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Introduction to Planar Microwave Sensors

Within today's paradigm of Internet of Things (IoT) [1–6], or, more generally, Internet of Everything (IoE) [7], and the advent of the Fourth Industrial Revolution (also known as Industry 4.0) [8–12], there has been an increasing demand for low-cost sensors, able to continuously monitoring a multiplicity of parameters, including environmental, physical, chemical, biological, or medical variables, among many others, of interest in diverse scenarios. This trend will continue with the progressive implantation of the 5th generation of mobile networks, designated as 5G, which is expected to satisfy the large-scale connectivity requirements that today's modern society demands (an interesting example is the autonomous and connected vehicle, necessarily equipped with hundreds of sensors). Sensors and sensor networks are key components in the so-called "Smart World" (or digital world), understood as an interconnected world equipped with sensors, actuators, displays, and computational elements, where the ultimate goals are to enhance the quality of life of citizens, to ease the action of policy decision-makers, and to contribute to the sustainability (maintenance and protection) of the overall environment [13]. Within this framework, Smart Cities, Ambient Intelligence, Smart Healthcare, Smart Agriculture, Smart Industry, etc., are specific areas that have experienced a significant transformation toward the digital world in recent years. Key enablers, including not only IoT and 5G (and related technologies), but also big data, artificial intelligence, cloud-computing, etc., have contributed to such progress. However, "Intelligence" is still in its infancy in most of the cited areas, and further technological efforts at different levels, and within different fields, are needed in order to make the "Smart World" concept a reality. Sensors constitute one of such fields, where a significant research activity is going on, particularly in the topic of planar microwave sensors, the subject of this book.

Microwave sensors implemented in planar technology are expected to play an increasingly important role within the IoT and the "Smart World," since these sensors can potentially satisfy many demanding requirements and provide technical solutions to several challenging aspects. Planar microwave sensors exhibit low cost, small size, and low profile, and can be implemented in many different types of substrates (by means of both subtractive and additive processes), including flexible and biodegradable substrates. Thus, implementing conformal sensors [14, 15] or environmentally friendly ("green") sensors [16, 17] operating at microwaves is feasible. It is also possible to fabricate planar microwave sensors in combination with other technologies, such as microfluidics [18, 19], micromachining [20], lab-on-a-chip [21–23], textiles (fabric) [24–26] and, thereby opening the sensing possibilities and application scenarios (e.g. liquid sensing, and wearables). Moreover, microwaves are very sensitive to the properties of the materials to which they interact. This means that, based on permittivity measurements, microwave sensors are very useful for material characterization and analysis. Defect detection, determination of material

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composition, biosensing, and chemical sensing, among others, are potential applications of planar microwave sensors, as it has been demonstrated in the available literature (and as it will be shown throughout this book and references included therein). Monitoring ambient variables, such as temperature and humidity, or other physical variables (e.g. pressure) is also possible by means of planar microwave sensors. In these cases, functional films (or "smart" films, a usual designation), with ambient-dependent dielectric properties, are typically used [27–30]. Many efforts have also been dedicated to the implementation of planar microwave sensors for measuring spatial variables (of interest, e.g. in motion control applications), where the key advantageous aspect, as compared with other competing technologies (e.g. optics), is their major robustness for operation in hostile and harsh environments [31]. Microwaves exhibit further interesting properties for sensing, such as low-cost generation and detection systems, interaction with the materials at different scales (i.e. through the near field or the far field), and wireless connectivity. This last aspect is critical for the implementation of IoT systems based on low-cost wireless sensor networks (WSN), implemented, for example, by means of radiofrequency identification (RFID) sensor nodes [27–37].

This chapter is an introduction to planar microwave sensors, with the aim of pointing out the main sensor types, their advantages and limitations as compared with other sensing approaches, and their categorization, or classification. Nevertheless, there are other sensors operating at radiofrequency (RF) and microwave frequeny, which will be succinctly reviewed in this chapter. A general overview of different sensing technologies, besides microwaves, as well as the relevant sensor characteristics indicative of their overall performance, are also included in the next section of the present chapter.

1.1 Sensor Performance Indicators, Classification Criteria, and General Overview of Sensing Technologies

Probably the most general, or less restrictive, definition of "sensor" is as follows: *a sensor is a device able to provide information of a certain variable*. Many types of variables (usually referred to as measurand) can be inferred, or measured, by means of sensors, including physical variables (e.g. temperature, velocity, pressure, and moisture), chemical variables (e.g. gas composition or detection), biological parameters (e.g. glucose or electrolyte content in blood), and medical health indicators (e.g. arterial pressure, or cholesterol level), among others. According to the general definition provided above, the scope of the term includes sensors whose complexity is low, or insignificant. For instance, measuring the height of a person, or the distance between opposite walls in a room, is as simple as using a length gauge, and visual inspection. Such "simple sensor" does not utilize any transduction mechanism. However, there are more sophisticated, accurate, and reliable options for measuring lengths and displacements, including optical, ultrasound, and microwave systems, among others, where the measurand (length in the considered case) is determined after at least one transduction process. In such process, energy conversion from one form to another is involved. For example, in an ultrasound distance-measurement sensor (usually referred to as SONAR – sound navigation and ranging – in aquatic navigation systems), where the time lapse between the emitted and received ultrasound pulse (echo) determines the distance to the target, the acoustic energy is converted to electric energy, and the measuring distance is shown, e.g. in a display, after several signal processing steps. The sensors of interest in this book are those that respond to a certain variable (stimulus) with an electrical signal (typically after one or more transduction mechanisms). Such signal can be monitored in a computer, processed, or transmitted by wires or wirelessly. In such sensors, the input variable is thus the measurand (or stimulus), whereas the output variable is an electric, or electronic, signal, in the form of a direct current (DC) or alternate current (AC), voltage, charge, etc., and described by means of the amplitude (or magnitude), frequency, phase, digital code, etc., of such signal.

1.1.1 Performance Indicators

The main relevant parameters indicative of sensor performance, and their definitions, are as follows [38]:

- Linearity: capability of the sensor to provide a linear response. The linearity is determined by the deviation of the transfer function, or dependence of the output signal with the input signal, from a straight line.
- Sensitivity: variation of the output signal in response to a variation in the input signal (or variable). In nonlinear sensors, the sensitivity is not constant, and it is given by the derivative of the output signal with respect to the input signal, or slope of the transfer function.
- Resolution: the smallest variation of the input signal that can be reliably detected. In analog sensors, the resolution is intimately related to the noise level, whereas in digital sensors, it is given by the span corresponding to a bit (for instance, in angular displacement sensors based on optical or electromagnetic rotary encoders, the angular resolution is determined by the number of pulses per revolution, PPR, as 360°/PPR).
- Input and output dynamic range: range of values of the input variable that the sensor can measure, and generated span in the output variable. The input and output dynamic ranges are related by the transfer function of the sensor. The dynamic range is usually limited by the floor noise and by saturation effects.
- Accuracy: degree of closeness to the true value of the measurand. It is the opposite concept of error, or difference between the measured and actual value of the magnitude or variable of interest.
- Repeatability and precision: sensor's ability to provide identical outputs for the same input. Within the context of sensors, precision and repeatability are synonymous. Precision is related to the standard deviation of measured data, but not to the proximity of the mean value to the true value. Thus, precision and accuracy should not be confused. A sensor might be very precise and exhibit a limited accuracy, or vice versa.
- Selectivity: capability of the sensor to selectively determining the value of a certain parameter of interest, in a multivariable measurement or in the presence of uncontrollable stimuli (e.g. caused by variations in ambient factors). For example, there are sensors where the input variable is the concentration of a certain substance in a mixture (e.g. a liquid solution with various solute substances). If the different substances have similar influence on the output variable, the selectivity is necessarily poor. Sensor selectivity is related to the existence of cross-sensitivities between the output variable and undesired stimuli. Lack of selectivity is the cause of sensor measuring errors or inaccuracies. Many sensors exhibit certain cross-sensitivities to environmental variables, such as temperature and humidity, or even atmospheric pressure. In such cases, it is convenient to perform the measurements in a controllable environment. Alternatively, differential sensors, to be defined later, robust against cross-sensitivities (since environmental parameters are seen as common-mode stimuli), can be used to mitigate the effects of ambient factors.
- Bandwidth: determines how fast the sensor responds to changes in the input signal. Fast-response sensors, or, equivalently, low-decay-time sensors, exhibit wide frequency bandwidths.
- Noise: disturbance in the output (generally) electrical signal of the sensor. The sources of noise can be diverse (thermal noise, shoot noise, flicker noise, etc.).

- Stability: degree to which sensor characteristics remain constant over time. Changes in sensor characteristics, or drifts, can be due to aging, wearing or degradation effects in certain components, and/or changes in the signal-to-noise ratio, etc.
- Robustness: ability of the sensor to reliably working under adverse conditions or extreme stimulus.
- Operating lifetime: time interval where the sensor is able to provide its functionality. In battery-assisted sensors (e.g. in certain WSNs), the lifetime is determined by power consumption. Nevertheless, there are several factors determining sensor lifetime, including the operational environment, etc.

1.1.2 Sensors' Classification Criteria

Sensors can be classified according to various criteria [39]. For example, depending on whether they need an external energy source for operation, or not, sensors can be divided in two categories: active and passive. Most sensors are active, in particular, most microwave sensors are based on the interaction of microwave signals with the material under test (MUT), analyte, or target, and therefore they need a microwave signal generator.[1] An exception is the radiometer, a sensitive microwave receiver able to detect thermal radiation of objects. Passive sensors, also called self-generating sensors, generate their own signals and do not require any external source of energy, i.e. passive sensors "listen to what is happening" (examples include thermocouples, piezoelectric sensors, photodiode sensors, and radiometers).

Another binary categorization of sensors concerns the nature of the output signal: analog or digital. Analog sensors generate an analog signal in response to what they sense, contrary to digital sensors. Typically, digital sensors include an analog-to-digital (A/D) converter. An example of a digital sensor is a chip-based electronic RFID sensor (to be discussed in Chapter 7), where the measured data is sent to the reader in digital form. Nevertheless, it should be mentioned that digital sensors might refer also to sensing devices where the output signal is a set of pulses, encoding the measured data. Canonical examples of such pulse-based sensors are the optical and electromagnetic rotary encoders [40, 41], useful for determining angular positions and velocities (the latter are discussed in detail in Chapter 4).

Sensors can also be divided between contact and contactless sensors [42–45]. In the former, the MUT, target, or analyte must be in physical contact with the sensitive element of the sensor. Contactless sensors, by contrast, are able to retrieve the measured data without physical contact. Many optical, microwave, and ultrasound sensors are contactless. For example, the measuring-distance ultrasound sensor mentioned before is an example of a contactless sensor. Radio detection and ranging (RADAR) sensors belong also to the category of noncontact sensors. In some cases, contact between the sensitive element and the target is not needed, but proximity is necessary. For example, in electromagnetic rotary encoders [41] (see Chapter 4), the rotating element, designated as rotor, is not in contact with the sensitive element, the stator. However, proximity between the rotor and the stator is required in order to detect the metallic inclusions printed, or etched, in the rotor (through near-field coupling). Such inclusions in motion generate the necessary pulses to infer the angular

1 It should be clarified that, in Chapter 7, certain types of RFID sensors have been classified as passive in the sense that such sensing systems, including the interrogator (reader) and the tag (the sensitive element), use tags that do not need a battery. In such passive tags, the required energy is obtained from the ambient (through harvesting) or from the interrogation signal. However, the tags, in general, are not able to provide their own signals and need a source of energy for operation. Clearly, the whole RFID sensing system, including not only the sensing tag but also the interrogator, is active, according to the definition given in the text (since the tags provide the measured data in response to an interrogation signal, generated by the reader, an active component).

position and velocity of the rotor (see further details in Chapter 4). Contactless sensors should not be confused with wireless sensors [34, 35, 46–51]. The most relevant characteristic of wireless sensors is that the sensor element (usually referred to as sensor node in WSNs) sends the measured data to a central unit, located at a certain distance, through a wireless link. Thus, the measured data is wirelessly, or contactless, forwarded to the central unit. However, the sensing mechanism might require contact with the stimulus. For example, chipless-RFID permittivity sensors devoted to the analysis of concrete samples are reported in Chapter 7 [52]. The communication between the sensor and the central unit (the reader, in the terminology of RFID technology) proceeds wirelessly, through the far field, but the samples (concrete) must be in contact with the sensitive element of the sensor (a delay line in the reported example). Thus, such device can be classified as a wireless contact sensor. Note that contact sensors not necessarily must be in contact with a certain sample or target to perform their function. For example, a sensor devoted to ambient temperature measurements, e.g. using the temperature-dependent dielectric constant of certain materials such as ferroelectrics or certain polyamides, provides the temperature information corresponding to the position where such sensitive material is located. Thus, the sensor provides the temperature of the "local" environment to which it is "in contact." However, the temperature of specific targets (objects) can be inferred remotely (i.e. contactless) by means of infrared temperature sensors, able to detect the infrared energy emitted by all materials [53, 54].

There are sensors that provide their measured data relative to a reference value, whereas other sensors react to the stimulus on an absolute scale. In the former case, the sensors are designated as relative, or incremental-type, sensors, whereas absolute sensor is the term coined for the second class. Concerning temperature measurements, there are two clear examples of sensors corresponding to each type. Thermistors are absolute sensors that utilize temperature-dependent resistors and are used in many industrial applications [55]. Thermocouples are relative sensors able to provide the temperature difference between two points [56]. Thermocouples exploit the Seebeck effect, or electromotive force generated between two points of an electrically conducting material when there is a temperature difference, or gradient, between them. The generated voltage depends on the specific conductive material. Therefore, by using two metallic wires of dissimilar materials connected at a junction (the temperature measuring junction), and leaving the two other extremes (terminations) of the wires unconnected but bonded to a region with uniform (reference) temperature, it follows that a temperature difference between the junction and the extremes of the wires will generate a voltage difference between such terminations. Sometimes, relative sensors are used to prevent from measuring errors caused by undesired cross-sensitivities to common-mode stimulus, typically caused by variations in ambient factors (temperature or humidity).[2] In certain applications, rather than measuring an absolute value of a variable, the interest is to compare a magnitude with a reference, or a sample (the MUT) with a reference (REF) sample. In this case, the sensor can be designated as comparator. One potential application of comparators is defect detection, where the analyzed (potentially defected) samples are compared with a reference [57]. Several examples of relative sensors, also called differential-mode sensors, and comparators are later reported in this book.

The previous classification schemes of sensors are binary, and, given a sensing device, it is relatively easy to discern to which category it belongs for either case. Sensors can be classified according to other (more complex) criteria. For example, sensors can be grouped as a function of their field of application. Examples include (but are not limited to) fields as diverse as agriculture, automotive,

2 Variations in temperature or humidity with position at the typical scales of the sensors (with sizes below few centimeters in many cases) are not expected, and therefore such variables are seen as common-mode stimuli by relative sensors.

space, health/medical, civil engineering, industrial engineering, energy/power, environment/meteorology, manufacturing, marine, military, scientific instrumentation, information/telecommunications, and domestic appliances.

The variable under measurement can also be considered for sensor classification. In this case, due to the innumerable list of potential measurands, several groups and subgroups (and even a further division) can be identified [39]. Thus, three main groups of sensors classified attending to the nature of the measurand can be identified: biological, chemical, and physical sensors. However, sometimes, it is difficult to determine to which group a certain variable, or sensor, belongs (in particular, there is some indeterminacy between biological and chemical sensors, because many biological variables, or substances, are also of chemical nature). Examples of chemical sensors include gas sensors, or electrolyte-concentration sensors based on electrochemical techniques, among others. Nevertheless, these latter sensors can be considered biosensors, as well, provided they are applied to the measurement of electrolyte content, e.g. in blood or urine, i.e. bio-samples. Most sensors belong to the group of physical sensors. In this case, several subcategories, such as acoustic, electric, magnetic, mechanical, optical, and thermal, can be distinguished, and many sensor types can be, in turn, identified within each subgroup. For example, mechanical sensors include displacement, position and velocity sensors, force/strain sensors, pressure sensors, etc. Measurands such as electric current, voltage, permittivity, conductivity, and many others can be inferred by means of electric-type sensors. Finally, examples of thermal sensors are temperature and thermal conductivity sensors, to cite some of them.

Sensors can be classified according to the involved sensing mechanism, exploited effect, or conversion phenomena. In this case, there are also three main groups, i.e. physical sensors (again the dominant one in terms of subcategories), chemical sensors, and biosensors. As a representative example, a thermocouple is a thermoelectric physical sensor where sensing is based on thermal-to-electric energy conversion. Further types of physical sensors categorized according to the involved physical phenomenon are photoelectric, piezoelectric, or magnetoelectric sensors, among many others. Electrochemical processes and chemical transformation are the basis of most chemical sensors, whereas biosensors typically exploit biochemical transformation.

There are additional sensor classification schemes, not discussed in this chapter (see [39] for a complete overview of such categorizations). However, probably the most useful classification of sensors is the one given by the dominant technology involved in sensing. In this regard, optical, magnetic, acoustic (including ultrasound), mechanical, electrical, and microwave (or, more generally, electromagnetic) sensors, among others, can be identified as sensor types that clearly exploit a specific technology. It is not the aim of this chapter to provide a detailed overview of such types of sensors but to briefly discuss some aspects of interest and to point out some representative examples of some of the cited groups (see next Section 1.1.3). Microwave sensors, the main subject of this book, are discussed separately in a dedicated unit (Section 1.2).

1.1.3 Sensing Technologies

In this section, the most relevant sensing technologies, as pointed out in the preceding paragraph, are briefly overviewed. For a more in-depth study, the authors recommend various general books and handbooks on sensors and sensing technologies (e.g. [38, 58–61]). Additional literature relative to the specific considered technologies is also given in the next sections.

1.1.3.1 Optical Sensors

Probably, optical sensors are those dominating the general sensor market. The reason is that optical technology offers a number of advantages, combined with limited cost, small size, and a broad range of applications in sensing [62–69]. In general, optical sensors are highly sensitive and accurate, and are relatively small. The small dimensions are related to the fact that the required optical source and detector (typically a light emitting diode – LED – and a phototransistor, respectively) are semiconductor devices, intrinsically small. Moreover, such components are relatively cheap, and therefore optical sensors are quite competitive in terms of cost. The limitative aspect comes from the fact that optical beams are not able to penetrate certain substances, as RF or microwave signals do, and consequently optical sensors cannot be applied in certain applications, such as subcutaneous or implant sensors, among others. Moreover, optical sensors are less robust than other sensors, e.g. magnetic sensors or microwave sensors, against harsh environments (i.e. subjected to extreme temperatures or radiation), or ambient conditions subjected to pollution or dirtiness, as those encountered in many industrial applications. Nevertheless, despite these limitations, optical sensors are probably the strongest competitors to microwave sensors, at least in certain applications. For example, optical rotary encoders typically exhibit very high resolutions by virtue of the achievable number of pulses per revolution (several thousands in many prototypes) [40, 70, 71]. By contrast, the microwave counterparts [41, 72–75] cannot provide such high number of pulses per revolution, since electromagnetic signals in the microwave range (with guided wavelengths of the order of few centimeters) are not able to detect inclusions in the sub-millimeter range.

