Chapter

Optimal Temperature Sensor Based on a Sensitive Material

Asma Bakkali, José Pelegri-Sebastia, Youssef Laghmich and Abdelouahid Lyhyaoui

Abstract

The context of this chapter is the development of passive sensors for temperature sensing applications. The purpose is to successfully reduce the energy consumption in wireless sensor networks. The sensor is based on the electromagnetic transduction principle, and its originality is based on the integration of a high temperature-sensitive material into passive structure. Variation in temperature makes the dielectric constant of this material changing, and such modification induces variation in the resonant frequencies of high-Q whispering-gallery modes in the millimeter-wave frequency range. In this way, the proposed device shows a linear response to the increasing temperature, and these variations can be remotely detected from a radar interrogation of an antenna loaded by the whispering-gallery mode resonator. Proposed device is a powerful tool for many interesting applications since it offers very low power consumption and provides environmentally friendly temperature measurement. The sensor is simulated in order to outline its performance and to show the benefit of the batteryless sensing device.

Keywords: energy consumption, wireless sensor networks, lifetime, energy conservation, whispering gallery mode, PLZT material, temperature, dielectric resonator

1. Introduction

From sensing motion to identifying a gas and measuring temperature, sensors are a key element in our daily lives for analytical, monitoring, and diagnostic applications [1–3]. Following the progress of technology and current concerns for the protection of the environment and people, the development of these devices is expanding significantly, to transform chemical, mechanical, and thermal phenomena into a measurable quantity: electrical signal. Nowadays, we are facing an explosion in the sensor market, and the number of applications is expanding in parallel with advances in electronics and wireless communication technologies.

Temperature detection is currently one of the most expected needs, as it is generally not well controlled at a low cost. Temperature sensors have been one of the first fields of application of micro-systems, and they now represent a very important part of this market due to the increasing demand in the consumer and domestic application sectors but also in production, aeronautics, and health. The main characteristics currently required of these components are most often to be miniature, efficient, and economical and can be integrated into complex electronic systems.

Several research projects focus on optimizing the energy consumption of sensors by using innovative conservation techniques to improve the network's performance, including maximizing its lifespan. The sensor proposed in this chapter presents an interesting technological solution for temperature detection, thus allowing an extremely low consumption compared to conventional techniques. This new, highly integrated device requires no onboard power supply and uses electromagnetic transduction for temperature measurement.

2. Passive and wireless temperature sensor design

For decades, dielectric resonators (RDs) have been very important in the microwave field for many applications, such as oscillators and filtering devices [4]. The significant progress in the development of dielectric materials, both in terms of reliability and in improving the loss tangent at microwave frequencies, makes it possible to use them from microwave frequencies to millimetric frequencies. As the dimensions of these resonators can nowadays be small, they can be integrated into many telecommunication systems, in particular filtering systems where dielectric resonators have made it possible to maintain very good characteristics while reducing their size. These fields have led to a mature technology that allows the realization of reliable devices.

We have included the device proposed by Guillon et al. [5], composed of a silicon platform with coplanar lines on membrane. The second part is a dielectric resonator mounted on a support between the two coplanar lines. The entire device was coupled to an Monolithic Microwave Integrated Circuit (MMIC) amplifier, which subsequently made it possible to design a millimetric oscillator [6]. We can see that the device designed by Guillon was intended for the realization of an oscillator, which is not the case for us. The objective was to explore the interest that this device can provide in measuring small fluctuations in the dielectric permittivity of a material sensitive to temperature change. Therefore, the proposed structure is designed with more powerful simulation tools than those that existed in the 1990s, since they allow us to simulate the entire structure: coplanar lines, sensitive material, and dielectric resonator. In addition, we have resized the device to have the best possible transmission signal.

The temperature sensor shown in **Figure 1** consists of two parts: the micromachined coplanar lines and the dielectric resonator covered with the sensitive material maintained by a support between and above these two lines. In the rest of this chapter, we will detail the design of this device before presenting the simulation results of the optimized structure.

2.1 Presentation of the gallery modes

Dielectric resonators operating in conventional electric (TE) or magnetic (TM) transverse modes radiate a significant portion of energy at millimeter wavelength frequencies [7]. In order to avoid dimensional problems and radiation losses at millimeter frequencies, we have chosen to use an excited dielectric resonator on gallery modes (whispering gallery modes).

