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Substrate-integrated waveguide (SIW) microwave sensor theory and model in characterising dielectric material: A review

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ABSTRACT

Microwave sensors offer appealing features such as susceptibility, quick response, and non-invasiveness, making them valuable tools for highly accurate measurements of material characterisation. A wide range of techniques, including cavity waveguide, planar transmission line, cavity waveguide perturbation, open-ended coaxial probe, and free-space transmission, have been employed to characterise materials that are essential for their cost-effectiveness, ease of manufacturing, high sensitivity, good quality factor (Q-factor), and compact size, allowing them to be applied to different material types. Among the microwave sensor types, the substrate-integrated waveguide (SIW) has emerged as a promising technology in order to characterise materials in an efficient manner. This paper presents a review of the current state and potential opportunities of SIW microwave sensors in the characterisation of dielectric materials. It provides insights into various design principles, techniques, and applications of SIW microwave sensors across different sectors, highlighting their advantages and limitations compared to conventional waveguide-based sensors. Furthermore, the paper summarises several fabrication methods that can be implemented for SIW microwave sensors to enable the production of efficient and reliable sensors. Additionally, the future directions provided in this paper aim to contribute to the ongoing development and optimisation of SIW-based microwave sensors for accurate and efficient dielectric material characterisation. Overall, this review article serves as a beneficial resource for new researchers seeking to understand the role of SIW microwave sensors in material characterisation. It outlines the current status, opportunities, and potential advancements of SIW sensors, shedding light on their significance and potential impact in the field of material characterisation.

1. Introduction

Sensors are electronic gadgets that act as transducers and collect data from their environment. Their main job is to convert the associated energy into useful information. This meaningful information can be easily processed and accessed. Chemical, electrical, magnetic, mechanical, radiative, and thermal energies are frequently used in sensing processes [1]. As an example, human health-related and safety regulation-related information has escalated the use of sensors, besides chemical and biological liquid tests [2,3]. The microwave band of the electromagnetic spectrum that is most frequently employed is in the characterisation of unknown materials, which is based on their dielectric properties using sensing electromagnetic radiation [1]. A broad range of applications, such as single-cell viability detection, material characterisation, spatial

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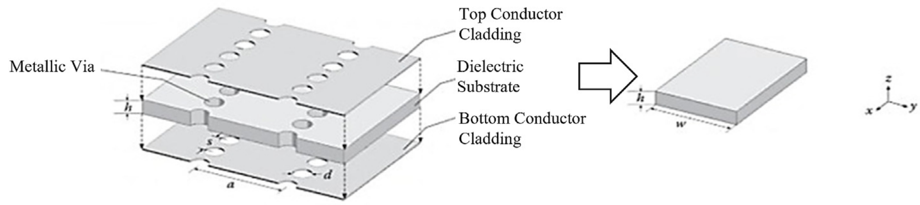


Fig. 1. Configuration of a SIW sensor [47].

displacement measurement, and noise measurement systems, have all made use of microwave sensing [4–7]. For instance, in material characterisation, a systematic approach has been developed to locate the particular grade of material by applying the concepts of reverse engineering, alteration of existing products, and material substitution [8]. Microwave technology is promising for developing sensors operating in microwave and millimetre wavebands [9,10]. The radio frequency (RF) band has been proposed for a wide variety of commercial applications [11,12]. Electromagnetic waves and the interaction of materials under test (MUT) are used in the production of different kinds of microwave sensors [13,14]. Biological and chemical systems are used by several microwave sensors to characterise the electromagnetic characteristics of diverse materials [15].

Various types of applications have been researched worldwide for the delineation of dielectric materials using microwave sensors [16,17]. However, their characterisation sensitivity has the limitation of a narrow frequency band [8]. Using a single resonator either directly or via transmission line (TL), these sensors build the sensing portion of a microwave material characterisation system [18–20]. In Ref. [21], a microwave ring-resonator sensor has been proposed to assess the moisture content of materials. The proposed technique resulted in a decrease in water holding capacity and represented a significant change in return loss and resonance frequency. While in Ref. [22], for the purpose of conducting a dielectric analysis on liquids, a microwave sensor based on a complementary split-ring resonator (CSRR) was utilised. A capillary glass tube was used to contain the samples, which ultimately altered the resonance frequency and quality factor (Q-factor) of the CSRR sensor. A method to calculate the permittivity of liquids was detailed in Ref. [23] in order to characterise their dielectric properties. The MUT was affected in terms of the sample's sensitivity [24]. However, it works well with materials that must withstand inhomogeneous dielectrics and high temperatures [25].

The implementation of microwave sensor systems in several substrate-integrated waveguide (SIW) microwave sensors [26,27] is because of their dependability and adaptability to a variety of situations and environments. One of the newest and most sophisticated microwave sensor technologies is the SIW sensor. The availability of less expensive equipment, which is required for mass production, especially in the case of image sensors and biological equipment components, has a great impact on diverse applications [28–30]. Current research on SIW technology has direct industry applicability and covers a wide range of disciplines [31]. It benefits from a minimal price, a great Q-factor, and simple integration into the constructed millimetre-wave and microwave circuits as a result [31–36]. There is also a way to make a conventional waveguide smaller by exploring the improvement of its SIW structure. SIW structures have become popular recently because of their ease of manufacturing, easy integration, and low profile, which make them good solutions for microwave microfluidic sensors, for example [37,38].

