

Review

High-Frequency Resonators for Dielectric Characterization: A Review of Design Techniques, Performance Trade-Offs, and Future Directions

Asma Benhamza ^{1,*}, Nadhir Djeflal ^{1,2}, Mounir Amir ¹, Salem Titouni ², Abdallah Hedir ^{1,3,*},
Mellissa Amazouz ¹, Idris Messaoudene ² and Hakim Achour ¹

¹ Faculty of Electrical Engineering and Computer Science, University of Mouloud Mammeri, Tizi Ouzou 15000, Algeria; nadhir.djeflal@ummto.dz (N.D.); mounir.amir@ummto.dz (M.A.); mellissa.amazouz@ummto.dz (M.A.); hakim.achour@ummto.dz (H.A.)

² Laboratoire d'Electronique et Télécommunications Avancées, University Mohamed El Bachir El Ibrahimi of Bordj Bou Arreridj, Bordj Bou Arreridj 34000, Algeria; salem.titouni@univ-bba.dz (S.T.); idris.messaoudene@univ-bba.dz (I.M.)

³ Advanced High Voltage Engineering Centre, School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, UK

* Correspondence: asma.benhamza@ummto.dz (A.B.); abdallah.hedir@ummto.dz (A.H.)

Abstract

The rapid expansion of microwave and millimeter-wave telecommunication systems has intensified the need for precise dielectric material characterization at high frequencies. As operating frequencies increase, small uncertainties in permittivity and loss tangent significantly degrade resonance stability, bandwidth control, and quality factor, directly affecting RF system reliability and performance. However, the growing diversity of resonator architectures and extraction methodologies has led to fragmentation in the literature, making it difficult to identify optimal solutions for telecommunication-oriented applications. This review provides a structured and application-driven assessment of high-frequency resonator-based dielectric characterization techniques relevant to modern telecommunication systems. Resonator topologies—including cavity, planar, substrate-integrated, metamaterial-inspired—are systematically classified and critically compared. Their sensing mechanisms and parameter-extraction approaches are analyzed in terms of frequency-shift sensitivity, Q-factor performance, scalability toward millimeter-wave bands, integration capability, and measurement robustness. By synthesizing performance trade-offs, practical limitations, and emerging research directions, this review establishes clear design guidelines and a forward-looking framework for advancing dielectric metrology in next-generation high-frequency telecommunication technologies.

Keywords: dielectric characterization; microwave resonators; millimeter-wave measurements; dielectric permittivity; loss tangent; quality factor



Academic Editor: Reza K. Amineh

Received: 15 May 2026

Revised: 13 June 2026

Accepted: 23 June 2026

Published: 6 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Dielectric material characterization is a key enabler for the design and optimization of modern telecommunication systems, where materials are extensively used in resonators, filters, antennas, oscillators, and frequency-selective components across applications such as cellular networks, satellite communications, radar, and navigation systems [1,2]. The accurate determination of electromagnetic parameters—particularly relative permittivity and dielectric loss tangent—is essential, as they directly influence resonance frequency,

bandwidth, quality factor, radiation efficiency, and overall system stability. Even small deviations in these parameters can significantly degrade RF performance.

The need for precise characterization becomes more critical as systems move toward microwave, millimeter-wave, and emerging terahertz frequency bands, where dielectric losses, dispersion, fabrication tolerances, and environmental sensitivities are more pronounced. At the same time, the increasing use of advanced materials such as polymers, composites, flexible substrates, and additively manufactured structures introduces additional challenges due to their complex and often non-ideal electromagnetic behavior [3–6]. These limitations reduce the effectiveness of conventional broadband and low-frequency techniques and motivate the adoption of resonator-based methods.

Resonator-based dielectric characterization techniques have gained significant attention due to their high field confinement, frequency selectivity, and capability to accurately extract both real and imaginary components of complex permittivity. Advances in planar integration, additive manufacturing, and RF miniaturization have further enabled compact resonant structures to be embedded within sensors, antennas, and front-end circuits, where dielectric loading effects enhance measurement sensitivity and device performance [6–9]. As a result, these techniques have become essential tools for dielectric metrology in modern 5G, 6G, and satellite communication systems.

Despite these advantages, resonator-based techniques still face several practical limitations. Measurement accuracy at high frequencies is strongly influenced by fabrication tolerances, coupling conditions, and environmental variations [3–5]. In addition, many established methods were originally developed for low-loss, rigid materials and are not directly applicable to flexible, composite, or highly lossy substrates [9,10]. Trade-offs in resonator topology further complicate design choices: cavity-based resonators offer high quality factors and accuracy but lack integration capability, whereas planar and metamaterial-inspired structures provide compactness and ease of fabrication at the cost of lower quality factors and higher sensitivity to parasitic effects [8,11]. Moreover, the lack of standardized calibration and validation procedures limits reproducibility and hinders direct comparison across different techniques and frequency ranges [12].

Some of the recently published review articles related to microwave sensors are summarized in Table 1. Existing review studies have mainly addressed performance enhancement strategies and metamaterial-based sensor designs [13–15], as well as antenna-based sensing approaches and their fabrication aspects [16,17]. In addition, several works have focused on fundamental principles and modelling approaches for permittivity extraction and dielectric characterization [3,18–20]. Significant attention has also been given to application-oriented studies, particularly in biomedical sensing and related sensor technologies [21].

However, despite the growing interest in microwave sensors in recent years, a unified review focusing on resonator-based design methodologies remains limited. In particular, the systematic classification of resonator topologies, comparative analysis based on performance metrics, and a consolidated discussion of sample loading techniques for different material types (solid, liquid, and gas) are still insufficiently addressed, while a consistent framework linking resonator characteristics—such as topology, quality factor, sensitivity, and parameter-extraction methods—to telecommunication system constraints is still lacking. To address these gaps, this work presents a structured review of resonator-based microwave sensors, integrating design strategies, sample loading approaches, performance evaluation, and emerging research directions, and places dielectric material characterization at the center of the analysis from a telecommunication-system perspective, explicitly relating resonator properties to RF integration, frequency scalability, and robustness against fabrication and environmental variations.

Table 1. Summary of recent review articles on microwave sensors for dielectric characterization

Ref.	Year	Scope	Key Contributions
[3]	2021	Planar resonator-based sensors	Complex permittivity extraction techniques, planar resonator designs, applications, challenges, and future research directions.
[16]	2023	Microwave antenna sensors	Antenna sensor designs, fabrication techniques, performance analysis, and application domains.
[14]	2023	Metamaterial-based sensors for material characterization	Metamaterial sensor principles, material characterization methods, performance enhancement strategies, and applications.
[15]	2024	Metamaterial-inspired resonator sensors	Metamaterial-loaded resonator designs, dielectric characterization methods, performance enhancement strategies, and applications.
[18]	2024	Permittivity measurement sensors	Sensor types, permittivity extraction, applications, measurement methods.
[13]	2025	Metamaterial biosensors	Design principles, metamaterial enhancement, performance improvement, applications.
[17]	2025	Antennas as sensors	Principles, architectures, applications, limitations, future prospects.
[20]	2025	Liquid characterization sensors	Sensor designs, microfluidics, liquid dielectric analysis, advances, applications.
[21]	2025	Glucose monitoring sensors	Sensor types, non-invasive methods, materials, fabrication, challenges, future trends.
[19]	2026	Dielectric characterization sensors	Fundamentals, classification, technological advances, recent developments.
This Work	2026	Resonator-based dielectric sensors	Classification and comparative analysis of resonator techniques; evaluation of sensitivity, Q-factor, and accuracy; permittivity extraction methods; limitations and emerging trends (AI, hybrid systems).

This review provides a structured and critical assessment of resonator technologies for dielectric characterization in telecommunication environments. The adopted methodology emphasizes classification, comparative analysis, and critical evaluation rather than exhaustive listing. Specifically, this work makes the following contributions:

- Classifies resonator-based characterization techniques according to topology, operating principle, frequency range, and integration capability;
- Compares resonator configurations in terms of sensitivity, quality factor, measurement accuracy, sample loading strategies, and fabrication complexity;
- Reviews extraction techniques with emphasis on applicability to microwave and millimeter-wave systems;
- Identifies key limitations related to accuracy, repeatability, integration, and environmental robustness;
- Discusses emerging research directions, including AI-assisted resonator design, machine-learning-based permittivity estimation, hybrid microwave–photonic systems, and standardization efforts.

By explicitly linking resonator design choices to telecommunication-driven performance requirements, this review provides practical guidance for researchers and engineers working on dielectric characterization and RF system development.

The remainder of this paper is organized as follows. Section 2 introduces dielectric properties relevant to telecommunication systems and presents a taxonomy of resonator-based characterization methods. Section 3 reviews resonator architectures, including cavity, planar, metamaterial-inspired, and additively manufactured designs. Section 4 discusses dielectric measurement techniques, distinguishing between resonant and non-resonant approaches, along with parameter extraction and uncertainty analysis. Section 5 highlights open challenges and research gaps. Section 6 presents key telecommunication applications. Section 7 outlines future research directions. Finally, Section 8 concludes the paper.

2. Dielectric Materials and Resonator-Based Characterization

Dielectric materials play a central and non-negotiable role in the performance, reliability, and scalability of modern telecommunication systems. Unlike low-frequency electronic circuits, where material properties often appear as secondary design parameters, RF, microwave, and millimeter-wave systems are intrinsically material-limited [2]. The relative permittivity (ϵ_r) governs electromagnetic wavelength compression, resonator

dimensions, and phase velocity, while the dielectric loss tangent ($\tan \delta$) fundamentally constrains the achievable quality factor, insertion loss, and noise performance of resonant components [22,23]. Consequently, dielectric material characterization has evolved from an auxiliary task into a primary design consideration that directly impacts system-level metrics such as spectral efficiency, link budget, phase noise, and long-term frequency stability.

This challenge becomes increasingly pronounced as telecommunication platforms migrate toward higher frequencies and greater functional integration. While conventional rigid printed circuit board (PCB) substrates typically exhibit very low dielectric losses, emerging platforms increasingly rely on flexible polymers, textiles, paper-derived dielectrics, and composite materials to enable conformal, wearable, and lightweight systems. These materials often exhibit higher loss tangents, stronger dispersion, and increased sensitivity to environmental conditions such as temperature and humidity, rendering accurate high-frequency dielectric characterization both challenging and indispensable [24–26].

At microwave and millimeter-wave frequencies, dielectric behavior becomes inherently frequency dependent, and even small variations in $\epsilon_r(\omega)$ or $\tan \delta(\omega)$ can induce measurable resonance shifts, bandwidth compression, and degradation of quality factor in high-Q components. In this context, resonator-based dielectric characterization techniques have emerged as the most reliable and physically grounded approach, exploiting strong electromagnetic field confinement and energy storage to amplify material-induced perturbations [1,3]. However, resonator performance is inherently governed by trade-offs between accuracy, sensitivity, integration capability, and operational bandwidth, and no single resonator topology can universally satisfy the diverse requirements of modern telecommunication systems. This reality motivates the need for a structured, application-driven framework for resonator selection and comparison [3].

2.1. Taxonomy of Resonator-Based Characterization Techniques

To systematically organize the wide range of resonator-based dielectric characterization approaches reported in the literature, a multi-dimensional classification framework is required. Figure 1 proposes a taxonomy structured by material class, frequency range, quality factor, and application constraints. High-Q cavity resonators are suited for ultra-accurate metrology, whereas planar and integrated resonators favor compact and manufacturable telecommunication systems. The taxonomy highlights these trade-offs to enable application-driven resonator selection.

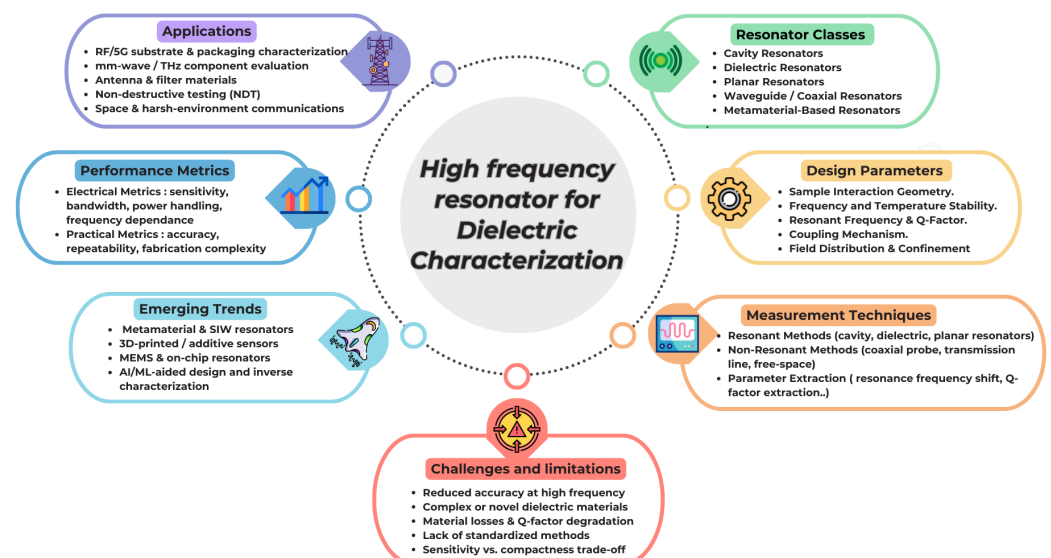


Figure 1. Taxonomy of design considerations for a high-frequency resonator for dielectric characterization.

2.2. High-Frequency Resonator Design for Dielectric Characterization in Telecommunications

The design and performance of high-frequency resonators for telecommunication applications are intrinsically linked to the dielectric properties of the constituent materials, particularly the relative permittivity (ϵ_r) and the loss tangent ($\tan \delta$). The dielectric constant primarily determines the effective capacitance of the resonator and, together with the geometrical configuration, sets the resonant frequency. In contrast, the loss tangent governs electromagnetic energy dissipation and directly impacts the quality factor. Emerging flexible substrates, such as fabrics, paper, or polymer films, often exhibit higher $\tan \delta$ than conventional rigid printed circuit board (PCB) materials, necessitating accurate dielectric characterization prior to resonator integration [22–24].

Dielectric behavior is commonly described using the complex permittivity:

$$\epsilon^* = \epsilon' - j\epsilon'', \quad (1)$$

where ϵ' represents the real part associated with stored electric energy arising from polarization mechanisms, while ϵ'' corresponds to dielectric loss due to dipolar relaxation and other dissipative processes.

The loss tangent quantifies the ratio of energy dissipated to energy stored in the dielectric medium and can be expressed as:

$$\tan \delta = \frac{\epsilon'' + \frac{\sigma}{\omega\epsilon_0}}{\epsilon'}, \quad (2)$$

where ϵ' and ϵ'' denote the real and imaginary parts of the relative permittivity, respectively, σ is the effective electrical conductivity of the material, ω is the angular frequency, and ϵ_0 is the vacuum permittivity.

This formulation expresses dielectric loss as contributions from polarization-related losses, represented by ϵ'' , and conductive losses represented by $\sigma/(\omega\epsilon_0)$.

For low-loss microwave substrates commonly employed in telecommunication resonators, the conductive contribution is typically negligible, such that $\frac{\sigma}{\omega\epsilon_0} \ll \epsilon''$ (i.e., conductive losses are negligible compared to polarization losses). Under this assumption, the loss tangent simplifies to the commonly used approximation $\tan \delta \approx \epsilon''/\epsilon'$. However, for flexible, composite, or printed materials, as well as materials exhibiting finite dc conductivity, the conductive term may become non-negligible. In such cases, separating conductive and polarization contributions is essential for accurate extraction of intrinsic dielectric parameters and for avoiding overestimation of dielectric losses.

Microwave and millimeter-wave resonators, including dielectric resonators (DRs), confine electromagnetic energy within discrete resonant modes, thereby minimizing radiation loss and enabling high field confinement. These resonators can often be approximated by equivalent RLC circuits with resonance frequency:

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \quad (3)$$

where L and C represent the effective inductance and capacitance determined by the resonator geometry and material properties.

When a material under test (MUT) is introduced into the resonator, its electromagnetic properties perturb the stored energy distribution, resulting in a measurable shift in resonance frequency. Under the assumptions of small perturbation, linear isotropic material response, and weak coupling, cavity perturbation theory yields [27].

$$\frac{\Delta f_r}{f_r} = -\frac{1}{2} \frac{\int_V (\Delta\epsilon |\mathbf{E}_0|^2 + \Delta\mu |\mathbf{H}_0|^2) dV}{\int_V (\epsilon |\mathbf{E}_0|^2 + \mu |\mathbf{H}_0|^2) dV}, \quad (4)$$

where $\mathbf{E}_0$ and $\mathbf{H}_0$ are the unperturbed electromagnetic fields of the resonator, and $\Delta\epsilon = \epsilon_{\text{MUT}} - \epsilon$ and $\Delta\mu = \mu_{\text{MUT}} - \mu$ represent deviations from the background medium (typically air or vacuum).

For non-magnetic materials commonly used in dielectric characterization, $\Delta\mu \approx 0$, and the frequency shift is primarily governed by permittivity variations.

This relation indicates that the sensitivity of the measurement depends strongly on the spatial overlap between the MUT and the electromagnetic field distribution. High permittivity sensitivity is achieved by positioning the MUT in regions of maximum electric-field intensity, whereas magnetic-field-sensitive configurations (when applicable) require placement in regions of strong magnetic-field concentration.

Resonator performance is commonly quantified through the quality factor and sensitivity. The measured quality factor is typically the loaded quality factor Q_L , which is related to the unloaded quality factor Q_0 and the external quality factor Q_e as shown in (5).

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_e} \quad (5)$$

Here, Q_0 denotes the unloaded quality factor of the resonator, accounting for intrinsic losses due to dielectric, conductor, and radiation mechanisms, while Q_e accounts for coupling to external circuitry. Accurate dielectric loss extraction therefore requires determination of Q_0 , since Q_L alone includes coupling-related losses.

Experimentally, the quality factor can also be estimated from the resonance bandwidth as given by (6):

$$Q_L = \frac{f_r}{\Delta f} = \frac{f_r}{f_2 - f_1}, \quad (6)$$

where f_r is the resonance frequency and f_1 and f_2 denote the frequencies corresponding to the -3 dB transmission points defining the resonance bandwidth.

For resonant dielectric characterization in low-loss regimes, the dielectric loss tangent can be approximated from the dielectric quality factor as (7):

$$\tan \delta \propto \frac{1}{Q_d}, \quad (7)$$

where Q_d represents the dielectric contribution to the intrinsic quality factor after removing conductor, radiation, and coupling losses.

The sensitivity of a resonator-based dielectric sensor is commonly defined as (8):

$$S = \frac{\Delta f_r}{\Delta \epsilon_r}, \quad (8)$$

A normalized form of the sensitivity is given by (9):

$$S_n = \frac{\Delta f_r / f_r}{\Delta \epsilon_r}. \quad (9)$$

High- Q resonators enable the detection of very small resonance-frequency shifts, thereby improving sensitivity. However, excessively high Q values may increase susceptibility to environmental perturbations such as temperature drift or mechanical vibration [1,28]. Consequently, practical resonator design requires a balance between intrinsic losses, coupling strength, and environmental stability. Undercoupling may result in weak signal levels, whereas overcoupling reduces Q_L and degrades frequency resolution [29,30].

Dielectric properties are inherently frequency dependent and often exhibit dispersion and relaxation phenomena that influence resonator response. An empirical representation

frequently used to describe broadband dielectric behavior is Jonscher's universal dielectric response, given by (10):

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\sigma_{dc}}{j\omega\varepsilon_0} + \frac{A}{(j\omega)^{n-1}\varepsilon_0}, \quad (10)$$

where ε_∞ is the high-frequency permittivity, σ_{dc} the dc conductivity, A a polarization strength factor, and $0 < n < 1$ characterizes deviation from ideal Debye behavior [31,32]. As an empirical model, this formulation captures the general frequency dependence of dielectric materials but does not explicitly describe microscopic polarization mechanisms.

At microwave frequencies, dielectric relaxation is often modeled using the Debye relaxation equation [33], as given by (11):

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}, \quad (11)$$

where ε_s is the static permittivity and τ denotes the characteristic relaxation time. For heterogeneous or composite materials, deviations from ideal Debye behavior are more accurately captured using extended models such as the Cole–Cole or Havriliak–Negami formulations, which account for distributed relaxation times and structural inhomogeneities [34].

Because resonators operate at discrete frequencies, the extracted dielectric parameters correspond strictly to the specific resonance frequency and resonant mode under consideration. Consequently, broadband dielectric modeling and multi-frequency validation are often necessary to ensure physically consistent parameter extraction across microwave and millimeter-wave frequency bands [35]. As summarized in Table 2, dispersion and relaxation phenomena introduce frequency-dependent variations in both resonant frequency and quality factor, directly impacting sensitivity and dielectric-loss estimation.

Table 2. Frequency-dependent dielectric phenomena and their implications for high-frequency resonator-based dielectric characterization.

Phenomenon	Frequency Regime	Effect on Resonator Response	Implication for Dielectric Extraction
Dielectric dispersion	Microwave–mmWave	Resonant frequency varies with operating band	Extracted relative permittivity ε_r is valid only at the resonance frequency f_r ; broadband dielectric models are required
Relaxation processes	GHz range	Frequency-dependent loss increase and phase delay	Single-frequency extraction may underestimate the dielectric loss tangent $\tan \delta$
Debye-type relaxation	Narrowband	Symmetric resonance broadening with predictable frequency shift	Accurate dielectric extraction for homogeneous, low-loss materials using single-pole dispersion models
Non-Debye relaxation	Broadband	Mode-dependent frequency shift and quality-factor degradation	Requires advanced dispersion modeling such as Cole–Cole or Havriliak–Negami formulations
Conductivity contribution	Low–mid microwave	Apparent reduction of resonator quality factor due to ohmic losses	Risk of misinterpreting conductive losses as dielectric losses if conductivity is not explicitly modeled
Polarization mechanism transition	Microwave–mmWave	Change in dominant polarization and loss mechanisms with frequency	Dielectric model parameters must be frequency-scaled for accurate extraction
Temperature–frequency coupling	All frequency bands	Resonant frequency drift and permittivity variation with temperature	Thermal stabilization or compensation is essential for high-Q resonator-based measurements
Mode sensitivity variation	Multimode resonators	Different resonant modes probe different effective material volumes	Enables multi-frequency validation and consistency checks of extracted dielectric parameters

2.3. Types of Resonators

Microwave resonators used for dielectric characterization can be classified according to their geometry, field confinement, and level of integration. Table 3 provides a comparative overview of the main resonator families reported in the literature, highlighting their key characteristics, representative applications, and principal limitations.