From an electromagnetic point of view, one of the essential characteristics of WGMs is the distribution of energy in the resonator. The energy of the gallery modes has the particularity of being confined in a region close to the air—dielectric interface. Moreover, one of the main advantages offered by this type of mode is the possibility of exciting a dielectric resonator with an oversized geometry while remaining at the millimetric frequencies [1, 2]. The dimensions of a resonator

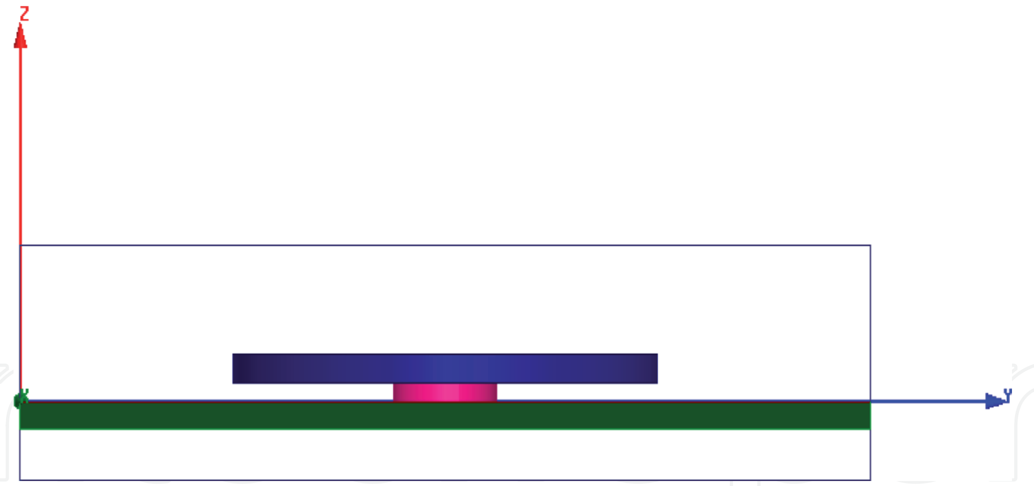

Figure 1.
Design of the temperature sensor: cross-section view.

excited in a gallery mode are much larger than those of the resonators used in conventional TE or TM modes. This makes it easier to use them at high frequencies since, given the dimensions of the resonator, it can be handled more easily.

The gallery modes of dielectric resonators are classified into two families: $WGH_{n,m,l}$ (magnetic field gallery modes) and $WGE_{n,m,l}$ (electric field gallery modes). This nomenclature makes it possible to identify each mode by taking into account the state of polarization and the importance of the transverse components of the electromagnetic field [3]. Thus, we are able to distinguish, on the one hand, WGE modes where the axial component of the field is essentially magnetic, while the transverse components are mainly electric. On the other hand, we distinguish the WGH modes, which correspond to the dual modes of the WGE. The three integers n, m, and l indicate the spatial configuration of the electromagnetic field inside the resonator (number of variations of the field in the three directions of the cylindrical reference mark):

- n: number of variations along the azimuthal direction
- m: number of variations according to radial direction
- l: number of variations according to the axial direction

It is important to mention that the azimuth number has an influence on the caustic radius. Indeed, a high azimuth number results in a higher caustic radius and therefore in a confinement of electromagnetic energy closer to the lateral surface of the resonator.

2.2 Advantages of gallery modes for temperature detection

Among the main advantages of gallery modes, we will note here the most important for our study. First of all, the dimensions of the resonator excited on a gallery mode are much larger than in the case of conventional TE or TM modes. This oversizing makes it possible to consider the use of this resonator at millimeter frequencies by facilitating temperature detection. On the other hand, thanks to the high-energy confinement in the dielectric, the vacuum quality factors are practically limited only to the loss tangent of the material used [3]. The latter will thus be very sensitive to the presence of a variation in the dielectric properties of the sensitive material, which will improve its detection thanks to an offset in the resonance frequency of a gallery mode.

In addition, it is important to note that the gallery modes have the particularity of not having any energy at the center of the resonator. As mentioned earlier, the larger the azimuth number, the larger the area. The central part can therefore be used to fix the resonator; we can add a shim to the circuit in order to maintain it or adjust its position in relation to the coupling circuit (lines) without disturbing its operation. Finally, these modes are no longer stationary but progressive when the resonator is excited by a progressive wave source, whose propagation constant is close to that of the gallery mode. The mode then propagates in the azimuthal direction. This type of excitation for gallery modes results in a directional coupling with the line. Therefore, this coupling will make it possible to consider the design of a directional filter with a narrow bandwidth, which in turn will allow temperature measurement thanks to the shift in its resonance frequency.

3. Sensor based on millimeter band resonant gallery modes

In order to define an innovative temperature sensor with high RF performance, we will take advantage of the dielectric properties of the sensitive material, the machining of coplanar membrane lines, and the characteristics of gallery modes. This new detection device is based on the modification of the resonance frequency of the dielectric resonator at the presence of a temperature variation. This is done by means of a perovskite material deposited above this resonator whose dielectric constant varies with a change in temperature.

The general concept chosen is to modify the electromagnetic coupling that exists in the device by temperature (see **Figure 2**). This concept allows for a very high sensitivity. Indeed, variable coupling can be achieved by modifying (globally or locally) the environment around the electromagnetic field lines by directly modifying the electromagnetic properties of the sensitive material.

