Tri Circle Split Ring Resonator Shaped Metamaterial With Mathematical Modeling for Oil Concentration Sensing

MD. RASHEDUL ISLAM\textsuperscript{1}, MOHAMMAD TARIQUL ISLAM\textsuperscript{1}, (Senior Member, IEEE), AHASANUL HOQUE\textsuperscript{1}, (Member, IEEE), MOHAMED S. SOLIMAN\textsuperscript{2,3}, (Senior Member, IEEE), BADARIAH BAIS\textsuperscript{1}, (Senior Member, IEEE), NORSUZLIN MOHD SAHAR\textsuperscript{4}, AND SAMI H. A. ALMALKI\textsuperscript{2}

\textsuperscript{1}Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor 43600, Malaysia
\textsuperscript{2}Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia
\textsuperscript{3}Department of Electrical Engineering, Faculty of Energy Engineering, Aswan University, Aswan 81528, Egypt
\textsuperscript{4}Space Science Center (ANGKASA), Universiti Kebangsaan Malaysia, Bangi, Selangor 43600, Malaysia

Corresponding authors: Md. Rashedul Islam (p100838@siswa.ukm.edu.my), Mohammad Tariqul Islam (tariqul@ukm.edu.my), and Badariah Bais (badariah@ukm.edu.my)

This work was supported in part by Universiti Kebangsaan Malaysia under Grant DIP-2021-011; and in part by Taif University Researchers Supporting Project through Taif University, Taif, Kingdom of Saudi Arabia.

\textbf{ABSTRACT} In this research paper, the sensing capabilities of a tri circle split ring resonator shaped metamaterial is shown within the X-band frequency range for detection of various oil samples both theoretically and experimentally. Mathematical modelling was used to analyze the sensor efficiency for the various oil samples. A new sample holder has been made for the proposed sensor structure, and it showed significant performance. The simulated and measured transmission coefficient has been revealed in this study and monitoring the shift of resonance frequency and sensitivity of the metamaterial sensor for different oil samples. Since the dielectric constants of the oil samples differ, hence the resonance frequency is shifted. The obtained result revealed that the proposed sensor can detect a wide range of liquids, including (i) coconut and extra virgin coconut oils, (ii) olive and extra virgin olive oils, (iii) clean and waste engine oils, (iv) sunflower and canola oils. The resonance frequency has shifted to about 210, 230, 170, and 200 MHz for the above-mentioned oil samples, respectively. The sensitivity of the proposed MTM sensor is $-83$ dB (mg/L) which is a new analysis and quite significant as a potential sensor structure. Surface current and electric field distributions were used to deduce the sensing process. Since the recommended sensor is cheap and highly sensitive; so, it can be used in a variety of fields, such as detection of various liquids, microfluidic sensing, and industrial applications.

\textbf{INDEX TERMS} Metamaterial, split ring resonator (SRR), tri circle, dielectric constant, mathematical modelling.

\section{I. INTRODUCTION}
Metamaterials (MTMs) are artificial materials made up of sub-wavelength resonant components capable of manipulating an electromagnetic (EM) field. It shows negative permeability and negative permittivity [1], but natural material does not show these properties. The MTMs physical features are widely reliant on the formed unit cells’ design, shape, dimensions, and orientation. In recent years, research into the sensor applications of metamaterial has exploded. MTMs have an advantage over natural materials in that they can be engineered and tuned by manipulating their structural geometry and arrangement. Various applications of MTMs are biosensors [2]–[4], absorbers [5], [6], antennas [7], [8], energy harvesting, microwave sensors [9], [10], SAR reduction, and microwave lenses [11], [12]. MTMs provide several topologies; the most used topology is the split-ring resonator (SRR). SRR-based MTMs are used in various applications...
due to the adaptability and practical shape of the resonator. This research intends to make a tri circle split ring resonator-shaped metamaterial sensor for detecting various oil samples with high sensitivity. In the field of microwave sensors, the design of the MTM based sensor has gained enormous attention to the researcher [13]. Emerging technology allows us to create a new material with exceptional EM properties. The resonant frequency is an important feature of the MTM sensor’s principle for material detection.

An SRR based microstrip chemical sensor was demonstrated in [14] for the differentiating of ethanol and methanol solvents at 1.90 GHz operating frequency. The size of the sensor is small, and the quality factor is low. An oval-shaped sensor is presented in [15] for the glucose concentration measurement in an aqueous solution. The sensor’s sensitivity was expected at 0.037 GHz per 30 mg/dl glucose solution. A triple ring resonator-based MTM sensor is described in [16] for fuel adulteration detection. A sample holder was attached with the designed structure in the frequency range of 8 to 12 GHz in this analysis. The resolution and quality factor of this MTM sensor are high, but the resonant frequency shift is low due to the small change of the sample’s dielectric constant. Some of the MTM sensors are described in [17], [18] based on the shift of the resonance frequency, but these values are low. An SRR-based MTM sensor is demonstrated in [19], for the microfluidic channel that is used to define resonance frequency shifts. Another MTM sensor demonstrated in [20] for the liquid’s dielectric properties measurements, 60 MHz resonance frequency shifted in this analysis. An MTM sensor is demonstrated in [21] for the detection of different oils. The resonance frequency shifted 70 MHz for clean and dirty transformer oils and 50 MHz for olive oil and corn oil.

In [15], a left-handed MTM based sensor was presented for glucose sensing in the S-band. The mechanism of this sensor is the change of resonance frequency with the change of permittivity. Several designs of MTM sensors are described in [22]–[24] for the identity of various types of liquids. Resonance frequency has been shifted for the effect of the dielectric constant of the mentioned liquids. However, various approaches are developing with a great tendency for the wide applications of MTM sensors [25], [26]. It is noticeable that the MTM based microfluidic sensor is used for fuel adulteration sensing and content of ethanol in fuels [4], [27]–[29]. Kerosene is the most used ingredient for adulteration in diesel and petrol. In [30], oil pollution was described, where kerosene burning produces more noxious waste emissions, resulting from diesel and petrol engine damage. A meander line shape MTM-based sensor is demonstrated in [31] for the application of polypropylene sensing. It has desired sensitivity, compact size, small accuracy, and low-quality factor. G-shaped resonator-based MTM sensor is presented in [32] to detect liquid chemicals in the 8 to 12 GHz frequency range. The sensor works well to identify several liquids using frequency shift.

