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RESEARCH ARTICLE

Highly Sensitive Electrical Metamaterial Sensor for Fuel Adulteration Detection

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ABSTRACT

Life of any automobile engine is largely dependent on the purity as well as the optimum ratios of their fuels, viz. petrol, diesel and ethanol. A device working on the electrical metamaterial concept, namely a complementary split ring resonator (CSRR), operating at 2.47 GHz (ISM band), is proposed to detect kerosene adulteration in petrol. Kerosene was varied upto 30 per cent with minimum detection limit as low as 10 per cent. Systematic shifts in the transmission resonance frequency were observed. The sensing was fast and the recovery was instantaneous. The underlying concept of interference of electromagnetic radiation through the CSRR circuit and its further manipulation with the changes in the dielectric ambience is elaborated.

Keywords: Electrical metamaterials, complementary split ring resonator, adulteration, flex fuel sensors

1. INTRODUCTION

Metamaterials have attracted lot of attention in recent times due to their unprecedented range of applications in electromagnetics. These are defined as artificially structured materials which attain their properties from the unit structure, and not from the constituent materials. They have their unit structure comparable to the wavelength of interest; due to which their electromagnetic response is expressed in terms of homogenized material parameters (i.e. effective permittivity and effective permeability)[1]. In 1968, Veselago theoretically proved the possibility of left handed materials[2]. Later, this domain of science (and mostly, the technology) initiated when Smith et al. published their works on a structured material with simultaneously negative permeability and permittivity at microwave frequencies, in the year 2000[3]. Various applications came in later, which exhibited the metamaterials in various sizes, shapes, materials and geometry for applications including cloaking, superlenses and antennas[4-5]. Sensors are also one domain of the applications, in which significant progress has been done, in recent 5 years or so[6-9]. Our own efforts have also been documented towards making of such structures, mainly electrical metamaterials for applications in sensing[10-12].

Fuel adulteration is a global menace especially in South Asian countries. For petrol and diesel, kerosene is the most widely used adulterant, mixed for monetary gains. Adulteration as high as 30 per cent is incorporated[13], which results in substantial loss to the country's economy. Further, kerosene is more difficult to burn than petrol, and hence its addition results in higher emission of carbon and carbon monoxide; leading to environmental pollution along with premature failure of engine components[14]. There are many methods to detect adulteration in fuel, like density measurement method, fiber grating sensor technology, emission testing, filter paper method, gas chromatography, ash contamination determination and so on[15-17]. However, these methods are either laboratory-based or equipments are too bulky and costly. So there is crucial need of a fuel detection device, which should be highly sensitive, selective, low-cost with quick recovery and response time. In this context, we propose a metamaterial based device designed in the industry scientific and medical (ISM) standard band for detection of adulteration in conventional fuel.

Using the preliminary studies done earlier[10], a device is being developed and projected here working in ISM standard band. The sensor is a complementary split ring resonator (CSRR) circuit, which exhibits sub-wavelength resonance (resonance at $\lambda/18$ in this case) having higher sensitivity and Q-factor. Further, a PDMS-based sample cavity is fabricated for micro-quantity sensing to make the device more sensitive, precise and selective. A device operating at 2.47 GHz is hence proposed for kerosene adulteration (in petrol, varying upto 30 per cent). Standard samples (unadulterated fuel) were derived from the Company operated Company owned (CoCo) petrol pump, and the adulterated samples were actually made in the laboratory for accurate calibration. Systematic changes in the resonance frequency as well as magnitude (power) were observed with adulterated fuels. The sensing measurements were done on vector network analyer (VNA, (Agilent PNA N5222A)). The sensing was fast and the recovery was almost instantaneous; promising an accurate and sensitive device for detection of adulterated petrol.

2. DESIGN AND THEORY

Electrical metamaterials made from the CSRRs are based on Babinet's principle[18], having two concentric rings etched out from a conductive surface which behaves as an electric dipole as they are excited by an axial electric field,applied

