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Research Article

Microfluidic Flexible Substrate Integrated Microstrip Antenna Sensor for Sensing of Moisture Content in Lubricating Oil

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In this paper, a flexible microstrip patch antenna sensor is proposed for monitoring of the moisture content of lubricating oil. The sensor identifies liquids having different effective dielectric constants by detecting changes in the resonance frequency. The proposed antenna comprises a radiation patch, a metal ground plane, and a PDMS substrate with microchannels. The microchannels are etched on the PDMS substrate. When the relative permittivity of the microfluidic channel is 1.8~12.5, the operating frequency of the proposed antenna changes from 2.230 to 2.116 GHz, and the amplitude of the reflection coefficient is greater than −26.3 dB. The simulation and measurement results show that the proposed sensor can monitor the lubricating oil with different moisture contents, which can cause frequency separation of at least 20 MHz and achieve a good linear response. Therefore, the proposed sensor has the feasibility of monitoring the quality of lubricating oil.

1. Introduction

The wear of mechanical devices affects the normal operation of mechanical equipment and its service life. Lubricating oil plays an important role in the normal operation of machinery and equipment. Deterioration of lubricating oil is a very slow process, and detection of oil is an effective measure to ensure the quality of the oil. There are many methods to evaluate the quality of oil, and the water content of oil is the most obvious sign that affects its quality [1, 2]. According to the survey, about 50% of lubricant changes are unnecessary [3, 4]. Therefore, it is necessary to monitor the mechanical state of lubricating oil and change the oil period.

RF and microwave technology for sensing liquids are important noncontact technologies, especially in the remote detection and analysis of liquids [5–7], such as microwave cavity waveguides [8], microwave resonators [9], and hypersurface absorbers [10]. Some liquids with different dielectric constants can be identified by detecting the change of resonance frequency of microwave devices. It has been previously reported that sensors for chemical analysis and water quality measurement require a large amount of liquid to fill the test tube for analysis [11, 12]. Most of the unused liquid is wasted during the measurement or analysis process. In order to control the waste of residual liquid, microfluidic system can be employed. The microfluidic system has the advantages of small sample volume, low energy consumption, and easy manufacturing. Therefore, the liquid can be measured in the range of nanoliters or microliters [13, 14]. Most microfluidic sensors require expensive and complex equipment to detect the change of liquid, and analysis equipment cannot provide remote monitoring [15–18]. The resonance method is the most accurate in liquid detection and quantification, but most of the devices are very bulky and not suitable for integration with planar circuits [19]. Wireless microfluidic sensors rely on low temperature cofired ceramics (LTCC) technology for detecting the concentration of glucose in water solution [20]. However, due to the complexity of manufacturing process, substrate shrinkage, warpage, interlayer alignment deviation, and other factors are easy to appear in the production. Recently, a slot-loaded microstrip patch antenna sensor was proposed to improve the sensitivity of relative permittivity [21]. The air gap between the material under test (MUT) and the antenna sensor can cause errors between simulation and measurement results. In order to measure the relative permittivity, a meander-line slot-loaded high-sensitivity microstrip patch antenna sensor was proposed. Compared with the conventional antenna, its size is reduced by about 44.9% [22]. A microstrip patch antenna sensor with a liquid chamber in the substrate was proposed for measuring the salinity in seawater [23]. The results show that the sensor based on microstrip antenna may be a promising method to develop microfluidic sensor [24–26]. In terms of sensing and communication, passive RFID tag antenna sensors were used for research and challenges in structural health monitoring applications [27]. In the study of these works, integration of microstrip patch antenna and flexible microfluidic substrate has not been systematically studied, and the sensor analysis has not been carried out by pumping a small amount of lubricating oil [28]. The physical and chemical indexes that affect the dielectric constant of the lubricating oil are moisture, acid value, and metal grinding, but mainly the influence of moisture. The dielectric constant is feasible as an indicator for evaluating the deterioration of the lubricating oil. Compared with the conventional dielectric constant methods, the sensor is nonpolluting and can be monitored by trace liquid [29]. Therefore, we propose a microfluidic sensor based on a flexible microstrip antenna that pumps a small amount of lubricating oil into the microfluidic channel to sensitively identify lubricating oils containing different moisture at the resonant frequency. It has a good application prospect in the quality monitoring of lubricating oil.

