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Review

Metamaterial Inspired Resonators as Microwave Sensors: A Review

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Received: 4 May 2023; **Revised:** 7 August 2023; **Accepted:** 11 August 2023

Abstract: Metamaterial-based devices show properties like negative magnetic permeability and negative electrical permittivity, which are not found naturally. Due to their extraordinary sensitivity to nearby perturbations, metamaterial structures have recently emerged as highly desirable and effective techniques of detection. Wide dynamic range, multi-functionality, and simple design and production are a few benefits of metamaterial-based structures. The sensitivity and limit of detection for sensors based on metamaterials can be enhanced by properly altering the device parameters. With the inclusion of microfluidics in metamaterial-based sensors, the sensitivity, selectivity, and detection limit can also be improved. In this review, we have focused on the various meta-surfaces employed for sensing purposes. We have provided a brief introduction to the principle and working of sensors based on meta-surfaces. The main content of the paper is a detailed review of metamaterial-inspired microwave sensor device applications in different fields. These fields include applications in biological sensing, chemical and fuel sensing, physical sensing (includes temperature, strain, displacement, and thickness measurement), and non-destructive techniques for structural health monitoring.

***Keywords*:** resonator, sensor, chemical sensing, biological sensing, physical sensing

1. Introduction

In recent times, enormous research has been carried out to develop and utilize sensors dependent on several periodic structures; these are termed metamaterial (MM) [1]-[4] based sensors. Figure 1 represents different structures used for sensing applications. These structures are made using synthetic composite materials with properties that are not naturally found [5]. They are fabricated using different elements like plastics [6], composites [7], and metals [8], [9] and show properties such as negative index of refraction, negative permeability, and negative permittivity. In other words, MMs are materials that possess periodic structures much smaller than that of exciting signal wavelength to obtain suitable electromagnetic response [10]-[14]. For reference, in our previous studies, we have already proposed a Complimentary Split Ring Resonator (CSRR) which resonates at λ/12. MM-based devices are components whose characteristics are mostly determined by their form and shape rather than the materials employed to realize them [15]. Due to their advantages, such as high sensitivity, high-quality factor, label-free detection, and real-time measurements, MM-based sensors are gaining high importance [16]. The sensor studies pertaining to MM-inspired structures can be classified into two parts, that is, studies based on resonant and non-resonant MM structures [17]. In resonant MMs, the atomic resonance is a result of oscillating current over the conducting surface while there is no oscillating current in non-resonant metamaterials. Since these MM-inspired sensors have a very small size, simple geometry, and easy

DOI: https://doi.org/10.37256/est.5120242960

fabrication method, there are many reported cost-effective methods and approaches to design sensors for different sensing purposes [18]. These can include gas sensing [9], [19], [20], chemical sensing [21]-[28], and biological sensing applications [29]-[35], along with sensors for angle and position detection [36]-[40], crack detection [41]-[45], and strain measurement [46], [47].

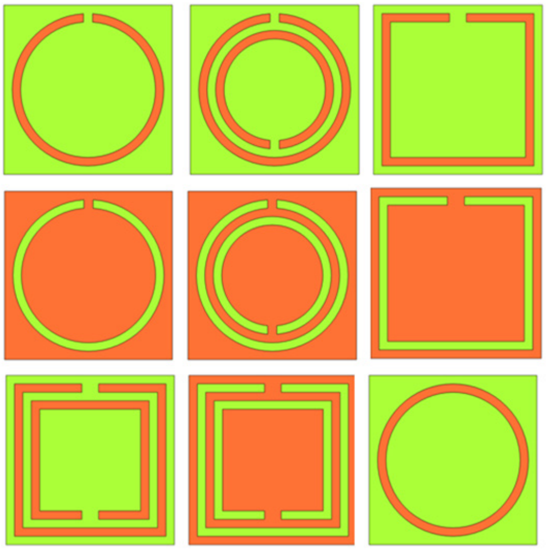

Figure 1. Basic structure pertaining to SRR, CSRR, and LRR

In order to function as an effective chemical sensing device, MM-inspired sensors make use of the mechanism of change in dielectric constant as a result of variation in surrounding environment factors [48]. They can also be of huge importance in the food industry for quality checks, and many more [49]-[52]. This is because any change in the value of the dielectric constant will lead to a consequent change in the resonant frequency of the structure [25], [53]. In several countries, fuel adulteration is a major concern, and thus we studied this in our previous paper [54]-[56]. Apart from chemical sensing, MM-based sensors can also be employed in crack detection. There are many techniques such as eddy current [57], acoustic emission [58], and others [59], [42] which are used for detecting sub-millimeter surface cracks. All these methods have certain limitations pertaining to cracks hidden under paint, or filled with other materials. MM sensors prove to be very handy when it comes to non-destructive detection of cracks as they can easily detect cracks under coatings or paints, they can also detect cracks occupied by materials like rust, dust, or any other foreign particle. This becomes feasible because the cracks present in different materials cause variation in the near-field distribution of electromagnetic fields. This change in the field is a consequence of changes in surrounding factors and thus can be used as a measure for crack detection. Several MM-based biosensors that are easy to use and practical for direct molecule detection have been reported in the past. [60]. Typically, biomaterials are liquids with water as their foundation; as a result, they exhibit high permittivity values [61]. Such biosensors can be utilized for detecting and sensing biomaterials both in a gaseous state and in aqueous form using a very thin layer of carbon nanotubes (CNTs) [62].

MM-inspired sensors structures can be used as a tool for vapor and gas sensing [8], [9] as they show several advantages when matched to conventional sensors like electrochemical gas sensors [19], metal-oxide-semiconductor (MOS) gas sensors, optical ring resonators based gas sensor [63]. They are less sensitive to temperature changes and can function at lower temperatures. The selectivity of these sensors can also be increased by adding a functionalized second layer on top of them. Many researchers have demonstrated the use of MM-based sensors for strain measurement. This can be achieved by mapping the deformation in the geometry of the resonator upon application of external forces to the change in the resonant frequency of the sensor [36], [47]. Despite the fact that there are other types of MM-based sensors that have been described, we will mostly concentrate on split ring resonators (SRR) and CSRR structures that are employed in a variety of sensing applications. In this review, we will be discussing the working principle or mechanism on which MM-based sensors work. We will also be focusing on the utilization of these sensors for different applications like chemical or vapor sensing, gas sensing, and physical parameters sensing.

2. Working principle

MM-inspired sensors are nothing but a combination of different materials like plastic, conducting elements, and ceramics to realize a periodic structure that can be excited using an electromagnetic field [64]. An MM-based sensor is made in its most basic form by sandwiching a dielectric material between a transmission line and a conducting layer. A periodic structure is created by etching the conducting layer, which subsequently aids in the resonance of induced current on the conducting surface.