However, there are many problems and issues with microwave sensors based on SIW technology, which include narrow bandwidth and low gain [39–42]. In an effort to find solutions to these issues, numerous strategies have been proposed and put into effect. These approaches include the use of numerous levels of dielectric substrate material type or increasing the number of slots on the sensor's planes. The leakage arising from the periodic gaps between the vias in SIW microwave sensors also

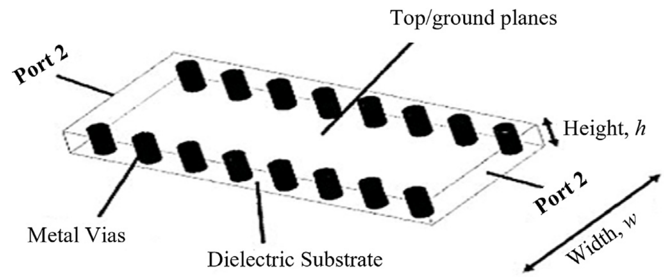


Fig. 2. A typical SIW sensor [50].

becomes an issue. Thereby, a sufficiently long time was evaluated by the SIW leaky-wave sensors in Refs. [43–45] to cater to the arising problem. Besides, a liquid-core optical ring resonator-type sensor was also investigated in Ref. [46] to overcome issues that arise in SIW technologies.

Thus, in this article, numerous sorts of SIW microwave sensor designs have been well explained, along with their design technique models as well as their performances in numerous applications. The rest of this article is organised into different sections, described as follows: The basic principles of the SIW microwave sensor are presented in Section 2. A brief explanation of different SIW microwave sensors with their design models, parameters, and performance is presented in Section 3. Section 4 explores an organised review of SIW sensor applications and their characteristics. The involvement of the SIW microwave sensor in material characterisation is well explained in Section 5, and a brief discussion of future recommendations is presented in Section 6, followed by a conclusion in Section 7.

2. Basic principles of SIW microwave sensor

Substrate integrated circuits (SICs) are the foundation for the development of SIW microwave sensor technologies [47]. The most developed and often-used SIC structure is in the SIW microwave sensor, depicted in Fig. 1 [47]. The figure shows that the basic structure of a SIW microwave sensor has conductor cladding on the top and bottom walls. This structure is made by putting two rows of metalized vias or metalized slot trenches into the dielectric substrate of the sensor [47].

In material characterisation, the main principles of sensing that are used in sensors are transmission and reflection signals [48]. The basic building blocks of sensing devices are a dielectric substrate, a ground plane, and a conductive strip [49]. The creation of numerous microwave integrated circuits has already attracted a great deal of interest in SIW technology [50]. On a substrate, two rows of metal vias are arranged in a matrix to develop the SIW guide. The SIW's field distribution resembles that of a typical rectangular waveguide. A typical SIW microwave sensor model is shown in Fig. 2. To minimise energy leakage, the nearby vias are spaced appropriately [9]. The construction of these waveguides is possible through the use of ordinary printed circuit boards (PCB), for example, in their fabrication methods [51].

The SIW's parameter size needs to adhere to the following guidelines in Eq. (1) to reduce electromagnetic leakage [52,53].

$$D < 0.1\lambda g, b < 4D, D < 0.2W_{eff} \tag{1}$$

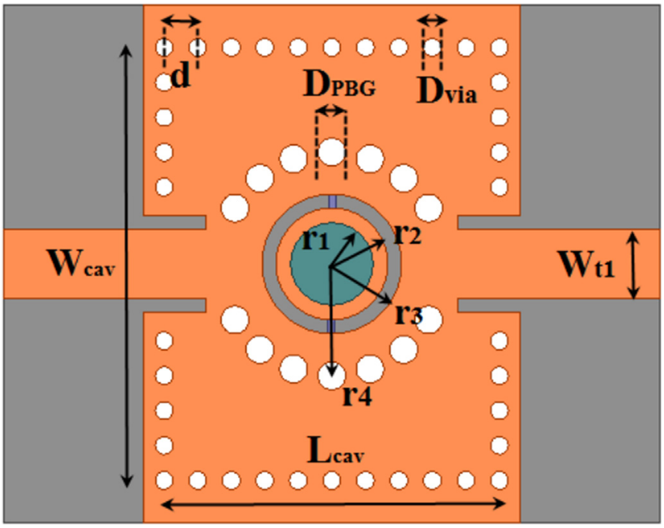


Fig. 3. Reconfigurable microwave SIW sensor geometry [58].

Where D is the sidewall metalized through-hole cylinder's diameter, whereas the centre-to-centre distance and the guided wave's effective wavelength are denoted by b and g, respectively. W_{eff} is the equivalent rectangular waveguide's effective width. While, the circular SIW resonator-type sensor's effective radius and actual radius used the following relationship [54]:

$$R_{eff} = R - \frac{D^2}{0 \cdot 95b} \tag{2}$$

where R and R_{eff} are the actual radius and effective radius, respectively. Hence, the resonant frequency, f_r of the SIC waveguide is expressed by using the following Eq. (3) [55]:

$$f_r = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \frac{P_{11}}{2\pi R_{eff}} \tag{3}$$

where ε_r and μ_r represent the relative permittivity and permeability of the dielectric material, respectively, and c is the light's speed in a vacuum. P_{11} is the first zero-point of the first-order Bessel function.

Many microwave sensors, including SIW sensors, are geared toward measuring dielectric permittivity [56]. In general, an isotropic material's permittivity is expressed as in Eq. (4).