In other words, a change in temperature leads to a change in the permittivity of the sensitive material and therefore a change in the electromagnetic field. This change affects the electrical parameters of the resonator, namely, the resonance frequency and the quality factor. Thus, a resonator designed to operate at a center frequency f_0 for a particular gallery mode sees this shift as a function of the variation in the dielectric constant of the sensitive material. The electromagnetic field is therefore used to measure the temperature variation. The detection principle is then based on the shift in the resonance frequency of the gallery modes in the dielectric resonator. The latter and the sensitive material are used here to measure the influence of the permittivity of this material and to deduce the temperature variation.

In addition, this type of detection technique based on electromagnetic transduction has shown interesting results for the realization of an oscillator in the first place and subsequently for specific gas and pressure detection applications. These passive microwave sensors have been designed using the relaxation phenomenon present in sensitive materials. In particular, the installation of a functional TiO_2-based

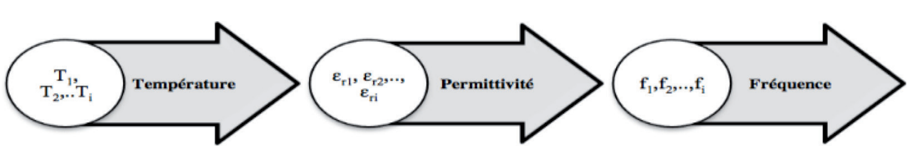

Figure 2.
Principle of electromagnetic transduction.

microwave sensor in the Ka-band has been proposed for gas concentration detection. This detector is based on the direct variation of the dielectric properties of the resonator at the presence of a gas.

4. Study of the geometric parameters of the sensor

There are parameters that can modify the dielectric characteristics of a material such as temperature, for example. In our case, the aim is for this modification to generate a frequency variation in the microwave domain. The basic element is the sensing material whose dielectric constant varies with temperature. The choice of the sensitive material is not obvious because of the requirements imposed, which complicate the integration of dielectric materials into microelectronic circuits or their use in the manufacture of the sensor. To achieve this, we have carried out an in-depth bibliographical study in order to find the appropriate material that meets our specifications. Among the materials proposed in the literature, we chose lead-lanthanum-zirconate-titanate (Abbreviated in PLZT). As a result, and as part of our collaboration with the Faculty of Computer Science and Materials Sciences, Silesian University of Poland (see **Figure 3**) [8, 9], we have several samples taken in his laboratory.

Also referred to as lanthanum-doped lead zirconate titanate, this material meets our needs in terms of temperature range and operating frequency. In particular, it has a dielectric property that depends on the change in temperature (see **Figure 4**) [10, 11]. Indeed, the variation in temperature has an impact on the properties of this material since it causes a relatively large change in its dielectric permittivity [12]. This PLZT will then detect the temperature change through its integration into the microwave circuit described in **Figure 1**, with a radius of RPLZT = 3.25 mm and a thickness of HPLZT = 10 μm.

The system is based relatively on the use of a dielectric resonator and two coplanar membrane lines. These lines serve as an excitation support for the RD gallery modes. The study of the mechanism of operation of these two components was widely discussed in the literature [13–15]. Thus, the RD has a radius of R_{RD} = 3.25 mm, a thickness of HRD 360 μm, and a relative dielectric permittivity of 80. This dielectric resonator is held on the line plane by an Alumina (Al_2O_3) wedge with $R_{Support}$ = 0.8 mm radius and $H_{Support}$ = 230 μm height.

The RD's gallery mode excitation mechanism and sensitive material were selected, and a radar interrogation was carried out to transmit temperature information.

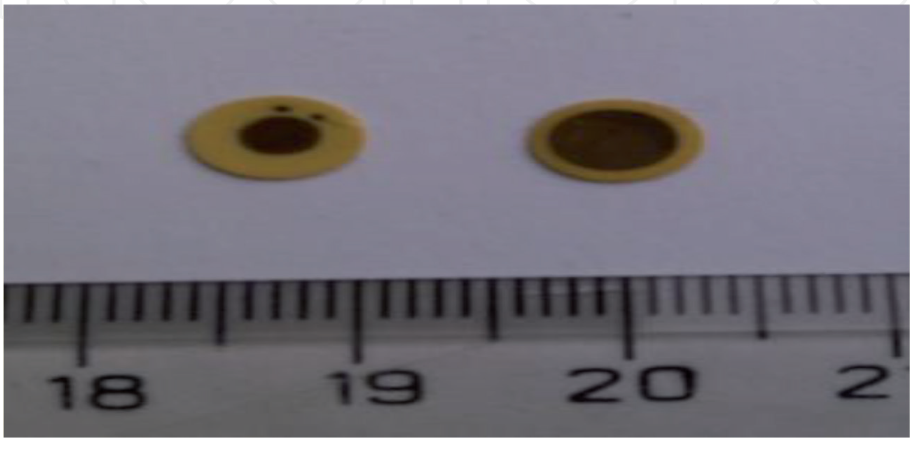

Figure 3.
Samples of PLZT material taken by Wawrzała and Korzekwa at the Silesian University of Poland.

