Review Article

Microwave Sensors Based on Coplanar Waveguide Loaded with Split Ring Resonators: A Review

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Abstract
This article reviews the application of physical, chemical and biological sensing of materials via microwave sensors based on a coplanar waveguide (CPW) loaded with a split ring resonator (SRR). Many CPWs loaded with SRR structures from the literature are reviewed in this article. CPWs loaded with many shapes of resonators have been proposed, such as circular, square and rectangular-shaped SRRs and CSRRs based on a paired and an array, folded stepped impedance (SIR), square and circular electric – LC (ELC) SRRs, circular, square, rectangular and golden ratio spiral S-shaped SRRs, diamond-shaped tapered SRRs, horn-shaped SRRs and others. The working principle for each device is briefly described and compared. The strength of this article is to introduce the application of microwave sensors based on CPWs loaded with SRRs for measurement and characterization of physical, chemical and biological materials through electromagnetic interaction.

Keywords: Microwave sensor, Coplanar waveguide, Split ring resonator, Physical, Chemical, Biological

1 Introduction

Microwave sensors have many advantages when compared with traditional sensors, such as non-invasive, non-destructive, non-contact, rapid and precise measurement, automated measurement in a laboratory or on-line [1]–[5]. The microwave sensing method can be divided into two kinds: non-resonant and resonant sensing. However, resonant sensing based on microwave sensors are more interesting than non-resonant sensors because they have many advantages, such as simpler signal processing, higher sensitivity and lower costs [6], [7]. Many parameters are detected and analyzed by microwave sensors, such as the resonant frequency, phase and quality factor of the resonant structure [8]. Split-ring resonator structures are popular sensor concepts for operation in a microwave regime because of their small electrical size and high Q factor.

In this article, CPWs loaded with SRR structures for physical, chemical and biological sensing are analyzed and discussed. In particular, Section 2 and Section 3 present the principle of waveguides and coplanar waveguides, respectively. Section 4 and Section 5 present the basics of SRRs and CPWs loaded with SRR structures, respectively. In Section 6, CPWs loaded with SRRs for microwave sensor applications are briefly described and compared. Finally, the main conclusions of the article are outlined in Section 7.

2 Waveguide

A waveguide is a structure that guides a wave, such as an electromagnetic or sound wave. It has the advantage of high power-handling capability and low loss. Therefore, the waveguide is used in many applications such as microwave communication, broadcasting,

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radar installations, radio and optical devices. Moreover, it is used in the non-destructive evaluation of materials. The propagation of electromagnetic waves inside a closed hollow tube were considered by Heaviside in 1893, but he rejected his idea because he believed that the transfer of electromagnetic energy could be transferred by more than a two conductor structure [9], [10]. In 1897, the wave propagation in waveguides was proved mathematically by Lord Rayleigh (John William Strutt) [11]. Lord Rayleigh showed that circular and rectangular cross sections could be used in wave propagation, but he did not perform an experiment for the verification of this concept. Almost 40 years later, the waveguide concept had been essentially forgotten until in 1936, it was rediscovered by two men, G. C. Southworth (AT&T) and W. L. Barron (MIT), who showed that a waveguide could be used as a small bandwidth transmission medium and it was capable of carrying high power signals [12], [13]. After preliminary experiments in 1932, G. C. Southworth and W. L. Barron presented, at the same meeting, rectangular and circular waveguides, respectively [10]. Early microwave systems relied on waveguides and coaxial lines for the transmission line media [10]. A waveguide has the advantage of low loss and high power capacity, and, in an ideal case, the loss during transmission through a waveguide is zero [14], but it is bulky and expensive. Coaxial lines have very high bandwidth, but are a difficult medium for microwave component fabrication. Nowadays, a planar transmission line is an alternative and many have been proposed, such as stripline, microstrip, slotline, coplanar waveguide and others. Planar transmission lines have many advantages such as compact size, low cost and easy integration with passive and active devices to form microwave integrated circuits. Physical, chemical and biological sensing with the help of planar transmission line waveguides is a recent area of research. The properties of the wave through the planar transmission line waveguide's structures also depend upon the properties of the material samples; the quantitative and qualitative aspects of the material sample are analyzed and discussed. The planar transmission line waveguides structures presented in this article are CPWs loaded with SRRs.