Table 3. Summary of resonator types commonly used for dielectric characterization.

Resonator Type	Main Characteristics	Typical Applications	Main Limitations
Rectangular cavity	Closed metallic cavity; TE/TM modes; very high Q ; uniform field; suitable for perturbation/inverse methods	High-accuracy solids and liquids; high-permittivity, low-loss materials	Bulky; non-planar; limited integration; accuracy drops for large samples
Cylindrical cavity	High- Q metallic cavity; compact; strong axial field (TM_{010}); flexible sample placement	Solids and liquids; low-loss materials; lab measurements	Alignment sensitive; limited planar integration; possible mode degeneracy
Split-post dielectric (SPDR)	Very high Q ; strong field confinement; optimized for thin planar samples	Thin films, substrates, laminates	Limited thickness; narrowband; careful alignment required
Microstrip/SIW	Planar, compact; resonance sensitive to permittivity; moderate Q ; low-cost fabrication	Substrates, sheet materials; integrated sensing	Conductor/radiation losses; fabrication tolerances; environmental sensitivity
Metamaterial (SRR/CSRR)	Subwavelength LC; high localized fields; highly sensitive to permittivity	Biosensing; microfluidics; sensitive dielectric detection	Narrowband; fabrication-sensitive; complex calibration
Coaxial/Dielectric resonator (DRA)	TEM-mode or dielectric-supported; compact; moderate Q ; low conductor loss	Solids, liquids, soils; in-situ measurements; biosensing	Sensitivity depends on filling factor; environmental variations; limited tuning flexibility

Hollow rectangular and cylindrical cavity resonators are widely employed for high-accuracy dielectric measurements due to their well-defined TE and TM modes and very high quality factors. Figure 2 illustrates the geometry and cylindrical coordinate system of a representative cylindrical cavity resonator.

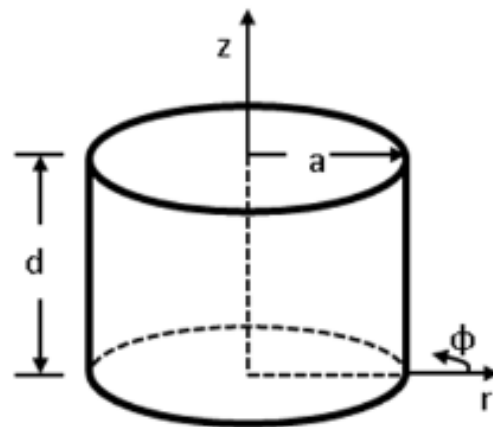


Figure 2. Geometry of a cylindrical cavity resonator showing the key dimensions and cylindrical coordinate system [36].

Split-post dielectric resonators (SPDRs) are optimized for thin planar samples, providing very high Q and strong field confinement, as illustrated in Figure 3.

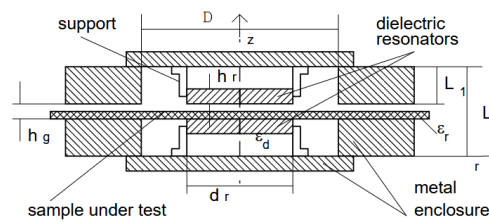


Figure 3. Split-post dielectric resonator (SPDR) configuration for planar sample characterization [10].

Planar resonators, such as microstrip or substrate-integrated waveguide (SIW) structures, provide compact, low-cost solutions suitable for integrated dielectric sensing, as illustrated in Figure 4.

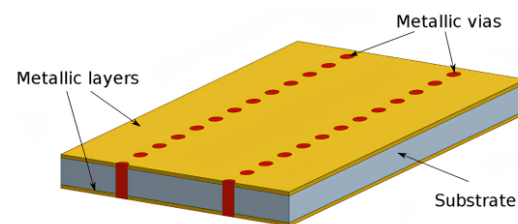


Figure 4. Substrate-integrated waveguide (SIW) resonator structure for planar dielectric characterization [37].

Metamaterial-inspired resonators, including split-ring resonators (SRRs) and complementary SRRs (CSRRs), exploit subwavelength LC resonances to achieve highly sensitive permittivity detection, as illustrated in Figure 5.

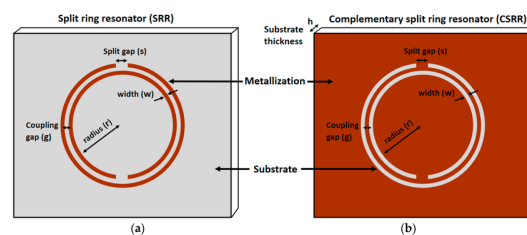


Figure 5. Planar metamaterial-inspired resonators: (a) SRRs and (b) CSRRs for sensitive microwave dielectric sensing [38].

Coaxial and dielectric resonators (DRAs) leverage TEM modes or dielectric-supported resonances for compact and moderately high- Q sensing of solids, liquids, and soils, as illustrated in Figure 6.

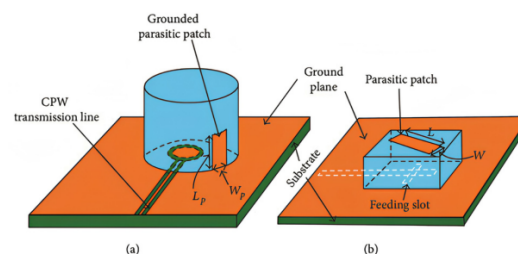


Figure 6. Dielectric resonator antenna (DRA) for dielectric characterization and sensing [39]. (a) overall configuration of the CPW-fed DRA sensor with a grounded parasitic patch; (b) detailed view of the parasitic patch and feeding slot geometry with dimensions L and W .

3. Resonator Architectures for Dielectric Characterization

Dielectric resonator design plays a key role in microwave and millimeter-wave material characterization, as its geometry and configuration strongly govern the Q -factor, field

distribution, and sensitivity, while a wide range of architectures has been developed and selected based on frequency, accuracy, sample geometry, and environmental conditions [1,3]. In general, resonator structures are optimized to efficiently confine electromagnetic energy with low losses, and recent advances in feeding and coupling techniques have further improved performance and design simplicity without compromising accuracy [40].

3.1. Cavity Resonators

Cavity resonators constitute the metrological benchmark for microwave dielectric characterization owing to their well-defined metallic boundary conditions, analytically tractable modal field distributions, and inherently high unloaded quality factors [41]. In resonance-based techniques, the primary measured quantities are the resonant frequency and the unloaded Q-factor of a specific mode excited within a closed structure containing the material under test (MUT). The closed volumetric configuration ensures strong electromagnetic energy confinement with negligible radiation losses, enabling highly accurate and repeatable dielectric characterization [2].

The interaction between the cavity field and the material under test (MUT) is governed by the overlap between the resonant electric field and the sample volume, commonly quantified through the filling factor, which represents the fraction of stored electromagnetic energy localized within the MUT region [41]. Consequently, dielectric sensitivity is maximized when the sample is positioned at electric-field antinodes where energy localization is strongest [5,41], whereas highly lossy materials may be placed in lower-field regions to preserve measurable resonance characteristics [41]. Therefore, resonator geometry, mode selection, and sample placement remain key factors governing measurement sensitivity and characterization accuracy. The associated parameter extraction methodologies are discussed in Section 4.

3.1.1. Rectangular Cavities

Rectangular cavity resonators have been extensively employed for high-accuracy dielectric characterization, with different implementations reflecting distinct trade-offs between accuracy, structural complexity, practical usability, and sample handling.

High-precision metrology-oriented designs prioritize maximum quality factor and permittivity range. Marksteiner et al. [4] demonstrated a multimode rectangular cavity achieving unloaded quality factors exceeding 10^4 and permittivity measurements beyond $\epsilon_r > 10^4$, making it particularly effective for ferroelectric ceramics. However, this performance requires large cavity volumes exceeding 50 cm^3 , increased structural complexity, and reduced usability at lower frequencies due to dimensional scaling.

In contrast, complexity-reduced designs aim to maintain accuracy while simplifying the resonator structure. Jha et al. [42] proposed a slot-loaded rectangular cavity combined with full-wave electromagnetic optimization, achieving characterization errors below 2% over a wide permittivity range with moderate quality factors (10^3 – 10^4). Compared to multimode cavities, this approach reduces structural complexity and sample volume (10 – 50 cm^3), but it relies on computationally intensive CST–MATLAB optimization and remains sensitive to model-dependent calibration.

A third category prioritizes experimental convenience and liquid sample handling. Hussain et al. [43] introduced a top-access rectangular cavity enabling milliliter-scale sample handling (1 – 5 mL). While this configuration improves experimental accessibility and simplifies sample placement, the top aperture introduces radiation leakage and reduced electromagnetic confinement, resulting in a lower quality factor ($\sim 10^3$) and limited loss tangent resolution ($\tan \delta \sim 10^{-3}$) compared to fully enclosed structures.

From a comparative standpoint, multimode cavities offer the highest quality factors and the widest permittivity measurement range but are also the most bulky and experimentally demanding. Slot-loaded optimized cavities provide a favorable compromise between accuracy, structural simplicity, and sample accommodation for solid dielectric characterization. Top-access configurations generally offer greater practicality for liquid characterization, although this advantage is accompanied by reduced electromagnetic confinement and measurement precision. Therefore, the selection of a rectangular cavity architecture should be guided by the relative importance of metrological accuracy, implementation complexity, and sample-handling requirements for the intended application. A representative rectangular cavity configuration and its transmission response are shown in Figure 7.

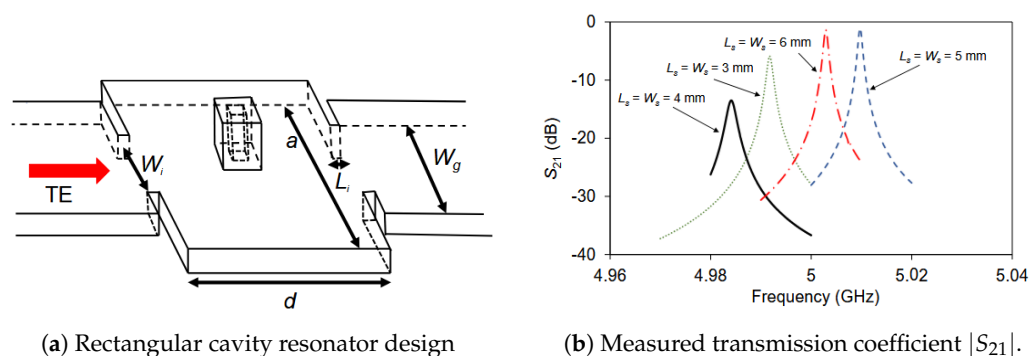


Figure 7. Rectangular cavity resonator-based characterization: (a) geometry of the rectangular cavity resonator with sample insertion arrangement; (b) measured transmission coefficient $|S_{21}|$ for different sample dimensions ($L_s = W_s$), showing the resulting shifts in resonance frequency and variations in transmission characteristics caused by changes in the sample size within the resonant field region [43].

3.1.2. Cylindrical Cavities

Cylindrical cavity resonators provide an alternative geometry characterized by rotational symmetry and well-defined transverse magnetic (TM) and transverse electric (TE) modes, with different implementations exhibiting trade-offs between quality factor, sensitivity, and sample volume. Typical configurations operate over a wide quality factor range (10^2 to $>10^4$), depending on geometry, losses, and boundary conditions, making them applicable to both bulk and liquid dielectric characterization.

Ribas et al. [44] employed a TM_{010} cylindrical cavity to realize a compact liquid concentration sensor operating with milliliter-scale sample volumes ($V_s \approx 4$ mL). The corresponding experimental configuration and the measured $|S_{21}|$ resonance shift response are illustrated in Figure 8. This configuration achieves high field sensitivity to permittivity variations; however, it exhibits a moderate quality factor (10^3 – 10^4), and its performance degrades when applied to lossy liquids due to increased dielectric absorption and reduced resonance stability.

To reduce physical size and improve integration capability, Varshney et al. [45] proposed planar cylindrical cavity configurations, achieving significant footprint reduction and enhanced sensitivity (up to +25%). However, this improvement in compactness is accompanied by additional dielectric and conductor losses introduced by planar substrates, leading to reduced quality factors (10^2 – 10^3) and limiting the achievable measurement precision in dielectric characterization applications.

In contrast, Sheen et al. [46] employed closed cylindrical cavities operating in the $TE_{01\delta}$ mode, achieving very high unloaded quality factors ($Q_0 > 10^4$) and excellent dielectric loss resolution, with measurable loss tangents down to 10^{-5} – 10^{-6} . This high performance results from strong electromagnetic confinement but requires strict mode purity and well-defined sample geometries, reducing measurement flexibility.

In summary, TM_{010} cylindrical cavities offer high sensitivity for liquid measurements, planar cylindrical structures favor compact integration but with lower quality factors, while closed $TE_{01\delta}$ cavities provide superior loss characterization through stronger field confinement. These designs therefore represent different trade-offs between sensitivity, compactness, and measurement accuracy. Table 4 summarizes their key performance metrics.

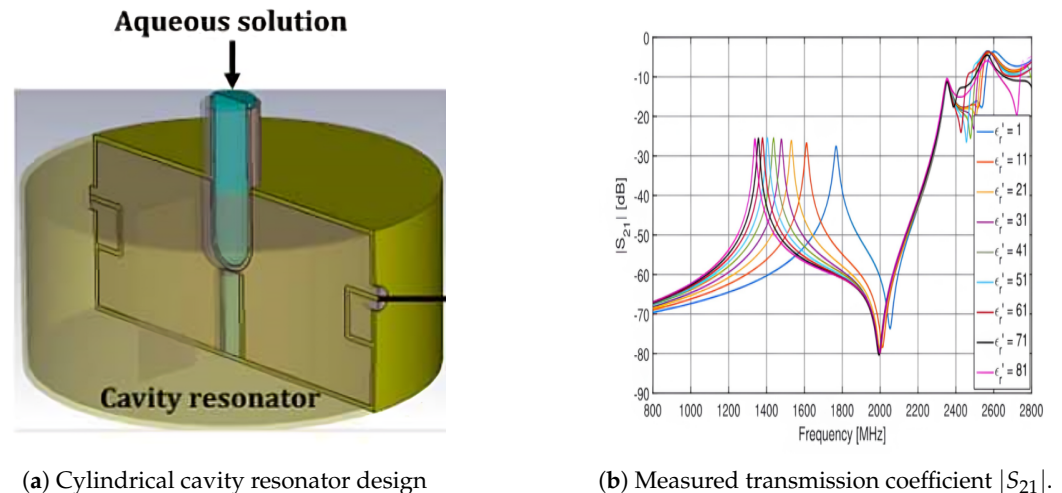


Figure 8. Cylindrical cavity resonator-based dielectric characterization using the TM_{010} mode: (a) cavity configuration with liquid sample insertion via capillary tube for milliliter-scale liquid insertion and dielectric sensing; (b) $|S_{21}|$ response showing resonant frequency shifts induced by changes in the permittivity of aqueous solutions, demonstrating high sensitivity to dielectric loading [44].

Despite their superior accuracy and traceability, cavity resonators exhibit intrinsic physical and practical limitations. The resonance frequency is fundamentally determined by the cavity dimensions—typically on the order of $\lambda/2$ —which leads to significant volumetric scaling at lower microwave frequencies and restricts miniaturization [47,48].

In terms of performance trade-offs, closed high- Q cylindrical cavity implementations such as the $TE_{01\delta}$ configuration reported in [46] mitigate several of these limitations by providing very high unloaded quality factors ($Q_0 > 10^4$) and improved dielectric loss resolution through strong field confinement and controlled conductor losses. However, this performance is achieved at the cost of strict mode purity requirements and reduced geometric flexibility, which limits applicability to a narrow range of sample configurations.

On the other hand, multimode rectangular cavity approaches such as those in [4] offer extended permittivity measurement ranges and very high quality factors, making them particularly effective for extreme high- ϵ_r materials. Nevertheless, these systems remain bulky and sensitive to environmental variations, which reduces their practicality outside controlled laboratory conditions.

More flexible implementations, such as the slot-loaded optimized cavity reported in [42], reduce structural complexity while maintaining good accuracy (error $< 2\%$) over a wide permittivity range. This configuration provides a more balanced compromise between accuracy, sample adaptability, and computational design effort compared to both multimode and high- Q closed cavity systems, although it still relies on full-wave optimization and precise calibration.

In addition, these structures are inherently narrowband due to their discrete resonant modes. Although unloaded Q -factors exceeding 10^4 can be achieved under controlled conditions, their bulky geometry, sensitivity to sample positioning, and limited compatibility with integrated platforms constrain their practical deployment [47].

Furthermore, the measurement accuracy strongly depends on controlled field-sample interaction conditions, including precise positioning and limited perturbation of the elec-

tromagnetic fields. Deviations from these conditions can introduce systematic errors, particularly when characterizing high-loss or electrically large specimens [48].

Table 4. Quantitative comparison of cavity-resonator-based dielectric characterization techniques.

Ref.	Cavity Type/Mode	Resonant Frequency, f (GHz)	Unloaded Quality Factor, Q_0	Relative Permittivity Range, ϵ_r	Sample Volume, V_s	Sensitivity	Min Loss Tangent, $\tan \delta_{\min}$	Measurement Error (%)
[4]	Rect. (multimode)	0.3–3.0	$>10^4$	$150 \rightarrow 10^4$	$>50 \text{ cm}^3$	medium	10^{-4}	1–3
[42]	Slot-loaded Rect. (TE_{107})	8–12	$10^3 \text{--} 10^4$	wide	$10 \text{--} 50 \text{ cm}^3$	high	10^{-4}	<2
[43]	Rect. (top-access)	5.0	$\sim 10^3$	~ 70	1–5 mL	medium	10^{-3}	2–5
[44]	Cyl. (TM_{010})	1.5	$10^3 \text{--} 10^4$	liquids	$\approx 4 \text{ mL}$	high	10^{-4}	–
[45]	Planar Cyl. (TM_{010})	1.5	$10^2 \text{--} 10^3$	2–4	$<2 \text{ mL}$	high	10^{-3}	–
[46]	Cyl. ($\text{TE}_{01\delta}$)	mode-dependent	$>10^4$	wide	$>10 \text{ cm}^3$	very high	$10^{-5} \text{--} 10^{-6}$	<1

3.2. Split-Post Dielectric Resonator (SPDR) Technique

The Split-Post Dielectric Resonator (SPDR) is a high-precision, non-destructive technique widely used for the characterization of planar dielectric materials at microwave frequencies. It consists of two dielectric posts separated by a narrow gap where the sample is inserted, typically operating in the $\text{TE}_{01\delta}$ mode. This configuration generates a predominantly azimuthal electric field strongly confined within the gap, ensuring continuous tangential field components at the sample interface and robust interaction with planar specimens [49,50]. A schematic representation is shown in Figure 9.

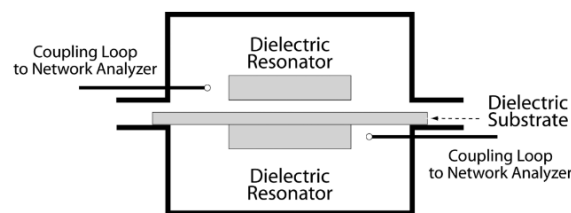


Figure 9. Schematic configuration of the split-post dielectric resonator (SPDR) used for planar dielectric characterization. Reproduced from [50].

The strong field confinement and low radiation losses enable high unloaded quality factors (Q_0), resulting in high sensitivity to thin dielectric layers. Moreover, the absence of normal electric-field discontinuities at the interface makes SPDR measurements inherently tolerant to air gaps perpendicular to the sample plane, improving measurement stability for laminar materials.

The sensing capability of the SPDR is fundamentally governed by the perturbation of the localized $\text{TE}_{01\delta}$ resonant field by the material under test (MUT). Operating typically in the $\text{TE}_{01\delta}$ mode, the resonator concentrates the electric field within the sample region, thereby enhancing the coupling between the resonant mode and the MUT [49,51]. The introduction of a dielectric specimen perturbs the modal electromagnetic field distribution by modifying the local electric energy density, leading to measurable shifts in the resonant frequency and unloaded quality factor [49]. The magnitude of this perturbation is governed by the electric-energy filling factor, which quantifies the fraction of the total stored electromagnetic energy contained within the sample volume [51]. Consequently, the measurement sensitivity is directly related to the overlap between the localized electric field and the MUT. Furthermore, maintaining a well-defined modal field distribution is essential for accurate parameter extraction, as interference from higher-order resonant modes can distort the resonant response and increase measurement uncertainty [50]. These mechanisms of energy localization, modal perturbation, and controlled field confinement collectively underpin the high precision and repeatability of SPDR-based dielectric characterization.

Conventional SPDR implementations, such as those proposed by Krupka et al. [51], operate in the 1–10 GHz range and provide uniform field distributions, enabling accurate extraction of relative permittivity (ϵ_r) and loss tangent ($\tan \delta$) for homogeneous substrates with typical uncertainties of the order of 0.3%. However, these configurations are primarily limited to global material characterization in a single-mode operation.

To overcome this limitation, scanning SPDR techniques introduce spatial displacement of the sample within the resonator, exploiting non-uniform field distributions to achieve localized probing. While this approach improves spatial selectivity and enables qualitative separation of electric and magnetic responses, it increases system complexity and requires precise positioning [52].

Further extensions include high-frequency SPDR designs operating at millimeter-wave frequencies [49], which enhance sensitivity to thin films and high-permittivity materials (ϵ_r up to 10^4). This improved sensitivity, however, comes at the cost of increased dependence on sample thickness and alignment due to reduced interaction volumes.

Temperature-controlled SPDR systems [53] extend the operational range to cryogenic conditions (20–400 K), enabling the characterization of temperature-dependent dielectric properties. In this context, complementary single-post dielectric resonators with superconducting boundaries (SuPDR) provide significantly higher Q_0 (up to 2.4×10^5), allowing enhanced resolution in loss tangent measurements for ultra-low-loss materials.