In general, a meta-surface is fabricated using a planar conductive periodic pattern over a dielectric substrate. In most of the reported studies, flame retardant 4 (FR4) [26] was used as a dielectric substrate but recently various other dielectric substrates such as RT/Duroid [65], metallo-phthalocyanines [19], metal oxide substrate [66], and others are also employed to achieve enhanced performance. The device's sensitivity to magnetic, electric, or both fields can be estimated and altered, as well as the device's resonance frequency, by making the right material choices.

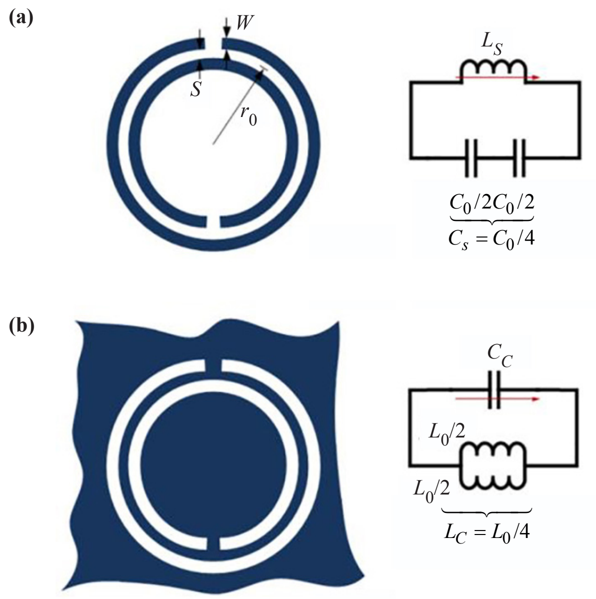

Figure 2. (a) Electrical equivalent circuit for SRR structure; (b) Electrical equivalent circuit for CSRR structure

2.1 *Split ring resonators*

These devices are represented in Figure 2(a) (along with their electrical equivalent circuit) as a conducting structure in the shape of a ring or square over a dielectric substrate. There is a hole or slit in this structure in an area along its length. A transmission line parallel to the structure is used to excite it, causing the magnetic field of the lines to fall perpendicularly over the conducting plane [61]. Current builds up in the ring structure as a result of the continuous change in the magnetic field [67]. The electrical equivalent of the circuit is comparable to an LC resonator circuit that has a resonance frequency of its own. At this resonant frequency, the permeability of the MM structure becomes negative if they are properly excited. The resonant frequency for the SRR can be given as

$$f_{srr} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$C = C_g + C_s \tag{2}$$

C_g = Gap capacitance and C_s = Surface capacitance.

$$C_g = \epsilon_{eff}\left(hw/g\right) + \epsilon_{eff}\left(h+g+w\right) \tag{3}$$

$$C_s = 2\,\epsilon_{eff}\left(\left(h+w\right)/\pi\right)\ln\left(4r/g\right) \tag{4}$$

$$L = \mu_0 R_m\left(\ln\left(\frac{8R_m}{h+w} - 0.5\right)\right) \tag{5}$$

$$R_m = r + w/2 \tag{6}$$

Here, 'r' is radius, 'h' is height, 'w' is width, and 'g' is the slit gap of the conducting structure. From the expression for the resonant frequency and the corresponding expressions, it is quite evident that the resonant frequency can be varied by varying the parameters like slit gap, width, and radius of the ring. Along with this, the resonant frequency also depends on the permittivity of the material present in the vicinity of the structure. Thus, the sensitivity of the structure can be given as

$$S = \frac{\Delta f_{res}}{\Delta \epsilon} \tag{7}$$

$$Q = \frac{f_{res}}{FWHM} \tag{8}$$

In addition to this, the researchers have also demonstrated a double-sided resonator structure. In the case of the double-sided resonator structure, mutual inductance and mutual capacitance are also present along with self-inductance and self-capacitance [48].

2.2 *Complimentary split ring resonators*

They have a ring etched over the surface of the dielectric, as seen in Figure 2(b) (along with its electrical equivalent circuit), which sets them apart from SRRs. In very close proximity to or in line with the resonance structure, there is a micro-strip line that is used for excitation. The formation of an electromagnetic field along the substrate during micro-strip line excitation leads to the induction of current loops in the ring. The induced current loops get trapped along the concentric rings as a result of the dispersed capacitance along the rings [68]. This causes the MM structure to resonate as expected. The expression for the resonant frequency of an equivalent circuit model [69] of CSRR can be given as

$$f_{csrr} = \frac{1}{2\pi\sqrt{L_r(C_c + C_r)}} \tag{9}$$

2.3 *Spiral/looped metamaterial resonator*

This type of MM sensor is composed of a conducting spiral structure attached to a dielectric substrate. Generally, the frequency of resonance for meta-surfaces can be altered by increasing the overall dimension of the structure, permittivity, or substrate thickness. But in the case of spiral/loop structure [70] low resonance frequency values are achieved even with a small overall size of the device [71]. The low resonance frequency is a result of the high inductance of the fabricated structure. The inductance of the coil is directly proportional to the number of spiral turns, thus the larger the number of spiral turns, the higher the value of overall inductance [72]. These types of devices are used when the system demands a very high signal-to-noise ratio (SNR) for example magnetic resonance imaging (MRI) systems [73].

3. Application of metamaterial-inspired sensors

3.1 *Biological sensing applications*

Information about the electrical properties of biological elements like cells and tissues at radiofrequency is very important to understand their current physiological state. Various parameters like cell type or cell morphology affect their dielectric properties and thus can be used for identification and distinction. Some reported applications of MM-inspired sensors are shown in Figure 3. Researchers have shown several ways in which different physical parameters of biological cells and tissues can be studied [74]. Since very long RF measurement [75] and microwave measurement techniques are utilized for this purpose [76], [77]. In these techniques, the properties like dielectric constant, complex permittivity, and losses for a biological element are studied by bringing it into the vicinity of the measuring device. Apart from this, in 1996, scholars differentiated between tumor tissue and normal tissue using the measurement of impedance spectra. The basis for this study was that normal cells have lesser sodium concentration and water content when compared to tumor cells.

