Lecture Notes in Electrical Engineering 1150

Ferran Martín
Enrique Bronchalo *Editors*

Coupled Structures for Microwave Sensing

Springer

Lecture Notes in Electrical Engineering

Volume 1150

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ISSN 1876-1100 ISSN 1876-1119 (electronic)
Lecture Notes in Electrical Engineering
ISBN 978-3-031-53860-5 ISBN 978-3-031-53861-2 (eBook)
https://doi.org/10.1007/978-3-031-53861-2

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Preface

Within the paradigms of the Internet of Things (IoT) and Industry 4.0, there has been an increasing research activity for the development of high-performance low-cost sensors and sensor networks in recent years. Among the different technologies useful for sensing (e.g., electrochemical, optics, acoustics, or microwaves), microwave technology has attracted a significant interest within the Sensors Community. Thus, microwave sensors (especially planar sensors) have been the subject of an intensive and progressively growing research in the last decade, with an exponentially increasing number of journal and conference papers devoted to this topic, and a proliferation of projects and contracts with companies. Various reasons explain the growing interest for planar microwave sensors, including their low cost and profile, their small size, or the possibility of sensor implementation on flexible substrates, including polymeric and organic substrates, as well as fabric. Their compatibility with other technologies (e.g., microfluidics, textiles, micromachining, 3D printing, etc.), and with both additive (e.g., inkjet- or screen-printing) and subtractive (e.g., photoetching) fabrication processes are also key factors that justify such growing interest. Additionally, microwaves are very sensitive to the electromagnetic properties of the materials to which they interact. Thus, microwave sensors are very useful for the dielectric characterization of materials (solids or liquids), and for the measurement of many variables related to material permittivity. Planar microwave sensors can operate by contact or contactless with the material under test (MUT) or analyte, and can be wirelessly connected to the reader (of special interest in many IoT applications), in schemes based on the so-called sensing tags (which act as a "smart skin", able to provide information of the material or sample under study). Let us also mention that the necessary associated electronics for signal generation, post-processing, and, eventually, communication purposes of planar sensors can be integrated within the sensor's substrate. This represents a simplicity in system design and reduces the overall sensor costs. Finally, microwaves, adopting the broadest sense of the term (i.e., including ultra-high frequency—UHF—waves, millimeter waves, and THz waves), are very versatile, as far as many different types of materials and analytes, as well as a wide variety of physical, chemical, and biological variables, can be measured, monitored, or characterized by means of microwave sensors (e.g., material properties and composition, vital constants, bacterial growth, medical variables, physical variables, such as temperature and humidity, displacements and velocities, etc.).

Several indicators determine the performance of planar microwave sensors (linearity, dynamic range, sensitivity, resolution, accuracy, repeatability, selectivity, etc.), but probably the most representative performance indicator is the sensitivity, intimately related to resolution, and critical in applications where tiny variations of the input variable (measurand) should be detected. Thus, sensitivity optimization has been the "battle horse" for researchers involved in microwave sensing for many years, and it is still a hot topic of research. Many strategies for sensitivity enhancement in planar microwave sensors have been reported in the recent literature, including active feedback in frequency-variation sensors, step-impedance configurations terminated with resonant elements in phase-variation sensors, or schemes based on resonance–anti-resonance in coupling-modulation sensors, to cite some of them. It has been recently demonstrated that coupled structures, including coupled lines and coupled resonators, are very interesting in order to implement highly sensitive microwave sensors. Thus, various international groups have dedicated a significant effort to optimize the sensitivity (as well as other performance indicators) in planar microwave sensors using schemes based on coupled lines and coupled resonators. This book is intended to provide an overview of such sensing schemes and strategies through the contribution of the most relevant and reputed international Groups in these topics.

The book contains two introductory chapters, one devoted to the topic of planar microwave sensors (Chapter "Planar Microwave Sensors"), and the other one (Chapter "Coupled Planar Microwave Resonators and Transmission-Line Structures") focused on coupled microwave structures. The main aim of these chapters is to familiarize the reader with the main concepts used in the subsequent chapters. Moreover, Chapter "Planar Microwave Sensors" provides an up-to-date state of the art in planar microwave sensors useful to appreciate, and understand, the potential of coupled structures for sensing. The book then covers in the following chapters the main proposed strategies for sensitivity optimization by using coupled structures, including coupled lines and directional couplers, as well as coupled distributed and semi-lumped resonators. Such strategies encompass coupling schemes used to enhance the variation of the frequency, the phase, the magnitude, or the quality factor (the typical output variables of the considered sensors) with the dielectric properties of the materials under study. A diversity of schemes, such as weakly coupled structures, electromagnetic induced transparency (EIT)-like structures, coupled line directional couplers, electrically/magnetically coupled resonators, etc., will be reviewed throughout the different book chapters. Essentially, the considered sensors in the different chapters are permittivity sensors. Nevertheless, a final book chapter will also be dedicated to sensors based on magneto-inductive (MI) wave transmission lines for contactless resonant imaging of conductive environments.

Chapter "Permittivity Sensors Based on Coupled Line Sections" focuses on coupled-line section sensors excited by a differential signal and is devoted to the dielectric characterization of solid and liquid samples. It is shown in the chapter that by locating the samples under study in the region between the coupled lines, where there is a high density of electric field lines, the sensitivity can be enhanced. Various types of configurations are considered, including edge-coupled and broadside-coupled structures, operating in reflection as well as in transmission, and an exhaustive analysis is carried out for all of them. It is shown that, from such analysis, using a systematic procedure, the complex permittivity of the materials under study can be obtained.

In Chapter “Coupled-Line Directional Coupler Permittivity Sensors”, the authors utilize a microstrip coupled-line directional coupler for dielectric constant sensing. The material under test is placed on top of the coupled lines, and the dielectric properties are retrieved from the coupler’s response, particularly from the coupling and isolation levels. It is shown in the chapter that high sensitivity can be achieved, especially when the isolation level is considered.

Reflective-mode phase-variation permittivity sensors based on coupled resonators (either distributed or semi-lumped), and operating at a single frequency, is the topic of Chapter “Reflective-Mode Permittivity Sensors Based on Distributed and Semi-Lumped Coupled Resonators”. Unprecedented sensitivities can be achieved by weakly coupling the resonant elements, a consequence of the proximity between the split resonances when the coupling is weak. It is shown in the chapter that by tuning the operating frequency in the region between such resonances, the sensitivity increases as the inverse square of the coupling coefficient. The effects of losses are also analyzed, and it is concluded that losses might benefit sensitivity, provided the sensor is adequately designed.

In Chapter “Transmission-Mode Permittivity Sensors Based on Coupled Resonators”, transmission-mode sensors consisting of a transmission line loaded with a pair of coupled resonators are presented. The frequency response of these sensors exhibits two zeros and a transmission peak in between. Such sensors can be considered to be based on the microwave analog of electromagnetic induced transparency (EIT), a well-known phenomenon in the field of optics, where a transmission zero in the response of a single resonator reverses to a peak (transparency) when an additional resonator is coupled to the existing one. It is demonstrated in the chapter that such transmission peak is very sensitive to variations in the dielectric properties of the samples under study, placed on top of the coupled resonators. The chapter also includes sensing structures with multiple transparent peaks based on spoof localized surface plasmon (spoof-LSP) resonators.