In this study, a new tri circle SRR shaped MTM with mathematical modelling is designed, analyzed, and fabricated for the detection of different oils within the X-band. To select the recommended resonator and size of the substrate, we analyzed the resonator size, split gap, radius, width, and the various dimension of the substrate. It is also noticeable that the suggested MTM sensor is cheap, high sensitivity, and suitable to be operated within X-band. Through the shifting of resonance frequency, the quality of the various samples has been detected. The recommended sensor is viable to be used in different applications, including industrial and liquid chemicals detection. The surface current and E-field distribution of the proposed sensor have been analyzed. The equivalent circuit has also been analyzed for the validation of the MTM structure.

II. DESIGN AND SIMULATION OF THE MTM SENSOR

The recommended MTM sensor has been presented in Figure 1. The electromagnetic high-frequency solver computer simulation technology (CST-2019) microwave studio has been used for the design and analysis of the sensor. The suggested MTM sensor consists of three circle SRR. The whole size of the MTM sensor is 22.86 \times 10.16 \text{mm}^2; this dimension is selected for the adjustment of the X-band waveguide (WR90) since the guided opening of the WR90 waveguide is 22.86 \times 10.16 \text{mm}^2. Three suitable layers are used in this MTM sensor design; these are substrate, resonator, and sample holder (sensor layer). The thickness of the sample holder is 7 mm. Flame retardant-4 (FR-4) was used as a substrate, because of its minimal loss, low cost, and superior mechanical intensity. The relative permittivity and loss tangent of the FR-4 substrate is 4.3, 0.025, and its thickness is 1.5 mm. The resonator has been made of copper metal which is printed on both sides of the substrate. The thickness and conductivity of the copper are 0.035 mm, and 5 \times 10^{-8} \text{ S/m}, in that order. The sample holder has been made by a different...
layer of acrylic sheet. The dimension of the sample holder is 22.86 × 10.16 mm² which is the same dimension of the guided opening of the extended wave, WR90 waveguide, and MTM sensor. The sample holder is attached to the backside of the substrate, the thickness of the acrylic sheet for the sidewall is 1.5 mm, and the front and backside layer is 1 mm; the loss tangent and permittivity of the sensor layer is 0.004 and 2.4, respectively. The sample holder was used to keep the samples under test. There are three key layers to the MTM sensor. It’s also worth noting that the proposed MTM sensor is inexpensive and suited for use in the X-band frequency. Since the recommended sensor is cheap and highly sensitive; so, it can be used in a variety of fields, such as detection of various liquids, microfluidic sensing, and industrial applications.

The boundary conditions were applied in the simulation to see the transmission response (S₂¹). Intrinsically, using the WR-90 waveguide together with a corresponding sample holder to calculate S₂¹. As shown in Figure 2, the boundary condition of the perfect electric conductor (PEC) was assigned to the x- and y-axes, while the z-axis (added space) along the propagation path is assumed to be free space. Due to the metallic structure of the side-wall waveguide, boundary conditions such as open space, periodic distribution, PEC/PMC, and PEC are suitable [32]. The basic reason for using PEC boundary conditions in the simulation study since we have realized experimental setup conditions. The simulation is carried out in the 8-12 GHz frequency range.

The novel idea of the proposed work is sensitivity analysis, mathematical modelling of the sensor, and designing a new sample holder for performance enhancement of the sensor. Also showed the better performance of the proposed sensor than the other reported MTM sensor (Table 4). The sensitivity is an essential feature of the microwave sensor to analyze the dielectric characteristic. The sensitivity of the proposed MTM sensor is −83 dB (mg/L) which is a new analysis and quite significant as a potential sensor structure. We have also used mathematical modelling to justify the sensor’s performance. Furthermore, a small change in the dielectric constant value causes a substantial shift in the resonance frequency, which proves the very good performance of the sensor. It’s also worth noting that the proposed MTM sensor is inexpensive and suited for use in the X-band frequency.

### Table 1. Design parameters of the recommended resonator.

| Parameters | Value (mm) | Parameters | Value (mm) |
|------------|------------|------------|------------|
| r₁         | 3.9        | w          | 0.6        |
| r₂         | 2.8        | g          | 0.5        |
| r₃         | 1.7        |            |            |

Figure 3(a, b) depicts the various resonator designs and transmission responses (S₂¹) to them. In design 1, only 1st ring has been used on the substrate, then the achieved S₂¹ magnitude is −27.79 dB at 11.38 GHz. To increase the electrical length, the 2nd ring is added with the 1st ring on the substrate, the obtained resonance frequency 8.23 GHz with a magnitude of −15.64 dB as shown in design 2. In design 3, the 3rd ring is added with the 1st ring on the substrate, the obtained S₂¹ value is −25.18 dB at 9.47 GHz. In designs 4, 2nd, and 3rd with the 1st ring on the substrate, the obtained S₂¹ value is −25.18 dB at 9.47 GHz. In designs 4, 2nd, and 3rd rings have been used on the substrate, the achieved magnitude of S₂¹ is −16.78 dB at 11.43 GHz. In the final design, 1st, 2nd, and 3rd rings have been used on the substrate for increasing the sensing effect, the S₂¹ values are −15.37 dB at 8.34 GHz and −19.35 dB at 11.59 GHz. Since the two resonance frequencies and more sensing effects have been found from the tri circle SRR, hence the tri circle SRR has been selected for the proposed MTM sensor.

The tri (multiple) circle SRR shape has been proposed; since it can remove bianisotropic reactions and cross-polarization results in the dielectric mode as compared with a single SRR, and two SRR, because of its broad-side character. Another advantage of using a tri circle SRR
form is that it increases capacitive loading in the structure, which results in stronger resonance behavior. Furthermore, the proposed tri circle shaped SRR can achieve considerable miniaturization factors [48], [49]. Hence the tri circle SRR has been used for the suggested MTM sensor.