They measured the complex impedance using an impedance meter for frequencies ranging from 1.5 kHz to 700 kHz [78]. In the year 2008, a group of researchers from Korea reported a biosensing device made of SRR and working at microwave frequencies [79]. They used an array of SRR and coated it with an Au layer along with single-stranded deoxyribonucleic acid (ss-DNA) linked biotin. In this study, the bare SRR array showed a resonance frequency of 10.82 GHz but when the coating was applied to the structure, it shifted to 10.70 GHz. After the introduction of streptavidin, the resonance frequency shifted to 10.66 GHz. The shift in resonance frequency after sensing was 40 MHz and this corresponds to the change in capacitance of the structure after binding. They further demonstrated the recognition of DNA hybridization using a single DSRR and not an array. In this case, they immobilized a thiol-linked ss-DNA over the gold-coated surface and performed hybridization using c-DNA. The recorded frequency shift after DNA hybridization was 60 MHz [67]. In 2014, researchers demonstrated a device that has two monopole antennas along with a single SRR on the top of the dielectric substrate. This device was used as a bio-molecular sensor to demonstrate the interaction between fibroblast growth factor 2 (FGF2) and heparin. For a concentration of 1 mg/ml of heparin, the frequency shift was obtained to be 3.7 MHz [35]. They also studied the behavior of the sensor with dielectric loading at various positions of the device. With the increasing need and demand for effective identification and treatment of diseases that are non-communicable, there was also a need to study continuous and non-invasive monitoring of critical biological parameters. In 2016, researchers demonstrated the functioning of CSRR sensors for the same purpose using the COMSOL simulation technique [29]. They showed that the relative permittivity of the device gets varied upon interaction with different concentrations of creatinine, thus showing potential for monitoring chronic kidney disease (CKD). This is because, in the case of CKD, the level of blood creatinine increases due to diminished filtration and distal tubular secretion of creatinine. They simulated and investigated the variation in dielectric properties of the blood by varying the relative permittivity of the blood in a range of 1-100 in a frequency range of 1-10 GHz simultaneously.

SRRs are also modeled and simulated with dimensions as small, so as to behave like a metamaterial [10]. The order of dimensions as reported in this work was as small as 441 μm^2 and 256 μm^2. Here, the researchers have deposited a mono-layered graphene of thickness 0.34 nm onto the resonator structure and used it as a biosensing device for the detection of haemoglobin. With this design, the group was able to achieve a sensitivity of around 5000 nm/RIU for haemoglobin concentration. The figure of merit (FOM) they achieved was around 176 RIU^{-1}. In one more instance, a research group has used two cells of circular SRRs and four triangular SRRs that are coupled to a coplanar line which acts as a waveguide for the two-port device [14]. The structure presented in this work also had a couple of cavities for samples that were used to perform glucose concentration detection. With the presented work, the research obtained a resolution of about 1.665 mmol/l.

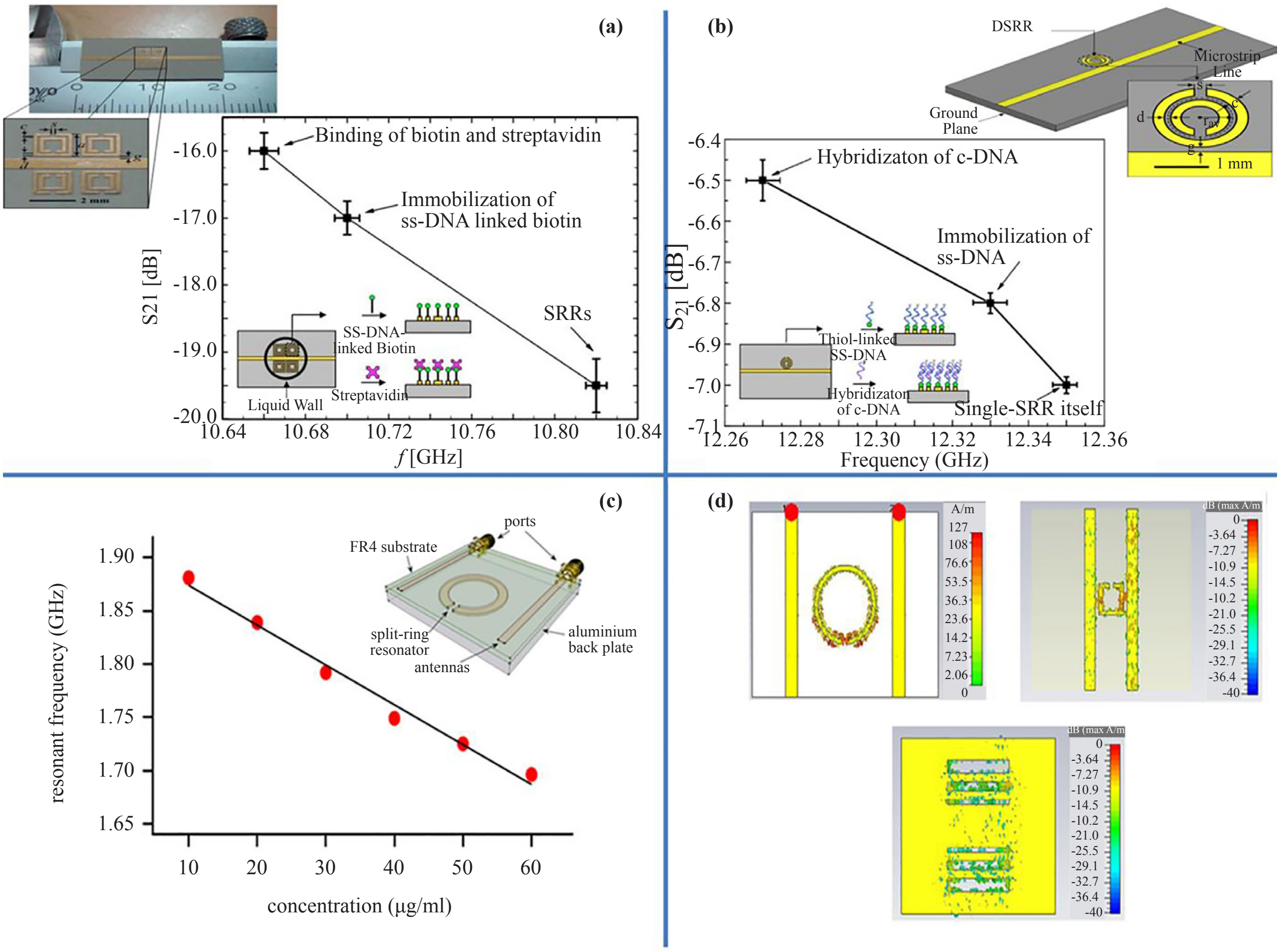

Figure 3. (a) Variation in frequency of resonance for the detection of streptavidin and biotin-binding along with fabricated sensor structure; (b) Shift in resonance frequency as a function of DNA hybridization and used sensor structure for biosensing; (c) 3-D view of an SRR structure with integrated monopole antennas and a plot showing variation in resonant frequency with concentration; (d) Simulated graphics of surface current density for square and circular SRR structure, and defected ground plane

A compact SRR-based sensor with coupled antenna was used for sensing the concentration of glucose in blood plasma [61]. This group deposited both square and circular types of rings over the substrate. They introduced a defected ground plane DGP in the device which produced a sharp cut-off frequency for resonance and deep band rejection frequency. Because of the introduction of DGP, the effective inductance of the device increases while the effective capacitance decreases. Thus it can be concluded that the resonant frequency can be varied upon varying the dimension of the defect. In this study, for a concentration of 150 mg/dl of glucose in plasma, the circular ring experiences a frequency shift from 1.93 GHz to 1.8 GHz, while, in the case of the square ring, the resonance frequency shifts from 8.33 GHz to 8.309 GHz.