Optical sensors are useful in many daily applications, and they are integral part of many commonly used devices and systems, such as computers, heavy machinery, elevators, copy machines, alarm systems, and ambient light systems. Optical sensors of different types are able to provide measurements of variables as diverse as position and velocity, vibrations, temperature, pressure, chemical and biological components, and strain. The optical rotary encoder, referred to before, is a canonical example of an optical sensor, useful to accurately measuring angular displacements and velocities. Encoders are used in elevators, spatial vehicles, servomechanisms, etc. Like many other optical sensors, optical encoders use a light emitter device (usually an LED or a LASER – light amplification by stimulated emission of radiation) and a detector (a photodiode or a phototransistor, typically), and the operating principle is based on the transmission and interruption of light. Specifically, in optical encoders, the apertures present in the rotor element (which must be positioned between the emitter and the detector) are transparent to light. Thus, the light beam can be detected when one of such apertures crosses the optical path between the emitter and the detector, thereby generating a pulse (see Chapter 4 for further details, specifically Fig. 4.29). These optical sensors, where the emitter sends the light beam to the detector (located in a separate position), are designated as through-beam sensors. In other optical sensors, light transmission/reflection is the considered sensing mechanism, i.e. the emitted beam is reflected back to the detector by an object or a target (retroreflective sensors). For example, distances to (or velocities of) a target can be accurately measured by means of LIDAR (light detection and ranging) systems, where a pulsed (typically infrared) LASER is used to determine the distance/velocity of the target from the time delay in the reflected signal [76, 77]. The operating principle of the LIDAR is identical to that of the RADAR or SONAR, the unique difference being that RADAR systems utilize radio waves (including also microwaves and even higher frequencies within the electromagnetic spectrum), and SONARs are based on acoustic waves, rather than optical signals. As compared with RADAR and SONAR sensors, LIDAR sensors are more accurate and fast. Moreover, LIDARs are extremely selective, since LASER beams are very directive. By contrast, as mentioned, light is not able to penetrate materials as radio or acoustic waves do. For that reason, RADARs or SONARs are necessary in certain applications where the space between the target and the emitter contains elements or materials opaque to light propagation (e.g. geo-localization). LIDARs have applications in many fields, including topography, astronomy, geology, physics of the atmosphere, traffic control, and imaging, among others.

Optical sensors are also very interesting for the analysis of biological samples [78, 79]. Indeed, optical sensors probably constitute the most common type of electromagnetic biosensors.[3] The main reason is the highly achievable sensitivity and selectivity for the detection of analytes as diverse as toxins, drugs, antibodies, proteins, tumor cells, viruses, etc. Moreover, as compared with other analytical techniques, optical biosensors enable the direct, real-time, and label-free.[4] (in some cases) detection of several types of biological components. Cost and size are also interesting characteristics of optical biosensors that make them very competitive against other biosensor types (e.g. electrochemical, piezoelectric, and magnetic). A bio-recognition (also called bio-receptor) sensing element and an optical transducer are constitutive parts of most optical biosensors (Fig. 1.1). The bio-recognition elements are enzymes, antibodies, antigen, nucleic acids, receptors, cells, tissues, etc., which interact with the optical field, providing information of the analyte, bound to the bio-receptor. Concerning the transduction mechanism, surface plasmon resonance, evanescent wave fluorescence, or optical waveguide interferometry exploit the evanescent field in order to detect the interaction between the bio-recognition element and the analyte. Nevertheless, there are other optical transducers, such as photonic crystals, and optical resonators, that can be used for optical biosensing. It is not the aim of this section to provide an exhaustive overview of optical biosensors. Nevertheless, the interested reader can find information in various surveys on the topic [80–88].

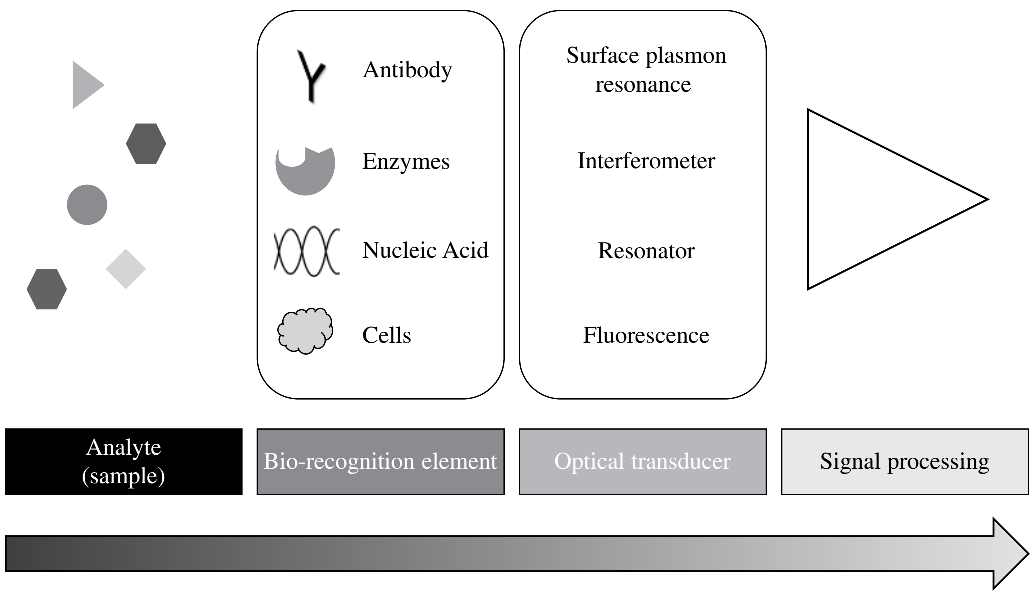

Figure 1.1 Sketch of an optical biosensors based on a bio-receptor and an optical transducer.

3 Nevertheless, the biosensor market is dominated by electrochemical sensors.

4 Label-free biosensors use the intrinsic properties of the analytes in order to detect their presence. However, there are biological analytes that are difficult to detect based on their intrinsic properties. In these cases, biosensors require labels in order to enhance the sensitivity (label-assisted sensors).

1.1.3.2 Magnetic Sensors

Similar to optical sensors, magnetic sensors can be strong competitors of microwave sensors in certain applications [89–95]. Magnetic sensors are devices able to detect magnetic fields, generated either by a magnet or by a varying current. These sensors can be useful in various applications, but there are a variety of devices focused on the measurement of linear and angular displacements, as well as proximity, based on magnetic sensors. Magnetic sensors use a wide variety of physical effects, but the most common sensors are coils [96], reed switches [97], Hall-effect sensors [98–100], and magnetoresistive sensors [101–103] (Fig. 1.2). Coils are the simplest form of magnetic sensors, able to detect variations in a magnetic field. In brief, approaching or moving away a magnet to a coil modifies the magnetic flux density in the coil, and, as a result, an electromotive force and current are induced in the coil. A reed switch is a sensor consisting of two metal pieces (reeds), typically made of a magnetic material (e.g. nickel), extending from the left and right side of a glass tube, with a gap in the central overlapping region. When an external magnetic field is applied, the reeds are magnetized, and the overlapping parts come into contact due to their mutual attraction. As a result, the switch turns on. Hall-effect sensors are able to detect static magnetic fields, contrary to coil-based sensors. These sensors are based on the Hall effect, or the voltage generation in a semiconductor or metallic material layer when a magnetic field is applied perpendicularly to a current flowing in that material. This voltage (Hall voltage) is a result of the electromotive force that arises

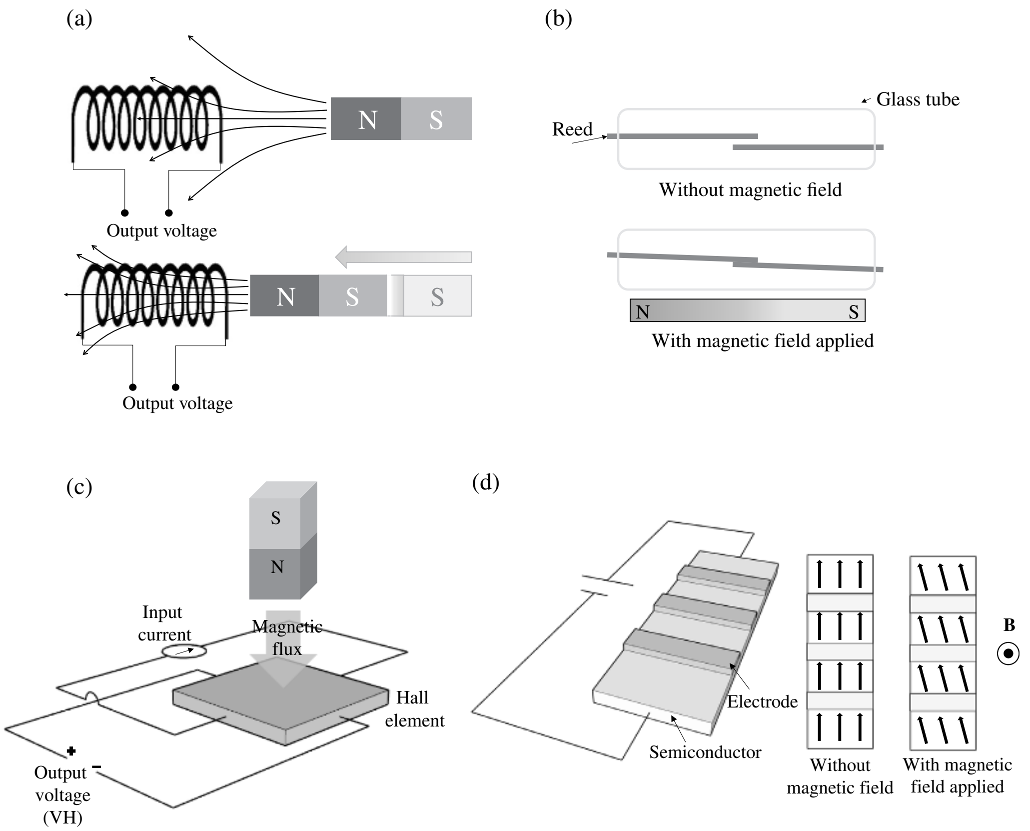

Figure 1.2 Sketch of various magnetic sensors. (a) Coil sensor; (b) reed switches; (c) Hall effect sensor; (d) magnetoresistive sensor.

orthogonally to both the current and the magnetic field. Hall-effect devices can be used as current sensors, angle sensors, proximity sensors, etc. Finally, magnetoresistive sensors base their operating principle on the variation in the resistance of certain magnetic materials, such as iron, nickel, or cobalt, caused by changes in a magnetic field. There are various types of magnetoresistive sensors, but the most sensitive are those based on the tunnel magnetoresistance effect, a quantum mechanical phenomenon (see further details in [104, 105]). Other magnetic sensors exploiting different physical effects can be found in [89–95].

1.1.3.3 Acoustic Sensors

Among acoustic sensors [106–108], acoustic sound sensors, or microphones, are well known for years. Such sensors are based on an acoustic-to-electric transducer that utilizes a thin piece of a material, called diaphragm, which vibrates when hit by sound waves. Such vibration is converted to an electrical signal through a capacitance variation. However, the devices that have generated the greatest interest among acoustic sensors are surface acoustic wave (SAW) sensors [109–115] (Fig. 1.3). Their working principle is the modulation of a surface acoustic wave caused by the physical phenomenon, or variable, under measurement. SAW sensors consist of a piezoelectric substrate with an input and an output interdigitated transducer, and a delay line in between, where the acoustic wave propagates. The input transducer transforms an electrical signal to a surface acoustic wave by virtue of the piezoelectric effect, whereas the output transducer converts the acoustic wave back to an electrical signal. Sensing relies on the fact that the output transducer captures any change caused in the mechanical wave, through their electrical response. Since the characteristics of the acoustic waves depend on the properties of the surface of the substrate, it follows that sensing any phenomenon, or variable, altering such properties is possible. Pressure, strain, torque, and temperature are variables that can be inherently measured by means of SAW sensors, since they alter the length along the surface of the device. Obviously, sensing films coated to the surface can also be used in order to enhance sensor sensitivity to certain variables. In particular, by using such films, the functionality of SAW sensors can be extended to the detection of chemical and biological species, or gases, or to the measurement of humidity, viscosity, etc. (see [114] and references therein). SAW sensors may exhibit performances superior to those of microwave sensors in certain applications, but their cost is usually higher. Chipless-RFID sensors based on SAW technology have also been proposed [116–119]. Sound sensors devoted to distance measurements and ranging, known as SONAR, are also acoustic sensors. Such sensors are of especial interest in subaquatic zones (underwater) due to the very good propagation of sound waves in water (and are common equipment in submarines and ships).

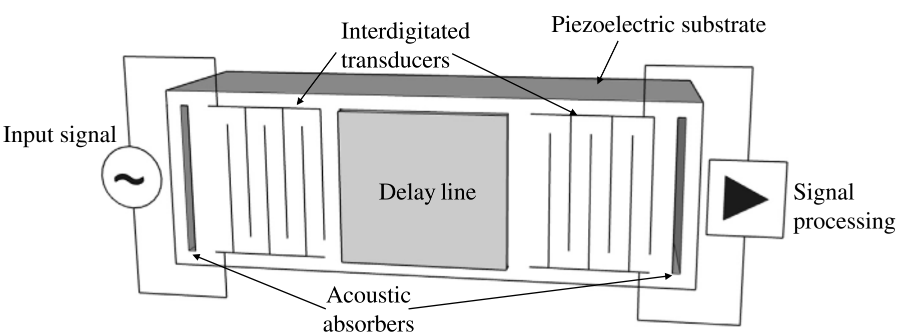

Figure 1.3 Sketch of a SAW sensor.

1.1.3.4 Mechanical Sensors

Mechanical sensors are sometimes defined as measuring devices sensitive to changes in mechanical properties [120, 121]. Nevertheless, there are many sensors of this type that utilize, e.g. optics, microwaves, or magnetism, rather than mechanics, as the main technology for sensing. For example, optical or microwave rotary encoders are sensitive to angular displacement and velocity (i.e. mechanical motion), but such sensors cannot be classified as mechanical sensors. However, there are sensors where a mechanical effect, such as vibration, is the fundamental mechanism. This is the case of the so-called micro-cantilevers [122, 123], i.e. mechanical sensors useful for ultrasensitive mass detection [124, 125] (Fig. 1.4). In such sensors, the bending or the frequency shift of an oscillating cantilever is the specific detection mechanism. Typically, the shift in resonance frequency is used to determine the mass attached to the cantilever. Other measurands that can be detected with micro-cantilevers are acceleration and force. In these cases, cantilever bending is exploited for sensing. Other mechanical sensors are based on the piezoresistive and piezoelectric effects. The former is the variation in the resistance of certain materials when they are subjected to strain or mechanical deformation. This effect can be canonically applied to the implementation of pressure and force sensors [126, 127]. The piezoelectric effect is the generation of an electric field when the material (a crystal, such as quartz) is subjected to stress. Piezoelectric sensors are useful for measuring pressure, force, acceleration, and temperature, among others [128, 129]. In these sensors, metallic electrodes are typically attached to the piezoelectric material in order to transduce the mechanical variable to an electrical one. Note that SAW sensors are also based on piezoelectric materials. Despite the fact that such sensors have been considered to belong to the class of acoustic sensors, sound waves are mechanical waves. Consequently, SAW sensors are, indeed, mechanical sensors, as well.

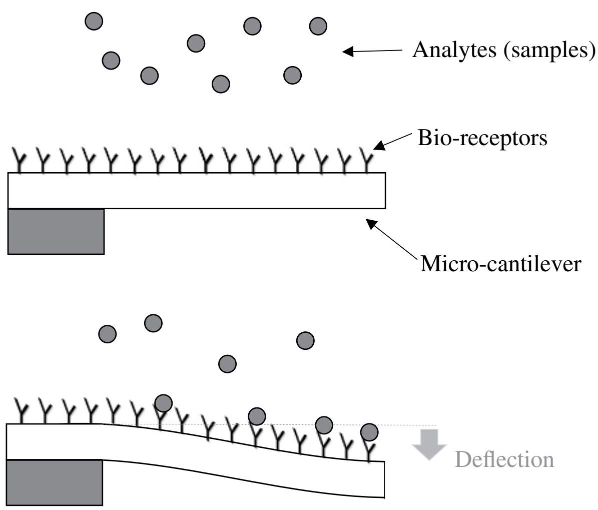

Figure 1.4 Sketch of a micro-cantilever sensor for mass or analyte sensing. When the analyte is settled in the receptor (e.g. a bio-receptor), the suspended mass of the cantilever changes, thereby causing bending. In the static mode of operation, the transduction mechanism is cantilever deflection, which can be retrieved by means of the angle of the reflected beam in response to an optical stimulus. In the dynamic operational mode, the shift in the resonance frequency of the cantilever, caused by the increment of suspended mass, is the mechanism used for sensing.

1.1.3.5 Electric Sensors

It could be accepted that electric sensors are devices devoted to the measurement of electrical variables, such as voltage or current. However, within the context of the present categorization scheme, based on the main involved sensing technology, electric sensors are devices that exploit a transduction mechanism of electrical nature. Capacitive, inductive, and resistive sensors are examples of electrical sensors, able to detect changes in capacitance, inductance, and resistance, respectively [130]. If such variables are inferred by means of electrical methods, the device can be considered a true electric sensor. However, there are other technologies, e.g. microwaves, which can be used for measuring such variables (for instance, a capacitance change can be detected by a shift in the resonance frequency of a microwave oscillator). In this case, the sensor cannot be categorized as an electric sensor. In electric capacitive sensors [131, 132], the capacitance can be measured from the frequency variation of an oscillator circuit (operating at low frequencies), or by means of the attenuation generated in a harmonic signal. It is also possible to infer the capacitance value by applying a harmonic signal to a capacitive divider, where one of the capacitances is the one under measurement, whereas the other one has a well-known value. By measuring the output voltage in the contact point between both capacitances, the unknown capacitance can be found from the ratio of capacitances, which equals the ratio of the output/input signal amplitudes. The potentiometer is a well-known example of a resistive sensor, able to convert a linear or an angular displacement into an output voltage by moving a sliding contact along the surface of a resistive element [133] (Fig. 1.5). Finally, inductive sensors are typically based on coils. Such coils have been discussed in the paragraph dedicated to magnetic sensors, since they actually exploit magnetism for sensing. However, as far as the output signal is typically an electric current, it is reasonable to consider that these sensors are electric sensors, as well.