An SRR is one of the most extensively used non-natural magnetic materials [33], and it is made up of metal rings that are produced in a dielectric mode; and these shapes are circular, rectangular, spiral, omega, and others. Each form has its coupling impact based on its shape and EM qualities, such as side coupling in a circular structure, broadside coupler in a rectangular shape, and so on. Furthermore, the SRR exhibits bianisotropic effects and cross-polarization effects as the E-field stimulates the magnetic dipole moment. The bianisotropic performance and cross-polarization results are abolished if the metallic rings have a broadside character [34]–[36]. The tri circle SRR shape has been proposed; since it can remove bianisotropic reactions and cross-polarization impacts in the dielectric mode as compared with a single SRR, because of its broadside character. Another advantage of using a tri circle SRR form is that it increases capacitive loading in the structure, which results in stronger resonance behavior. Furthermore, the proposed tri circle shaped SRR can achieve considerable miniaturization factors [37], [38]. Hence the tri circle split ring resonator has been used for the proposed MTM sensor.

The revised circuit has given by including the characteristics impedance on the terminal part of ADS simulation as like CST simulation. The corresponding value is 377Ω at both terminals. In addition, an LC tank was added between the outer, and 2\textsuperscript{nd} ring due to high field concentration and surface current distribution. Therefore, the modified equivalent circuit is illustrated as in Figure 4(a). The inclusion of these new components does not change the overall S-parameter response significantly except a −10 dB magnitude decrease in \( S_{21} \). Overall, the resonance points remain the same, and bandwidth is approximately the same as the previous response. The LC tank circuit contributes to maintaining the overall response frequency. Therefore, a logical approach of equivalent circuit modification was performed to further clarify the proposed resonator. For each circle ring, a lumped component equivalent LC circuit has been analyzed to construct the geometry of the unit cell. Numerical analysis of these LC resonating components performed by commercially available Advanced Design System (ADS) software to approximate the RF nature. The estimation of the LC network was performed using the approximation mentioned in [15]. The equivalent circuit enhances the geometry estimation by presenting split gap and patch using LC network and each of the LC tank circuits mutually connected by a gap capacitor. After the simulation in ADS and CST, both \( S_{21} \) performances were compared, as shown in Figure 4(b–d). The RF lumped component ADS response indicates that each potential resonance point exists with an approximate value of −38.11 dB at 11.32 GHz, −18.53 dB at 8.67 GHz, −25.20 dB at 9.01 GHz, and −38.75 dB at 11.63 GHz. All these points have a close approximation compared to each ring’s corresponding CST response in the proposed unit cell. Therefore, a tri circle ring combination of the unit cell geometry would be a potentially...
balanced and compact SRR choice to implement the sensing application.

The electric field distribution has been investigated to understand the designed sensor’s mechanism. The electric field distribution provides information about the device’s energy contained and losses. The electric field is created across the gap between the CSRR capacitive plate and the circled resonator during the resonances, making the region adjacent and inside the CSRR sensitive to dielectric changes. As a result, this region inside the CSRR can be used to test the dielectric characteristics of materials. In the empty sensor layer, the distributions are achieved at the resonance frequencies of 8.34 and 11.59 GHz.

The electric field strength is more concentrated in the resonator components, especially in the resonator’s capacitive elements, as shown in Figure 5(a, b). At 8.34 GHz resonance frequency, the E-field distribution is effectively seen on the resonator, but at 11.59 GHz, it affects resonator parts with its surroundings due to the capacitive effect. Therefore, any small change in the sample’s electrical characteristics in the sensor layer can be a sense in the proposed structure.

Figure 6(a, b) shows the surface current distribution simulation graphs at the resonance frequency of 8.34 and 11.59 GHz. It is seen from the Figure; surface current is more accumulated on the inner and middle inductive circles due to the strong magnetic fields. In addition, that, more currents are disseminated in the resonator’s left and right sides, regulating the electric and magnetic response, respectively. Parallel and anti-currents occurred at resonators, as seen in the Figure. Parallel currents were caused by the electric field, whereas anti-parallel currents were caused by the magnetic response to the applied EM field. The importance of resonators in resonant states is further explained in the Figure. The resonators are affected differently by each part of the resonators. The simulated surface current distribution for the recommended structure is a clear indicator of the presence of the electric dipole that generates the resonance phenomena.

Figure 7 shows the reflection response ($S_{11}$) and transmission response ($S_{21}$) when the sample holder was empty. The Figure shows that the coefficients of reflection and transmission in the frequency spectrum of the X-band. This influence shows that when various oils are put in the sensor layer, then this is controlled within the 8-12 GHz frequency spectrum, the recommended MTM-based sensor form can be efficiently used to differentiate distinct oils. The $S_{21}$ values are $-15.37$ dB at 8.34 GHz and $-19.35$ dB at 11.59 GHz. As a result, various oil samples with electrically sensitive qualities have been selected to be examined in the preferred frequency range, both theoretically and experimentally.

III. PROPOSED SENSOR ANALYSIS WITH MATHEMATICAL MODELLING BASED ON SIMULATED AND MEASURED RESULTS

In this segment, using the FIT-based high-frequency EM solver CST microwave studio, a mathematical analysis is
carried out on the suggested resonator for sensing various oil samples. The resonators are placed on both sides of the FR-4 substrate. The sensor layer was designated as a 7 mm thick reservoir to be filled with different oils, where the transmitted EM wave’s magnetic field is perpendicular to it in the z-axis. Port 1 and port 2 of the waveguide were attached to the front and back sides of the intended structure for numerical analysis and experimental testing of the transmission response ($S_{21}$). For the X-band waveguide, the guided opening dimensions are $22.86 \times 10.16 \text{ mm}^2$, which is the same size as the proposed structure.

To reveal the metamaterial property, the real and imaginary portions of the relative permeability ($\mu_r$), relative permittivity ($\varepsilon_r$), refractive index ($n$), and impedance ($Z$) of the sensor were acquired from the CST simulation, which is revealed in Figure 8(a-d).

The frequency range of negative effective parameters is listed in Table 2.

From Table 2, it is seen that the real part of the relative permittivity and relative permeability are negative in the frequency range of 10.98-11.57 GHz, which identifies the proposed resonator structure has potential MTM property.

The resonance frequency ($f_0$) of the suggested sensor has been affected by the resonator width, which is shown in Figure 9(a). When the sample holder was empty, the simulation has been done to show the shift of resonance frequency. In the proposed sensor, the resonator width has been changed, and observed the effect of the resonance frequency. There are five different widths of the resonator that has been used in this MTM based sensor, such as $w = 0.4$, 0.5, 0.6, 0.7, and 0.8 mm. It is seen that the $f_0$ is 8.20 and 11.21 GHz for the 0.4 mm resonator width and 8.46 and 11.79 GHz for the 0.8 mm resonator width. Since the resonator width is inversely proportional to the inductance, and inductance is inversely proportional to the $f_0$, hence $f_0$ is increasing with increasing the width of the resonator. So, the sensor is properly obeying the relation of $f_0$ and inductance. The resonator width of 0.6 mm has been selected for the suggested MTM sensor.