Beyond experimental configurations, recent work by Gungor et al. [40] highlights the importance of advanced electromagnetic modelling. By combining finite-element (FEM) and finite-difference time-domain (FDTD) methods, they achieve prediction errors below 0.3% compared to measurements. In contrast to classical analytical formulations, this approach enables the inclusion of multiphysics effects, particularly for semiconductor materials, where coupled charge transport models capture conductivity variations and nonlinear effects. Notably, while the fundamental $TE_{01\delta}$ mode remains weakly sensitive to uniform doping, higher-order modes such as $TM_{01\delta}$ exhibit measurable resonance shifts, extending SPDR applicability beyond purely dielectric characterization.

SPDR architectures present a trade-off between measurement accuracy, spatial resolution, and modelling complexity. Standard configurations offer robust and precise bulk characterization, whereas advanced implementations—such as scanning, high-frequency, cryogenic, and multiphysics-enhanced SPDR—extend functionality toward localized, high-frequency, and semiconductor-aware measurements. Among these, high-frequency SPDR designs represent a particularly effective compromise for modern RF and microwave applications, combining strong field confinement with sensitivity to advanced dielectric materials, as clearly illustrated by the comparative trends in Table 5.

Table 5. Quantitative comparison of Split-Post Dielectric Resonator (SPDR) architectures.

Ref.	SPDR Type	Frequency, f (GHz)	Relative Permittivity, ϵ_r	Frequency Shift/Measurement Accuracy, Δf	Unloaded Quality Factor, Q_0	Loss Tangent, $\tan \delta$	Field Interaction Type
[40]	SPDR (FEM/FDTD, $TE_{01\delta}/TM_{01\delta}$)	4.8–5.3	dielectric/semiconductor	$\approx 0.3\%$	$\sim 10^4$	—	EM–multiphysics
[51]	Standard SPDR ($TE_{01\delta}$)	1–10	~ 2 –10	$\approx 0.3\%$	$(1\text{--}3) \times 10^4$	2×10^{-5}	Uniform azimuthal E-field
[52]	Scanning SPDR	2.67, 4.90	—	$\Delta f \leq 60$ MHz	$\sim 10^3$ – 10^4	—	Spatial E/H variation
[49]	High-f SPDR (thin films)	~ 19	10^2 – 10^4	—	$\sim 7.3 \times 10^3$	1×10^{-4}	Strong confined E-field
[53]	Cryogenic SPDR (+ SuPDR reference)	9.95/10.8	~ 4 –24	$\approx 0.5\%$ /—	2.5×10^4 / 2.4×10^5	2×10^{-5} / 2×10^{-6}	Uniform E-field/high-Q validation

3.3. Planar and SIW Microwave Resonators

Planar microwave resonators have emerged as compact and cost-effective alternatives to volumetric cavities and Split-Post Dielectric Resonator (SPDR) systems, offering advantages in integration, scalability, and compatibility with modern RF circuits. However,

this improved integration comes at the cost of reduced electromagnetic confinement and increased sensitivity to radiation and substrate losses compared to fully enclosed cavity structures [54].

Within planar implementations, microstrip-based resonators such as microstrip ring resonators (MRRs) are among the earliest and most widely adopted configurations. Fang et al. [55] demonstrated that these structures enable dielectric interaction through distributed fields along the resonant path, benefiting from simple geometry and straightforward fabrication. In contrast to cavity-like structures, their open-field nature allows a significant portion of the electromagnetic energy to radiate into the surrounding environment, which results in lower field confinement and consequently limited quality factor.

To partially mitigate these limitations, several extensions have been proposed. Rashidian et al. [56] expanded the operating frequency range and material coverage, while Sarabandi et al. [57] demonstrated broader permittivity sensing capability. However, both approaches still suffer from moderate quality factors due to intrinsic radiation losses. Similarly, suspended resonator configurations such as Verma et al. [58] enhance field interaction by increasing fringing fields, but this improvement is accompanied by higher sensitivity to external perturbations and reduced structural stability.

In contrast to microstrip resonators, Substrate-Integrated Waveguide (SIW) structures provide a fundamentally different confinement mechanism by emulating rectangular waveguide behavior within a planar substrate. Jha et al. [59] showed that SIW cavities significantly improve electromagnetic confinement and reduce radiation losses compared to microstrip-based resonators. However, this improvement is still limited by moderate quality factors when low-loss materials are introduced, mainly due to dielectric and coupling losses inherent to the substrate-integrated implementation.

From an electromagnetic perspective, the superior sensing performance of SIW resonators originates from their ability to confine the resonant mode within a quasi-closed cavity formed by the metallic via walls and the top and bottom conductor planes. Unlike microstrip resonators, where a significant fraction of the electric field exists as fringing fields exposed to the surrounding environment, SIW cavities support well-defined waveguide modes with reduced radiation leakage and stronger energy storage inside the resonator volume [59]. The sensing mechanism is governed by cavity perturbation theory: when a dielectric sample is introduced into a region of high electric-field intensity, the local electric energy distribution is modified, resulting in a measurable shift of the resonance frequency and a variation of the unloaded quality factor. Consequently, the sensitivity of the resonator is strongly dependent on the degree of field localization at the sample position and on the overlap between the sample volume and the stored electromagnetic energy. In SIW cavities operating in the dominant TE_{101} mode, the electric field exhibits spatial maxima at specific locations, enabling efficient modal perturbation when the material under test is placed within these high-energy regions. This enhanced confinement not only increases the interaction between the resonant field and the sample but also improves measurement stability by minimizing radiation-related losses and external environmental perturbations [59,60].

Further developments, such as the tunable SIW resonator proposed by Chen et al. [61], introduce reconfigurability and extended functionality. In comparison with fixed SIW structures, these designs provide flexibility in frequency tuning; however, this is achieved at the expense of increased circuit complexity and potential degradation of resonator stability due to active or tunable components.

A more recent advancement is the enhanced SIW cavity resonator reported by Varshney et al. [60]. Beyond the geometric modification itself, the proposed architecture improves the electromagnetic sensing process by achieving substantially looser external coupling through a transition offset between the SIW cavity and the feeding network. This

coupling optimization suppresses excessive energy leakage from the resonator, allowing a larger fraction of the stored electromagnetic energy to remain localized within the cavity where the dielectric perturbation occurs. As a result, stronger modal perturbation sensitivity and a significantly higher unloaded quality factor are obtained without the need for active compensation circuitry. Consequently, the resonator achieves an unloaded quality factor of approximately 515 while maintaining a fully planar structure.

Complementing these efforts toward improving SIW-based dielectric sensors, Mohammadi et al. [62] proposed a compact half-mode substrate integrated waveguide (HMSIW) sensor loaded with an interdigital capacitor (IDC) for permittivity characterization. Unlike approaches primarily focused on quality-factor enhancement, this design simultaneously addresses sensor miniaturization and sensitivity improvement. The HMSIW topology reduces the footprint by nearly 50% compared with conventional SIW structures, while the embedded IDC strongly concentrates the electric field within the sensing region, increasing the interaction between the resonant mode and the material under test. The sensing mechanism relies on monitoring shifts in a transmission zero generated by the IDC-loaded resonator, enabling accurate dielectric characterization over a wide permittivity range. Experimental results demonstrated a normalized sensitivity of approximately 3.16%, corresponding to a frequency shift of about 113 MHz per unit change in relative permittivity around 3.5 GHz. Furthermore, the proposed sensor achieved a miniaturization factor of 71.6% while preserving a simple planar architecture suitable for low-cost fabrication. The fabricated prototype and its measured scattering-parameter responses are shown in Figure 10.

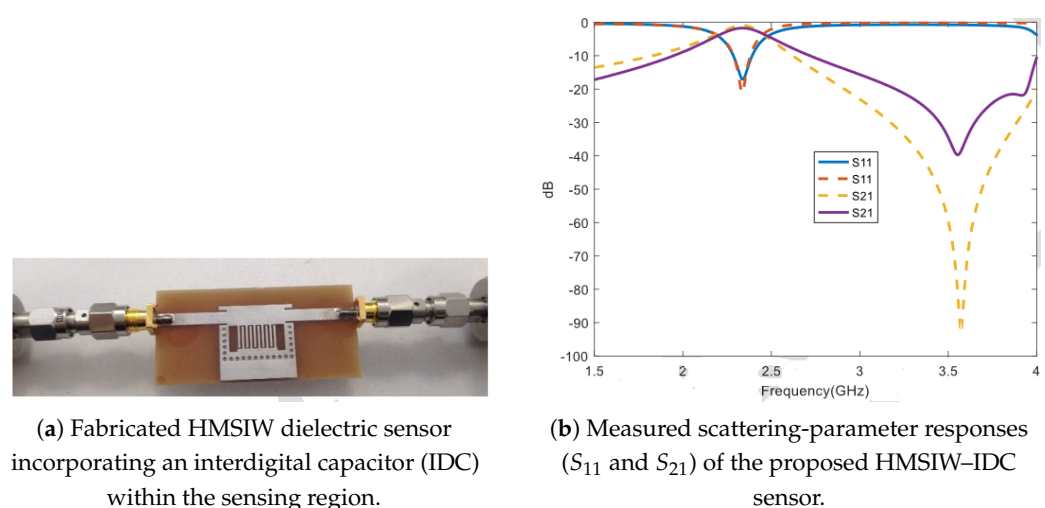


Figure 10. IDC-loaded HMSIW dielectric sensor reported in [62]: (a) fabricated HMSIW sensor incorporating an interdigital capacitor within the sensing region; (b) measured scattering-parameter responses illustrating the transmission-zero-based sensing mechanism and resonant behavior of the proposed structure.

From a comparative standpoint, microstrip resonators prioritize simplicity and fabrication flexibility but are fundamentally limited by radiation losses and moderate quality factors. SIW resonators, on the other hand, offer improved confinement and higher Q -factor, but often involve trade-offs in complexity or performance consistency depending on the implementation. A quantitative comparison of these resonator technologies in terms of frequency, unloaded quality factor, sensitivity, dielectric constant range, and loss tangent is provided in Table 6.

Based on the criteria of electromagnetic confinement, unloaded quality factor, planar compatibility, and suitability for low-loss dielectric characterization, the enhanced SIW cavity resonator proposed by Varshney et al. [60] represents the most balanced and high-performance solution among the reported planar and SIW resonators.

Table 6. Comparative performance analysis of planar microstrip and SIW-based resonators for dielectric characterization.

Ref.	Resonator Type	Freq. (GHz)	Q_0	Sensitivity (MHz/ $\Delta\epsilon_r$)	ϵ_r Range	$\tan \delta$
[55]	Microstrip ring resonator	2–8	–	–	10.97	$\sim 3 \times 10^{-3}$
[56]	Modified ring resonator	2–40	–	~ 50 –200	2.17–6.15	9×10^{-4} – 4×10^{-2}
[57]	Ring resonator	1.25	–	~ 200	3–25	0.01–0.07
[58]	Suspended patch resonator	2.6	–	~ 300	1.97–2.37	0.003–0.009
[59]	SIW cavity resonator	2.45	44–58	~ 6	1–101	~ 0.01 –0.9
[61]	Tunable SIW (PLL)	3.85	–	~ 65	5.3–15	–
[60]	Enhanced SIW cavity	3.0	431–515	~ 20	2.1–10.2	$\geq 3.2 \times 10^{-4}$

3.4. Metamaterial-Based Resonators

It is important to note that, although Substrate-Integrated Waveguide (SIW) technology was discussed in the previous subsection as a planar waveguide-based resonator, it is also frequently combined with metamaterial elements (e.g., SRR/CSRR) to enhance field confinement and sensitivity. In such cases, the sensing behavior is primarily governed by the metamaterial-induced resonance rather than the SIW cavity itself. Therefore, in this subsection, the classification is based on the dominant sensing mechanism rather than the physical implementation platform.

Metamaterial-inspired resonators constitute a class of electrically small, high-field-confinement sensing structures for microwave dielectric characterization, where the sensing mechanism is governed by subwavelength LC resonances that are strongly perturbed by variations in the effective permittivity of the material under test (MUT) [63]. As widely discussed in the literature, SRR-, CSRR-, and hybrid metamaterial configurations achieve enhanced sensitivity through localized electric-field concentration in subwavelength gaps, making them particularly suitable for compact sensing applications [64,65].

From a fundamental perspective, Falcone et al. [63] first introduced the CSRR concept based on Babinet's principle, establishing the duality between slot and metallic resonant particles. However, this work remains primarily conceptual and simulation-oriented, without direct experimental extraction of dielectric properties or quantitative sensitivity metrics, and thus serves mainly as a theoretical foundation rather than a practical sensing platform.

Subsequent studies, such as Gavrilua et al. [66], extended metamaterial resonator analysis by investigating the influence of substrate permittivity, thickness, and losses on resonance behavior. Their results confirm strong resonance dependence on dielectric loading, with frequency shifts reaching several hundred MHz (e.g., $\Delta f \approx 550$ MHz), but the approach remains largely parametric and simulation-driven, without real-time sensing validation or complex permittivity extraction.

In contrast, experimental SRR-based sensing implementations [67,68] demonstrate practical dielectric characterization in the GHz range, with measurable frequency shifts of approximately 50–128 MHz. These works confirm the feasibility of metamaterial-based sensing in real environments; however, their performance is strongly influenced by fabrication tolerances and coupling variations, and the extracted sensitivity remains limited when compared across different permittivity ranges and loss conditions. In particular, CSRR-based implementations provide higher field confinement than SRR structures, but still suffer from narrowband operation and reduced robustness in lossy media due to degradation of the effective quality factor.

A different category of metamaterial-based sensors relies on differential operation to improve stability and suppress environmental perturbations. Vélez et al. [11,69] demonstrated that frequency splitting in SRR-loaded differential configurations enables real-time comparison between reference and sensing channels, providing enhanced immunity to common-mode effects such as temperature and substrate variations. As shown in Table 7,

these architectures achieve frequency splitting on the order of $\Delta f_z \approx 152$ MHz for liquid mixtures, while also enabling quantitative extraction of ionic concentration through normalized sensitivity parameters. Nevertheless, their performance is intrinsically tied to calibration accuracy and is mainly optimized for liquid environments, limiting general applicability to broader dielectric characterization scenarios.

Advanced CSRR-based differential designs [70] have significantly expanded the permittivity detection range (approximately $\epsilon_r = 1$ –111), while improving immunity to environmental disturbances through differential operation. However, these benefits come at the cost of increased implementation complexity and strict symmetry requirements, which may limit robustness in practical fabrication environments. From an electromagnetic standpoint, the sensing performance of CSRR-based resonators is governed by the strong confinement of electric fields within the complementary slot regions. Based on Babinet's principle, the CSRR acts as the dual counterpart of the conventional SRR, exhibiting an electrically dominant resonance in which the etched rings provide distributed capacitive loading while the surrounding current paths contribute the inductive response [63]. At resonance, intense fringing electric fields are concentrated around the slot edges, resulting in highly localized electric energy density. When a material under test (MUT) is introduced into these high-field regions, its dielectric properties perturb the local electromagnetic boundary conditions and alter the effective capacitance of the resonator. According to cavity perturbation theory, the resulting resonance-frequency shift depends on the overlap between the localized electric field distribution and the dielectric perturbation introduced by the sample [70]. Consequently, maximum sensitivity is achieved when the MUT occupies regions where the stored electric energy is most strongly concentrated. Furthermore, the subwavelength nature of CSRRs promotes enhanced field confinement and stronger field–matter interaction, producing larger resonance shifts for a given permittivity variation and thereby improving dielectric sensing performance [11]. Therefore, the sensing mechanism in CSRR-based sensors is fundamentally controlled by electric-field localization, resonant-mode perturbation, and the redistribution of stored electromagnetic energy caused by dielectric loading.

Multi-resonant and hybrid architectures, such as the dual-band system proposed by Liu et al. [71], further extend metamaterial sensing capability by enabling simultaneous operation at multiple frequencies (4.15 and 9.18 GHz). Although this improves functionality and redundancy, it introduces sensitivity trade-offs between resonant modes and increases dependency on precise microfluidic alignment, which may affect repeatability.

More recently, advanced metamaterial-inspired resonators have focused on simultaneously enhancing field localization, sensitivity, and practical deployability. Rahman et al. [72] introduced a high- Q H-shaped nested split-ring resonator (H-NSRR) for complex-permittivity characterization of small-volume liquids. By co-locating the electric and magnetic fields within a common sensing gap, the nested geometry intensifies field–matter interaction while preserving a high unloaded quality factor ($Q_u \approx 346$), achieving a normalized sensitivity of approximately 1.19% per unit change in permittivity. The sensor further eliminates microfluidic channels, vias, and multilayer fabrication through an open-tray loading approach, improving manufacturability and reducing dielectric losses. Similarly, Su and Liu [73] demonstrated that incorporating interdigital electrodes (IDEs) into an open complementary split-ring resonator (OCSRR) substantially increases the effective capacitance and electric-field concentration within the sensing region. Implemented on a coplanar-waveguide platform, the resulting OCSRR–IDE sensor achieved a normalized sensitivity of 5.51% for solid dielectric characterization with measurement errors below 1.35%, highlighting the effectiveness of capacitively enhanced field confinement for improving resonance perturbation sensitivity. Beyond dielectric characterization alone, Kooshki et al. [74]

proposed a concentric triple-ring metamaterial SRR (M-SRR) sensor for transformer-oil condition monitoring, where strong mutual coupling between adjacent resonant rings amplifies the dielectric-induced frequency shift and expands the operational dynamic range. In a related direction, Wang et al. [75] introduced a compact near-equidistant multimode resonator based on a skyrmionic metamaterial integrated within a substrate-integrated waveguide (SIW) cavity. The structure exploits coupled SM-SIW cavity resonators to generate multiple pairs of split resonant modes arising from electromagnetic mode hybridization, where the resulting in-phase and anti-phase modes exhibit strong sensitivity to dielectric perturbations through variations in both resonance frequency and mode-splitting degree. This enables simultaneous extraction of permittivity and thickness information across multiple resonant states, while benefiting from enhanced electromagnetic confinement and higher quality-factor operation compared to purely planar metamaterial resonators.

Finally, radiating SRR-loaded antennas such as those reported by Prakash et al. [76] offer a low-cost and highly integrable solution, but their sensing performance is significantly affected by radiation losses and environmental coupling, resulting in reduced measurement stability compared to transmission-line-based metamaterial sensors.

In the context of microwave dielectric characterization targeted in this work, the most balanced performance is achieved by differential CSRR-based architectures, particularly the design reported by Das et al. [70]. This configuration offers the widest permittivity range, enhanced differential stability, and improved immunity to external perturbations compared to SRR-based and single-ended CSRR sensors. However, when considering a broader perspective including real-time operation and differential fluidic compatibility, the SRR-loaded splitter/combiner approach of Vélez et al. [11] remains the most practically effective solution for liquid characterization, due to its inherent common-mode rejection and real-time measurement capability.

Nevertheless, despite these advances, metamaterial-based resonators remain intrinsically limited by moderate Q -factors and strong dependence on calibration, and therefore still underperform high- Q cavity and SPDR-based techniques in terms of absolute permittivity accuracy. The quantitative comparison of representative architectures is summarized in Table 7.

Table 7. Comparison of metamaterial-based microwave resonator sensors for dielectric characterization.

Ref.	Resonator Type	Frequency (GHz)	Δf (MHz)/Sensitivity/ ϵ_r Range	MUT
[63]	CSRR/SRR metasurface	4.41	–	Dielectric substrates
[66]	Modified SRR	1.1–2.07	$\Delta f = 550$	RO3003, Alumina
[11]	Differential SRR splitter/combiner	1.04	$\Delta f_z = 152$	DI water/ethanol
[69]	Differential SRR transmission lines	~1	Sensitivity: 0.033 (NaCl), 0.032 (KCl), 0.021 (CaCl ₂)	Ionic solutions, urine
[71]	Dual-band SIW + IDC–SRR	4.15/9.18	$\Delta f = 14/11$	Liquid mixtures
[76]	SRR-loaded monopole antenna	2.4	Sensitivity: 2.83 dB/5%	Ethanol–water
[68]	CSRR microstrip two-port	2.65	$\Delta f = 128$	Liquids
[67]	Single CSRR	5.39	$\Delta f = 50$	Liquids
[70]	Differential CSRR	2.35	$\epsilon_r = 1$ –111	Liquids
[75]	SIW cavity-based skyrmionic multimode resonator	0.9–2.8	123.5 MHz/ $(\Delta\epsilon_r = 1)$, 517.8 MHz/mm	Solid dielectrics (thickness + permittivity characterization)
[73]	CPW OCSRR + IDE	2.44	Sensitivity: 5.51%; $\epsilon_r = 1$ –7	Solid dielectrics
[74]	Multi-ring SRR (M-SRR)	0.9–1.4	High normalized sensitivity for transformer-oil degradation monitoring	Transformer oils
[72]	H-shaped Nested SRR (H-NSRR)	5.9	$Q_u = 346$, $S_u = 1.19\%$, $\Delta f \approx 1.79$ GHz (water span)	Small-volume liquids (0.5 mL PET tray)

3.5. Unified Performance Comparison and Design Trade-Offs

While the previous sections reviewed individual resonator families and their associated dielectric characterization approaches, direct comparison across different architectures remains challenging due to variations in operating frequency, sample type, calibration

methodology, and reported performance metrics. To provide a more unified perspective, Table 8 summarizes the principal characteristics of the major resonator categories discussed in this review.

Although the values reported in the literature originate from different experimental conditions and therefore should not be interpreted as absolute benchmarks, they provide a useful framework for evaluating the relative strengths and limitations of each resonator family. The comparison highlights four key performance indicators that strongly influence dielectric characterization performance: unloaded quality factor (Q_0), sensitivity, dynamic range, and measurement robustness.

In general, cavity resonators exhibit the highest unloaded quality factors ($Q_0 > 10^4$) and the lowest measurement uncertainty, making them the preferred choice for precision dielectric metrology [4,46]. However, their bulky structure and limited integration capability restrict their deployment in compact telecommunication platforms [4,46]. Split-post dielectric resonators (SPDRs) provide a favorable compromise between measurement accuracy and practical implementation, offering very high quality factors together with excellent repeatability and low uncertainty for planar dielectric samples [40,51].

Planar microstrip and substrate-integrated waveguide (SIW) resonators prioritize compactness, low fabrication cost, and compatibility with modern RF systems [37,54]. Although their quality factors are generally lower than those of cavity-based approaches, SIW implementations partially recover performance through improved electromagnetic confinement [59,60].