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left(\varepsilon_r' - j\varepsilon'' rd - j\frac{\sigma}{\omega \varepsilon_0} \right) = \varepsilon_0 \varepsilon_r' (1 - \mathrm{j}\tan\delta) \tag{4}$$

Where $\tan\delta$ is the total dielectric loss tangent given by Eq. (5).

$$\tan\delta = \tan\delta_d + \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r'} \tag{5}$$

While, in terms of free space, the electric permittivity and magnetic permeability are defined in Eqs. (6) and (7) [57],

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta_\varepsilon) \tag{6}$$

$$\mu^* = \mu' - j\mu'' = \mu'(1 - j\tan\delta_\mu) \tag{7}$$

Where ε_r is the relative permittivity, μ^* is the magnetic permittivity, ε^* is the electric permittivity, σ is the electric permittivity, ω is the angular frequency, $\varepsilon_0 = 1/[c^2\mu_0] \approx 8.8542 \times 10^{-12}$ [Fm^{-1}] indicates the vacuum's permittivity, and $\tan\delta$ is the tangent for all other dielectric loss mechanisms, while conductivity is given by $\tan\delta_d$.

3. Types of SIW microwave sensor in material characterisations with their fundamental characteristics

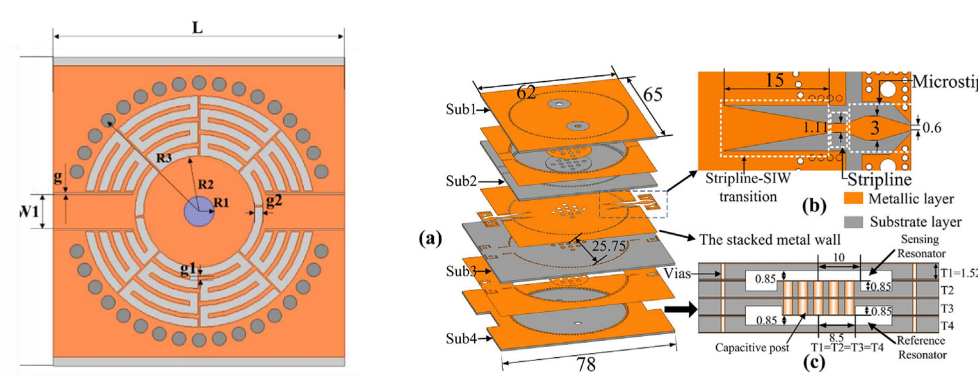
In industrial applications, microwave sensors are widely used to identify material composition in solid, gaseous, or fluid environments. They are made in a variety of forms, depending on the electric field in a small region, using various methods. Most microwave sensors are designed to detect the complex dielectric permittivity of materials since it provides information about the MUT, such as density, moisture content, temperature, microwave absorption, and others. This section gives a quick overview of SIW microwave sensor properties, principles, design, and performance for different materials like liquids, solids, and gases.

3.1. SIW microwave sensor in liquid characterisations

Sensing or detecting the electric field can be performed by using an SIW cavity-based microwave sensor in order to determine the industrial liquids' permittivity [58]. In reality, the fundamental parameter for regulating a sensor of the resonance type was capacitance [58]. A reconfigurable microwave SIW sensor for different types of materials testing was made by modifying the capacitance geometry, as shown in Fig. 3.

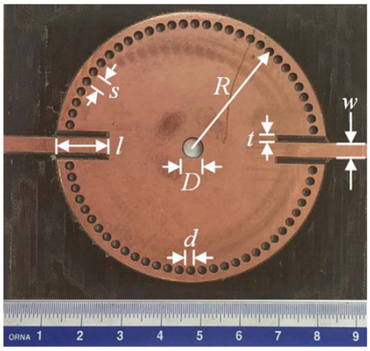
The findings in Ref. [58] show that the suggested arrangement was a viable option for determining transformer oil age. While the results of Ethanol and Butanol show single-Debye relaxation behavior, according to Debye theory, and their permittivity is given by Eq. (8).

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s \varepsilon_\infty}{1 + \frac{jf}{f_r}} \tag{8}$$



(a) Circular cavity (b) Differential microfluidic

Fig. 4. A miniaturised SIW sensor geometry; (a) circular cavity [59] (b) differential microfluidic [60].



Parameter	Dimension (mm)
d	2.0
D	5.1
s	2.88
l	12.8
t	1.5
R	31.2
w	4.0

Fig. 5. Geometry structure of SIW cavity-type sensor [61].

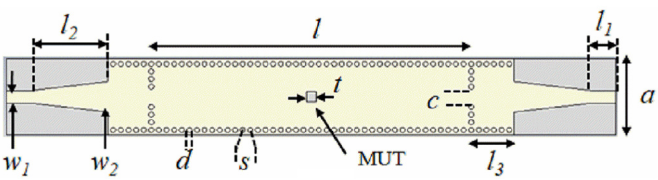


Fig. 6. SIW cavity-type microwave sensor using several high-order modes [62].

Where the relaxation frequency, static permittivity, and theoretical high frequency relaxation limit are denoted by the letters f_r, ε_s and ε_∞ respectively. As a function of frequency, f the complex permittivity ε^* is determined.