Analytical methods to retrieve the permittivity of dielectric samples by means of symmetrically coupled resonators are covered in Chapter “Analytical Methods to Retrieve the Permittivity by Means of Coupled Resonators”. By using a circuit model of the coupled resonators and the responses of reference materials with known dielectric properties, the permittivity and the loss tangent of the sample under test can be expressed in terms of the coupling coefficient between the resonators. Moreover, the different geometries of the electric field in the even and odd resonances are used to measure the dielectric properties of samples with uniaxial anisotropy.

Chapter “Planar Microwave Sensors Based on Coupled Ring Resonators and Applications”, focused on sensors based on coupled ring resonators, shows how the coupling between the ring resonators can enhance the sensitivity, dynamic range, selectivity, and detection range in microwave sensors. The chapter illustrates how utilizing coupled ring configurations can optimize the detection of physical quantities, such as UV radiation, mass of material samples, etc. The chapter also includes wireless sensors, based on antenna configurations used to excite the resonant elements. Practical applications are also reported in the chapter.

Chapter "Solute Concentration Sensing in Aqueous Solutions with Coupled Microstrip Resonators" focuses on the application of sensors based on coupled microstrip resonators to the determination of the solute concentration in aqueous solutions. After presenting the dielectric and conductive properties of these solutions, based on broadband experimental measurements, the chapter presents an exhaustive analysis of the proposed sensors, where the influence of the mutual and self-capacitances of the resonators on the sensitivity is discussed. The chapter also reports two practical examples of sensors applied, respectively, to binary (water–glucose) and ternary (water–sucrose–sodium chloride) solutions.

Finally, Chapter "Sensing Using Magnetoinductive Waves" is devoted to microwave sensing based on magneto-inductive (MI) waves, a type of wave supported by an array of magnetically coupled resonators. Recently, MI waves have been used in contactless resonant imaging of conductive environments, both in the frequency and in the time domain. The underlying physics is that a perturbation due to the presence of a conductive object in the vicinity of a meta-atom (a resonant element of the array) causes reflections of MI waves within the array. The focus in the chapter is time-domain reflectometry, where accurate single and multiple defect localization and characterization is demonstrated. Potential applications for real-time contactless monitoring of inhomogeneous conductive environments ranging from in situ 3D printing quality monitoring to medical imaging are discussed.

To end this preface, let us mention that the contributors of the different chapters included in the book have been given full freedom to conceive and structure their respective assigned chapters at their convenience. For this main reason, certain overlapping between some chapters, as well as some differences in the considered terminology and nomenclature from chapter to chapter, have been accepted by the book Editors. It is the Editors' hope that the present book results of interest to Academia and Industry, especially to researchers, postgraduate students, and professionals involved in microwave and sensor technologies.

Barcelona, Spain
Elche, Alicante, Spain
December 2023

Ferran Martín
Enrique Bronchalo

Acknowledgments

The Editors would like to express their most sincere gratitude to the contributors of the present book. It has been really a pleasure to work with them on this project, with the result of a complete and up-to-date manuscript on the topic of microwave sensors based on coupled structures. We would like also to thank Anna Cedenilla for her effort in handling the permissions of reproduced figures, as well as for her assistance to the book contributors on this subject. The contents presented in this book have been the result of a research activity carried out by authors of the different chapters in the last years. The Editors would like to thank, on behalf of all the book contributors, the funding Agencies and Institutions that have supported our activity through many research projects and contracts. A list of the most representative is given below:

- Grants PID2019-103904RB-I00, PID2022-139181OB-I00, and PID2022-139783OB-I00, Agencia Estatal de Investigación, Ministerio de Ciencia e Innovación, Spain (MCIN/AEI 10.13039/501100011033).
- Grant 2019/34/E/ST7/00342, National Science Centre, and Subvention of the Institute of Electronics, AGH University of Science and Technology, Krakow, Poland.
- Grant 62301104, National Natural Science Foundation of China, Grant 2022RQ034, Dalian Youth Science and Technology Star Project, Grant K202202, State Key Laboratory of Millimeter Waves, and Grant JYTMS20230170, Basic Scientific Research Project of Education Department of Liaoning Province.
- SYMETA grant EP/N010493/1, Engineering and Physical Sciences Research Council (EPSRC), United Kingdom.
- Grant CIAPOS/2021/267, APOSTD Program, Conselleria d'Innovació, Universitats, Ciència i Societat Digital, Generalitat Valenciana, and European Social Fund.
- Grants RYC2022-036257-I and RYC2022-035819-I (Ramón y Cajal Program), grant IJC2019-040786-I (Juan de la Cierva Program), and FPU Grant FPU20/05700 (Ayudas para la formación de profesorado universitario), Ministerio de Ciencia e Innovación, and Ministerio de Universidades, Spain, and European Union.

The authors of some chapters would like also to express their gratitude to several persons for their support to the research activities reported in this book:

- The authors of Chapters 1 and 5 are grateful to Gerard Sisó and Javier Hellin for fabricating the prototypes, and to the Administrative Staff of the Departament d'Enginyeria Electrònica (Marta Mora, Mari Carmen Cosano, Mònica Mateu, Laura Romera, and Ton Vendrell), Universitat Autònoma de Barcelona, for their support concerning management and administrative issues.
- The authors of Chapter 6 are grateful to Mengqi Li and Suiqing Xu for their support.
- The authors of Chapter 9 would like to thank Anyela Aquino Velasquez, Thierry Aubry, Ernesto Ávila-Navarro, Odette Sandrine Bakam Nguenouho, Jessica Benedicto, Jean Luc Carré, Rubén Martínez, Juan M. Morcillo de Miguel, Christian Person, Patrick Queffelec, Philippe Roquefort, José M. Sabater-Navarro, Bernard Simon, Mahdi Srour, and UBO Open Factory team.
- The authors of Chapter 10 are grateful to Grahame Faulkner for assistance with the setup and to the colleagues from the OxiMeta network for fruitful discussions.

The Editors are also indebted to their respective families for their patience and understanding during the preparation of this manuscript and for their continuous and unconditional support. Thank you very much!

Ferran Martín
Enrique Bronchalo

Contents

Planar Microwave Sensors

Ferran Martín

Abstract In this introductory chapter to planar microwave sensors, the main sensing approaches and working principles are presented, and some representative illustrative prototype examples are reported. Some strategies devoted to sensor performance optimization (manly the sensitivity) are discussed, excluding those strategies based on coupled structures, which are the subject of the subsequent chapters in the book. The chapter also highlights how machine learning can be applied to improve sensor robustness and selectivity. Finally, a section is devoted to outline those aspects of coupled structures that make them useful for sensing.

Microwave sensors have been the subject of an increasing research activity in recent years. Such growing interest for the development of novel sensing elements based on microwave technology has been motivated by a series of causes, including the advent of the fourth industrial revolution [1–5], also known as Industry 4.0, the progressive deployment of the so-called Internet of Things (IoT) [6–10], and the proliferation of Smart Systems [11] in a variety of scenarios (e.g., smart cities, smart health, smart agriculture, or structural health monitoring—SHM, to cite some of them). It is obvious that in an intelligent and interconnected world, aligned with the digital transformation associated with the previous paradigmatic (and revolutionary) concepts (Industry 4.0, IoT, and Smart Systems), sensors and sensor networks are key components. Thus, data collection from the environment or from a certain system is fundamental in order to retrieve information from that system and take actions (typically autonomously) when necessary. For example, structural damage in civil and urban infrastructures caused, e.g., by corrosion, or by extreme ambient conditions, might represent a critical risk for citizens (unfortunately, there are various

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F. Martín and E. Bronchalo (eds.), *Coupled Structures for Microwave Sensing*,
Lecture Notes in Electrical Engineering 1150,
https://doi.org/10.1007/978-3-031-53861-2_1

well-known examples of bridges or buildings that have collapsed). Thus, the continuous monitoring of structural health in civil and urban infrastructures (for automatically detecting any potential damage without human intervention) using sensors and sensor networks is of the highest interest, and the research activity in this field has experienced an exponential growth in recent years [12–30].