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perpendicular to the CSRR plane. This excitation can be accomplished by using a microstrip transmission line with the CSRR etched on the ground plane. The resonant frequency is given by the following standard expression[19]:

$$\omega_o = 2\pi f_o = \left(L_C C_C\right)^{-1/2} \tag{1}$$

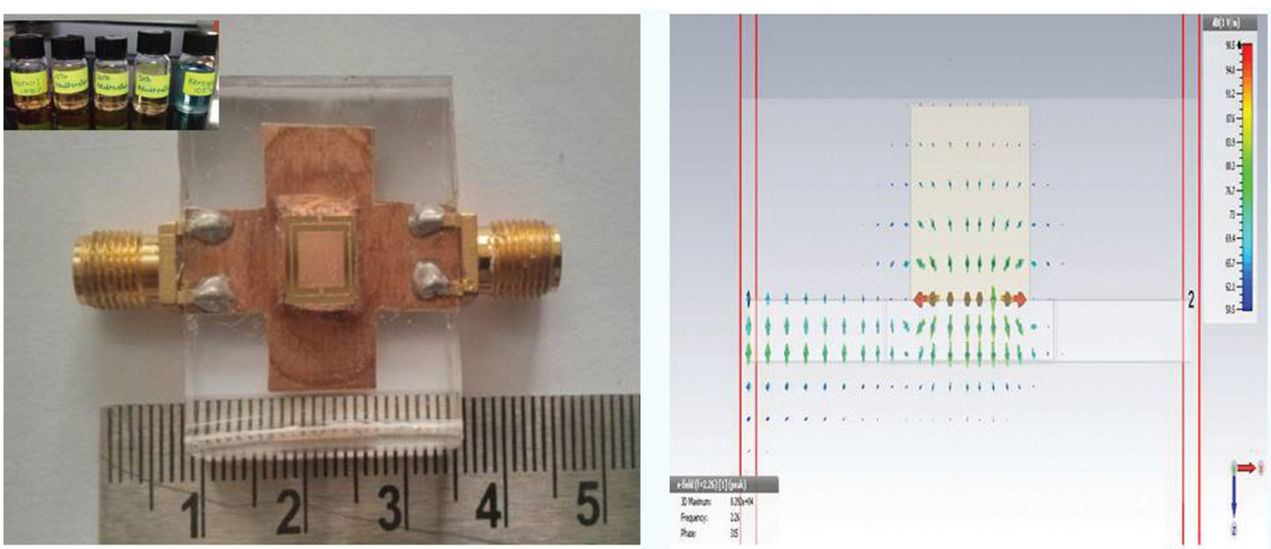
ω_o is the angular resonant frequency L_C and C_C are inductance and capacitance of the CSRR. Change in the permittivity of the sample material reflects the change in the capacitance of the CSRR (C_C) of the sensor[20]. The CSRR was designed with specific dimensions to yield the resonant frequency of 2.51 GHz. Figure 1(a) shows the copper structure which was fabricated on a commercially available FR4 epoxy (ε_r= 4.4 thickness h = 1.6 mm) substrate. The structure was embedded in the PDMS mould, to make a cavity for liquid confinement which shifted the resonating frequency of the sensor to 2.47 GHz. A micro-pipette was used to drop-cast the liquids in the cavity, completely filling the cavity for pure as well as adulterated fuels. The color difference in the adulterated fuels, when compared to pure petrol, is hardly differentiable as shown in inset of Fig. 1(a). The measurements were carried out for 10 per cent, 20 per cent and 30 per cent adulterated fuels. The PDMS cavity was so designed that the walls of the cavity restricted the liquid sample strictly over the active area of the sensor. The CSRR unit cell structure and experimental set up has been mentioned in detailed by Rawat[10], *et al*. The cell dimensions of the CSRR for the desired resonant frequency area = 6.82 mm, c =0.52 mm, d = 0.2 mm and g = 0.32 mm. The shape of the microstrip line was changed from rectangular to plus-sign as to further reduce the size while retaining the Q-factor of the device. Dimensions of the device was 26 mm x 20 mm.

3. RESULTS AND DISCUSSION

The simulation of CSRR design (with and without PDMS cavity) was carried out using CST Microwave Studio which matched well with experimental results (not shown). Fig 1(b) shows E-fields at the time of the resonance of the simulation setup of the CSRR cavity. The figure clearly shows more flux of E-fields above the CSRR structure rather than below. This suggests that upon insertion of the sample inside the cavity, significant change in the E-fields path will lead to change in C_c (dependent on the real part of relative permittivity of sample) and hence the inherent resonance frequency shift (of the CSRR frequency). Table 1 shows the experimental values of the permittivity measurements done using Agilent Dielectric Probe Kit (85070E) for the fuels[21] along with the simulation and experimental response for petrol and kerosene. On exposing the sensor with 300 µL of petrol and kerosene, the resonant frequency of the empty cavity shifted from 2.47 GHz to 2.254 GHz and 2.281 GHz by 216 MHz and 189 MHz, respectively. Figure 2 shows the S21 response of the sensor for adulterated combination for 10 per cent, 20 per cent, and 30 per cent kerosene in petrol. This indicated that it is easy to identify contamination (adulterated fuel), if the adulteration is around 10 per cent or more. Figure 3 shows the data for various percentages of adulterated fuels, both in terms of magnitude (power) as well as frequency change where the transmission frequency shifted to 6 MHz, 9 MHz, and 13 MHz with respect to petrol. There was negligible change in transmission magnitude of all the samples (approx. 1.5 dB for petrol and kerosene). Further detailed studies are ongoing, which can offer a proper calibration scale with this device; for adulteration in petrol.