Metamaterial-inspired resonators, including SRR and CSRR configurations, achieve the highest localized field enhancement and therefore exhibit excellent sensitivity to dielectric perturbations [38,64]. Nevertheless, these structures remain more susceptible to fabrication tolerances, environmental variations, and calibration uncertainties [77,78].

Consequently, resonator selection depends strongly on the target application. High-accuracy dielectric metrology favors cavity and SPDR architectures, whereas integrated sensing platforms and telecommunication-oriented systems often benefit from SIW and metamaterial-based solutions despite their lower measurement robustness.

Table 8. Comparative performance of different resonator families for dielectric characterization.

Resonator Family	Typical Q_0	Sensitivity	Dynamic Range	Accuracy	Integration Capability	Environmental Robustness
Cavity Resonators	$>10^4$	Medium–High	Very Wide	Excellent	Low	Medium
SPDR	10^4 – 10^5	High	Moderate	Excellent	Low–Medium	High
Microstrip Resonators	10^2 – 10^3	Medium	Moderate	Moderate	Very High	Low
SIW Resonators	40–515	Medium	Wide	Good	High	Medium
SRR/CSRR Resonators	10^2 – 10^3	Very High	Limited	Moderate	High	Low
Differential CSRR/SRR	10^2 – 10^3	High–Very High	Wide	Good	High	Medium–High

4. Dielectric Measurement and Extraction Techniques

While the previous section focused on resonator architectures and their performance, dielectric characterization fundamentally depends on how these structures are used to extract material properties. This section therefore adopts a measurement-oriented perspective, introducing the theoretical foundations and extraction frameworks used to determine complex permittivity from resonant responses, without reclassifying resonators according to their geometry.

4.1. Resonant Methods

4.1.1. Fundamental Principles of Dielectric Extraction

Building upon the resonator architectures discussed in the previous section, dielectric characterization using resonant techniques is fundamentally governed by the perturbation of the electromagnetic energy stored within the resonator due to the introduction of the material under test (MUT). This perturbation modifies the field distribution, leading to measurable variations in the resonant frequency and quality factor. These two observables are directly related to the real and imaginary parts of the complex permittivity, ϵ' and ϵ'' , respectively, although the accuracy with which they can be extracted depends on the specific resonator implementation.

From a theoretical standpoint, most resonant extraction techniques are based on electromagnetic perturbation theory under the small-perturbation approximation, where the presence of the MUT does not significantly disturb the original field distribution. Within this framework, the fractional frequency shift and the variation of the inverse quality factor can be expressed as [77,79]:

$$\frac{\Delta f}{f_0} = -\frac{1}{2} \frac{\int_{V_s} (\epsilon' - \epsilon_0) |E|^2 dV}{\int_{V_c} (\epsilon |E|^2 + \mu |H|^2) dV} \quad (12)$$

$$\Delta\left(\frac{1}{Q}\right) = \frac{\int_{V_s} \epsilon'' |E|^2 dV}{\int_{V_c} (\epsilon |E|^2 + \mu |H|^2) dV} \quad (13)$$

where V_s denotes the sample volume and V_c the total resonator volume. These expressions establish a direct relationship between measurable quantities (frequency shift and quality factor variation) and the electromagnetic energy stored in the system, providing a unified theoretical basis for resonant dielectric characterization.

Despite this common foundation, the practical extraction of ϵ' and ϵ'' is strongly influenced by the electromagnetic properties of the resonator, including field confinement, mode purity, and loss mechanisms. High- Q closed resonators, such as metallic cavities and dielectric resonators, concentrate electromagnetic energy within well-defined volumes, thereby enhancing perturbation sensitivity and enabling high-resolution characterization of both permittivity components. In contrast, planar and open resonant structures exhibit weaker confinement and increased radiation and substrate losses, which makes the extraction process more dependent on calibration procedures and electromagnetic modeling assumptions.

Consequently, while the perturbation framework remains universally applicable, its effectiveness is inherently linked to the underlying resonator characteristics. This unified perspective provides the foundation for the different extraction strategies discussed in the following subsections, including frequency-shift-based, quality-factor-based, and differential approaches.

4.1.2. Resonant Frequency Shift

Building on the resonant perturbation principles introduced previously, frequency-shift-based extraction methods determine the real part of the permittivity ϵ' from variations in the resonant frequency induced by dielectric loading. Compared to Q -factor-based approaches, this technique is inherently more robust and less sensitive to measurement noise, coupling variations, and parasitic losses. However, it does not provide direct access to dielectric losses. Owing to its simplicity, stability, and ease of implementation,

frequency-shift analysis remains one of the most widely adopted strategies for dielectric characterization [2].

From a methodological perspective, frequency-shift techniques can be broadly differentiated according to their sensitivity enhancement mechanisms and their reliance on calibration models, both of which directly influence accuracy, robustness, and generalization capability.

Haq et al. [80] proposed a calibration-driven implementation based on a complementary crossed-arrow resonator operating at 15 GHz, as illustrated in Figure 11. The strong electric-field interaction enabled consistent and monotonic frequency shifts over a relative permittivity range of 2.5–10.2. The extraction of ϵ' was achieved through an inverse regression model incorporating the sample thickness. As shown in Figure 11b, distinct shifts in the resonant response are observed for different dielectric loadings. While this approach provides reliable accuracy and stable operation, it requires prior knowledge of the MUT thickness and depends on calibration data, which limits its applicability outside the calibrated parameter space.

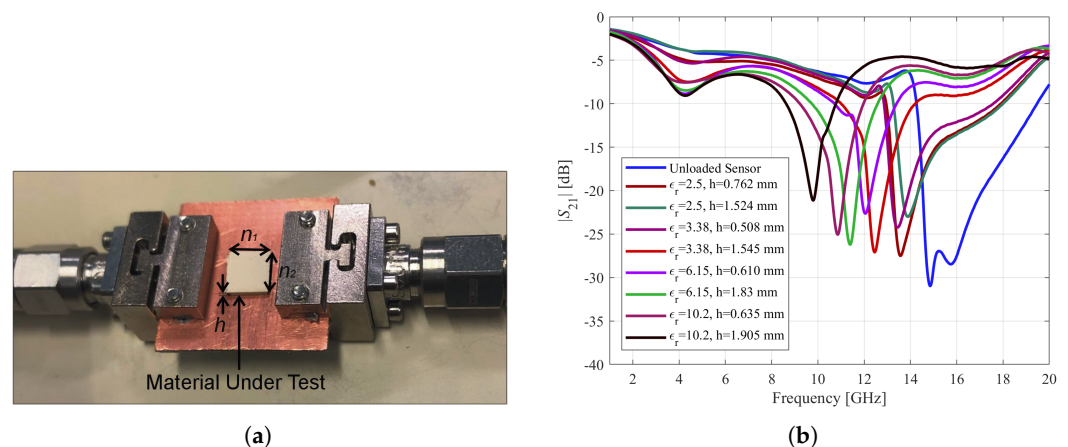


Figure 11. Resonant frequency shift-based dielectric characterization using a complementary crossed-arrow resonator operating at 15 GHz: (a) sensor structure; complementary crossed-arrow resonator sensor geometry. (b) frequency-shift response under different dielectric loadings [80]. Measured $|S_{21}|$ responses showing resonant frequency shifts for different dielectric loadings.

In contrast, Nogueira et al. [68] proposed a compact planar CSRR-based microwave sensor for the characterization of dielectric materials in the 2–3 GHz frequency range. The sensor, shown in Figure 12, employs a complementary split-ring resonator integrated into a two-port microstrip structure to enhance the interaction between the electromagnetic field and the material under test (MUT). Experimental validation demonstrated good agreement between simulated and measured transmission responses for representative dielectric samples such as FR-4 and glass, confirming the reliability of the proposed approach. The extracted dielectric properties were associated with low relative errors (below 3%), while the sensor achieved a normalized sensitivity of 4.82%. Nevertheless, the parameter extraction procedure relies on polynomial curve fitting and multiple calibration equations, which may limit its generalization capability when characterizing materials outside the calibrated permittivity range.

A complementary perspective was provided by Chowdhury et al. [81], where interconnected metamaterial unit cells were used to investigate sensitivity trends rather than absolute permittivity extraction. Compared to the previous approaches, this work highlights the strong dependence of sensitivity on electric-field intensity and quality factor. However, the presence of multiple resonant modes introduces peak-tracking ambiguity and reduces extraction accuracy, particularly when compared to optimized single-resonance configurations.

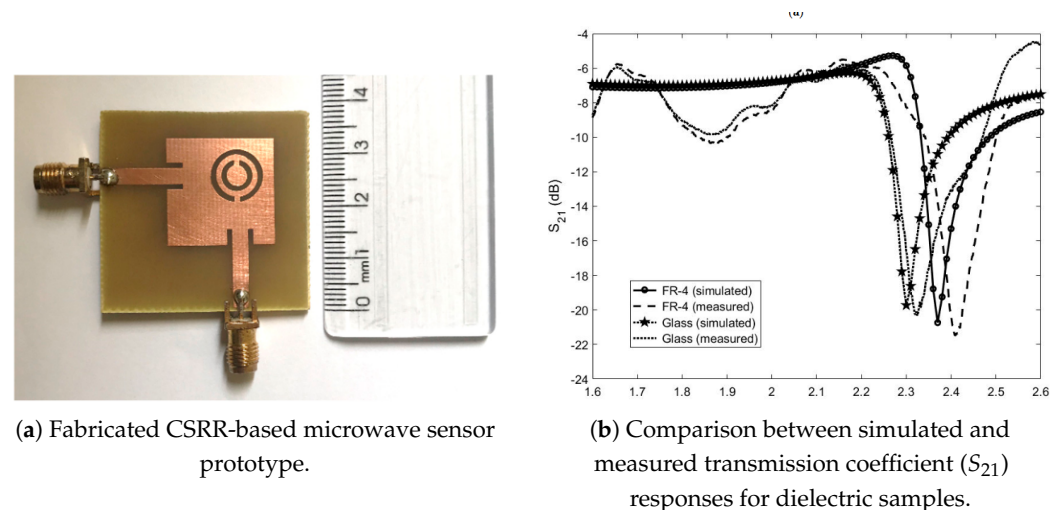


Figure 12. Experimental validation of the compact CSRR-based microwave sensor proposed by [68]: (a) fabricated sensor prototype; (b) simulated and measured S_{21} responses for dielectric material characterization.

Finally, Wang et al. [82] explored an alternative use of frequency-shift information at lower frequencies (0.4–0.5 MHz), where frequency variations are treated as features for machine-learning-based material classification. While this approach demonstrates robustness in material identification under harsh conditions, it does not aim at quantitative permittivity extraction and is therefore not directly comparable to microwave resonant characterization techniques.

Frequency-shift-based techniques exhibit a clear trade-off between sensitivity, robustness, and model dependency. High-field-confinement structures such as the TRB-CSRR proposed by Singh et al. [83] maximize sensitivity and enable wide permittivity coverage, making them particularly suitable for sensing applications where relative variations are of primary interest. In contrast, calibration-driven approaches such as that of Haq et al. [84] provide improved stability and physical interpretability, making them more appropriate for controlled dielectric characterization where repeatability and model transparency are critical.

Despite their advantages, all frequency-shift techniques remain fundamentally limited by their dependence on calibration models and their inability to directly capture dielectric losses. Consequently, they are often complemented by Q-factor-based or hybrid extraction methods when full complex permittivity characterization is required.

4.1.3. Q-Factor-Based Loss Tangent Extraction

In contrast to frequency-shift-based techniques, which primarily retrieve ϵ' , Q-factor-based methods focus on dielectric losses through the loss tangent $\tan \delta$. Across the literature, these approaches are consistently more challenging, since the measured quality factor is simultaneously affected by dielectric dissipation, conductor losses, radiation leakage, and external coupling. As reported in multiple studies [85], accurate extraction therefore depends on how effectively each work models or compensates these intertwined contributions.

From a methodological viewpoint, existing approaches differ significantly in terms of field confinement, loss-separation complexity, and the balance between measurement accuracy and experimental feasibility.

Among classical implementations, cylindrical cavity resonators are widely used as a reference due to their strong field confinement and well-established analytical frameworks.

For instance, Peñaloza et al. [86] achieved reliable extraction for liquid samples using a TE_{111} cavity, relying on stable resonant modes and standard perturbation theory. In comparison with more recent formulations, this approach remains simpler but is limited in both bandwidth and applicability to moderate-loss materials. Extending this framework, Zou et al. [26] demonstrated that incorporating coupling effects and geometric corrections significantly improves accuracy for low-loss dielectrics. However, when compared to classical cavity models, this improvement comes at the cost of substantially higher analytical and computational complexity.

When moving toward higher sensitivity regimes, ultra-high-Q cavity configurations provide improved resolution of loss tangent values. Ni et al. [87] showed that evanescent-wave coupled cavities outperform conventional perturbation-based setups in terms of sensitivity. However, when compared across studies, this gain is consistently accompanied by stronger constraints on coupling stability and sample positioning, making the approach less robust experimentally. Similarly, Shan et al. [88] proposed overmoded cylindrical cavities to extend operational bandwidth. While this broadens measurement capability compared to single-mode cavities, it introduces increased modal interference and inversion instability, which is not present in classical high-Q configurations.

A different comparison emerges in compact and planar cavity designs. Varshney et al. [45] demonstrated that planar cylindrical cavities can simultaneously retrieve permittivity and loss tangent in a more integrated platform. Compared to volumetric cavities, this improves experimental simplicity and integration; however, across reported results, accuracy becomes more dependent on calibration and numerical fitting. Similarly, rectangular TE_{0mn} cavities such as those studied by Jin et al. [89] are better suited for thin-film characterization, but when compared to cylindrical high-Q cavities, they consistently exhibit reduced sensitivity due to lower intrinsic Q-factors.

Further comparisons arise in substrate-integrated and dielectric resonator-based approaches. Saeed et al. [90] showed that SIW cavities enable broadband characterization in a compact form factor; however, when benchmarked against conventional cavities, loss tangent extraction becomes more sensitive to fabrication tolerances and calibration errors. Likewise, dielectric resonator antennas such as that reported by Pan et al. [91] prioritize radiation performance, and across studies they consistently show reduced suitability for precise loss extraction due to lower resonant purity.

In contrast to closed resonators, Fabry–Perot open resonators (FPORs) provide a more balanced compromise between sensitivity and experimental practicality. Salski et al. [92,93] developed a unified framework linking both frequency shift and Q-factor variations to complex permittivity. Compared to closed cavity approaches, FPOR systems reduce modal coupling issues and improve stability in plano–concave configurations. Importantly, across their analysis, optimal accuracy is achieved not at maximum Q-factor, but when the loaded Q is approximately 40–50% of the unloaded value, highlighting the importance of controlled coupling conditions. Nevertheless, when compared to cavity-based techniques, FPOR performance remains sensitive to sample alignment, thickness variations, and filling factor estimation.

Finally, in multi-resonant planar systems, Juan et al. [94] proposed a coupled resonator architecture enabling simultaneous extraction of permittivity, loss tangent, and thickness, as illustrated in Figure 13. Compared to both FPOR and classical cavity approaches, this method improves compactness and enables multi-parameter retrieval within a single platform. As demonstrated in Figure 13b, multiple resonance peaks are exploited to extract f_r , BW, and Q_u . However, relative to cavity-based techniques, accuracy remains more dependent on calibration and is strongly affected by air gaps and imperfect contact conditions.

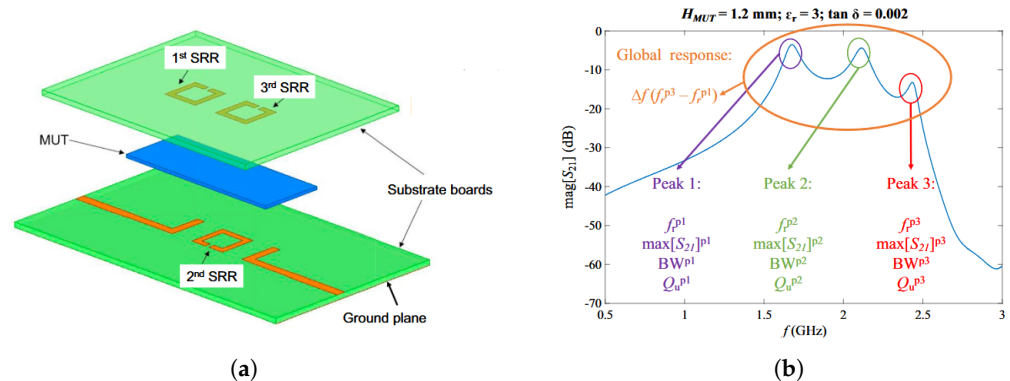


Figure 13. Multi-resonant planar sensor proposed in [94] for dielectric characterization. (a) Multi-layer coupled SRR-based resonator structure with the material under test (MUT) placed between the substrate boards. (b) Transmission response $|S_{21}|$ showing multiple resonance peaks used to extract the resonant frequency f_r , bandwidth BW, and unloaded quality factor Q_u .

Q-factor-based techniques constitute the primary resonant strategy for direct loss tangent estimation. However, across the literature, a consistent pattern emerges: high-Q cylindrical and evanescent-wave coupled cavities maximize sensitivity but require strict experimental control; FPOR systems provide a more robust compromise between accuracy and practicality; while planar, SIW, and compact resonators favor integration at the expense of reduced precision due to lower Q-factors and stronger calibration dependence.

4.1.4. Differential/Reference-Based Extraction

In contrast to absolute resonant techniques, differential or reference-based methods rely on comparing two electromagnetically matched resonators, one loaded with the material under test (MUT) and the other used as a reference. By exploiting relative observables such as frequency splitting or differential shifts, these approaches inherently suppress common-mode errors, environmental drift, and instrumentation offsets, leading to improved robustness compared to single-resonator configurations [95].

Among planar implementations, Buragohain et al. [96] proposed a differential interdigitated-capacitor split-ring resonator with enhanced electric-field confinement, achieving high normalized sensitivity. Relative to conventional single-resonator sensors, this configuration reduces systematic errors and supports wide-range liquid characterization. Its main limitation, however, lies in substrate losses (FR4), with validation primarily focused on organic liquids.

A more physically grounded differential mechanism is introduced by Almuhlaifi et al. [97], who exploit avoided mode crossing in coupled resonators. Unlike conventional differential frequency-shift methods, this approach relates permittivity variations directly to coupling-induced resonance splitting through coupled-mode theory, improving resilience to fabrication tolerances and resonance drift. Nevertheless, sensitivity is strongly dependent on inter-resonator spacing and decreases for high-permittivity materials.

Li et al. [98] extended differential sensing toward multi-parameter extraction using cascaded LC resonators combined with data-driven mapping. Compared with purely analytical differential schemes, this strategy enables simultaneous retrieval of ϵ' and ϵ'' , which is particularly advantageous for liquid characterization. However, the use of neural-network inversion reduces physical interpretability and introduces calibration dependence under varying measurement conditions.

From a stability standpoint, Nikkhah et al. [99] proposed a differential frequency comparison method optimized for long-term monitoring. Compared with conventional

differential architectures, it exhibits superior immunity to thermal drift and environmental variations, making it well suited for continuous sensing applications. This robustness originates from the differential formulation, where common-mode perturbations are inherently cancelled. Specifically, the differential parameter is defined as the variation between the frequency spacing in loaded and unloaded conditions, expressed as

$$FDR_p = \frac{D_P}{\Delta\epsilon}, \quad D_P = |(f_{MD} - f_{MU}) - (f_{BD} - f_{BU})|. \quad (14)$$

This formulation ensures that any external disturbance affecting both resonances equally is eliminated, preserving measurement accuracy over time.

The effectiveness of this approach is illustrated in Figure 14, which shows the evolution of the differential frequency response FDR_p as a function of the MUT permittivity. A strong agreement between theoretical, simulated, and measured results can be observed, confirming the validity of the differential model. Moreover, the curve-fitting behavior highlights the nonlinear decrease of FDR_p with increasing ϵ'_M , indicating that sensitivity is higher at low permittivity values and gradually stabilizes at higher values. This trend reflects the intrinsic dependence of the resonant frequencies on the effective permittivity predicted by the analytical model. Its limitation, however, lies in reduced sensitivity to geometrical parameters such as MUT thickness, as the differential operation primarily emphasizes permittivity-induced variations rather than structural perturbations.

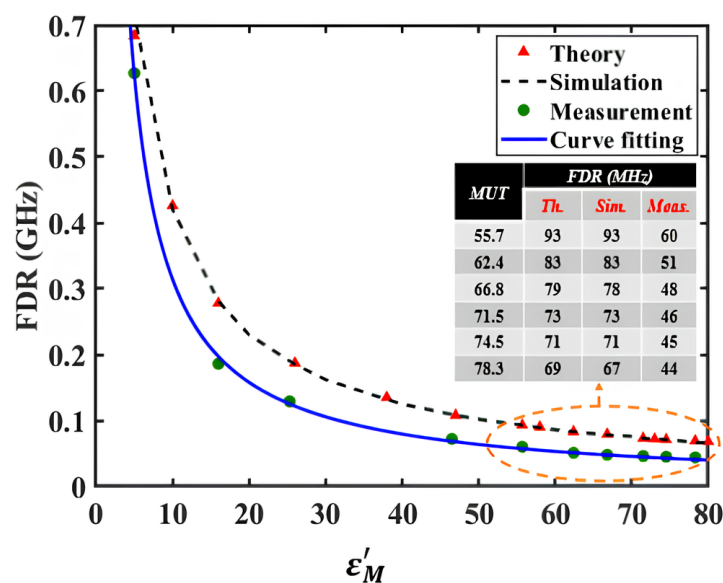


Figure 14. Differential frequency response FDR_p as a function of MUT permittivity ϵ'_M , showing theoretical, simulated, and measured results along with curve fitting. The nonlinear decrease highlights reduced sensitivity at high permittivity values. Adapted from [99].

In summary, avoided-crossing-based approaches provide the most physically rigorous and drift-robust differential mechanism, whereas data-driven methods enhance functionality at the expense of interpretability. Planar differential resonators, despite lower accuracy than high-Q cavity or FPOR systems, remain among the most practical solutions for compact and real-time dielectric characterization.

For a clearer comparative perspective, Table 9 summarizes the main techniques for resonant characterization, categorized into three sections: dielectric Frequency-Shift-Based Techniques (Real Permittivity Extraction) [80–83], Q-Factor-Based Techniques (Loss Tangent Extraction) [26,45,86–90,92–94], and Differential/Reference-Based Techniques [96–99] according to their extraction methodology.