3.2 *Chemical sensing applications*

Detection of chemical samples, especially high-energy materials is an important issue in the domain of chemical and biological warfare diagnostics. There are several categories of sensors which employ methods like electrochemical sensing [80], [81], optical [82], and mass measurements [83]. Although these methods have many advantages, there are several challenges associated with conventional sensors including the high cost of fabrication, complex design, and bulky size. Some of the applications of MM-inspired sensors are shown in Figure 4. In earlier research, we proposed a metamaterial resonator that resonates at λ/12 compared to λ/2 general microwave resonators [26]. This results in a size reduction of approximately 83%. The study comprised of high energy materials like bis (1,3-diazido prop-2-yl) malonate (AM), 2-bromo, 2-nitropropane-1,3-diol (BNP), and bis(1,3-diazido prop-2-yl) glutarate (AG). The resonance frequency shift for 0.5 µl of BNP was 20 MHz, for 0.5 µl of AG, it was 80 MHz, and for 0.5 µl of AM, it was 100 MHz. Since the device gave different shifts in resonance frequencies for different chemicals, it can prove to be extremely handy for surveillance in the sensitive zone.

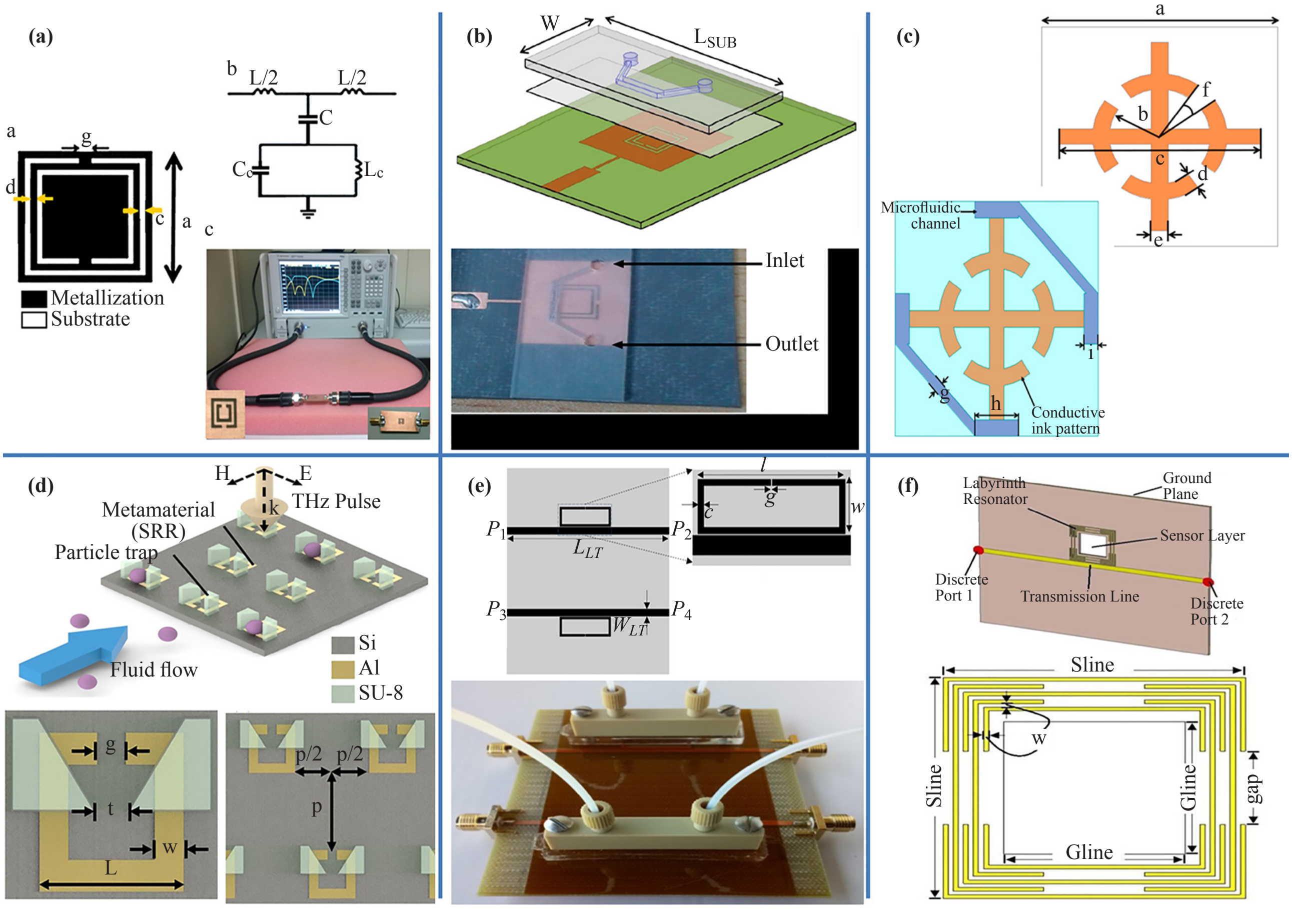

Figure 4. (a) CSRR design with its equivalent circuit and experimental setup used for measurement; (b) CSRR with and integrated microfluidic channel for ethanol sensing; (c) A meta-surface absorber for detecting ethanol; (d) MM sensor array operating in the THz regime shown with trapping structure; (e) MM sensor with microwave structure, fluidic channels, and connectors; (f) Labrynth resonator with proposed sensor structure

For chemical and biological sensing, the sensor performance must be optimized so as to obtain better sensing results. There exist several ways in which the sensitivity of an SRR and CSRR can be enhanced such as; using a substrate with smaller dielectric values, high frequencies of resonance, and many others. Albishi and the group proposed a methodology in which they used multiple coupled resonators over the micro-strip line for enhancing the sensitivity of the device [11]. In this work, the group used a slit for the insertion of thin sheets of the substrate so as to measure the dielectric of the material. Here, using a 4-CSRR, the resonant frequency shift from 2.5 GHz to 4 GHz was observed, thus, increasing the resonant frequency by around 1.5 GHz and power attenuation by around 15 dB. This results in a subsequent increase of overall FWHM and in turn quality factor (Q). Another method using which researchers have enhanced the performance of SRR and CSRR is by increasing the number of concentric rings. This was demonstrated by a group of researchers in the year 2023 [84]. In this work, they have used more than two split rings over the ground structure for enhancing the device's performance. In most of the previous works, the modification was mostly based on ground plane and structure, but in this work, they also tried to modify the transmission line. Here, instead of using a straight feed line, these researchers have used a curved feed line as the transmission line in the active plane. This was done in order to improve the quality factor of the sensor as power attenuation increases. As stated in this work, by using a single ring and a straight feed line, the resonant frequency and quality factor were 3.23 GHz and 91 respectively. When the number of rings was increased to three split rings and the straight feed line was replaced by a curved feed line then the resonant frequency shifted to 2.5 GHz while the quality factor increased approximately by 6 times to a value of 520. Such types of design changes and modifications are easy and feasible to enhance the performance of the sensor based on CSRR and SRR structure. There are some more reported design modifications performed by different research groups in the THz and another region for the optimization of device performance [85], [86].