2. Structure Design

The dielectric substrate with different dielectric constants will cause the resonance frequency offset of the antenna. By etching the microfluidic channel in the dielectric substrate, the oil containing different moisture is pumped into the microchannel, thereby causing a change in the dielectric constant of the dielectric substrate. Therefore, the resonance frequency of the antenna is shifted. As shown in Figures 1(a) and 1(b), the proposed sensor is composed of three layers. The top layer has a conductive pattern etched on the F4B board with a permittivity of 2.65, loss tangent of 0.002, and thickness of 0.6 mm. The middle layer has a microfluidic channel etched on the PDMS substrate with a permittivity of 2.65, loss tangent of 0.02, total thickness of 0.8 mm, and microchannel thickness of 0.4 mm. The bottom layer has a copper coating on the surface of the F4B board. By using f_1 and ε_r, the width (W) and length (L) of the microstrip sensor can be obtained as follows [30]:

$$\begin{aligned}
W &= \frac{c_0}{2f_1}\sqrt{\frac{2}{\varepsilon_r + 1}},\\
\varepsilon_e &= \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right)^{-(1/2)},\\
\Delta L &= 0.412h\frac{(\varepsilon_e + 0.3)((W/h) + 0.264)}{(\varepsilon_e - 0.258)((W/h) + 0.8)},\\
L &= \frac{c_0}{2f_0}\frac{1}{\sqrt{\varepsilon_e}} - 2\Delta L,
\end{aligned} \tag{1}$$

where W and L are the width and length of microstrip antenna, c_0 is the speed of light, h is the thickness of the substrate, ΔL is the extension of patch length due to fringing effects, and ε_e is the effective dielectric constant which is related to the relative permittivity ε_r of the substrate. Figure 1(c) shows that the parameters of the proposed antenna are $h = 2$ mm; $t = 0.4$ mm; $w1 = 48$ mm; $w2 = 30$ mm; $w3 = 2$ mm; $w4 = 18$ mm; $w5 = 15.6$ mm; $w6 = 2$ mm; $w7 = 2$ mm; $l1 = 48$ mm; $l2 = 40$ mm; $l3 = 32$ mm; $l4 = 4.9$ mm; $l5 = 1.95$ mm; $l6 = 7$ mm; $l7 = 45$ mm. In Figure 1(d), the microfluidic channel made of PDMS material has an outlet and an inlet, which ensures the inflow and outflow of liquid.

The equivalent circuit of microstrip patch is shown in Figure 2. Compared with the traditional patch antenna, the proposed antenna has dual resonance frequency by adding a slot, and the lower frequency has a narrower bandwidth [31, 32]. The proposed antenna consists of a rectangular patch fed by a 50-Ω microstrip line. By simulating the increase of the slot width, the resonance frequency of the antenna will gradually decrease as shown in Figure 3(a). In Figure 3(b), the amplitude of S_{11} gradually decreased with increases in the length of the slot. Figure 4 shows that the position of the microfluidic channel will cause a corresponding shift in the antenna resonance frequency. The resonant frequencies with dielectric constants of 1 and 81 are simulated, respectively. Considering the need to punch holes in the production and other factors, we chose the original position with a large resonance frequency offset. The e-field distribution of the microstrip antenna is shown in Figure 5. It can be seen that the electric field mainly concentrates on the slot and two edges of the antenna. The sensitivity of the sensor can be improved by combining the analysis with the simulation design of the microchannel. At the same time, it is of great significance to design the size of microchannel. Therefore, we can improve the sensitivity of the sensor by simulating the microfluidic channels. When the ε_r of the microfluidic channel changes, the lubricating oil with different moisture contents can be better distinguished according to the change of the resonance frequency of the antenna. The sensitivity of the sensor can be calculated as follows:

$$S = \frac{\Delta f}{\Delta \varepsilon_r}, \tag{2}$$

where Δf is the relative resonance frequency shift and $\Delta\varepsilon_r$ is the change of the relative permittivity. We simulate the