The fundamentals of TM_{010} mode [59] were implemented as an operational mode in order to miniaturise the size by providing a reasonably compact structure and a concentrated distribution of electric fields at the cavity's centre. The model of a miniaturised SIW sensor geometry design is shown in Fig. 4 (a). The water-ethanol combination was used as the sample for testing the sensor's sensitivity. Moreover, longitudinally integrating two SIW re-entrant cavity resonators (RECRs) of the type reported would be able to allow a miniature differential in a microfluidic sensor for testing liquid dielectrics [60], as shown in Fig. 4 (b). The permittivity value of the dielectric substrate used in the sensor was 3.48. Based on Fig. 4 (b), the stacked metal wall between the two RECRs prevents the mutual connection between them.

In [61], a low-cost microwave sensor for detecting a material's dielectric permittivity and loss tangent is presented in Fig. 5. Two microstrip lines that are introduced for measurement purposes form a hole in the centre of the cylindrical resonator of SIW cavity-type sensors that have two ports. The sensitivity of the device is greatly improved by the insertion of a metal sheath around the glass pipe, which boosts the electromagnetic field's penetration into the pipe. Several binary mixes of water and isopropanol showed varying permittivity values as a result of the characterisation process.

The use of several layers of higher-order modes in SIW cavity-type microwave sensor substrates that provide broadband detection of permittivity of medium-loss dielectric properties is shown in the sensor model design in Fig. 6 [62].

For the simulation of SIW cavity-type microwave sensor model analysis described in Ref. [62], a novel microstrip-to-SIW cavity-type feeding topology is being used. The model analysis is first evaluated statistically using distinct data produced with the aid of a full-wave electromagnetic solver. The accompanying Eqs. (9)–(11) were used to calculate the effective dimension of the proposed cavity sensors [52,62, 63].

$$a_{eff} = a - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{a} \tag{9}$$

$$l_{eff} = a - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{l} \tag{10}$$

$$f_{TE_{10p}} = \frac{c_0}{2\sqrt{\varepsilon_s}}\sqrt{\left(\frac{1}{a_{eff}}\right)^2 + \left(\frac{p}{l_{eff}}\right)^2} \tag{11}$$

Where s denotes the separation between adjacent vias, d the diameter of the metalized via, and l and w, correspondingly, the length and width of the SIW cavity, and f_{TE10p}, a_{eff}, l_{eff}, c_o, ε_s were the relative permittivity and the resonant frequency, respectively.

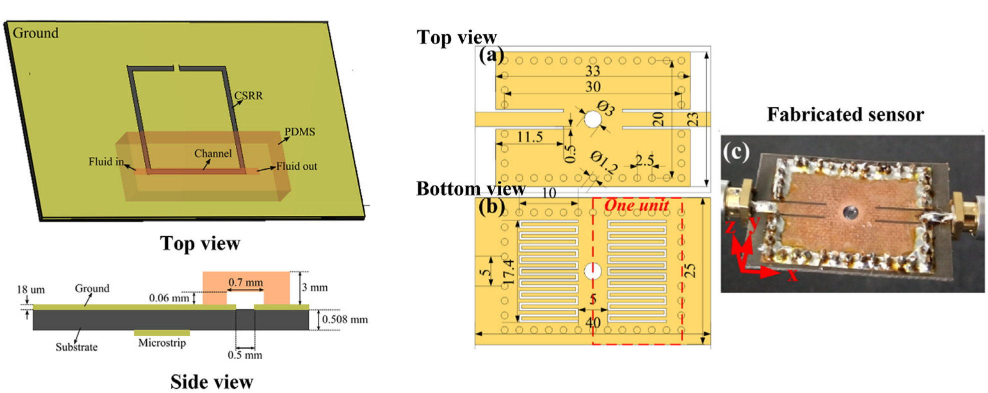
While the SIW cavity perturbation method that can be applied in sensor development may be expressed in Eqs. (12) and (13),

$$\varepsilon_r = \varepsilon_s'\left[1 + \frac{2}{c_c}\left(\frac{f_0 - f}{f}\right)\right] \tag{12}$$

$$\varepsilon_r'' = \frac{1}{\varepsilon_s'\left[\frac{(\varepsilon_s')^2}{c_c}\left(\frac{1}{Q} - \frac{1}{Q_0}\right) + \varepsilon_r'\varepsilon_s''\right]} \tag{13}$$

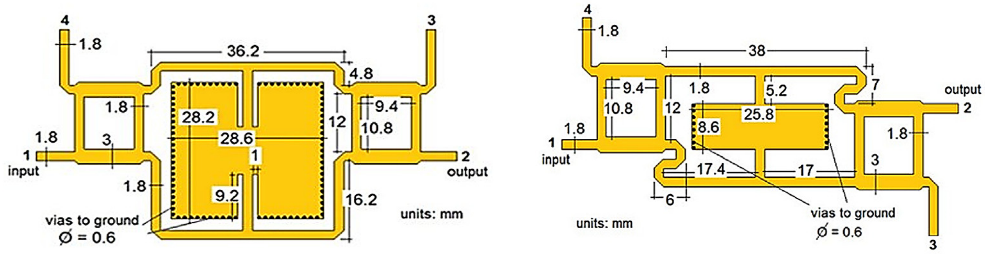
The symbols of $\varepsilon_{s'}$ and $\varepsilon_{r'}$ stand for the imaginary parts of the permittivity of the substrate and MUT, respectively, whereas the symbols of $\varepsilon_{s''}$ and $\varepsilon_{r''}$ stand for the relative permittivity of the substrate and MUT. The loaded SIW cavity's resonant frequency and quality factor are denoted by the symbols f and Q

In order to offer a broader portion of the fringing electric field and enhance the appropriate communication zone with the MUT in the detection of microwave sensors, a principal component resonator (CSRR) was being used, as shown in Fig. 7 (a) [64]. The system works with a lab-on-a-chip and runs at nearly 2 GHz. Several binary mixes of water and ethanol were used to test the proposed sensor, which successfully showed



(a) CSSR sensor (b) SIW resonator sensor

Fig. 7. Microwave sensor structure; (a) top and side view of the CSRR-type [64] (b) top, bottom, and fabricated views of the SIW resonator type [65].