Table 9. Comparative classification of resonant dielectric characterization techniques grouped by extraction methodology.

Ref.	Resonator/Structure	Extraction Principle	Band	MUT Type	Primary Output Metric
[80]	Complementary crossed-arrow resonator	Calibration + regression model	15 GHz	Solids ($\epsilon_r = 2.5\text{--}10.2$)	Sensitivity = 5.74%
[83]	TRB-CSRR planar resonator	Polynomial fitting + thickness dependence	4.86 GHz	Solids ($\epsilon_r = 1.006\text{--}12.9$)	Sensitivity = 20.2%
[81]	Interconnected metamaterial resonator	Frequency-shift sensitivity analysis	C/X band	Solid + liquid samples	Sensitivity = 0.08–0.33%
[82]	Low-frequency dielectric sensor	Machine learning classification	0.4–0.5 MHz	Geological materials	Accuracy = 98.3%
[86]	Cylindrical cavity TE ₁₁₁	Q-factor perturbation method	2.5 GHz	Liquids	$\tan \delta = 0.03\text{--}0.048$
[26]	Cylindrical cavity TE ₁₁₁	Coupling-corrected Q extraction	2–5 GHz	Dielectrics	$\tan \delta = 3 \times 10^{-4}\text{--}3 \times 10^{-2}$
[87]	High-Q cylindrical cavity	Evanescent-wave perturbation	38–88 GHz	Low-loss materials	$\tan \delta \sim 10^{-4}\text{--}10^{-3}$
[92]	Fabry–Perot resonator	Coupled Q + frequency shift model	2–10 GHz	Planar dielectrics	$\tan \delta = 5 \times 10^{-4}\text{--}10^{-2}$
[93]	Plano-concave Fabry–Perot	Optimized loaded-Q condition	4–9 GHz	Dielectric slabs	$\tan \delta = 5 \times 10^{-4}\text{--}5 \times 10^{-3}$
[94]	Coupled resonator system	Multi-mode Q decomposition	2.16–9.23 GHz	Dielectrics	$\epsilon_r + \tan \delta$ simultaneous
[45]	Planar cavity resonator	Q-factor fitting model	2–3.5 GHz	Dielectrics	$\tan \delta = 0\text{--}0.09$
[88]	Overmoded cylindrical cavity	Multi-mode Q analysis	~8 GHz	Dielectrics	$\tan \delta \approx 0.1$
[89]	Rectangular cavity TE _{0mn}	Q-factor extraction method	~21 GHz	Thin films	$\epsilon_r \approx 21$
[90]	SIW cavity resonator	Q-based extraction	1–20 GHz	Dielectrics	$\epsilon_r = 1\text{--}20$
[96]	IDC differential resonator	Reference-based frequency shift	2 GHz	Liquids	$\Delta f = 1450$ MHz
[97]	Coupled SRR system	Avoided mode crossing (AMC)	3.64 GHz	Dielectrics	$\Delta f = 312\text{--}431$ MHz
[98]	Cascaded LC resonators	Differential + machine learning inversion	1.811 GHz	Liquids	$\Delta f = 643$ MHz
[99]	Spiral resonator pair	Long-term differential tracking	12.09 GHz	Multi-material systems	$\Delta f = 5130$ MHz

4.2. Non-Resonant Methods

Non-resonant methods provide broadband characterization of dielectric materials by measuring the propagation or reflection of electromagnetic waves through or from the material under test (MUT). These techniques are particularly advantageous for frequency-dependent behavior, though they generally offer lower sensitivity compared to resonant methods [100].

4.2.1. Transmission-Line-Based Techniques

Transmission-line methods for dielectric characterization can be classified into three broad categories based on their primary objective: improving inversion robustness, enabling loss separation, or extending frequency scalability.

The first category focuses on refining the inversion process to achieve broadband consistency. Costa et al. [100] enhanced the classical Nicolson–Ross–Weir (NRW) method by incorporating dispersion-aware optimization based on Debye and Lorentz models. Compared to conventional NRW implementations, this approach reduces ambiguity in permittivity extraction and enforces physically consistent dispersion behavior across a wide frequency range. However, despite these algorithmic improvements, the method remains fundamentally sensitive to calibration errors, air gaps, and electrically thin samples.

The second category targets the separation of dielectric and conductor losses through planar implementations. Janezic et al. [101] proposed a microstrip-based technique enabling independent extraction of the propagation constant and characteristic impedance. Compared to Costa’s waveguide-based formulation, this approach facilitates partial separation of loss mechanisms, making it particularly suitable for thin-film characterization.

However, this advantage diminishes at higher frequencies, where conductor losses become dominant and degrade extraction reliability.

The third category extends these techniques to higher frequencies. Lin et al. [102] demonstrated a hybrid microstrip-line method for millimeter-wave characterization, achieving improved permittivity resolution. Compared to both Costa's and Janezic's approaches, this method extends the operational frequency range but requires more complex electromagnetic modeling and stricter characterization of conductor losses.

4.2.2. Coaxial Probe Method

The open-ended coaxial probe (OECF) method determines complex permittivity from the reflection coefficient measured at the probe aperture. Permittivity is extracted by relating the measured reflection coefficient to the probe admittance through analytical or numerical models, enabling broadband characterization with minimal sample preparation [103]. In practice, performance differences arise primarily from the modeling strategy and its robustness to measurement non-idealities.

Simplified equivalent-circuit formulations prioritize computational efficiency and experimental practicality. Marsland and Evans [104] introduced a bilinear-transformation approach enabling simultaneous calibration and measurement correction within a compact analytical framework. Compared to more rigorous full-wave descriptions, this formulation is computationally attractive and well-suited for rapid characterization of lossy materials. However, its reliance on simplified field assumptions makes it particularly vulnerable to probe-sample contact quality, and its accuracy degrades when operating conditions deviate from the quasi-static regime, especially at higher frequencies.

More rigorous approaches attempt to overcome these limitations by explicitly modeling electromagnetic interactions at the probe-material interface. La Gioia et al. [103] proposed a comparative framework between quasi-static and full-wave formulations, providing a more physically consistent description of probe loading effects. Compared to the equivalent-circuit model of Marsland and Evans, this strategy improves modeling fidelity and extends the valid frequency range. However, this gain in accuracy comes at the expense of increased sensitivity to external perturbations such as contact pressure, temperature variations, and material heterogeneity, which can significantly affect repeatability.

Subsequent investigations [105,106] further highlight that, despite improvements in electromagnetic modeling, OECF techniques remain fundamentally limited by measurement conditions. Compared to transmission-line or resonant techniques, the OECF method offers clear advantages in simplicity, speed, and minimal sample preparation, but this comes at the cost of higher uncertainty and reduced robustness, particularly for heterogeneous or porous media.

Overall, Marsland and Evans' formulation remains attractive for fast, low-complexity characterization of lossy media, whereas La Gioia et al.'s model provides improved physical rigor for broader frequency applications. Nevertheless, both approaches are ultimately constrained by probe contact effects and environmental sensitivity, which limit their suitability for high-precision dielectric metrology.

4.2.3. Free-Space Measurement

Free-space techniques extract dielectric properties from transmission and reflection measurements performed using horn antenna systems, enabling non-contact characterization of materials. These methods are particularly suitable for large or fragile samples, although their sensitivity decreases for low-loss or electrically thin materials [77]. The main distinctions between implementations arise from calibration rigor and the extent of signal-processing used to mitigate propagation artifacts.

Approaches that prioritize calibration accuracy rely on strict electromagnetic referencing and time-domain signal conditioning. Ghodgaonkar et al. [107] introduced a broadband extraction framework based on through-reflect-line (TRL) calibration combined with time-domain gating to suppress multiple reflections and diffraction effects. This strategy enforces a well-defined measurement plane and significantly reduces systematic errors associated with antenna coupling and free-space propagation. However, its effectiveness depends critically on precise antenna alignment and accurate sample positioning, making the method experimentally demanding despite its high electromagnetic rigor.

In contrast, more application-oriented formulations relax calibration constraints in favor of experimental simplicity and broader material applicability. Trabelsi et al. [108] proposed an approach based on attenuation and phase-shift measurements normalized to material density, combined with mixture models for effective permittivity estimation. While this reduces experimental complexity and improves adaptability to heterogeneous or composite materials, it introduces additional uncertainty sources, particularly related to density estimation and spatial non-uniformity, which limit quantitative accuracy.

These differences highlight a fundamental trade-off in free-space metrology: calibration-intensive methods achieve higher accuracy and better control of systematic electromagnetic errors but require stringent alignment and controlled measurement conditions, whereas simplified formulations improve usability at the expense of increased modeling uncertainty. This trade-off is consistently reported in the literature [109], where both approaches are shown to be highly sensitive to multipath interference, environmental reflections, and setup geometry.

Free-space techniques are best understood as a compromise between non-contact flexibility and metrological precision. While calibration-driven implementations are better suited for homogeneous materials requiring higher accuracy, application-oriented models extend usability to complex media but remain limited in precision. As a result, these methods are generally more appropriate for large-scale or in-situ characterization where experimental practicality outweighs strict measurement accuracy requirements.

4.2.4. Transmission/Reflection Method

Transmission/reflection methods extract dielectric properties directly from measured scattering parameters using analytical or numerical inversion techniques, enabling broadband characterization without relying on resonant-field perturbation. The main differences between approaches arise from the inversion strategy and their ability to ensure physical consistency over a wide frequency range.

Inversion-robustness approaches focus on improving extraction reliability through algorithmic enhancements. Costa et al. [100] improved the classical Nicolson–Ross–Weir (NRW) method by incorporating dispersion-aware optimization based on Debye and Lorentz models. Compared to conventional NRW implementations, this approach reduces ambiguity in permittivity extraction and significantly improves broadband consistency by enforcing physically meaningful dispersion behavior. However, the method remains sensitive to sample thickness and exhibits reduced accuracy for electrically thin materials.

Comparative-evaluation studies examine intrinsic technique limitations rather than proposing algorithmic improvements. Sheen et al. [79] provided a systematic comparison of transmission/reflection techniques against other non-resonant methods. Their analysis shows that, while transmission/reflection approaches offer superior broadband capability and perform well for high-loss materials, they exhibit fundamentally lower accuracy for low-loss materials due to limited sensitivity in phase and attenuation measurements. Compared to Costa's formulation, which focuses on improving inversion robustness,

Sheen’s work highlights intrinsic physical limitations that cannot be fully overcome by algorithmic enhancements.

Application-oriented implementations extend these techniques to specific material classes while illustrating practical trade-offs. Juan et al. [110] demonstrated that transmission/reflection methods can effectively capture dispersive behavior in liquid media. However, compared to Costa’s optimized inversion approach, their method shows reduced capability in resolving small dielectric contrasts. Similarly, Hasan et al. [111] introduced software-assisted extraction techniques enabling faster and near real-time characterization. While this represents an improvement in computational efficiency compared to traditional post-processing methods, it does not address the fundamental limitations in measurement accuracy, which remain governed by calibration precision and noise sensitivity.

A direct comparison of these works highlights a fundamental trade-off: Costa’s formulation improves inversion stability and broadband consistency, Sheen’s analysis reveals the intrinsic sensitivity limitations of the technique, and application-driven approaches prioritize usability and speed over accuracy. Despite significant algorithmic and implementation-level improvements, transmission/reflection methods remain fundamentally constrained by sensitivity to sample thickness, calibration accuracy, and reduced resolution in low-loss regimes.

To provide a global overview of the two main families of dielectric characterization techniques discussed in this section, Table 10 summarizes their fundamental differences in terms of operating principle, frequency coverage, sensitivity, and practical limitations. This synthesis highlights the complementary nature of resonant and non-resonant approaches and helps clarify their respective roles in microwave dielectric characterization.

Table 10. Global comparison between resonant and non-resonant dielectric characterization techniques.

Technique Class	Physical Principle	Frequency Coverage	Accuracy/Sensitivity	Strengths	Limitations
Resonant methods	Field perturbation in high-Q resonant structures (cavity, dielectric, planar resonators)	Narrowband (discrete resonant frequencies)	Very high sensitivity and high absolute accuracy	Excellent precision, strong field confinement, and efficient loss separation	Narrow bandwidth and strict sample size/placement requirements
Non-resonant methods	Wave propagation and reflection using S-parameters (transmission lines, probes, free-space, Tx/Rx methods)	Broadband (continuous frequency range)	Moderate sensitivity, calibration-dependent accuracy	Wide frequency coverage and flexible measurement setups	Lower sensitivity and higher dependence on calibration and inversion models

5. Applications in Telecommunications

5.1. RF and Microwave Passive Components and Circuits

The Fabry–Perot open resonator (FPOR) combined with CPWG structures [112] enables broadband dielectric characterization up to 40 GHz and provides reliable extraction of permittivity for low-loss polymers, making it suitable for high-speed interconnect substrates. However, its strong dependence on sample preparation and environmental stability reduces measurement robustness, particularly when repeatability and compact implementation are required.

In contrast, resonant approaches such as SRR and CRR structures [113] offer improved sensitivity, especially for powders and semi-liquid materials, with closed-ring resonators achieving higher accuracy than split-ring configurations. Nevertheless, their limited frequency scalability and lack of compatibility with planar integration make them less suitable for high-frequency circuit applications.

More advanced planar implementations, such as CSRR-based sensors integrated into GCPW–microstrip transitions [114], address these limitations by operating efficiently in the 10–35 GHz range while providing strong field confinement and high sensitivity. Compared to SRR/CRR structures, CSRR-based designs are significantly more compatible with planar fabrication and enable more effective characterization of thin-film and polymer materials. Although their accuracy depends on fabrication tolerances and electromagnetic modeling, they offer a more favorable compromise between performance and integration compared to FPOR and conventional ring resonators.

High-Q resonators [95] achieve the highest sensitivity and accuracy due to their strong energy confinement. However, their complex implementation and limited compatibility with planar technologies reduce their practicality for integrated microwave systems, particularly at higher frequencies.

Application-specific approaches, such as RF filter-based characterization using modified PPE dielectrics [115] provide realistic evaluation conditions for low-loss substrates. While these methods better reflect actual circuit operation than FPOR techniques, they remain material-dependent and less flexible than resonator-based sensing approaches.

Similarly, system-level studies on mmWave antennas and platforms [12,116] highlight the importance of dielectric materials in advanced RF systems but do not provide the same level of accuracy in dielectric extraction as dedicated resonator-based techniques. Dielectric resonator antennas and filters [117,118] offer high efficiency in specific bands, yet their narrowband operation limits their suitability for broadband characterization.

Planar resonator-based approaches, particularly CSRR configurations [114], provide the most balanced solution for dielectric characterization in the 10–40 GHz range, combining adequate sensitivity with strong integration capability. In contrast, high-Q resonators, although more accurate, remain less practical for scalable and integrated microwave circuit applications.

5.2. Millimeter-Wave and 5G/6G Systems

Millimeter-wave systems for 5G and emerging 6G applications impose significantly stricter requirements on dielectric characterization compared to conventional RF circuits, as small deviations in permittivity or loss tangent directly impact antenna efficiency, beam-forming accuracy, and propagation losses [119,120]. While early studies mainly emphasize the impact of material properties on channel behavior and system performance, they remain largely descriptive and do not provide practical solutions for accurate dielectric extraction at these frequencies.

Resonator-based techniques provide a more suitable approach under these constraints, enabling higher sensitivity and improved accuracy compared to non-resonant or purely system-level methods. In particular, substrate-integrated waveguide (SIW) resonators [121] combine relatively high quality factors with planar integration capability, making them more practical than bulky high-Q cavities while preserving good electromagnetic confinement.

The work of Federico et al. [122] further enhances SIW-based characterization by employing grounded coplanar waveguide–fed cavities operating in the 10–30 GHz range, where the material under test fully fills the cavity, effectively reducing air-gap-induced errors and improving the reliability of permittivity extraction compared to previous SIW implementations.

Despite these advantages, SIW resonators still exhibit lower quality factors than classical cavity-based approaches, which limits their ultimate sensitivity. In contrast, planar resonators such as CSRR-based structures provide stronger surface field confinement,

making them inherently more sensitive to thin films and layered substrates commonly used in 5G/6G technologies, although they remain more sensitive to fabrication tolerances [114].

For millimeter-wave and 5G/6G applications, SIW-based resonators therefore represent an effective compromise for integrated and in-situ characterization, whereas CSRR-based planar resonators offer superior sensitivity for thin-material analysis. While high-Q cavity resonators still achieve the highest accuracy, their limited scalability and integration restrict their practical use in next-generation systems, making planar resonator approaches particularly well-suited for advanced 5G/6G dielectric characterization.

5.3. System-Level Integration of Portable RF Sensing Systems

System-level integration of microwave and millimeter-wave dielectric sensing has progressively evolved from isolated sensing components toward fully integrated, portable, and application-driven RF architectures spanning biomedical, industrial, and communication-oriented domains. Early and foundational system-level perspectives on radar-based sensing highlight that non-contact vital sign detection can be implemented using multiple RF front-end architectures, including continuous-wave Doppler, UWB pulse radar, heterodyne receivers, and self-injection-locked systems, each offering trade-offs in sensitivity, robustness, and implementation complexity [123]. These architectures demonstrate that RF front-end design is a key factor in enabling portable and low-power sensing systems, particularly when implemented as radar-on-chip solutions integrated into handheld or embedded platforms for pervasive monitoring and search-and-rescue applications. Building on this integration trend, recent system-level reviews further emphasize that improvements in detection accuracy and robustness are strongly linked to advances in front-end architecture, baseband processing, and system-level integration strategies, with a growing number of compact radar chips and portable sensing systems enabling continuous monitoring of physiological parameters such as heart rate, respiration rate, and lung water levels in non-contact scenarios [124]. This evolution toward integrated sensing platforms is further extended in fully monolithic millimeter-wave and terahertz implementations, where sensing and readout functionalities are co-designed within a single chip. In particular, SiGe BiCMOS implementations demonstrate that dielectric characterization can be embedded directly into integrated RF front-ends operating from 28 GHz up to 240 GHz, where on-chip transducers, mixers, frequency multipliers, and vector detection circuits collectively form compact lab-on-chip systems capable of complex permittivity extraction [125,126]. Such architectures enable the transition from standalone resonator-based sensing elements to complete vectorial measurement systems, including VNA-like readout functionality implemented directly on silicon, thereby eliminating the need for external laboratory instrumentation. Furthermore, these systems demonstrate that highly integrated THz sensing front-ends can achieve wideband dielectric spectroscopy within compact form factors, reinforcing the feasibility of real-time material characterization in embedded environments. Across these developments, a consistent trend emerges toward highly integrated RF sensing platforms in which sensing, signal generation, down-conversion, and digital readout are unified at the chip or system level, enabling portable, low-power, and application-specific sensing systems that bridge the gap between microwave metrology and real-world telecommunication and biomedical applications.

5.4. Satellite and Space Communication Systems

Satellite and space communication systems impose stringent requirements on dielectric materials and resonator structures, where thermal stability, low loss, and high power-handling capability are more critical than broadband operation or compact planar integration. In this context, dielectric resonators and dielectric resonator antennas (DRAs)

provide a reliable solution due to their inherently low loss and excellent thermal and mechanical stability [117,118]. Compared to planar resonators used in terrestrial systems, these structures offer superior frequency stability over wide temperature variations, making them particularly suitable for operation in C- and X-band satellite links. However, their narrow bandwidth and band-specific design significantly limit their flexibility, especially when broadband characterization or multi-band operation is required.

High-*Q* dielectric resonators based on temperature-stable ceramic materials further improve frequency stability and measurement accuracy by enabling strong electromagnetic energy confinement [127]. While these resonators outperform planar and SIW-based structures in terms of precision and stability, their implementation requires highly controlled measurement environments and becomes increasingly complex as the quality factor increases, limiting their practicality for compact or reconfigurable satellite subsystems.

In contrast, dielectric resonator filters and output multiplexers (OMUXs) enable efficient channelization in satellite payloads with low insertion loss and high selectivity [118]. Nevertheless, their performance strongly depends on the temperature stability of the dielectric material, and their design complexity increases significantly for multi-channel systems, making optimization more challenging compared to simpler resonator configurations.

Metallic waveguide resonators remain the preferred solution for high-power satellite applications, particularly in filters and diplexers operating in Ku-, K-, and Q-bands. Advanced geometries such as cascaded step and stub-loaded resonators improve power-handling capability and reduce insertion losses compared to dielectric-based structures, while also mitigating multipactor effects [128]. However, these waveguide-based implementations are inherently bulky and less compatible with miniaturized or integrated platforms, highlighting a clear trade-off between power robustness and system compactness.

Dielectric resonators provide the best compromise for stable and low-loss operation in moderate-power satellite subsystems, whereas metallic waveguide resonators are more suitable for high-power applications requiring robustness and reliability.

Table 11 provides a comparison of the resonator-based dielectric characterization techniques used in telecommunications from an application-oriented perspective. Highlights trade-offs in terms of sensitivity, size, implementation cost, frequency range, and suitability for different use cases, while employing qualitative indicators to provide a normalized evaluation across diverse technologies and fabrication conditions.

Table 11. Application-oriented comparison of resonator-based dielectric characterization techniques in telecommunications.

Technique	Freq. Range	Sensitivity	Size	Cost	Best Use Case	Key Limitations
FPOR (CPWG-based)	up to 40 GHz	Moderate	Large	Moderate	Bulk materials, interconnect substrates	Sensitive to environment and sample preparation
SRR/CRR	Microwave	High (powders/liquids)	Compact	Low	Material screening	Limited scalability; weak planar compatibility
CSRR (planar)	10–40 GHz	High (thin films)	Compact	Low	Integrated RF and mmWave circuits	Sensitive to fabrication tolerances
SIW resonators	10–30 GHz	Moderate	Moderate	Moderate	Integrated 5G/6G systems	Lower sensitivity than high- <i>Q</i> cavities
High- <i>Q</i> cavity resonators	Microwave–mmWave	Very High	Large	Very High	Metrology-grade characterization	Bulky and complex implementation
RF filter-based methods	10–40 GHz	Moderate	Compact	Low	Circuit-level material evaluation	Material-specific; limited flexibility
Dielectric resonators (DRA/filters)	Microwave bands	Moderate	Moderate	Moderate	Satellite communication systems	Narrow bandwidth
Waveguide resonators	Ku–Q bands	Moderate	Large	High	High-power satellite systems	Bulky; not suitable for integration

6. Current Challenges and Research Gaps

6.1. Limited Accuracy at Very High Frequencies (mm-Wave, THz)

Extending resonator-based dielectric characterization toward millimeter-wave (mm-wave) and terahertz (THz) frequencies introduces fundamental accuracy limitations driven by dimensional scaling and loss mechanisms [129]. As resonant structures shrink with increasing frequency, the relative impact of fabrication tolerances increases, since fractional frequency deviation scales with geometric perturbation (i.e., $\Delta f/f \propto \Delta L/\Delta L$). Consequently, micrometer-scale deviations in cavity dimensions, surface roughness, or alignment can induce significant resonance shifts and Q-factor degradation.

