Simulation of Various Resonators as Viscometer for Engine Oils

(Simulasi Pelbagai Resonator sebagai Alat Pengukur Kelikatan Minyak Mesin)

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Abstract

The viscometer is an instrument used to identify the resistance of a fluid to shear or tensile stress. Accurate characterization of viscosity is important in analyzing many engineering situations, especially in the automation industries, which consume engine oils that associate with the functionality or performance of vehicles and machinery. Therefore, this work aims to simulate various sensors via resonators before the fabrication process is performed. The viscosity is justified based on the variation of dielectric properties of the fluid. T-resonator shows the highest sensitivity in all designs with an S11 value of -54.212dB and DSRR with Roger 3003 performs the best in terms of Q-factor with 1883. This simulation results can be verified through experimentation as future works.

Keywords: Dielectric, Viscometer, engine oils

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INTRODUCTION

Viscosity is a parameter used to describe the resistance of a fluid to gradual deformation by shear stress or tensile stress. In the quality control system, viscosity is also an important control variable when it comes to differentiating between different qualities of raw materials and eliminating problems when further processing them (Leblanc, Secco, & Kostic, 1999). Knowing the viscosity is of great importance in different types of industries such as food processing (Cataldo, Piuzzi, Cannazza, De Benedetto, & Tarricone, 2009), industrial (Afoakwa, Paterson, & Fowler, 2007), hemorheology (Fu, Ji, Han, Xu, Pan, Hu, & Zhong, 2017), automotive industrial (Singh, Singh, & Sehgal, 2016; Wang, 2001) and so on. It is found that dielectric properties such as dielectric constant, loss factor, loss tangent, and conductivity can be related closely to the viscosity.

The interrelationship between material properties such as viscosity and dielectric properties, especially in oils has been shown by several researchers. Kumar, Singh, & Tarsikka (2013) measured with the correlation between viscosity and electrical properties for edible oils using an experimental method and found that the best correlating relations along with correlation constants, valid for the temperature in the selected range. They were able to develop the regression equation relating viscosity with loss tangent and electrical conductivity with the high correlation coefficient. Additionally, Milan (2012) examined the correct measurements of the dynamic viscosity, density, and electrical properties of insulation oils. The results showed different conductivity values for respective oils associated with the different fatty acids contain in natural oils. Therefore, electrical properties provide opportunities for non-destructive sensing of quality characteristics in products where those quality material properties can be well correlated with the electrical properties. Furthermore, sensor development has been receiving more attention over the method investigation both for data interpretation and industry applications (Wu, Wu, Du, & Peng, 2013). The successful application of on-line oil monitoring technology will be beyond traditional diagnosis and prognosis and will be expanded to be the core technology for the digitalization of the lifetime performance of machines. Sensor developments and their industrial applications have been reviewed comprehensively and many sensors based on diverse physical and chemical principles have been grown and applied for detection and analysis of oil quality degradation, pollution, and wear debris concentration and constituents. Other researchers also found this method has high accuracy and reliability but also low-cost and portability features (Guan, Feng, Xiong, & Xie, 2011; Piuzzi, Cataldo, & Catarinucci, 2009). These findings convinced the approach suggested in this research is practicable.

Automated viscosity measurement based on dielectric assessment is not available in the market yet. This technique enables in-situ measurement; hence it reduces time, energy, and testing cost. The viscosity results can be achieved directly, stored for monitoring purposes. Currently, the viscosity measurements are conducted based on techniques such as U tube, falling sphere, falling piston, rotational viscometer, bubble viscometer as so on (Leblanc et al., 1999). In general, these techniques require the liquid to be tested in the laboratory. For example, in a falling sphere technique, a specific amount of liquid is inserted into a cylinder. A ball is then dropped into the cylinder and fall naturally until it reaches the bottom of the cylinder. A stopwatch is used to record the time taken for the ball to travel in between two marks on the cylinder. The recorded time will be used together with other parameters such as the density of the liquid, the density of ball, the radius of ball, and gravitational constant for viscosity calculation (Leblanc et al., 1999). This measurement process is not automated as the duration of the ball falling is strongly dependent on the human factor. Furthermore, the level of difficulty increases especially when the liquid is in a dark color. Extra information such as the density of the liquid must be included during the calculation, this also means additional measurement to determine the density of the liquid, the density of the ball, and the radius of the ball must be carried out before the viscosity measurement. Hence, this increases the measurement duration.