(a) RFID sensor-A (b) RFID sensor-B

Fig. 8. Geometry and dimensions of (a) RFID Sensor-A and (b) RFID Sensor-B integrated with SIW technologies [66].

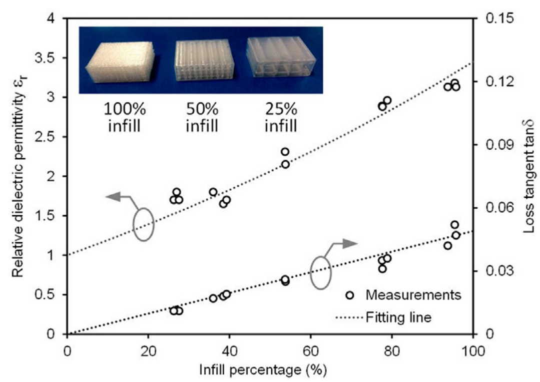
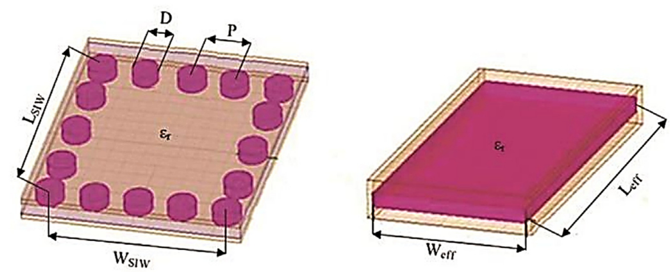


Fig. 9. Narrowband waveguide measurement of dielectric permittivity and loss tangent versus infill percentage [67].



(a) SIW cavity structure

(b) Conventional rectangular waveguide cavity structure

Fig. 10. SIW cavity sensor and its conventional rectangular waveguide structure [68].

the appropriate permittivity values during the characterisation process. Another approach to the SIW microwave sensor was applying two meandering slots or interdigital capacitors at the bottom layer of the sensor, as shown in Fig. 7 (b) [65]. The type of SIW sensor that was implemented was a resonator-type detector sensor. The proposed sensor in Ref. [66] tested binary solvents that come from water and alcohol in order to validate the sensor's performance. During the testing, the liquid sample was placed in the centre hole of the cavity. The material that was used to plug the bottom hole in the sensor was made of silica gel.

A wireless sensing method known as a radio-frequency identification (RFID) sensor was proposed for determining the dielectric permittivity of solvent solutions as shown in Fig. 8 (a) and (b) [66]. For sample testing, two types of sensing tags that come from sensors A and B were implemented to act as a transmitter and receiver. The cavities of both sensors are symmetrically filled via microstrip hybrid couplers. While the initial tag makes use of a hollow resonator, the second tag utilises the epsilon-near-zero effect. The proposed sensor described in Ref. [66] used a planar type SIW sensor to create a circuit capable of operating at 4 GHz.

At 4 GHz, a TE_{101} SIW cavity resonator was well approximated using Eq. (14).

$$f_{101}=\frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{1}{a}\right)^2+\left(\frac{1}{d}\right)^2} \tag{14}$$

Where f_{101} is the resonant frequency, c is the speed of light in a vacuum, and a and d, are, correspondingly, the width and length of the SIW cavity. The liquid under tests (LUTs) used to validate the capability of the proposed sensors were acetone, carbon tetrachloride chlorobenzene, acetonitrile, xylene, ethanol, isobutane, isopropyl alcohol, and methanol [66].

In [67], an additive manufacturing technique and 3D printing were used to improve the dielectric material used in the SIW sensor, thereby initiating the broad-band type of SIW for liquid characterisation purposes. The improvements were made by changing the percentage of infill in the dielectric material used for the sensor, known as the substrate-integrated slab waveguide (SISW), which is a modified version of the standard SIW with increased single-mode bandwidth. The infill percentage was decided based on the graph shown in Fig. 9. The result from the improvement of infill in the proposed sensor shows a 50% bandwidth increment from the standard SIW sensor.

While, in Ref. [68], the researchers developed the SIW cavity sensor to investigate how different types of dielectric materials influence operational characteristics, notably quality factor (Q-factor), fractional bandwidth, and insertion loss (S_{21}) in sensor performance when characterising the liquid material. The structure of the proposed SIW cavity sensor is depicted in Fig. 10. The results indicated that the thickness of the dielectric substrate influenced the increment of the permittivity values and improved the Q-factor of the proposed sensor, thereby minimizing the size of the proposed SIW cavity sensor.