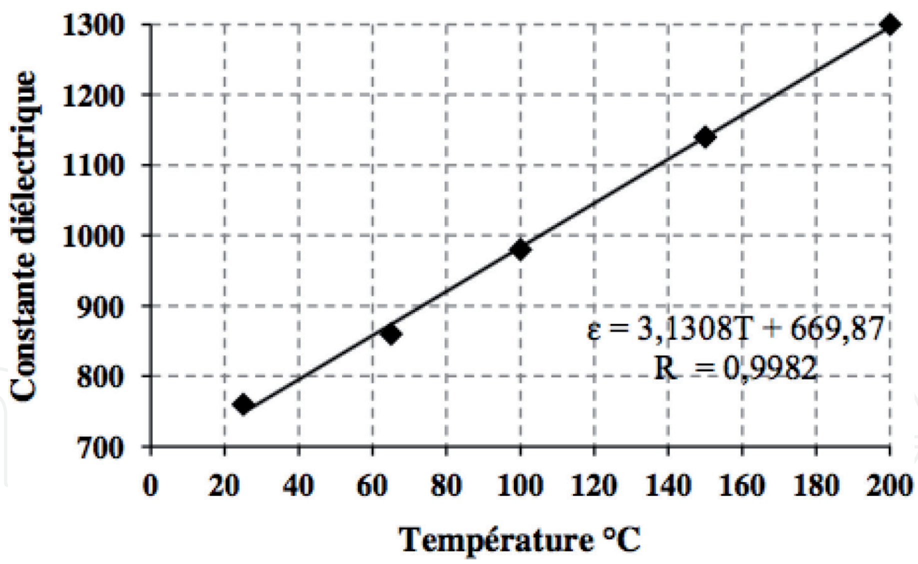

Figure 4.
Dielectric constant of PLZT as a function of temperature.

5. Sensor interrogation method

The transduction mode, size, and frequency of operation of this sensor are important characteristics that represent a technological break with the existing systems of passive wireless temperature sensors RFID and SAW.

To be remotely accessible, the sensor requires a reader that is compatible with its operating characteristics. Technical criteria for the use of a reader must be defined to satisfy the detection but also to ensure that the interrogation range is as long as possible. The existing readers for passive sensor interrogation, present in RFID and SAW technologies, do not meet the problems imposed on our study in terms of high frequencies of use and a range greater than 10 m.

As a result, the characteristics of our sensor (wide range of detection, analysis, and processing of high frequency signals) guide us to consider a radar technology reader. Its operating principle, as with any radar, is to send a flow of electromagnetic waves to the sensor, which will return an echo whose power amplitude and will depend on the measured temperature. Indeed, radar is used in many applications such as level measurement, obstacle detection for automobiles, meteorology, or the military [16]. Its use for passive sensor network interrogation with RF transduction presents an innovative solution.

The proposed temperature sensor uses a millimeter radiofrequency transduction. The resonant frequencies of the sensor are included in the Ka band and shift from a bandwidth of a few hundred MHz to a few GHz. An antenna to communicate remotely with the reader will connect the sensor. To interrogate this sensor, we turned to a radar technology reader developed during Chebila's thesis [17], according to precise technical criteria in terms of operating frequency satisfying wireless communication over a range greater than 20 m. This distance remains a key point because many applications in the aeronautics, construction, and nuclear sectors refer to it for the installation of sensor networks. The modulation technique of this radar and its architecture based around a voltage-controlled oscillator (VCO) facilitated its realization and adjustment (see **Figure 5**).

The radar developed in 2011 is a frequency-modulated continuous radar (FMCW), used in the Ka band around 30 GHz (see **Figure 6**) [17]. This HF radar will be used to remotely detect the temperature sensor measurements. The signals received by the reader must therefore inform us about the distance between the radar and the sensor but also about the temperature value coming from the