Table 1. Comparison of simulation and experimental values of petrol and kerosene.

Fuels	Permittivity (real part)	Loss tangent	S21 resonance frequency (GHz)	
			Simulation	Experimental
Kerosene (300 uL)	2.26	~0.00	2.280	2.281
Petrol (300 uL)	2.41	~0.00	2.260	2.256



(a) (b)

Figure 1. (a) shows the CSRR device with the PDMS cavity along with photograph of fuel samples (inset) (b) Simulation of E-fields of CSRR cavity sensor.

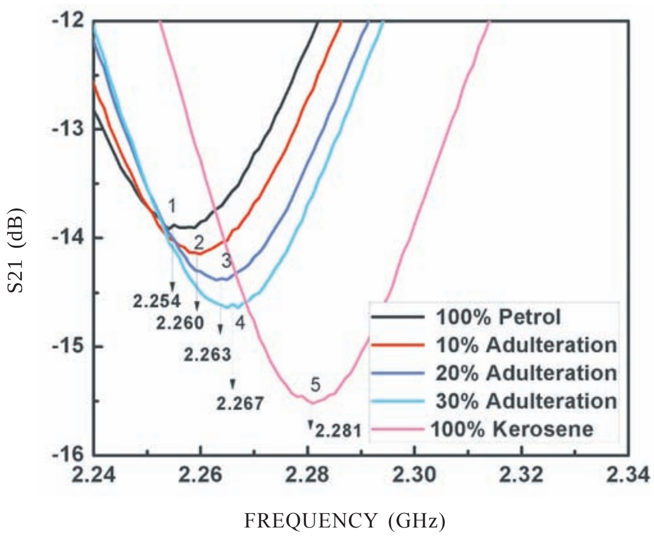


Figure 2. Shows the variation in S21 response for various adulterated concentrations of kerosene in petrol.

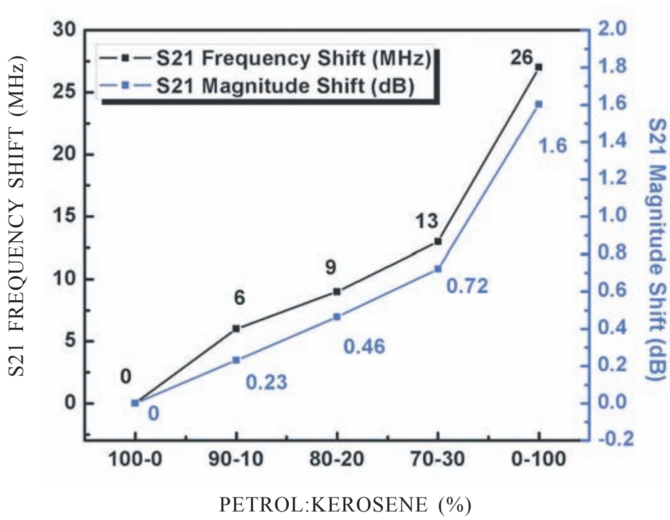


Figure 3. Shows the combined picture of the actual frequency and magnitude shifts wrt compositions of adulterated fuels.

It is important to mention that the sensor had good repeatability, rapid recovery, and cheap fabrication technique. Substantial shift in the resonance frequency of the sensor ensures its practical applicability not only at gas stations, and to the consumers, but also the fuel owners, to check the quality and hence life of their automobile engines. Extreme miniaturization due to the metamaterial approach is the prominent advantage of the envisaged device.

4. CONCLUSION

In conclusion, a CSRR based sensor has been designed which provide good sensitivity in detecting a small amount of liquid samples of adulterated fuels. The sensors also provides extreme miniaturization, micro-quantity, fast sensing and repeatability; thus promising a practically implementable product. The cavity based approach, along with the ISM band applicability provides impetus for ease in manufacturing.

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