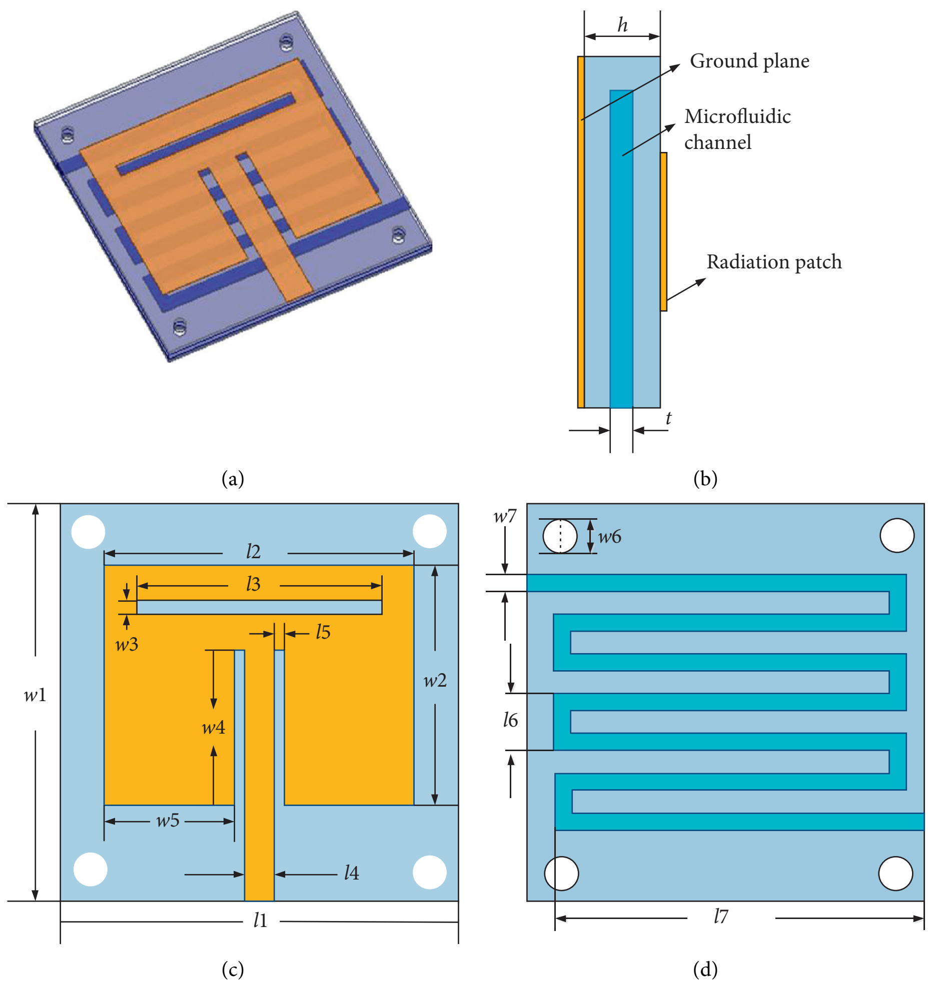

Figure 1: Geometry of the proposed antenna: (a) 3D view; (b) side view; (c) the radiation patch; (d) the microfluidic channels.

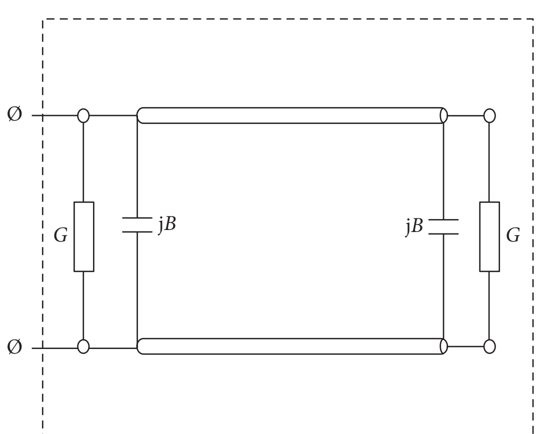

Figure 2: The equivalent circuit of microstrip patch.

resonance frequency offset of air and water, respectively. In the simulation, the dielectric constant and loss tangent of water at 25°C room temperature are set as 76.5 and 0.1 [33]. Figure 6(a) shows the resonance frequencies of microchannels with different widths when the dielectric constant is 1. Figure 6(b) shows the resonance frequencies of microchannels with different widths when the dielectric constant is 76.5. When the relative permittivity is constant, the sensitivity of the sensor can be improved by simulating the width of the microchannel. Therefore, we need to balance the amount of liquid and the resonance frequency offset of the antenna. It can be clearly seen in Table 1 that the greater the width $w7$ of the microfluidic channel, the more the amount of liquid and the wider the resonance frequency shift. By comparing the sensitivity of the sensor for each 0.1 mm increase in the width of the microchannel, we chose a microchannel with a width of 2 mm.

