Flexible Interdigital Sensor for Nondestructive Detecting Wear and Thickness of Tire Tread

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Abstract: A novel type of interdigital sensor that has been introduced in this paper can non-destructively detect the thickness of insulating materials, e.g. tire. The sensor was manufactured by jet printing technology with high efficiency. The function of the developed sensor is based on the hindering effect on the transmission of electromagnetic signals. The thickness of the insulating materials can be therefore obtained by monitoring the degree of signal reflection through transmission. For optimization, sensors made with three recipes have been experimentally tested. It is concluded that the sensor with double layers’ structure possesses the optimal performances. Practically, the application of the developed sensor in detecting the wear of tire tread has been carried out.

1. Introduction
Interdigital electrodes are electrodes with a periodic pattern in a finger-like or comb-like surface. Compared with traditional electrodes, microelectrodes have higher sensitivity [1]. Among various microelectrodes, interdigital electrodes have the advantages of reduced impedance, rapid establishment of steady-state signals and high signal-to-noise ratio [2]. A significant advantage of interdigital electrode sensors is their simple structure, low production cost, large-scale manufacturing process and the ability to use them for many different applications without significant changes to the design [3]. As the core component of electrical signal transmission, it is widely used in biomedicine [4], environmental monitoring [5], industrial applications [6] and public safety [7].

Despite the conventional manufacturing process of interdigital electrodes based on lithographic mask process, the use of inkjet printing technology to fabricate interdigital electrodes increases [8-9]. This inkjet printing technology has the characteristics of simplicity, low cost and low energy consumption. Interdigital electrodes can be prepared quickly and efficiently by this technique.

Thickness detecting sensors have a wide range of uses. There are many thickness detection methods, such as electromagnetic detection [10], acoustic emission technology [11] and laser sensor [12]. In addition, thickness sensors have applications in health management. The thickness of biological tissue can be measured by a fiber optic confocal catheter [13]. The demand for sensors has
increased with the development of the automotive industry [14]. So far, tire pressure monitoring sensors have become an essential monitoring system in every car [15-16]. People have been researching new sensing technologies to monitor tire performance parameters [17-19]. Tire tread wear reduces tire life and affects driving safety [20], however, monitoring tire tread wear is a challenge. It is feasible to measure the wear of tire tread using a kind of electrode sensor [21].

In this study, a novel interdigital sensor for detecting materials thickness has been proposed. Using these sensors to measure thickness change in insulating materials gets successful. The sensors appear flexible enough, so they can be attached to the inside of tires to measure the tire tread thickness noninvasively. All sensors in this work are fabricated by jet printing technology, which is simple, low-cost and can print electrodes with different materials and sizes. We print sensors with silver ink and carbon nanotube ink. Through the test, it is verified that the sensors have a certain ability to detect the thickness of the insulating materials. In addition, its application in tire tread wear detection turns out to be successful.

2. Materials and Methods
First, combining CAD technology and laser engraving technology to engrave an interdigital sensor template on a 0.5 mm thick copper plate. Then, the inks used in the experiment are sprayed on the substrate through the template with a sprayer. Finally, the jet-printed interdigital sensors are left to dry at room temperature for 3 hours. The entire preparation process of interdigital sensors is shown in Figure 1a.

Silver ink and carbon nanotube ink are used to fabricate sensors in the experiment. Due to the high temperature resistance, electrical insulation properties and flexibility of the Kapton films, using Kapton films as substrates is perfect.

VNA (Vector Network Analyzer) is a test equipment for electromagnetic wave energy. It can measure the amplitude of various parameters of a single-port network or a two-port network. In this paper, using NANO-VNA to measure the return loss. Return loss is a parameter that expresses the performance of signal reflection. It is defined as the ratio of incident power to reflected power and calculated as formula 1.

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RL = 10 \log_{10} \frac{\text{incident power}}{\text{reflected power}}
\]  

So, connecting the port I of the VNA to the interdigital sensor and provide a high-frequency excitation signal by the VNA. The signal is reflected back to the port I after passing through the sensor. At the same time, connecting port II to the other side of the sensor to achieve the purpose of stabilizing the signal. The test process is illustrated by Figure 1b.
3. Results and Discussion

3.1 Thickness detection of three insulating materials

The return loss in the scattering matrix was used as the detection quantity for measure the thickness of the materials. The VNA generated a continuous frequency sweep signal and then the signal passed through the interdigital sensor printed by silver ink. The rubber sheets covering the sensor affected the transmission of the signal, which also affected the return loss response curve. The sweep frequency range of VNA was from 100 MHz to 1000 MHz and the thickness of the rubber covering the sensor was increased from 0 mm to 8 mm. Ten scans were performed for each thickness to calculate the average value. The return loss response curve shifted to a certain extent with the thickness of the rubber sheets covering the sensor as shown in Figure 2a.