Recent studies highlight that maintaining dimensional precision and electromagnetic stability at mm-wave and THz frequencies remains a major obstacle [12]. In silicon-based or integrated platforms, elevated substrate losses further reduce achievable Q-factors and dynamic range. Moreover, resonant configurations such as Fabry–Perot and split-cylinder resonators experience diffraction losses, coupling uncertainties, and calibration instability in the mm-wave regime [77]. In combination, these factors indicate that beyond tens of gigahertz, fabrication-induced perturbations and uncertainty propagation within inversion models become dominant contributors to permittivity extraction error. Improved microfabrication control, advanced electromagnetic modeling, and traceable high-frequency calibration standards are therefore essential for reliable operation in the mm-wave and THz domains.

6.2. Characterization of Novel Dielectric Materials (Composites, Nanomaterials, Polymers)

Emerging dielectric materials—including composites, nanomaterials, and polymer-based substrates—introduce additional complexity due to heterogeneity, anisotropy, and processing-dependent variability, particularly in additively manufactured structures where material composition and dielectric properties can vary spatially within the same sample [130]. Many classical resonant techniques were developed for homogeneous and isotropic materials, where uniform field distributions and single-valued permittivity assumptions are valid. In contrast, composite and additively manufactured materials often exhibit spatially varying dielectric properties, invalidating simplified inversion models and reducing extraction robustness [130].

Measurement accuracy has been shown to depend strongly on material type, intrinsic loss, geometry, and fabrication conditions [77]. In 3D-printed or polymer-based resonators, porosity, unintended air gaps, filler agglomeration, and non-uniform filler distribution alter both the effective dielectric constant and loss tangent, thereby modifying the resonance condition and Q-factor [6]. These material-induced inhomogeneities introduce reproducibility challenges that extend beyond pure measurement error.

Furthermore, advanced devices such as dielectric resonator antennas (DRAs) fabricated from novel materials frequently rely on incomplete or insufficiently validated high-frequency permittivity datasets [12]. The absence of comprehensive, frequency-resolved material databases limits simulation fidelity, inverse design strategies, and device optimization. This highlights the urgent need for standardized characterization protocols and validated dielectric data for emerging engineered materials.

6.3. Integration with Compact, On-Chip Telecom Devices

The integration of resonator-based dielectric characterization into compact, on-chip telecommunication systems presents both electromagnetic and metrological challenges. Traditional high-Q cavities and bulk resonators are inherently volumetric, whereas modern communication hardware increasingly relies on planar, sub-wavelength, and monolithically integrated architectures. At mm-wave frequencies, even minor misalignment, air gaps,

or imperfect coupling between resonators and feed networks can significantly degrade efficiency, bandwidth, and repeatability [12].

Silicon-based implementations further suffer from elevated substrate losses, constraining achievable Q-factors and limiting sensitivity. From a measurement standpoint, adapting resonant techniques to planar, on-wafer, or fully integrated platforms remains insufficiently explored. Established systems—including Fabry–Perot resonators, coaxial fixtures, and free-space setups—are often incompatible with miniaturized devices or confined field geometries [77]. Challenges associated with coupling complexity, field confinement, and calibration traceability continue to restrict the development of compact, high-accuracy on-chip dielectric metrology systems.

6.4. Standardization, Calibration Stability, and Measurement Robustness

A persistent limitation across the literature is the absence of standardized calibration and uncertainty-evaluation frameworks for high-frequency dielectric measurements. Most techniques are optimized for specific frequency ranges, sample geometries, or material classes, hindering cross-platform comparability and reproducibility [77]. Variations in sample positioning, surface contact quality, and air gaps introduce systematic deviations that propagate through inversion algorithms.

Reported measurement errors range from approximately 3–15% in microfluidic sensors to $\leq 3\%$ in differential resonator configurations and $\leq 1\%$ in metamaterial-assisted designs [18]. Although performance improvements are evident, systematic uncertainties remain significant, particularly in liquid measurements where temperature, humidity, and surrounding permittivity alter the effective boundary conditions. The absence of traceable reference materials and unified calibration artifacts further limits metrological reliability.

Beyond calibration methodology itself, measurement repeatability and long-term robustness represent equally important practical considerations that are often underreported in the dielectric characterization literature. Experimental investigations have shown that fabrication-induced dimensional variations, sample-positioning errors, environmental fluctuations, and instrumentation non-idealities can introduce measurable deviations between repeated measurements and contribute significantly to the overall uncertainty budget. Ramella et al. [95] demonstrated that measurement uncertainty is frequently dominated by practical setup limitations, including manufacturing tolerances, mechanical instability, cavity imperfections, and calibration-related constraints, rather than by resonance-fitting procedures alone.

Fabrication tolerances become particularly critical for resonant structures operating at microwave and millimeter-wave frequencies, where small geometric deviations can alter field confinement and shift the resonance frequency. Haq et al. [78] reported discrepancies of 3.65% and 3.03% between simulated and measured resonance frequencies for circular and square complementary split-ring resonators, respectively, highlighting the impact of fabrication variability on measurement accuracy. The same study further identified air gaps between the sample and resonator, sample-condition variations, humidity, and temperature fluctuations as major contributors to calibration variability. Repeated calibration measurements exhibited noticeable frequency dispersion, emphasizing the importance of repeatability assessment in practical sensing applications. Similarly, Gugliandolo et al. [131] showed that sample repositioning, environmental disturbances, and instrumentation uncertainty can significantly affect reproducibility, while differential self-calibrating architectures can substantially reduce temperature-induced drift and improve long-term measurement stability.

6.5. Environmental Challenges in Dielectric Characterization

Environmental factors, particularly temperature and moisture, introduce nonlinear and material-dependent perturbations in dielectric characterization. Both the dielectric constant (ϵ') and loss factor (ϵ'') are strongly influenced by moisture content, with even small humidity variations inducing significant and sometimes non-monotonic changes in permittivity [132]. Temperature effects are often coupled to moisture levels, and the direction of permittivity variation may depend on critical material thresholds.

Material composition further complicates environmental sensitivity, as constituents such as sugars, fibers, oils, and salts modify polarization mechanisms and relaxation dynamics [132]. In liquid-phase measurements, elevated temperatures introduce additional constraints including pressure control, boiling suppression, and thermal expansion of sample holders, which can generate systematic errors unless compensated through stable materials such as quartz or alumina [133].

In resonator-based systems, environmental perturbations modify both the real and imaginary components of complex permittivity, thereby altering the entire resonance condition rather than merely shifting frequency. Accurate high-frequency characterization therefore requires controlled environmental conditions, temperature-compensated models, and multi-parameter calibration strategies to ensure reliable and repeatable permittivity extraction.

7. Future Perspectives

7.1. AI/ML-Assisted Resonator Design and AI-Enabled Dielectric Characterization

Artificial intelligence (AI) and machine learning (ML) are increasingly transforming resonator-based dielectric characterization by enabling automated resonator synthesis, sensitivity-aware design optimization, inverse electromagnetic modeling, and data-driven extraction of complex permittivity from measured resonant responses. Recent studies demonstrate that deep neural networks, convolutional neural networks (CNNs), interpretable ML frameworks, inverse-designed sensing architectures, and unsupervised learning strategies can assist in resonator optimization, inverse electromagnetic modeling, and complex permittivity extraction with competitive accuracy relative to conventional inversion techniques [134–140]. In particular, ML-driven surrogate models can substantially reduce the computational burden associated with repeated full-wave electromagnetic simulations during geometry optimization and parameter retrieval.

Beyond these general trends, recent works have more explicitly integrated AI into the resonator design loop itself, moving from passive performance prediction to active electromagnetic synthesis and inverse modeling. In [134], a fully unsupervised AI-driven framework is introduced for the automated synthesis of high-sensitivity microstrip ring-resonator sensors, where the device topology and geometric parameters are optimized simultaneously without human intervention. The problem is formulated as a coupled topology–parameter optimization task, enabling evolutionary exploration of discrete resonant building blocks (e.g., circular and square resonant cells, slots, and stubs), followed by gradient-based refinement to maximize dielectric sensitivity under resonance constraints. This hybrid optimization strategy embeds AI directly into the electromagnetic design loop and enables inversion-free sensor synthesis, where sensitivity is explicitly optimized as an objective function rather than being implicitly achieved through geometry selection. However, the method remains computationally demanding due to repeated full-wave simulations.

Complementing this approach, Haq et al. [84] proposes a hybrid AI-assisted optimization framework for complementary multiple concentric split-ring resonators (CMC-SRRs), where a structured two-stage optimization strategy is used. The first stage enforces reso-

nance alignment and transmission notch depth using a penalty-based formulation, while the second stage directly optimizes dielectric sensitivity. This represents a key shift toward sensitivity-aware resonator design, where sensing performance becomes a primary optimization variable. In addition, a regression-based inverse model is integrated to map resonant features and sample thickness to complex permittivity, enabling data-driven dielectric characterization without explicit electromagnetic inversion.

Further extending AI integration into full sensing pipelines, Khusro et al. [141] replace classical cavity perturbation theory with machine-learning-based surrogate inversion in an IoT-enabled microwave dielectric characterization system. Regression and ensemble learning models are trained to predict complex permittivity and loss tangent from resonator-derived features such as resonance frequency shifts, quality factor variations, and scattering parameters. This transforms the resonator into a real-time inference platform capable of operating in nonlinear regimes where analytical models fail, while ensemble strategies improve robustness against noise and measurement uncertainty.

Similarly, in [142], artificial neural networks (ANNs) are employed to learn the nonlinear mapping between multimode resonant responses and fluid-induced dielectric variations in a microfluidic-integrated plasmonic skyrmion-based metamaterial resonator. By exploiting multiple resonant frequency modes (f_1 – f_6), the ANN effectively acts as an inverse model that translates complex electromagnetic spectra into dielectric property variations under dynamically changing conditions, significantly improving robustness compared to conventional analytical approaches.

Beyond computational acceleration, AI is increasingly addressing fundamental limitations of resonator-based dielectric sensing. Conventional microwave characterization methods often rely on isolated resonant features such as resonance frequency, amplitude variation, or Q-factor extraction. However, in multicomponent and dispersive material systems, these features frequently exhibit cross-sensitivity and non-unique parameter mappings, where multiple material compositions generate nearly identical sensor responses [138,139]. Such ambiguity becomes especially critical in ternary and quaternary mixtures, where single-frequency or narrowband sensing approaches become mathematically insufficient for selective constituent identification.

Together, these studies demonstrate that AI is no longer limited to accelerating electromagnetic simulations or parameter extraction, but is increasingly being integrated across the entire resonator lifecycle, from inverse electromagnetic design and sensitivity optimization to real-time dielectric characterization and intelligent sensing.

Recent work suggests that future dielectric characterization systems will increasingly transition toward broadband spectrum-aware AI frameworks capable of processing the entire electromagnetic response rather than isolated resonant features. CNN-based architectures trained on broadband S-parameter spectra have demonstrated significantly improved robustness and prediction accuracy compared with conventional feature-based neural networks [138,139]. These approaches exploit the frequency-dispersive behavior of materials across multiple resonances, enabling selective characterization of complex liquid mixtures, electrolytes, biomolecular solutions, and heterogeneous dielectric systems [139]. Similarly, deep-learning-enhanced microwave photonic sensing platforms based on inverse-designed Fabry–Pérot cavities have demonstrated that AI-assisted RF spectral interpretation can extract informative features from noisy low-Q resonator responses, enabling highly accurate sensing even under limited interrogation bandwidth conditions [140].

The integration of discrete microwave spectroscopy with AI-assisted inverse modeling further opens promising pathways for noninvasive biomedical sensing applications, including glucose, sodium, and potassium monitoring in aqueous environments. Multi-resonance resonator architectures capable of generating dense spectral signatures over

broad frequency bands may become increasingly important for selectively identifying weak dielectric perturbations in biologically relevant media [139]. In this context, future microwave sensors are expected to evolve toward fully automated platforms integrating fluidic control systems, temperature stabilization, autonomous dataset acquisition, adaptive spectral interrogation strategies, and real-time AI inference engines. Recent demonstrations combining inverse-designed resonators, microwave photonic interrogation, and deep-learning-based feature extraction further highlight the potential of intelligent resonator systems capable of maintaining sensing accuracy under noisy and dynamically varying operating conditions [140].

Another promising research direction involves physics-informed and uncertainty-aware machine-learning models. Most currently reported ML approaches remain strongly dependent on simulated datasets generated under idealized electromagnetic conditions, whereas practical measurements are affected by fabrication tolerances, parasitic coupling, connector repeatability, environmental drift, and temperature-dependent dielectric variations [138,143]. Embedding Maxwell-equation constraints, electromagnetic priors, and material dispersion models directly into neural-network architectures may improve physical consistency, generalizability, and extrapolation capability while reducing overfitting and training-data requirements.

Despite recent progress, several major challenges remain unresolved. One critical limitation is the scarcity of standardized, experimentally validated dielectric datasets spanning broad frequency ranges, heterogeneous material classes, environmental conditions, and fabrication variations. The absence of open benchmarking databases limits reproducibility, uncertainty quantification, cross-platform transferability, and fair comparison between AI models [143,144]. Moreover, many existing studies rely on relatively small datasets acquired under controlled laboratory conditions, raising concerns about long-term robustness and deployment in real-world environments [138–140].

Future resonator platforms may also incorporate adaptive and self-calibrating AI systems capable of dynamically tuning resonator geometry, coupling conditions, biasing states, or operating frequencies to maintain optimal sensing sensitivity under varying operating conditions [143]. Such adaptive architectures could compensate in real time for temperature fluctuations, aging effects, humidity changes, and manufacturing deviations, thereby improving stability and reliability in long-term operation.

In the longer term, the convergence of inverse electromagnetic design, inverse-designed resonator architectures, digital twins, edge computing, and AI-assisted material modeling may enable fully autonomous resonator co-design frameworks in which resonator geometry, sensing objectives, substrate selection, and material properties are optimized simultaneously [134,140,143]. These developments could accelerate the realization of compact high-Q resonators and scalable non-contact dielectric sensing platforms for biomedical diagnostics, wireless sensing, industrial process monitoring, and Industry 4.0 environments [137,139].

7.2. Integration with Lab-on-Chip and MEMS Technologies

The convergence of microwave resonators with microfluidic, MEMS, and lab-on-chip platforms provides a pathway toward miniaturized and high-resolution dielectric metrology [145]. Demonstrations such as IDC-SRR resonators integrated with PDMS microchannels and CSRR-enabled digital microfluidic chips have achieved microliter-scale liquid characterization with high sensitivity [146,147]. More recently, reflective-mode CPW sensors terminated with compact series LC resonators have demonstrated single-frequency complex permittivity extraction using simultaneous phase and amplitude variations of the reflected signal, thereby eliminating the need for frequency-sweeping interrogation systems

while maintaining high sensitivity for microfluidic dielectric characterization [148]. Recent CSRR-based planar microwave sensors further demonstrate that optimized resonator geometries, enhanced electric-field confinement, and compact capillary-compatible layouts can substantially improve sensing sensitivity while preserving compatibility with standard PCB and microfluidic fabrication processes [149]. These systems reduce sample volume requirements while enhancing field–material interaction within confined regions.

Recent developments further indicate a transition from purely frequency-shift-based sensing toward phase- and amplitude-modulated microwave interrogation strategies capable of operating with simplified and lower-cost measurement architectures [148]. In particular, reflective-mode resonators integrated with PDMS microchannels enable highly localized electric-field confinement within sub-microliter sensing regions, improving sensitivity to weak dielectric perturbations in liquid mixtures and biochemical solutions. Compact CSRR architectures additionally provide robust resonance behavior, strong field localization, and improved sensing precision while remaining compatible with scalable planar fabrication technologies [149].

Future research must address scalability, multiplexing capability, and GHz–THz signal integrity in densely integrated platforms [150]. Key directions include improved electromagnetic field confinement within microchannels, low-loss conductive and dielectric materials, and packaging strategies that minimize parasitic coupling and thermal drift. Coupling active microfluidic control with on-chip signal processing and AI-assisted extraction algorithms could enable closed-loop, real-time monitoring of multicomponent or dynamically evolving fluids [151]. Physics-based equivalent-circuit modeling and nonlinear inverse extraction techniques may also become increasingly important for translating measured phase and amplitude responses into accurate complex-permittivity estimates under practical operating conditions [148]. Additional miniaturization challenges include reduced electromagnetic field confinement, increased conductor and dielectric losses, degradation of resonator Q-factor, and tighter fabrication tolerances as resonator dimensions approach sub-millimeter lab-on-chip scales [149].

Achieving reproducible calibration and uncertainty control at the microscale remains a central challenge for transitioning these systems from laboratory prototypes to robust application-ready devices [38]. Additional challenges include fabrication tolerances, microchannel alignment errors, temperature-dependent dielectric drift, and repeatability of fluid delivery mechanisms, all of which can significantly affect resonator response stability and extracted permittivity accuracy [148]. Furthermore, maintaining high sensing performance during large-scale miniaturization may require advanced lithographic fabrication methods, high-permittivity substrates, and optimized resonator geometries to compensate for increased losses and reduced Q-factors in highly compact implementations [149].

7.3. Standardization and Calibration Frameworks for Industrial Implementation

For resonator-based dielectric sensors to achieve industrial adoption, calibration robustness and uncertainty quantification must comply with metrological standards. Mechanical tolerances, sample thickness variations, and air-gap formation directly affect resonance depth, frequency shift, and loaded Q-factor, thereby necessitating highly controlled and repeatable fixture designs. Fabrication-tolerant geometries, such as square split-ring resonators, further enhance inter-device reproducibility and reduce sensitivity to assembly imperfections [78].

For conventional coaxial and waveguide-based measurement systems, calibration is commonly performed using established vector network analyzer (VNA) procedures such as Short–Open–Load–Through (SOLT), Through–Reflect–Line (TRL), and Line–Reflect–Match (LRM), which are supported by commercially available calibration kits [152]. Additional

validation is often conducted using reference materials with well-characterized dielectric properties. In integrated resonator sensors, differential and self-referencing architectures can further reduce sensitivity to calibration errors and environmental variations [95]. However, calibration requirements remain strongly dependent on resonator topology, operating frequency, and measurement configuration. Consequently, no universally accepted calibration framework currently exists for many emerging resonator technologies, particularly metamaterial-inspired and substrate-integrated waveguide (SIW)-based sensors, highlighting the need for standardized calibration and validation protocols [77].

Universal calibration strategies require frequency-scalable and geometry-independent reference datasets spanning wide permittivity and thickness ranges [153]. Physics-informed and regression-based inversion algorithms can compensate for nonlinear frequency-permittivity relationships, extend the dynamic range, and enable uncertainty quantification within the extraction process. Recent microwave–photonic interrogation architectures additionally demonstrate that simultaneous magnitude-, phase-, and resonance-based analysis can improve sensing robustness and facilitate self-compensation against source fluctuations and environmental perturbations, thereby enhancing calibration stability in multiplexed sensing systems [154].

At mm-wave and THz frequencies, accurate permittivity retrieval additionally depends on resolving phase ambiguity through analytical selection of the appropriate “ $n\pi$ ” transmission condition, particularly in the presence of multiple internal reflections. Sensitivity analysis with respect to sample thickness, operating frequency, refractive index, and transmission magnitude $|S_{21}|$ enables controlled error propagation and improves repeatability of the extracted parameters [129]. Moreover, joint time–frequency-domain interrogation and phase-sensitive resonance tracking techniques developed in microwave photonic resonator systems may provide additional pathways for uncertainty-aware dielectric extraction and multiparameter compensation in future industrial sensing platforms [154].

The coordinated integration of controlled mechanical design, validated inversion methodologies, traceable reference standards, and uncertainty-aware procedures will ultimately determine the feasibility of transitioning resonator-based dielectric characterization from research laboratories to standardized industrial metrology platforms.

8. Conclusions

This review has provided a systematic and application-oriented analysis of resonator-based dielectric characterization techniques for microwave and millimeter-wave telecommunication systems. By establishing a unified comparative framework encompassing cavity resonators, split-post dielectric resonators, planar and substrate-integrated waveguide structures, and metamaterial-inspired resonators, the study has linked resonator topology, electromagnetic confinement, quality factor, sensitivity, and dielectric extraction performance within a single coherent perspective—a contribution that has been largely absent from the prior literature.

Three principal findings emerge. First, resonator topology fundamentally governs the trade-off between metrological accuracy, compactness, and integration capability. High-Q cavity and SPDR systems remain the benchmark for low-loss material characterization, while planar, SIW, and metamaterial-inspired resonators offer superior scalability and circuit compatibility at the cost of increased sensitivity to parasitic effects and fabrication tolerances. No single architecture universally satisfies all telecommunication requirements; resonator selection must therefore be driven by application-specific constraints including frequency range, integration level, and required accuracy.

Second, dielectric extraction performance is critically determined by electromagnetic field confinement and the robustness of perturbation-based extraction methodologies.

Strong electric-field localization improves sensitivity but simultaneously increases susceptibility to environmental drift, coupling instability, and calibration dependence. Achieving reliable dielectric metrology therefore demands not only optimized resonator design, but also rigorous calibration procedures, uncertainty-aware extraction frameworks, and stable coupling conditions—requirements that remain inconsistently addressed in the current literature.

Third, dielectric characterization is evolving into a multidisciplinary system-level challenge. AI-assisted extraction, hybrid microwave–photonic architectures, and additive manufacturing are actively reshaping the boundaries of what resonant sensing platforms can achieve. These developments indicate that future dielectric metrology will increasingly integrate electromagnetic design, computational intelligence, and advanced fabrication within unified characterization frameworks.