3 Coplanar Waveguide

A CPW is a type of planar transmission line; it was invented in 1969 by Cheng P. Wen [15], as shown in Figure 1(a). CPWs are widely used for microwave integrated circuit design, which can be built into monolithic microwave integrated circuits [16]. In general, CPWs can be divided into two types, which are CPWs not ground-backed with the bottom of the substrate not having a metallic plane and CPWs that are ground-backed with a metallic plane added at the bottom of the substrate, as shown in Figure 1(a) and Figure 1(b), respectively. In the case of CPWs not ground-backed, the structure of the CPW consists of a conductor strip line in the middle and two ground planes that are located on either side of the center conductor lying in the same plane. In the case of CPWs that are ground-backed, the structure is the same as the CPW with no ground-backing but it is added to the ground plane opposite the conductor strip line.

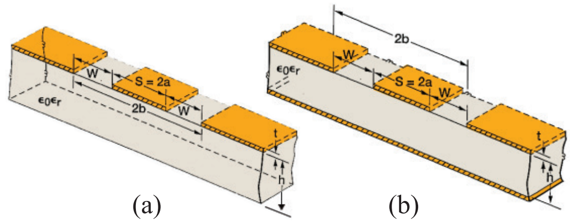
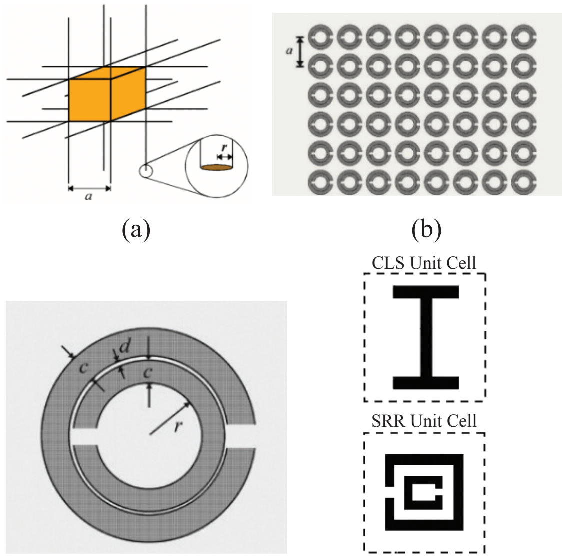


Figure 1: Coplanar waveguide structure: (a) not ground-backed [16] and (b) with ground-backed [16].

CPWs have many advantages over conventional microstrip lines, such as simple fabrication, easy shunt, no need for wraparound and via holes, reduced radiation loss, without limit for size reduction and cross talk effects are very week. In manufacturing, CPWs have attracted more interest than other structures because, firstly, the CPW lends itself to the use of automatic pick-and-place and bond assembly equipment for surface mount component placement and interconnection of components, respectively. Secondary, CPWs allow the use of computer controlled on-wafer measurement techniques for device and circuit characterization up to several tens of GHz. CPWs are used in many field applications, such as amplifier circuits, active combiners, frequency doublers, mixer circuits, switches, microelectromechanical systems (MEMS), photonic bandgap structures and antennas. Moreover, they can be used for many sensors, such as physical sensors [17]–[24], chemical sensors [25], [26] and biological sensors [27]–[33]. The CPW structures support a quasi-TEM mode of propagation that has low dispersion and hence



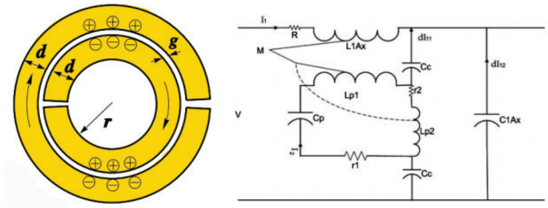
(a) (b) (c) (d)

Figure 2: Split ring resonator structures: (a) periodic structure of copper wire [35], (b) SRR in square array [36], (c) top view of SRR [36], [37], and (d) combination between CLSs and square SRRs [38].

offers the potential to construct wide band circuits and components.

