Title of the Research Article:

An approach to design a quad-band NRI metamaterial for multipurpose sensor applications

Short running title:

NRI metamaterial and its sensor applications

Abstract:

The governing topic of this article is the design and investigation of a novel negative refractive index (NRI) metamaterial (MTM) in the microwave region. This multi-band MTM is realized by employing a square ring resonator along with two triangular-shaped resonators. Here, the designed unit cell produces double negative (DNG) regions to the extent of 3.6–3.9 GHz, 6.8–7.6 GHz, 10.11–10.4 GHz, and 13.4–13.7 GHz and shows NRI properties in S-, C-, X-, and Ku-bands. Moreover, the design and performance evaluation of the 2×2 and 4×4 array configurations are investigated. Both of the structures create NRI band around S-, C-, X-, and Ku-bands. Also, the proposed MTM has an effective medium ratio of 13.8. The performance of the proposed MTM is validated by the sensor design study. Hence the proposed MTM is assigned for sensing pressure variation, for distinguishing used and unused transformer oil, and also to detect the several chemicals and chemical-water mixtures. The distinctive observation of the sensor study reveals 80 MHz frequency difference between dark and clear oil and more than 340 MHz resonance frequency shifting phenomena in X-bands for chemical sensing applications. Besides pressure sensor study exposes linear shifting of the resonances in S-, C-, X-, and Ku-bands.

Keywords: Chemical sensor, multi-band, negative refractive index (NRI) metamaterial, transformer oil aging sensor, pressure sensor

1 Introduction

Encouraging an enormous process to accomplish the pinnacle of achievement, wireless communication presently has a large field for research. With the start of the century, another examination field showed up in the area of science and technology: Metamaterials (MTMs). MTMs can be viewed as a transversal subject, including a wide range of controls and fields, for example, acoustics, electromagnetism, RF and microwave designing, millimetre-wave and THz innovation, miniaturized scale and nanotechnology, photonics and optics, and medicinal building, etc. The electromagnetic properties of natural material can be violated by modifying the material structure. The artificial inclusion of periodic material shows lucrative characteristics, such as negative Doppler effect, reversed Cherenkov radiation effect, violation of Snell's law, chirality, negative refractive index (NRI), and beam steering, etc. The numerous application of MTMs can be found in the microwave, radio frequency (RF), and higher frequency applications. The MTMs are efficiently used in absorber design[1], filter design[2], cloaking[3], multi-band antenna design[4] and bandwidth improvement of antenna[5], etc.

The MTMs are classified according to their value of the parameters such as permittivity (ε) and permeability (μ). The permittivity and permeability are negative in ε-negative and μ-negative materials, respectively or simply called as a single negative (SNG) materials. Whereas in the double negative (DNG) material both ε and μ are negative. The DNG materials are also known as negative index material (NIM) as their refractive index (η) is negative. A Ukrainian physicist named Victor Georgievich Veselago first developed a theoretical idea of DNG material in 1986.[6] Most of the NIM has been realized by combining the responses of the split-ring resonator (SRR) and back wire.[7] But the reported design has a strong partial dispersion problem and create anomalies in designing a NIM with higher effective medium ratio (EMR).[8] If the value of EMR is greater than four, then parasitic diffraction fatalities can be avoided. To solve these issues, several NIM design structures have been introduced, such as pair of SRR and electric-LC (ELC) resonators[8], S-shaped resonators[9], G-shaped[10] and omega-shaped[11] structures. However, the designs mentioned above are single-band in operation, and they are not competitive with the advance requirements of the wireless technology.

Because of the innovative prerequisite, multi-band structures of NIM have gained significant consideration. So different techniques have been revealed to design a multi-band NIM, for example, stacked arrays of unit cell method[12], stacked cell approach[13], and a combination of resonant SRRs and non-resonant wires[14]. In stacked cell-based design, multiple unit cells of different sizes have to be used close to each other to realize the negative index property. As a result, higher-order Bloch modes affect the operation of the meta-structure, and the effective parameter cannot be accurately determined. Whereas, the latter method creates a cross-cell interconnection problem. It is essential to take note of that the issues of cross-cell interconnection and excitation of higher-order Bloch mode commonly emerge in MTM exposed to along the plane. However, the large separation between unit cells can solve this, but the EMR decreases. However, higher accuracy of effective parameter approximation can be achieved with high EMR. Literature 15 offers a discontinuous engineered dual-band NIM structure that is free from the disadvantages of stacked cell-depended technology. Moreover, the accommodation problem of the back wire structure can be suppressed by this ELC and loop resonators combination.

In current times, various researchers have structured and investigated the alphabet-shaped multi-band MTM unit cells having C-shape[16], cross S-shape[17], H-shape[18], modified H-shape[19], bare H-shape[20], Z-shape[21], etc. However, literature 17 is a single NRI band. Also, dual and triple NRI bands are represented by literature in references 18, 20 and 16, 19, and 21, respectively. Except for H-shaped structure[18], all other works of literature have a very modest EMR. The authors have reported another hexagonal-shaped[22] NIM for quad-band applications. In this case, the size of the unit cell is 10×9.8 mm^2 having an EMR of 18.2.

The NIM features are suitable for multi-band applications, for examples, satellite communications, mobile phones, GPS, weather radar, and surface radar etc. Moreover, NIM structures are also famous in MTM based high sensitive sensors and filters. The performance evaluation of MTM sensors is dependent on the variation of the transmission or reflection resonances. An SRR based chiral MTM has been utilized to design a multipurpose sensor.[23] Here reflection coefficient variation method is used for sensing purpose. This chiral MTM sensor is employed for fuel adulteration sensing as well as chemical purity detection purpose. Several MTM based transformer oil sensors[24-26] have been employed to clarify the used and unused oil based on the dielectric constants. All of the sensors show a small resonance difference based on the permittivity of the liquids. Different types of MTM constructed sensors have been demonstrated for multipurpose sensing applications such as oil sensor[27] and liquid chemical sensors[28-30]. Based on the resonance frequency shifting approach, the concentrations of the industrial liquid are evaluated in these articles. Two MTM based pressure sensors have been realized by MTM absorber[31] and SRR[32] configurations. Both sensors are operated in X-band. The aforementioned sensor studies have not analyzed the basic behavior of the MTM structures. Only resonance frequency variations are noted for sensor studies. Moreover, the illustrated oil sensors have resonance difference not more than 70 MHz. Also, reported pressure sensors are the single band in function. Besides, the reported frequency bandwidths of the different liquid chemical sensors are very modest. Moreover, none of the literature investigates the mathematical model of the sensor structure to relate the electrical and resonance characteristics of the sensor.