Different sizes of balls are used with different ranges of viscosity. This makes the measurement process even more complex. After the viscosity is calculated, they are stored manually for further analysis, it is not suitable especially for monitoring purposes.

This research embarks on the objective to simulate the dielectric properties of various engine oils using different resonators design. The relationship between the viscosity and dielectric properties of engine oil will enable the fabrication of a viscometer prototype to enhance portability.

METHODOLOGY

In this research, microwave resonators that serve as a sensor were proposed for viscosity measurement. These microwave resonators were designed by using CST MICROWAVE STUDIO® (Figure 1).

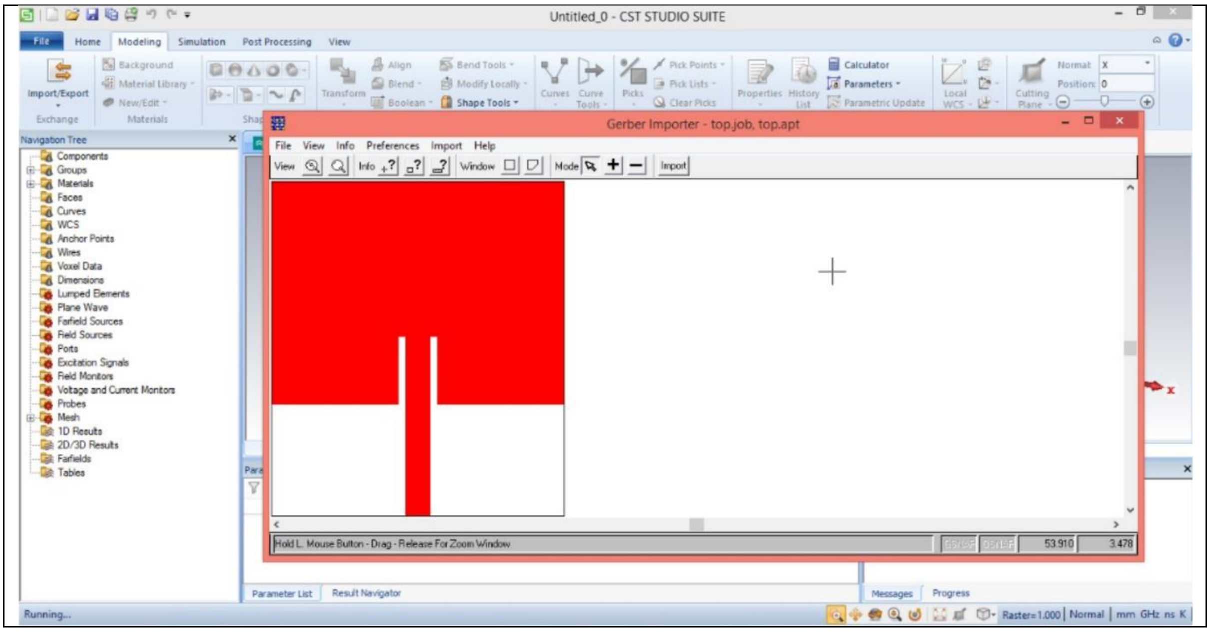

Figure 1. Simulation process using CST Studio Suite

This scope of this research was to investigate the sensitivity of complementary double split-ring resonators (DSRRs) DSRR- FR4 & Roger 3003, split ring resonator, and T-resonator in detecting permittivity variation. In this section, all the sensors were introduced with a variant of dielectric permittivity in simulation. An oil block with a height of 7 mm was designed to cover the resonator part. The permittivity of oil is around 2.33 under the room temperature, therefore, the simulation of dielectric constant variation of an oil sample is in between 2 to 3.8 with a step size of 0.2. Figure 2 represents the designed oil block with 7 mm height to cover only the resonator part.