In a very similar way, researchers have designed an ethanol sensor that has a CSRR structure loaded with a microfluidic channel. The substrate used in this study was Rogers RT/Duroid 5870 substrate and not FR4 because of its loss properties and stable dielectric properties at varying temperatures. The frequency of resonance for the designed structure before integrating the microfluidic channel was 4.72 GHz and after loading the channel, it becomes 4.16 GHz [87], [22]. When the sensor is exposed to deionized (DI) water, the resonant frequency gets shifted to 3.34 GHz. After replacing the DI water with ethanol, the resonance frequency shifted to 3.89 GHz. The introduction of the microfluidic patch enhances the sensitivity of the sensor as it cut-offs the interaction of the sensor with the external environment other than the analyte. One analogous research in which a flexible periodic array of split ring cross resonators (SRCRs) with a microfluidic channel was demonstrated [23]. In this study, periodic structures using silver nanoparticles were inkjet printed on paper. The sensor showed a frequency shift from 8.9 GHz to 10.04 GHz when exposed to a 100% change in ethanol concentration. One important observation, in this case, is that the sensor observed a linear shift in frequency for the variation of ethanol concentration from 20% to 80%. Since paper was used as dielectric material, the reported sensor was cos-effective, and surprisingly, the sensor demonstrated a better sensitivity to ethanol. A similar type of approach was used by one of the researchers in which he used a single SRCR structure to sense ethanol. In this case, he used a FR4 substrate, instead of paper and achieved a frequency shift from 12.12 GHz to 11.46 GHz [25]. As observed, in SRR, the electric field gets highly confined in the capacitive gap along the slit. This location on the meta-surface proves to be highly sensitive to perturbation in that area. Thus, a design based on trapping and sensing the analyte. This was done by introducing a trapezoidal structure near the slit so as to contain maximum analyte near the gap [53]. In this model, the SRR gets excited using a terahertz (THz) wave which is electrically parallel to the gap of the SRR. The microfluidic structure and the substrate, both are made using quartz because it is highly transparent to THz wave. Initially, the fabricated device showed a resonant frequency of 0.85 THz and after it is exposed to the analyte, that is, when polystyrene particles get trapped along the trapezoidal structure, the resonant frequency gets shifted to 0.87 THz. The fabrication and designing of this sensor are relatively more difficult than the one used in the microwave regime.

In 2018, an SRR-based sensor was reported for determining the electrolyte concentration of NaCl, KCl, and $CaCl_2$ mixed with DI water. Later, the same sensor was used to analyze the variation of electrolyte concentration in different urine samples [88]. This was an important study because the concentration of electrolytes is essential for maintaining blood pressure and pH levels, muscle and nerve functions, body hydration, and many more. In the experimental results, the maximum sensitivity attained for NaCl was 0.033 $(g/L)^{-1}$, for KCl it was 0.032 $(g/L)^{-1}$ and for $CaCl_2$ it was obtained to be 0.021 $(g/L)^{-1}$.

In 2019, a study was conducted by a group of researchers in which they studied the properties of transformer oil at different stages [89]. This was important as transformer oil becomes useless after a period of continuous usage. This is because it is continuously exposed to huge electrical power. In the presented model, they used a different type of metamaterial resonator based on SRR called the Labrynth resonator. Labrynth resonators are nothing but several nested SRRs which a gap in the center. This gap is called the sensing layer. The Labrynth resonator was deposited over an FR4 substrate with a transmission line adjacent to the labrynth resonator. Using this device the researchers obtained a frequency shift of 40 MHz between unused oil and waste oil samples. To date, people have used several techniques for detecting fuel adulteration like using nano-porous silicon micro-cavity, heating the fuel to its boiling point, grating periods in optical fiber, and metamaterial-based resonators. The use of nano-porous silicon micro-cavity proved to be an efficient way for sensing but at the same time, the fabrication of the nano-porous silicon was complex and costly [90]. In this method, a reflectance spectrum was observed as the reflectance notch shifts with a shift in the refractive index of the fuel adulteration. The refractive index of the fuel changes with an increase in adulteration. The other method used the heating of the fuel up to its boiling point such that only the adulteration is left. After the standard time for complete evaporation of the original fuel, the level of left liquid was measured to obtain the percentage of adulteration [90]. Though this method was simple and cost-effective, it posed several challenges including the kind of adulteration, response time, and repeatability of measurement. One more efficient way of detecting fuel adulteration was demonstrated by applying long-period grating fiber. The detection was quantified by analyzing the wavelength spectrum [91]. This method was able to detect fuel adulteration as low as 1%, but the complexity, cost, and sensing phenomenon were a challenge for the researchers.

In 2014, we demonstrated ultrafast sensing of petrol using the MM-inspired structure CSRR [54]. The design showed ample shift in resonance frequency for ethanol and petrol individually. For the bare sensor, the frequency of resonance was 4.48 GHz in free space. But with exposure to ethanol, the resonance frequency shifted to 4.23 GHz, thus an overall shift for ethanol was 250 MHz with a change in power level from -25 dBm to -11 dBm. For petrol, the frequency shift of 100 MHz was obtained for 1 µl. As the sensor showed a different shift for ethanol and petrol in terms of both power and frequency, thus it can be suggested that the device performance would vary for adulteration in petrol with ethanol or any other compound. Later in 2016, we proposed a sensor to detect flex fuel using the CSRR structure. In this reported device, the resonance frequency of the bare CSRR structure was observed to be 2.47 GHz. For 10 µl of petrol, the shift in frequency of resonance was obtained to be 36 MHz and for the same amount of ethanol, the shift was 163 MHz. when ethanol and petrol were mixed in a ratio of 2:8, the resonance frequency shift was about 16 MHz while it was 9 MHz for 5% of ethanol adulteration. Thus, this can be an efficient, cost-effective way to quantify fuel adulteration.