4 Split Ring Resonators

SRRs are the artificial structures used to construct Left Handed Materials (LHM), the index of refraction is less than zero, which is not readily available in nature, namely as metamaterials. This phenomenon was first proposed in 1968 by Veselago [34] and first suggested based on theory in 1996 by Pendry *et al*. [35], [36], as shown in Figure 2(a) and (b). Subsequently, a split ring resonator was successfully fabricated in 2000 by Smith *et al*. [37], as shown in Figure 2(c), and in 2003 double negative metamaterials from the combination between the capacitively loaded strips (CLSs) and square SRRs was proposed by Ziolkwoski [38], as shown in Figure 2(d). The materials are created by using SRRs that can handle the strong magnetic coupling to an applied electromagnetic field more than conventional materials. In general, a SRR consists of a pair of enclosed loops with splits in them at opposite ends. It is made of a nonmagnetic metal material, such as copper, and has a small gap between them. The loop structures can be created using circle, triangle, square, rectangular, rhombic and others shapes.



(a) (b)

Figure 3: Single SRR: (a) double circular SRR and (b) equivalent circuit of SRR [39].

The equivalent circuit of SRRs was proposed by Xu *et al*. in 2006 [39], as illustrated in Figure 3. The equivalent circuit consists of some electrical parameters, such as resistors (*R*, *r1*, and *r2*), capacitors (*C1Ax*, *Cc*, and *Cp*), inductors (*L1Ax*, *Lp1* and *Lp2*) and mutual inductance (*M*). R represents the conductor loss of the outer split ring. *r1* and *r2* represent the conductor loss of the inner split ring. L1Ax denotes the magnetic response of the outer split ring. *Lp1* and *Lp2* represent the magnetic response of the inner split ring. *C1Ax* and *Cp* denote the capacitance at the outer and inner split rings, respectively. The top *Cc* and bottom *Cc* represent the capacitance between the upper half of the outer split ring and the upper half of the inner split ring and the lower half of the outer split ring and the lower half of the inner split ring, respectively. *M* represents the mutual inductance between the inner and outer split rings.

SRRs have been proposed in various geometries, such as single circular SRR, single circular complementary SRR, single square SRR, single square complementary SRR, double circular SRR, double circular complementary SRR, double square SRR, double square complementary SRR, Schottky SRR [40]–[43], open split ring resonator (OSRR) [44], open complementary split ring resonators (OCSRR) [45], ELC SRR, four-fold rotational-symmetry ELC SRR, rectangular ELC SRR, complementary ELC SRR [41], [46]–[48], single ring with one, two and four cuts, SRR with two and four cuts [42], broadside coupled split ring resonators (BC-SRR), non-bianisotropic split ring resonator (NB-SRR), double slit split ring resonator (DS-SRR) [49], Giant Electric Field Enhancement in SRRs [50], S-shaped SRR [51] and Quadruple P-SRR (QPS-SRR) [52].

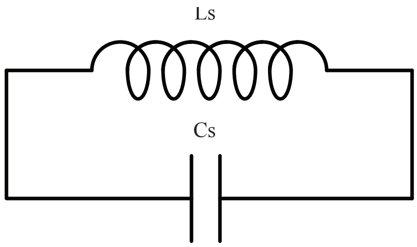


Figure 4: Equivalent-circuit models of SRRs [53].

When the electromagnetic field excites the SRR, it is coupled to a magnetic field component that oscillates in the axial direction; a current is established and flows around the split ring. This effect causes a magnetic dipole parallel or antiparallel to the magnetic field. The equivalent circuit of the loop inductance and gap capacitance of the split ring can be defined by an LC resonant circuit, as shown in Figure 4, and the resonant frequency (f_0) of the SRR is given by $f_0 = (LsCs)^{-1/2}/2\pi$ [53]. The resonant frequency can be decreased using the inner concentric split ring. This behavior causes the net capacitance of the double SRR to increase. The inner split ring boosts the ratio between the operating wavelength and the lattice constant, but makes sure that the SRRs appear more homogeneous to the electromagnetic excitation.