1.2 Microwave Sensors

This section provides a general overview of microwave sensors. The aim is to briefly discuss the main microwave sensor types, their categorization, and their advantages and drawbacks as compared with other sensors. A section is dedicated to planar microwave sensors, the subject of this book. Such section is an introductory excerpt, since the next chapters will deal exhaustively with such sensors. Nevertheless, the classification of planar microwave sensors, according to various

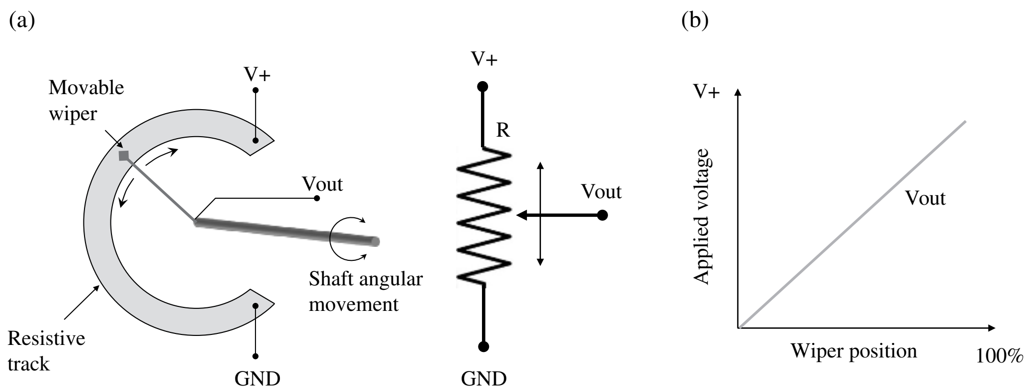

Figure 1.5 Sketch of a potentiometer used as angle sensor (a) and working principle (b).

criteria, is treated in detail in Section 1.3, whereas Section 1.4 provides a qualitative comparison of planar microwave sensors with other (nonplanar) microwave sensors and other sensing technologies.

In the broadest sense of the term, microwave sensors utilize devices and electromagnetic fields in the range between hundreds of MHz up to several THz. That is, such “broad” designation includes millimeter-wave and THz sensors, since their working principles are very similar to those of the microwave counterparts, and, in general, different from those governing optical sensors. The scope of the term may also include sensors operating at the ultrahigh frequency (UHF) band (300 MHz–1 GHz) since the limit between that band and microwaves is very diffuse. Nevertheless, sensor performance, cost, size, and other characteristics may significantly vary with the operating frequency. It should also be mentioned that the planar sensors discussed throughout this book operate at frequencies mainly circumscribed within the UHF band and the lower sub-bands of the microwave spectrum (and, indeed, in the sensor categorization by frequency of operation, to be discussed later, the distinction between THz, millimeter-wave, microwave, and UHF sensors is adopted).

There are two main types of microwave sensors: those based on RADAR technology or, more generally, on remote sensing, and those devoted to the analysis of material properties and measurement of physical, chemical, or biological variables based on the in situ interaction of microwaves with matter (the sensors subject of this book belong to the second class). The next sections succinctly review these sensor types, with special emphasis on the latter category.

1.2.1 Remote Sensing: RADARs and Radiometers

Remote sensors gather information of an object or a phenomenon without physical contact with it, and, typically, the sensing element is located at significant distances from the target[5] [134–137]. Remote sensing can be applied in different fields, including Earth observation, land surveying, atmosphere analysis, agriculture, geology, geography, space, meteorology, oceanography, traffic control, and many others. Remote sensors can be divided in two groups: active and passive. In active remote sensing, the sensor includes a source of electromagnetic radiation (a transmitter) that illuminates the target and a detector (receiver) that collects the signal reflected back from the target. The so-called RADAR sensor belongs to this class [138–142]. In passive remote sensing, the sensor detects the electromagnetic energy emitted by an object or scattered by it.

Microwave radiometers are an example of passive remote sensors, able to detect microwave radiation emitted by matter (radiometers are self-generating sensors, as indicated before) [143, 144]. The architecture of a microwave radiometer consists of an antenna, the front-end, composed of a mixer and a low noise amplifier, and a back-end for signal processing at intermediate frequencies. Down conversion to a lower (intermediate) frequency (heterodyning) is often used in order to ease signal amplification and signal processing. Nevertheless, low noise amplifiers are becoming available at higher frequencies, i.e. up to 100 GHz, making heterodyne techniques obsolete. Radiometers are mainly used for water vapor and temperature observations in weather and climate monitoring, but there are other applications, such as remote sensing of Earth’s ocean and land surfaces (i.e. gathering ocean temperature and wind speed, ice characteristics, soil and vegetation properties, etc.) [145–148].

RADAR sensors, as active devices generating their own electromagnetic signal, use the time delay between such emitted signal and the signal reflected back by the target (collected in the receiver) in order to determine its location, velocity, and direction. RADAR sensors are useful for localization purposes and are of special interest in geology, archeology, and civil engineering, among other

5 For example, remote sensors located in satellites or aircrafts are applied to detect and identify objects on Earth.

sectors, due to their capability to detect underground-buried targets. The so-called ground-penetrating RADAR (GPR) is a clear example of an active remote sensor useful in such mentioned fields (e.g. for the detection of buried pipes and mines, and measurement of ice thickness in frozen areas) [149–151]. Traffic control, anti-collision systems, and automotive driving assistance are additional well-known applications of RADAR (and LIDAR) sensors [142, 152–156]. Nevertheless, RADAR sensors are also of interest for microwave imaging [138, 157–160]. In this case, the working principle is the unique and characteristic interaction between the different targets and the incident electromagnetic radiation (described by the spectral response).

There are different types of RADAR sensors. In pulsed RADARs, either monostatic or bistatic,[6] the distance to the target is determined by the transit time a short pulse emitted by the transmitter antenna needs to reach the receiver after being reflected back by the target. This simple form of RADAR has limitations, especially for short-range distance measurements, where very short pulses are needed (the accuracy of the distance measurement is inversely related to the length of the pulse). A different form of distance measurement using RADAR exploits frequency modulation. In these systems, referred to as frequency-modulation continuous-wave (FM-CW) RADAR, the frequency of the transmitted signal is continuously varied over time [161]. Since such signal needs a finite time to return back to the receiver, it follows that the frequency of such signal is different to the one of the signal being broadcasted by the transmitter. By comparing the frequency difference between both signals, the distance to the target can be obtained. FM-CW RADARs can operate at relatively low frequencies, and their cost is typically low. These systems have been used as altimeters, and have found application in those industrial scenarios where dust and pollution prevent from the use of infrared and optical sensors. For the measurement of the relative velocity of the target with regard to the RADAR sensor, it is possible to use pulsed or FM-CW RADAR systems. It suffices to infer the distance at two different instants of time. However, for quasi-instantaneous speed measurements, Doppler RADARs are preferred [162]. In such RADAR, the transmitter sends an unmodulated continuous wave (CW). The velocity is determined from the frequency shift of the reflected signal, caused by the relative velocity between the target and the sensor (Doppler effect).[7] Doppler RADARs are also simple and low-cost systems that have found applications in diverse scenarios, in particular, vehicle speed control. Such systems are also useful in environments subjected to dirt or pollution. Techniques for improving the performance of RADAR systems, including impulse compression techniques, ultrawide band (UWB) RADAR, etc., have been proposed [140, 163, 164], but are out of the scope of this book. Figure 1.6 depicts the basic architecture corresponding to an FM-CW RADAR and (CW) Doppler RADAR system.

The frequency of electromagnetic waves used in RADAR depends on the specific application, but the frequency range is comprised between the UHF band (or even lower frequencies in certain cases) and the millimeter-wave band. For example, GPRs operate at low frequencies (typically below 2–3 GHz) because such frequencies penetrate more efficiently in Earth. As frequency increases, the attenuation caused by atmosphere (due to absorption) also increases, but high-frequency RADARs are prone to generate tightly focused beams with relatively small-sized high-gain antennas. Thus, medium-range RADARs, such as airborne RADARs, operate between the L and the K_a bands, but many short-range targeting RADARs, e.g. automotive RADARs and collision avoidance RADARs, operate in the millimeter-wave band.

Let us mention, to end this section, that RADAR technology has also been applied to the implementation of presence and motion detectors [165–169]. As compared with their infrared

6 Monostatic RADARs use the same antenna for transmission and reception, whereas in bistatic RADARs, signal transmission and reception is performed by two different antennas.

7 Nevertheless, there are also pulsed Doppler RADARs and FM-CW Doppler RADARs.

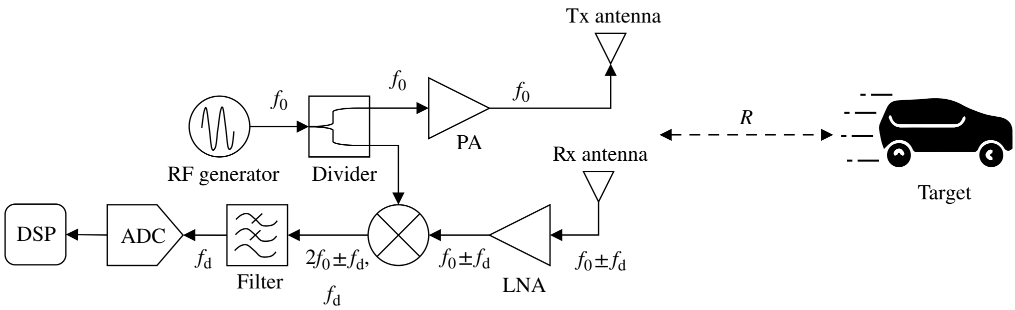

Figure 1.6 Basic architecture of a CW Doppler RADAR devoted to the determination of the velocity of a moving target, which causes a Doppler shift of $\pm f_d$. The frequency of the signal generator is f_0. The Doppler frequency f_d, necessary to infer the target velocity, is obtained by filtering the higher frequency component, $2f_0 \pm f_d$, at the output port of the mixer. The PA and LNA blocks correspond to a power amplifier and low-noise amplifier, respectively. The target speed is determined after an analog-to-digital conversion (ADC) and digital signal processing (DSP) stages. The basic architecture of a FM-CW RADAR, useful to provide the range (distance) of the target, is essentially the same. The unique difference is that a VCO is needed in order to generate the frequency-varying (FM-CW) signal injected to the power divider. In this case, the distance of the target is determined also by the incremental frequency at the input ports of the mixer, caused by the time delay of the transmitted signal.

counterparts (the passive infrared –PIR– detector, a pyroelectric sensor able to detect different levels of infrared radiation), RADAR presence and motion detectors are not affected by ambient temperature and exhibit a wider detection range (though their cost is higher and they are more power consuming than PIRs). Further details on RADAR sensors and radiometers can be found in the literature [134–144].

1.2.2 Sensors for *In Situ* Measurement of Physical Parameters and Material Properties: Non-remote Sensors

RADAR sensors and radiometers are contactless and free space (*ex situ*) sensors, where the sample under test, or target under study, is located at significant distances from the sensing element (sensing is performed remotely). This section deals with another type of microwave sensors, i.e. those that require proximity, not necessarily contact, with the sample or material under analysis. In such in situ sensors, the electromagnetic field interacts with the sample, which modifies certain measurable characteristics of the sensing element (e.g. a resonance frequency, magnitude, phase, or quality factor). Note that wireless and RFID sensors (to be studied in Chapter 7) are proximity sensors, despite the fact that the measured data is wirelessly sent to a central unit or reader (in some cases located at substantial distances from the sample). The reason is that in these devices, the sensitive element (a sensing tag in the nomenclature of RFID sensors) must be in proximity, or even in contact, with the target. By contrast, in remote sensing, the entire sensing function is carried out by a system distantly separated from the target.

Microwave sensors are of special interest for the dielectric characterization of samples or analytes, including solids, liquids, gases, chemical components or composites, bio-samples, etc. By virtue of the dependence of the typical output variables of the sensors with the permittivity of the surrounding medium, microwave sensors are good permittivity sensors, useful for the measurement of any variable related to it, or influenced by it (e.g. material composition and defects in samples). Variables such as temperature, humidity, and pressure do also alter the permittivity of dielectric materials. Therefore, microwave sensors can also be applied to the measurement of such (and many other) variables. Nevertheless, for that purpose, specific sensitive materials,[8] with strong dependence of their permittivity, or conductivity, with the variable under measurement, are typically used in order to boost up the sensitivity.

There are many types of non-remote microwave sensors, and such sensors can be classified according to various criteria. The next section discusses such categorization schemes. Then additional sections are dedicated to briefly discuss the most relevant types and methods of non-remote microwave sensing, i.e. cavity sensors, the Nicolson–Ross–Weir method, coaxial probe sensors, and planar sensors (the subject of this book).

1.2.2.1 Classification of Non-remote Microwave Sensors

A first, and probably the most remarkable, binary categorization of non-remote microwave sensors distinguishes between planar and nonplanar sensors. Planar microwave sensors are devices implemented in planar technology, using additive or subtractive techniques, typically, although not exclusively, based on transmission line elements, e.g. microstrip or coplanar waveguide (CPW), usually combined with other planar elements, such as resonators.[9] Nonplanar sensors, by contrast, are based on waveguides, resonant cavities, or coaxial probes, typically, i.e. nonplanar structures.

Both planar and nonplanar microwave sensors can be either resonant or nonresonant. In general, resonant sensors are more sensitive and accurate than nonresonant sensors [170]. Concerning size and cost, a relevant aspect from a practical viewpoint, resonant sensors are usually smaller and cheaper.[10] However, resonant sensors cannot be used to perform broadband characterization of materials (e.g. dielectric spectroscopy [171]), due to their narrowband nature. In resonant sensors, at least one resonant sensing element is used, and the output variable is, typically, although not exclusively, or not always, the resonance frequency, influenced by the dielectric properties of the material or medium surrounding the resonator. In nonresonant microwave sensors, the amplitude and/or phase of the reflection and/or transmission coefficient are the typical output variables, also influenced by the material or medium surrounding the sensing element (in contact or contactless), for example a transmission line section or a waveguide section.

Another binary classification scheme considers the operation mode of the sensor, either transmission or reflection. Transmission-mode sensors are two-port devices where the output variable is a certain characteristic of the transmission coefficient (magnitude, phase, resonance frequency, quality factor, etc.). Reflective-mode sensors are, in general, one-port structures, where the information of interest is contained in the reflection coefficient. Reflective-mode sensors are especially suited for applications requiring "sensing probes." A coaxial probe is an example of reflective-mode sensor that can be in contact with the sample under test, or introduced in it (e.g. for liquid sensing). Submersible reflective-mode sensors based on transmission lines have also been reported [172]. It should be mentioned that there are microwave material characterization techniques, such as the so-called Nicolson-Ross-Weir method (to be discussed later) [173, 174], that use two-port structures,

8 Such materials, sometimes designated as "smart" materials, are discussed in Chapter 7.

9 In most planar sensors, a transmission line (or a transmission-line-based structure) is used for exciting the sensing element, usually a planar resonator. Nevertheless, there are planar sensors where the excitation of the sensing element is carried out by irradiating it with an electromagnetic signal (using an antenna). In such sensors, a transmission line is, in general, not required, and the sensor typically consists of a planar resonant element, an array of resonant elements, a planar antenna, or any other pattern (e.g. a frequency selective surface, or a metasurface) whose characteristics can be altered by the target or by the stimulus. Frequency-domain chipless-RFID backscattering sensors, to be analyzed in Chapter 7, constitute an example of this type of planar sensors. There are also planar microwave sensors based exclusively on transmission line elements.

10 Resonant cavities are an exception.

typically a coaxial line or a waveguide, and retrieve the information (permittivity and permeability of the sample under test) from both the measured reflection and transmission coefficients.

Finally, non-remote microwave sensors can be contact or contactless. It is not always necessary for the sample under test, or target, to be in contact with the sensing element in order to obtain, or guarantee, the functionality of the sensor. Proximity might be enough to alter the electromagnetic field generated by the sensor and thus obtain the measurement of the parameter of interest. Most microwave sensors are guide-wave or transmission-line-based sensors operating under contact or contactless, i.e. by proximity. Nevertheless, there is another class of contactless sensors, i.e. the so-called free-space sensors [175–179], where the sample under test is located in the path between a transmitter and a receiver antenna [Fig. 1.7(a)]. The amplitude and phase of the signal collected in the receiver antenna depend on the dielectric characteristics, as well as dimensions and shape, of the sample under test. Consequently, by measuring the transmission coefficient, information relative to the sample of interest can be inferred. Such free-space sensors can also be implemented as reflective-mode structures, similar to a monostatic or a bistatic RADAR configuration. Free-space sensors are indeed remote sensors, as far as the sample is "distant" from the transmitter and receiver antennas (i.e. the sample does not interact with the near-field). However, these permittivity sensors are not true remote sensors, such as RADARs, LIDARs, or SONARs, with targets typically located "very far" from the sensor.

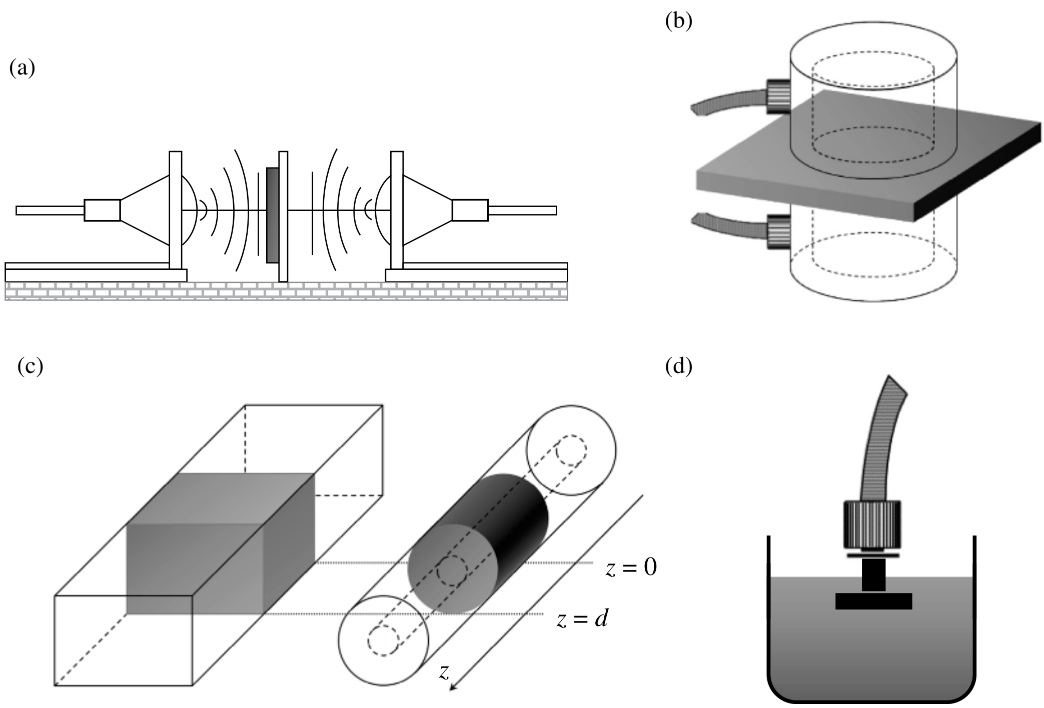

Figure 1.7 Nonplanar microwave sensors devoted to material characterization. (a) Free-space; (b) split cylinder resonator; (c) T/R NRW sensor; (d) coaxial probe.