Figure 9(b) indicates that the impact of the different split gaps on the resonance frequency ($f_0$). When the split gap varies from 0.3 mm to 0.7 mm with an increment of 0.1 mm, then the $f_0$ has been seen 8.15 and 11.50 GHz for the 0.3 mm split gaps and 8.27 and 11.64 GHz for the 0.7 mm split gaps. Since the split gap is inversely proportional to the capacitance and capacitance is inversely proportional to the $f_0$, hence $f_0$ is increasing with increasing the split gap, i.e., the sensor properly obeying the relationship between $f_0$ and capacitance.
The 0.5 mm split gap was used to fix the suggested MTM sensor design. Figure 9(b) indicates that the impact of the different split gaps on the resonance frequency \( f_0 \). When the split gap varies from 0.3 mm to 0.7 mm with an increment of 0.1 mm, then the \( f_0 \) has been seen 8.15 and 11.50 GHz for the 0.3 mm split gaps and 8.27 and 11.64 GHz for the 0.7 mm split gaps. Since the split gap is inversely proportional to the capacitance and capacitance is inversely proportional to the \( f_0 \), so the value \( f_0 \) increases with increasing the split gap, i.e., the sensor properly obeying the relationship between \( f_0 \) and capacitance. The 0.5 mm split gap was used to fix the suggested MTM sensor design.

The effect of varied sample holder sizes on the \( f_0 \) is shown in Figure 9(c). If the size of the sample holder varies from 5 to 9 mm with an increment of 1 mm, then the lower \( f_0 \) values vary from 8.19 to 8.28 GHz and the higher \( f_0 \) value varies from 11.58 to 11.63 GHz. Here the size of the sample holder is inversely proportional to the capacitance, and capacitance is inversely proportional to the \( f_0 \), so the value of \( f_0 \) is increasing with increasing the size of the sample holder i.e., the proposed sensor properly follows the \( f_0 \) and capacitance relation. In the proposed MTM sensor, the size of the sample holder 7 mm is selected.

The effect of unit cell orientation on the \( f_0 \) is shown in Figure 9(d). When the unit cell placed in the X-direction for simulation, got two values of \( f_0 \), these are 8.34 and 11.59 GHz. If the unit cell is placed in the Y-direction, it also got two values of \( f_0 \), these are 8.34 and 11.59 GHz which are the same as the X-direction. So, it can be said that there is no effect of unit cell orientation in the simulation.

Figure 10 reveals the dielectric constant and loss tangent measurement setup for various oil samples. An open-ended coaxial probe was used to investigate the electrical properties of each sample. In this analysis, dielectric constant, and loss tangent measurements were carried out utilizing the N1500A dielectric probe kit. The probe kit was connecting with a power network analyzer (PNA)-L series vector network analyzer (VNA) N5224A in the 50 MHz to 43.5 GHz frequency range. The dielectric probe was calibrated using air and pure water at room temperature (25 °C) with well-known EM features in the frequency range of 8-12 GHz. In this frequency range, the dielectric constant and loss tangent of the different oils were obtained. The same process was repeated for each oil sample.
Figure 11 depicts the measurement procedure of the proposed MTM sensor. The front and back views of the fabricated MTM sensor are indicated in Figure 11(a-b). Figure 11(c) shows the oil insertion process in the sample holder. To fill oils, there is a gap on the upper side of the holder, which is closed with the same material to prevent adverse effects on the environment. By using the syringe, oils have been filled in the sample holder. The sample holder is filled with the 1.625 ml oil samples. To prevent contamination between the samples, each oil sample was placed in a different sample holder. The MTM sensor outputs are directly influenced by the dielectric constant of oils positioned inside the sample holder. Two waveguide ports and one extended guided wave attached to the coaxial cable linked by TNC female connector and N5227A PNA microwave network analyzer using the PNA-L series vector network analyzer (VNA) in the 10 MHz to 67 GHz frequency range is depicted in Figure 11(d). The MTM sensor is attached to the waveguide, which is shown in Figure 11(f). A calibration kit Agilent N4694–60001, was used to calibrate the VNA. Firstly, the fabricated metamaterial sensor is attached with the guided opening of the X-band waveguide. The capacitive parts relate to split gaps of the resonator are assembled as sensor layers.

Figure 13 shows the measured (a) dielectric constant and (b) loss tangent for the coconut oil and extra virgin (EV) coconut oil. The sample holder is placed on the suggested sensor between the waveguide and the extended guided wave, as shown in Figures 11(e). So, there is no direct contact between the oil sample and the metallic layer of the suggested sensor. This configuration was used to measure the transmission response ($S_{21}$) in the 8-12 GHz frequency range. For each sample, the same experimental procedure was followed.
A. MATHEMATICAL MODELLING OF THE METAMATERIAL SENSOR

During the sensing measurement, the waveguide port (WR90) considers the standard model for classical EM wave propagation. Medium variation during the propagation deals with relatively narrow bands of radiation; hence studying fixed frequency problems is quite reasonable to establish the mathematical modelling. During the measurement, the extended waveguide connected to port 1 passes through the air inside the guided path. Immediate medium changes such as substrate and sample oil interact with the propagated wave. After that, waveguide port 2 receives that wave passed through the resonator. Therefore, the transmission coefficient \( S_{21} \) of sensing element receives EM energy deviation using different samples during wave propagation. Assuming all time-dependent components in both electric and magnetic fields as \( e^{-j\omega t} \) using the following form [39]

\[
\nabla \times E - j\omega \mu H = 0
\]

\[
\nabla \times H + j\omega \varepsilon E = 0
\]