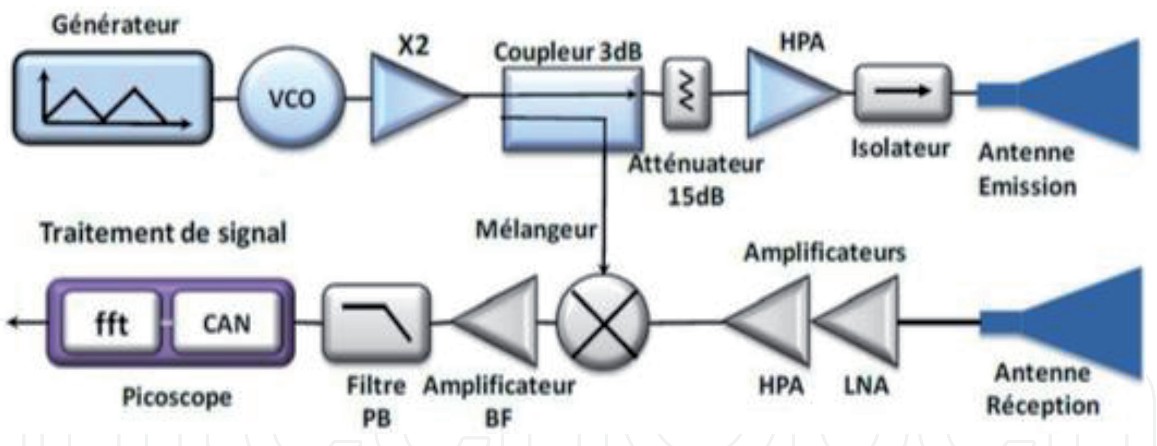

Figure 5.
Synoptic diagram of the 30 GHz radar.

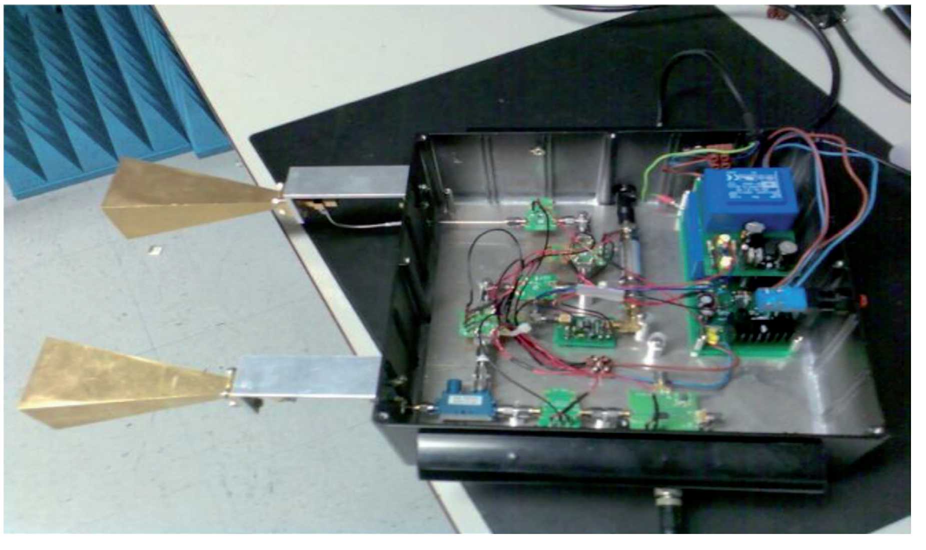

Figure 6.
Picture of the radar.

questioned measuring cell. In conclusion, the radar in question satisfies three important parameters for remote reading: its range is greater than 20 m, works at a frequency compatible with the proposed sensor, and contains a system for identifying cells within a network.

The potential advantages of this type of transducer are:

- A significant reduction in signal losses thanks to the direct modulation of the microwave signal by the quantity to be measured

- A high sensitivity of the electromagnetic propagation to the environment used to perform the sensor function

- High spatial and temporal resolution due to the high operating frequency

- A more flexible choice of operating frequency that can be adapted to the different operating constraints of the sensor

- Easy integration into a measurement chain (radar and antennas)

The following section is devoted to the results of microwave measurements made using a high-performance simulator, allowing the frequency offset to be monitored and a direct relationship to be established between the temperature variation and the observed frequency offset. In this way, a temperature measurement is carried out via an electromagnetic transduction.

6. Simulation results of the complete sensor

Series of free oscillation simulations (eigenmode) using the HFSSTM software, applied to the dielectric resonators, determine the diameter, thickness, permittivity of the dielectric resonator, as well as the distribution of the electromagnetic field necessary to define the caustic and the optimal coupling with the coplanar lines (see **Figure 7**). The determination of caustic makes it possible to establish the distribution of the electromagnetic field in the RD and leads to the definition of the position of the coplanar lines. In addition, the diameter of the resonator and the confinement of the electromagnetic field in it impose the distance between these two micro-machined lines.

In this study, we studied a dielectric resonator with a relative permittivity of 80 and no losses. The thickness and diameter of the dielectric resonator are used to determine the resonance modes and frequencies associated with them. Subsequently, we are interested in the modification of the physical properties of the PLZT material in the presence of a change in temperature, more precisely the variation of its dielectric permittivity. As shown in **Figure 8**, we observe the distribution of the electric field of the $WGE_{8.0.0}$ mode in the dielectric resonator; it is thus isolated around 30 GHz.