1.2.2.2 Resonant Cavity Sensors

Resonant cavities are closed metallic structures, generally implemented by means of a waveguide section (rectangular or circular) short-circuited at both ends [180, 181]. Resonant cavities are able to confine electromagnetic energy corresponding to different resonant modes,[11] with frequencies that depend on the geometry of the cavity and dielectric constant of the material filling the cavity. For a rectangular waveguide cavity resonator with width a, height b, and length d, the frequencies of the different modes, TE_{mnl} or TM_{mnl}, are given by [181]

$$f_{mnl} = \frac{c}{2\sqrt{\varepsilon_r \mu_r}} \cdot \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{d}\right)^2} \tag{1.1}$$

where c is the speed of light in vacuum, ε_r and μ_r are the relative permittivity and permeability, respectively, of the material filling the cavity, and m, n, and l are the mode numbers. For a circular waveguide cavity resonator (or cylindrical cavity), the resonance frequencies of the different modes are given by expressions similar, but different, to (1.1) (such expressions, different for the TE_{mnl} and TM_{mnl} modes, can be found in [181]). In view of (1.1), it is obvious that from the resonance frequency of a certain mode, it is possible to obtain the dielectric constant of the material filling the waveguide (note that for a dielectric material, $\mu_r = 1$). Thus, the resonant cavity, either rectangular or cylindrical, is a dielectric constant sensor.

Some power dissipation is inevitable due to the finite conductivity of the metallic walls of the cavity and to the dielectric losses of the material filling the cavity, if it is present. It is well known that air-filled metallic waveguide resonators, or cavities, exhibit very high unloaded quality factors by virtue of the small losses associated with the metallic walls. However, such quality factor is obviously degraded if the cavity is filled, or partially filled, with a (lossy) dielectric material. Let us assume that a rectangular cavity resonator is completely filled with a dielectric material with loss factor $\tan\delta$. The unloaded quality factor is given by

$$Q_0 = \left(\frac{1}{Q_c} + \frac{1}{Q_d}\right)^{-1} \tag{1.2}$$

where Q_c is the unloaded quality factor due to the lossy conductor, but lossless dielectric, and Q_d is the unloaded quality factor associated with the lossy dielectric with perfect conducting metallic walls. For the TE_{10l} mode,[12] Q_c is [181]

$$Q_c = \frac{(kad)^3 b\eta}{2\pi^2 R_s} \frac{1}{\left(2l^2a^3b + 2bd^3 + l^2a^3d + ad^3\right)} \tag{1.3}$$

whereas Q_d is given by

$$Q_d = \frac{1}{\tan\delta} \tag{1.4}$$

regardless of the resonant cavity mode [181]. In (1.3), $k = \omega\sqrt{\varepsilon_r}/c$, where ω is the angular resonance frequency of the mode, $R_s = \sqrt{\omega\mu_0/2\sigma}$ is the surface resistance of the metallic walls, μ_0 and σ being the permeability of vacuum and the conductivity of the metallic walls, respectively, and $\eta = \eta_0/\sqrt{\varepsilon_r}$ is the wave impedance of the dielectric material, where η_0 is the wave impedance of free space. By

11 The electromagnetic fields in the cavity are excited through external coupling, by means of a small aperture, a small wire probe (e.g. a coaxial probe), or a loop.

12 For a rectangular cavity resonator with dimensions satisfying $b < a < d$, the dominant TE mode (i.e. the one exhibiting the lowest resonance frequency) is the TE_{101} mode [181].

measuring the unloaded quality factor of the cavity resonator, the loss tangent of the material filling the waveguide can be inferred.[13] The unloaded quality factor Q_0 is dominated by Q_d, since $Q_d << Q_c$, even for low-loss dielectrics. For that reason, cavity resonators are appropriate devices to accurately determining the loss tangent of low-loss materials, where other methods find some difficulty.[14] Moreover, due to their inherent high quality factor, cavity resonators provide a precise measurement of the resonance frequency of the mode of interest. Consequently, the dielectric constant of the MUT can also be determined with a high level of precision.

The main limitation of the resonant cavity method, as it has been presented, concerns the fact that the MUT must occupy the whole volume of the cavity, and this is not practical in most situations. However, resonant cavity sensors can also be applied to the dielectric characterization of material samples occupying a small portion of the cavity volume. In this case, the technique, usually referred to as perturbation method [181, 183, 184], is based on the variation experienced by both the resonance frequency and quality factor of the cavity, when it is loaded (or perturbed) with the sample under test. In this technique, it is assumed that the fields in the cavity loaded with the sample are slightly perturbed as compared with those of the unloaded (unperturbed) cavity, a reasonable approximation in many practical situations (small samples, or samples with small dielectric constants). An approximate expression providing the resonance frequency of the perturbed cavity was derived in [181]. Let us call such (angular) frequency ω_p, and the resonance frequency of the unperturbed cavity ω_0. The fractional change experienced by the resonance frequency by perturbing the cavity is given by

$$\frac{\omega_p - \omega_0}{\omega_0} = - \frac{\int_{V_0} \left(\Delta\varepsilon \left| \vec{E}_0 \right|^2 + \Delta\mu \left| \vec{H}_0 \right|^2 \right) dv}{\int_{V_0} \left(\varepsilon \left| \vec{E}_0 \right|^2 + \mu \left| \vec{H}_0 \right|^2 \right) dv} \tag{1.5}$$

where V_0 is the volume of the cavity, $\vec{E}_0$ and $\vec{H}_0$ are the fields of the unperturbed cavity, ε and μ are the permittivity and permeability, respectively, of the unperturbed cavity ($\varepsilon = \varepsilon_0$ and $\mu = \mu_0$ for air-filled cavities), and $\Delta\varepsilon$ and $\Delta\mu$ are the changes in the permittivity and permeability, respectively, caused by the perturbation. This is the general expression obtained in [181], which considers possible variations in both the permittivity and permeability of the cavity. Nevertheless, for dielectric materials, $\Delta\mu = 0$, and the expression can be further simplified. The integrals in (1.5) extend over the whole volume of the cavity, but it is obvious that the decrease in the resonance frequency of the perturbed cavity is more significant if the permittivity perturbation occurs in regions where the electric field intensity is large.

A variant of the resonant cavity sensor, that exists commercially [185] and is very appropriate for the nondestructive and accurate measurement of the complex permittivity (or dielectric constant and loss tangent) of low-loss and narrow dielectric slabs, is the so-called split cylinder resonator [186–191].[15] This permittivity sensor uses a cylindrical cavity separated into two halves [Fig. 1.7 (b)], with the sample placed in the gap between both parts. Typically, one of the halves is fixed, whereas the other one is movable, in order to accommodate samples of different thickness.

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13 Techniques to measure the unloaded quality factor can be found in several textbooks, e.g. [181, 182], and are out of the scope of this book.

14 Planar resonant methods can also be applied to the determination of the dielectric constant and loss tangent of dielectric materials, as it will be shown later in this book. However, these planar sensors are implemented on lossy (although typically low-loss) dielectric substrates. Therefore, the determination of the loss tangent with such planar techniques is not as accurate as with the resonant cavity technique, especially for low-loss materials.

15 The split cylinder resonator can be found as integral part of many microwave laboratories for the accurate measurement of the dielectric constant and loss tangent of (uncladded) microwave substrates.

Concerning the sample geometry, the only requirement is that the sample must be flat and it must extend beyond the diameter of the two cavity sections. Thus, it is not necessary to cut a small piece of the sample in order to introduce it in any cavity or to machine it in order to adapt it to the volume of the cavity. In this method, the TE_{011} resonance is excited,[16] and from the measurement of the resonance frequency and quality factor, the complex permittivity of the sample under test is obtained, as detailed in several sources [189–191] corresponding to research activities mainly carried out at the National Institute of Standards and Technology (NIST), Boulder, Colorado. For resonance excitation and measuring purposes, small coupling loops (introduced through small holes in the side of each cylinder half) are used in the commercial version of [185].

Another technique for the nondestructive measurement of the complex permittivity of narrow dielectric slabs is the split (or single) post-dielectric resonator [192–195]. Other dielectric resonator sensing techniques can be found in the literature [196–199]. In these techniques, the sample under test creates a "dielectric resonator," and hence the samples need to be machined in the form of discs or cylinders in order to perform the measurements. Dielectric resonator techniques are very accurate, but determination of the complex permittivity of the samples from the measurement of the resonance frequency and quality factor requires, in general, complex numerical electrodynamic methods [200].

1.2.2.3 The Nicolson–Ross–Weir (NRW) Method

The Nicolson-Ross-Weir (NRW) method is a nonresonant reflection/transmission (R/T) technique for the measurement of the complex permittivity and permeability of the sample under test [178, 179, 201–204]. It utilizes closed-form expressions providing the material properties as a function of the measured S-parameters in the considered two-port test structure, typically a coaxial line or a closed waveguide, containing the sample under test. Such sample should be made of a homogeneous and isotropic material occupying completely the region between the planes $z = 0$ and $z = d$ of the guided wave structure, while the regions $z < 0$ and $z > d$ are assumed to be air-filled [Fig. 1.7(c)]. Let us clarify that the method applies to any guided wave structure operated in the TEM mode (e.g. coaxial lines, or striplines) and to guided wave structures with either a single TE or TM mode present in all regions (e.g. a rectangular waveguide). Nevertheless, the NRW method also contemplates that the specimen under test can be illuminated in free space by either a parallel- or a perpendicular-polarized plane wave that is incident at a certain angle from the normal to the material. In this case, the material should be semi-infinite in the transverse (x and y) directions.

Let us next derive the relevant expressions of the NRW method by considering a TEM guided wave structure (the expressions for TE/TM waveguides or for free-space can be found, e.g., in [203, 204]). The S-parameters, S_{11} and S_{21}, of the guided wave filled with the sample (of finite length d) can be expressed as [178, 203, 204]

$$S_{11} = \frac{\Gamma\,(1 - T^2)}{1 - T^2\Gamma^2} \tag{1.6a}$$

$$S_{21} = \frac{T(1 - \Gamma^2)}{1 - T^2\Gamma^2} \tag{1.6b}$$

where Γ is the interfacial reflection coefficient, defined as

$$\Gamma = \frac{Z_1 - Z_0}{Z_1 + Z_0} \tag{1.7}$$

16 This mode provides maximum field intensity in the position of the sample under test.

and T is the propagation factor, i.e.

$$T = e^{-\gamma d} = e^{-jkd} \tag{1.8}$$

In (1.7), Z_1 and Z_0 are the transmission line characteristic impedances in the region with and without sample, respectively. In (1.8), γ is the propagation constant, and k is the wavenumber. From (1.6), Γ and T can be isolated, i.e.

$$\Gamma = K \pm \sqrt{K^2 - 1} \tag{1.9}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{1.10}$$

where K is a factor that depends on the S-parameters

$$K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{1.11}$$

Thus, by measuring the scattering parameters of the sample-loaded guided wave structure, K, and hence Γ and T, can be obtained. Note that the sign in (1.9) is determined by forcing $|\Gamma| < 1$, as corresponds to a passive sample.

Once Γ and T are known, the propagation factor can be obtained, i.e.[17]

$$k = \frac{1}{d}[j \ln |T| - \phi] \tag{1.12}$$

where T has been expressed in phasor notation as $T = |T|e^{j\phi}$. Finally, the complex relative permittivity and permeability of the sample are calculated according to [203, 204]

$$\varepsilon_r = \frac{k}{k_0}\frac{1-\Gamma}{1+\Gamma} \tag{1.13a}$$

$$\mu_r = \frac{k}{k_0}\frac{1+\Gamma}{1-\Gamma} \tag{1.13b}$$

where $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$ is the free space wavenumber.

Additional literature related to the NRW technique and related T/R methods for retrieving material properties can be found in [205–216]. In particular, a simplified version of the NRW method that employs only a single-port network analyzer for data collection is reported in [216]. The NRW method has also been applied to retrieve the constitutive parameters of engineered materials and metamaterials [206, 213, 214].

1.2.2.4 Coaxial Probe Sensors

The open-ended coaxial probe [Fig. 1.7(d)] is a reflective-mode nonresonant sensor very useful for the *in vivo*[18] (and *ex vivo*) dielectric characterization of solid, semisolid, and liquid samples over broad frequency bands. It consists of a coaxial line truncated with an open-end termination, which

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17 Actually, depending on the sample dimension d, an additional phase term $2\pi n$ (n being an integer) should be added in (1.12) [203, 204]. This means that, if the electrical length kd of the sample is unknown, there is an intrinsic indeterminacy (designated as branching) in the method. This indeterminacy is solved by considering thin samples, with d smaller than a half-wavelength in the analyzed frequency range, so that $n = 0$, and thereby (1.12) can be used as it is written (i.e. without such additional phase term). Nevertheless, techniques to solve this branching issue that do not need to consider thin samples have been reported [205, 206].

18 Many biological samples (e.g. tissues) demand in vivo characterization techniques, and coaxial probes are very appropriate for this type of materials.

should be in contact with the sample under test (solid or semisolid samples), or submersed in it (liquid samples). Typically, a flat metallic flange transversally extends the ground plane at the open end, as depicted in Fig. 1.7(d). As compared to cavity sensors or to T/R guided wave sensors exploiting the NRW method, a relevant advantage of coaxial probes is the fact that there is no need to machine the sample under test to fit it to the sensing element, i.e. the coaxial probe method is non-destructive. Nevertheless, for solid or semisolid samples, good contact with the probe is required (uneven sample surfaces in contact with the probe can result in measurement inaccuracies), and for liquid samples, air bubbles should be avoided. The coaxial probe technique is accurate for moderate and high-loss materials, but it cannot compete against resonant cavities for the dielectric characterization of low-loss materials.

Coaxial probes are sensors able to provide the complex dielectric constant ($\varepsilon^* = \varepsilon' - j\varepsilon''$) of the sample material from a simple measurement of the reflection coefficient determined by the impedance seen from the aperture (looking at the sample). Such impedance depends on the dielectric properties of the sample. Thus, the complex dielectric constant can be retrieved from the collected data of the reflection coefficient. Due to its inherent measurement simplicity, the coaxial probe method has been extensively used for the dielectric characterization of different types of materials, with special emphasis on biological samples (it is impossible to enumerate the huge number of references, but a representative list is [217–227]). There are available commercial versions that automatically provide the complex permittivity of the sample from the reflection coefficient data acquired with a vector network analyzer (VNA) [228]. Obviously, such commercial coaxial probe sensor kits include algorithms (based on numerical methods) that convert the measured reflection coefficient to permittivity. The relation between the complex permittivity of the sample and the impedance seen from the open-end termination of the coaxial line is not simple, and there are different methods/models that have been developed to infer the complex permittivity from that impedance (inverse problem methods). The analysis of such methods is out of the scope of this book, but is available in different sources [228–241]. The main drawback of the coaxial probe method concerns the relative complexity of the numerical techniques necessary to retrieve the permittivity of the material sample. Such complexity is inherent to inverse problems, but it is magnified by the rich phenomenology of the physical system, where radiation from the aperture, or the generation of higher order modes, among other effects, is present and adds difficulty to the electromagnetic modeling of the structure and its solution.

Other sensors similar to the coaxial probes are the open-ended rectangular or circular waveguide probes, proposed many years ago [242–246], but still of interest today for different applications (crack and corrosion detection, microwave imaging, etc.), as revealed by the recent activity on these sensors [247–252].

1.2.2.5 Planar Sensors

Planar microwave sensors is the subject of this book. Therefore, as it has been previously mentioned, this section merely intends to provide a general and succinct overview of this type of sensors. An exhaustive analysis and study is left for the subsequent chapters (and sensor categorization, attending to different criteria, is left for a dedicated unit, Section 1.3). Nevertheless, the research activity in planar microwave sensors has experienced such a significant growth in recent years that it is impossible to cover all the reported sensor types, working principles, performance characteristics, and their main applications in a chapter section, or even in a complete book. Thus, the present subsection and Section 1.3 (in brief), and the entire book (exhaustively), focus on the main sensing strategies, working principles, and applications of microwave sensors implemented in planar technology, according to the authors' criteria and perspective. Naturally, many ideas, sensor prototypes and applications, reported by researchers working in this field, will not be included (nor cited) in this book. Indeed, the literature related to planar microwave sensors is innumerable and widespread among very different disciplines, including not only RF/microwave engineering but also electrical and electronics engineering, telecommunications, biology, chemistry, mechanics, medicine, physics, civil engineering, space, automotive engineering, agriculture, robotics, etc. This further hinders the inclusion, and discussion, of the whole research activity on the topic of this book in a single document. Nevertheless, the objective of the authors in writing this book has been to provide a representative, and significant, subset of the research activity and achievements on planar microwave sensors (by the authors and other groups) to date, with special emphasis on discussing those aspects related to sensor performance.