There was also an approach in Ref. [37], where an eighth-mode potting medium waveguide (EMSIW) sensor with a microfluidic channel has been developed to exhibit the transportable and quasi-chemical flow in the testing method of the proposed sensor [37]. The result showed that, when the ethanol content was changed from 0 to 100%, the resonance frequency was finally converted from 4.2 to 4.6 GHz. For the improvement of the accuracy of the classification performance in RF-type sensors [67], blend the SIW technology and the circular type of sensor design to achieve a higher Q-factor. In Ref. [69], a compact microfluidic chemical sensor that comprises two circular complementary split-ring resonators (CSRRs) packed with a quarter mode substrate integrated waveguide (QMSIW) was developed to characterise the mixture of distilled water and ethanol. In addition, the application of perturbation techniques in the development of SIW sensors can improve the sensitivity and accuracy of the measurement of even very small volumes of liquid [70,71].

3.2. SIW microwave sensor in gaseous material characterisations

In the development of an SIW microwave sensor that can characterise the material as gaseous, two distinct SIW-based cavity resonators integrated with a ring-slot resonator and a complementary split ring resonator (CSRR) were used [72]. A graphene sheet is one of the materials to avoid because, in Ref. [72], they reported that the existence of graphene elements extensively disturbed both polar and non-polar compounds in the development of the SIW microwave sensor, thereby affecting their performance. A cost-effective, high-sensitivity gas characterisation, and environment control system inside the proposed SIW microwave sensor can be achieved using the specified device in conjunction with radio frequency (RF) front ends. Several topologies of SIW microwave sensors are manufactured and evaluated experimentally to confirm the theoretical analysis and offer the optimal design to optimise sensitivity [73].

3.3. SIW microwave sensor in powder material characterisations

A re-entrant cavity sensor (RECS) with a folding substrate integrated waveguide (FSIW) was developed for thorough characterisation of magnetic-dielectric powder materials [74]. The researchers employed planar technology to produce microwave SIW sensors with a folding slot [74].

3.4. SIW microwave sensor in binary and mixed material characterisations

In several industrial, academic, and clinical uses, evaluating a material's absorption coefficient is essential. Microwave cavities are widely used because they offer high Q-factors and improved sensitivity. For complicated permittivity measurements utilising SIW cavities [75], the fundamental expression of the cavity perturbation technique (CPT) is shown in Eq. (15).

$$\frac{\omega_2-\omega_1}{\omega_1} = -\left(\frac{\varepsilon_2-\varepsilon_1}{2\varepsilon_1}\right)\frac{\int\int\int V_S E_1^{*}.E_2 dV}{\int\int\int \mathrm{V}c E_1^2 dV} \tag{15}$$

For a rectangular SIW cavity in TEM_{01} mode, the resonance frequency is described in Eq. (16).

$$f_0 = \frac{c}{2\sqrt{\varepsilon_r\mu_r}}\sqrt{\left(\frac{m}{a_{eff}}\right)^2+\left(\frac{1}{d_{eff}}\right)^2} \tag{16}$$

Here, a_{eff} and d_{eff} are used to denote the effective length and width of the cavity, respectively. In addition, c is the velocity of light in a vacuum.

The circular substrate integrated waveguide (CSIW) with a defective microstrip structure (DMS) incorporated in it served as the foundation for the physical design [76]. When compared to conventional resonator sensors (Q-factors >400), the accuracy was increased, with a maximum relative error of 0.37%. The electrical properties characterisation of binary liquids can be characterised in detail using a new sensor based on SIW technology [77]. A table summary of numerous kinds of material characterisations for the SIW microwave sensor techniques is provided in Table 1.

4. Application of SIW microwave sensor in material characterisation

Microwave sensors are appealing for their susceptible, quick, and non-invasive measurements. Numerous techniques have been used to authenticate materials that are affordable, simple to create, and, because of their tiny and compact size, have always had the capability to achieve responsiveness and a high Q-factor for a wide range of materials. These techniques include planar transmission lines, free-space transmission, cavity waveguide perturbation, and an open-ended coaxial probe. Microwave equipment such as the SIW has several applications, particularly in the characterisation of materials.

Table 1
Summary of SIW microwave sensor techniques in various types of material characterisations.

Reference	Sensor Model Type	Material Under Test
L. Fu et al. [60]	Re-entrant cavity resonator	Deionization (DI) water, Methanol, Ethanol
E. Massoni et al. [61]	Resonant cavity with a hole middle	Isopropanol, Isopropanol and water combination, Water
M. A. Ali et al. [72]	Complementary ring-slot resonator	Ammonia gas
Y. Xiang et al. [74]	Re-entrant cavity	SiO_2 and Fe_3O_4 powders
H. Morales et al. [75]	Cavity perturbation	Air, Teflon, Acrylic, Polyamide, RO4003C, Nylon, Wood, Quartz, 6010.2LM, 6010.8LM

4.1. SIW microwave sensor for humidity sensing

Humidity is a factor that must be maintained in numerous industries to provide a clean environment. As a result, both corporate and academic research is becoming increasingly interested in the creation of humidity sensors and the analysis of connected challenges [78,79]. Most humidity sensors are currently active technology [80]. An air-filled area in the centre of the sandwich enhances the sensitivity to humidity [81]. The sensor's performance is highly dependent on the substance it can detect. Black phosphorus (BP), a novel kind of two-dimensional nanomaterial, has been investigated for use in humidity sensing and detection [82]. The material has a large surface area, which consists of a remarkable molecule adsorption capacity. Based on planar technology, an ultra-thin microwave SIW resonator humidity sensor that consists of a folding slot was described by the researchers [83].