We should also mention that the overall circuit of our detection system represents a directional filter consisting of two parts:

- Coplanar lines (CPWs) used for RD excitation and field propagation electromagnetic

- Dielectric resonator used for coupling and excited in WGM as well as the material PLZT as an element of recognition

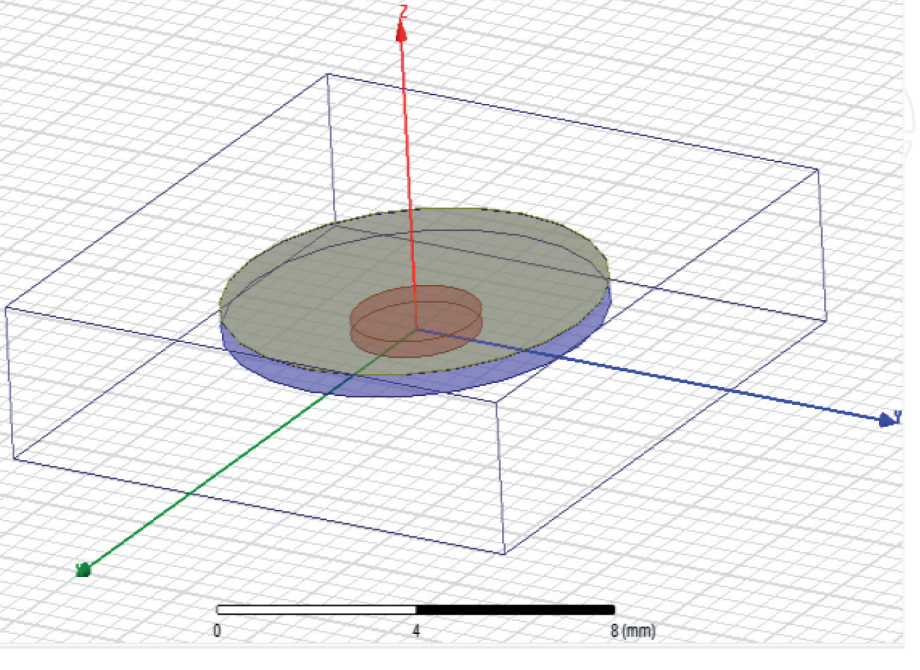

Figure 7.
The sensitive material and the resonator in the cavity with a holder.

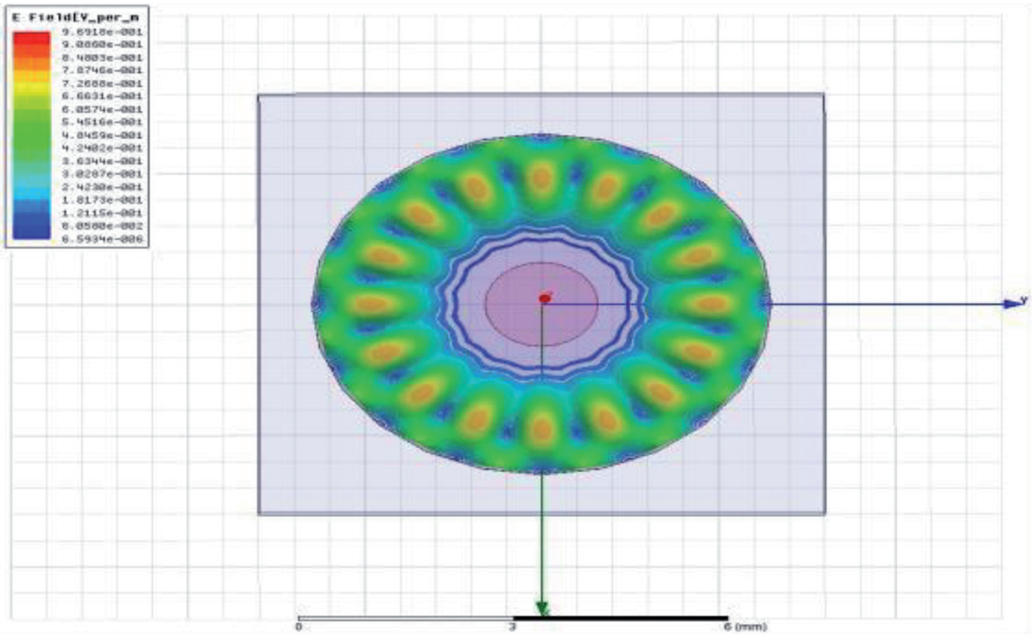

Figure 8.
The field distribution of the $WGE_{8.0.0}$ to 30 GHz mode for eigenmode calculation (HFSS™).

From the coupling coefficient S_{12} between access 1 and 2 (simulated) given as a function of frequency, the gallery modes WGE and WGH were identified over a frequency range of 25–40 GHz. **Figure 9** shows the look of the transmission parameter between access 1 and 2 in the Ka-band.

Figure 10(a) and **(b)** shows examples of simulation results corresponding to amplitudes of the magnetic field of the gallery modes at their resonant frequencies.