The sensitivity of proposed sensor is determined based on the ratio of resonant frequency shifting, Δfr (GHz) over variation steps of dielectric permittivity, $\Delta\varepsilon_r$. The sensitivity, S can be calculated based on the variation of resonant frequency, ΔFr and variation of dielectric permittivity, $\Delta\varepsilon_r$. (Equation 1)

$$S = \frac{\Delta f_r}{\Delta \varepsilon_r} \quad (1)$$

The modelling and simulation results were used as a guideline to determine the best design as the fabrication process can be a tedious and challenging process due to high precision and sensitivity are essential to ensure quality and precise results.

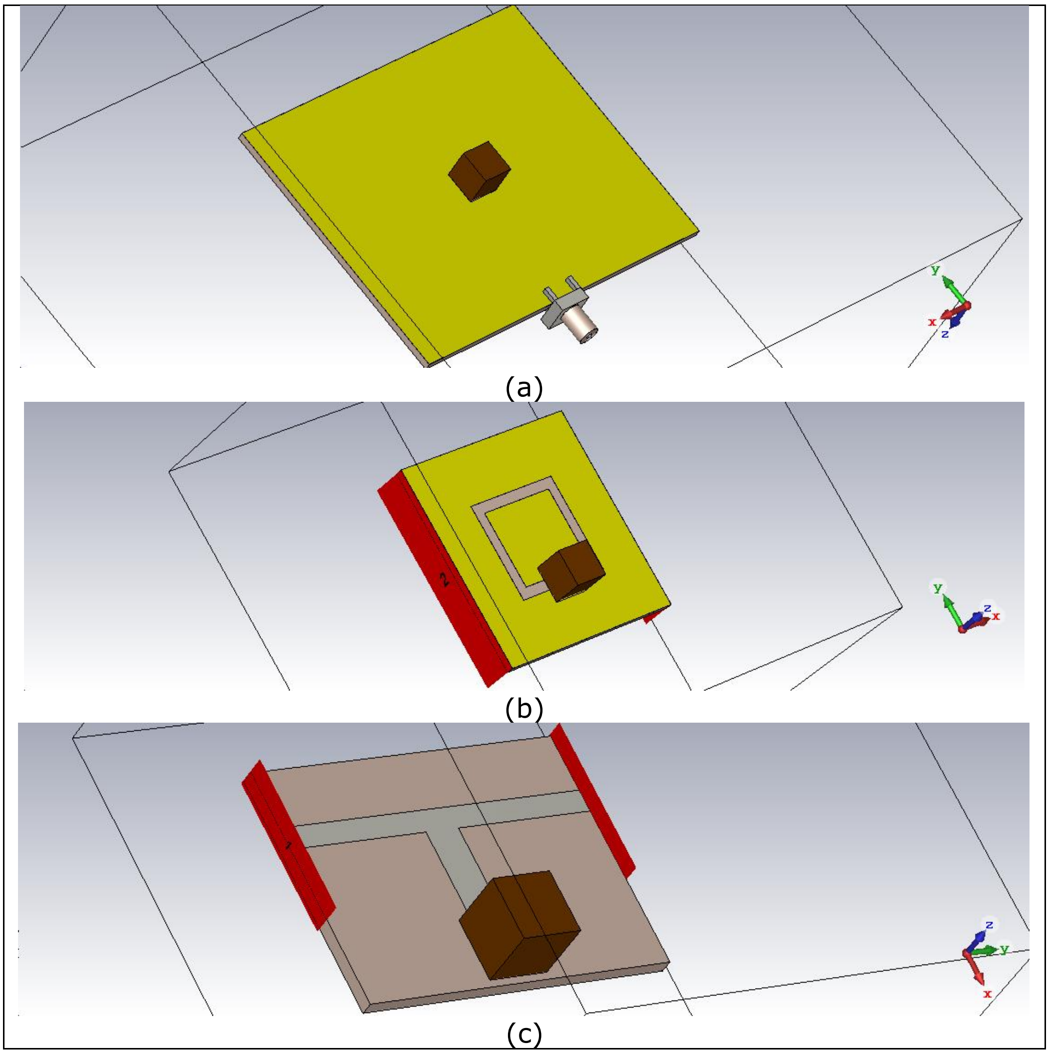

Figure 2. Design oil block on different resonator; (a) resonator with different substrate (FR4 & Roger 3003), (b) split ring resonator, (c) T-resonator