4.2. SIW microwave sensor in food and agriculture industry

In the food and agricultural sectors, moisture has a significant impact on the quality of food and seed. Continuous and precise monitoring of soil water content is an important and valuable indicator to maintain the quality of the product. In Ref. [84], a soil moisture sensor based on a metamaterial perfect absorber (MPA) was introduced. MPA-based sensors may be produced from materials that are extremely durable, making them more resilient than conventional sensors. The MPA-based sensor is particularly advantageous for remote and passive sensing in contemporary agriculture since it does not demand an external source of power [84,85].

4.3. SIW microwave sensor in health applications and pharmaceutical

Currently, wearable sensors and "smart skins" play a tremendous role in smart health and real-time health monitoring [86]. To enhance the performance of the SIW microwave sensor device, the study characterises air-filled SIW transition losses [87]. A novel planar substrate integrated waveguide cavity resonator approach is appropriate for dielectric measurement equipment used in pharmaceutical companies to measure complex permittivity [88]. When it comes to drug adsorption on polymeric pharmaceutical carriers, both ionised and non-ionised, the dielectric method offers a lot of potential [89]. Another health application is in the field of biomedical sensing, where the development of a blood glucose concentration (BGC) monitoring band-stop filter based on a SIW cavity sensor is currently underway [90]. The enhanced sensitivity of non-invasive BGC detection is being observed through the utilisation of finger placement and the influence of fingerprints. In the proposed method [90], a hexagonal slot is etched on the top surface of the SIW cavity, and a modified split ring resonator (SRR) is directly connected to the edge of the slot, thereby creating the planar sensing region. This allows for the creation of a precise and accurate BGC monitoring capability using the SIW cavity sensor. Table 2 provides a summary of the

Table 2
Summary of different applications in SIW microwave sensor.

Application Type	Software	Operating Frequency [GHz]	Sensor Operation Principle	Material Type	Material Under Test
Commercial liquids' high-accuracy permittivity characterisation employs a repositionable microwave SIW sensor based on a Photonic band gap (PBG) structure [58].	ANSYS high-frequency structure simulator (HFSS)	5–6	Photonic Band Gaps (PBG)	Industrial liquids	Butanol, Ethanol and Gasoline
Multimode SIW cavity application for determining material permittivity [62].	CST	10–20	Cavity perturbation	–	RT6010, Dupont, RO4460
RFID-based wireless measurement of the liquid's dielectric permittivity [66].	–	4	Resonant	Liquid	Ethanol and methanol
Development of SIW cavities using cavity perturbation techniques for permittivity measurement [75].	HFSS	7	Cavity perturbation	Solid	Teflon, Air, wood, Nylon, Acrylic and Gaseous
Permittivity measurement using an enhanced SIW sensor [91].	Computer simulation technology (CST)	6	Resonant	Solid	Plexiglass, PVC, Teflon
Development of a band-stop filter sensor based on SIW cavities for sensitive blood glucose concentration measurement [90].	HFSS	5.360–5.455	Resonant	Soft-solid	Fingerprints (Skin)

descriptions of several applications for SIW microwave sensor development along with their performances.

5. Fabrication method of SIW microwave sensor

Fabrication is the most important and critical part of a sensor's development. In recent years, a variety of manufacturing techniques have been used in the development of sensors. The development of a high-performance SIW microwave sensor is a new concept that is only beginning to show its possibilities. Thus, different fabrication methods are discussed in this section for better understanding.

5.1. Fabrication of SIW microwave sensor using PCB method

A sandwiched, laminated structure comprised of conducting and insulating layers is known as a printed circuit board (PCB). To connect components mechanically and electrically to the PCB, components are frequently soldered to the latter. The sensor, which is made up of many layers of printed circuit board [81], has repeatability, high sensitivity, and a fast recovery time. To construct the desired differential sensor, two SIW RECRs are longitudinally connected [60]. In general, increasing the depth of the channel will increase the sensor's sensitivity. The innovative design [92] offers a low-cost passive sensor solution that is simple to integrate into a PCB production process.

5.2. Fabrication of SIW microwave sensor in 3D printing

The phrase "3D printing" can refer to a variety of methods where material is added, combined, or solidified to produce three-dimensional structures, frequently layer by layer, which are controlled by a computer. A customised microfluidic sensor may be inserted directly during substrate preparation because of the diverse forms afforded by this new technology [93,94]. A simpler approach to sensor design may be achieved with this method, as well as a decrease in manufacturing time, costs, and total sensor complexity. Several tube designs were simulated, and a single multi-folded pipe was chosen. To ensure a continuous flow of fluid within the pipe, two vertical outlets have been built. The diameters of the pipes and exits are the same. The construction of the pipes is adjusted to fill as much of the SIW cavity as possible to enhance the frequency shift because of the presence of fluid. Table 3 summarises the different types of fabrication of SIW microwave sensors.

6. Future recommendation of SIW microwave sensor

In the fields of material characterisation and sensing, various sensor technologies, including SIW microwave sensors, terahertz (THz) sensors, optical sensors, and plasmonic infrared (IR) sensors, offer unique capabilities and potential for diverse applications. Precise measurement of material parameters is essential in numerous fields, such as medicine, food production, national defence, and public health [95,96]. However, in recent years, the development of SIW microwave sensors has gained significant attention due to their numerous advantages and promising potential. One area where SIW microwave sensors excel is non-invasive sensing for biomedical applications, such as blood glucose monitoring. Operating at radio frequencies, SIW microwave sensors provide a safe and user-friendly solution by detecting changes in the dielectric

Table 3
Summary of different types of fabrication of SIW microwave sensors.