5 Coplanar Waveguide Loaded with Split Ring Resonators

A shunted CPW loaded with pairs of SRRs was first proposed by Martin *et al*. in 2003 [53], as shown in Figure 5(a), and then the microstrip line was loaded with an array of Complementary Split Ring Resonators (CSRRs) following a proposal by Falcone *et al*. in 2004 [54], as shown in Figure 5(b). A CPW loaded with pairs of SRRs and a shunted microstrip line loaded with an array of CSRRs were proposed by Baena *et al*. in 2005 [55], as shown in Figure 5(c) and (d), respectively.

CPWs loaded with a symmetric circular-shaped SRR and rectangular-shaped SRR were proposed in 2011 by Naqui *et al*. [22], as shown in Figure 6(a) and (b), respectively. CPWs loaded with symmetric square-shaped SRR and CSRR were proposed in 2012 by Naqui *et al*. [57], as shown in Figure 6(c) and (d), respectively.

Moreover, CPWs have been loaded with symmetric folded SIR [58], [59], ELC SRR [8], [59], [60], square

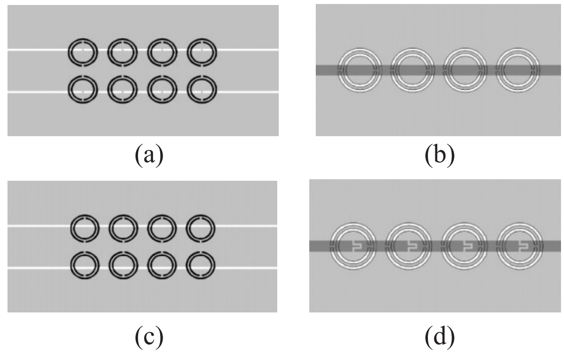


Figure 5: CPW structure: (a) loaded pairs of SRRs with shunt metal strips [53], (b) loaded array of CSRRs [54], (c) loaded pairs of SRRs [55], [56], and (d) loaded an array of CSRRs [55].

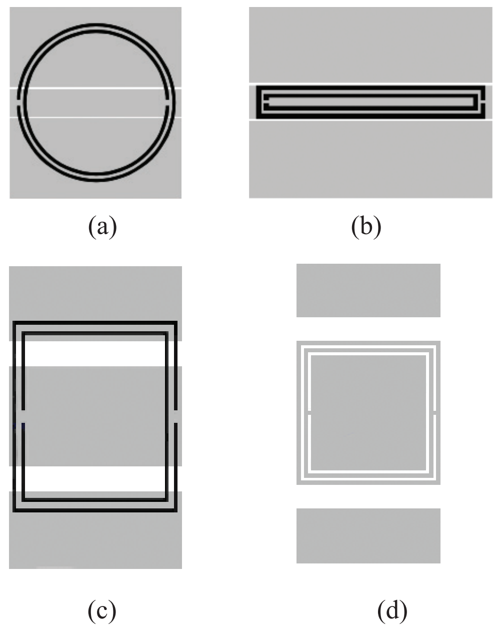


Figure 6: CPW structure: (a) symmetric circular-shaped SRR [22], (b) symmetric rectangular-shaped SRR [22], (c) symmetric square-shaped SRR [22], [57], and (d) symmetric square-shaped CSRR [57].

S-shaped SRR [60], pair of rectangular SRRs [60], pair of square SRRs [60], ELC tapered SRR [8], [60], S-shaped tapered SRR [60], S-shaped golden spiral-tapered SRR [23], S-shaped SRR [20] and rectangular S-shaped SRR [20], as shown in Figure 7(a)–(j), respectively.