Behavioral analysis and design of a compact quad-band NRI MTM with an enhanced EMR are highlighted in this article. Moreover, three types of sensor applications are also investigated to validate the performance of the proposed MTM. The proposed MTM consists of a square ring resonator and two triangular shaped resonators. Under the normal incidence of the EM wave, the unit structure is able to operate in S-, C-, X- and Ku-bands along with NRI property and having an EMR of 13.8. Moreover, the operational mechanism of the proposed MTM is explored by surface current distribution, electric field distribution, and equivalent circuit analysis. To check whether the proposed design is able to exhibit multi-band NRI property in a bulk material, the 2×2 array and 4×4 array analysis are accomplished. Finally, the array structures are also able to generate quad-band NRI behavior. The proposed MTM's effectiveness is demonstrated by utilizing it to design a pressure sensor, transformer oil sensor, and a chemical sensor. A linear movement of the resonance frequencies in the S-, C-, X- and Ku-bands is detected from the pressure sensor simulation. The transformer oil sensor exhibit 80 MHz frequency difference at the observation points, which is preferred for accurate detection of the substances being sensed. The liquid chemical sensing scheme is able to differentiate liquid chemicals such as ethanol, methanol, acetone, and also their binary mixture with 0% to 100% volume fraction of water. The binary mixture sensing applications show more than 340 MHz frequency difference. Moreover, a mathematical model is constructed to determine the electrical and resonance properties of binary solutions. So, the proposed multi-band NRI MTM could be a good solution for S-, C-, X- and Ku-bands multipurpose sensor applications along with other wireless communication applications.

2 Design of the proposed DNG MTM unit cell

The geometry of the proposed MTM unit cell is given in Fig. 1. The unit cell is made up of an outer square ring resonator and two triangular resonators which are located inside the square ring resonator. The schematic and cross-sectional views of the proposed design are illustrated in Fig. 1a. The overall size of the unit cell ($q\times q$) is 6×6 mm^2. The arm length of the square ring resonator p is 5.8 mm. Two almost identical right-angled triangles are used as resonators (TR1 and TR2). TR1 is a closed triangle, whereas a 0.2 mm gap, denoted by s, is located between two arms that form a right angle in the TR2. TR2 is rotated in the clockwise direction by 90° with respect to TR1; as a result, a common arm is shared by TR1 and TR2. Therefore, the right-angled sides of TR1 and TR2 are aligned along $-y$-axis and $-x$-axis, respectively. Length of the inclined arms in TR1 and TR2 is l. The opposite corners of TR1 and TR2 are connected to square ring resonator by two short metal strips of l_1. The arm of TR2 that is not common of TR1 is connected to a metal strip of l_2 aiming to connect with the square ring resonator by a short microstrip line. Here, the length of the inclined metal strip l_2 is identical to l. The capacitive gaps of the outer square ring resonator are of the same size (0.4 mm) and denoted by g, g_1, and g_2 in the figure. In the schematic diagram of the unit cell, some similar dimensions are defined individually due to the ease of explanation in the following sections. Here, the spacing (n) between parallel conductors of the square ring resonator and two triangular resonators is 0.2 mm. The whole unit cell is engraved on the FR4 substrate of permittivity 4.4, the height h of 1.6 mm, and loss tangent of 0.0025. The thickness of the copper conductor is 0.035 mm and width e of 0.5 mm. Under normal incidence of the EM wave, the simulation is conducted. For normal incidence, the direction of the electrical polarization is considered along the y-axis ($E|y$) whereas magnetic polarization is considered along the x-axis ($H|x$). Here, the unit cell is exited by placing it between two waveguide ports and in the direction of the positive and negative z-axis ($k|z$) as shown in Fig. 1b. Fig. 2 represents the reflection coefficient (S_{11}) and transmission coefficient (S_{21}) curves of the proposed unit cell. The operating bands of the proposed unit cell can be observed in the S_{21}. So, the simulated transmission resonances of the multi-resonant NRI MTM are 3.66 GHz, 6.66 GHz, 9.36 GHz, and 12.85 GHz, respectively.

3 Simulation results and analysis

The effective parameters of the MTM unit cells are permeability (μ), permittivity (ε), and refractive index (η). Generally, the scattering parameters are used to determine the EM properties of an MTM. In this work, the wave impedance and refractive index are utilized to extract the permittivity and permeability of the MTM. The *S*-parameters of normally incident plane wave on a slab of MTM unit cell can be expressed as follows[33] :

$$S_{11} = \frac{R_{01}(1-e^{j2\eta k_0 d})}{1-R_{01}^2 e^{j2\eta k_0 d}} \tag{1}$$

$$S_{21} = \frac{(1-R_{01}^2)e^{j2\eta k_0 d}}{1-R_{01}^2 e^{j2\eta k_0 d}} \tag{2}$$

where, $R_{01} = \frac{(z-1)}{(z+1)}$.

Inversion of Equations (1) and (2) provides

$$z = \pm\sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}} \tag{3}$$

$$e^{jnk_0 d} = \frac{S_{21}}{1-S_{11}\frac{z-1}{z+1}} \tag{4}$$

$$\eta = \frac{1}{k_0\, d}\{\, Im\,[\ln(e^{j\eta k_0 d})] + 2m\pi - jRe\,[\ln(e^{j\eta k_0 d})] \quad m = 0,1,2 \ldots, \tag{5}$$

where η is the refractive index; z is the wave impedance; k_0 is the wavenumber; d is the maximum length of the unit element; m is the branch index due to the periodicity of the sinusoidal function.

There are multiple solutions of Eq. (5) due to the square root function of wave impedance and different branches of sinusoidal functions. According to Kramers-Kronig relation, appropriate branch selecting can avoid discontinuity in the ensuing refractive index and also knowing the passive material nature.[34] Moreover, branch ambiguity of electrically thin slab cab be overcome by choosing the fundamental branch to obtain a continuous refractive index. The permittivity (ε) and permeability (μ) are related to η and z by the following manner :

$$\varepsilon = \frac{\eta}{z} \tag{6}$$

$$\mu = \eta\, z \tag{7}$$

In these relations, the metamaterial is denoted through proper excitations and boundary conditions. The material is presumed to be homogeneous, having an effective refractive index and impedance. This hypothesis is valid, as the sizes of the unit element are typically less than 1/10th of the wavelength. As the designed MTM is less than one-tenth of the wavelength at lower resonance, fundamental branch selection is allowed.

The reason behind choosing the above-stated method is due to avoid the sign ambiguity of the S-parameter extraction method. The direct extraction of permittivity and permeability from *S*-parameters is associated with sign ambiguity. Specifically, this phenomenon affects the real and imaginary parts of the wavenumber. The widespread effective parameter extraction method such as Nicolson Rose weir (NRW) is also ambiguous due to this problem when guided wavelength $\lambda_g < 2d_1$, where $d_1 = \lambda_0/2\pi$. The inability to provide a unique sign of the complex function leads to the obscure value of intrinsic impedance and wavenumber (or refractive index). As the guided wavelength of the proposed MTM is smaller than $2d_1$, the described method is chosen. In comparison, problems introduced in the above-denoted method can be easily solved by proper branch parameter selection.[34]

Fig. 3 represents the simulated effective permittivity, permeability, and refractive index of the proposed multi-band negative indexed meta atom. The real and imaginary values of permittivity are shown in Fig. 3a. Negative permittivity region ranges from 1.4–3.9 GHz, 6.8–7.6 GHz, 10.1–10.4 GHz, and 12.2–13.8 GHz, as shown in Fig. 3a. Negative permeability regions covered by the proposed MTM are 3.6–3.9 GHz, 6.8–8 GHz, 10.1–10.4 GHz, and 13.4–

13.7 GHz, as presented in Fig. 3b. Similarly, from Fig. 3c, negative refractive index expanses from 3.7–3.9 GHz, 6.8–7.1 GHz, 10.11–10.4 GHz, and 13.4–13.7 GHz. Moreover, the DNG regions extended from 3.6–3.9 GHz, 6.8–7.6 GHz, 10.1–10.4 GHz, and 13.4–13.7 GHz equivalent to a bandwidth of 0.3 GHz, 0.8 GHz, 0.29 GHz, and 0.3 GHz, respectively. The negative permittivity regions are due to the gap capacitances. In the negative permeability regions, the current flow doesn't cope up with the applied field and lags behind the applied field.