Even though, besides microwaves, there are many other technologies useful for sensing, including optics, ultrasounds, mechanical, magnetic, electrical, electrochemical, etc., microwave sensors (adopting the broadest sense of the term, from ultra-high frequency—UHF—sensors up to THz sensors) exhibit a relevant advantage, i.e., their inherent wireless connectivity. This is an important aspect within the framework of the IoT and digital world, where sensor networks wirelessly connected to a central unit are necessary. The so-called radiofrequency identification (RFID) sensors, also designated as sensing tags, are considered an enabling technology for IoT, and an increasing research activity, especially for the implementation of chipless and battery-free RFID-sensors, is going on (see [31–43] and [44], Chap. 7). Thus, although optical sensors probably dominate the sensors' market, and there are many applications where such sensors exhibit superior performance (as compared with other sensing technologies),[1] the (unique) wireless connectivity of microwave sensors has been a key aspect towards the expansion of such sensing technology (both at research level and commercially) and penetration in the market. Nevertheless, there are many other advantages of microwave sensors over their optical counterparts. For example, microwaves are very sensitive to the dielectric properties of the materials to which they interact. Thus, microwave sensors are canonical permittivity sensors, able to provide the complex dielectric constant of the so-called material under test (MUT) [45–49], as well as many other variables related to it, such as material composition, or certain physical variables related to material's permittivity (e.g., temperature and humidity)[2] [50–52]. Moreover, the presence of defects in samples correlates with the average, or effective, dielectric constant "seen" by the sensing element (typically a transmission line, a waveguide, or a resonator). Thus, microwave sensors are very useful for defect detection (a canonical application might be structural health monitoring). Another advantage of microwaves over optical radiation concerns the fact that microwaves penetrate certain substances (dielectrics), and therefore can be useful to retrieve information non-intrusively and non-invasively. Thus, microwave sensors can potentially be useful in medical applications, for example for monitoring vital signals [53, 54], or for the detection of malignant tissues or tumors, among many others[3] [55, 56]. Another benefit that derives from the capability of microwaves to

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[1] For example, optical sensors exhibit very high sensitivity and selectivity for the detection of many types of biological analytes, such as toxins, drugs, antibodies, proteins, viruses, etc.

[2] In order to enhance the sensitivity of the sensor to temperature or humidity, functional materials exhibiting a strong dependence of the permittivity with those variables can be used. Examples of such materials are polyvinyl alcohol (PVA), with a dielectric constant very sensitive to humidity, or polyamide, a material that exhibits a temperature dependent dielectric constant. This aspect will be further considered in Sect. 2.1.4.

[3] Obviously, there are several commercial techniques for the diagnosis of cancer, e.g., magnetic resonance imaging (MRI), computerized tomography (CT), positron emission tomography (PET),

penetrate dielectric media (not transparent in general for light) is the possibility to detect buried objects. This is the case of the so-called ground penetrating RADAR (GPR), a type of remote microwave sensor commercially available and useful in dozens of applications (e.g., in archaeology, civil engineering, etc.) [57–59].

Further advantages of microwaves for sensing result by implementing the sensors in planar technology [44]. Thus, planar microwave sensors exhibit low cost and profile, as compared to non-planar sensors (such as cavity sensors [45–49], waveguide sensors [60, 61], or coaxial probes [62–66]). Moreover, planar sensors can be implemented in a variety of substrates, including rigid (e.g., low-loss commercial microwave substrates or general-purpose substrates, such as FR4) and flexible substrates (e.g., polymeric substrates, organic substrates, such as paper, and textile substrates, such as fabric), and by means of both subtractive (e.g., photoetching) and additive (e.g., screen- or inkjet-printing) fabrication processes. Therefore, planar microwave sensors can be useful for the implementation of conformal elements that adapt to the surface of the sample under study (e.g., bracelet sensors [67]), or can be of interest for the implementation of wearables (integrated in garments and clothes) [68–71], or green sensors (e.g., on paper substrates combined with organic conductive inks [72]). Additional advantages of planar technology for sensing include the possibility of integration of the associated electronics (needed for signal generation, post processing, and, eventually, for communication purposes) in the same substrate (with the consequent reduction in cost and overall dimensions), as well as the compatibility of planar sensing structures with microfluidics, micromachining, and 3D-printed elements (e.g., mechanic holders). Thus, liquid monitoring and characterization with planar sensors is possible by combining the sensitive elements (e.g., semi-lumped resonators) with micro-channels [73–75], micro-pipes [76], or 3D-printed holders (pools) [77, 78] containing the liquid under test. Applications of such sensors include the identification of impurities in liquid samples, the determination of volume fraction of components in liquid mixtures, or the detection of deterioration in certain agrifood products by usage (e.g., oils subjected to frying processes), among others.

The present book focuses on the design and implementation of planar microwave sensors based on coupled structures (coupled lines, directional couplers, and coupled resonators) as sensing elements, as well as on the different reported strategies for performance optimization (mainly to boost up the sensitivity, or derivative of the output variable with the input variable). Unprecedented sensitivities with such sensors, proposed in recent years, have been demonstrated (to be reported later in this book). Nevertheless, there are many other approaches for the implementation of planar microwave sensors. Such approaches, obeying to different working principles, have their own advantages and drawbacks, which should be discussed in order to better understanding the high potential of planar microwave sensors based on coupled structures, the subject of this monograph. Thus, the present introductory chapter briefly analyzes (in Sect. 1) the different types of planar microwave sensors

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or ultrasounds, among others, but these techniques are, in general, very expensive, and, in some cases, annoying for the patients.

grouped by working principle and provides some illustrative examples (excluding those sensors based on coupled structures, exhaustively studied in the subsequent chapters of this book).[4] The chapter also dedicates a unit (Sect. 2) to present some strategies for performance optimization (with especial emphasis on sensitivity enhancement). Section 3 concisely outlines the potential of machine learning (ML) for selectivity and robustness improvement in microwave sensors (a topic that has attracted the interest of the Microwave Sensors Community). Finally, Sect. 4 briefly highlights the potential of coupled structures for microwave sensing, as a link between the planar microwave sensors overviewed in this chapter and those to be studied in detail in the subsequent chapters. A general overview of other sensor technologies, including optical, acoustic, mechanical, magnetic, electrical, electrochemical, as well as microwave (non-planar and remote) sensors, is out of the scope of this book, but the interested reader can find detailed information in other sources, e.g., in [44]. A detailed list (and description) of the main sensor performance indicators (sensitivity, resolution, dynamic range, linearity, error, etc.) is also given in [44].

1 Classification of Planar Microwave Sensors

Microwave sensors can be divided in two main categories: remote and non-remote. Remote sensors, mainly RADARs (radio detection and ranging) and radiometers, gather information of an object (e.g., the velocity of a moving target) or physical phenomenon/system (e.g., rainfall detection in a certain region) without physical contact with it [57–59, 79–82]. Moreover, the target is typically located at significant distances from the sensing element. By contrast, in non-remote microwave sensors, the measurand (e.g., the dielectric properties of a certain MUT, or any physical, chemical, or biological variable of interest) is retrieved by proximity (not necessarily by contact), through the in situ interaction of microwaves with matter. Non-remote microwave sensors can be further divided between non-planar and planar. The latter, those of interest in the present book, as mentioned, are implemented by either additive or subtractive fabrication processes on a planar substrate, and their advantages over the non-planar counterparts (mainly cavity, waveguide, and coaxial sensors) have been indicated before. There are many different classification criteria for planar microwave sensors, including the application type, the frequency of operation, or the working principle. In this section, the adopted classification scheme for planar microwave sensors follows their working principle, since such categorization provides physical insight on the mechanisms governing sensor's functionality and performance. Nevertheless, there is a set of binary classification schemes (applicable in most cases to other sensor types) that should be briefly presented, since such schemes are exhaustively used throughout this book.