3.3 *Crack detection application*

Crack or fatigue detection in the case of metals is one of the most important parameters which is required to be continuously monitored. This is because almost everything around us is composed of metal in one or the other way. Any sudden failure can lead to a huge loss of life and property. There exist several non-destructive techniques for detecting superficial cracks in metals like eddy current testing, acoustic emission testing, radiographic testing, and ultrasonic testing. All these techniques have their own advantages and disadvantages associated with them.

Some of the reported applications of MM-inspired sensors for crack detection are shown in Figure 5. In 1994, researchers demonstrated one more non-destructive technique using an open-ended waveguide. In this technique, phase reversal takes place when there is a crack at the edges of the waveguide [44]. A similar technique was used to evaluate the depth of shallow superficial cracks [45], [92]. It utilizes the phenomena in which we can determine the frequency of resonance by accurately measuring the reflecting coefficient magnitude.

In 2012, a group of researchers used a CSRR meta-surface for detecting cracks in metals with sub-millimeter dimensions [42], [68]. In this study, the metal surface under analysis alters the propagating electromagnetic field, thus resulting in a shift of resonant frequency. For sensing the crack, the surface under test was scanned by using the device. It was observed that for a 100 µm wide crack with 1 mm of depth, the resonance frequency shifted by about 240 MHz, and for a 200 µm wide crack with a similar depth, the shift was about 260 MHz. This device was also able to demonstrate the detection of cracks spaced by a distance of 1 mm. the same group went a step ahead and used CSRR for the detection of cracks on the surface and sub-surface in both metals and non-metals. The device when used for the detection of cracks in fibre glass with crack of 150 µm and depth of 200 µm, demonstrated a shift of about 312 MHz [68].

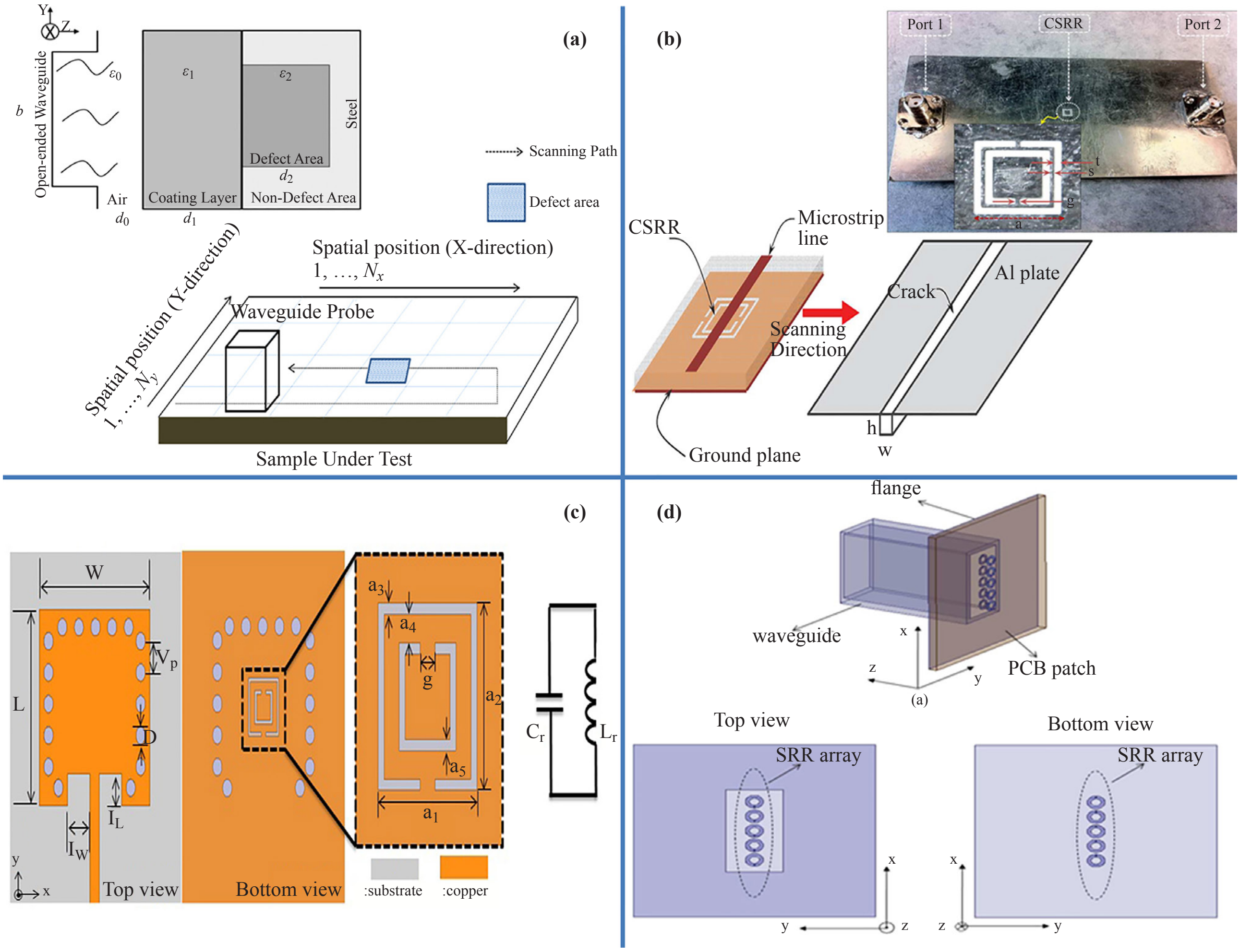

Figure 5. (a) Setup for crack detection using electromagnetic wave reflection and transmission; (b) CSRR structure and scanning procedure for crack detection; (c) Schematic view of the SIW loaded with CSRR and lossless equivalent circuit model of the CSRR; (d) Waveguide probe with an assembly of SRR structures with a schematic view of the probe along with top and bottom views of the printed circuit board

A study for crack detection was conducted using a substrate-integrated waveguide microwave device loaded with CSRR. This proposed device was miniaturized and showed high-quality factors. In this case, silicon integrated waveguide was used so as to replace conventional waveguide and reduce the complexity of fabrication. They also prove to be very compatible with planar structures. For a crack of 1 mm with a depth of 1 mm, the shift in resonance frequency was obtained to be 630 MHz. Thus, these sensors exhibit greater resolution and sensitivities at lower frequency values [112]. In 2014, researchers used an array of SRR loaded on waveguide probes for the detection of cracks in metallic surfaces. This proposed device demonstrated a resonant frequency of 16.65 GHz. This device successfully detected a crack of width 25.4 μm from a distance of 0.6 mm. It also demonstrated a spatial resolution of about 2 mm [43]. A similar application was demonstrated by the same group going a step further and applying artificial intelligence (AI) technology for the smart detection of cracks with good accuracy and classification [41]. This detection of cracks using MM-inspired sensors proves to be a highly sensitive, cost-efficient, and smart way of detection.