CPWs loaded with resonators have been applied in many application, such as filters [45], [46], [61],

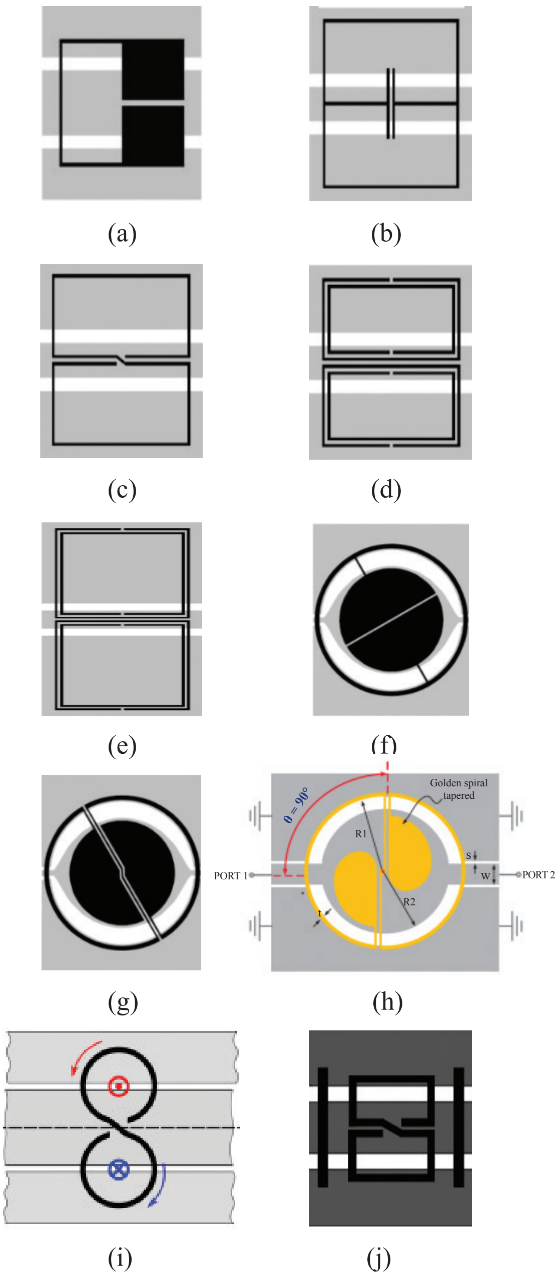


Figure 7: CPW structure: (a) loaded with symmetric folded SIR [58], [59], (b) ELC SRR [8], [59], [60], (c) square S-shaped SRR [60], (d) pair of rectangular SRRs [60], (E) pair of square SRRs [60], (f) ELC tapered SRR [8], [60], (g) S-shaped tapered SRR [60], (h) S-shaped golden spiral-tapered SRR [23], (i) S-shaped SRR [20], and (j) rectangular S-shaped SRR [20].

antennas [62]–[64], barcodes [65], [66] and microwave sensors [17]–[20], [27]–[29], [67], [68]. They are designed based on a microstrip transmission line [67], [69] or a CPW transmission line loaded with resonators, such as SIRs [58], [59], SRRs [27]–[29], spiral resonators [23] and other resonators.

6 Microwave Sensors Based on Coplanar Waveguide Loaded with Split Ring Resonators

The microwave sensing technique can be used to measure the properties of materials based on the electromagnetic wave in the frequency range of the microwave interactions with matter, and it can be used to provide information about the physical, chemical and biological properties of the materials. Microwave sensors offer many advantages over traditional sensors, such as rapid measurement, nondestructive, precise and fully automated, and they can be made in a laboratory or on-line. In this section, microwave sensors based on CPWs loaded with SRRs for physical, chemical and biological sensing are presented and discussed.

6.1 *Physical sensing*

Many microwave sensors based on CPWs loaded with SRRs have been proposed for physical sensing applications, as shown in Figure 8.