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[4] Nevertheless, other binary classification schemes of planar microwave sensors are also included in Sect. 1.

1.1 Binary Classification Schemes

Planar microwave sensors can be binary classified as follows: contact/contactless, invasive/non-invasive, intrusive/non-intrusive, wired/wireless, single-ended/differential, resonant/non-resonant, and reflective-mode/transmission-mode. Let us next give some more details of each binary classification scheme.

1.1.1 Contact and Contactless Sensors

In contact sensors, the MUT is in direct contact with the sensitive element, e.g., a planar resonator or a transmission line section, whereas in contactless sensors, such contact is inexistent. Nevertheless, proximity between the sample and the sensitive element is required in contactless sensors, so that the MUT modifies the electromagnetic properties of the sensitive element (e.g., the resonance frequency or quality factor in resonant-type sensors, or the phase of the reflection or transmission coefficient in non-resonant sensors) through the interaction with the electromagnetic fields generated by such sensitive element.

In contact sensors, there are two main issues that should be briefly discussed: (i) the air gap between the sensitive element and the MUT (for solid MUTs), and (ii) substrate absorption, when the MUT is a liquid. The air gap is the cause of inaccuracies in the determination of the permittivity of the MUT. To circumvent the presence of the air gap, a usual procedure is to pressure the MUT against the sensitive element (e.g., by means of Teflon screws, or by means of clamps). Substrate absorption might also generate false measurement results since it alters the permittivity of the substrate. The usual approach to avoid substrate absorption is to coat the sensitive region with a narrow dry film able to repel liquids (for instance, in [74], a 0.12-mm thick glass film, with dielectric constant $\varepsilon_r = 5.5$, was used). Note that with the presence of such film, the MUT is prevented to be in direct contact with the sensitive part of the sensor. Nevertheless, such dry film can be considered part of the sensing element, and therefore such sensors are contact devices, provided the MUT (a liquid) is in contact with such film (the typical situation in microfluidic sensors, in liquid sensors based on mechanical holders, or in submersible sensors).

In some contactless sensors, the sensitive element is not in direct contact with the MUT, but with an element that contains the MUT, for example, a pipe or a channel, where a certain liquid flows. There are examples of sensors where such elements (pipes or channels) are positioned on top of the sensor substrate [83], in contact with (or close to) the sensitive region, whereas in other cases, small micro-channels or micro-pipes are embedded within the sensor substrate [84]. There are also cases where a pipe containing the liquid under study crosses transversally the sensor substrate (i.e., with the axis of the pipe orthogonally oriented with regard to the substrate plane) [76, 85], but typically such sensors exhibit a limited sensitivity, as compared to those sensors where the pipe or channel axis is parallel to the substrate plane. Figure 1 illustrates all these possibilities.

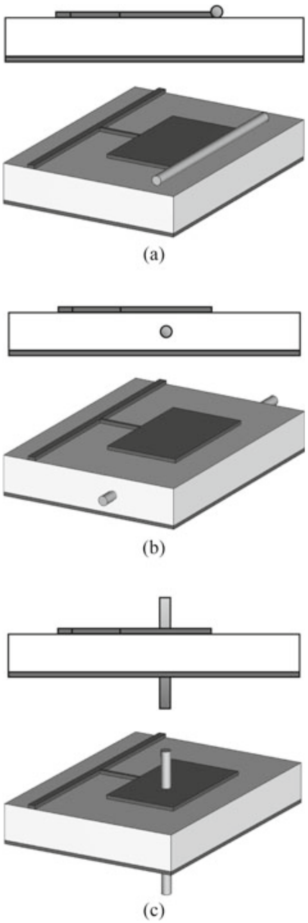

Fig. 1 Cross-sectional and perspective views (schematic) of contactless liquid sensors based on circularly shaped pipes (the element driving the liquid under study) placed on top of the substrate (**a**), embedded in the substrate (**b**), or transversally oriented with regard to the substrate, crossing it (**c**)

1.1.2 Invasive and Non-invasive Sensors

Such terminology mainly refers to liquid sensors and the difference lies in whether the sensitive element of the sensor "invades" the liquid under study or not. Invasive sensors are necessarily contact sensors, whereas in non-invasive sensors, the sensitive element is placed outside of the pipe or channel containing the fluid. Figure 2 illustrates the difference between invasive and non-invasive sensors.

1.1.3 Intrusive and Non-intrusive Sensors

Non-intrusive sensors, either invasive or non-invasive, do not interfere with the flow profile. By contrast, intrusive sensors protrude into the flow and distort the flow profile, as it can be appreciated in Fig. 2. In general, non-intrusive and non-invasive

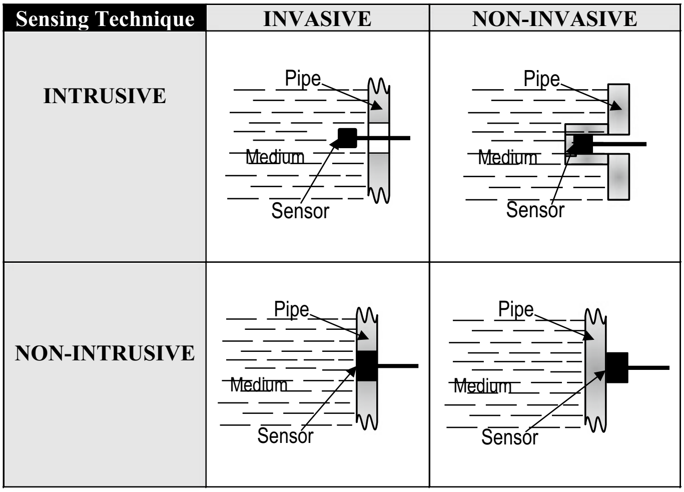

Fig. 2 Distinction between invasive/non-invasive and intrusive/non-intrusive sensors. Reprinted with permission from [44], copyright 2023 Wiley

sensors are preferred in order to prevent from any potential alteration of the liquid under study caused by direct contact with the sensing element, and to avoid perturbing the element driving the liquid (a tube, a pipe, or a channel, typically).

1.1.4 Wired and Wireless Sensors

Wired/wireless sensors should not be confused with contact/contactless sensors. The latter terminology, as it has been explained in Sect. 1.1.1, is used to differentiate whether the sensitive element is in direct contact with the MUT, or not. By contrast, the “wireless” or “wired” characteristic refers to the type of communication (data transfer) between the sensing element and the central unit. Thus, both wired and wireless sensors can be either contact or contactless, depending on the specific transduction mechanism (contact or contactless) to retrieve the sensing data from the sample under study or stimulus. Wireless sensor networks (WSNs) and RFID sensors are examples of wireless sensors.