Table 1. Device parameters for reported MM-based sensor structures

References	Meta-structure	Resonant frequency	Frequency shift	Sensitivity
[93]	Hexagonal CSRR	8.28 GHz	920 MHz	11.11
[22]	SRR	2.56 GHz	205 MHz	-
[87]	CSRR	4.72 GHz	550 MHz	-
[94]	Double split ring	3.1035 GHz	61.5 MHz	1.9806
[95]	Joined SRR	617 GHz	21 GHz	3.403
[96]	a-DSR	5.99 GHz	36 MHz	0.6010
[37]	CSRR	1.875 GHz	305 MHz	-
[61]	Circular SRR/Square SRR	1.9 GHz/8.3 GHz	100 MHz/21 MHz	-
[97]	Tilted metallic crosses	1.52 THz	200 GHz	13.157
[98]	CSRR	2.7 GHz	720 MHz	26.66
[99]	a-DSR	875 GHz	4 GHz	0.4571
[100]	H-shaped resonator	9.38 GHz	520 MHz	5.54
[101]	CSRR	0.85 THz	70 GHz	8.235
[23]	SRCR	8.9 GHz	1.14 GHz	-
[35]	SRR	2.12 GHz	~30 MHz	3.17
[33]	a-SRR	11.27 GHz	76.92 MHz	-
[67]	DSRR	12.35 GHz	60 MHz	-
[79]	SRR	10.70 GHz	40 MHz	-
[102]	A-G-MSRR/C-G-MSRR	4.90 GHz/4.53 GHz	380 MHz/340 MHz	7.755/7.50
[103]	OSRR	6.5 GHz	576 MHz	10.28
[104]	Double SRR	460 GHz	36 GHz	7.826
[105]	CSRR	2.54 GHz	170 MHz	-
[69]	CSRR	2.65 GHz	285 MHz	10.7
[106]	SRR	4.5 GHz	50 MHz	1.14
[107]	SRR	2.85 GHz	400 MHz	14.03
[108]	SRR	3 GHz	60 MHz	1.98
[109]	SRR	785 nm	20 nm	2.5
[110]	Nested SRR	7.54 GHz	230 MHz	3.05
[111]	SRR	2.1 GHz	433 MHz	30.14

3.4 *Physical sensing applications*

The basic mechanism for sensing used by MM-inspired structures is to determine the change in surrounding medium dielectric properties. Any variation in environmental parameters like pressure, humidity, temperature, and concentration can lead to changes in the dielectric properties of a surrounding medium, thus they can be sensed using these structures. Some of the applications of MM-based physical sensing are shown in Figure 6. These sensors also experience a change in their resonant frequency when subjected to a change in a dimensional parameter, thus phenomena like strain, rotation, and displacement can also be detected. This technique was used by researchers to demonstrate a sensor that sensed mechanical loading over the metallic plates implanted to provide stability along the fractured bone [47]. They used MM-based wireless Micro-Electro-Mechanical Systems (MEMS) for strain measurement. They used an array of gold-fabricated SRR structures over silicon nitride film deposited on a silicon substrate. Under applied strain, the sensor experiences a change in the dielectric area and thus capacitance. The demonstrated sensor showed a linear change in frequency with a change in applied force. In 2014, researchers proposed a design of an MM-inspired sensor called a split ring resonator with double slits (SRDS). In this design, they sandwiched a sensor layer between two meta-surfaces. These meta-surface have a ring inside a squared structure such that both had two slits each at the same position [111]. This proposed sensor can be used to detect changes in temperature, pressure, humidity, and calcium chloride density and thus proved to be multifunctional. The pressure sensing was performed by keeping one of the surfaces fixed and the other open to pressure, thus varying the space between two meta-surfaces which resulted in variation in resonant frequency. While for measuring changes in density, temperature, and humidity, different dielectric materials were used to replace the sensing layer.