Two resonance peaks were monitored, one is around 300 MHz and the other is around 770 MHz. Near the second resonant frequency, the relationship between the offset of the curve and the thickness of the rubber proves more sensitive. Therefore, through the data analysis of the smooth area near the second resonant frequency, the relationship between the return loss and the rubber thickness at a certain frequency can be established. Finally, at 632 MHz, a linear relationship between rubber thickness and return loss was determined as shown in Figure 2c.

In order to further verify that the sensor in this paper can detect the thickness of other materials, the same test was also carried out on silica gel and glass. Comparing the thickness test curves of the three materials, at the signal frequency of 632 MHz, the relationship between material thickness and return loss was obtained as demonstrated in Figure 2c. The result proves that the thickness of the insulating materials can be detected by the sensor.
3.2 Comparison of Test Results of Three Interdigital Sensors

To determine the effectiveness of the interdigital sensors, three kinds of interdigital sensors were investigated. One was printed with silver ink, one was printed with CNT ink, and the last sensor has a double layers’ structure—the bottom layer was printed with silver ink and the top layer was printed with CNT ink. The resistance values of the three sensors were measured by the electrochemical workstation. According to the resistance value obtained from the volt-ampere characteristic curve in Figure 3, the conductivity of the sensor printed with silver ink presents the best, and the conductivity of the sensor with double layers’ structure is between the other two sensors. The surface microstructures of the three sensors are shown in Figure 3, too. Through the surface microstructure, it can be drawn that CNT overlaid on silver layer increase the high surface-to-volume ratio of the sensor.

The sensor of double layers’ structure combines the advantages of both inks: high conductivity of silver ink improves the distribution of electric field across sensor and high surface-to-volume ratio of the CNT to enhance sensitivity [21]. To verify the performance of the sensor with double layers’ structure in material thickness detection, the results of three sensors applied to rubber thickness detection were compared. The comparison results are illustrated by Figure 2d.

In rubber thickness detection with sensor printed by CNT ink, the value of the return loss changes very little with the increase of rubber thickness. It is not easy to analyze the relationship between them. In the test with sensor printed by silver ink, the test sensitivity of the sensor will decrease when the thickness of the rubber exceeds 3 mm. The sensor with double layers’ structure in the test can not only provide a significant relationship between the rubber thickness and return loss, but also have a high sensitivity to ensure the accuracy of the test result. Therefore, the sensor with double layers’ structure exhibits the best test performance in the detection of material thickness.
3.3 Application of Interdigital Sensor in Tire Tread Thickness Detection

The wear of the tire tread affects the driving safety of the car. Therefore, it becomes very important to detect the degree of tire tread wear. Once the tire tread become too worn, it is necessary to replace the tire to prevent driving accidents. Since the main component of the tire tread is rubber, the interdigital sensor can be used to detect the tread thickness of the tire. However, a metal grid is embedded inside the tire to increase the firmness of the tire. The metal grid has a certain shielding effect on the transmission of electromagnetic signal. This shielding effect is more pronounced for low frequency signal. So, it is necessary to analyze the relationship between tire tread thickness and return loss from a higher frequency.

Placed the sensor which has the best test performance in rubber thickness detection inside the tire approaching wear limit. Then, the rubber sheets were placed on the outer surface of the tire at a location corresponding to the sensor to simulate an increase in tire tread thickness. Similarly, using VNA for 100 MHz to 1000 MHz sweep detection to obtain the return loss response curve as shown in Figure 2b. The small offset of the curve is due to the metal grid inside the tire. So the test data needs to be analyzed from the high frequency region. When the detection signal frequency is 946 MHz, a correlation between tire tread thickness and return loss is obtained. The test result is illustrated by Figure 4b.
Fig. 4. (a) Detecting tire tread wear with interdigital sensor. Tire tread wear was simulated in reverse by gradually increasing the thickness of the rubber sheets. (b) Result of tire tread wear testing and the confidence interval histograms show the 99% confidence range.

It can be seen from the test result that the relationship between tire tread thickness and return loss is not completely linear. And the overlap ratio between the interval histograms is large. Therefore, the relationship between tire tread thickness and return loss cannot be quantitatively calibrated. However, tire tread wear level can be set as shown in Table 1. When the wear level reaches first level, an alarm needs to be issued to remind the owner to replace the tire in time.

Table 1. Tire tread wear level

| Tire tread wear level | First level | Second level | Third level | Fourth level |
|-----------------------|-------------|--------------|-------------|--------------|
| Return loss value (dB)| < -6.35     | -6.35 ~ -6.30| -6.30 ~ -6.20| -6.20 ~ -6.15 |

4. Conclusions

Through detecting the thickness of three insulating materials (rubber, silica gel and glass), the developed interdigital sensor can effectively indicate the thickness of insulating materials without placing double-side electrodes or causing any damage of the testing samples. The sensor with optimal thickness detecting performance has a double layers’ structure, consists of silver ink layer and covered by carbon nanotube ink layer. Practically, this sensor has been experimentally proved that it can be applied to tire tread wear detection to ensure the driving safety of the car.

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