1.1.5 Single-Ended and Differential Sensors

Single-ended sensors, also called absolute sensors, consist of a single sensing element that provides the (absolute) output variable in response to a certain stimulus or measurand. Differential-mode, or relative, sensors are based on two independent (typically identical) sensing elements (the sensing pair), each one responding to its own stimulus or measurand. However, in differential sensors, the considered input variable is the difference between the input variable present in either sensor, whereas the difference between the output variable in each sensor is the considered output (differential) signal. Differential sensors are costly and oversized, as compared to their single-ended counterparts, for obvious reasons. Nevertheless, differential-mode sensors are robust against cross-sensitivities caused by ambient factors (e.g., temperature or humidity), since such environmental variables are “seen” as common-mode stimuli by such sensors. This is the main advantageous aspect of differential-mode sensors over single-ended sensors. To reduce costs and sometimes to alleviate the effects of sensor imbalance (causing inaccurate results),[5] single-ended sensors can operate “differentially” by simply performing two consecutive single-ended measurements (two-step process differential measurements). As far as ambient factors do not change in the time lapse between the two measurements, sensor robustness against such cross-sensitivities is preserved. However, retrieving the differential sensor data by means of a two-step process (using single-ended sensors) is not a real-time measurement, and such approach cannot be applied in many applications (e.g., in measurements where the input variable changes very fast or should be monitored continuously). Differential sensors are of special interest in applications where differences between a sample (sample under study) and a reference (REF) sample should be detected. In such comparator functionality, tiny differences between the MUT sample and the REF sample can be discriminated provided the sensor exhibits high sensitivity (intimately related to resolution) and sensor imbalances are negligible. The authors recommend the review paper [86], focused on balanced transmission lines, circuits, and sensors, to those readers interested in differential-mode sensors.

1.1.6 Resonant and Non-resonant Sensors

Planar microwave resonant sensors are typically implemented by means of a transmission line coupled to a planar resonator (the sensitive element) [77] or loaded with it [87]. Nevertheless, there are other possible configurations of planar resonant sensors, e.g., a planar antenna loaded with an electrically small resonant element [88], or simply a resonator, or a set of resonators, etched on a dielectric substrate, and excited by a certain interrogation signal (this is the approach used in backscattering sensing RFID tags) [18, 52]. Figure 3 depicts all these possible configurations. There are many types of planar resonant elements useful for sensing, including distributed resonators (e.g., open ended or short-circuited quarter- and half-wavelength transmission lines) and semi-lumped resonators, either metallic (e.g., the split ring resonator, SRR, or the step-impedance resonator, SIR, among others) or slotted (e.g., the complementary split ring resonator, CSRR, or the dumbbell-shaped defect ground structure, DB-DGS, resonator, among others) [44].

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[5] By sensor imbalance, we mean potential differences between the sensors constituting the differential sensor pair, typically caused by fabrication related tolerances. Such imbalances might generate a non-negligible output (differential) signal, despite the fact that the input differential signal is null. Thus, the accuracy in the manufacturing process is critically important in differential-mode sensors.

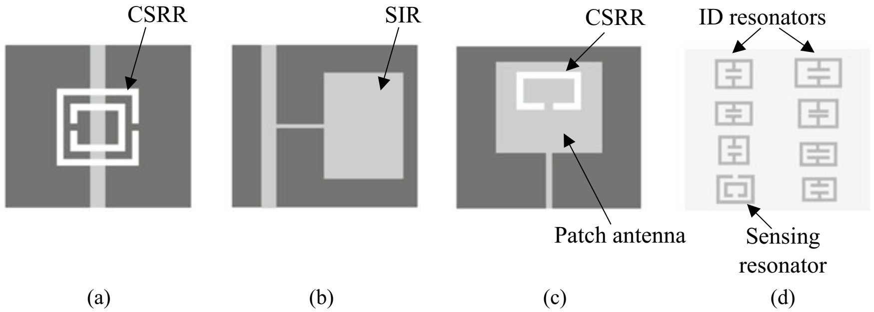

Fig. 3 Topologies of some possible configurations of resonant sensors. **a** Transmission line coupled to a semi-lumped resonant element (CSRR); **b** transmission line loaded with a semi-lumped resonator (SIR); **c** patch antenna loaded with a resonant element (CSRR); **d** back-scattered chipless-RFID sensor based on a set of resonators for identification, and one resonator for sensing. The upper metal level is depicted in soft grey, whereas the lower metal level is depicted in dark grey

By contrast, planar non-resonant sensors typically consist of a transmission line section, which acts as sensitive element, and, eventually, of other planar elements. To reduce the dimensions of the sensing region, a common procedure is to meander the sensing line [89]. Nevertheless, there are other useful approaches to decrease the size of the sensor, for example, by implementing the sensitive part with artificial transmission lines, including slow-wave transmission lines [90], composite right/left handed (CRLH) transmission lines [91], or electroinductive-wave (EIW) transmission lines [92]. Such artificial lines exhibit a strong dispersion, with the result of a small phase or group velocity, and hence dimensions. Nevertheless, it should be clarified that despite the fact that sensors implemented by means of EIW transmission lines, and based on the same principles as those of ordinary lines, have been reported [92], such sensors cannot actually be considered non-resonant, since EIW transmission lines consist of a chain of electrically coupled (slotted) resonators (CSRRs in [92]). These planar sensor topologies, aimed to reduce the size of the sensing region, are depicted in Fig. 4.

In general, it is considered that planar resonant sensors are more sensitive, accurate, smaller, and cheaper than non-resonant sensors. Nevertheless, resonant sensors cannot be applied to the dielectric characterization of materials over broad frequency bands (as required in dielectric spectroscopy [93, 94]), as consequence of their narrowband nature.[6] The typical (canonical) output variable in resonant sensors is the resonance frequency, influenced by the dielectric properties of the MUT. Nevertheless, sometimes, the magnitude of the resonant notch, or peak, as well as the quality factor, or the phase of the reflection or transmission coefficient, can be used for sensing. In non-resonant sensors, the typical output variable is the magnitude and/

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[6] For broadband characterization of materials, non-resonant sensors should be used. However, it should be clarified that artificial lines, such as slow-wave, CRLH, or EIW transmission lines, inherently exhibit a limited transmission band. Therefore, such artificial lines are not useful to retrieve the dielectric characteristics of materials over broad bands.