When neglecting the influence of impurity contained in lubricating oil, the moisture content of the lubricating oil may be approximately regarded as a mixture of pure oil and pure water. When the water content is high, its relative permittivity can be expressed by the following empirical formula:

$$\sqrt{\varepsilon_1} = A\sqrt{\varepsilon_2} + (1 + A)\sqrt{\varepsilon_3}. \tag{3}$$

In (3), ε_1 is the dielectric constant of the mixed medium, ε_2 is the dielectric constant of pure water, ε_3 is the dielectric constant of pure oil, and A is the volume fraction of the medium water. The dielectric constant of water is about 80,

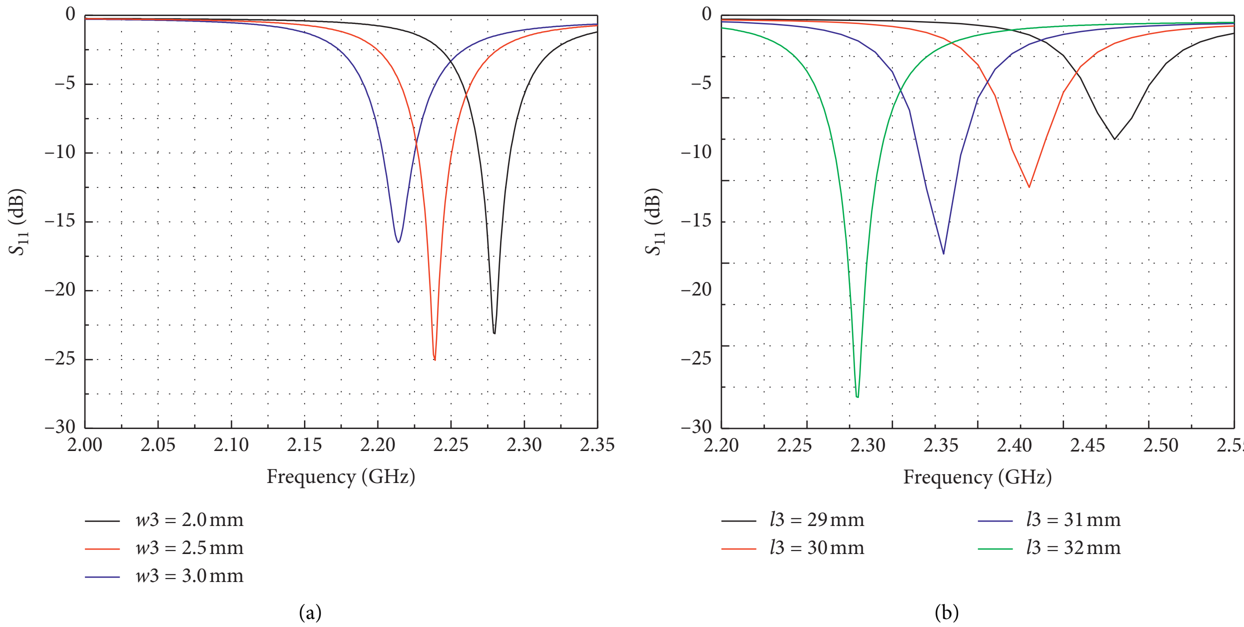

FIGURE 3: Resonant frequency of microchannels of different sizes: (a) width; (b) length.

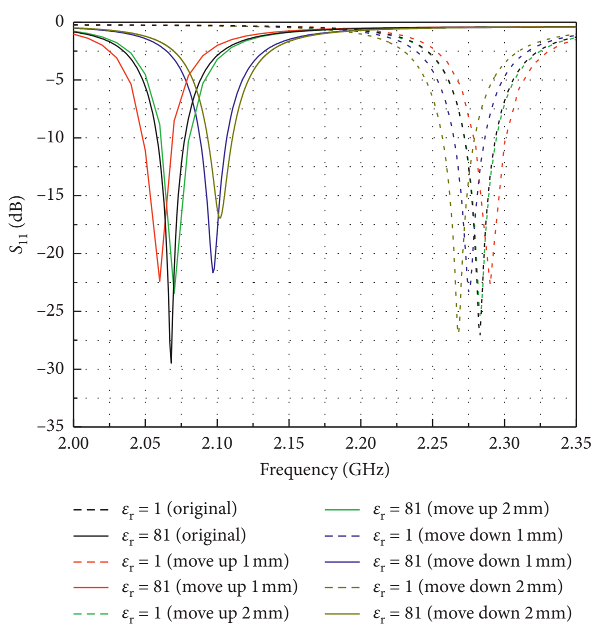

FIGURE 4: Resonance frequency offset caused by the change of microfluidic channel position.