Inside the waveguide, permittivity, and permeability \((\varepsilon_{\text{air}}, \mu_{\text{air}})\) consider as a general parameter and the physical structure of propagation medium. The rectangular waveguide dielectric constant assumes a uniform distribution of dielectric constant \( \varepsilon(x) = (x_1, x_2, x_3) \) in each point of consideration. Periodicity in propagation direction inside the waveguide along the extended line should be the same for uniform distribution. Since the resonator structure is attached with the opening edge of the line, a variation of dielectric medium occurs and passes through two different mediums. The substrate permittivity and permeability symbolized as \((\varepsilon_s, \mu_s)\) whereas for sample oil as \((\varepsilon_{\text{oil}}, \mu_{\text{oil}})\), respectively (Figure 12). Generally, EM wave propagation through the material with dielectric properties losses its magnitude and phase velocity. So, the absorbing capacity of the dielectric materials (substrate and oil samples in our case) characterizes the energy absorption and further synthesis describes the sensing characteristics of the proposed resonator mathematically. Besides, the structure has a finite extent in each point of consideration. Therefore, assuming non-conductive permittivity component for point \( x_1 \) rather than point \( x_2, x_3 \). Hence, EM wave before entering the resonator and sample considered as periodic form whereas during the dielectric medium propagation considered as quasi-periodic following well known ‘Floquet-Bloch’ theorem. So, for substrate and resonator field equations \( E_{as} = e^{-j\omega s}E(s) \) and \( H_{as} = e^{-j\omega s}H(s) \), for oil sample, \( E_{ao} = e^{-j\omega s}E(o) \) and \( H_{ao} = e^{-j\omega s}H(o) \). Now substituting these values with
where modified ‘∇ operator’ represents the differential component with complex quantity for respective medium variation. Now, the two different dielectric mediums lose the orthogonal property of EM waves due to the loss tangent and conical diffraction of the incident wave. The method of separation of variables for solving these partial differential equations is quite subtle and difficult for general description. Hence, the simplest solution approach is to find a second-order partial differential equation in ‘n’ variables by reducing equation (3) into second-order ordinary differential equations. So, Maxwell’s equations reduce to simple scalar ‘Helmholtz equation’ [41] as

\[
\begin{align*}
\Delta_{ao} + \omega^2 \varepsilon_{ao} \mu_{ao} u_{ao} &= 0 \\
\Delta_{as} + \omega^2 \varepsilon_{as} \mu_{as} u_{as} &= 0
\end{align*}
\]

where \(\Delta_{ao}\) and \(\Delta_{as}\) represent second-order differential equation based on medium and \(u_{ao}\) and \(u_{as}\) field component in Z-direction. Now, discretization of the equation (4) by applying the ‘finite-difference time domain’ method [42], [43] gives,

\[
S_{\text{c,z}}(x, y) = MRe(E_{ao}H_{ao}^* - E_{as}H_{as}^*)
\]

where \(M\) represents the magnitude of the S-parameter with respect to resonator and oil sample. Extracting the S-parameter signal from another edge of the waveguide collect to analyze the sensitivity for the realization of the sensing element.

The mathematical modeling shows that any oil sample should include the transmission coefficient component jointly propagated through the measurement setup. So, in any arbitrary sample, the dielectric property and concentration is constant, but varying the sample would hamper these two parameters \(S_{21}\) response. Figure 13 shows the overall response of all samples that have been analyzed during measurement. From this graph, it is seen that the \(f_0\) gradually shifting over eight (8) samples signify the magnitude variation of transmission response \(S_{21}\) (dB). When the oil concentration is high, the magnitude becomes low, and the lower concentration shows a higher magnitude response. In this study, we have used eight (8) oil samples; the number of oil samples is 1. olive oil 2. extra virgin olive oil 3. coconut oil 4. extra virgin coconut oil 5. canola oil 6. sunflower oil 7. clean engine oil and 8. waste engine oil. For example, coconut oil, olive oil, and EV olive oil have high concentrations shows \(S_{21}\) as −22.48 dB, −21.77dB and −22.33 dB, respectively. On the other hand, clean engine oil and waste engine oil magnitude
FIGURE 19. Transmission response (S_{21}) (a) simulated (b) measured for the clean engine oil and waste engine oil.

Hence, we propose the definition of sensitivity of the resonator structure as

\[ S = \frac{G_{arg}}{\Delta C_{oil}} \]  

where \( G_{arg} \) is an average gain variation for different oil samples and \( \Delta C_{oil} \) is concentration variation of oil sample which is 0.28 mg/L in our case. The average gain variation was \(-23.375\) dB. Therefore, the sensitivity approximately comes as \(-83.48\) dB/(mg/L), which is quite significant as a potential prototype.

B. ANALYSIS OF THE COCONUT OIL AND EXTRA VIRGIN (EV) COCONUT OIL

Different types of oil may be of quality depending on their elements and natural conditions. Therefore, it was expected that the oil’s electrical properties could be utilized as a feasible instrument for investigating quality assurance and conception of their health benefit results. Coconut oil is extracted from dried and old coconuts and refined at high heat. Since refined coconut oil may have additional chemicals, so it is not recommended for external use, i.e., skin and hair. Extra virgin coconut oil is unrefined oil obtained by cold-pressed. Unrefined oil is that the least processed oil, and it contains no extra additives. Unrefined oil could also be recommended for skin and hair care, in addition to dietary preferences. Firstly, the dielectric constant (DK) and loss factor (LF) of these two oils were measured using an open-ended coaxial dielectric probe kit at 8-12 GHz frequency range, shown in Figure 14. It is noticeable that the DK of coconut oil and extra virgin coconut oil is 2.16 and 2.24, where the LF of these two samples are 0.28 and 0.22 at the 8 GHz frequency.

From Figure 15, it is seen that the simulated and measured results of transmission coefficient (S_{21}) for coconut oil and extra virgin coconut oil in the X-band frequency range. The simulated magnitude of S_{21} for coconut oil is \(-20.71\) dB at 10.87 GHz and \(-20.93\) dB at 10.66 GHz for extra virgin coconut oil. Besides, the measured magnitude of S_{21} for coconut oil is \(-22.49\) dB at 11.10 GHz and \(-22.76\) dB at 10.85 GHz for extra virgin coconut oil. These results indicate that despite the near similarities of their dielectric behavior, the recommended structure accurately detects various types of liquids.

C. ANALYSIS OF THE OLIVE OIL AND EXTRA VIRGIN (EV) OLIVE OIL

Olive oil is a mixture that includes both cold-pressed and processed oils, while extra-virgin olive oil is made from
pure, cold-pressed olives. Extra virgin olive oil is the least processed or refined type of oil. Extra-virgin olive oil is rich in monounsaturated fats and contains a small amount of vitamins E and K; it is also high in antioxidants, some of which have important health benefits. The dielectric constant (DK) and loss factor (LF) of these two oils are measured using an open-ended coaxial dielectric probe kit at the 8-12 GHz frequency range, shown in Figure 16. It is noticeable that the DK of olive oil is 2.54 and extra virgin olive oil is 2.63, where the LF of these two samples are 0.20 and 0.17 at the 8 GHz frequency.