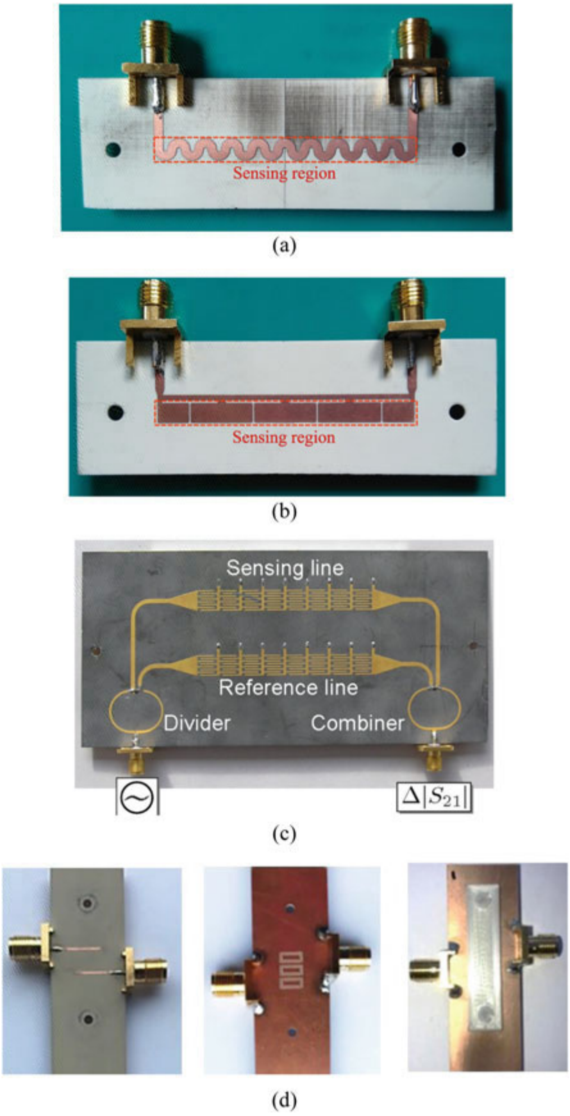

Fig. 4 Examples of topologies (photographs) of planar non-resonant sensors based on non-ordinary lines. **a** Meander line-based sensor; **b** slow-wave transmission line based sensor; **c** CRLH line based differential sensor; **d** EIW transmission line based sensor. In (**d**), the top (left figure) and bottom (center figure) views of the EIW sensor, as well as the sensing region (chain of three rectangular CSRRs) loaded with a dielectric sample (right figure), are depicted. Reprinted with permission from [90] (**a**) and (**b**), [91] (**c**), and [92] (**d**); copyright 2021, 2009 and 2020 IEEE

or phase of the reflection or transmission coefficient of the transmission line used as sensitive element, also influenced by the MUT.[7]

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[7] The presence of the MUT in contact or in proximity to the sensing line modifies the characteristic impedance and the complex propagation constant of the line, which in turn affects the reflection and transmission coefficient of such line.

1.1.7 Reflective-Mode and Transmission-Mode Sensors

The last binary categorization of planar microwave sensors distinguishes between reflective- and transmission-mode sensors. The former are one-port structures, either resonant or non-resonant, and the output variable is a certain characteristic of the reflection coefficient (e.g., the resonance frequency, resonance magnitude and/or quality factor, or the phase and/or magnitude of the reflection coefficient measured at a certain frequency/ies). Transmission-mode sensors are two-port structures where the sensing data is naturally retrieved through the information contained in the transmission coefficient (nevertheless, the sensing data can also be collected from the reflection coefficient, as complementary, or redundant, information).

At prototype (laboratory) level, vector network analyzers (VNAs) are commonly used equipment to infer the reflection and/or the transmission coefficient of the sensor. However, the use of such expensive measurement instruments is prohibitive (in general) in real operational environment. Magnitude (envelope) and/or phase detectors constitute the solution for retrieving the sensing data without the use of VNAs [95]. Nevertheless, in reflective-mode sensors, the same (and unique) port is used for sensor excitation and for collecting the sensing data simultaneously. Therefore, solutions based on circulators or directional couplers are needed in order to physically separating the input and output signals, a necessary condition to retrieve the sensing data through the use of envelope and/or phase detectors [96, 97].

1.2 Classification by Working Principle

The purpose of this section is to briefly present the different working principles of planar microwave sensors, as well as some illustrative examples (for a detailed analysis/study of each sensor type, the authors recommend the book [44]). The main working principles, or sensor types (classified according to such principles and presented in dedicated subsections), are frequency-variation sensors, frequency-splitting sensors, coupling modulation sensors, and phase-variation sensors. Rather than a working principle, differential sensing is a mode of operation. Nevertheless, differential-mode sensors are also the subject of a specific subsection, since there are specificities in such sensors that are worthy to be discussed. Figure 5 illustrates a representative topology (sketch) and the working principle of the different sensor types, to be discussed in the next sections.

1.2.1 Frequency-Variation Sensors

Frequency variation is probably the most extended working principle in planar microwave sensors [55, 56, 75–77, 98–136]. The main reason is that frequency-variation sensors exhibit a good combination of size, cost, accuracy, and sensitivity.

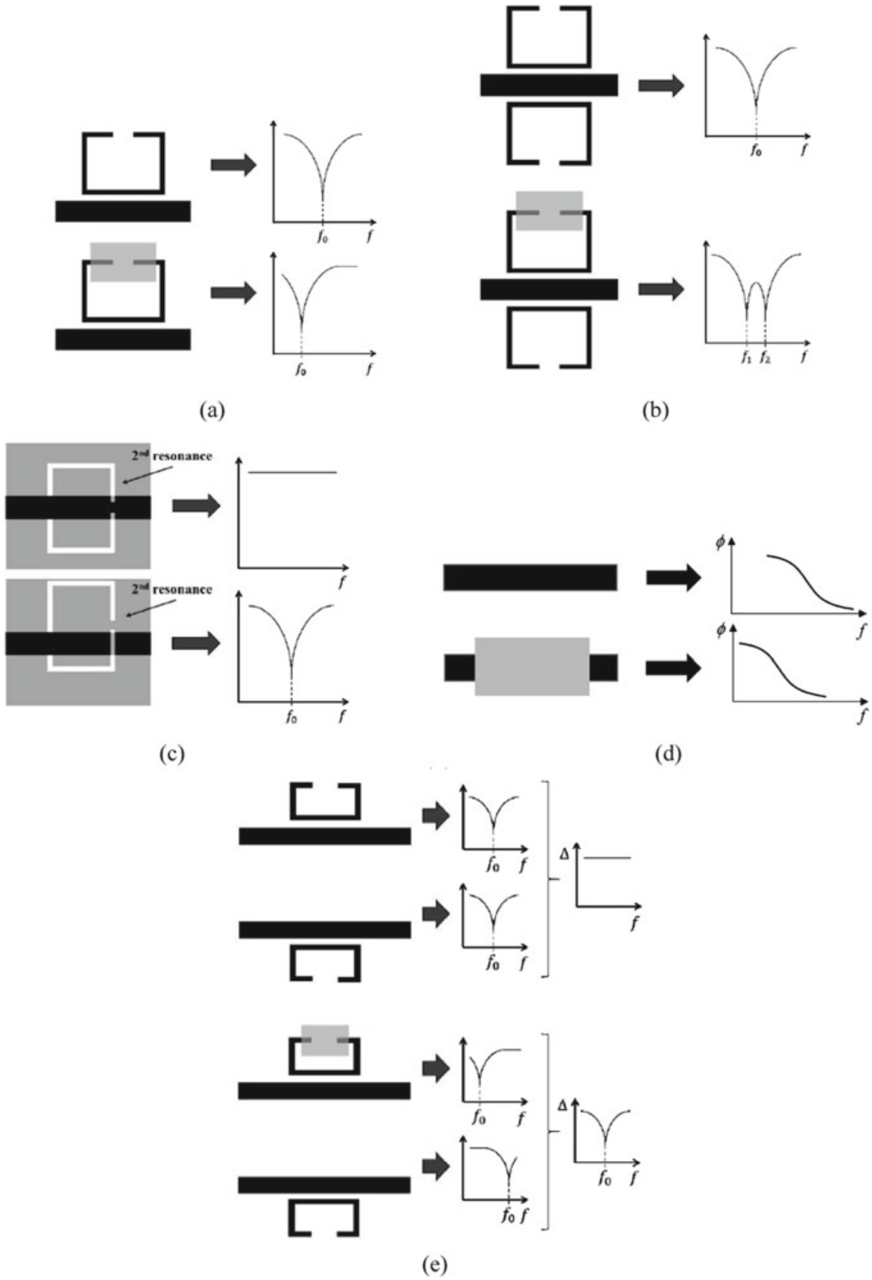

Fig. 5 Illustration of the working principle of the different types of planar microwave sensors and representative topologies. **a** Frequency variation; **b** frequency splitting; **c** coupling modulation; **d** phase variation; **e** differential sensing

Frequency-variation sensors are resonant-type devices typically consisting of a transmission line coupled or loaded with a planar resonator (either metallic or slotted) that can operate either in reflection or in transmission (or in reflection and transmission simultaneously). The canonical output variable in these sensors is the resonance frequency, intimately related with the dielectric constant of the MUT, ε_{MUT}, or with any other physical variable affecting the dielectric constant of a certain material (functional material, or film) in contact or in proximity with the sensing resonator. The variation in the resonance frequency is due to the changes in the capacitance of the resonant element caused by perturbations in the value of ε_{MUT}. An additional output variable in frequency-variation sensors is the magnitude, or quality factor, of the resonance notch (notched-type sensors) or peak (bandpass-type sensors). Such output variable correlates with the loss factor (loss tangent or imaginary part of the complex permittivity) of the MUT, but it typically exhibits cross sensitivity with the dielectric constant.