Figure 8(a) is the displacement and rotation based on a CPW loaded with a movable SRRs on the back substrate side as proposed by Naqui *et al*. in 2011 [22]. Figure 8(b) is alignment and position sensors based on a CPW loaded with SRRs as proposed by Naqui *et al*. in 2012 [17]. The structure consists of a CPW loaded with four SRRs tuned at different frequencies, two SRRs are the direction sensing resonators and the others are the displacement sensing resonators; it is used for measuring the two-dimensional linear displacement magnitude. This proposed sensor detects the direction and displacement using the shift in the transmission coefficient and the resonance frequencies. The detection principle of the proposed device is based on the loss of the symmetry properties of SRRs coupled to CPWs. The CPW loaded with a circular, square or rectangular shaped SRR are the structures that have been validated through theory and experiments in this work. Figure 8(c) is a rotation sensor based on a horn-shaped SRR as proposed by Horestani *et al*. in 2013

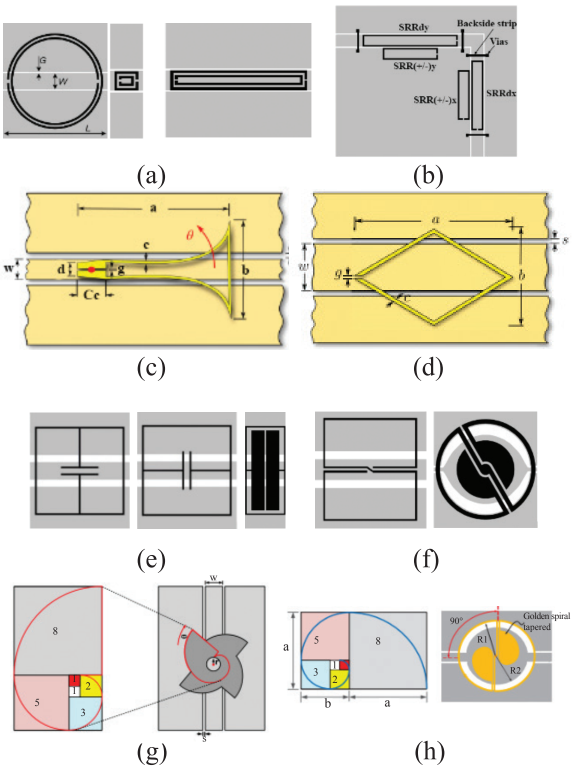


Figure 8: Physical sensing based on CPW loaded with SRRs: (a) sensors based on symmetry properties of SRR [22], (b) alignment and position sensors based on SRR [17], (c) rotation sensor based on horn-shaped SRR [18], (d) displacement sensor based on diamond-shaped tapered SRR [19], (e) angular displacement and velocity sensors based on CPWs loaded with circularly shaped ELC resonators [8], (f) angular displacement and velocity sensors based on S-SRR [60], (g) CPW loaded with GS-RR [23], and (h) CPW loaded with SGS-SRRs [24].

[18]. The device consists of a CPW loaded with a horn-shaped SRR, as shown in Figure 8(c). The structure of the device is adjusted and optimized to achieve a fixed operating frequency. The proposed structure has higher linearity and dynamic range when comparing the rotation angle dependence of the response for the rectangular shape. Figure 8(d) is a displacement sensor based on a diamond-shaped tapered SRR as proposed by Horestani *et al*. in 2013 [19]. The device is based on a diamond-shaped SRR with higher linearity and dynamic range when compared to the rectangular shaped double-ring SRR. However, the diamond-shaped SRR structure shifts in the resonant frequency. To solve this problem, a diamond-shaped tapered SRR was proposed. A displacement sensor based on the diamond-shaped tapered SRR can be fixed to operate at a frequency and pushes the resonant frequencies to lower frequencies without increasing the overall size of the SRR. Figure 8(e) is an angular displacement and velocity sensor based on a CPW loaded with circularly shaped ELC resonators, as proposed by Naqui *et al*. in 2013 [8]. Figure 8(f) is an angular displacement and velocity sensor based on a CPW loaded with S-shaped SRR (S-SRR), as proposed by Naqui *et al*. in 2015 [60]. This proposed device detected the angular displacement and velocity from the transmission coefficient. The operation concept is the same as the ELC structure. Figure 8(g) is an angle sensor based on a CPW loaded with a golden spiral–shaped tapered ring resonator (GS-RR), as proposed by Harnsoongnoen *et al*. in 2015 [23]. The electromagnetic coupling between the GS-RR and the CPW transmission line is the main source of the sensing mechanism for the proposed angle sensor. The proposed device is composed of a CPW and a SGS-SRR that was designed based on the golden ratio number. The device detected the angle from the magnitude of the transmission coefficient. Figure 8(h) is an angular displacement sensor based on a CPW loaded with S-shaped golden spiral-tapered split ring resonators (SGS-SRRs), as proposed by Harnsoongnoen *et al*. in 2016 [24]. The structural design was based on the GS-RR and S-SRR structure, which was designed based on the golden ratio number and S-shaped, respectively. The device detected angular displacement from a shift in the resonant frequency. Physical sensing based on CPWs loaded with SRRs is discussed and compared in Table 1.