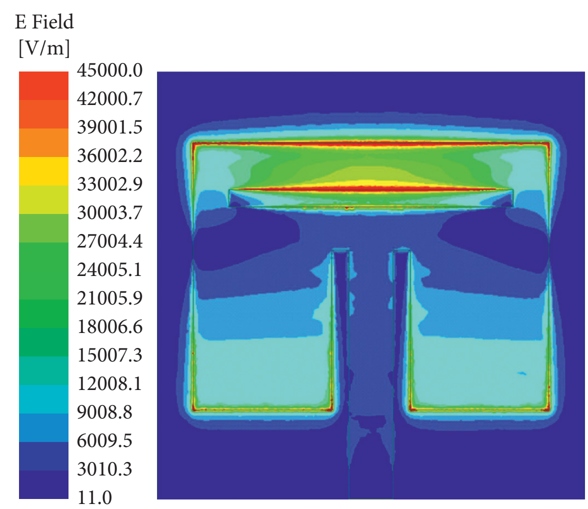

FIGURE 5: Electric field distribution of microstrip antenna.

and that of lubricating oil is about 2.3, which is quite different. The metal abrasive particles and acid value in the lubricating oil have no significant effect on the change of the dielectric constant, but the trace moisture in the lubricating oil has a significant effect on the dielectric constant, because water can emulsify lubricating oil, decompose additives, promote the oxidation of oil products, and enhance the corrosion of machinery by low molecular organic acids. Based on the method of dielectric constant, the value of dielectric constant is obtained by measuring lubricating oil with different moisture contents [34]. A bottle with distilled water was washed and dried in an electric constant temperature drying oven. A microburette was used to add a certain amount of water to the lubricating oil sample, a solution with a moisture content of 1% was configured, and then it was diluted step by step. Finally, the dielectric constant of the sample was immediately measured using a lubricant quality tester. When the moisture content of lubricating oil is from 0% to 0.8%, the dielectric constant changes from about 1.8 to 12.5.

3. Experimental Measurements

The proposed sensor was simulated using the ANSYS High Frequency Structure Simulator (HFSS). When the relative

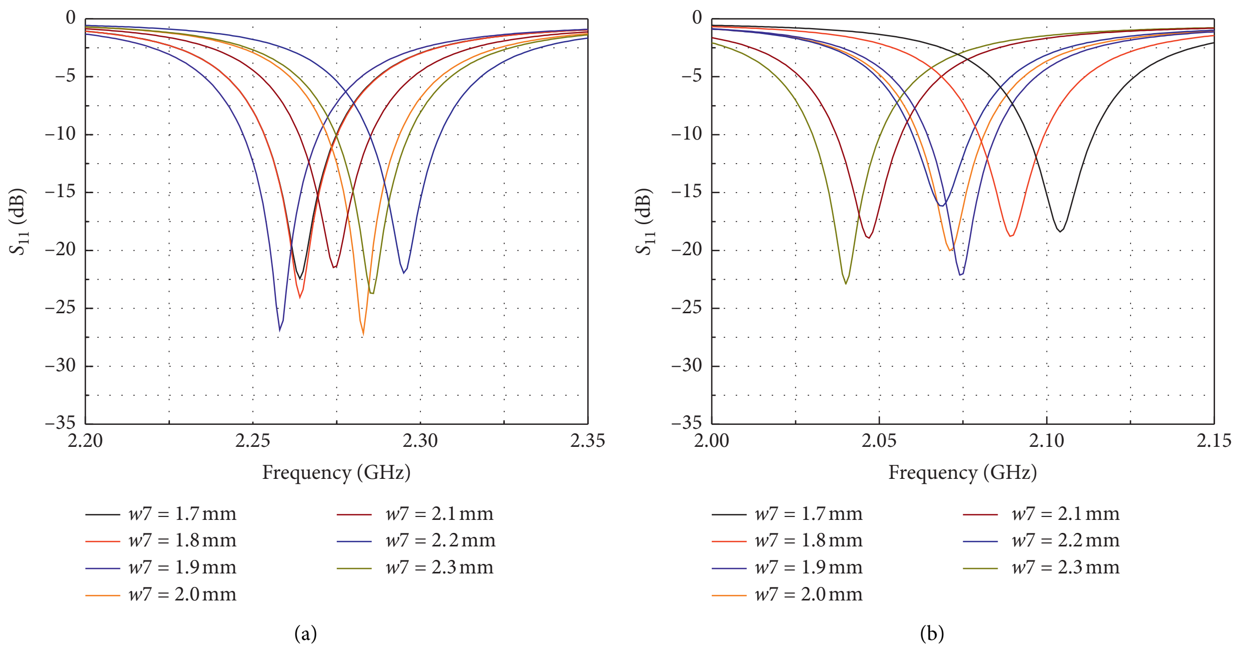

FIGURE 6: Resonant frequency of microchannels of different widths: (a) $\varepsilon_r = 1$; (b) $\varepsilon_r = 76.5$.

TABLE 1: Microfluidic channels of different widths affect antenna resonance frequency offset.