Several important challenges remain open. The absence of standardized calibration and uncertainty quantification protocols across resonator topologies continues to impede result comparability and industrial adoption. At millimeter-wave and sub-THz frequencies, surface roughness, conductor losses, and thermal instabilities impose increasingly severe constraints on achievable accuracy. Metamaterial-inspired resonators, despite their high sensitivity, remain limited by narrow bandwidths and calibration dependency, while AI-assisted methods still face unresolved issues of dataset generalization and physical interpretability.

Future research should prioritize three converging directions: the development of standardized metrological frameworks with unified calibration and uncertainty protocols; the design of hybrid resonator architectures combining SIW platforms with metamaterial-inspired structures for simultaneous sensitivity, compactness, and broadband operation; and the integration of physics-informed machine learning capable of real-time adaptive calibration and inverse dielectric extraction for complex, heterogeneous, and environmentally sensitive materials.

Resonator-based dielectric characterization remains a cornerstone of high-frequency electromagnetic engineering. As telecommunication systems advance toward 6G, mm-wave integrated platforms, and intelligent RF architectures, the ability to accurately characterize materials within compact and scalable sensing environments will become increasingly critical. The convergence of high-Q resonant design, AI-assisted metrology, and advanced fabrication technologies represents the most promising pathway toward robust, industry-ready dielectric characterization for next-generation communication systems.

Author Contributions: Conceptualization, A.B. and N.D.; methodology, M.A. (Mellissa Amazouz) and S.T.; validation, A.B., N.D. and M.A. (Mounir Amir); formal analysis, M.A. (Mounir Amir) and M.A. (Mellissa Amazouz); investigation, A.B., N.D. and M.A. (Mounir Amir); resources, I.M. and A.H.; data curation, S.T. and H.A.; writing—original draft preparation, A.B., N.D. and M.A. (Mounir Amir); visualization, S.T. and M.A. (Mellissa Amazouz); supervision, I.M., A.H. and H.A.; project administration, N.D. and H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Le Floch, J.M.; Fan, Y.; Humbert, G.; Shan, Q.; Férachou, D.; Bara-Maillet, R.; Aubourg, M.; Hartnett, J.G.; Madrangeas, V.; Cros, D.; et al. Invited article: Dielectric material characterization techniques and designs of high-Q resonators for applications from micro to millimeter-waves frequencies applicable at room and cryogenic temperatures. *Rev. Sci. Instrum.* **2014**, *85*, 031301. [[PubMed](#)]
2. Krupka, J. Frequency domain complex permittivity measurements at microwave frequencies. *Meas. Sci. Technol.* **2006**, *17*, R55–R70. [[CrossRef](#)]
3. Alahnomi, R.A.; Zakaria, Z.; Yussof, Z.M.; Althuwayb, A.A.; Alhegazi, A.; Alsariera, H.; Rahman, N.A. Review of recent microwave planar resonator-based sensors: Techniques of complex permittivity extraction, applications, open challenges and future research directions. *Sensors* **2021**, *21*, 2267. [[CrossRef](#)] [[PubMed](#)]
4. Marksteiner, Q.R.; Treiman, M.B.; Chen, C.F.; Haynes, W.B.; Reiten, M.; Dalmas, D.; Pulliam, E. Cavity resonator for dielectric measurements of high- ϵ , low loss materials, demonstrated with barium strontium zirconium titanate ceramics. *Rev. Sci. Instrum.* **2017**, *88*, 064704. [[CrossRef](#)] [[PubMed](#)]
5. Orloff, N.D.; Obrzut, J.; Long, C.J.; Lam, T.; Kabos, P.; Novotny, D.R.; Booth, J.C.; Liddle, J.A. Dielectric characterization by microwave cavity perturbation corrected for nonuniform fields. *IEEE Trans. Microw. Theory Tech.* **2014**, *62*, 2149–2159. [[CrossRef](#)]
6. Sofokleous, P.; Paz, E.; Herraiz-Martínez, F.J. Design and Manufacturing of Dielectric Resonators via 3D Printing of Composite Polymer/Ceramic Filaments. *Polymers* **2024**, *16*, 2589. [[CrossRef](#)] [[PubMed](#)]
7. Alimenti, A.; Torokhtii, K.; Vidal García, P.; Pompeo, N.; Silva, E. Design and test of a new dielectric-loaded resonator for the accurate characterization of conductive and dielectric materials. *Sensors* **2023**, *23*, 518. [[CrossRef](#)] [[PubMed](#)]
8. Bozzi, M.; Georgiadis, A.; Wu, K. Review of substrate-integrated waveguide circuits and antennas. *IET Microwaves Antennas Propag.* **2011**, *5*, 909–920. [[CrossRef](#)]
9. Lee, C.K.; McGhee, J.; Tsipogiannis, C.; Zhang, S.; Cadman, D.; Goulas, A.; Whittaker, T.; Gheisari, R.; Engstrom, D.; Vardaxoglou, J.; et al. Evaluation of microwave characterization methods for additively manufactured materials. *Designs* **2019**, *3*, 47. [[CrossRef](#)]
10. Krupka, J. Split post dielectric resonators for measurements of the complex permittivity of laminar dielectric materials at microwave frequencies. In Proceedings of the Conference Workshop on Applied Radio Science (WARS'2002), Newport Beach, CA, USA, 31 August–1 September 2002.
11. Vélez, P.; Su, L.; Grenier, K.; Mata-Contreras, J.; Dubuc, D.; Martín, F. Microwave microfluidic sensor based on a microstrip splitter/combiner configuration and split ring resonators (SRRs) for dielectric characterization of liquids. *IEEE Sens. J.* **2017**, *17*, 6589–6598. [[CrossRef](#)]
12. Zhang, Y.; Ogurtsov, S.; Vasilev, V.; Kishk, A.A.; Caratelli, D. Advanced dielectric resonator antenna technology for 5G and 6G applications. *Sensors* **2024**, *24*, 1413. [[CrossRef](#)] [[PubMed](#)]
13. Wang, J.; Wang, R.; Shen, Z.; Liu, B.; Sun, C.; Xue, Q. Microwave biosensors utilizing metamaterial enhancement: Design and application. *Nanotechnol. Precis. Eng.* **2025**, *8*, 015001.
14. Singh, K.K.; Kumar Mahto, S.; Sinha, R. A review: Material characterization with metamaterial based sensors. *Sens. Rev.* **2023**, *43*, 41–51. [[CrossRef](#)]
15. Sim, M.S.; You, K.Y.; Dewan, R.; Esa, F.; Salim, M.R.; Khe, C.S.; Kew, S.Y.N.; Hamid, F. Microwave sensors loaded with metamaterial-inspired resonators for dielectric material characterization: A review. *Sens. Actuators A Phys.* **2024**, *372*, 115322. [[CrossRef](#)]
16. Haq, M.A.U.; Armghan, A.; Aliqab, K.; Alsharari, M. A review of contemporary microwave antenna sensors: Designs, fabrication techniques, and potential application. *IEEE Access* **2023**, *11*, 40064–40074. [[CrossRef](#)]
17. Subad, R.A.S.I.; El Kashouty, M.F.; Das, S. Antenna as sensors: A mini review. *J. Mater. Chem. C* **2025**, *13*, 20862–20879. [[CrossRef](#)]
18. Liu, C.; Liao, C.; Peng, Y.; Zhang, W.; Wu, B.; Yang, P. Microwave sensors and their applications in permittivity measurement. *Sensors* **2024**, *24*, 7696. [[CrossRef](#)] [[PubMed](#)]
19. Sharma, S.; Singh, M.; Kumar, R. Microwave sensors for dielectric characterization of materials: A review. *Phys. Scr.* **2026**, *101*, 092001. [[CrossRef](#)]
20. Palandoken, M.; Gocen, C. Microwave sensor designs for liquid material dielectric characterization: Technological advances and applications. *Sens. Actuators A Phys.* **2025**, *387*, 116381. [[CrossRef](#)]
21. Shi, J.; Fernández-García, R.; Gil, I. Sensor technologies for non-invasive blood glucose monitoring. *Sensors* **2025**, *25*, 3591. [[CrossRef](#)] [[PubMed](#)]
22. Tu, H.; Hong, H.; Zhang, Y.; Zhou, L.; Li, X. Influence of Dielectric Loss on RF Performance of Microstrip Multi-Resonant Circuits. *J. Sens.* **2022**, *2022*, 3866692. [[CrossRef](#)]
23. Barker-Jarvis, J.; Janezic, M.D.; Paulter, N.G.; Blendell, J.E. Dielectric and conductor-loss characterization and measurements on electronic packaging materials. *NIST Tech. Note* **2001**, *1520*, 3–19.
24. Egorov, V. Resonance methods for microwave studies of dielectrics. *Instrum. Exp. Tech.* **2007**, *50*, 143–175. [[CrossRef](#)]

25. Zhou, D.; Pang, L.X.; Wang, D.W.; Li, C.; Jin, B.B.; Reaney, I.M. High permittivity and low loss microwave dielectrics suitable for 5G resonators and low temperature co-fired ceramic architecture. *J. Mater. Chem. C* **2017**, *5*, 10094–10098. [[CrossRef](#)]
26. Zou, J.; Li, C.J.; Zheng, C.; Wang, D.; Zhang, J.; Wang, X.; Zhang, J.Y.; Hou, Z.L. A Novel Strategy for Detecting Permittivity and Loss Tangent of Low-Loss Materials Based on Cylindrical Resonant Cavity. *Sensors* **2023**, *23*, 5469. [[CrossRef](#)] [[PubMed](#)]
27. Saadat-Safa, M.; Nayyeri, V.; Khanjarian, M.; Soleimani, M.; Ramahi, O.M. A CSRR-based sensor for full characterization of magneto-dielectric materials. *IEEE Trans. Microw. Theory Tech.* **2019**, *67*, 806–814.
28. Wang, Q.; Zhang, D.; Yang, H.; Tao, C.; Huang, Y.; Zhuang, S.; Mei, T. Sensitivity of a label-free guided-mode resonant optical biosensor with different modes. *Sensors* **2012**, *12*, 9791–9799. [[PubMed](#)]
29. Krupka, J.; Breeze, J.; Centeno, A.; Alford, N.; Claussen, T.; Jensen, L. Measurements of permittivity, dielectric loss tangent, and resistivity of float-zone silicon at microwave frequencies. *IEEE Trans. Microw. Theory Tech.* **2006**, *54*, 3995–4001. [[CrossRef](#)]
30. Hopcroft, M.; Melamud, R.; Candler, R.N.; Park, W.T.; Kim, B.; Yama, G.; Partridge, A.; Lutz, M.; Kenny, T.W. Active temperature compensation for micromachined resonators. In *Proceedings of the Solid-State Sensor, Actuator and Microsystems Workshop*; IEEE: Piscataway, NJ, USA, 2004; pp. 364–367.
31. Jonscher, A. The ‘universal’ dielectric response. I. *IEEE Electr. Insul. Mag.* **2002**, *6*, 16–22.
32. Chakraborty, S. Frequency-dependent dielectric properties of sodium silicate. *Mod. Phys. Lett. B* **2018**, *32*, 1850411. [[CrossRef](#)]
33. Kremer, F.; Schönhals, A. *Broadband Dielectric Spectroscopy*; Springer Science & Business Media: New York, NY, USA, 2002.
34. Giannoukos, G.; Min, M.; Rang, T. Relative complex permittivity and its dependence on frequency. *World J. Eng.* **2017**, *14*, 532–537. [[CrossRef](#)]
35. Krupka, J. Microwave measurements of electromagnetic properties of materials. *Materials* **2021**, *14*, 5097. [[CrossRef](#)] [[PubMed](#)]
36. Sharma, P.; Lao, L.; Falcone, G. A microwave cavity resonator sensor for water-in-oil measurements. *Sens. Actuators B Chem.* **2018**, *255*, 560–567.
37. Nwajana, A.O.; Obi, E.R. A review on SIW and its applications to microwave components. *Electronics* **2022**, *11*, 1160. [[CrossRef](#)]
38. Salim, A.; Lim, S. Review of recent metamaterial microfluidic sensors. *Sensors* **2018**, *18*, 232. [[CrossRef](#)] [[PubMed](#)]
39. Keyrouz, S.; Caratelli, D. Dielectric resonator antennas: Basic concepts, design guidelines, and recent developments at millimeter-wave frequencies. *Int. J. Antennas Propag.* **2016**, *2016*, 6075680. [[CrossRef](#)]
40. Gungor, A.C.; Olszewska-Placha, M.; Celuch, M.; Smajic, J.; Leuthold, J. Advanced modelling techniques for resonator based dielectric and semiconductor materials characterization. *Appl. Sci.* **2020**, *10*, 8533. [[CrossRef](#)]
41. Gregory, A.P.; Clarke, R.N. A review of RF and microwave techniques for dielectric measurements on polar liquids. *IEEE Trans. Dielectr. Electr. Insul.* **2006**, *13*, 727–743. [[CrossRef](#)]
42. Jha, A.K.; Akhtar, M.J. A generalized rectangular cavity approach for determination of complex permittivity of materials. *IEEE Trans. Instrum. Meas.* **2014**, *63*, 2632–2641. [[CrossRef](#)]
43. Hussain, N.S.M.; Azman, A.N.; Yusof, N.A.T.; Mohtadzar, N.A.A.H.; Karim, M.S.A. Design of resonator cavity for liquid material characterization. *TELKOMNIKA (Telecommun. Comput. Electron. Control)* **2022**, *20*, 447–454. [[CrossRef](#)]
44. Ribas, R.A.; Gelosi, I.E.; Uriz, A.J.; Moreira, J.C.; Bonadero, J.C. A high-sensitivity cylindrical cavity resonator sensor for the characterization of aqueous solutions. *IEEE Sens. J.* **2020**, *21*, 7581–7589. [[CrossRef](#)]
45. Varshney, P.K.; Akhtar, M.J. A compact planar cylindrical resonant RF sensor for the characterization of dielectric samples. *J. Electromagn. Waves Appl.* **2019**, *33*, 1700–1717. [[CrossRef](#)]
46. Sheen, J. Microwave measurements of dielectric properties using a closed cylindrical cavity dielectric resonator. *IEEE Trans. Dielectr. Electr. Insul.* **2007**, *14*, 1139–1144. [[CrossRef](#)]
47. Phakaew, T.; Oo, T.P.; Uzair, M.; Kowitwarangkul, P.; Chuchay, P.; Yeetsorn, R.; Torrungrueng, D.; Chudpooti, N.; Chalermwisutkul, S. Additively Manufactured Mechanically Tunable Cavity Resonator for Broadband Characterization of Liquid Permittivity. *Sensors* **2025**, *25*, 7145. [[CrossRef](#)] [[PubMed](#)]
48. Meng, B.; Booske, J.; Cooper, R. Extended cavity perturbation technique to determine the complex permittivity of dielectric materials. *IEEE Trans. Microw. Theory Tech.* **1995**, *43*, 2633–2636. [[CrossRef](#)]
49. Krupka, J.; Huang, W.T.; Tung, M.J. Complex permittivity measurements of thin ferroelectric films employing split post dielectric resonator. *Ferroelectrics* **2006**, *335*, 89–94. [[CrossRef](#)]
50. Janezic, M.D.; Krupka, J. Split-post and split-cylinder resonator techniques: A comparison of complex permittivity measurement of dielectric substrates. *J. Microelectron. Electron. Packag.* **2009**, *6*, 97–100.
51. Krupka, J.; Gregory, A.; Rochard, O.; Clarke, R.; Riddle, B.; Baker-Jarvis, J. Uncertainty of complex permittivity measurements by split-post dielectric resonator technique. *J. Eur. Ceram. Soc.* **2001**, *21*, 2673–2676. [[CrossRef](#)]
52. Krupka, J.; Gwarek, W.; Kwietniewski, N.; Hartnett, J.G. Measurements of planar metal–dielectric structures using split-post dielectric resonators. *IEEE Trans. Microw. Theory Tech.* **2010**, *58*, 3511–3518.
53. Mazierska, J.; Krupka, J.; Jacob, M.V.; Ledenyov, D. Complex permittivity measurements at variable temperatures of low loss dielectric substrates employing split post and single post dielectric resonators. In *Proceedings of the 2004 IEEE MTT-S International Microwave Symposium Digest (IEEE Cat. No. 04CH37535)*; IEEE: Piscataway, NJ, USA, 2004; Volume 3, pp. 1825–1828.

54. Muñoz-Enano, J.; Vélez, P.; Gil, M.; Martín, F. Planar microwave resonant sensors: A review and recent developments. *Appl. Sci.* **2020**, *10*, 2615. [\[CrossRef\]](#)
55. Fang, X.; Linton, D.; Walker, C.; Collins, B. Dielectric constant characterization using a numerical method for the microstrip ring resonator. *Microw. Opt. Technol. Lett.* **2004**, *41*, 14–17. [\[CrossRef\]](#)
56. Rashidian, A.; Aligodarz, M.T.; Klymyshyn, D.M. Dielectric characterization of materials using a modified microstrip ring resonator technique. *IEEE Trans. Dielectr. Electr. Insul.* **2012**, *19*, 1392–1399. [\[CrossRef\]](#)
57. Sarabandi, K.; Li, E.S. Microstrip ring resonator for soil moisture measurements. *IEEE Trans. Geosci. Remote Sens.* **1997**, *35*, 1223–1231. [\[CrossRef\]](#)
58. Verma, A.; Nasimuddin; Omar, A. Microstrip resonator sensors for determination of complex permittivity of materials in sheet, liquid and paste forms. *IEE Proc.-Microwaves Antennas Propag.* **2005**, *152*, 47–54. [\[CrossRef\]](#)
59. Jha, A.K.; Akhtar, M.J. SIW cavity based RF sensor for dielectric characterization of liquids. In *Proceedings of the 2014 IEEE Conference on Antenna Measurements & Applications (CAMA)*; IEEE: Piscataway, NJ, USA, 2014; pp. 1–4.
60. Varshney, P.K.; Akhtar, M.J. Permittivity estimation of dielectric substrate materials via enhanced SIW sensor. *IEEE Sens. J.* **2021**, *21*, 12104–12112. [\[CrossRef\]](#)
61. Chen, S.; Guo, M.; Xu, K.; Zhao, P.; Hu, Y.; Dong, L.; Wang, G. A dielectric constant measurement system for liquid based on SIW resonator. *IEEE Access* **2018**, *6*, 41163–41172. [\[CrossRef\]](#)
62. Mohammadi, P.; Mohammadi, A.; Kara, A. Enhanced half-mode SIW loaded with interdigital capacitor for permittivity measurements. *IEEE Transactions on Instrumentation and Measurement* **2023**, *72*, 1–8. [\[CrossRef\]](#)
63. Falcone, F.; Lopetegi, T.; Laso, M.; Baena, J.; Bonache, J.; Beruete, M.; Marqués, R.; Martín, F.; Sorolla, M. Babinet principle applied to the design of metasurfaces and metamaterials. *Phys. Rev. Lett.* **2004**, *93*, 197401. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Bahar, A.A.M.; Zakaria, Z.; Isa, A.A.M.; Ruslan, E.; Alahnomi, R.A. A Review of Characterization Techniques for Material's Properties Measurement using Microwave Resonant Sensor. *J. Telecommun. Electron. Comput. Eng. (JTEC)* **2015**, *7*, 1–6.
65. Su, L.; Mata-Contreras, J.; Vélez, P.; Martín, F. A Review of Sensing Strategies for Microwave Sensors Based on Metamaterial-Inspired Resonators: Dielectric Characterization, Displacement, and Angular Velocity Measurements for Health Diagnosis, Telecommunication, and Space Applications. *Int. J. Antennas Propag.* **2017**, *2017*, 5619728. [\[CrossRef\]](#)
66. Gavrilă, R.; Mocanu, I. Investigation on modified SRR for accurate dielectric measurements. In *Proceedings of the 2020 IEEE 26th International Symposium for Design and Technology in Electronic Packaging (SIITME)*; IEEE: Piscataway, NJ, USA, 2020; pp. 118–121.
67. Alotaibi, S.A.; Cui, Y.; Tentzeris, M.M. CSRR based sensors for relative permittivity measurement with improved and uniform sensitivity throughout [0.9–10.9] GHz band. *IEEE Sens. J.* **2019**, *20*, 4667–4678. [\[CrossRef\]](#)
68. Nogueira, J.K.; Oliveira, J.G.; Paiva, S.B.; Neto, V.P.S.; D'Assunção, A.G. A compact CSRR-based sensor for characterization of the complex permittivity of dielectric materials. *Electronics* **2022**, *11*, 1787. [\[CrossRef\]](#)
69. Velez, P.; Munoz-Enano, J.; Grenier, K.; Mata-Contreras, J.; Dubuc, D.; Martín, F. Split ring resonator-based microwave fluidic sensors for electrolyte concentration measurements. *IEEE Sens. J.* **2018**, *19*, 2562–2569. [\[CrossRef\]](#)
70. Das, G.S.; Buragohain, A.; Beria, Y. Microwave differential CSRR sensor for liquid permittivity measurement. *J. Electron. Mater.* **2024**, *53*, 3541–3547. [\[CrossRef\]](#)
71. Liu, W.; Zhang, J.; Huang, K. Dual-band microwave sensor based on planar rectangular cavity loaded with pairs of improved resonator for differential sensing applications. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 8005808. [\[CrossRef\]](#)
72. Rahman, M.Z.A.; Idris, M.I.; Jemaludin, N.H.; Mat, M.R.; Johari, S.; Alam, S.; Zakaria, Z. High-Q H-Shaped Nested Split-Ring Resonator Sensor for Liquid Complex-Permittivity Characterization. *IEEE Sens. J.* **2026**, *26*, 5510–5518.
73. Su, C.; Liu, G. High Sensitivity CPW Microwave Sensor Based on OCSRR and IDE Structure for Permittivity Characterization. *IEEE Sens. J.* **2025**, *25*, 21512–21519. [\[CrossRef\]](#)
74. Kooshki, S.S.; Ghalibafan, J.; Dehghani, F.; Kaboutari, K. M-SRR-based Microwave Sensor Design and Modeling for Evaluating Transformer Oil Quality and Lifespan Employing Relative Permittivity. *IEEE Sens. J.* **2026**, *26*, 15172–15184.
75. Wang, S.; Wan, C.; Chung, K.L.; Zheng, Y. Investigation of compact near-equidistant multimode resonator integrating skyrmionic metamaterial with SIW cavity and its application in dielectric material detection. *IEEE Trans. Microw. Theory Tech.* **2024**, *73*, 3565–3580. [\[CrossRef\]](#)
76. Prakash, D.; Gupta, N. Microwave grooved SRR sensor for detecting low concentration ethanol-blended petrol. *IEEE Sens. J.* **2023**, *23*, 15544–15551. [\[CrossRef\]](#)
77. Zable, M.A.H.; Ismail Khan, Z.; Abdul Rashid, N.E.; Zakaria, N.A.Z.; Ibrahim, I.P.; Ab Rahim, S.A.; Mahmood, M.K.A. Dielectric material measurement method: A review. *J. Electr. Electron. Syst. Res. (JEESR)* **2023**, *22*, 19–28. [\[CrossRef\]](#)
78. Haq, T.; Koziel, S. Rapid design optimization and calibration of microwave sensors based on equivalent complementary resonators for high sensitivity and low fabrication tolerance. *Sensors* **2023**, *23*, 1044. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Sheen, J.; Mao, W.; Liu, W. *Study on the Measurement Techniques of Microwave Dielectric Properties*; NST: Taipei, Taiwan, 2007; pp. 349–352.