Target	Fabrication Type	Quality Factor	Material Type	Dielectric Used
Reconfigurable microwave SIW sensor based on photonic band gap (PBG) structure for high accuracy permittivity characterisation of industrial liquid [58].	PCB (Etching)	–	Industrial liquid	RT/Duroid 5880
Develop an SIW sensor that can detect multiple changes in the environment [60].	PCB (Etching)	–	Liquid	RO4350
Solve the SIW topology constraint by changing the sensor dimension with the cavity perturbation technique [61].	PCB (Etching)	516, 464, 423, 350	Solid	RT5880
Propose a folded SIW re-entrant cavity senor (RECS) for characterising magnetic-dielectric powder type material [74].	PCB (Etching)	318	Powder	F4BM
Develop an SIW cavity resonator using cavity perturbation for permittivity evaluation [75].	PCB (Etching)	–	Solid, Gas	RT/duroid 5880, RT/duroid 6006, RT/duroid 6010.2LM
Enhance the SIW cavity sensor by optimising the external coupling topology and incorporating a transition offset to the conventional microstrip feed [91].	Chemical etching photolithography printing technique	515	Solid	RT5880, FR4, Plexiglass, Polyethylene, PVC, Rogers RT6006, Teflon
Propose a 3D-printed cavity resonator microfluidic SIW sensor that embeds a multifolded pipe [93].	3D printing	17–44	Air, Liquid	Air, Isopropanol, Water, Several mixtures of water and isopropanol

Table 4
Comparison for the SIW, THz, optical, and plasmonic IR sensors.

Sensor Technology	Characteristics	Important Parameters	Potential Applications
SIW Microwave Sensor [29], [96–101]	Compact size Low transmission loss	Dielectric properties Frequency response	Biomedical sensing (e.g., blood glucose monitoring) Industrial sensing and process monitoring Material characterisation
THz Sensor [103,104,109,110]	Penetrating ability High-resolution spectroscopy	Frequency range Signal-to-noise ratio	Biomedical imaging Non-destructive testing Material characterisation
Optical Sensor [105,106,111,112]	Non-contact sensing High sensitivity	Wavelength Intensity Refractive index	Biomedical imaging Environmental monitoring Industrial process monitoring Quality control
Plasmonic IR Sensor [107,108,113,114]	High sensitivity to molecular interactions	Surface plasmon resonance Refractive index	Biosensing (e.g., label-free detection) Chemical analysis

properties of substances like blood glucose without disrupting the skin [29,97–102]. Their accurate and reliable measurements make them ideal for enabling optimal performance and minimizing errors in industrial environments as well [29].

While SIW microwave sensors have their strengths, it is crucial to compare and evaluate them alongside other sensor technologies to address specific challenges and advance the field. For instance, THz sensors offer the potential for advanced biomedical sensing applications that require fine-scale analysis of molecular vibrations and material properties. These sensors can penetrate materials and provide high-resolution spectroscopic information [103,104]. Optical sensors, on the other hand, utilise light-based techniques and offer non-contact and highly sensitive measurements, making them suitable for biomedical imaging and environmental monitoring [105,106]. Plasmonic IR sensors leverage surface plasmon resonance phenomena and exhibit excellent sensitivity for label-free and real-time detection of molecular interactions in biosensing applications [107,108].

To further enhance material characterisation and sensing technologies, it is recommended to conduct comparative studies evaluating the performance, cost-effectiveness, and applicability of SIW microwave sensors, THz sensors, optical sensors, and plasmonic IR sensors in specific application domains. Such studies will contribute to the development of tailored sensing solutions that cater to the unique requirements of diverse industries, including the biomedical, industrial, and environmental sectors. Table 4 is the comparison table, which includes characteristics, important parameters, and potential applications for the sensors of the SIW Microwave sensor, THz sensor, optical sensor, and plasmonic IR sensor.

7. Conclusion

SIW microwave sensors provide a powerful tool for material characterisation, offering non-destructive testing, high sensitivity, and compact size that allow for characterisation without damaging or altering the properties of the samples. This is particularly important when working with valuable or delicate materials. It can operate across a wide frequency range, from microwave to millimetre-wave frequencies. This flexibility allows for the characterisation of various materials with different dielectric properties. SIW microwave sensors benefit from low-loss propagation within the waveguide structure, which helps to maintain a high signal-to-noise ratio. This allows for accurate measurements and enhances the sensitivity of the sensors. These features make them valuable in industries such as manufacturing, aerospace, automotive, and electronics for quality control, research, and development purposes. This article provides several models of SIW microwave sensors, including their designs, their theoretical basis, the technical solutions to their problems, and an overall study of their potential applications across a wide range of domains. Various experimental designs in the field of SIW for the characterisation of materials have been presented and discussed, while certain recommendations for future work have been provided in a way that is both innovative and concise. The majority of studies focused on characterising liquid materials in binary mixtures or concentrations, although certain investigations focused on specialised applications, for example, the classification of foods, aqueous glucose, and solid materials. As a consequence of this, there is a desire for one-of-a-kind SIW microwave sensors that can be manufactured for a variety of applications for measurement and that offer effective performance while maintaining a low cost of manufacturing.

Declaration of competing interest

The authors have no conflict of interest.

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