$w7$	Frequency (GHz)			
	Air	Water	Offset	S
1.7 mm	2.264	2.104	0.160	0.0021
1.8 mm	2.264	2.089	0.175	0.0023
1.9 mm	2.258	2.074	0.184	0.0024
2.0 mm	2.283	2.071	0.212	0.0028
2.1 mm	2.274	2.047	0.227	0.0030
2.2 mm	2.295	2.069	0.226	0.0029
2.3 mm	2.286	2.040	0.246	0.0032

permittivity of the microfluidic channels is increased from 1 to 12.5, the frequency of the proposed antenna is changed from 2.283 GHz to 2.116 GHz, and the amplitude of reflection coefficient is greater than −26.3 dB. This shows that the matching impedance of the antenna is better. The simulation results are shown in Figure 7.

From Figure 8, it can be clearly seen that, when the relative permittivity of the microfluidic channel increases, the resonance frequency of the proposed antenna decreases gradually. The simulation results show that the antenna can be used to distinguish lubricating oil containing different moisture contents; in particular, when the relative permittivity of liquid is less than 12.5, it is more obvious.

Figure 9 shows a fabricated antenna sensor that has undergone a PCB etching process on a F4B substrate. The size of the sensor was approximately 48 mm × 48 mm × 2 mm, and the width and height of the microchannel were about 2 mm and 0.4 mm, respectively.

The holes around the antenna are fixed holes that connect the top antenna patch, the middle layer microchannel, and the bottom floor to form a sensor. The test

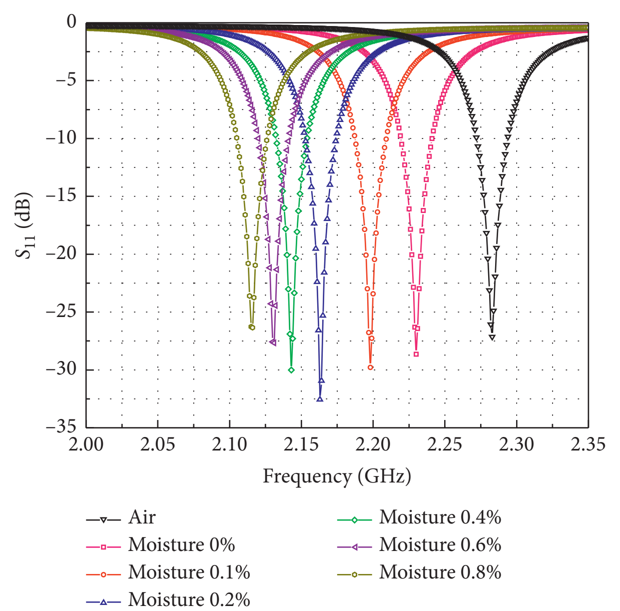

FIGURE 7: Simulation results for the different relative permittivity values of the microfluidic channels.

platform of the microfluidic sensor is connected to the vector network analyzer. This sensor has potential as a wireless sensor. We can place a broadband receiving antenna at a certain distance, which can receive the electromagnetic wave radiated from the sensor antenna to the free space. In order to extract the wireless signal steadily during each measurement, the receiving antenna is placed around the wireless sensor. It is worth noting that the wireless signal will decrease as the distance increases. The simulation was verified experimentally, and the

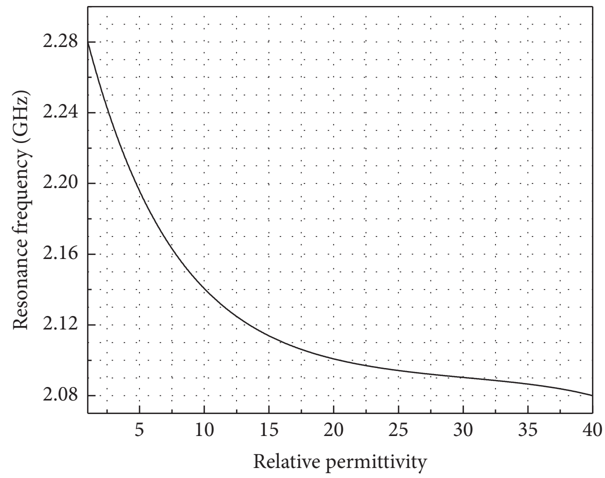

Figure 8: Relationship between the different relative permittivity values of the microfluidic channels and the resonant frequency of the antenna.