80. Haq, T.; Koziel, S. New complementary resonator for permittivity-and thickness-based dielectric characterization. *Sensors* **2023**, *23*, 9138. [PubMed]
81. Chowdhury, N.M.; Hakim, M.L.; Alam, T.; Maash, A.A.; SinghSingh, M.J.; Soliman, M.S.; Islam, M.T.; Islam, M.S. Interconnected four split rectangular ring resonator flexible metamaterial for microwave sensing application. *Sci. Rep.* **2025**, *15*, 21230. [CrossRef] [PubMed]
82. Wang, X.; Wu, M.; Zhao, P. Dielectric identification method and system design of coal gangue based on frequency shift characteristics. *Sci. Rep.* **2025**, *15*, 8712. [CrossRef] [PubMed]
83. Singh, K.K.; Singh, A.K.; Mahto, S.K.; Sinha, R.; Al-Gburi, A.J.A. Enhanced accuracy and high sensitivity in dielectric characterization through a compact and miniaturized metamaterial inspired microwave sensor. *Sens. Actuators A Phys.* **2024**, *370*, 115271. [CrossRef]
84. Haq, T.; Koziel, S. Novel complementary multiple concentric split ring resonator for reliable characterization of dielectric substrates with high sensitivity. *IEEE Sens. J.* **2024**, *24*, 16233–16241. [CrossRef]
85. Baker-Jarvis, J.; Janezic, M.; Grosvenor, J.H., Jr.; Geyer, R. Transmission/Reflection and Short-Circuit Line Methods for Measuring Permittivity and Permeability, 1992. Provided by the SAO/NASA Astrophysics Data System. Available online: <https://ui.adsabs.harvard.edu/abs/1992STIN...9312084B> (accessed on 1 April 2023).
86. Peñaloza-Delgado, R.; Olvera-Cervantes, J.L.; Sosa-Morales, M.E.; Kataria, T.K.; Corona-Chávez, A. Dielectric characterization of vegetable oils during a heating cycle. *J. Food Sci. Technol.* **2021**, *58*, 1480–1487. [PubMed]
87. Ni, E.; Jiang, X. Microwave measurement of the permittivity for high dielectric constant materials using an extra-cavity evanescent waveguide. *Rev. Sci. Instrum.* **2002**, *73*, 3997–4002. [CrossRef]
88. Shan, X.; Shen, Z.; Tsuno, T. Wide-band measurement of complex permittivity using an overmoded circular cavity. *Meas. Sci. Technol.* **2008**, *19*, 025702. [CrossRef]
89. Jin, H.; Dong, S.; Wang, D. Measurement of dielectric constant of thin film materials at microwave frequencies. *J. Electromagn. Waves Appl.* **2009**, *23*, 809–817. [CrossRef]
90. Saeed, K.; Pollard, R.D.; Hunter, I.C. Substrate integrated waveguide cavity resonators for complex permittivity characterization of materials. *IEEE Trans. Microw. Theory Tech.* **2008**, *56*, 2340–2347. [CrossRef]
91. Pan, Y.; Leung, K.; Guo, L. Compact laterally radiating dielectric resonator antenna with small ground plane. *IEEE Trans. Antennas Propag.* **2017**, *65*, 4305–4310. [CrossRef]
92. Salski, B.; Pacewicz, A.; Kopyt, P. Measurement errors and uncertainties in the complex permittivity extraction with a Fabry–Perot open resonator. *IEEE Trans. Microw. Theory Tech.* **2023**, *71*, 4639–4648. [CrossRef]
93. Salski, B.; Karpisz, T.; Warecka, M.; Kowalczyk, P.; Czekala, P.; Kopyt, P. Microwave characterization of dielectric sheets in a plano-concave Fabry–Perot open resonator. *IEEE Trans. Microw. Theory Tech.* **2022**, *70*, 2732–2742.
94. Juan, C.G.; Potelon, B.; Aquino, A.; García-Martínez, H.; Quendo, C. Multi-parameter simultaneous extraction with a novel microwave sensor based on coupled resonators. *Sci. Rep.* **2024**, *14*, 23076. [CrossRef] [PubMed]
95. Ramella, C.; Pirola, M.; Corbellini, S. Accurate Characterization of High-Q Microwave Resonances for Metrology Applications. *IEEE J. Microwaves* **2021**, *1*, 610–624.
96. Buragohain, A.; Das, G.S.; Beria, Y.; Kalita, P.P.; Doloi, T.; Al-Gburi, A.J.A. Interdigitated capacitor based frequency splitting differential microwave sensor for complete dielectric characterization of organic liquids. *Sens. Actuators A Phys.* **2025**, *382*, 116127.
97. Almuhlafi, A.M.; Alshaykh, M.S.; Alajmi, M.; Alshammari, B.; Ramahi, O.M. A microwave differential dielectric sensor based on mode splitting of coupled resonators. *Sensors* **2024**, *24*, 1020. [CrossRef] [PubMed]
98. Li, Z.; Tian, S.; Tang, J.; Yang, W.; Hong, T.; Zhu, H. High-Sensitivity Differential Sensor for Characterizing Complex Permittivity of Liquids Based on LC Resonators. *Sensors* **2024**, *24*, 4877. [CrossRef] [PubMed]
99. Nikkhah, N.; Keshavarz, R.; Abolhasan, M.; Lipman, J.; Shariati, N. Highly sensitive differential microwave sensor using enhanced spiral resonators for precision permittivity measurement. *IEEE Sens. J.* **2024**, *24*, 14177–14188. [CrossRef]
100. Costa, F.; Borgese, M.; Degiorgi, M.; Monorchio, A. Electromagnetic characterisation of materials by using transmission/reflection (T/R) devices. *Electronics* **2017**, *6*, 95.
101. Janezic, M.D.; Williams, D.F.; Blaschke, V.; Karamcheti, A.; Chang, C.S. Permittivity characterization of low-k thin films from transmission-line measurements. *IEEE Trans. Microw. Theory Tech.* **2003**, *51*, 132–136.
102. Lin, X.; Seet, B.C. Dielectric characterization at millimeter waves with hybrid microstrip-line method. *IEEE Trans. Instrum. Meas.* **2017**, *66*, 3100–3102. [CrossRef]
103. La Gioia, A.; Porter, E.; Merunka, I.; Shahzad, A.; Salahuddin, S.; Jones, M.; O'Halloran, M. Open-ended coaxial probe technique for dielectric measurement of biological tissues: Challenges and common practices. *Diagnostics* **2018**, *8*, 40. [CrossRef] [PubMed]
104. Marsland, T.; Evans, S. Dielectric measurements with an open-ended coaxial probe. In *Proceedings of the IEE Proceedings H (Microwaves, Antennas and Propagation)*; IET: Central, Hong Kong, 1987; Volume 134, pp. 341–349.
105. Filali, B.; Boone, F.; Rhazi, J.; Ballivy, G. Design and calibration of a large open-ended coaxial probe for the measurement of the dielectric properties of concrete. *IEEE Trans. Microw. Theory Tech.* **2008**, *56*, 2322–2328. [CrossRef]

106. Kundu, A.; Gupta, B. Broadband dielectric properties measurement of some vegetables and fruits using open ended coaxial probe technique. In *Proceedings of the 2014 International Conference on Control, Instrumentation, Energy and Communication (CIEC)*; IEEE: Piscataway, NJ, USA, 2014; pp. 480–484.
107. Ghodgaonkar, D.; Varadan, V.; Varadan, V.K. Free-space measurement of complex permittivity and complex permeability of magnetic materials at microwave frequencies. *IEEE Trans. Instrum. Meas.* **2002**, *39*, 387–394.
108. Trabelsi, S.; Nelson, S.O. Free-space measurement of dielectric properties of cereal grain and oilseed at microwave frequencies. *Meas. Sci. Technol.* **2003**, *14*, 589.
109. Venkatesh, M.; Raghavan, G. An overview of dielectric properties measuring techniques. *Can. Biosyst. Eng.* **2005**, *47*, 15–30.
110. Juan, C.G.; Bronchalo, E.; Torregrosa, G.; Ávila, E.; García, N.; Sabater-Navarro, J.M. Dielectric characterization of water glucose solutions using a transmission/reflection line method. *Biomed. Signal Process. Control* **2017**, *31*, 139–147. [\[CrossRef\]](#)
111. Hasan, S.S.; Sundaram, M.; Kang, Y.; Howlader, M.K. Measurement of dielectric properties of materials using transmission/reflection method with material filled transmission line. In *Proceedings of the 2005 IEEE Instrumentation and Measurement Technology Conference Proceedings*; IEEE: Piscataway, NJ, USA, 2005; Volume 1, pp. 72–77.
112. Lee, T.N.; Lau, J.H.; Ko, C.T.; Xia, T.; Lin, E.; Yang, K.M.; Lin, P.B.; Peng, C.Y.; Chang, L.; Chen, J.S.; et al. Characterization of low-loss dielectric materials for high-speed and high-frequency applications. *Materials* **2022**, *15*, 2396. [\[PubMed\]](#)
113. Kapoor, M.; Daya, K.; Tyagi, G. Coupled ring resonator for microwave characterization of dielectric materials. *Int. J. Microw. Wirel. Technol.* **2012**, *4*, 241–246. [\[CrossRef\]](#)
114. Chehade, G.; Jarrix, S.; Sorli, B.; Vena, A. CSRR-based resonator for complex dielectric permittivity measurements up to 35 GHz. *Sens. Actuators A Phys.* **2025**, *399*, 117394. [\[CrossRef\]](#)
115. Kakutani, T.; Suzuki, Y.; Koh, M.; Sekiguchi, S.; Matsumura, S.; Oki, K.; Mishima, S.; Ishikawa, N.; Ogata, T.; Erdogan, S.; et al. Material design and high frequency characterization of novel ultra-low loss dielectric material for 5G and 6G applications. In *Proceedings of the 2021 IEEE 71st Electronic Components and Technology Conference (ECTC)*; IEEE: Piscataway, NJ, USA, 2021; pp. 538–543.
116. Yang, Y.; Mao, M.; Xu, J.; Liu, H.; Wang, J.; Song, K. Millimeter-Wave Antennas for 5G Wireless Communications: Technologies, Challenges, and Future Trends. *Sensors* **2025**, *25*, 5424. [\[CrossRef\]](#) [\[PubMed\]](#)
117. Sharma, A.; Khare, K.; Shrivastava, S. Dielectric resonator antenna for X band microwave application. *Res. Rev. Int. J. Adv. Res. Electr. Electron. Instrum. Eng.* **2016**, *2*, 2247–2252.
118. Singh, V.; Parikh, K.; Singh, S.; Bavaria, R. DR OMUX for satellite communications: A complete step-by-step design procedure for the C-band dielectric resonator output multiplexer. *IEEE Microw. Mag.* **2013**, *14*, 104–118.
119. Rappaport, T.S.; Sun, S.; Mayzus, R.; Zhao, H.; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Gutierrez, F. Millimeter wave mobile communications for 5G cellular: It will work! *IEEE Access* **2013**, *1*, 335–349. [\[CrossRef\]](#)
120. Rappaport, T.S.; Xing, Y.; Kanhere, O.; Ju, S.; Madanayake, A.; Mandal, S.; Alkhateeb, A.; Trichopoulos, G.C. Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond. *IEEE Access* **2019**, *7*, 78729–78757. [\[CrossRef\]](#)
121. Chen, X.P.; Wu, K. Substrate integrated waveguide filter: Basic design rules and fundamental structure features. *IEEE Microw. Mag.* **2014**, *15*, 108–116. [\[CrossRef\]](#)
122. Federico, G.; Hubrechtsen, A.; Caratelli, D.; Smolders, A.B. Relative Permittivity Measurements with SIW Resonant Cavities at mm-Wave Frequencies. In *Proceedings of the 2022 52nd European Microwave Conference (EuMC)*; IEEE: Piscataway, NJ, USA, 2022; pp. 103–106.
123. Wang, H.; Cheng, J.H.; Kao, J.C.; Huang, T.W. Review on microwave/millimeter-wave systems for vital sign detection. In *Proceedings of the 2014 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*; IEEE: Piscataway, NJ, USA, 2014; pp. 19–21.
124. Abd El-Hameed, A.S.; Elsheakh, D.M.; Elashry, G.M.; Abdallah, E.A. Cutting-edge microwave sensors for vital signs detection and precise human lung water level measurement. *Magnetism* **2024**, *4*, 209–239. [\[CrossRef\]](#)
125. Wessel, J.; Schmalz, K.; Yadav, R.K.; Zarrin, P.S.; Jamal, F.I.; Wang, D.; Fischer, G. Microwave and Millimeter Wave Sensors for Industrial, Scientific and Medical Applications in BiCMOS Technology. In *Proceedings of the 2020 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*; IEEE: Piscataway, NJ, USA, 2020; pp. 241–243.
126. Wang, D.; Yun, J.; Eissa, M.; Kucharski, M.; Schmalz, K.; Malignaggi, A.; Wang, Y.; Borngräber, J.; Liang, Y.; Ng, H.; et al. 207–257 GHz Integrated Sensing Readout System with Transducer in a 130-nm SiGe BiCMOS Technology. In *Proceedings of the 2019 IEEE MTT-S International Microwave Symposium (IMS)*; IEEE: Piscataway, NJ, USA, 2019; pp. 496–499.
127. Wang, C.; Zaki, K.A. Dielectric resonators and filters. *IEEE Microw. Mag.* **2007**, *8*, 115–127. [\[CrossRef\]](#)

128. Peverini, O.A.; Addamo, G.; Tascone, R.; Virone, G.; Cecchini, P.; Mizzoni, R.; Calignano, F.; Ambrosio, E.P.; Manfredi, D.; Fino, P. Enhanced topology of *E*-plane resonators for high-power satellite applications. *IEEE Trans. Microw. Theory Tech.* **2015**, *63*, 3361–3373.
129. Kazemipour, A.; Wollensack, M.; Hoffmann, J.; Hudlička, M.; Yee, S.K.; Rüfenacht, J.; Stalder, D.; Gäumann, G.; Zeier, M. Analytical uncertainty evaluation of material parameter measurements at THz frequencies. *J. Infrared Millim. Terahertz Waves* **2020**, *41*, 1199–1217. [[CrossRef](#)]
130. Ma, Q.; Dong, K.; Li, F.; Jia, Q.; Tian, J.; Yu, M.; Xiong, Y. Additive manufacturing of polymer composite millimeter-wave components: Recent progress, novel applications, and challenges. *Polym. Compos.* **2025**, *46*, 14–37.
131. Gugliandolo, G.; Arruzzoli, L.; Latino, M.; Crupi, G.; Donato, N. Self-Calibrating Resonant Sensor for Dielectric Material Characterization. *IEEE Trans. Instrum. Meas.* **2025**, *74*, 6009010. [[CrossRef](#)]
132. Solyom, K.; Lopez, P.R.; Esquivel, P.; Lucia, A.; Vásquez-Cañedo. Effect of temperature and moisture contents on dielectric properties at 2.45 GHz of fruit and vegetable processing by-products. *RSC Adv.* **2020**, *10*, 16783–16790. [[CrossRef](#)] [[PubMed](#)]
133. Baker-Fales, M.; Gutiérrez-Cano, J.D.; Catalá-Civera, J.M.; Vlachos, D.G. Temperature-dependent complex dielectric permittivity: A simple measurement strategy for liquid-phase samples. *Sci. Rep.* **2023**, *13*, 18171. [[PubMed](#)]
134. Haq, T.; Koziel, S.; Pietrenko-Dabrowska, A. Unsupervised design and geometry optimization of high-sensitivity ring-resonator-based sensors. *Sci. Rep.* **2025**, *15*, 17986. [[PubMed](#)]
135. Liao, J.; Shi, Z.; Dou, D.; Lu, H.; Ni, K.; Zhou, Q.; Wang, X. Deep Learning-Assisted Design for High-Q-Value Dielectric Metasurface Structures. *Materials* **2025**, *18*, 1554. [[PubMed](#)]
136. Sheng, Y.; Wu, Y.; Jiang, C.; Cui, X.; Mao, Y.; Ye, C.; Zhang, W. Interpretable model of dielectric constant for rational design of microwave dielectric materials: A machine learning study. *J. Mater. Inform.* **2025**, *5*, 7. [[CrossRef](#)]
137. Palandoken, M.; Gocen, C. RFID-enabled ML-assisted microwave liquid sensor design for complex dielectric characterization of water-methanol mixture. *Sens. Actuators A Phys.* **2025**, *382*, 116142. [[CrossRef](#)]
138. Abdolrazzaghi, M.; Kazemi, N.; Nayyeri, V.; Martin, F. AI-assisted ultra-high-sensitivity/resolution active-coupled CSRR-based sensor with embedded selectivity. *Sensors* **2023**, *23*, 6236. [[PubMed](#)]
139. Casacuberta, P.; Vélez, P.; Paredes, F.; Martín, F. Artificial Intelligence (AI)-Assisted Measurement of Glucose, Sodium, and Potassium Concentrations in Diluted Aqueous Solutions Using Microwaves. *IEEE Sens. Lett.* **2025**, *9*, 3503804.
140. Tian, X.; Sved, J.; Chen, Y.; Li, L.; Zhou, L.; Nguyen, L.; Minasian, R.; Yi, X. Deep Learning-Enhanced Microwave Photonic Sensing With Inverse-Design Assisted Fabry-Pérot Cavity. *J. Light. Technol.* **2025**, *43*, 9812–9819.
141. Khusro, A.; Akhter, Z.; Jha, A.K.; Shamim, A.; Hashmi, M.S. IoT-Driven Regression Tree Models for Efficient Microwave Dielectric Material Characterization: Addressing Non-Linear Cavity Sensing. *IEEE Internet Things J.* **2025**, *12*, 31891–31906.
142. Wang, S.; Xie, X.; Xu, B.; Shen, Y.; Zheng, Y. Plasmonic Skyrmion-Based Microfluidic-Integrated Flexible Microwave Meta-Resonator for Noninvasive Intelligent Flow Rate Sensing. *IEEE Trans. Microw. Theory Tech.* **2026**, *74*, 3833–3844.
143. Ma, J.; Qiao, L.; Watkins, G.; Dang, S.; Piechocki, R.; Haine, J.; Beach, M. Revolutionizing microwave circuit design with machine learning: Challenges and opportunities. *IEEE Commun. Mag.* **2024**, *62*, 100–106. [[CrossRef](#)]
144. Rayas-Sánchez, J.E.; Koziel, S.; Bandler, J.W. Advanced RF and microwave design optimization: A journey and a vision of future trends. *IEEE J. Microwaves* **2021**, *1*, 481–493. [[CrossRef](#)]
145. Chretiennot, T.; Dubuc, D.; Grenier, K. A microwave and microfluidic planar resonator for efficient and accurate complex permittivity characterization of aqueous solutions. *IEEE Trans. Microw. Theory Tech.* **2012**, *61*, 972–978. [[CrossRef](#)]
146. Ye, W.; Wang, D.W.; Wang, J.; Wang, G.; Zhao, W.S. An improved split-ring resonator-based sensor for microfluidic applications. *Sensors* **2022**, *22*, 8534. [[PubMed](#)]
147. Aggarwal, D.; de Campos, R.P.S.; Jemere, A.B.; Bergren, A.J.; Pekas, N. Integration of complementary split-ring resonators into digital microfluidics for manipulation and direct sensing of droplet composition. *Lab Chip* **2024**, *24*, 4461–4469. [[CrossRef](#)] [[PubMed](#)]
148. Sandarenu, U.; Ebrahimi, A.; Ghorbani, K. Microwave microfluidic sensor for dielectric characterization of liquids using phase and amplitude variations. *Sens. Actuators Phys.* **2025**, *396*, 117158. [[CrossRef](#)]
149. Yeap, K.H.; Tan, K.B.; Lee, F.W.; Lee, H.K.; Effendy, N.; Chin, W.C.; Toh, P.L. Enhanced Sensitivity Microfluidic Microwave Sensor for Liquid Characterization. *Processes* **2025**, *13*, 2183. [[CrossRef](#)]
150. Liu, S.; Orloff, N.D.; Little, C.A.; Zhao, W.; Booth, J.C.; Williams, D.F.; Ocket, I.; Schreurs, D.M.P.; Nauwelaers, B. Hybrid characterization of nanolitre dielectric fluids in a single microfluidic channel up to 110 GHz. *IEEE Trans. Microw. Theory Tech.* **2017**, *65*, 5063–5073. [[CrossRef](#)]
151. Dai, L.; Zhao, X.; Guo, J.; Feng, S.; Fu, Y.; Kang, Y.; Guo, J. Microfluidics-based microwave sensor. *Sens. Actuators A Phys.* **2020**, *309*, 111910. [[CrossRef](#)]
152. Dunsmore, J.P. *Handbook of Microwave Component Measurements: With Advanced VNA Techniques*; John Wiley & Sons: Hoboken, NJ, USA, 2020.

153. Joler, M. An Efficient and Frequency-Scalable Algorithm for the Evaluation of Relative Permittivity Based on a Reference Data Set and a Microstrip Ring Resonator. *Sensors* **2022**, *22*, 5591. [[CrossRef](#)] [[PubMed](#)]
154. Li, S.; Zhu, C. Microwave photonic fiber ring resonator for optical sensing based on in-ring and out-of-ring modulation. *IEEE Sens. J.* **2025**, *25*, 26653–26662.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.