Based on the results obtained as well as those in the literature, PLZT appears to be the right candidate for frequency temperature transduction. Indeed, it has been previously demonstrated that the dielectric permittivity of this material can be modified in the presence of a temperature variation. We therefore aim to analyze the impact of such a modification on the resonance frequency of a gallery mode. For this purpose, the dielectric constant ε_r was varied between 700 and 900 with a

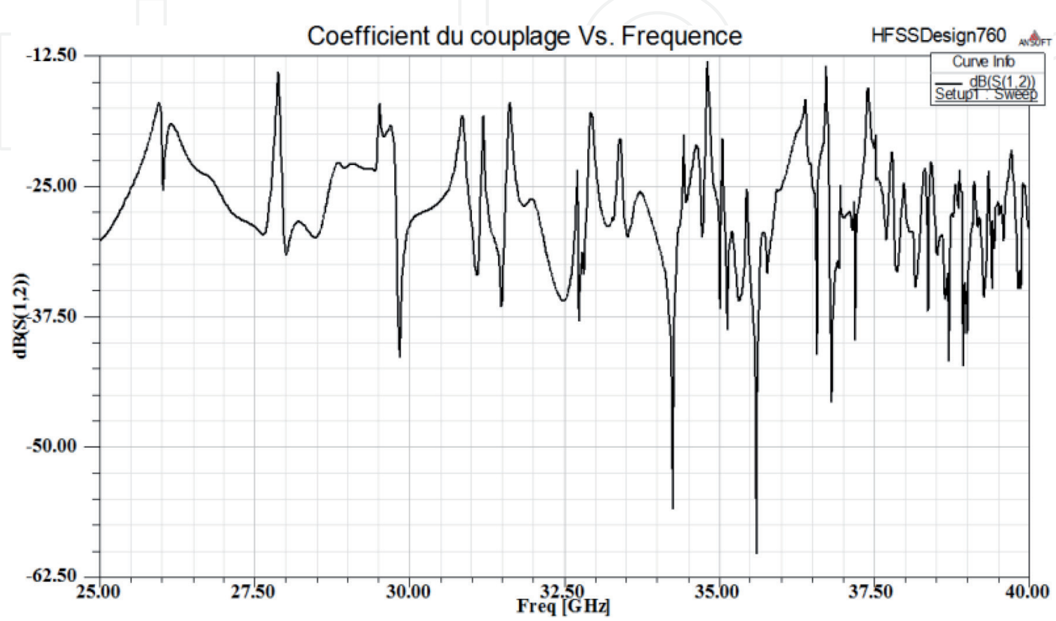

Figure 9.
Coupling coefficient S_{12} as a function of frequency for ε_{PLZT} = 760.