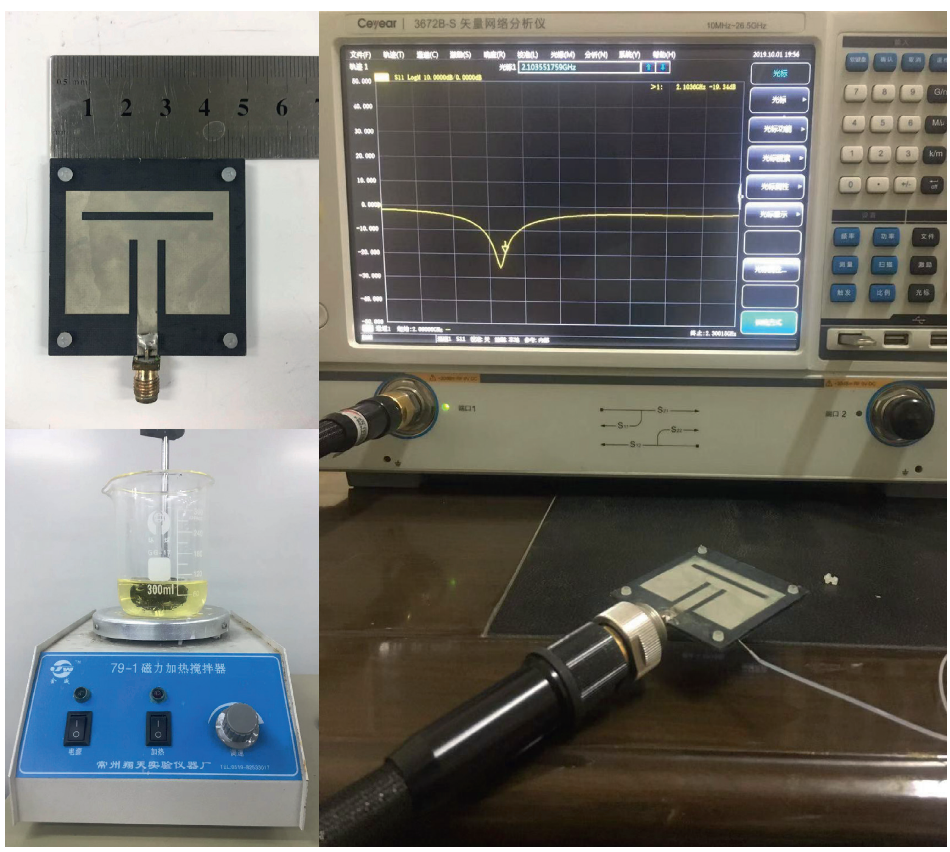

Figure 9: Fabricated microfluidic sensor and experiment setup.

lubricating oil with moisture content of 0%~0.8% is prepared in the beaker. The lubricating oil with different moisture contents is stirred by magnetic heating mixer for 30 minutes to make uniform distribution. The capillary needle and the catheter are connected together for filling and draining the liquid, and the peristaltic pump is used for making the liquids flow into the microfluidic channel of the sensor evenly and keep it stable for a period of time, thereby testing the moisture content of the lubricating oil in the sensor. After each measurement, the microchannel is rinsed with clean water, and air is injected into the channel to remove residual liquid; then, it is dried at 40°C for 5 minutes to keep the resonance frequency of the sensor in the original state.

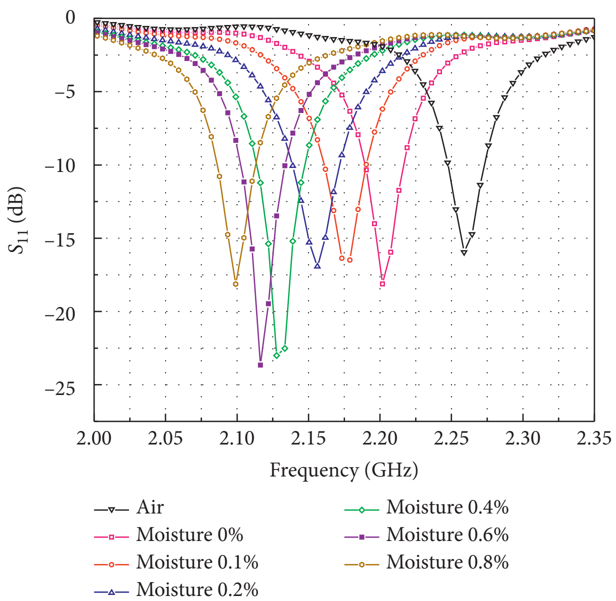

Figure 10: Measuring the moisture content of the lubricating oil in the microfluidic channel.

Table 2: The resonance frequency changes between the simulation and measurement of lubricant oil with different moisture contents.