As noted at the beginning of this chapter, one of the main reasons explaining the increasing research activity in planar microwave sensors in recent years is their potential in the framework of the IoT and the "Smart World." Key aspects to the envisioned leadership of planar microwave sensors in next future are their low cost and profile, their compatibility with many different types of substrates (including flexible, organic, and textile/fabric substrates) and fabrication technologies (subtractive and additive), as well as the unique properties of microwaves, e.g. propagation across (and penetration in) many substances, and interaction with matter at different scales. Wireless connectivity, inherent to microwave technology, and the easy integration with the associated electronics (for sensor feeding, post-processing and, eventually, for communication purposes) are additional (and even more important) aspects that explain the increasing interest for planar microwave sensors in Academia and Industry. As an enabling (although not exclusive) technology, planar microwave sensors may contribute to the deployment of the IoT and ease the path toward the "Smart World" in many different fields (e.g. health, agriculture, civil engineering, automotive industry, and space). An additional attractive aspect of planar microwave sensing technology concerns the possibility of implementing eco-friendly sensors using biodegradable/recyclable substrates and organic conductive inks. In a future interconnected and intelligent world, with thousands of sensing elements (present everywhere, in everything, and in everyone), the development of "green sensors" is a demanding need. It is also a big challenge, due to the inevitable performance degradation related to the use of "green" materials.[19]

A planar microwave sensor can be defined as a device where the sensing element/s is/are implemented in planar technology and operates at microwave frequencies. Nevertheless, planar microwave sensors may include additional elements, necessary for sensing, that are not necessarily planar. For example, as it will be later shown, there are liquid sensors implemented in planar form (e.g. by means of resonator-loaded transmission line) that include fluidic channels in order to force the liquid under test to be in contact, or in proximity, to the sensitive element [18, 19]. The associated sensor electronics, needed for signal generation, post-processing, and communication purposes in a real scenario, represents also the addition of nonplanar elements, since it is typically based on commercial integrated circuits (voltage controlled oscillators – VCOs – microcontrollers, detectors, etc.), that must be soldered to the sensor substrate (or implemented in an independent electronic module). Indeed, in any microwave non-remote sensor (planar or nonplanar), three main modules, or blocks, can be distinguished (see Fig. 1.8): (i) the electromagnetic block, constituted by the sensing element and, eventually, by other components necessary to perform the sensing function through microwaves (fluidics channels, tuning elements, etc.); (ii) the electronic

19 Recyclable substrate materials, such as paper or compostable materials, exhibit high loss factors, as compared with other materials typically used for the implementation of microwave components (e.g. RT/duroid) or general purpose circuits (e.g. *FR4*). Organic conductive inks exhibit smaller conductivities than silver-based inks, in turn smaller than those of metallic laminates, such as copper, gold, or aluminum. These high-loss factors and low conductivities of green "materials" limit the achievable performance of microwave components based on their use.

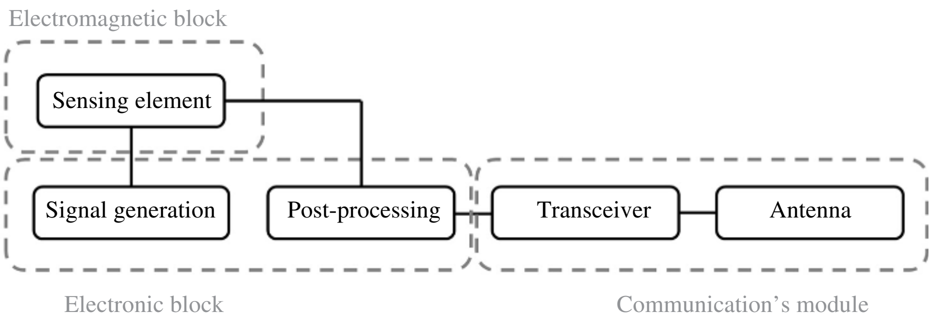

Figure 1.8 General block diagram of a microwave non-remote sensor.

block, in charge of signal generation and post-processing; and (iii) the communication's module (including the transceiver and the antenna). Eventually, depending on the type of sensor and its complexity, mechanical elements/accessories should also be required (for instance, capillaries, Teflon screws, mechanical connectors, and holders, among other elements, are part of microwave fluidic sensors [18, 19]). In this book, the emphasis is on the electromagnetic block and its optimization, despite the fact that in some of the reported prototypes, part of the electronics is also included (e.g. in certain sensors, particularly, microwave encoders, amplitude modulator detectors are essential to infer the envelope function needed to retrieve the information relative to the input variable, see [41, 72] and Chapter 4).

There are many different types of planar microwave sensors, exploiting different working principles, and useful for many diverse scenarios and applications. However, planar microwave sensors essentially detect, or measure, the input variable through the changes that such variable generate in the immediate environment of the sensing element. Such sensing element can be a planar resonator, a planar transmission line, a planar antenna, or a combination of various planar elements. Planar microwave sensors are essentially (at least in most cases) permittivity sensors, where the presence of a certain material in proximity, or in contact, with the sensitive element modifies its (measurable) characteristics (phase, resonance frequency, quality factor, magnitude, etc.). For example, an open transmission line, e.g. a microstrip line or a CPW, covered with a certain material (sample) exhibits transmission and reflection coefficients with phase and magnitude (measurable quantities by means of a VNA) that depend on the complex dielectric constant of the sample. This is an example of a nonresonant planar microwave permittivity sensor [Fig. 1.9(a)]. The complex permittivity can also be retrieved by means of resonant structures. For example, in an open transmission line loaded with a planar resonator (e.g. a split-ring resonator), the resonance frequency and the quality factor depend on the dielectric constant and loss tangent of the material in contact with the resonator [Fig 1.9(b)]. These two illustrative examples, and many other permittivity sensors, will be studied in more detail later in this book, but are pointed out in this short overview of planar microwave sensors for clarification purposes.

Since the permittivity of a material correlates with many other variables, e.g. temperature, pressure, humidity, material composition, and presence of certain analytes or defects, it follows that permittivity sensors are useful in multiple applications. As indicated before, to enhance the sensor sensitivity, it is sometimes necessary to coat the sensitive elements with "smart" films, with highly sensitive permittivity to the variables of interest (see Section 7.3 in Chapter 7, where an exhaustive list of materials of interest for sensing is reported). Motion sensors (i.e. displacement and velocity sensitive devices) can also be implemented by means of planar microwave sensors. In this case, the relative position between the movable part of the sensor and the sensitive (fixed) element

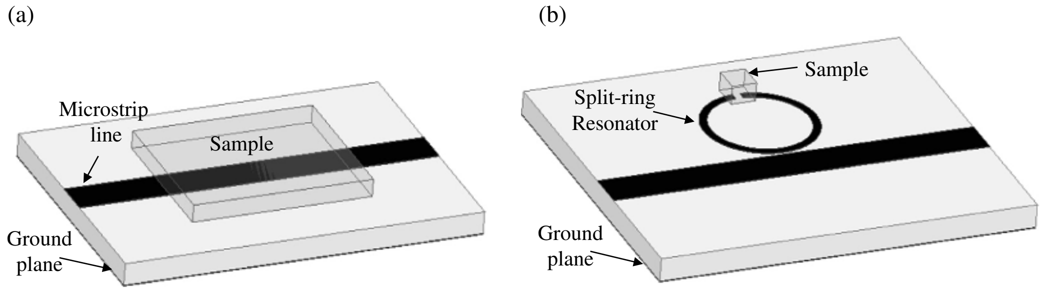

Figure 1.9 Sketch of a planar nonresonant (a) and resonant (b) sensor.

determines the "effective" permittivity in the surrounding environment of the sensitive element, and the position and velocity can be determined from the measurement of a certain characteristic of it.

Most planar microwave sensors are open structures where the sample under test does not need to be machined, contrary to cavity- or waveguide-based sensors. Nevertheless, similar to coaxial probe sensors, in case of solid samples, it is in general necessary that the samples exhibit at least a flat surface, the one that should be in contact, or close, to the sensing element. In contact sensors, in order to minimize the effects of the air gap, or space between the sample and the sensing element, it is necessary to press the sample against the sensor's surface. The thickness and transverse dimensions of the sample can be, in principle, arbitrary. However, by considering semi-infinite samples, i.e. in practice with dimensions exceeding the regions where the electromagnetic fields extend, it is possible to infer analytical expressions linking the output and input variables (as it will be shown in future chapters). For liquid samples, or gases, the air gap is not an issue. However, in the case of liquids, the use of dry films coating the sensing element might be necessary in order to prevent from substrate absorption.[20] Such films are typically very thin, but tend to degrade somehow the sensitivity. The problem of substrate absorption is solved by considering contactless liquid sensors, where, rather than fluidic channels, or liquid holders (containers), the liquid is syringed to a small capillary, or pipe, located close to the sensitive element. However, the sensitivity of these contactless liquid sensors is, in general, worse than those sensitivities achievable with contact-based sensors. The reason is that the electromagnetic field intensity decays with the distance from the sensing element. Thus, in general, for sensitivity optimization, contact sensors are preferred. There is, however, a class of planar microwave sensors where contact is not possible, or is not convenient, i.e. those sensors devoted to the measurement of displacements, velocities, and proximity. In this case, in order to avoid friction, the movable element should be separated from the fixed (sensitive) element. Linear or angular microwave rotary encoders, studied in Chapter 4, are examples of contactless displacement and velocity sensors, where the motion of the movable element is in a plane parallel to the one of the sensitive element. In other motion sensors, e.g. certain proximity sensors, the motion of the movable element is in the orthogonal direction to the plane of the sensing element [253]. Thus, in this case, the device is intrinsically contactless (except for the extreme position where the movable element is in contact with the sensor surface, usually the reference position).

20 For aqueous liquid samples, hydrophobic substrates also prevent from substrate absorption.

Another important characteristic of planar microwave sensors is the possibility of device implementation in flexible substrates. This opens the path toward the implementation of conformal and wearable sensors, of interest, e.g. in applications related to health monitoring, and food control [14, 15, 254–259].

For all the reasons explained in the preceding paragraphs, and for their potential as key enablers of the IoT and the "Smart World," planar microwave sensors are the subject of an intensive, and increasing, research activity. Planar sensors can be useful for a wide variety of appliances in many different sectors. Their low cost, small dimensions, compatibility with other technologies, robustness against harsh and hostile environments, potentially wireless connectivity, and the possibility to implement "green" sensing nodes are key advantages as compared with nonplanar sensors. Nevertheless, nonplanar sensors, such as resonant cavities, may exhibit superior performance, which may be needed in certain applications (at the penalty of higher cost and other limitative aspects). For example, the accurate measurement of the complex permittivity of low-loss samples should be preferably carried out by means of resonant cavities, with very high-quality factors, as compared with those of planar resonators [260]. Nevertheless, planar sensors similar to resonant cavities, implemented in substrate integrated waveguide (SIW) technology, have been reported [261, 262] and have demonstrated to exhibit reasonable accuracy for the determination of the dielectric constant and loss tangent of medium loss dielectrics.

The present section should be simply understood as a brief overview of planar microwave sensors at the same depth level of previous sections devoted to other microwave sensor types (nonplanar sensors and remote sensors). In Section 1.3, various classification schemes for planar microwave sensors, obeying different criteria, are reported. One of such classification schemes, the one that considers the working principle for sensor categorization, is adopted to present the different planar sensors throughout the different chapters of this book.

1.3 Classification of Planar Microwave Sensors

Planar microwave sensors can be classified according to various criteria. Some of them coincide with those of Section 1.1.2, relative to the general categorization of sensors and sensing technologies, or with those of Section 1.2.2.1, devoted to the classification of non-remote microwave sensors, whereas other classification schemes are specific of planar microwave sensors. Let us mention, however, that some of the classification schemes of Section 1.1.2 do not apply to planar microwave sensors, or are not representative (i.e. do not provide a useful separation among different categories). For example, according to the definition of active and passive sensors of Section 1.1.2, most (if not all) planar microwave sensors are active, i.e. they require a microwave source for the generation of the electromagnetic fields needed for sensing. Even battery-free RFID sensors, cataloged as passive (in the terminology of RFID), are indeed active, since the sensing tag must be fed by the interrogation signal, generated by the reader (see further details in Chapter 7). Nevertheless, such RFID sensing tags, powered by the interrogation signal, do not include a source of power, and for that reason, they are considered as passive in the usual RFID nomenclature (the one adopted in Chapter 7). Concerning the binary analog/digital categorization of sensors, also discussed in Section 1.1.2, most planar microwave sensors are analog, with the exception of certain types of RFID sensors where the retrieved information is digitally encoded, and microwave encoders, based on pulses. Other binary classification schemes, more interesting for planar microwave sensors, are contact/contactless, wired/wireless, single-ended/differential, resonant/nonresonant,

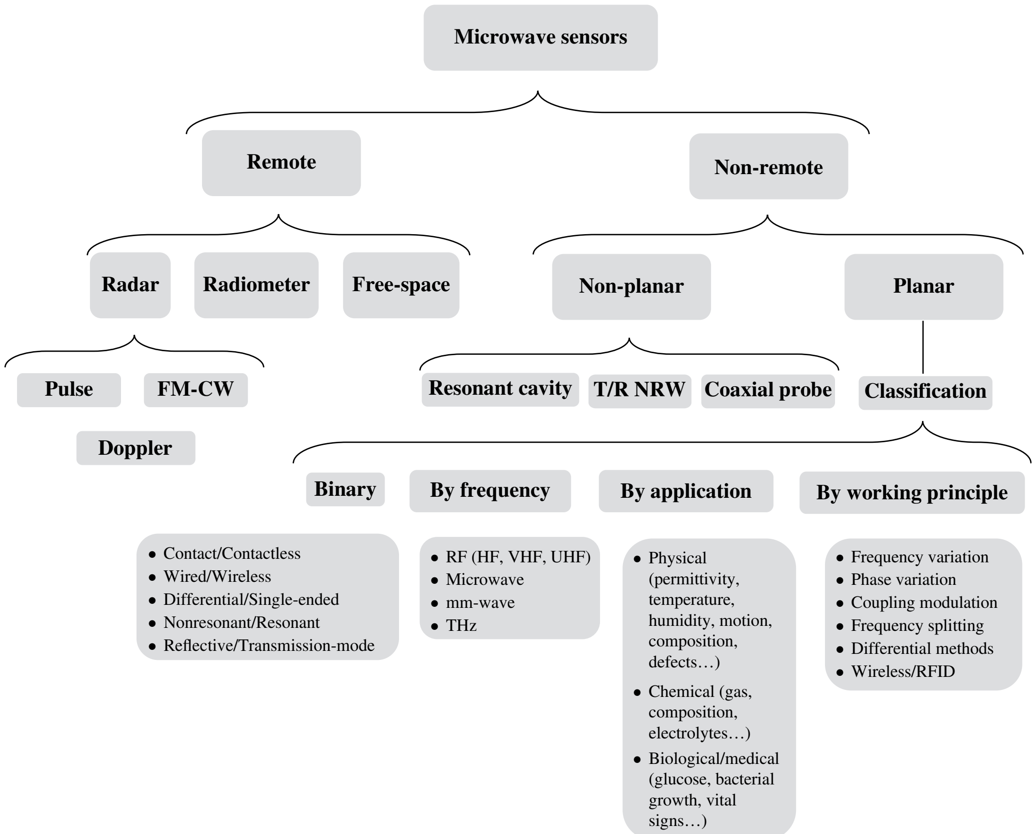

Figure 1.10 General classification of microwave sensors. As indicated in the text (see end of Section 1.2.2.1), there is some controversy in regard to the categorization of free-space permittivity sensors, but it has been opted to consider such sensors as remote in this scheme.

and reflective-mode/transmission-mode.[21] For any of these binary divisions, many different types of sensors can be identified that represent each binary group. Planar microwave sensors can also be cataloged by frequency of operation, by application, or by their working principle (the most convenient scheme, according to the authors' criteria, for the analysis and study of these sensors, and the one considered in this book). Let us next briefly discuss such binary and nonbinary classification schemes (the classification of planar microwave sensors is depicted in Fig. 1.10, where it is shown that such sensors are a subclass of non-remote sensors, in turn a subset of microwave sensors, i.e. all microwave sensor types discussed in this chapter, non-remote and remote, are included in Fig. 1.10).

1.3.1 Contact and Contactless Sensors

Planar microwave sensors are non-remote sensors that need contact or proximity with the sample under test, or analyte. The reason is that sensing in these devices is based on the interaction of the electromagnetic fields generated in a planar structure with the sample, and such fields decay with

21 Some of these binary classification schemes do also apply to non-remote (not necessarily planar) microwave sensors, as discussed in Subsection 1.2.2.1, but such schemes are further discussed in this section, where the specificities related to planar technology are considered.

distance. As anticipated in Section 1.2.2.5, for the measurement of material parameters (permittivity), determination of material properties (composition, defect detection, etc.), or for retrieving/detecting other physical, chemical, or biological variables with influence on the properties of a certain ("smart") material (e.g. temperature, humidity, and gas composition), contact is, in general, preferred. The reason is that higher levels of sensitivity result when the sample, or "smart" material, contacts the sensitive part of the sensor. Nevertheless, contact sensors are not exempt of certain difficulties, as also discussed in Section 1.2.2.5, particularly, the air gap effect for solid samples and substrate absorption for liquids (solutions to these issues were pointed out in that section and will be further detailed in subsequent chapters).

Most planar microwave sensors devoted to dielectric characterization and material composition (of solids, liquids, and gases) reported in the literature are contact sensors. Many different examples of such sensors can be found throughout this book. Nevertheless, there are also examples of planar microwave sensors devoted to material characterization, where direct contact between the sample and the sensitive element is inexistent (most of these sensors are used for the characterization and monitoring of liquids). For example, there are liquid sensors where, rather than through fluidic channels, the liquids are forced to be in proximity, but contactless, to the sensitive element by means of small pipes or capillaries [263]. In these sensors, substrate absorption is avoided, and dry films are not required (i.e. higher levels of tolerance against aging effects are expected in such sensors). Other contactless planar microwave liquid sensors are reported in [264–271]. Let us clarify that in certain contactless fluidic sensors, the element used to drive the liquid sample (channel, container, tube, pipe, etc.) is embedded in the planar structure (although, certainly, there is no contact between the sample and the sensitive part of the sensor). Such sensors, and also those where the driving element of the liquid is not embedded in the substrate, but separated from it, can be designated as noninvasive sensors, because the liquid under test is protected by the driving element (it is not "invaded," and hence perturbed, by the sensor). By contrast, contact liquid sensors are invasive, even if a dry film prevents from a direct contact between the liquid under test and the sensitive element. Another subtle terminology distinguishes between intrusive and nonintrusive sensors. In the former, the sensitive part of the sensor is placed, or mounted, within the fluidic element driving the liquid (but not necessarily in contact with the liquid sample). If, alternatively, the sensitive part of the sensor is not located inside the fluidic element, the sensor is classified as nonintrusive. Most planar microwave liquid sensors are nonintrusive (intrusive sensors are uncommon). Figure 1.11 shows schematically the differences between these types of liquid sensors. The microfluidic sensors and other liquid sensors reported later in different chapters of this book are contact sensors, and consequently invasive, but nonintrusive. Being invasive, the sensitivity is optimized, as far as there are no layers (with the exception of the dry film, if it is present) between the sensing element and the fluidic sample.