RESULTS

Figure 3 shows the comparison of the S11 parameter of the complementary double split-ring resonator (DSRR) with different substrate material (FR4 and Roger 3003), split ring resonator, and T-resonator. Most circuit boards are made of a material known as FR4 (Flame Retardant level 4), which is a glass fiber/epoxy composite, with copper foil laminated on one or both sides. Meanwhile, Roger 3003 is better known for cores with better high-frequency properties, such as PTFE (Teflon). In this attempt, the quality factor or Q factor is a dimensionless parameter that describes how underdamped an oscillator or resonator is. Higher Q indicates a lower rate of energy loss and the oscillations die out more slowly. Resonators with high-quality factors have low damping. The operating frequency for complementary DSRR with FR4 and Roger 3003 are 2.4 GHz and 4 GHz whereas, for split-ring resonator and T-resonator, their operating frequencies are 3 GHz and 3.5 GHz respectively. Based on the simulated results in Table 1, the simulated resonance frequency for complementary DSRR with FR4 is 2.338 GHz with 599.487 of Q-factor meanwhile the sensor with Roger 3003 substrate is resonating at 3.766 GHz with Q-factor of 1883. The resonance frequency of split-ring resonator and T-resonator are 1.426 GHz and 3.505 GHz respectively whereas the Q-factor for each design is about -274.231 and 565.323 respectively. Furthermore, T-resonator shows the best performance in the S11 parameter which is -54.212 dB meanwhile complementary DSRR with Roger

3003 performs the best in terms of Q-factor. Table 1 summarizes the performance of all designs.

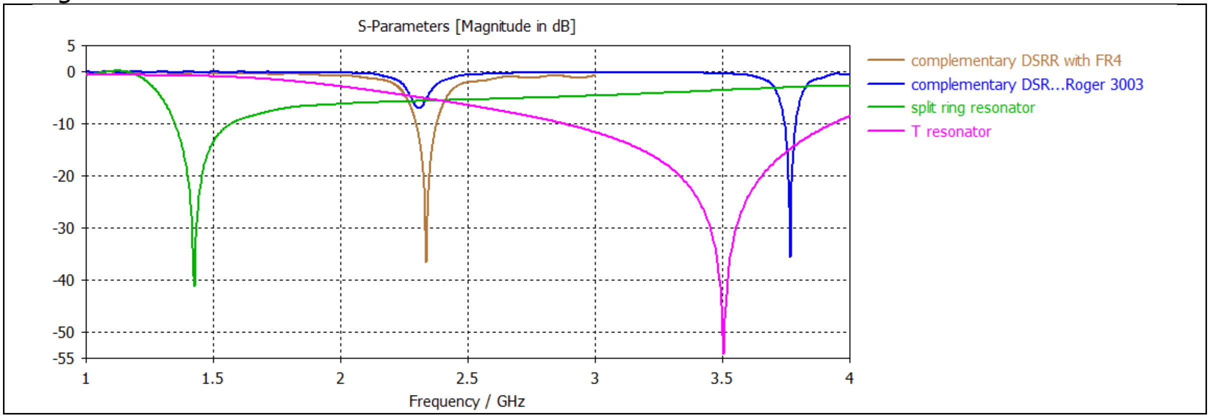

Figure 3. Comparison between performance of complementary DSRR with FR4 and Roger 3003, T-resonator and split-ring resonator

Table 1. Comparison between performance of complementary DSRR with FR4 and Roger 3003, T-resonator and split-ring resonator

Proposed sensor	Resonant frequency, fr (GHz)	S_{11} parameter (dB)	3dB bandwidth (GHz)	Q-factor
Complementary DSRR with FR4	2.338	-36.537	0.0039	599.487
Complementary DSRR with Roger 3003	3.766	-35.493	0.002	1883
Split-ring resonator	1.426	-41.136	0.0052	274.231
T-resonator	3.505	-54.212	0.0062	565.323

Figure 4(a) represents the simulation result of complementary DSRR with FR4 when the dielectric constant of the samples is ranging in between 2 to 3.8 with a step size of 0.2 whereas figure 4(b) represents the simulation result of complementary DSRR with Roger 3003. Furthermore, figure 4 (c) and 4 (d) show the simulated results for the split-ring resonator and T-resonator respectively.