Lubricating oil moisture	Frequency (GHz)		
	Simulation	Measurement	Offset
Moisture 0%	2.230	2.202	0.028
Moisture 0.1%	2.198	2.179	0.019
Moisture 0.2%	2.163	2.156	0.007
Moisture 0.4%	2.143	2.127	0.016
Moisture 0.6%	2.131	2.116	0.015
Moisture 0.8%	2.116	2.099	0.017

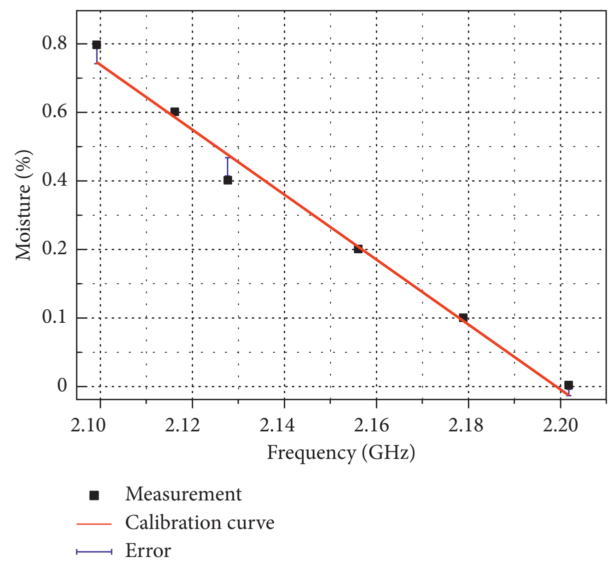

Figure 11: Relationship between moisture content of lubricating oil in microfluidic channel and antenna operating frequency.

4. Results and Discussion

The result is shown in Figure 10. At room temperature of 25°C, the proposed antenna resonance frequency is 2.26 GHz because there is no liquid in the microfluidic channel. When the moisture-free lubricating oil is pumped into the microfluidic channel, the resonance frequency becomes 2.2 GHz. When the lubricating oil containing 0.8% moisture is pumped into the microfluidic channel, the resonance frequency shifts to 2.1 GHz. The measurement results show that the measured resonance frequency is basically consistent with the HFSS simulation results.

Usually, the real part of the complex permittivity determines the resonance frequency, and the imaginary part determines the reflection coefficient. We can observe that the error of the imaginary part of the complex permittivity causes a difference between the reflection coefficients. The lubricating oil contains base oil and additives. Adding a small amount of water will lead to oxidation and deterioration of lubricating oil, and some additives (especially metal salts, etc.) in the lubricating oil will hydrolyze with water and become invalid. Therefore, we cannot accurately extract the imaginary part of lubricating oil. When different complex permittivity is designed in the microfluidic channel, the electric field is disturbed and the resonance frequency moves to different frequencies. Table 2 summarizes the resonance frequency changes between the simulation and measurement of lubricant oil with different moisture contents.

The results in Figure 11 show that the regression analysis shows that the sensor has a good linear relationship in measuring the moisture content of the lubricating oil. The flexible microchannel integrated into the sensor reduces the error caused by the air gap and makes the sensor more sensitive to liquid detection. At the same time, if the microfluidic channel is damaged, it can be replaced. The sensor is suitable for monitoring liquids with a lower permittivity. For liquids with a higher permittivity, the sensor has low sensitivity. When the moisture content of lubricating oil increases from 0% to 0.8%, an average interval of about 20 MHz occurs at the resonance frequency. By judging the service performance and deterioration of the lubricating oil, it is determined whether or not the replacement period is reached. Therefore, the proposed sensor has the feasibility of monitoring the moisture content of lubricating oil.

5. Conclusions

This paper presents a flexible microstrip patch antenna as a sensor. According to the change of the dielectric constant of the microfluidic channel, the sensor can sensitively detect the moisture content in the lubricating oil, and the lubricating oil-water mixture having a dielectric constant of 1.8 to 12.5 is pumped into the microfluidic channel for simulation and experiment, which can be achieved. The resonant frequency offset of the proposed antenna is approximately 100 MHz. When measuring the mixture of lubricating oil and water, the deterioration degree of the lubricating oil can be measured and replaced in time to avoid mechanical wear, but the sensor cannot distinguish the mixed liquid with similar dielectric constant. The proposed sensor has the characteristics of low cost, ease of manufacturing, noncontact, and high sensitivity. And microfluidic channel is flexible, corrosion-resistant, and inexpensive material and can be disassembled and replaced. Most importantly, it is nonpolluting and uses only trace liquids. Therefore, it has a good application prospect in monitoring the quality of lubricating oil.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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