For the characterization of solids, direct contact with the sample is in general preferred (despite the mentioned air gap effect) because it enhances the sensitivity. However, there is a class of planar microwave sensors, motion sensors, which is intrinsically contactless. In these sensors, two parts can be distinguished: the stator, which includes the sensitive element, and the movable unit, usually (although not exclusively) made of a dielectric material in planar microwave motion sensors (such movable part is usually designated as rotor in angular displacement and velocity sensors). The relative motion between the stator and the movable element can be of different types, i.e. three dimensional, two dimensional, or one dimensional (linear). For two-dimensional and one-dimensional motion sensors, where the plane of movement of the mobile unit is parallel to the substrate where the sensing element is present, contact is potentially possible. However, friction should be avoided in order to prevent from wearing in both the stator and the movable element. Microwave encoders, either linear or angular, constitute a good example of these contactless sensors [41, 72–75],

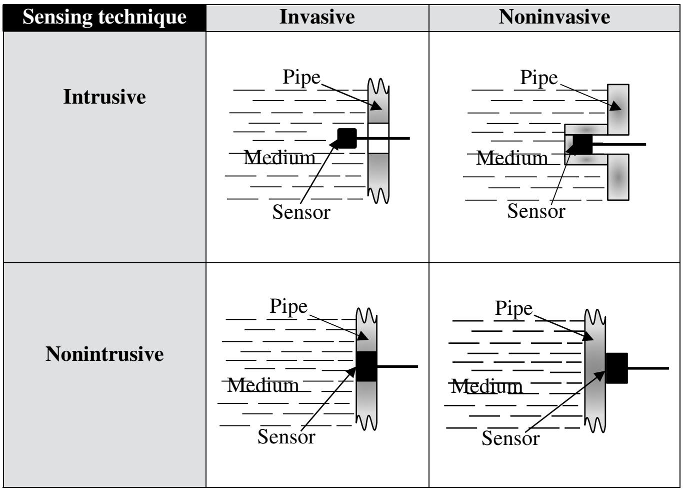

Figure 1.11 Distinction between invasive/noninvasive and intrusive/nonintrusive sensors.

but there are many other displacement and velocity sensors (linear, angular, and two dimensional) where the relative displacement between the stator and the movable part proceeds in a plane parallel to the sensor substrate (see, for example [272, 273]). In other sensors, the dominant relative motion between both sensing units is vertical [253] (i.e. orthogonal to the plane of the substrate), and, naturally, these sensors are contactless. A possible sensing mechanism in these contactless motion sensors is the variation in the “effective” permittivity of the immediate environment surrounding the sensitive element caused by the motion of the movable part (e.g. made of a dielectric material) [74]. It is also possible, and generally more sensitive, to infer the relative position and velocity by etching planar resonators, or other metallic inclusions, in the movable part, that perturb the sensing element, usually a planar resonator, through their motion [41, 72]. For example, in many sensors reported later in this book, inter-resonator coupling, modulated by the relative position/orientation between the fixed (sensitive) and the movable resonator/s, modifies the resonance characteristics, and such position/orientation can be inferred, e.g., from the magnitude variation of the sensor’s response at a fixed frequency (such sensors will be studied in detail later in this book, see Chapter 4). In other motion sensors, the resonance frequency is the output variable [274].

1.3.2 Wired and Wireless Sensors

As indicated in Section 1.1.2, wireless sensors are characterized by the fact that the measured sensing data, collected by the sensor node (adopting the terminology of WSNs), are sent to a central unit, located at certain distance, through a wireless link. However, the sensing element, or node, should operate by either contact or contactless. Thus, wireless sensors should not be confused with contactless sensors, despite the fact that in wireless sensors, data transfer proceeds contactless. The “wireless” or “wired” attribute in sensors refers to the type of communication (data transfer) between the sensing element and the central unit, not to the transduction procedure or mechanism (contact or contactless) to retrieve the sensing data from the sample under test or stimulus. The typical architecture of classical wireless sensor nodes in WSN, which is explained in detail in Chapter 7, includes the sensor unit, a battery (for sensor feeding), a microcontroller, and a transceiver (for communication purposes). The sensor unit can be of any type, not necessarily planar, and not necessarily a microwave sensor (despite the fact that RF/microwaves are involved in the communication link). Thus, these "classical" wireless sensor nodes are within the interest of this book, as far as the sensing unit is a planar microwave sensor. However, the wireless connectivity does not represent a distinctive aspect that deserves a special analysis in the context of the book. There is, however, another type of wireless sensors, i.e. the so-called RFID sensors, based on sensing tags, either battery-free or with battery, chipped or chipless. The main difference as compared with the classical sensor nodes of WSNs is that RFID sensor tags, at least in most cases, act as transponders, sending the data to the central unit (the reader) in response to an interrogation query. Some of these RFID sensor tags can be categorized as planar microwave sensors, provided the sensing function is performed by means of a planar component, e.g. the tag antenna, or another planar element (typically a resonator). Chapter 7, devoted to RFID sensors, includes many examples of planar microwave wireless sensors, with chipped and chipless tags. Chipless RFID sensor tags are fully planar low-cost devices that have attracted an increasing interest in recent years due to their potential as key enablers for the implementation of "green" IoT systems, as will be discussed in Chapter 7, although there are still many challenging issues to solve.

1.3.3 Single-Ended and Differential-Mode Sensors

In the general classification of sensors of Section 1.1.2, a binary distinction was made between relative (or incremental-type) and absolute sensors. In the framework of microwave sensors, the terms "differential-mode" (equivalent to relative) and "single-ended" (in reference to absolute) are preferred, or, at least, widely accepted in the literature. As indicated in Section 1.1.2, differential-mode sensors are interesting in applications where cross-sensitivities to undesired (usually external) stimuli (e.g. ambient factors, such as temperature or humidity) are significant. Typically, such environmental variables do not vary at the typical scales of the sensors. Therefore, despite the fact that a hypothetical sensing element might be sensitive to the effects of such variables (e.g. permittivity sensors can potentially exhibit a non-negligible cross-sensitivity to humidity and temperature, depending on the considered material), by using two sensing units, rather than one, the undesired variables will affect equally both elements. Thus, the differential output variable, or difference between the output variables of each sensing unit, will be minimally perturbed by the undesired external stimulus.

True differential-mode sensors consist of two independent (in principle identical) sensor elements (sensor pair). The input variable is defined as the difference between the input variables of both sensors, whereas the output variable is the difference between the respective output variables. Namely, in a differential sensor, both the input and the output variables are incremental. Usually, one of the sensors of the pair, and the corresponding input variable (well known), is considered as reference, and therefore the absolute value of the magnitude of interest can be inferred from the measurement of the output (differential) variable, correlated with the input (differential) variable by the transfer function. One interesting utility of differential-mode sensors is as comparator, a device able to detect relative differences, or variations, between a reference stimulus (a sample, or a variable) and the stimulus of interest. For example, defect detectors based on differential-mode sensors, able to discriminate the presence of tiny defects in samples, are later reported in this book (see, e.g., Chapter 3). Differential-mode sensors are also interesting for the measurement of solute concentration in diluted liquid solutions, where the reference is the solvent (Chapter 6 reports diverse examples of such sensors).

Let us clarify that there are certain planar microwave sensors that have been designated as differential-mode devices [275, 276], despite the fact that such sensors do not use two independent and noninteracting sensor units. Some frequency-splitting sensors, to be discussed in Chapter 5, are representative of such sensors. There are also frequency-splitting sensors consisting in two-port planar devices that divide the input signal between two parallel branches (by means of a splitter) that converge at the output port (combiner), where the output signal is collected (such devices have been designated as splitter/combiner frequency-splitting sensor in [18, 277], see also Chapter 5). Each branch is equipped with an identical sensing element (a resonator), sensitive to the stimulus (permittivity in most reported frequency-splitting sensors). Thus, these sensors consist of two sensing elements, but not of two independent and noninteracting sensor units (as a true differential-mode sensor requires).[22] Naturally, a differential input signal can be defined in frequency-splitting sensors, i.e. the difference in the stimulus of both sensing elements. The output variable is the frequency difference between the two notches (or peaks in certain implementations) that are generated by an asymmetry in the stimulus of both sensing elements (i.e. when the input variable in not null). In this sense, it is reasonable to consider that these frequency-splitting sensors are differential-mode devices. However, such sensors do not use a differential sensor pair, with two identical, independent, and noninteracting sensor units. It is also remarkable that, in frequency-splitting sensors, coupling between the sensing elements, if it is present, may degrade sensor performance (specifically the sensitivity) at small perturbations (or for small values of the differential input variable). Chapter 5 discusses this aspect and its solution (see also [277]).

Obviously, the main drawback of differential-mode sensors, as compared with their single-ended counterparts, is their larger dimensions and cost. In this regard, frequency-splitting sensors may represent an interesting trade-off, since similar characteristics to those of differential-mode sensors can be achieved with such sensors, yet keeping sensor dimensions and cost within reasonable limits (similar to those of single-ended sensors).

1.3.4 Resonant and Nonresonant Sensors

In Section 1.2.2.1, it was already pointed out that a relevant partition of non-remote microwave sensors differentiates between resonant and nonresonant sensors. The former tend to be, in general, more accurate and especially useful for the dielectric characterization of low-loss materials at a certain frequency, or discrete set of frequencies. The resonant cavity sensor (see Section 1.2.2.2) is a good example of a highly accurate resonant sensor. By contrast, nonresonant methods, though less accurate, offer the possibility to characterize the materials over broad frequency bands. The waveguide-based T/R sensor (see Section 1.2.2.3) and the coaxial probe (presented in Section 1.2.2.4) are canonical nonresonant sensors, the latter exhaustively used due to their facility of use (especially for liquid samples, where submersing the probe suffices to perform the measurements[23]).

The cited sensors in the previous paragraph are microwave (non-remote) sensors, either resonant or nonresonant, but nonplanar. Concerning resonant and nonresonant planar sensors, many strategies (or sensing approaches), topologies, and technologies have been reported in the literature (it is impossible to cite all of them, but many of these sensors are studied in the next chapters of this book and reported in references therein).

Nonresonant planar microwave sensors essentially consist in transmission line sections, either open (microstrip or CPW, typically) or closed (e.g. strip lines). Sensing is based on the changes in the characteristic impedance and complex propagation constant of the line, caused by the material or sample under test, which in turn affect the magnitude and phase of the reflection and transmission coefficients. The advantage of open lines is that sample preparation and placement is, in

22 Indeed, unless the device is adequately designed, the two resonance frequencies in splitter/combiner frequency-splitting sensors are consequence of the interference (i.e. interaction) between both branches. For this main reason, such sensors cannot be considered true differential sensors (despite the fact that each branch, independently, has the functionality of a single-ended frequency-variation sensor).

23 Although calibration and specific algorithms to retrieve the material parameters are needed.

general, simple. Namely, the material to be tested (either solid or liquid) is typically placed on top of the line, as a superstrate.[24] The thickness of the sample can be, in principle, arbitrary, although considering semi-infinite samples tends to facilitate the determination of the variable of interest from the measurement of the output variable/s (e.g. the phase and/or the magnitude of the reflection or transmission coefficient) and the use of simple analytical expressions [278]. Most nonresonant planar microwave sensors are contact devices, but it is possible to implement noncontact sensors, as well. For example, noninvasive and nonintrusive liquid sensors can be implemented by using capillaries or micro pipes to drive the fluid toward the sensitive region of the sensor. For closed transmission lines, micromachining techniques can be applied in order to generate micro-cavities in the substrate, either for direct sample placement (solids) or for the insertion of capillaries (liquids). Clearly, nonresonant sensors based on closed transmission lines are more complex. However, because the sample is typically buried in the substrate, the sensitivity of these sensors can be superior to those sensitivities achievable in the open-line counterparts.

In other nonresonant planar sensors, rather than ordinary lines, artificial transmission lines [279] are used for sensing. As compared to ordinary lines, the dispersion and characteristic impedance of these artificial lines can be further engineered. As a result, highly sensitive sensors based on such artificial lines can be implemented. Chapter 3 reports examples of phase-variation sensors implemented by means of artificial lines, specifically, slow-wave, electro-inductive-wave (EIW), and composite right/left-handed (CRLH) transmission-line-based sensors [280–283], with good sensitivities. However, the design of these sensors is, in general, more complex, since artificial lines consist, typically, in a host (ordinary) line periodically loaded with reactive elements (usually semi-lumped components, such as capacitors, inductors, and/or resonators).[25] It should also be mentioned that artificial lines are intrinsically narrow (or moderate) band structures. Therefore, the intrinsic broadband functionality of nonresonant planar microwave sensors does not apply if artificial lines are considered (indeed, the phase-variation sensors based on the indicated artificial lines, and reported in Chapter 3, operate at a single frequency, the one that optimizes the sensitivity).

With regard to resonant planar microwave sensors, most approaches are based on transmission lines loaded with, or coupled to, electrically small resonators, either metallic or slot (also called defect-ground-structure – DGS) resonators, the sensing elements. Most sensors are based on two-port structures and operate in transmission, but reflective-mode sensors have also been reported (such distinction between transmission-mode and reflective-mode sensors is the subject of the next subsection). The resonant sensing elements can also be distributed, typically quarter- or half-wavelength, resonators. Naturally, these distributed components tend to increase sensor dimensions, or, more specifically, the size of the sensing area, but their modeling (needed to predict the sensor behavior, i.e. sensitivity) is simple. Moreover, sensors based on fully distributed components (resonators) are, in general, robust against fabrication-related tolerances. Typically, the output variables in resonant sensors are the resonance frequency and the quality factor, or magnitude of the resonance peak or notch (Chapter 2 describes various sensors of this type). Nevertheless, there are sensors that exploit the phase (e.g. the phase of the reflection coefficient in reflective-mode

24 In case of CPWs, or other planar transmission lines open on both substrate sides, sample placement at either the top or the bottom sides is possible. However, for sensitivity optimization, it is convenient to locate the material sample in contact with the substrate interface where the electromagnetic fields are more intense.

25 EIW transmission lines are an exception. Such artificial lines are propagative structures consisting in a chain of coupled slot resonators, but are also subjected to certain design difficulty. Moreover, such lines exhibit very narrow propagation bands. It should also be mentioned that, despite the fact that EIW transmission lines are based on chains of coupled resonators, EIW-based sensors are not considered to be resonant sensors, since, rather than a resonance phenomenon, such sensors utilize the enhanced dispersion, intrinsic to these lines, for sensing.

resonant sensors), rather than the frequency. As an example, Chapter 3 reports highly sensitive phase-variation reflective-mode resonant sensors, based on open-ended quarter-wavelength and half-wavelength resonators,[26] and based on planar semi-lumped resonators (specifically, open-complementary split-ring resonators – OCSRRs). Frequency-splitting sensors, referred to before and exhaustively discussed in Chapter 5, are also resonant devices, where the canonical output variable is the difference in the split resonance frequencies generated by asymmetric dielectric loads in the sensing resonators. Coupling- modulation sensors, the subject of Chapter 4, are also resonant sensors, but in this case, the canonical output variable is the magnitude of the transmission, or reflection coefficient, modulated by the coupling between the sensing resonator and a transmission line, or another resonator. Typically, such coupling correlates with a spatial variable, such as a linear or angular displacement, and hence, these coupling-modulation sensors are mostly applied to displacement and velocity sensing. Chapters 2–6, and references therein, include many resonant planar microwave sensors.

Let us also mention that there are resonant planar sensors, similar to cavity resonators, implemented in SIW technology [261, 262, 268, 284–287]. By using low-loss substrates, such sensors can operate at relatively high frequencies and exhibit good quality factors, thereby being useful for the dielectric characterization of moderate and low-loss dielectric materials. However, SIW technology is more costly and complex than other planar technologies, either open or closed, for transmission line implementation (note that in SIW cavities, metallic vias and transitions are typically required). Concerning sample placement in SIW cavities, the procedure is similar to the one in closed transmission lines. For liquid measurements, capillaries parallel or transversally oriented to the plane of the substrate, and penetrating it in the region of the cavity where the field intensity is maximum for the considered mode, are used [285, 287]. These SIW-based resonant sensors are not considered further in this book, but the interested readers can find detailed information in various sources [261, 262, 268, 284–287].

Most planar microwave sensors discussed throughout this book are resonant and implemented by means of electrically small resonators. Such sensors are attractive because they combine good performance and size, and can be applied to many different scenarios and applications (e.g. dielectric characterization of solids and liquids, determination of analytes in bio-samples, and measurement of velocities and displacements, to cite some of them).

1.3.5 Reflective-Mode and Transmission-Mode Sensors

The last binary categorization of planar microwave sensors divides them between reflective-mode and transmission-mode sensors. The latter are two-port planar structures, resonant or nonresonant, closed or open. In transmission-mode nonresonant sensors, the output variable/s is/are typically the magnitude or/and the phase of the transmission coefficient, whereas the output variable/s in resonant sensors is/are the frequency, or/and the magnitude or/and the quality factor of the resonance notch, or peak. Nevertheless, sensing data can also be retrieved from the reflection coefficient (as redundant, or complementary, information). In transmission-mode sensors, a VNA is generally used to retrieve the sensing data (i.e. the transmission coefficient) at prototype level (or in proof-of-concept demonstrators), but this represents a high-cost solution in a real scenario. Magnitude and/or phase detectors can be cascaded to the output port of the electromagnetic sensor module, in order to reduce overall costs by avoiding the use of VNAs. For example, in coupling-modulation

26 Indeed, such sensors are not categorized as resonant in Chapter 3, since there is not a priori reason that forces to use quarter- or half-wavelength open-ended lines (i.e. resonators). However, as it is demonstrated in Chapter 3, the sensitivity of such sensors is optimized when the length of these lines is either a quarter or a half-wavelength at the operating frequency.

transmission-mode sensors, the canonical output variable is the modulus of the transmission coefficient, but conversion to voltage magnitude is possible by connecting an envelope detector to the output port of the sensing module [41, 72].

Reflective-mode sensors (resonant or nonresonant) utilize the same output variables as transmission-mode sensors, but referred to the reflection coefficient (these sensors are one-port structures). However, retrieving the sensing information by avoiding a VNA is more complex in this case, since the same port (indeed the unique port) is used for sensor excitation and for collecting the sensing data simultaneously. Thus, solutions based on the use of circulators or couplers are necessary for that purpose. For example, Section 3.2.2.4 reports a phase-variation differential sensor, operating in reflection mode, where the canonical output variable, i.e. the phase of the reflection coefficient of the sensing one-port structure (an open-ended quarter-wavelength resonator), is converted to magnitude by properly using a rat-race hybrid coupler [288]. The resulting structure is a two-port device, where the magnitude of the transmission coefficient correlates with the phase of the sensing arm. Thus, similar to transmission-mode sensors, it is possible to add further low-cost components to reflective-mode sensors (e.g. an envelope detector) in order to transform the magnitude of the transmission coefficient into a voltage, easily measurable by means of low-cost devices. Reflective-mode planar sensors (resonant or nonresonant) can be canonically used as sensing probes for liquids (similar to coaxial probes), by submersing the sensing element (the probe) in the liquid under test. Various examples of reflective-mode planar sensors are reported in this book, mainly in Chapter 3, devoted to sensing devices based on phase variation. Nevertheless, reflective-mode sensors exploiting coupling modulation between a sensing resonator and a transmission line have also been proposed (see Section 4.3.1 and Fig. 4.8 in Chapter 4).