3.1 Electric field distribution and surface current distribution

To analyze the operation of the proposed multi-band NRI MTM, surface current distribution and electric field distribution of the four NRI frequencies are investigated. In the proposed design, inductances are framed by the metal strip, and the split gaps shape the capacitances. When the applied EM wave propagates along with the MTM structure, electric resonances are delivered by coupling between the split gaps and electric fields. Additionally, magnetic resonances are framed by the coupling between the magnetic fields and loops. The split gaps of the proposed MTM structure act as a capacitor as they will store energy regarding an electric field. Contrary, an electric resonance has a dielectric reaction that gives us a permittivity. Then a magnetic resonance that ascends to permeability is generated from the stored magnetic field. The electric field is responsible for producing magnetic dipole and creates artificial magnetic behavior of the resonator. The magnetic dipole moment, in the long run, ends up being an effective negative permeability. From one perspective, the magnetic resonance is superimposed to the relating electric resonance, which is corresponded to effective negative permittivity. The electric field distribution and surface current distribution of the four NRI frequencies are investigated and depicted in Figs. 4,5, 6 and 7.

As the electric field is oriented to the *y*-axis, there is an accumulation of charges at the top and bottom edges of the MTM structure. Mainly, intercell capacitance (C_p) is originated from the accumulated charge. However, it is a normal phenomenon because MTM is a periodic structure, and multiple-unit cells are connected adjacent to each other. The electric resonance is responsible for negative permittivity generation. So there is no existence of the magnetic field near the electric resonance. As a result, an anti-parallel activity of the surface current is presented at the capacitive gaps of the structure where electric resonance occurred. Moreover circulating current of the structure is the source of negative permeability generation.

Figs. 4a and 4b illustrate the electric field and surface current distribution at 3.75 GHz. According to the Fig. 4a, the distribution of the electric field is higher in the capacitive gaps of *g*, *s*, and *n.* Fig. 4b shows that the surface currents are opposite in these mentioned gaps and the magnetic fields nullify each other. Moreover, the circulating current loop responsible for magnetic resonance is located in the TR1. In the same way, the split gaps shape the capacitances, and the metallic discharge path of capacitive gaps create inductance.

Fig. 5a illustrates that electric resonance at 6.95 GHz is due to the formation of the intense electric field in the gap g_1 and also due to the accumulation of electric field near the bottom side of the outer resonator. A little accretion of charges is noticeable at the top edges of the MTM structure. According to the previous statement, the anti-parallel surface current is evident in this area. The surface current at 6.95 GHz is depicted in Fig. 5b. The magnetic resonance is strengthened by the uni-directional current flow between the conductors separated by split gap *s*. The gap capacitance discharged through the bottom part of the MTM structure.

According to Fig. 6a, the localized electric field is located close to capacitive gaps of *g*, g_1, and *s* at 10.25 GHz. As a result, capacitive action is dominant in these areas. Also, Fig. 6b bears proof of this issue. The capacitor of gap *g* is discharged through the TR1 and capacitors of gap g_1 and *s* released through the l_2 and TR2. From Fig. 6b, the current direction is same at the top and bottom parts of the outer square ring resonator and also in the outermost right and left parts of the square ring resonator. That is why the magnetic field gets stronger at this frequency, and negative permeability occurred.

The electric field and surface current distributions at 13.55 GHz are illustrated in Figs. 7a and 7b. The presence of the electric is due to capacitive gap g_2, and capacitance of parallel conductors, as shown in Fig. 7a. In this case, the capacitive gap *s* is not considered, and the fact is described previously. The capacitors are discharged through the parallel conductors, which generates a current loop. The parallel conductors of the top and right side of the MTM structure are not equal in length. So they cannot neutralize each other completely. So, the strength of the magnetic resonance at 13.55 decreased, as shown in Fig. 3b.

3.2 Equivalent circuit design

To get a deeper insight into the operation of the proposed NRI MTM, the equivalent circuits for each band are designed and analyzed numerically. The size of the proposed meta-structure is significantly smaller than its guided wavelength. So its equivalent circuit can be compared to an LC resonator. The condense electric field in a split gap can be modelled as a capacitor, and the metallic discharge path can be modelled as an inductor. So, inductance can be increased or decreased by increasing or decreasing the length of the metal strip, and capacitance can be varied by altering the distance of the split gap. Using this theory, NRI frequency can be extended in the upper or lower frequency region. Now the capacitance can be expressed by the following equation:[35-36]

$$\text{The gap capacitance, } C = \varepsilon_0 \varepsilon_{eff} \frac{k\left(k_0^{'}\right)}{k\left(k_0\right)} \tag{8}$$

where ε_0 is the free space permittivity and ε_{eff} is the effective permittivity. If ε is relative permittivity and q is fill factor, then $\varepsilon_{eff} = 1 + (\varepsilon - 1)q$ and q can be stated as

$$q = \left(\frac{1}{2}\right)\left(\frac{K\left(k^{'}\right)}{K(k)}\right)\left(\frac{K\left(k_0\right)}{K\left(k_0^{'}\right)}\right)$$

Where K is the elliptical function of the first kind and $k_0 = \dfrac{\sinh\left(\dfrac{\pi w}{2h}\right)}{\sinh\left(\dfrac{\pi u}{2h}\right)}$, $k_0^{'} = \sqrt{\left(1-k_0^2\right)}$, $k = \dfrac{w}{u}$, $k^{'} = \sqrt{1-k^2}$ and h is the height of the substrate. If g and e are the spacing between two conductors and the width of the conductor, then $w = \dfrac{g}{2}$ and $u = \dfrac{g}{2} + e$. Moreover, the approximated inductance of the proposed design is[35]:

$$\text{Inductance, } L = \left(\frac{\sqrt{(2e+h)^2 + l^2}}{e} + \frac{2e}{2w+h}\right)\mu_0 h \tag{9}$$

where, μ_0 is the free space permeability.

The frequencies are calculated based on the responsible parts of the inductance and capacitance generation and using the above-stated equations. The idea of inductance and capacitance formation is illustrated in Figs. 4, 5, 6, and 7, respectively. Figs 8a, 8b,8c, and 8d illustrate the equivalent circuit at 3.75 GHz, 7.2 GHz, 10.25 GHz and, 13.55 GHz. So, the equivalent capacitance (C_1) and inductance (L_1) responsible for 3.75 GHz NRI frequency are 0.705 pF and 2.68 nH, correspondingly. The calculated equivalent inductance, L_2 = 2.24 nH and equivalent capacitance, C_2 = 0.233 pF hence the second calculated frequency is 6.96 GHz which is very close to the simulated NRI resonance frequency of 6.95 GHz. Similarly, the third calculated NRI frequency is 10.35 GHz and the calculated equivalent inductance, L_3 = 0.2 nH and equivalent capacitance, C_3 = 1.13 pF, whereas the simulated negative indexed frequency is 10.25 GHz. Moreover, the fourth calculated NRI frequency is 13.43 GHz; however, the simulated NRI frequency is 13.55 GHz. Here, the calculated equivalent inductance, L_4 = 0.0618 nH and equivalent capacitance, C_3 = 2.27 pF. The difference between simulated and calculated NRI frequencies is due to the negligence of intercell capacitance C_p.