Frequency-variation sensors are robust against electromagnetic interference (EMI) and noise, as far as the main output variable in such sensors is a frequency (the resonance frequency), quite immune to the effects of EMI and noise. However, frequency-variation sensors require a sweeping interrogation signal able to cover the output dynamic range (or frequency span generated by the variation of the resonance frequency caused by the changes in the ε_{MUT} within the considered input dynamic range).[8] Such interrogation signal should be generated by means of a voltage-controlled oscillator (VCO) in operational environment.[9] Thus, a wideband VCO, or an array of VCOs (e.g., managed by a microcontroller), might be needed in order to cover the whole (potentially wide) output dynamic range in highly sensitive frequency-variation sensors in which a significant variation of the dielectric constant of the MUT (or a certain related variable) is expected. The use of such wideband VCOs, or VCO arrays, represents a penalty in terms of cost, at least as compared with other planar microwave sensors operating at a single frequency (single-frequency sensors), such as coupling-modulation or phase-variation sensors.

As mentioned in Sect. 1.1.6, metallic and slotted resonators are useful for the implementation of planar resonant sensors, and examples of frequency-variation sensors based on both types of resonators can be found in the literature (see the references indicated at the beginning of this subsection). Nevertheless, in sensors based on microstrip lines loaded with slotted resonators (e.g., CSRRs or DB-DGS resonators), etched in the ground plane beneath the excitation line, any potential interference between the MUT and the excitation line is prevented, due to the backside isolation caused by the ground plane. Such isolation also extends to potential related accessories, such as mechanic holders, fluidic channels, or pipes, necessary for liquid

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[8] Note that the output dynamic range is determined by the input dynamic range and by the sensor sensitivity, or variation of the resonance frequency of the sensing resonator with the dielectric constant of the MUT.

[9] At laboratory level, a signal generator or a VNA is typically used for the generation of the interrogation signal of the sensor.

sensing. Thus, slotted resonators in combination with microstrip technology are very attractive for microwave sensing.

As an example of frequency-variation sensor, let us report a transmission-mode device consisting of a microstrip line loaded with a DB-DGS resonator, transversally etched in the ground plane, as Fig. 6 illustrates [122]. This structure, with substrate parameters and dimensions indicated in the caption of Fig. 6, exhibits good sensitivity of the resonance frequency (the canonical output variable) with the dielectric constant of the MUT. The reason is that this structure behaves as a parallel resonant tank series connected to the line, so that a variation in the capacitance of the DB-DGS resonator caused by a change in the dielectric constant of the MUT directly affects the resonance frequency. By contrast, in CSRR-based sensors, the coupling capacitance between the line and the resonator, not affected by the MUT, degrades the sensitivity [44, 137] (this aspect will be further discussed in Sect. 2.1.1). Figure 7 depicts the simulated and measured responses corresponding to different MUTs (indicated in the figure), all semi-infinite,[10] placed on top of the DB-DGS sensing resonator.[11] From an analytical method presented in [122], where the second output variable is the notch depth at resonance, the dielectric constant and the loss tangent of the MUT can be retrieved. The results reported in [122] are in reasonably good agreement with the nominal values of the different samples. Nevertheless, cavity sensors, in general, provide better accuracy in the determination of the loss tangent, especially for low-loss materials.

1.2.2 Frequency-Splitting Sensors

In frequency-splitting sensors, the canonical output variable is also a frequency, but unlike frequency-variation sensors, frequency-splitting sensors use two identical sensing resonators, one for the MUT (or measurand of interest), and the other one for the so-called reference (REF) sample (or measurand) [71, 74, 87, 138–147]. The simplest configuration of a frequency-splitting sensor is a transmission line symmetrically loaded with (or coupled to) the pair of (identical but not necessarily symmetric) resonators (see Fig. 8) [138–140]. In such configuration, the necessary proximity between both resonators (needed for resonator's excitation by the signal line) generates inter-resonator coupling, which tends to degrade sensor sensitivity at small perturbations [138–140]. Thus, unless certain stratagems for coupling cancellation are considered [144, 145], the cascaded configuration [87], or the divider/combiner configuration [74, 141], are preferred (see Fig. 9).[12] The working principle

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[10] By semi-infinite we mean a MUT of sufficient thickness and transverse dimensions to guarantee that the electromagnetic field generated by the DB-DGS does not reach the boundaries of the MUT. The semi-infinite MUT approximation is not a general requirement for sensing, but a requisite of the analytical method reported in [122].

[11] For DI water, a mechanical holder (acting as a pool or container) was fabricated by means of a 3D printer and attached to the ground plane of the sensing structure (see further details in [122]).

[12] The divider/combiner configuration, similar to the cascaded configuration, prevents from inter-resonator coupling, since the resonant elements are significantly separated. However, in the divider/

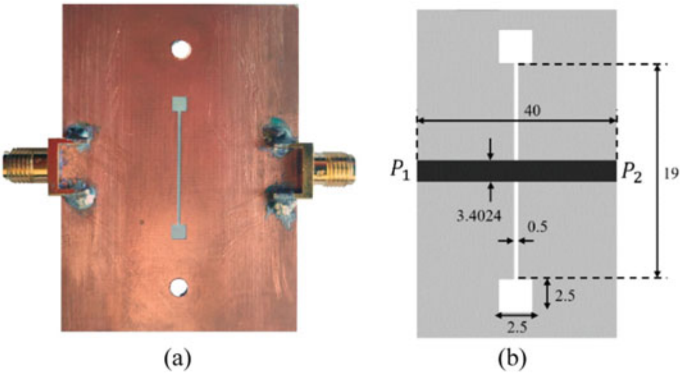
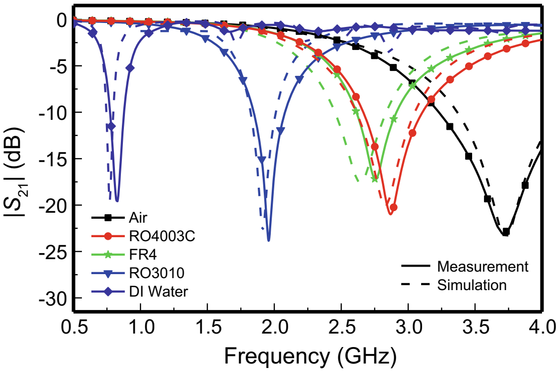


Fig. 6 Photograph from the backside (**a**) and layout (**b**) of a planar frequency-variation sensor based on a DB-DGS (slotted) resonator and devoted to permittivity sensing. The dimensions are indicated in mm. The sensor was implemented in the *Rogers 4003C* substrate with dielectric constant $\varepsilon_r = 3.55$, thickness $h = 1.524$ mm, and loss factor tan $\delta = 0.0022$. The ground plane in (**b**) is depicted in grey. Reprinted with permission from [122]; copyright 2022 IEEE

