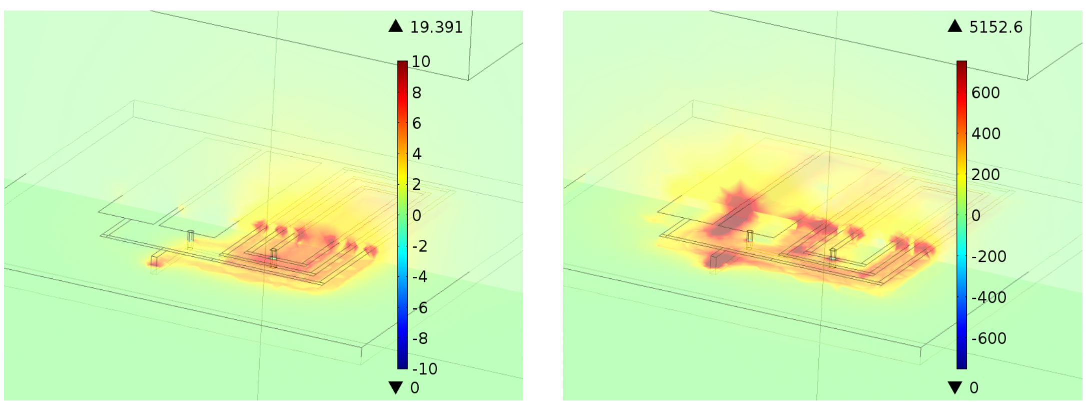


Figure 3. Simulation model in COMSOL Multiphyics.

structure and the simulation domain. The field distribution around the sensing structure is simulated and shown in Fig. 4. Below resonant frequency, the magnetic field distribution in Fig. 4(a) is significantly higher around the spiral structure; while the electric field distribution at above resonant frequency (shown in Fig. 4(b)) is more concentrated on the capacitive patches. The simulation result confirms our theoretical predictions.



(a) (b)

Figure 4. Simulated field distribution: (a) magnetic field distribution at $100MHz$; (b) electric field distribution at $500MHz$.

4. FABRICATION & EXPERIMENT

The sensing structure is fabricated with typical PCB technology. The substrate is FR4 epoxy, with a relative permittivity of 4.5 and a thickness of 1.6 mm. The fabricated structures can be seen in Fig. 5. Three types of structures are displayed in Fig. 5: (a) with both inductive and capacitive components; (b) with only inductive component; (c) with only capacitive component.

The reflected phase as a function of frequency is measured with a vector network analyzer for each structure. First, the inductive (Fig. 5(a)) and capacitive (Fig. 5(a)) structures are measured respectively. Based on these measurements, the effective inductance and capacitance can be extracted and a lumped circuit model can be built. Then a circuit model of the combined sensor can be obtained, which is illustrated in the inset of Fig. 6.

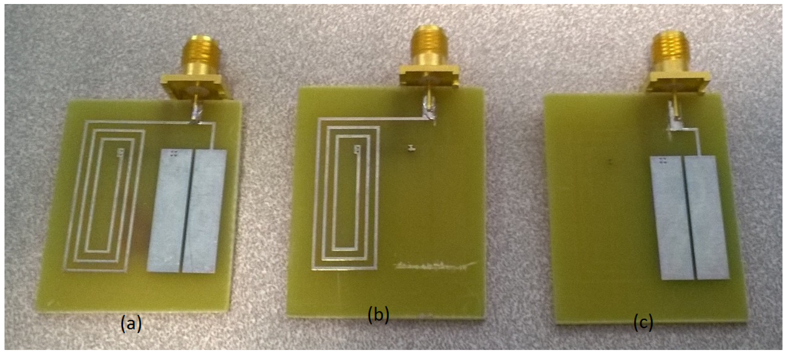


Figure 5. Fabricated sensing structures: (a) with both inductive and capacitive components; (b) with only inductive component; (c) with only capacitive component.

Based on the circuit model, the reflected phase as a function of frequency can be plotted, as shown by the dashed curve in Fig. 6. The reflected phase is also measured experimentally, and plotted as the solid curve in Fig. 6. The modeled result is close to the measurement result. We can also see from Fig. 6 that the resonant frequency is about 200 MHz, where the reflected phase crosses zero. Therefore, in order to realize combined sensing, we need to measure at one frequency below 200 MHz, and another frequency above 200 MHz. In the following measurements, 100 MHz and 500 MHz are chosen.