3.3 Parametric analysis

A parametric analysis is done by varying the different parameters of the proposed MTM. Fig. 9a shows the effects of the variation of the length of triangular resonator l on the S_{21} curve. The length of l is varied from 1.5 mm to 2.4 mm, having a step width of 0.3 mm. As a result, the first resonant frequency is shifted to the lower frequency region after rising the value of l. This can be attributed to the rise of the total inductance of the meta-structure. But the second, third, and fourth resonant frequencies tend to increase after increasing l. The approximate value of 2.1 mm is chosen for length l. Fig. 9b illustrates the consequences of the variation of parameter p on the S_{21} curve of the proposed MTM. The operating resonant frequency is shifting to the lower frequency region after increasing the length of p in a step of 0.4 mm. The value of p is 5.8 mm for the proposed design because it satisfied all the criteria of an NRI MTM, as shown in Fig. 9b. Variation of the metal strip width e does not largely affect the operating frequency, which is presented in Fig. 9c. However, a slight increase in resonance frequency to the higher frequency region is observed at each operating band due to the reduction of the self-inductance with a rising value of e. The optimum value of e is 0.5 mm.

4 Design of 2×2 and 4×4 array structure of the proposed unit cell

The 2×2 and 4×4 array configurations are designed to observe the behavior of the proposed unit cell when it has to be used as a periodic structure. The schematic layouts of the 2×2 and 4×4 arrays MTM are shown in Figs. 10a and 10b, respectively. The spacing between the two horizontal and vertical unit cell is 0.4 mm. The overall dimension of the 2×2 array is 12×12 mm^2, and the overall dimension of the 4×4 array is 24×24 mm^2. The effective parameters of the proposed MTM arrays are shown in Figs. 11 and 12. The negative frequency band covered by the array structures and unit cell are listed in Table I. Here, the unit cell exhibits several double negative regions in the span of 3.6–3.9 GHz, 6.8–7.6 GHz, 10.1–10.4 GHz, and 13.4–13.7 GHz equivalent to a bandwidth of 300 MHz, 800 MHz, 290 MHz, and 360 MHz. Besides, DNG regions of the 2×2 array are from 3.2–4.2 GHz, 7–7.5 GHz, and 10.2– 10.6 GHz, and 13–13.4 GHz. Similarly, DNG regions shown by the 4×4 array are spread from 3.4–4.1 GHz, 6.7–7.6 GHz, 10.1–11 GHz and 12.8–13.5 GHz, respectively. Moreover, the NRI properties are visible in the frequency ranges of 3.5–3.8 GHz, 7–7.3 GHz, 10.1–10.8 GHz, and 13–13.4 GHz for 2×2 array of proposed MTM as represented in Fig. 11c and 3.7–3.9 GHz, 6.8–7.3 GHz, 10.3–10.8 GHz, and 12.9–13.4 GHz for 4×4 array of proposed MTM as shown in Fig. 12c. So, both array structures reveal the NRI frequency regions in the S-, C-, X-, and Ku-bands.

5 Comparative study

In Table II, the proposed MTM is compared with several previously reported NRI MTMs. Compared to the literature listed in table II, the proposed MTM is compact, having an overall size of 6×6 mm^2 and an effective medium ratio (λ_0/p) of 13.8. This higher value of λ_0/p attributes the compactness of the proposed NRI MTM. Moreover, none of the literature is able to present multi-band operation except the literature in reference 22. But the size of the unit cell is comparatively large to the proposed design, and the proposed unit cell structure is simpler than literature in reference 22. So, the proposed NRI MTM could be an attractive candidate for S-, C-, X-, and Ku-bands applications.

6 Sensor applications of the proposed NRI Metamaterial

In this section, three types of sensors by employing the proposed NRI metamaterial are presented. Microwave sensor applications have been established by scientists in the field of solid and liquid materials because of robust localization of EM fields. The unique property of a substance is the permittivity. MTM based sensors utilize resonant frequency shifting approach, which is directly related to the permittivity. Typical sensing approach of MTM structure depends on variation in wavelength or resonant frequency as a consequence of loading samples or materials. So sensing mechanism differs in optical and RF and microwave region. In the RF and microwave frequency region, the capacitance of the MTM structure becomes affected after unknown sample loading for sensing purpose. As a result, LC-resonance alters. So it is called permittivity based sensing. However, in optical materials, restrained wavering free electrons on MTM arrangement gets exaggerated based on the refractive index of loaded material, and because of which change in surface Plasmon resonance occurs.[37]

In this part of the article, transformer oil sensor application, chemical sensing application, and pressure sensor application of the proposed MTM are discussed. The unit cell and 2×2 array configurations are investigated for transformer oil aging sensor. Also, the 2×2 array configuration is investigated for liquid chemical sensing applications. Besides, unit MTM structure is used for pressure sensing application. Though, any suitable arrangement of the suggested MTM structure can be used because all of them satisfy quad-band NRI operation. For sensor study, the boundary environments are set to the PEC along x- and y-axis and z-axis is the propagation axis because sidewalls of waveguide are PEC in nature.

6.1 Transformer oil aging sensor application

Disclosure and quantification of hazardous compounds used in various environments is an essential process. Nevertheless, the microfluidic sensor applications, fuel degradation and transformer oil ageing sensor are another kind of utilization region for MTM sensors. Power transformers are key components and the most costly parts in electrical systems. In this way, it is of incredible significance to screen their properties intermittently. Most of the imperfections emerging in power transformers can be recognized in the protection oil and early anticipation can be led. One of the huge imperfection sources is simply the oil which loses its protection ability with maturing, occasioning a development of the conductivity, a slight variation of permittivity, oxidation, pollution, and unreasonable temperature. So, the maintenance of transformer oil is crucial for uninterrupted functioning. The fuel adulteration strategies are lab-based, and the costs of the equipment utilized in these techniques are high.[24] So microwave-based MTM sensors could be a possible solution. The significant properties of transformer oil are specific gravity, flash point, viscosity, total acid number, oxidation stability, dissipation factor, breakdown voltage, volume resistivity and dielectric constant. But permittivity does not have a pronounced and noticeable relationship with oil age.[38] So, the transformer oil aging sensor study in this subsection is only accomplished by the complex permittivity of the used (clear) and unused (dark) transformer oil.