Tables 2 and 3 represent the sensitivity analysis of all sensors. Based on the results in Tables 2 and 3, the complementary DSRR with Roger 3003 and T-resonator is capable to determine the variation of 0.2 permittivities in the sample with the highest sensitivity, S which is around 9×10^{7} and 1.2×10^{8} respectively. The resonance frequencies of both sensors tend to shift to a lower frequency as the permittivity increased. The frequency shifting of complementary DSRR with Roger 3003 has occurred in the range of 3.559 GHz to 3.706 GHz, meanwhile, in T-resonator, the resonance frequency has occurred in the range of 3.204 GHz to 3.376 GHz. T-resonator shows the highest sensitivity towards the permittivity variation of oil samples with a narrower bandwidth compared to complementary DSRR 3003.

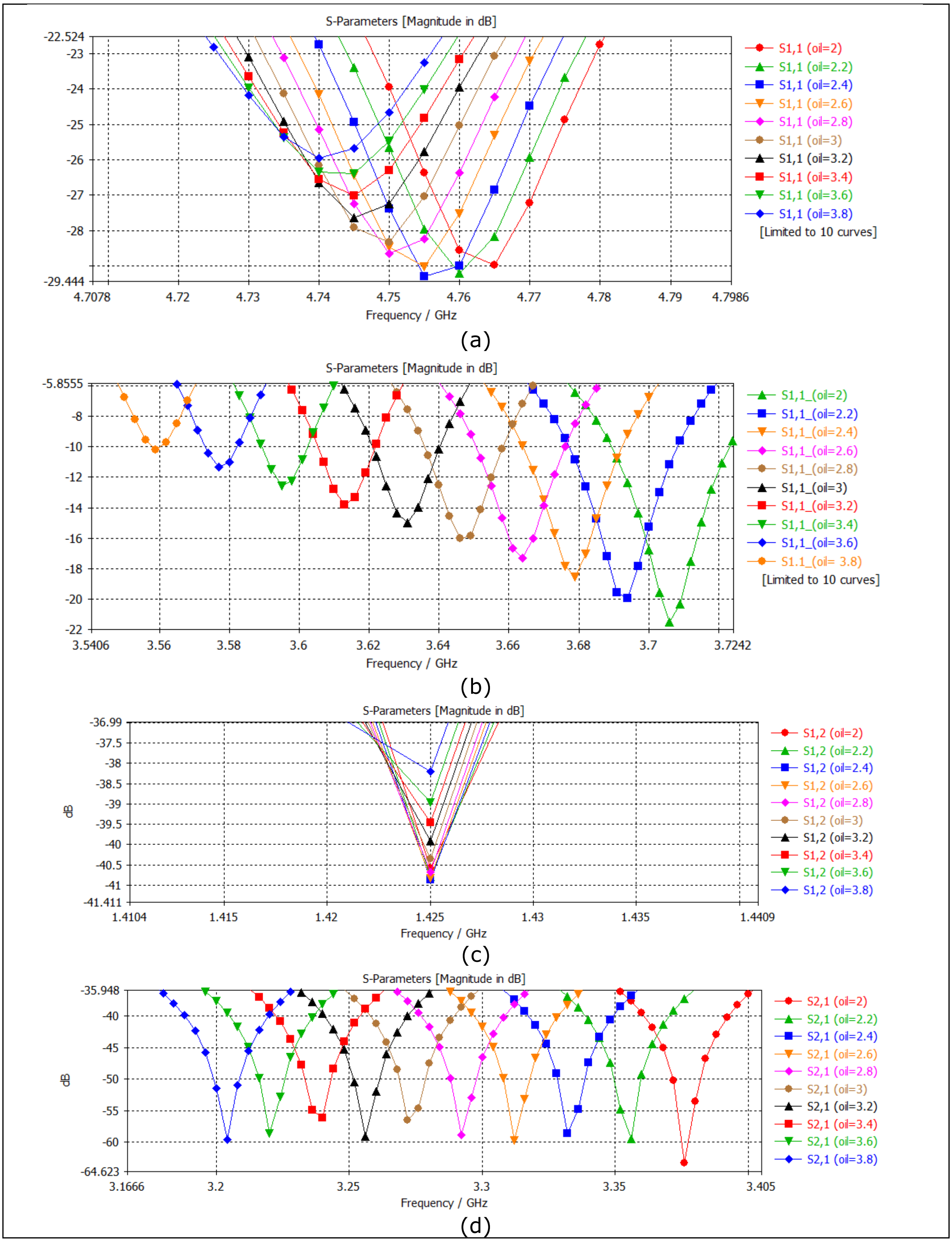

Figure 4. Simulation result of different resonator when the dielectric constant of the samples is ranging in between 2 to 3.8 with a step size of 0.2;(a) complementary DSRR with FR4, (b) complementary DSRR with Roger 3003, (c) split-ring resonator, (d) T-resonator

Table 2. Sensitivity analysis of complementary DSRR with FR4 and Roger 3003

Dielectric permittivity, ε_r	DSRR with FR4				DSRR with Roger 3003			
	Resonant frequency, Fr (GHz)	Variation of resonant frequency, ΔFr (GHz)	Variation of dielectric permittivity, $\Delta\varepsilon_r$	Sensitivity, S	Resonant frequency, Fr (GHz)	Variation of resonant frequency, ΔFr (GHz)	Variation of dielectric permittivity, $\Delta\varepsilon_r$	Sensitivity, S
Unloaded	2.338	-	-	-	3.766	-	-	-
2.0	4.765	-	-	-	3.706	-	-	-
2.2	4.76	0.005	0.2	2.5×10^7	3.694	0.012	0.2	6×10^7
2.4	4.755	0.005	0.2	2.5×10^7	3.679	0.015	0.2	7.5×10^7
2.6	4.755	0	0.2	0	3.664	0.015	0.2	7.5×10^7
2.8	4.75	0.005	0.2	2.5×10^7	3.646	0.018	0.2	9×10^7