The simulated and measured $S_{21}$ results for olive oil and extra virgin olive oil are within X-band shown in Figure 17. The simulated magnitude of $S_{21}$ for olive oil is $-21.07$ dB at 10.82 GHz and $-22.04$ at 10.65 GHz for extra virgin olive oil. Besides, the measured magnitude of $S_{21}$ for olive oil is $-20.27$ dB at 11.05 GHz and $-23.41$ dB at 10.82 GHz for extra virgin olive oil. These results indicate that despite the near similarities of their dielectric behavior, the recommended MTM inspired sensor accurately detects various liquids.

D. ANALYSIS OF THE CLEAN ENGINE OIL AND WASTE ENGINE OIL

Waste oil of the engine affects the engine due to the thicker and lack of lubricant. Waste oils degrade engine efficiency, reduce horsepower, reduce mileage, and shorten engine life. The dielectric constant (DK) and loss factor (LF) of the clean engine and waste engine oils are measured using an open-ended coaxial dielectric probe kit at 8-12 GHz frequency range, shown in Figure 18. It is noticeable that the DK of clean engine oil and waste engine oil is 2.33 and 2.24, where the LF of these two samples are 0.14 and 0.15 at the 8 GHz frequency.

Figure 19 shows the simulated and measured results of the $S_{21}$ for clean engine and waste engine oil operating in X-band. The simulated magnitude of $S_{21}$ for clean engine oil are $-23.18$ dB at 10.73 GHz and $-22.39$ dB at 10.88 GHz for waste engine oil. Besides, the measured magnitude of $S_{21}$ for clean engine oil is $-25.95$ dB at 10.86 GHz and $-25.02$ dB at 11.03 GHz for waste engine oil.

E. ANALYSIS OF THE SUNFLOWER OIL AND CANOLA OIL

The primary distinction between sunflower and canola oils is the type of fat they contain. Sunflower oil is high in monounsaturated and polyunsaturated fats, which help lower cholesterol, and canola oil is high in omega-3 fatty acids, a form of polyunsaturated fat that can help lower triglycerides. Firstly, the dielectric constant (DK) and loss factor (LF) of these two oils were measured using an open-ended coaxial dielectric probe kit at 8-12 GHz frequency range, shown in Figure 20. It is noticeable that the DK of sunflower oil and canola oil is 2.92 and 2.83, where the LF of these two samples are 0.11 and 0.16 at the 8 GHz frequency.

Figure 21 depicts the simulated and measured results of $S_{21}$ for sunflower oil and canola oil in the frequency spectrum of the X-band. The simulated magnitude of $S_{21}$ for sunflower oil is $-23.26$ dB at 10.60 GHz and $-22.26$ at 10.80 GHz for canola oil. Besides, the measured magnitude of $S_{21}$ for sunflower oil is $-23.86$ dB at 10.79 GHz and $-23.01$ dB at 10.97 GHz for canola oil.

Some ripples exist in the measurement transmission coefficient ($S_{21}$), which is the drawbacks of the presented work.
But these ripples occurred due to the waveguide port’s mutual coupling effect, and the fabrication tolerance of the prototype. Also, the mutual resonance effect of the transmitting and receiving ends of two waveguide ports always affect the readings and cause some variation in measurement data. We will try to optimize the drawbacks in future work. Furthermore, in the simulation result, all conditions are ideal, but in the measurement result, all are not ideal conditions; hence there are minor differences between these two results. So, it can be said that the proposed MTM sensor performs satisfactorily both theoretically and experimentally.

**Figure 22(a, b)** shows the simulated and measured $S_{21}$ for the eight oil samples. It is noticeable that the transmission response ($S_{21}$) changes with changing the concentration and dielectric constant of oil samples. From **Figure 22**, we can easily distinguish between the clean engine oil and extra virgin olive oil or any two other oils. By using the suggested sensor, we can also know the transmission resonance frequency shifting and sensitivity of the oil samples. The close dielectric values are a big challenge in identifying the oil samples, but the proposed sensor identifies the oil samples by changing the resonance frequency. But when we have used the tri circle SRR in the MTM sensor, the sensor is working well, and one can easily detect the oil samples by the resonance frequency shifting and sensitivity of the samples.
Since frequency is inversely proportional to the dielectric constant, hence there are some differences between extracted and reported dielectric constants due to different frequencies. Table 3 shows the comparison between extracted and reported dielectric constant values.

Table 4 shows the comparison between the proposed study and other similar studies regarding the sensing materials, dielectric constant, resonance frequency shift, and sensor type. From references [16], [24], [21], [22] and [23], we can see that the resonance frequency shift of these references is slight. Besides, the resonance frequency shift is moderate, in the references [16], [24], [26], but the resonance frequency shift is high, in our proposed work. So, the performance of the proposed MTM sensor is better than other similar sensors, as stated in Table 4.

IV. CONCLUSION
A tri-circle SRR shaped metamaterial sensor was effectively developed and fabricated such that it can be utilized for the detection of various liquids in the X-band frequency. The proposed sensor was shown to be capable of discriminating between various oil samples with ease. The mathematical modelling of the recommended MTM structure was also explained for sensitivity analysis. The dielectric constant depends on the oil concentration and frequency. The dielectric constant of the coconut oil and extra virgin coconut oil are 2.16 and 2.24, although the dielectric values are very close between these two oils; even after that, the resonance frequency has shifted to 210 MHz. The resonance frequency has shifted 230 MHz, though the dielectric constant values are nearby each other, 2.54 for olive oil and 2.63 for extra virgin olive oil. The dielectric constant values are 2.33 and 2.23 for clean engine oil and waste engine oil, respectively; cause of this small difference, the resonance frequency has shifted 170 MHz. To summarize, the proposed sensor is well suited for detecting sunflower and canola oil. The measured dielectric constant values for sunflower and canola oils are 2.92 and 2.83, respectively; for example, the resonance frequency shift between these two oils was around 200 MHz.