The schematic diagram of the proposed unit cell-based transformer oil aging sensor is illustrated in Fig. 13. In addition to NRI MTM, the proposed structure uses a sensor layer. The thickness of the sensor layer t_s is of 10 mm, and the permittivity is ε_s. The thickness of the sensor layer is selected according to the thickness of the X-band sample holder. The sensor layer is filled with transformer oil. According to ε_s, the capacitance of the proposed structure varies that is related to the resonance frequency. So resonance frequency is expected to change as per the complex permittivity of the transformer oil. As the frequency enlarges, the impacts of the material become progressively prominent contrasted with the lower frequencies. Hence, this work is focused on X-band, which is somewhere in the range of 8 GHz and 12 GHz, where the referenced impacts are progressively visible. The real permittivity values of clear and dark oil are 2.7 and 2.8, respectively that are taken from the literature[24] at 8–12 GHz and used in the simulation software to recognize the referenced oils.

Fig. 14 illustrates the simulated transmission resonances of the proposed unit MTM cell incorporated transformer oil aging sensor. At the first step, the sensor layer is filled with air, and the simulated resonance frequency is noticed at 9.54 GHz. Then, the sensor layer is filled with clear transformer oil (unused). Employing the unit cell based transformer oil aging sensor, the simulated resonance frequency of clear transformer oil is observed at 9.51 GHz. After that, dark transformer oil (used) is placed in the sensor layer. The resonance frequency of dark transformer oil is found at 9.44 GHz. Hence alteration in resonance frequency is 70 MHz after sample loading. That attributes the inverse relation of permittivity and resonance frequency. Basically, the series capacitance formed after the oil sample loading and added with the total equivalent capacitance of the unit cell. Consequently, resonance shifting phenomenon occurred. The quality factor (Q factor) of the sensor is the ratio of the centre frequency to the frequency difference. As the permittivity increases, resonance frequency decreases, and the Q factor of the sensor structure increases.

Then, the 2×2 array configuration is modified to detect the purity of the transformer oil and illustrated in Fig. 15. Fig. 16 illustrates the performance of the 2×2 array incorporated transformer oil aging sensor of Fig. 15. The simulated resonance frequency of clear transformer oil is observed at 9.5 GHz using proposed 2×2 MTM array-based sensor. The resonance frequency of dark transformer oil is found at 9.42 GHz. So, the frequency variation is 80 MHz. This 80 MHz resonance difference is significant enough to distinguish the oil samples. It seems to be small but happened due to the little difference in the permittivity of the oil samples. Moreover, the sensitivity of the 2×2 array configuration based transformer oil aging sensor is greater than the unit cell-based transformer oil aging sensor. In 2×2 array configuration, localization of electric field increases; as a result, frequency shifting phenomena is also increased.

6.2 Design of the NRI MTM based chemical sensor for concentration detection of binary mixtures of water with ethanol, methanol, and acetone

Another application of the proposed MTM as a chemical sensor is represented in this section. The 2×2 array structure is used to determine the industrial liquid chemicals and their concentrations. Geometrical construction of chemical sensor is the same as Fig. 15 except the filling substances of the sensor layer. The thickness of the sensor layer is $t_s = 10$ mm. The operating principle is the same as permittivity based sensing that has been described earlier. Multipurpose liquid chemicals are used to prove the usage of the NRI MTM as a chemical sensor.

The electrical properties such as permittivity and loss tangent values of liquid chemicals are assigned as a frequency reliant material to the simulation software and calculated from literature in references 39 and 40. The calculated real permittivities of pure ethanol, methanol, and acetone are 6, 10, and 20, respectively. Moreover, loss tangents are considerably dissimilar, particularly for methanol and acetone. As there is a considerable difference between the permittivities, subsequently, it is expected that a microwave structure can distinguish the sorts of the substances. Because of the noteworthy distinction between the electrical properties of the liquid materials, significant modification between the resonance frequency can be expected. Fig. 17 denotes the transmission coefficients curves of the proposed microfluidic sensor. When the sensor layer is empty, the resonance frequency is at 9.54 GHz. The simulated transmission resonances of pure ethanol, methanol, and acetone are at 9.47 GHz, 9.27 GHz, and 9.031 GHz, correspondingly. Based on Fig. 17, transmission resonance frequencies are altered from 9.031–9.47 GHz whereas permittivity changed from 6–20. So a total of 439 MHz bandwidth is obtained, and the average sensitivity is 4.75%. Moreover, the Q factor is higher when the permittivity of the chemical is larger. A relation between the real value of permittivity (ε_r) and resonance frequency can be build up by a polynomial function. Through the permittivity of test material, the resonant frequency can be estimated by parabolic approximation, and it is presented in the following equation:

$$\text{Resonant frequency, } f = 2\times10^{6}\varepsilon_r^{2} - 77\times10^{6}\varepsilon_r + 9.9\times10^{9} \tag{10}$$

Moreover, the responses of the proposed chemical sensor are investigated by creating a simulation environment having 0% to 100% volume fraction of liquid chemical with a step size of 10%. The complex permittivity of the binary mixtures (chemical-water) can be determined by Debey model[39] at 8–12 GHz as follows:

$$\varepsilon_{smp} = \varepsilon_h + \frac{\varepsilon_d}{1 + j\omega\tau_d} \tag{11}$$

where ε_{smp} is the complex permittivity of a specific sample. The Debye relaxation time τ_d, high-frequency relative permittivity ε_h, and dielectric decrement ε_d are readily accessible in reference 39.

Fig. 18a represents the complex permittivity of the ethanol-water mixture at 25°C. Here, when the volume fraction of water changes from 0% to 100%, the volume fraction of ethanol varies from 100% to 0%. The real part of permittivity is highest when the sensor layer is filled with 100% water and lowest when the sensor layer is occupied with 100% ethanol. Fig. 18b presented that the resonance frequencies of 0% to 100% ethanol samples are varied from 9.13 GHz to 9.47 GHz. Besides, the total frequency difference for 100% alteration of ethanol purity is 340 MHz. The Q factor of the proposed sensor is in inverse relation with the resonance frequency. The obtained highest Q factor is 13.04 when the water content is 100% by volume.

At 25°C, the complex permittivity of the methanol-water mixture is presented in Fig. 19a. According to Fig. 19b, the simulated resonance frequencies are varied from 8.77 GHz to 9.27 GHz corresponding to the change of methanol content from 0% to 100%. The total obtained bandwidth is 500 MHz for methanol samples, and this value is adequate to discriminate the mentioned concentration of the methanol. Fig. 19b also represented that the reduction of the resonance frequency and rise of Q factor with the increase in water content in the methanol-water mixture.

Similarly, the calculated complex permittivity of acetone is described in Fig. 20a corresponding to 0% to 100% volume fraction of acetone in the acetone-water mixture.[40] From Fig 20b, it can be seen that the simulated resonance frequencies are altered from 8.66 GHz to 9.03 GHz, corresponding to 0% to 100% purity ratio of acetone. So, a total of 370 MHz frequency deviation is obtained for 100% variation of acetone purity, and this value is quite sufficient to distinguish the mentioned concentration of the acetone. Therefore, it can be concluded that the proposed NRI MTM is applicable for microfluidic sensor design.