6.2 *Chemical and biological sensing*

Recently, many different methods to estimate chemical and biological parameters from an electromagnetic measurement have been developed. Figure 9 shows many microwave sensors based on CPWs and CPWs loaded with SRR for chemical and biological sensing applications. Figure 9(a) is a CPW for the measurement of mortar permittivity as proposed by Torrents *et al*. in 2010 [25]. The permittivity is a combination of the dielectric constant of the mortar, the substrate and the

Table 1: Comparison of physical sensing based on CPW

Structure	Area (mm^2)	Physical Sensing	Data	Fig.	Ref.
CPW loaded circular, square and rectangular SRRs	78.54; 3.46; 20.71	Displacement and rotation	S_{21}	8(a)	[22]
CPW loaded four rectangular SRRs	22.38; 16.62; 13.03; 11.77	Alignment and position	S_{21}	8(b)	[17]
CPW loaded horn-shaped SRRs	< 98.28	Rotation	S_{21}	8(c)	[18]
CPW loaded diamond-shaped tapered SRRs	< 60.00	Displacement	S_{21}	8(d)	[19]
CPW loaded bisymmetric (square ELC, circular ELC) resonators	48; 203.58	Angular displacement and velocity	S_{21} α f_0	8(e)	[8]
CPW loaded S-Shaped SRRs	100; 203.58	Angular displacement and velocity	S_{21} α f_0	8(f)	[60]
CPW loaded GS-SRRs	>201.06	Angle	S_{21}	8(g)	[23]
CPW loaded SGS-SRRs	>706.86	Angular displacement	f_0	8(h)	[24]

surrounding air. The results showed that the mortar permittivity decreased over time due to the sample hydration, and a decrease in the insertion loss was associated with the amount of water in the sample. Figure 9(b) is a microwave coplanar sensor for non-destructive dielectric measurements as proposed by Bassey *et al*. in 1998 [26]. Figure 9(c) is a CPW loaded with a SRR for monitoring sucrose, sorbitol, D-glucose and D-fructose concentrations as proposed by Harnsoongnoen *et al*. in 2017 [27]. In this study, the authors found that the notch magnitude transmission coefficients of four sugars had a correlation with the concentration. The water mobility in the sugar solution allowed for the differentiation of each of the sugars, which followed the order D-fructose > sorbitol > D-glucose > sucrose. Figure 9(d) is a CPW transmission line loaded with an ELC resonator for determination of the glucose concentration sensing, as proposed by Harnsoongnoen *et al*. in 2017 [28]. The principle of this sensor is based on the notch magnitude transmission coefficient depending on the glucose concentration. The results show that the magnitude of the transmission