1.3.6 Sensor Classification by Frequency of Operation

The frequency of operation of planar microwave sensors can be very diverse, ranging from UHF frequencies (or even lower frequencies) up to the millimeter-wave frequency band and beyond. Obviously, microwave sensors (either planar or nonplanar) can be classified according to their frequency of operation. For that purpose, different frequency band designations can be considered. Nevertheless, probably the most commonly accepted adoption, at least in the framework of microwave sensors, is the designation established by the Institute of Electrical and Electronics Engineers (IEEE), depicted in Fig. 1.12, and originally conceived to distinguish the different frequencies used in RADAR. Needless to say that certain broadband (nonresonant) sensors might cover several bands simultaneously, but the operational frequency (or spectrum) of most planar microwave sensors can be circumscribed within a specific frequency band.

When designing a planar microwave sensor, the choice of the operational frequency, or frequency band, depends on many factors. For example, certain applications inexorably dictate the frequency coverage (band) of the sensor, provided the interest is to study the behavior, or characteristics, of a certain material, or variable, within that band. A clear example is dielectric spectroscopy aimed to determine the complex dielectric constant of a certain substance within a predefined band of frequencies. In other cases, frequency regulations determine the operational frequency of the sensor. This is the case, for example, of the chip-based UHF-RFID sensor tags, a class of RFID sensors to be studied in Chapter 7, where the use of commercial chips and readers forces the design of the tag to be operative at specified frequencies within the UHF band (such specific frequencies depend on the different world regions).

However, in most sensing applications, other aspects related to technical issues, size, cost, etc., determine the operational frequency of the sensor. Size and cost are progressively becoming more important, taking into account the continuously increasing need of including sensors and sensor networks everywhere, in everything, and in everyone. Since planar microwave circuits scale with

IEEE Standard Radar Band Nomenclature		
Designation	**Frequency**	**Wavelength**
HF	3 – 30 MHz	100 m –10 m
VHF	30 – 300 MHz	10 m – 1 m
UHF	300 – 1000 MHz	100 cm – 30 cm
L Band	1 – 2 GHz	30 cm – 15 cm
S Band	2 – 4 GHz	15 cm – 7.5 cm
C Band	4 – 8 GHz	7.5 cm – 3.75 cm
X Band	8 – 12 GHz	3.75 cm – 2.5 cm
Ku Band	12 – 18 GHz	2.5 cm – 1.67 m
K Band	18 – 27 GHz	1.67 cm – 1.11 cm
Ka Band	27 – 40 GHz	1.11 cm – 0.75 cm
V Band	40 – 75 GHz	7.5 mm – 4.0 mm
W Band	75 – 110 GHz	4.0 mm – 2.7 mm
mm Band	110 – 300 GHz	2.7 mm – 1 mm

Figure 1.12 Frequency band designations according to the IEEE standard for RADAR (the indicated wavelength corresponds to wave propagation in free space).

the inverse of frequency, high-frequency operation would be, in principle, desirable. However, it is well known that at high frequencies within the microwave band (dozens of GHz and beyond), the performance of planar circuits degrades significantly. Moreover, the cost of the associated sensor electronics (for signal generation, post-processing, and, eventually, communication purposes) increases with frequency. Consequently, a trade-off is necessary, and planar microwave sensors generally operate at frequencies comprised between the UHF and the X bands. As indicated previously, SIW technology exhibits the advantages of planar and waveguide technologies, i.e. reasonable performance at relatively high frequencies (and hence small size) with moderately low cost, but SIW-based sensors are closed structures that require vias and transitions, and their fabrication, as well as sample placement, is complex (at least as compared with other planar sensors).

Despite the trade-off pointed out in the previous paragraph, sensor operation outside the indicated spectral frequency range is necessary in certain applications. For example, within the healthcare domain, subcutaneous sensors and implants are sometimes inductively coupled to the external unit and typically operate at frequencies below (or in the lower region of) the UHF frequency band [289]. There are also examples of near-field wireless sensors for healthcare applications (implants) based on loop inductors, compatible with the near-field-communications (NFC) regulated band at 13.56 MHz (HF band) [290, 291]. Nevertheless, many other implantable sensors utilize planar antennas operating at the Industrial, Scientific, and Medical (ISM) band [292, 293]. At the other extreme of the spectrum (millimeter-wave and THz bands), an innumerable variety of sensors, especially devoted to chemical sensing and biosensing, have also been proposed (see, e.g., [294–297]). At THz frequencies, extremely high sensitivities for the detection of small volumes of substances, i.e. in the nanoscale, can be achieved. Moreover, there are many chemical and biological analytes with spectral signatures at these frequencies. However, these sensors require specific and expensive micro/nanofabrication techniques that generally increase their production cost.

1.3.7 Sensor Classification by Application

Planar microwave sensors can also be designated according to their applications. The list of applications is so diverse that it is impossible to enumerate all of them. Physical variables as diverse as temperature, humidity, force, strain, pressure, velocity, displacements, and many others can be measured by means of planar microwave sensors, mainly exploiting the permittivity changes generated in the immediate surroundings of the sensing elements, as noted before. Nevertheless, there are many other applications in chemistry, biology, medicine, pharmaceutics, etc., based on the dielectric and electromagnetic properties of the materials and analytes under test (dielectric behavior, spectral signatures, absorption, etc.). Determination of material and liquid composition, or the concentration of components in solutions, including bio-samples, as well as the detection of specific specimens (e.g. bacterial growth) are only a few of the multiple possibilities of chemical sensors and biosensors operating at microwaves. The fields of applications are very transversal, including healthcare and medicine, agriculture, food industry and smart packaging, civil engineering and structural health monitoring, motion control, automotive industry, space, and smart cities.

1.3.8 Sensor Classification by Working Principle[27]

Probably the most useful, and convenient, classification of planar microwave sensors is the one that obeys their working principle. This is the one adopted in this book, as seen in the different chapters. Nevertheless, it is difficult in some cases to establish clear frontiers between the different approaches. Specifically, the categorization proposed in this book for the presentation and analysis of the different planar microwave sensors is as follows (by order of appearance in the book chapters, and with some representative references indicated): (i) frequency-variation sensors [19, 298–301], (ii) phase-variation sensors [281, 302–305], (iii) coupling-modulation sensors [41, 72, 272, 306], (iv) frequency-splitting sensors [18, 277, 307, 308], and (v) differential-mode sensors [309–311]. Then, an additional chapter is devoted to RFID sensors [312–316], the relevant feature being their wireless connectivity, rather than the specific working principle (very different among the various considered RFID sensor prototypes). Let us next briefly summarize the cited working principles in order to provide an early bird's-eye overview to the readers (further details are given in the subsequent chapters of the book).

1.3.8.1 Frequency-Variation Sensors

These planar sensors, discussed in Chapter 2, are essentially resonant sensors, where the output variable/s is/are the resonance frequency or/and the resonance notch (or peak) magnitude. The resonance frequency is mainly correlated with the dielectric constant of the material in contact, or in the immediate environment, with the sensing element, a planar resonator. The resonance magnitude depends principally on the loss factor of the sample (loss tangent or imaginary part of the complex dielectric constant). Alternatively to the resonance magnitude, the quality factor can be used as output variable, as it also correlates with losses. Probably frequency-variation sensors dominate the planar microwave sensor arena, and the main reasons are their small size, low cost, and high achievable accuracy and sensitivity. However, frequency-variation sensors require a frequency-varying source for measuring purposes. Depending on the input dynamic range, the required bandwidth coverage might be relatively narrow, but such sensors are not single-frequency sensors by nature. For input variables experiencing wide spans, and depending on the sensitivity, the output dynamic frequency range might be so broad, that wideband VCOs might be needed for sensing, with a penalty in overall sensor costs (at prototype level, sensor characterization or validation is usually performed by means of VNAs). Most planar frequency-variation microwave sensors are transmission-mode structures, but there are also many examples of reflective-mode sensors in the literature (see Chapter 2, and references therein, for further details).

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27 This subsection presents the classification used in this book to introduce the different considered planar microwave sensors, grouped by working principle. There are many references of each subclass, which are cited in the subsequent chapters of the book. Therefore, this subsection only quotes a few (but representative) number of works of each sensor type, in order to avoid an excessive number of references in this introductory chapter.

1.3.8.2 Phase-Variation Sensors

In phase-variation sensors, the main output variable is the phase of either the transmission or the reflection coefficient of the sensing device, which depends on the material surrounding the sensitive element, either a planar resonator or a transmission line section. Similar to frequency-variation sensors, the magnitude of the reflection or transmission coefficient can also be useful to gain further insight on material properties (loss tangent). Potentially, very high sensitivities can be obtained with phase-variation sensors implemented by means of transmission line sections, but at the expense of large sensing areas (note that a strong phase variation requires long lines). Meandering is a possibility, as discussed in Chapter 3, in order to avoid oversized sensors [302]. Nevertheless, a technique is proposed in Chapter 3 that boosts up the sensitivity without the need to extend the area of the sensing region [305]. These highly sensitive devices are reflective-mode structures consisting in step impedance quarter-wavelength line sections terminated with a resonant element (the sensitive part), either semi-lumped or distributed (e.g. an open-ended quarter-wavelength or half-wavelength line section). As compared with frequency-variation sensors, phase-variation sensors operate at a single frequency. There is no need to perform a frequency scan, as it is needed to identify the resonance frequency position in frequency-variation sensors. Nevertheless, phase-variation sensors can perform their functionality at different (selectable) frequencies (potentially, with a loss of performance if the frequency is different from the nominal one). Sensor sensitivity in phase-variation sensors can also be enhanced by means of artificial lines exhibiting high dispersion, as noted before [280–283]. Small variations in the permittivity of the sample under test, placed on top of such artificial lines, generate significant phase changes. Nevertheless, in some of these sensors, reported in Chapter 3, the output variable is not a phase, but a magnitude (inferred by means of phase-to-magnitude conversion techniques). Moreover, artificial lines exhibit pass bands and stop bands, and in some cases (e.g. EIW transmission lines [283]), the fundamental (lower frequency) pass band is very narrow. Thus, in sensors based on such artificial lines, the magnitude or/and frequency of the main pass band vary with the stimulus and can be considered to be the output variable/s.

1.3.8.3 Coupling-Modulation Sensors

In most coupling-modulation sensors, the variation in the coupling level between, at least, a planar resonator and a transmission line (host line), caused by the measurand, is the physical sensing mechanism. Such varying electromagnetic coupling modifies the magnitude of the frequency response of the sensing structure, usually, but not necessarily, a transmission-mode device. Thus, the canonical output variable in coupling-modulation sensors is the magnitude of the transmission (or reflection) coefficient (though magnitude to voltage conversion is possible, as indicated before). The strongest variation, or excursion, experienced by the magnitude of the transmission (or reflection) coefficient occurs at resonance or nearby frequencies. Thus, coupling-modulation sensors are typically designed to operate at a single frequency, tuned to the vicinity of resonance. Relative displacements (linear or angular) between the sensing resonator and the host line modulate line-to-resonator's coupling. Thus, most coupling-modulation sensors are devoted to displacement and velocity sensing. It should be mentioned that the resonance frequency in these structures might experience variations due to coupling modulation, but such changes are usually small and hence not useful for sensing. The main aim in coupling-modulation sensors is to generate the strongest possible excursion in the magnitude of the transmission (or reflection) coefficient at the design frequency, caused by the input variable (usually a relative movement). Although not unique, a possible coupling modulation strategy exploits the electromagnetic symmetry properties of transmission lines loaded with a single symmetric resonator [279, 317–319]. A section is dedicated to this interesting topic in Chapter 4. In brief, in a transmission line symmetrically loaded with a planar symmetric resonator, the line is not necessarily able to excite the resonator (even at the fundamental resonance or certain harmonics). This occurs if the symmetry plane of the line and one of the resonator are of different electromagnetic sort, one a magnetic wall and the other one an electric wall. Under these circumstances, line-to-resonator coupling is inexistent, and the line is transparent. However, any relative motion (linear, angular, or both) between the line and the resonator that truncates the symmetry activates their coupling, modulated by the level of asymmetry. The consequence is a variation in the response of the line, usually manifested by a notch with a depth dependent on the magnitude of the perturbation (i.e. dependent on the variation of the resonator position with regard to the reference, or symmetric, position). Obviously, in such coupling-modulation motion sensors, the host line and the symmetric resonator must be etched in independent substrates in relative motion. Such symmetry perturbation can also be achieved by loading asymmetrically the (fixed and symmetrically placed) resonator with a dielectric material, but this strategy has been rarely used, since for the dielectric characterization of materials, there are approaches that are more accurate.

Chapter 4 reports various examples of coupling-modulation sensors based on symmetry perturbation. In other coupling-modulation sensors, the level of proximity between the line (the static part) and the resonator (the movable part) is the coupling mechanism.[28] This is the case of the so-called electromagnetic, or microwave, encoders, either angular or linear, exhaustively discussed in Chapter 4, and potential candidates to replace the well-known optical encoders in certain applications or environments subjected to extreme ambient conditions or pollution. Such encoders essentially consist in a chain (linear or circular) of metallic inclusions (usually resonators) in relative motion over the sensitive part of the sensor (a transmission line or a resonator-loaded transmission line) in proximity but contactless with it. By chain (or encoder) motion, the response (magnitude) of the line at the operating frequency is modulated, and the result is an amplitude modulated (AM) signal at the output port of the line, with peaks or dips in the envelope function correlated with the presence of inclusions in the encoder chain. Thus, the information relative to the velocity and displacement can be easily inferred, through simple post-processing algorithms.

An example of a coupling-modulation sensor devoted to permittivity sensing is also reported in Chapter 4 [320]. As mentioned, coupling-modulation sensors are single-frequency sensors, requiring simple electronics for signal generation. However, amplitude (or magnitude) measurement are prone to the harmful effects of noise or electromagnetic interferences (by contrast, frequency or phase measurements exhibit major tolerance against such effects). Despite that fact, let us mention that electromagnetic encoders have demonstrated very good performance and robustness, even by implementing the encoders in conveyor or elevator belts made of rubber, by means of additive (printing) processes.

1.3.8.4 Frequency-Splitting Sensors

Frequency-splitting sensors, the topic of Chapter 5, are symmetric planar structures loaded with pairs of identical resonators. If such resonators are identically loaded, or perturbed, a single resonance notch, or peak, in the frequency response arises. However, such resonance splits into two notches, or peaks, if the resonators are asymmetrically loaded, or perturbed. Thus, the difference in the resonance frequencies or/and resonance magnitudes can be used as output variable/s for sensing. Such sensors are mostly utilized as quasi-differential permittivity sensors, or for the

28 It is possible to implement motion (or proximity) sensors similar to coupling-modulation sensors by replacing the resonant elements with other metallic or dielectric inclusions, as far as such inclusions are able to alter the frequency response of the line (sometimes loaded with a resonant element) and generate a significant excursion in the transmission or reflection coefficient at a certain frequency.

measurement of related variables, but frequency-splitting sensors can also be applied to the measurement of displacements (see, for example, Section 5.6.2). Although frequency-splitting sensors are not true differential sensors, as discussed before, they exhibit some of the advantageous aspects of them, particularly, good tolerance against cross-sensitivities of common-mode stimulus (ambient factors, typically). Similar to frequency-variation sensors, frequency-splitting sensors need excitation signals covering, at least, the frequency range corresponding to the output (differential) dynamic range, but are quite robust against the effects of noise and electromagnetic interference. As compared with differential-mode sensors, the dimensions of frequency-splitting sensors tend to be smaller, since they use a unique element for resonator's excitation (a transmission-line-based structure) plus two sensing resonators, rather than two independent sensor units.

1.3.8.5 Differential-Mode Sensors

Differential-mode sensors, the subject of Chapter 6, were defined in Section 1.3.3. Actually, differential sensing is not exactly a working principle, but rather a strategy to cancel (or minimize) the effects of undesired common-mode stimulus (that may perturb or even obscure the accuracy of measurements), and/or to retrieve the value of a variable in comparison to a reference (incremental measurements or comparison functionality). Thus, differential sensors can exploit any of the working principles indicated in the previous sections, provided the independent sensor units of the differential pair are (individually) based on them.[29] Exceptionally, there are examples of differential sensors in Chapter 3, where the exploited principle is phase variation.[30] However, most differential-mode sensors discussed in this book are jointly presented in a dedicated Chapter 6. Such differential sensors utilize two independent sensor units (a requisite of a true differential sensor). However, in some cases, the sensor includes additional elements, or components, devoted to collect the sensing data in a single port, and/or to use a unique port for sensor feeding.

In the devices reported in Chapter 6, the sensor units (pair) are essentially transmission line sections loaded with planar resonators. In some cases, they operate in transmission; in other cases, such units are reflective-mode structures (loaded or terminated with a resonant element). The essential phenomenon involved in sensing is the relative variation of the resonance frequency and magnitude (or quality factor) in the sensor units. Obviously, the differential output variable/s of the sensor can be the differential resonance frequency or/and the differential resonance magnitude (or quality factor). However, in most sensors, the considered output variable is the cross-mode transmission coefficient (in four-port transmission-mode differential sensors) [309, 310] or the cross-mode reflection coefficient (in two-port reflective-mode differential sensors) [321]. Such cross-mode coefficients (see details in Chapter 6) are differential variables by nature. The magnitude and the frequency position of the maximum in the modulus of the cross-mode coefficients are the usual output variables, which correlate with the considered measurands, typically the real and imaginary parts of the complex dielectric constant of the sample under test (a liquid in most of the sensors of Chapter 6). In certain cases, however, a single output variable suffices for sensing. This is the case of solute concentration measurements in binary mixtures of liquids, where the usual output variable is the magnitude of the cross-mode transmission, or reflection, coefficient [309, 310].

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29 The exception is frequency splitting, which is indeed a quasi-differential sensing approach by itself, as discussed in the text.

30 The reason for including some differential sensors in Chapter 3 is that such sensors are based on phase variation, the subject of that chapter, and are indeed very similar to other single-ended phase-variation sensors reported in Chapter 3. Thus, for thematic coherence, the authors have (exceptionally) preferred to report and discuss such differential-mode, and phase-variation, sensors in Chapter 3, rather than in Chapter 6.