Fig. 7 Measured and simulated transmission coefficient of the bare DB-DGS-based sensor of Fig. 6, and sensor loaded with stacks of *FR4*, *Rogers RO3010*, and *Rogers 4003C*, as well as DI water. Reprinted with permission from [122]; copyright 2022 IEEE



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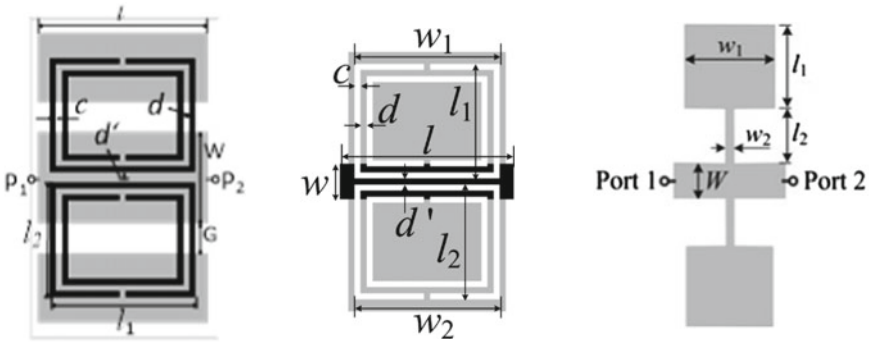
combiner frequency-splitting sensor, the notches appear, in general, as consequence of an interfering phenomenon. Namely, at the resonance frequency of the resonator of one of the branches, signal propagation through that branch is precluded. However, signal propagation is not necessarily reflected back to the source, since it can be transmitted, or partially transmitted, through the other (parallel) branch. Thus, in general, the notches are not given by the resonance frequencies of the resonators (except for the symmetric case), but by those frequencies where the signals propagating at both branches destructively interfere at the output T-junction. This mode of operation (signal interference) also degrades sensor sensitivity at small perturbations [141]. However, if the line section between the T-junctions and the plane of the resonators is conveniently chosen, a short at the resonance frequency of the resonators when they are loaded with the REF sample is generated at the input and output T-junctions, and under these circumstances, sensitivity degradation is circumvented, as it is demonstrated in [141]. If the sensing resonant elements are CSRRs or SIRs, the line section between the T-junctions and the plane of the resonators should be a half-wavelength [or $\theta_1 = \pi$, see Fig. 9b]. By contrast, the electrical length of such line sections should be $\theta_1 = \pi/2$



(a) (b) (c)

Fig. 8 Different configuration of frequency-splitting sensors consisting of a transmission line loaded with (or coupled to) a pair of identical symmetrically placed resonators. **a** Coplanar waveguide (CPW) transmission line (in grey color) magnetically coupled to a pair of SRR (depicted in black), etched in the backside of the substrate; **b** microstrip line (depicted in black) electrically coupled to a pair of CSRRs, etched in the ground plane (depicted in grey color); **c** microstrip line loaded with a pair of SIRs

of frequency-splitting sensors is very simple. If the dielectric loads on both sensing resonators are identical, a single resonance in the form of a notch (according to the configurations of Figs. 8 and 9) appears. However, when symmetry is truncated, two notches, with frequency separation related to the level of asymmetry, arise.[13] Thus, the canonical output variable in frequency-splitting sensors is the frequency difference (or split) between the two resonances. The difference in the notch magnitude can also be used as an additional variable for sensing (this is necessary in applications devoted to the determination of the complex permittivity of the sample under study [74]).

Similar to differential-mode sensors, frequency-splitting sensors are robust against cross sensitivities to common-mode stimuli (e.g., ambient factors), as far as the output and input variables in frequency-splitting sensors are of differential nature. Nevertheless, frequency-splitting sensors are not true differential-mode sensors, since they are not implemented by means of two independent (single-ended) sensors, but through a pair of sensing resonators and a common microwave structure.

As a prototype example of frequency-splitting sensor, let us briefly report the microfluidic device presented in [74], devoted to the characterization of liquid samples, in particular to the determination of the complex permittivity of mixtures of ethanol and DI water. The topology of the sensor is based on the splitter/combiner configuration, and the sensing resonators are SRRs (see Fig. 10, where a photograph of the whole sensor, including the fluidic channels, is also depicted). By injecting pure

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(i.e., a quarter-wavelength) for SRRs. The difference is explained by the fact that CSRRs and SIRs generate a short at resonance, whereas SRRs open the line when they resonate.

[13] Nevertheless, frequency-splitting sensors based on bandpass structures are also possible [146]. In this case, the resonances manifest as peaks in the frequency response of the sensor.

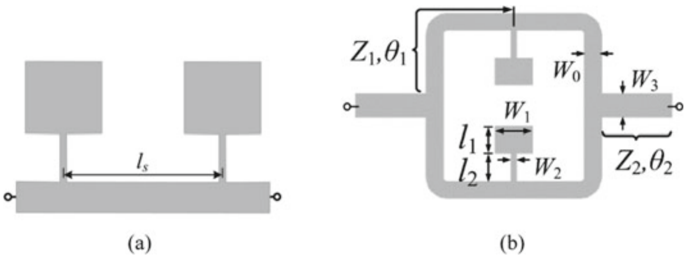

Fig. 9 Configurations of a frequency-splitting sensor based on a pair of SIRs. **a** Cascade configuration of a microstrip line loaded with a pair of SIRs; **b** splitter/combiner configuration of a microstrip line loaded with a pair of SIRs in either branch

DI water in the REF channel and mixtures of DI water and ethanol (with different volume fractions) in the MUT channel, the frequency responses of the device change, see Fig. 11a. In all the cases, two notches appear, since the load of the SRRs is asymmetric. Note that the notch magnitudes are very limited due to the effect of losses of the considered liquid samples. Figure 11b depicts the differential (splitting) frequency, Δf_z, as well as the differential notch depth, ΔS_{21}, the considered output variables, as a function of the volume fraction of ethanol. Note that the sensitivity in the limit of small perturbations (small volume fractions of ethanol) is somehow degraded. The reason is that such sensor was not optimized, since it was conceived as a general-purpose liquid sensor (i.e., the electrical length of the line sections between the T-junctions and the SRRs central position was not set to $\theta_1 = \pi/2$ at the resonance frequency of the SRR loaded with DI water). Nevertheless, it was demonstrated in [74] that the sensor is useful to provide the complex permittivity (real and imaginary parts, i.e., the input variables) of mixtures of DI water and ethanol. For that purpose, a mathematical model was developed, where a linear dependence between the output and input variables was assumed. Calibration of the model was carried out from the knowledge of the complex permittivity of pure ethanol (100% volume fraction), and by considering an additional volume fraction of ethanol (e.g., 10% ethanol), with the complex permittivity of that mixture inferred from the complex permittivity of the constituent components using, e.g., the Weiner model [148] (see further details in [74]). Using that model and the output variables of Fig. 11b, the complex permittivity as a function of the volume fraction of ethanol was obtained. The results, depicted in Fig. 12, reveal that the real and the imaginary parts of the permittivity are circumscribed between the static lower (WL) and upper (WU) limits of the Weiner model, thereby validating the functionality of the sensor for the determination of the complex permittivity of liquid samples.

1.2.3 Coupling-Modulation Sensors

The working principle of coupling-modulation sensors is the variation of the coupling level between, at least, a planar resonant element and a transmission line (excitation