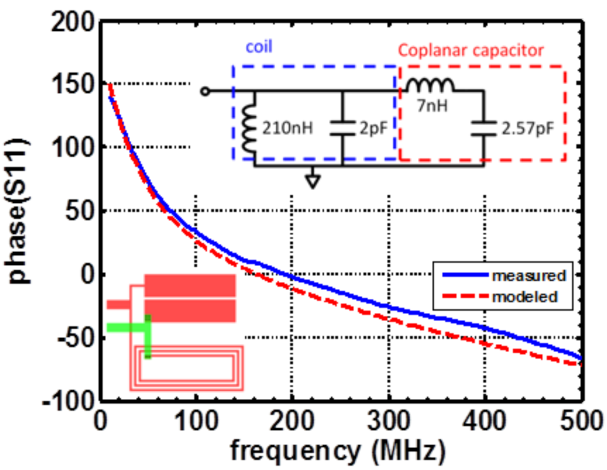


Figure 6. Measured and modeled reflection phase of the unloaded sensor as a function of frequency. The equivalent circuit model is shown in the inset.

Fig. 7 shows the measurement setup. The designed sensor structure is vertically mounted on a stand which is fixed on a platform with scale on it. The object to be detected, aluminum or wood, is placed in front of the sensor with different distances. The phase change of S_{11} is recorded by Agilent network analyzer N5230A.

Measured results are shown in Fig. 8. Fig. 8 (a) and (b) plots the change of the phase of S_{11} at 100 MHz and 500 MHz as the function of distance. It is clear to see that wood causes no change at 100 MHz, but a change from -63.8 to -65.2 degrees at 500 MHz; whereas the copper causes significant phase change at 100 MHz (122 to 135 degrees) and also at 500 MHz (-63.8 to -65.2 degrees). Therefore, the difference can be seen from the response at 100 MHz. Thus the structure can be used as proximity sensor for both metallic and dielectric objects, has the capability of telling them apart. The effective sensing range, as indicated in the phase change in Fig. 8, is about 10 mm. When normalized with the size of sensor, the sensing range is comparable to commercially available inductive or capacitive sensors.

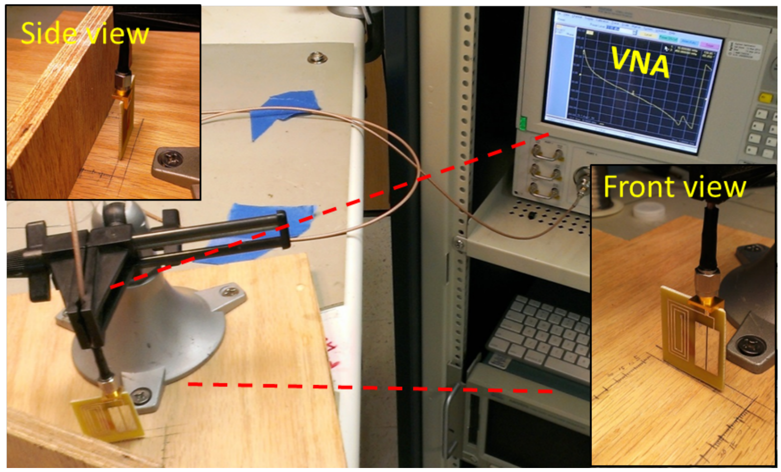
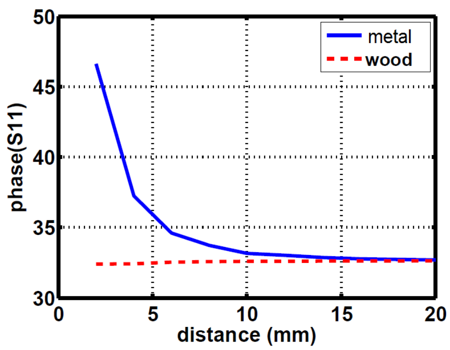
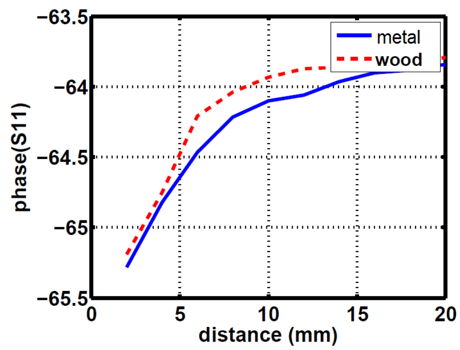


Figure 7. Experiment setup, with fabricated sensing structure shown in the inset.



(a)



(b)

Figure 8. Measured phase of S_{11} with wood or copper approaching to the sensor at (a)100 MHz and (b) 500 MHz.

5. CONCLUSIONS

In this paper, a combined inductive-capacitive sensing method for detecting and distinguishing metallic and dielectric objects was proposed. The sensing structure was inspired by metamaterial particle designs can be easily fabricated and implemented. By operating at off-resonant frequencies, the approaching of metallic and dielectric objects give different responses to reflected phase, and can thus be detected and distinguished by the sensor.

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