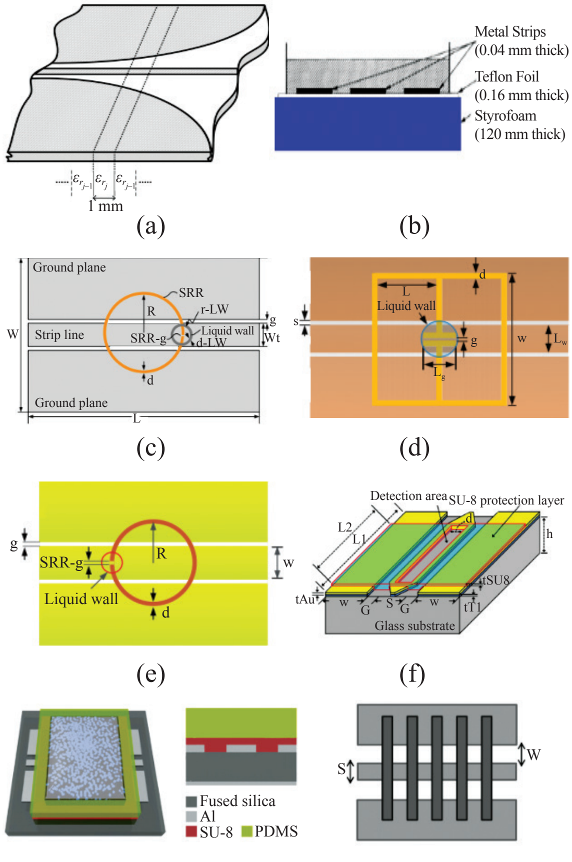


Figure 9: Chemical and biological sensing based on CPW loaded with SRRs: (a) CPW for measurement of mortar permittivity [25], (b) microwave coplanar sensors for dielectric measurements [26], (c) a CPW loaded with a SRR [27], (d) CPW transmission line loaded with ELC resonator [28], (e) CPW loaded with SRR based microwave sensor [29], (f) CPW transmission line for cancer cells [30], (g) surveying colloid sedimentation by CPW [31], and (h) CPW with distributed DMTL [32], [33].

coefficient shifted as a function of the D-glucose in the deionized water and the PBS solution concentration. Figure 9(e) is a CPW loaded with a SRR based microwave sensor that was developed for the detection of aqueous sucrose solutions [29]. Figure 9(f) is a CPW transmission line for cancer cells. This technique is a new label-free biosensor based on a microwave CPW transmission line for the dielectric characterization of HepG2 cells [30]. Figure 9(g) is a survey of colloid sedimentation by a CPW [31]. A volume of 60 μL of solution was placed, using a pipette, in the PDMS container and the S-parameters of the CPW were obtained, and Figure 9(h) shows a CPW with a distributed microelectromechanical systems transmission line (DMTL) [32], [33]. The reflection coefficient S_{11} was measured under various conditions. Both the DMTL device and assembled biosensor were measured in the frequency range of 0–40 GHz.

Chemical and biological sensing based on CPW loaded with SRRs are discussed and compared in Table 2.

Table 2: Comparison of chemical and biological sensing based on CPW

Structure	Area (mm^2)	Physical Sensing	Data	Fig.	Ref.
CPW	45,000	of Mortar	S_{11} @ S_{21}	9(a)	[25]
CPW	5,628	Ethanol, methanol and distilled water	S_{11} @ S_{21}	9(b)	[26]
CPW loaded SRR	3,784	Sucrose, sorbitol, D-glucose and D-fructose	S_{21}	9(c)	[27]
CPW loaded ELC SRR	3,188	D-glucose and PBS	S_{21}	9(d)	[28]
CPW loaded SRR	3,784	sucrose	S_{21}	9(e)	[29]
CPW	19.87	Cancer cell (HepG2)	S_{11} @ S_{21}	9(f)	[30]
CPW	27	Aqueous solution with different diameter of Polystyrene beads	S_{21} @ S_{12}	9(g)	[31]
DMTL	2.295	Pathogenic bacteria	S_{11}	9(h)	[32]

7 Conclusions

In this article, recent progress in microwave sensors based on CPWs loaded with SRRs is reviewed. They are used for many sensing applications such as physical, chemical and biological properties of materials. The author has briefly described the principle of waveguide, CPW, SRRs and CPW loaded with SRR, which hopefully will be useful for researchers interested in microwave sensors and help them to develop novel sensors that will have better performance and many functionalities.

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