3.0	4.75	0	0.2	0	3.631	0.015	0.2	7.5×10^7
3.2	4.745	0.005	0.2	2.5×10^7	3.613	0.018	0.2	9×10^7
3.4	4.745	0	0.2	0	3.595	0.018	0.2	9×10^7
3.6	4.745	0	0.2	0	3.577	0.018	0.2	9×10^7
3.8	4.74	0.005	0.2	2.5×10^7	3.559	0.018	0.2	9×10^7

Table 3. Sensitivity analysis of split ring resonator and T-resonator

Dielectric permittivity, ε_r	Split ring resonator				T- resonator			
	Resonant frequency, Fr (GHz)	Variation of resonant frequency, ΔFr (GHz)	Variation of dielectric permittivity, $\Delta\varepsilon_r$	Sensitivity, S	Resonant frequency, Fr (GHz)	Variation of resonant frequency, ΔFr (GHz)	Variation of dielectric permittivity, $\Delta\varepsilon_r$	Sensitivity, S
Unloaded	1.426	-	-	-	3.505	-	-	-
2.0	1.425	-	-	-	3.376	-	-	-
2.2	1.425	0	0.2	0	3.356	0.02	0.2	1×10^8
2.4	1.425	0	0.2	0	3.332	0.024	0.2	1.2×10^8
2.6	1.425	0	0.2	0	3.312	0.01	0.2	0.5×10^8
2.8	1.425	0	0.2	0	3.292	0.02	0.2	1×10^8
3.0	1.425	0	0.2	0	3.272	0.016	0.2	0.8×10^8
3.2	1.425	0	0.2	0	3.256	0.016	0.2	0.8×10^8
3.4	1.425	0	0.2	0	3.24	0.016	0.2	0.8×10^8
3.6	1.425	0	0.2	0	3.22	0.02	0.2	1×10^8
3.8	1.425	0	0.2	0	3.204	0.016	0.2	0.8×10^8

CONCLUSION

In this work, a viscometer operated based on dielectric spectroscopy is proposed. Various types of resonators as the dielectric sensors were designed via the simulation process. T-resonator shows the highest sensitivity towards the permittivity variation of oil samples with a narrower bandwidth compared to complementary split-ring resonators (DSRRs) DSRR- FR4 & Roger 3003 and split ring resonator. Therefore, the T - resonator is the best-designed resonator compared to others. Based on the simulation results gained, future works involving fabrication of resonators especially the T-resonator can be implemented and deploy them for experimental works.

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