Note that in differential transmission-mode four-port sensing structures, without further sensor components, sensor validation by measuring the cross-mode transmission coefficient requires four-port measurements. Sensor's excitation proceeds at the input differential port, and data is collected at the output port pair. Alternatively, two-port measurements of the transmission coefficient of each sensor unit, and subsequent subtraction is possible, but this is not a real-time measurement. By contrast, in differential reflective-mode two-port sensors, two-port measurements are needed in order to directly infer the cross-mode reflection coefficient (sensor feeding and data collection are realized at the same differential port). Obviously, a two-step single-port measurement (at either port), followed by a subtraction, is an alternative. It is clear, according to these words, that measurements using differential sensors are not exempt of certain complexity, at least as compared with the simplicity that represents sensor feeding and data retrieving in a single-ended device. Thus, to simplify the measurement in microwave differential sensors, they are sometimes equipped with additional planar components, such as dividers, couplers, and isolators [322]. With such additional elements, the differential sensors (either transmission-mode or reflective) are transformed to two-port structures, where the natural output variable, usually the transmission coefficient (an easily measurable quantity), is related to the cross-mode transmission, or reflection, coefficient of the differential sensor pair. As previously indicated, the transmission coefficient can be further processed and converted into other variables, such as a voltage, which can even be more easily measured. It is noteworthy that the addition of the cited components increases the whole sensor dimensions, but not the size of the sensing area. Chapter 6 reports an example of a differential reflective-mode sensor, where it is shown that a rat-race coupler suffices to transform the device to a two-port structure, providing the cross-mode reflection coefficient of the sensor pair (see Fig. 6.29). Other examples of differential sensors (in reflection or transmission) that utilize rat-race hybrid couplers for similar purposes can be found in Chapter 3. Chapter 6 also includes a differential sensor where a power splitter and a slotline-to-microstrip transition are conveniently combined with the pair of sensing elements in order to implement a two-port structure (see Fig. 6.31).

1.3.8.6 RFID Sensors

RFID sensors, as a subclass of wireless sensors, were already (succinctly) discussed in the binary categorization of planar microwave sensors of Section 1.3.2, devoted to wired and wireless sensors. Thus, like differential sensors, RFID sensors do not exploit a specific working principle (though in many cases, it is frequency variation). Nevertheless, in coherence with the previous sections, with a correspondence with the subsequent chapters, the authors have opted to consider RFID sensors, the subject of Chapter 7, in the present section list. As mentioned, the main relevant characteristic of RFID sensors is the wireless connectivity between the sensing element (the tag) and the central unit (the reader, or interrogator). Such feature, combined with the low tag cost and size, the low energy consumption of the tags (or null, in battery-free tags), and the potential to implement full planar (chipless), and "green," sensor tags, makes RFID sensors very attractive for IoT applications. As discussed in Chapter 7, there are many types of RFID sensors (see Fig. 7.9), and not all of them (the tags) can be considered to be planar, according to the previously indicated description of planar microwave sensors. Nevertheless, almost all RFID sensor types are, at least, briefly discussed in Chapter 7, though the main emphasis is on the so-called chipless-RFID sensors. Chipless-RFID sensor tags are full planar devices that probably constitute the main subject of research in the field of wireless sensors nowadays, and where more efforts are required in order to address the many challenges that the massive deployment of IoT needs.

1.4 Comparison of Planar Microwave Sensors with Other Sensing Technologies

Comparing different technologies, approaches, or devices is not straightforward, as there are many factors that can influence the assessment (application, working principle, etc.). In general, useful quantitative comparisons require that the subjects (sensors in our case) subjected to evaluation are judged using similar standards, and this is not always possible. To be more specific, comparing the performance of two different sensors (which necessarily implies a quantitative analysis) is meaningless, unless a common indicator of such performance can be identified. For example, a figure of merit in optical and microwave rotary encoders, which determines the angular resolution, is the number of pulses per revolution. Thus, optical and microwave encoders can be meaningfully compared, at least, with the light of such shared figure of merit (indeed, a performance parameter), despite the fact that both types of encoders use very different technologies and working principles. Obviously, comparing other quantitative characteristics, such as size and cost, is always possible, since these are aspects transversal to any technology, approach, or device. Rotary encoders constitute a good example where dissimilar sensors in terms of the exploited technology (but devoted to the same application) can be quantitatively compared. But, conversely, there are examples of sensors based on the same technology and focused on the same application, where performance comparison (e.g. considering the sensitivity as the main indicator) might not be representative to determine the preferred option. For example, there are many different types of microwave sensors (planar and nonplanar) useful for dielectric characterization of materials. However, the output variables in the specific sensor implementations under analysis might be diverse (e.g. a phase, a magnitude, and a frequency), and this hinders the comparison, as far as the sensitivities are given by different variables. Nevertheless, even in such cases, it is a common practice in the literature to include comparative tables with the sensor performance. The main reason is that such tables provide a fast quantitative overview of the potential of the considered realizations, but not necessarily give an insightful information (representing a true and faithful quantitative comparison) between them, at least not in all cases.

A qualitative comparison is more feasible, even when very dissimilar sensors, or sensing approaches, or technologies, are considered. Nevertheless, such qualitative comparison is useful to gain insight on the relative advantages and limitations, as well as potential, of the different technologies, or approaches, rather than specific implementations. The main aim of this section is to provide a non-exhaustive qualitative comparison of planar microwave sensors, the subject of this book, with other sensor types, including nonplanar microwave sensors, and other sensing technologies. To make the comparison insightful, a specific set of sensor applications, where microwave sensors are relevant, is considered, in particular, dielectric characterization of materials (and related variables), displacements and velocities (i.e. measurements related to motion), and chemical/bio sensing.

In regard to dielectric characterization of materials, the most extended measuring techniques/devices are resonant cavities, T/R waveguide methods (i.e. mainly the NRW approach), coaxial probes, the free-space method, and planar microwave sensors. All these techniques are non-remote, with the exception of the free-space method, which can be considered to be remote to some extent. The reason is that in free-space dielectric characterization, the sample can be located at distances from the sensor where interaction with the microwave radiation (generated typically by means of a horn antenna) is through the far field. Such dielectric characterization (microwave) techniques have been briefly discussed in Sections 1.2 and 1.3, where some of their advantages and limitations have been pointed out. Nevertheless, let us summarize them in tabular form (see Table 1.1, inspired by the comparison presented in [323], but extended).

Table 1.1 Qualitative comparison of microwave techniques for dielectric characterization of materials.

Method	Materials	Frequency range	Advantages	Drawbacks
Resonant cavity	Mainly solids	Single frequency	• Easy sample preparation • Suitable for low-loss materials • Very accurate method • High-temperature capability • No repetitive calibration • Very useful for the characterization of low-loss microwave substrates	• Measurements only at single frequencies • Suitable for small-sized samples • Bulky and expensive • Complex design and fabrication
T/R (NRW)	Solids and liquids	Broadband	• Useful for both permittivity and permeability measurements • High-frequency operation • Useful for engineered materials	• Require sample machining • Branching issue • Bulky and expensive (if waveguides are used) • Complex design and fabrication
Coaxial probe	Solids and liquids	Broadband	• Easy to use • Nondestructive • Potential for *in vivo* measurements • Simple sample preparation (only a flat surface for solids) • Submersible in liquids • High accuracy for high-loss materials • Very useful for bio-samples • Moderate cost	• Need calibration • Air gap issue (for solids) • Complex algorithms for retrieving the permittivity
Free space	Solids	Broadband	• Wide frequency ranges • Nondestructive • Easy sample preparation • Noncontacting method • High-temperature capability	• Require large flat and solid materials • Diffraction problem • Expensive
Planar resonant	Solids and liquids	Single-frequency or narrow band	• Compatible with subtractive and additive process and other technologies (e.g. microfluidics) • Small size and low profile • Potential for conformal, wearable sensors and implants • Potential for “green” sensors • Potential for integrating the associated electronics in the same substrate • Easy sample preparation and low-sized samples • Low cost • Good accuracy • High versatility (measurement of many physical variables by using smart materials)	• Air gap issue (for solids) • Absorption (in contact liquid sensors) • Single frequency operation or narrow band operation • Subjected to detuning effects

Table 1.1 (Continued)

Method	Materials	Frequency range	Advantages	Drawbacks
			• Potential for wireless and RFID sensors • Very useful for the determination of material composition and characterization of liquid mixtures	
Planar nonresonant	Solids and liquids	Broadband	• Compatible with subtractive and additive process and other technologies (e.g. microfluidics) • Moderate size and low profile • Potential for conformal, wearable sensors and implants • Potential for "green" sensors • Potential for integrating the associated electronics in the same substrate • Easy sample preparation • Low cost • Very simple sensor design[a] • High versatility (measurement of many physical variables by using smart materials) • Potential of wireless and RFID sensors • Useful for dielectric spectroscopy	• Air gap issue (for solids) • Absorption (in contact liquid sensors) • Limited accuracy[b] • Broadband, but up to dozens of GHz[c]

[a] Except for those sensors based on artificial transmission lines.
[b] In general, it is considered that for the determination of the complex permittivity of materials (including the real and the imaginary parts), resonant sensors are more accurate. Nevertheless, sensor accuracy, especially in regard to the imaginary part of the complex permittivity, or loss tangent, is mainly determined by the losses in the sensing element. Thus, for the accurate determination of the loss factor in low-loss materials, resonant cavities are the best solution, but, at the expense of high cost.
[c] Nevertheless, it does not mean that all nonresonant planar microwave sensors exploit the potentially broadband operability. Indeed, many nonresonant planar sensors, e.g. the phase-variation sensors studied in Chapter 3, operate at a single frequency, optimized to boost up the sensitivity.
Source: Based on [323].

In view of Table 1.1, it is clear that planar microwave sensors (either resonant or nonresonant) exhibit many advantageous aspects, as compared with the other (nonplanar) techniques. Let us mention, additionally, that planar microwave sensors exhibit a high versatility (intrinsic to planar implementation) relative to their operational mode, reflection or transmission, single-ended or differential, contact or contactless, wired or wireless. These attributes are indicative of the importance of planar microwave sensors as key components for the measurement of material properties and related variables, and justify the significant research activity on the topic in recent years.

Another field where microwave sensors, especially planar sensors, have found diverse applications is in short-range motion measurements. Proximity sensors, angular displacement and velocity sensors, vibration sensors, etc., can be implemented by means of planar microwave sensors made of a static part, containing the sensing element, and a movable part, in relative motion. Examples of such sensors are electromagnetic encoders, presented in Chapter 4, but there are other planar microwave sensors, most of them reported in that chapter, useful for the accurate determination of variables related to motion. The natural competitors of these short-range motion sensors are optical sensors (e.g. optical encoders), magnetic sensors (e.g. tachometers), and resistive sensors (e.g. potentiometers). Nevertheless, in order to provide a wide overview of the sensing technologies devoted to the measurement of velocities and displacements (and related variables), let us extend the (qualitative) comparative analysis to long-range (remote) motion sensors, i.e. RADARs, LIDARs, and SONARs. Such analysis is presented in Table 1.2 and reveals that microwave technologies (mainly microwave encoders for short-range measurements, and RADAR sensors for long-ranging) constitute a good option that combines high performance, with moderate or low cost, and robustness against harsh conditions, intrinsic to microwaves.

Table 1.2 Qualitative comparison of sensor technologies for displacement, velocity, and ranging measurements.

Range	Technology	Advantages	Drawbacks
Short range (non-remote)	Planar microwave (electromagnetic encoders)	• Small size and low cost • Operation in harsh environments and subjected to pollution • Medium resolution • Potentially unlimited dynamic range (for both displacement and velocity)[a] • Contactless • Operation at a single frequency • Potential to implement the encoder (movable part) in very different dielectric materials (including plastics and rubber)	• Difficult to implement absolute encoders • Issues related to misalignments and vibrations • Potential wearing related to (undesired) friction • Require relatively complex post-processing electronics for retrieving the information relative to motion • No commercially available to date
	Planar microwave (other approaches[b])	• Small size and low cost • Operation in harsh environments and subjected to pollution • Contactless • Simple post-processing electronics • Easy design and fabrication	• Limited resolution and sensitivity • Limited dynamic range • Sometimes a frequency scan is needed for sensing (specially in frequency-variation or frequency-splitting displacement sensors)
	Optical encoders	• Small size • Extremely high resolution • Both incremental type and absolute encoders are possible • Potentially unlimited dynamic range (for both displacement and velocity)[a] • Contactless • Commercially available	• Relatively high cost • Low robustness in hostile environments (with pollution, grease, dirtiness) or in ambient subjected to radiation and extreme temperatures
	Magnetic (Hall effect sensors)	• Very robust • Operation in harsh environments and subjected to pollution • Versatile (linear or angular position and velocity, proximity, etc.). • Operate under static fields • Contactless • Commercially available	• Expensive • Require magnets • Limited accuracy and resolution

Table 1.2 (Continued)

Range	Technology	Advantages	Drawbacks
	Electric resistive (potentiometer)	• Small size and low cost • Simple transduction mechanism	• Very limited dynamic range • Require contact
Long range (remote)	RADAR	• Robust against adverse meteorological conditions • Good directivity (especially in millimeter wave RADAR) • RF and microwaves penetrate media that are not transparent for light (use for buried objects) • Versatility (useful for both medium-range and very long-range applications, depending on the operational frequency) • Very extended technology for military applications, navigation, automotive industry, space, civil engineering, geology and archeology (e.g. ground penetrating RADAR), and study of the atmosphere and Earth	• Susceptible to signal interference • Limited accuracy • Difficult to resolve targets obscured by conducting materials
	LIDAR	• Very accurate and fast • Very selective • Very good directivity	• Need a region transparent to light between the source and the object • Of no use for buried objects or under adverse meteorological conditions
	SONAR	• Sound waves propagate very well in water (specially devoted to underwater communication purposes and ranging)	• Limited accuracy • Limited selectivity and directivity

[a] In linear encoders, the displacement that can be measured depends only on the length of the encoder. In rotary encoders, the number of revolutions can be as high as desired, but methods are needed to infer the cumulative number of revolutions. Nevertheless, encoders (either electromagnetic or optical) are considered to be short-range measuring devices since proximity between the movable part and the static part is needed. By unlimited velocity, the authors mean within reasonable limits considering the typical applications of linear or angular encoders (servomechanisms, conveyor belts, elevators, inertial wheels, etc.).

[b] By other approaches, the authors refer to short-range planar microwave displacement and velocity sensors implemented by means of a transmission line, or a resonator-loaded transmission line element (static part), whose characteristics (resonance frequency, magnitude or phase of the transmission or reflection coefficient, etc.) are determined by the relative displacement and/or orientation between the static part and the movable part, in most cases a dielectric slab with an etched, or printed, inclusion (or a set of inclusions), usually metallic resonators. Examples of such short-range displacement and velocity sensors are reported in Chapter 4, since most of them are based on coupling modulation.

Concerning chemical and biological sensors, planar microwave technology can be useful depending on the specific application. Nevertheless, the leading technologies for sensing chemical and biological species (analytes) are those based on optical and electrochemical methods [324]. Indeed, electrochemical biosensors dominate the commercial market, but their electromagnetic counterparts (including RF, microwave, millimeter-wave, THz, and optical biosensors) are very attractive due to several beneficial aspects, such as low cost, minimal invasiveness, real-time operability, and (potentially) label-free functionality. Mechanical sensors, e.g. based on piezoelectric materials, such as quartz, or micro-cantilevers, are also interesting for the monitoring of mass changes related, e.g., to certain bio-processes such as analyte binding to bio-recognition molecules.

The main advantages of optical and electrochemical sensors over microwave sensors for the detection of specific analytes, as most applications in chemical sensing and biosensing require, are their high selectivity and sensitivity. For example, in many biosensors, bio-recognition elements, also known as bio-receptors, specific for the target analyte, are immobilized onto the transducer (e.g. optical or electrochemical) forming a functionalized surface (detection region), and the sample containing the analyte is directly contacted with that surface, or allowed to flow across it. The transducer then generates a signal (e.g. optical or electrical) that depends on the changes in that surface, caused by the affinity of interaction between the analyte and its bio-receptor, and thus the concentration of the specific analyte in the sample can be determined. Sensor sensitivity is sometimes optimized by means of labels, i.e. components sensitive to the considered transduction mechanism that can bind to the analyte, but this increases complexity, measuring time, and cost (thus, label-free biosensing is in general preferred).

To detect biological changes at the micro/nanometer scale, as many applications require, optical sensors are, in general, more sensitive than other electromagnetic sensors (THz, millimeter-wave, and microwave sensors). Optical biosensors essentially sense optical properties of biomatter, whereas the THz, millimeter-wave, and microwave counterparts employ permittivity sensing, mostly using planar interdigital capacitors, resonators, antennas, and transmission line structures. The size of these planar (sensitive) components determines the discrimination capability of the sensor. Therefore, it follows that the detection of micro/nanoscale analytes requires high-frequency sensors, with dimensions of the sensitive structures close to those of the analytes.

For the detection of chemical species, e.g. gases, functionalized materials that strengthen certain properties (e.g. electromagnetic or electrical) when such substances are in contact with them can be used. Selectivity in chemical sensing and biosensing can (potentially) be achieved also by means of specific reagents, that is, substances or compounds added to the sample (e.g. a liquid solution containing the analyte/s) in order to cause a chemical reaction. Nevertheless, such reagents tend to be expensive, and the presence of multiple analytes in a certain sample may degrade measurement accuracy/selectivity (due to cross-sensitivities to multiple analytes). This is a limitation of microwave biosensing and chemical sensing. For example, the measurement of the concentration of electrolytes in blood or urine, or other components such as glucose, is typically carried out by means of electrochemical sensors, commercially available but expensive, though very selective and sensitive. However, the determination of the complete composition of such (blood or urine) samples by means of (cheaper) microwave methods is by far more complicated, since such techniques are based on permittivity measurements, as mentioned, and the real and the imaginary parts of the dielectric constant of the sample are influenced by the various components present in the sample in a complex and *a priori* unknown way.

Through microwaves, it is possible, however, to detect the collective changes of permittivity, even in small samples, provided the frequency of operation of the sensor is high enough (as indicated before). In this regard, millimeter-wave and THz sensors can be useful in certain applications involving small-sized analytes or samples [325–329]. Nevertheless, let us mention that planar microwave sensors operating at moderate (microwave) frequencies have been demonstrated to be useful for biosensing and chemical sensing (a subset of recent works is given in [269, 298, 330–335]). For example, in [298], two-dimensional arrays of split-ring resonators have been applied to the analysis of organic tissues. Such sensor can be useful for the detection of malignant tissues, similar to the work presented in [330], where a CPW-based sensor is devoted to the detection of several cancer cells. In [332], a SIW-based cavity biosensor useful for the analysis of small-sized liquid samples is proposed. In [333, 334], it is demonstrated the potential of split-ring resonator fluidic sensors for the determination of electrolyte concentration in liquid (aqueous) solutions, and it is shown the potential of the proposed devices to determine the total concentration of electrolytes in animal (horse) urine (but not the individual concentration of electrolytes, as noted in the preceding paragraph). Finally, papers [269, 335] are devoted to testing the concentration and growth of pathogenic bacteria (particularly, *Escherichia coli*) in different medium solutions by using also split-ring resonator fluidic sensors. These works point out the high potential of planar microwave sensors based on electrically small resonators, such as split-ring resonators and other planar resonators, as it will be shown throughout this book. Indeed, there are various review papers on the topic of planar microwave resonant sensors (including not only biosensors) [336–341].

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