ACKNOWLEDGMENT
This work was supported in part by Universiti Kebangsaan Malaysia under Grant DIP-2021-011; and in part by Taif University Researchers Supporting Project through Taif University, Taif, Kingdom of Saudi Arabia.

REFERENCES
[1] M. Bayindir, K. Aydin, E. Ozbay, P. Markoš, and C. M. Soukoulis, “Transmission properties of composite metamaterials in free space,” Appl. Phys. Lett., vol. 81, no. 1, pp. 120–122, Jul. 2002.
[2] W. Withayachumnankul, K. Jarowongrungsee, C. Fumeaux, and D. Abbott, “Metamaterial-inspired multichannel thin-film sensor,” IEEE Sensors J., vol. 12, no. 5, pp. 1455–1458, May 2012.
[3] Z. Vafapour, Y. Hajati, M. Hajati, and H. Ghahraloud, “Graphene-based mid-infrared biosensor,” J. Opt. Soc. Amer. B, Opt. Phys., vol. 34, no. 12, pp. 2586–2592, 2017.
[4] M. Bakir, “Electromagnetic-based microfluidic sensor applications,” J. Electrochem. Soc., vol. 164, no. 9, pp. B488–B494, 2017.
[5] H. Xiong, T. B. Long, T. Shi, B. X. Jiang, and J. T. Zhang, “Wideband and polarization-insensitive metamaterial absorber with loading lumped resistors,” Appl. Opt., vol. 59, pp. 7092–7098, Aug. 2020.
[6] M. Bakır, M. Karaaslan, E. Ünal, O. Akgöl, and C. Sabah, “Microwave metamaterial absorber for sensing applications,” Opto-Electron. Rev., vol. 25, no. 4, pp. 318–325, 2017.
[7] M. C. Johnson, S. L. Brunton, N. B. Kundtz, and J. N. Kutz, “Sidelobe canceling for reconfigurable holographic metamaterial antenna,” IEEE Trans. Antennas Propag., vol. 63, no. 4, pp. 1881–1886, Apr. 2015.
[8] N. Misran, S. H. Yusop, M. T. Islam, and M. Y. Ismail, “Analysis of parameterization substrate thickness and permittivity for concentric split ring square reflectarray element,” Jurnal Kejuruteraan, J. Eng., vol. 23, pp. 11–16, Nov. 2012.
[9] C. Liu and F. Tong, “An SIW resonator sensor for liquid permittivity measurements at C band,” IEEE Microw. Wireless Compon. Lett., vol. 25, no. 11, pp. 751–753, Nov. 2015.
M. R. Islam et al.: Tri Circle Split Ring Resonator Shaped MTM With Mathematical Modeling

[10] E. L. Chuma, Y. Iano, G. Fontgalland, and L. L. B. Roger, “Microwave sensor for liquid dielectric characterization based on metamaterial complementary split ring resonator,” IEEE Sensors J., vol. 18, no. 24, pp. 9978–9983, Dec. 2018.

[11] M. Q. Qi, W. X. Tang, H. F. Ma, B. C. Pan, Z. Tao, Y. Z. Sun, and T. J. Cui, “Supersensitive side-lobe radiations of horn antenna by loading metamaterial lens,” Sci. Rep., vol. 5, no. 1, pp. 1–6, Aug. 2015.

[12] S. Mukherjee, Z. Su, L. Udpa, S. Udpa, and A. Tamburro, “Enhancement of microwave imaging using a metamaterial lens,” IEEE Sensors J., vol. 19, no. 13, pp. 4962–4971, Jul. 2019.

[13] M. Huang, J. Yang, and A. Petrin, “Microwave sensor using metamaterials,” Wave Propag., pp. 13–36, Mar. 2011.

[14] Y. I. Abdulkarim, L. Deng, M. Karaaslan, O. Altıntaş, H. Awl, F. Muhammadsharif, H. N. Awl, C. Sabah, and K. S. L. Al-Badri, “Design and study of a metamaterial based sensor for the application of liquid chemicals detection,” J. Mater. Res. Technol., vol. 9, no. 5, pp. 10291–10304, Sep. 2020.

[15] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Magnetism from conductors and enhanced nonlinear phenomena,” IEEE Trans. Microw. Theory Techn., vol. 47, no. 11, pp. 2057–2084, Nov. 1999.

[16] R. Marqués, F. Mesa, J. Martel, and F. Medina, “Comparative analysis of edge-and broadband-co coupled split ring resonators for metamaterial design-theory and experiments,” IEEE Trans. Antennas Propag., vol. 51, no. 10, pp. 2572–2581, Oct. 2003.

[17] R. Marqués, F. Medina, and R. Rafii-El-Idrissi, “Role of bianisotropy in negative permeability and left-handed metamaterials,” Phys. Rev. B, Condens. Matter, vol. 65, Apr. 2002, Art. no. 144440.

[18] S. I. Maslovski, P. M. Ikonen, J. Kolmakov, S. Tretyakov, and M. Kaunisto, “Artificial magnetic materials based on the new magnetic particle: Metasolenoid,” Prog. Electromagn. Res., vol. 54, pp. 61–81, 2005.

[19] L. Yousefi and O. M. Ramahi, “Artificial magnetic materials using fractal Hilbert curves,” IEEE Trans. Antennas Propag., vol. 58, no. 8, pp. 2614–2622, Aug. 2010.

[20] J. D. Baena, R. Marqués, F. Medina, and J. Martel, “Artificial magnetic metamaterial design by using spiral resonators,” Phys. Rev. B, Condens. Matter, vol. 69, no. 1, Jan. 2004, Art. no. 014402.

[21] M. N. Sadiku and S. V. Kulkarni, Principles of Electromagnetics. Oxford, U.K.: Oxford Univ. Press, 2009.

[22] C. P. Boyer, E. G. Kalnin, and W. Miller, “Symmetry and separation of variables for the Helmholtz and Laplace equations,” Nagoya Math. J., vol. 60, pp. 35–38, Feb. 1976.

[23] A. I. Kozlov, L. P. Ligthart, and A. Logvin, Mathematical and Physical Modelling of Microwave Scattering and Polarimetric Remote Sensing: Monitoring the Earth’s Environment Using Polarimetric Radar: Formulation and Potential Applications, vol. 3. New York, NY, USA: Kluwer, 2007.