As resonance frequency and Q factor are related to the complex permittivity of the mixtures, a simplified mathematical model is used to interrelate their dependency. The empirical model is described as follows:

$$\begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon^{\mathrm{r}} \\ \Delta\varepsilon^{\mathrm{i}} \end{bmatrix} \tag{12}$$

Where, $\Delta\varepsilon^{\mathrm{r}} = \varepsilon_{\mathrm{S}}^{\mathrm{r}} - \varepsilon_{\mathrm{R}}^{\mathrm{r}}$, $\Delta\varepsilon^{\mathrm{i}} = \varepsilon_{\mathrm{S}}^{\mathrm{i}} - \varepsilon_{\mathrm{R}}^{\mathrm{i}}$, $\Delta f_0 = f_{\mathrm{S}} - f_{\mathrm{R}}$, $\Delta Q_0 = Q_{\mathrm{S}} - Q_{\mathrm{R}}$, with the subscript 'S' for sample, 'R' for reference and superscript 'r' for real and 'i' for imaginary. This scheme of linear equations is predictable around an arbitrary reference solution with $\varepsilon_{\mathrm{R}} = \varepsilon_{\mathrm{R}}^{\mathrm{r}} + \mathrm{j}\varepsilon_{\mathrm{R}}^{\mathrm{i}}$, which yields the resonance frequency of f_R and Q factor of Q_R. Here, the 50% volume fraction is preferred as a reference solution. The characteristic matrix of Eq. (12) has some unknown coefficients. The least-square method can be used to approximate the coefficients of the characteristic matrix. The formulas are:

$$[A_{11} \quad A_{12}]^T = (B^T B)^{-1} B^T C \tag{13}$$

$$[A_{21} \quad A_{22}]^T = (B^T B)^{-1} B^T D \tag{14}$$

Where, B, C, and D are the three matrices that are constructed from the reported complex dielectric constant, simulated resonance frequency, and Q factor. The subscript '11' indicate mixtures with a volume fraction of water from 0% to 100%.

$$B = \begin{bmatrix} \Delta\varepsilon_1^{\mathrm{r}} & \Delta\varepsilon_1^{i} \\ \Delta\varepsilon_2^{\mathrm{r}} & \Delta\varepsilon_2^{i} \\ \vdots & \vdots \\ \Delta\varepsilon_{11}^{\mathrm{r}} & \Delta\varepsilon_{11}^{\mathrm{i}} \end{bmatrix} \quad C = \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \vdots \\ \Delta f_{11} \end{bmatrix} \qquad D = \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_{11} \end{bmatrix}$$

So, the characteristics matrix that relates complex permittivity of the ethanol-water mixture to the resonance properties can be expressed as:

$$\begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} = \begin{bmatrix} 0.0002 & 0.0097 \\ 0.0212 & -0.1316 \end{bmatrix} \begin{bmatrix} \Delta\varepsilon^{\mathrm{r}} \\ \Delta\varepsilon^{\mathrm{i}} \end{bmatrix} \tag{15}$$

$$\text{And} \begin{bmatrix} \Delta\varepsilon^{\mathrm{r}} \\ \Delta\varepsilon^{\mathrm{i}} \end{bmatrix} = \begin{bmatrix} 573.49 & 42.47 \\ 92.23 & -0.77 \end{bmatrix} \begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} \tag{16}$$

Similarly, the set of equations for methanol-water mixture can be stated as the following manners:

$$\begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} = \begin{bmatrix} -0.0037 & 0.0113 \\ 0.1125 & -0.2556 \end{bmatrix} \begin{bmatrix} \Delta\varepsilon^{\mathrm{r}} \\ \Delta\varepsilon^{\mathrm{i}} \end{bmatrix} \tag{17}$$

$$\text{And} \begin{bmatrix} \Delta\varepsilon^{r} \\ \Delta\varepsilon^{i} \end{bmatrix} = \begin{bmatrix} 791.961 & 34.983 \\ 348.739 & 11.492 \end{bmatrix} \begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} \tag{18}$$

Besides, the relation between electrical properties and resonance properties of the acetone-water mixture can be indicated as follows:

$$\begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} = \begin{bmatrix} -0.0057 & 0.0045 \\ 0.1459 & 0.0302 \end{bmatrix} \begin{bmatrix} \Delta\varepsilon^{r} \\ \Delta\varepsilon^{i} \end{bmatrix} \tag{19}$$

$$\text{And} \begin{bmatrix} \Delta\varepsilon^{r} \\ \Delta\varepsilon^{i} \end{bmatrix} = \begin{bmatrix} -36.269 & 5.449 \\ 175.471 & 6.796 \end{bmatrix} \begin{bmatrix} \Delta f_0 \\ \Delta Q_0 \end{bmatrix} \tag{20}$$

To validate the Eqs. (15), (17), and (19), the simulated resonance properties are compared with the calculated (using Eqs. (15), (17), and (19)) resonance properties. Fig. 21 illustrates the difference between the simulated and calculated resonance frequency of the chemical sensor. The calculated and simulated values of resonance frequencies and Q factors of the ethanol-water mixture, methanol-water mixture, and acetone-water mixture at various steps are quite reasonable. However, some discrepancies are likely from the first-order approximation of the sensor's mathematical model. Higher-order approximation of the mathematical model can solve this issue. Similarly, the complex permittivity of the chemical-water mixture can also be determined from the inverse of the characteristic matrix.

6.3 NRI MTM based pressure sensor

Dependable, simple to manufacture, and low power consuming pressure sensors are progressively being utilized in biomedical and automobile applications. Most of the pressure sensors concentrate on transduction procedures dependent on the utilization of a deformable film. Moreover, extra readout circuitry is essential in close proximity to sensors. So, zero-power and chipless sensors comprise an extremely advantageous answer for the estimation of any physical or chemical quantity, and mainly remote observing of any physico-chemical amounts in harsh situations because of its prolonged lifetime.

Here, the design of a pressure sensor using the proposed NRI MTM is discussed. The configuration of the recommended pressure sensor is illustrated in Fig. 22. The proposed pressure sensor has three parts: two unit cells layer and a sensor layer. The projected sensor layer is presented as a pressure sensor. The sensor layer can be relaxed or squeezed by adjusting the pressure. The sensing interface is filled by air ($\varepsilon_s = 1$) for simulation purpose. One of the unit cells is permitted to slide along the *z*-axis. So air gap (t_s) is supposed to change, and the subsequent change in resonance frequency generates idea about the applied pressure.

Fig. 23 illustrates the transmission coefficients curve of the proposed MTM based pressure sensor. As a confirmation of idea, a pressure sensor is reenacted by setting $\varepsilon_s = 1$ while allotting four distinct qualities to the detecting parameter $t_{s.}$ As t_s decreases from 2 mm to 0.5 mm, resonance frequencies decrease as a consequence of increasing mutual inductance and capacitance. From Fig. 23 it is noticeable that S-, C-, and X-bands are sensitive about the applied pressure. That is why the type of resonance frequency shifting of any band can be utilized to investigate the given pressure to the sensor layer.

6.4 Comparative study of the proposed sensor structures with others in the literature

The outcome assessment of the proposed sensors discussed in section 6 with different works in term of resonance frequency shift and permittivity are shown in Tables III, IV, V, and VI. The proposed transformer oil aging sensors are greater sensitive in terms of resonance shifting comparable to the other references illustrated in Table III. The unit cell-based MTM exhibits 70 MHz frequency shifting in X-band. However, the performance of the 2×2 array-based sensor is superior to the unit cell-based transformer oil aging sensor. A total of 80 MHz frequency deviation is observed for transformer oil aging sensor (2×2 configuration). This feature of 2×2 array-based sensor can be attributed as an advantage of the 2×2 MTM array. Furthermore, the highest resonance difference is not more than 67 MHz among all other sensors listed in Table III. So, the performance of both proposed transformer oil aging sensors is superior.