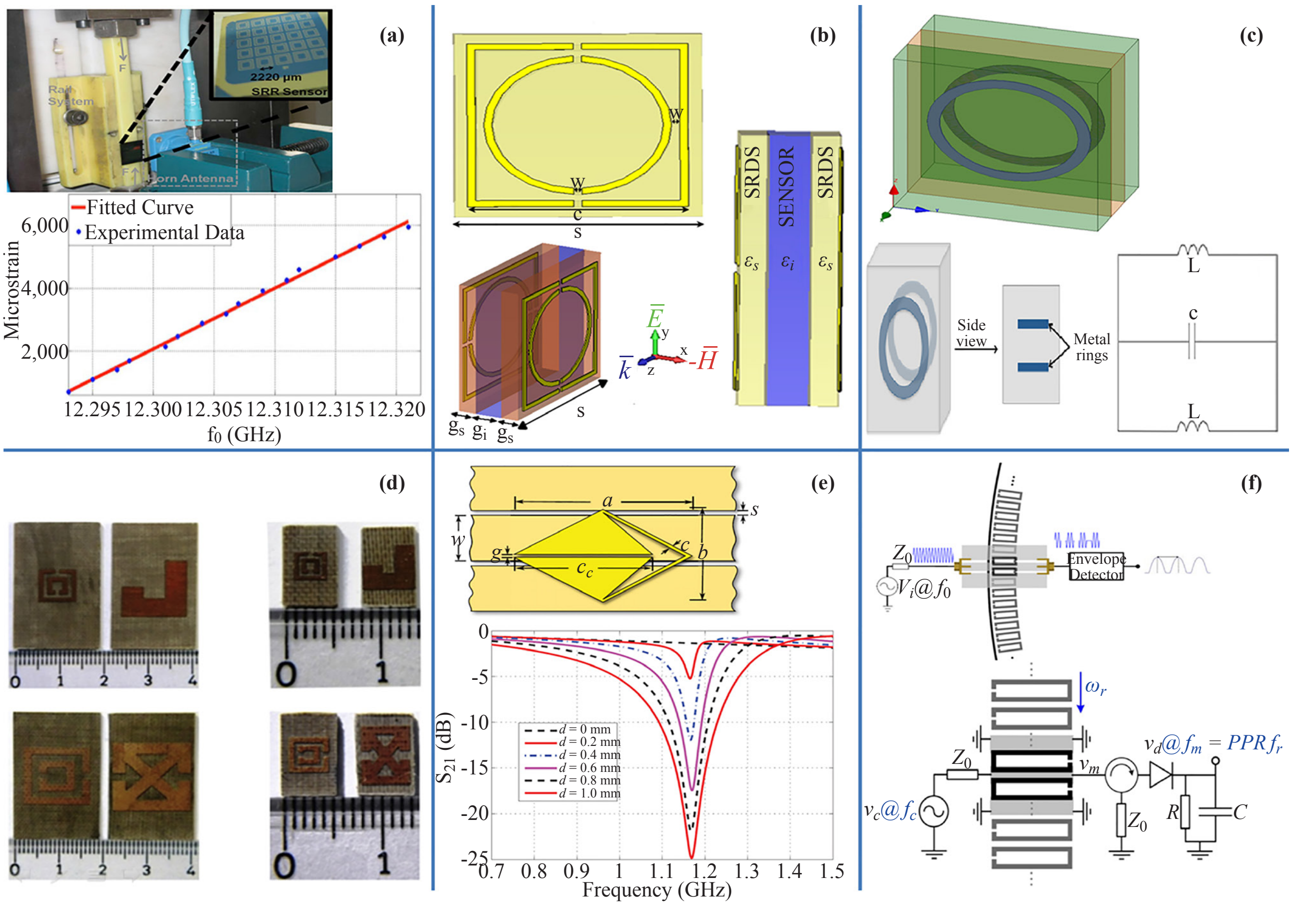

Figure 6. (a) Miniaturized SRR array for strain sensing in the compression apparatus for testing; (b) SRDS based MM sensor, with a schematic view of single cell; (c) CRR model with electrical equivalent circuit; (d) Fabricated structures of DSRR, double-sided L-type resonator (DLTR), and double-sided closed-cross-ring resonator (DCCR) for X-band and S-band; (e) Schematic view of tapered diamond shaped SRR and corresponding transmission spectrum with power shift; (f) Rotation sensor based on the edge configuration and its signal conditioning circuit

In the same year, researchers proposed a design of a wireless temperature sensor that was based on a closed/loop ring resonator [113]. The model consisted of two looped conducting ring resonators at the opposite sides of a dielectric substrate. These conducting loops were covered using another dielectric material which protects them from harsh environments and also acts as a medium to transfer temperature change. In this study, the dielectric medium used was $LiNbO_3$ for temperatures varying from 450 °C to 800 °C and it was observed that for closed ring resonator (CRR), the sensitivity was 7.286 MHz/°C. They also presented a similar work using an array of CRR and replacing the dielectric material with a mixture of 70% Boron Nitride and 30% Barium Titanate [114]. It observed a sensitivity of 0.462 MHz/°C for a temperature up to 200 °C. Several different architectures using SRR were reported including a design which implemented a bow-tie antenna model connected to SRR for wireless temperature sensing [115]. Table 1 provides qualitative information about various reported sensors based on MM structure.

In 2017, a group of researchers demonstrated the working of CSRR-based MM sensors for the thickness measurement of the thin film. For this purpose, they measured the thickness of a mica sheet [116]. When a mica sheet with a thickness of about 0.125 mm was used, then the resonant frequency shift obtained was 0.616 GHz, and for a thickness of 0.25 mm, the shift observed was 0.41 GHz. People have also reported the use of MM-based humidity sensors in the THz regime. Though, the achieved detection limit was quite low [117]. In a study reported in 2019, different meta-surfaces like double-sided SRR (DSRR), double-sided closed cross-ring resonator (DCCR), and double-sided L-type resonator (DSLR) for detecting humidity of chickpea powder. The sensitivity of DSRR for a 1% change in humidity is 9.32 MHz, for DLTR, it was obtained to be 23.18 MHz, and for DCCR, it was 19.01 MHz. Thus, it is quite evident that DLTR proved to be more sensitive when compared to DSSR and DCCR structures [48]. Researchers have also demonstrated a displacement sensor based on SRR with a design of a tapered diamond structure. This proposed sensor showed several advantages over others [118] like a long dynamic range and response at a single frequency, avoiding frequency sweep. In this sensor, the resonant frequency did not change with displacement but there was a considerable change in power transmitted. One added advantage of this sensor was low operating frequency, which is very desirable [36].

There are many other sensor designs based on MM structures to detect displacement, angular motion, and rotation. In 2013, researchers proposed and demonstrated a design which had a stator and rotor, such that the stator consisted of a pair of SRRs at the back side of the transmission line and is fixed. While the rotor had hundreds of SRR structures chained all along the interacting surface. When the rotor rotates, the SRR structure over it interacts with the SRR on the stator, thus modulating the continuous wave feed signal on the stator. They achieved an angle resolution of 1.2°, 0.6°, and 0.3° depending on the number of pulses per revolution (PPR). Although it demonstrated good sensing capability, it also had several drawbacks like the cost of fabrication, alignment of stator and rotor, and a limited dynamic range [38].

4. Future scopes and challenges

Similar to other types of sensing devices, MM-inspired sensors have their own challenges associated with implementation in the field. Hybridization of sensors based on meta-surfaces with microfluidics becomes necessary as we move forward to implement it in day-to-day life. The use of microfluidic technology with these device structures can make them reusable and also protect them from environmental contamination. For this purpose, extensive research is needed to be done to evaluate the adhesiveness of microfluidic structures with different substrates along with the effect of adhesive film, and coating materials. One of the major challenges for these devices is their implementation in the human-machine interface. Since most of these devices are based on rigid substrates like FR4 or Duroid, their utilization in wearable electronic devices becomes difficult. Thus, there is a need for advanced study for analyzing the effects of different flexible substrates when used with these devices. These devices also require a network analyzer for studying the variation in the transmission spectrum, such devices are very costly and bulky. Thus, a portable detection system with the necessary electronics can make the device suitable for real-time detection and independent of the network analyzer. As the size of these device goes diminished, the frequency of resonance increases drastically, thus making the device vulnerable to instability. Since the resonant frequency can be manipulated by using different structures and varying the dimension, it becomes essential to fabricate such a device which is miniaturized and operates at low frequency at the same time. With the advancements in lithographic techniques, we can move towards single molecule or cell detection using metamaterial-inspired sensors. Usually, the characterization and testing using these devices is done by a unit cell, and thus it restricts the capacity of these devices to perform multi-functionality. More advancement is required to utilize these devices by fabricating them in an array format and testing for multi-functionality. Although there have been several reported cases of implementation of these devices as gas or vapor sensing, still there is a need to conduct extensive studies for direct gas sensing. This is because most of the reported cases have used a sensitive film or coating over the substrate to perform gas sensing. This adds to the overall cost and reduced the frequency shift as the intermediate coating degrades the overall shift in resonance frequency. All these challenges can be considered as a future scope for several studies pertaining to sensors inspired using metamaterials. Moreover, the study of response for metamaterial-based sensors in optical regimes can also be investigated for its application in photonics.

Acknowledgement

The authors would like to thank the institution (Defence Institute of Advanced Technology) and the Department of Applied Physics for providing us the constant support and motivation throughout the research.

Conflict of interest

The authors declare no competing financial interest.

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