[24] S. Haffa, D. Hollmann, and W. Wiesbeck, “The finite difference method for S-parameter calculation of arbitrary three-dimensional structures,” IEEE Trans. Microw. Theory Techn., vol. 40, no. 8, pp. 1602–1610, Aug. 1992.

[25] W. C. Chew, “Lectures on theory of microwave and optical waveguides,” 2021, arXiv:2107.09672.

[26] H. Lizhi, K. Toyoda, and I. Ihara, “Dielectric properties of edible oils and fatty acids as a function of frequency, temperature, moisture and composition,” J. Food Eng., vol. 88, no. 2, pp. 151–158, Sep. 2008.

MD. RASHEDUL ISLAM received the B.Sc. and M.Sc. degrees in applied physics and electronic engineering from Rajshahi University, Bangladesh, in 2008 and 2009, respectively. He is currently pursuing the Ph.D. degree with Universiti Kebangsaan Malaysia (UKM), Malaysia. From January 2012 to January 2014, he worked as a Lecturer with the Pabna University of Science and Technology (PUST), Bangladesh, where he worked as an Assistant Professor, from February 2014 to August 2019. He is currently a Graduate Research Assistant with the Department of Electrical, Electronic and Systems Engineering, UKM. He has authored or coauthored a number refereed journals and conference papers. His research interests include the antenna design, metamaterial, microwave sensor, and wireless communication.
MOHAMMAD TARIQUL ISLAM (Senior Member, IEEE) is currently a Professor with the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM) and a Visiting Professor with the Kyushu Institute of Technology, Japan. He is the author and coauthor of about 500 research journal articles, nearly 175 conference papers, and a few book chapters on various topics related to antennas, metamaterials, and microwave imaging with 20 inventory patents filed. Thus far, his publications have been cited 6000 times and his H-index is 38 (Source: Scopus). His Google scholar citation is 8200 and H-index is 42. His research interests include communication antenna design, satellite antennas, and microwave imaging. He is serving as an Executive Committee Member for IEEE AP/MTT/EMC Malaysia Chapter, from 2018 to 2020, a Chartered Professional Engineer-CENG, a Member of IET, U.K., and a Senior Member of IEICE, Japan. He was a recipient of more than 40 research grants from the Malaysian Ministry of Science, Technology and Innovation, Ministry of Education, UKM Research Grant, international research grants from Japan and Saudi Arabia. He currently serving as a Guest Editor for Sensors journal, an Associate Editor for IEEE Access and he was an Associate Editor for IET Electronics Letter. He received several international gold medal awards, a Best Invention in Telecommunication Award for his research and innovation, and Best Researcher Awards, in 2010 and 2011, at UKM. He was a recipient of 2018 and 2019 IEEE AP/MTT/EMC Malaysia Chapter, Excellent Award. He also won the best innovation award, in 2011, and the Best Research Group in ICT niche, in 2014, by UKM. He was also a recipient of Publication Award from Malaysian Space Agency, in 2014, 2013, 2010, and 2009, respectively, and the Best Paper Presentation Award, in 2012, International Symposium on Antennas and Propagation, (ISAP 2012) at Nagoya, Japan, and, in 2015, in Icon Space, Malaysia. He has supervised about 30 Ph.D. theses, 20 M.Sc. theses, and has mentored more than ten postdoctoral and a Visiting Scholars.

AHASANUL HOQUE (Member, IEEE) received the B.Sc. Eng. degree in electrical & electronic engineering (EEE) from the Chittagong University of Engineering & Technology (CUET), Chittagong, Bangladesh, in 2008, the Master of Science (M.Sc.) degree in electrical engineering from Karlstad University, Sweden, in 2012, with specialization in microwave communication and signal processing, and the Ph.D. degree from Universiti Kebangsaan Malaysia (UKM). He has been an Assistant Professor with the Department of Electrical and Electronics Engineering, International Islamic University Chittagong, Bangladesh, from 2015 to 2018. He has authored or coauthored a number refereed journals and conference papers. His research interests include the metamaterial absorber, microwave engineering, wireless communication, solar energy harvesting & metamaterial. He received the Graduate on Time (GoT) Award for his Ph.D. degree.

MOHAMED S. SOLIMAN (Senior Member, IEEE) received the Ph.D. degree in communications engineering from the Graduate School of Engineering, Osaka University, Japan. He is currently an Assistant Professor with the Department of Electrical Engineering, Faculty of Energy Engineering, Aswan University, Egypt. He is also with the Department of Electrical Engineering, Faculty of Engineering, Taif University, Saudi Arabia. He was granted many research projects from Deanship of Scientific Researches, Taif University. His research interests include wireless communications, phased and timed array signal processing, UWB microstrip patch antennas, dielectric resonant antennas, numerical methods in electromagnetics, mimo antenna, optimization techniques in antenna design, and antenna measurement techniques. He serves as a reviewer in many scientific journals (i.e., PIER journals and International Journal of RF and Microwave Computer-Aided Engineering) and a TPC member in many international conferences. He is a Senior Member in IEEE-MTT/AP Society, KAUST chapter, Saudi Arabia.

BADARIAH BAIS (Senior Member, IEEE) received the B.Sc. degree in electronics engineering and the M.Sc. degree in microelectronics from the Worcester Polytechnic Institute, Worcester, MA, USA, in 1990 and 1992, respectively, and the Ph.D. degree from the Institute of Microengineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia, in 2007. Since 1997, she has been working with the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, as an Academic Staff. She is currently an Associate Professor with the department. Her research interests include MEMS sensors and microfabrication. She is also a Senior Member of the Electron Devices Society (EDS).

NORSUZLIN MOHD SAHAR received the B.Eng. degree in communication engineering from International Islamic University Malaysia (HUM), in 2006, the M.Eng. degree from Universiti Teknologi Malaysia (UTM), in 2010, and the Ph.D. degree for research in reconfigurable antenna using RF MEMs switches for RFID and GPS applications from UKM, in 2016. She is currently a Senior Lecturer with the Space Science Centre (ANGKASA), Institute of Climate Change, Malaysia (UKM). Her research interests include the microwave device for wireless application and systems particularly in broadband microstrip antennas and reconfigurable antennas.

SAMI H. A. ALMALKI received the bachelor’s degree in electronics & communication engineering from Taif University, in 2014, and the master’s degree in communication from the King Abdullah University of Science and Technology, in 2018. He is currently a Lecturer with the Electrical Engineering Department, Taif University. His research interests include antenna design and wireless communication.