Table IV, V, and VI highlight the comparative study of the proposed chemical sensor with the existing literature. Regarding the difference of the resonance frequency with the permittivity over the considered input variable span, it can be seen that the values given in the table are very different. However, the working frequencies are also significantly dissimilar. Moreover, the concentrations of the chemicals are dissimilar too. All of the sensors listed in Table IV, V, and VI show the linear movement of resonance according to the concentration of the chemical. So frequency bandwidth of literature having a chemical concentration difference of 100% can be estimated to be lower than the proposed sensors. The frequency differences for 100% change in concentration of ethanol, methanol, and acetone are 340 MHz, 500 MHz, and 370 MHz, respectively. Nevertheless, it is worth mentioning that the values are greater than the reported values listed in Table IV, V, and VI. Moreover, none of the literature explores the mathematical model of the chemical sensor configurations to relate the electrical and resonance characteristics of the sensor. But in this research article, three characteristics matrices are constructed from the electrical and resonance feature for three binary mixtures. Also, the accuracy of the mathematical model is scrutinized by comparing the simulated and calculated quantities.

Table VII represents the comparative study of the proposed pressure sensor with other works of literature. The frequency deviation of the proposed sensor in X-band is much more improved than the sensor of reference 32. Additionally, the proposed pressure sensor exemplifies S- and C-bands response, though the listed sensors are single-band in operation. The S- and C-bands response of the proposed pressure sensor represent frequency shift more remarkable than the literature of reference 32. So the multi-band operation of the proposed pressure sensor offers design flexibility in terms of operating bands.

The NRI MTM used to design the abovementioned sensors is of multi-band. So any suitable band depending on the requirement (such as waveguide size) can be utilized to sensor design. This is another principal advantage of the proposed MTM sensors. Besides, this feature is not available in any other literature of Table III, IV, V, VI, and VII. So, the recommended multi-band NRI MTM could be a virtuous solution for S-, C-, X- and Ku-bands versatile sensor applications along with other wireless communication applications.

7 Conclusion

An analysis of a novel quad-band NRI MTM along with its application as a sensor has been highlighted in this article. A combination of square and triangular resonators is used to design the multi-band MTM unit cell. The unit structure of the proposed MTM can exhibit DNG characteristics simultaneously at S-, C-, X-, and Ku-bands with NRI bandwidth in the region of 3.7–3.9 GHz, 6.8–7.1 GHz, 10.1–10.4 GHz, and 13.4–13.7 GHz, respectively. Moreover, the unit cell is compact with a figure of merit of 13.8. Furthermore, the 2×2 array and the 4×4 array structures are also investigated to explore the behavior of the proposed MTM when they have to be used as bulk. All of these structures show a good commitment to effective parameters and capable of operating in S-, C-, X-, and Ku-bands with NRI frequency bands. As the proposed MTM exhibits strong localization of electric field in its operating bands, this paves the way to design high sensitive MTM sensors. The proposed 2×2 array-based transformer oil aging sensor study reveals 80 MHz frequency difference between dark and clear transformer oil which is superior to the proposed unit MTM cell-based transformer oil aging sensor. Also, the proposed MTM is utilized for quantification and characterization of binary mixtures (methanol, ethanol, acetone with water) in X-bands. However, the sensors study can also be performed in S-, C-, and Ku-bands, as the MTM is quad-band in nature. The main advantage of the chemical sensing applications is its large frequency shifting phenomenon for binary mixtures. The frequency variances for 100% alteration in the concentration of ethanol, methanol, and acetone are 340 MHz, 500 MHz, and 370 MHz, respectively. Additionally, an empirical model is utilized to obtain the resonance frequency and Q factor of the binary mixtures from the complex dielectric constant and vice-versa. The proposed MTM can also be used to design a multi-band pressure sensor, in which quad-band operation of the sensor helps to detect the pressure variation more accurately. Owing to its competency of composition quantification and categorization, the NRI MTM is very promising for various microwave applications.

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Tables

Table I A comparative study among negative permittivity, permeability, and refractive index regions of the proposed MTM unit cell, 2×2, and 4×4 MTM array structures.

Effective parameters	Structure	Frequency range (GHz)	Bandwidth (GHz)	Application bands
Permittivity	Unit cell	1.4–3.9	2.5	S, C, X, Ku
		6.8–7.6	0.8	
		10.1–10.4	0.3	
		12.2–13.8	1.6	
	2×2 array	1.6–4.2	2.6	S, C, X, Ku
		7–8	1	
		10.2–10.8	0.6	
		12.2–13.4	1.2	
	4×4 array	3.2–4.6	1.4	S, C, X, Ku
		6.7–7.6	0.9	
		10.1–11	0.9	
		12.7–13.5	0.5	
Permeability	Unit cell	3.6–3.9	0.2	S, C, X, Ku
		6.8–8	1.2	
		10.1–10.4	0.3	
		13.4–13.7	0.3	
	2×2 array	3.2–4.8	0.3	S, C, X, Ku
		6.3–7.5	0.4	
		9.5–10.6	1.1	
		13–13.8	0.8	
	4×4 array	3.4–4.1	0.7	S, C, X, Ku
		6.6–8	1.3	
		9.5–11.3	1.7	
		12.8–13.8	1	
Refractive Index	Unit cell	3.7–3.9	0.2	S, C, X, Ku
		6.8–7.1	0.3	
		10.11–10.4	0.29	
		13.4–13.7	0.3	
	2×2 array	3.5–3.8	0.3	S, C, X, Ku
		7–7.3	0.3	
		10.1–10.8	0.7	
		13–13.4	0.4	
	4×4 array	3.7–3.9	0.2	S, C, X, Ku
		6.8–7.3	0.5	
		10.3–10.8	0.5	
		12.9-13.4	0.5	

Table II Comparison of the proposed MTM unit cell with other literature.

Reference	Shape of NRI unit cell	Covered NRI frequency band	Resonant frequency	Application frequency band	Size of unit cell (mm^2)	Effective medium ratio, λ_0/p	Publication year
[10]	Double G	4-4.95 & 5-5.57	2.7, 5.6	C	12×12	9.25	2015
[15]	ELC and loop resonator	1.95-2.13, 2.30-2.41, & 4.63-4.87	2.03, 2.36, 4.81	L, S	8×8	18.47	2016
[16]	C	4.906-10.632 & 10.884-13.348	3.36, 8.574, 11.57	C, X, Ku	12×12	7.4	2017
[17]	Crossed S	13.4-18.6	14	Ku	5.2×5.2	4.12	2016
[18]	H	8.31-15.43 & 17.43-18	1.63, 10.93	X, Ku	12×12	15.33	2018
[19]	Modified H	7.615-8.46, 8.755-9.36, & 10.68-15	6.8, 10.8, 12.5	C, X, Ku	7.92×7.92	5.57	2018
[20]	Bare H	7.37-7.66, 8.47-10.12, 10.39-10.57, & 11.26-11.33	4.29, 9.93	C, X	20×20	3.49	2014
[21]	Z	3.482-7.096, 7.876-10.047, & 11.594-14	7.32, 11.84	C, X, Ku	10×10	4.09	2016
[22]	Hexagonal	3.36-3.52, 5.34-5.52, 5.63-8.69, 9.71-10.55, & 11.84-13.90	1.64, 3.6, 7.23, 10.225	S, C, X, Ku	10×9.8	18.2	2018
Proposed design	Combination of square and triangular resonators	3.7–3.9, 6.8–7.1, 10.11–10.4, & 13.4-13.7	3.66, 6.66, 9.8, 12.58	S, C, X, Ku	6×6	13.8	------

Table III Performance comparison of the proposed transformer oil sensor with other MTM based transformer oil sensors.

References	Configuration of MTM	Resonance frequency (GHz)	Permittivity for clean & dark oil	Frequency range (GHz)	Resonance frequency shift (MHz)	Publication year
[24]	Square ring resonators	—	2.7 & 2.8	8–12	70	2019
[25]	Labyrinth Resonator	4.62	2.7 & 2.9	4–5	40	2019
[26]	Omega shaped resonator	1.9	2.74 & 2.87	1–8	63	2020
[27]	Omega shaped resonator	9.85	2.7 & 2.9	8.5–10.5	77	2020
This work	Combination of square and triangular resonators	9.54	2.7 & 2.8	8–12	80	—

Table IV Comparison of the proposed methanol sensor with other MTM based methanol sensors.

References	Configuration of MTM	Resonance frequency (GHz)	Concentration of methanol	Permittivity	Frequency range (GHz)	Resonance frequency shift, (MHz)	Publication year
[23]	Chiral	9.26	10%–90%	62–50, 12–7	8–12	270	2018
[24]	Square ring resonators	—	20–100%	55–40, 11–7	8–12	210	2019
[25]	Labyrinth Resonator	4.62	0–40%	75-73, 45–39	4–5	60	2018
[26]	Omega shaped resonator	1.9	0–40%	78-76, 55–53	2.5–3	230	2020
[28]	SRR	4.62	10–95%	77.5–55	4–6	20	2017
This work	Combination of square and triangular resonators	9.54	0–100%	65–10	8–12	500	—

Table V Performance evaluation of the proposed ethanol sensor with other MTM based ethanol sensors.

References	Configuration of MTM	Resonance frequency (GHz)	Concentration of ethanol	Permittivity	Frequency range (GHz)	Resonance frequency shift (MHz)	Publication year
[25]	Labyrinth Resonator	4.62	0–40%	75–73, 45–39	4–5	100	2018
[26]	Omega shaped resonator	1.9	0–40%	77–76, 51–50	2.5–3	250	2020
[28]	SRR	4.62	10–95%	70–11, 21–11	4–6	50	2017
This work	Combination of square and triangular resonators	9.54	0–100%	65–6	8–12	340	—

Table VI Performance evaluation of the proposed acetone sensor with other MTM based acetone sensors.

References	Configuration of MTM	Resonance frequency (GHz)	Concentration of acetone	Permittivity	Frequency range (GHz)	Resonance frequency shift (MHz)	Publication year
[28]	SRR	4.62	10%–30%	72–68, 60–52	4–6	40	2017
[30]	S-shaped resonator and circular ring resonator	9.5	10–90%	62–50, 26–21	8–12	220	2020
This work	Combination of square and triangular resonators	9.54	0–100%	65–20	8–12	370	—

Table VII Performance evaluation of the proposed pressure sensor with other MTM based pressure sensors.

References	Configuration of MTM	Thickness change of sensor layer (mm)	Operating band	Frequency range (GHz)	Resonance frequency shift (MHz)	Publication year
[31]	SRR	2–0.4	X	12.1–11	1100	2013
[32]	MTM absorber	2–0.5	X	10.25–10.1	150	2017
This work	Combination of square and triangular resonators	2–0.5	S	3.34–3.93	590	—
			C	6–6.6	600	
			X	9.9–9.10	800	
				11.5–10.98	610	

Figure Legends

Fig. 1 Geometry of the proposed multi-band MTM unit cell. (a) Schematic layout and cross-sectional views (aa') (b) Simulation setup.

Fig. 2 Reflection (S_{11}) and transmission coefficient curves (S_{21}) of the proposed MTM unit cell.

Fig. 3 Effective parameters of the proposed metamaterial unit cell: Real and imaginary values of (a) permittivity, (b) permeability, (c) refractive index.

Fig. 4 (a) Localization of electric field and (b) Distribution of surface current at 3.75 GHz.

Fig. 5 (a) Localization of electric field and (b) Distribution of surface current at 6.95 GHz.

Fig. 6 (a) Localization of electric field and (b) Distribution of surface current at 10.25 GHz.

Fig. 7 (a) Localization of electric field and (b) Distribution of surface current at 13.55 GHz.

Fig. 8 Equivalent circuit at (a) 3.75 GHz, (b) 6.95 GHz, (c) 10.25 GHz, and (d) 13.55 GHz.

Fig. 9 Analysis of the proposed MTMs basic parameters by varying (a) l, (b) p, and (c) e.

Fig. 10 Arrangement of arrays designed by employing the proposed MTM unit cell. (a) 2×2 and (b) 4×4.

Fig. 11 Effective parameters of the 2×2 array. (a) μ, (b) ε, and (c) η.

Fig. 12 Effective parameters of the 4×4 array. (a) μ, (b) ε, and (c) η.

Fig. 13 Schematic diagram of the proposed unit cell-based transformer oil aging sensor. (a) perspective view and (b) Left view.

Fig. 14 Simulated transmission coefficients of the proposed unit cell-based transformer oil aging sensor.

Fig. 15 Schematic diagram of the proposed 2×2 MTM array-based transformer oil aging sensor. (a) Perspective view and (b) Left view.

Fig. 16 Simulated transmission coefficients of clear and dark transformer oil.

Fig. 17 S_{21} curves of the multipurpose chemical sensor.

Fig. 18 (a) Complex permittivity of ethanol-water mixture when the water content increases from 0% to 100% with a step of 10% by volume. (b) Simulated transmission coefficient curves for ethanol-water mixture when the ethanol content increases from 0% to 100%.

Fig. 19 (a) Complex permittivity of methanol-water mixture when the water content increases from 0% to 100% with a step of 10% by volume. (b) Simulated transmission coefficient curves for methanol-water mixture when the methanol content increases from 0% to 100%.

Fig. 20 (a) Complex permittivity of acetone-water mixture when the water content increases from 0% to 100% with a step of 10% by volume. (b) Simulated transmission coefficient for acetone-water mixture when the acetone content increases from 0% to 100%.

Fig. 21 Simulated and calculated resonance frequency and Q factor. (a) Ethanol-water mixture, (b) Methanol-water mixture, and (c) Acetone-water mixture.

Fig. 22 Schematic diagram of the proposed NRI MTM based pressure sensor (a) Perspective view, (b) Front view, (c) Back view, and (d) Left view.

Fig. 23 S_{21} curves of the pressure sensor.