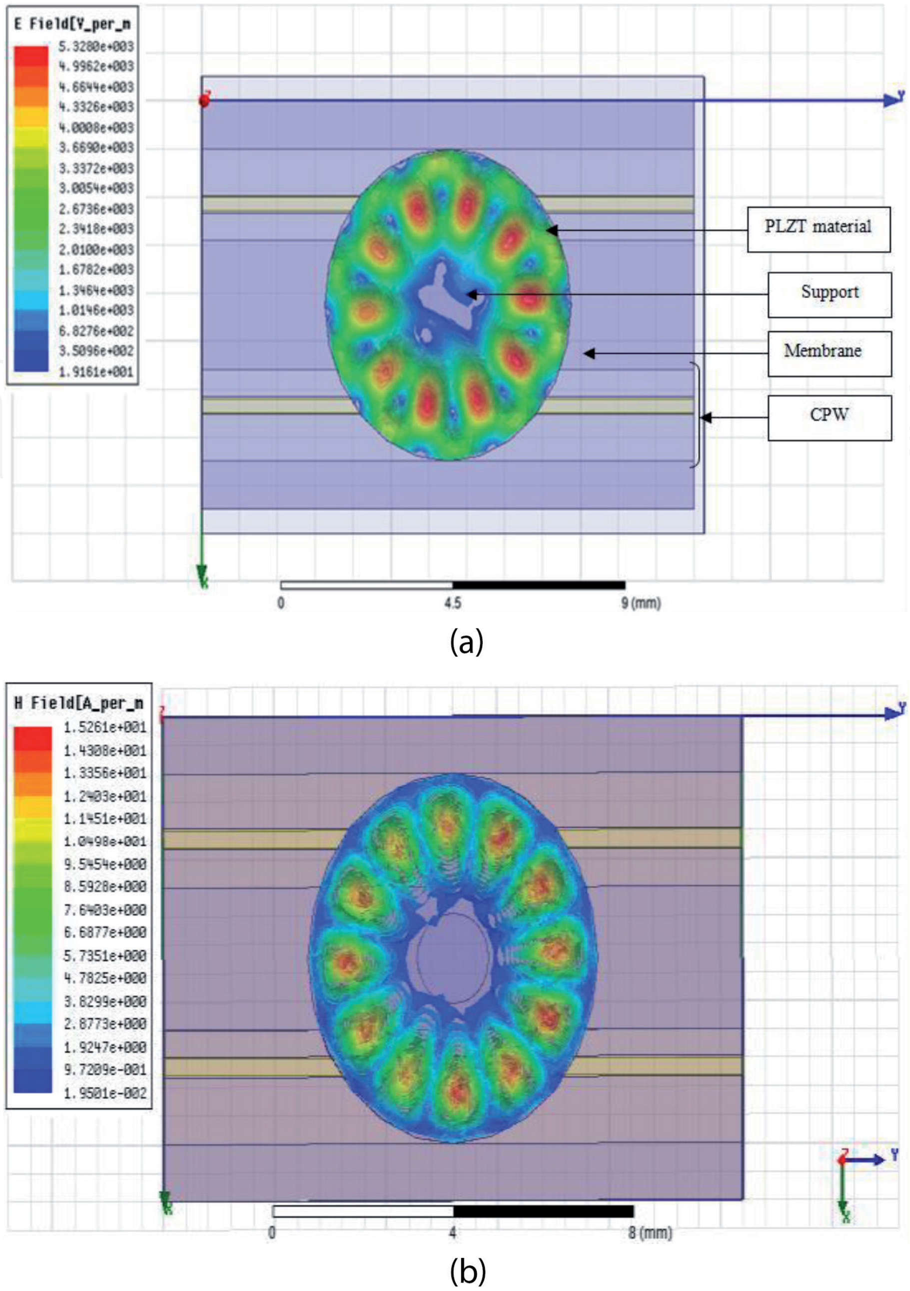

Figure 10.
Amplitude of the magnetic field of the gallery modes: (a) $WGH_{6,0,0}$ and (b) $WGE_{5,0,0}$.

14% variation. As shown in **Figure 11**, the variation in PLZT permittivity produces measurable changes in resonance frequency, reflected in a shift to low frequencies of about 1 GHz, for example, in the case of $WGE_{4.0.0}$ mode.

These modifications on the resonance frequency for variations in the permittivity of the PLZT material highlight the high sensitivity of this type of device. This sensitivity represents that of the electromagnetic transducer, which transforms a variation in permittivity into a variation in the resonance frequency of a WGM. In order to evaluate this sensitivity, we have shown in **Figure 12(a)** and **(b)** the resonance frequencies of the $WGH_{7.0.0}$ and $WGE_{9.0.0}$ modes, respectively, as a function of the permittivity of the PLZT when there is a temperature variation. The results obtained with a cylindrical dielectric resonator have shown that the resonance frequencies of the gallery modes are very sensitive to the change in the permittivity of the sensitive material. The relationship between permittivity and resonance frequencies is approximately linear.

The sensor sensitivity is the combination of the transducer sensitivity with the variation in PLZT permittivity as a function of temperature.

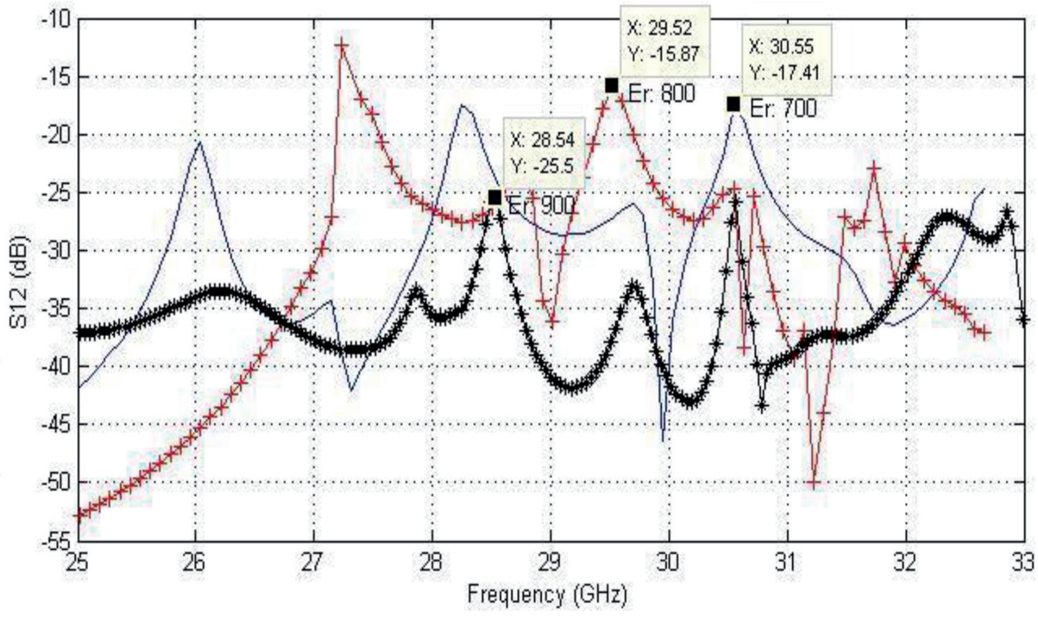

Figure 11.
Transmission coefficient (S_{12}) as a function of frequency for variations in PLZT permittivity (ε_r = 700, 800, and 900).

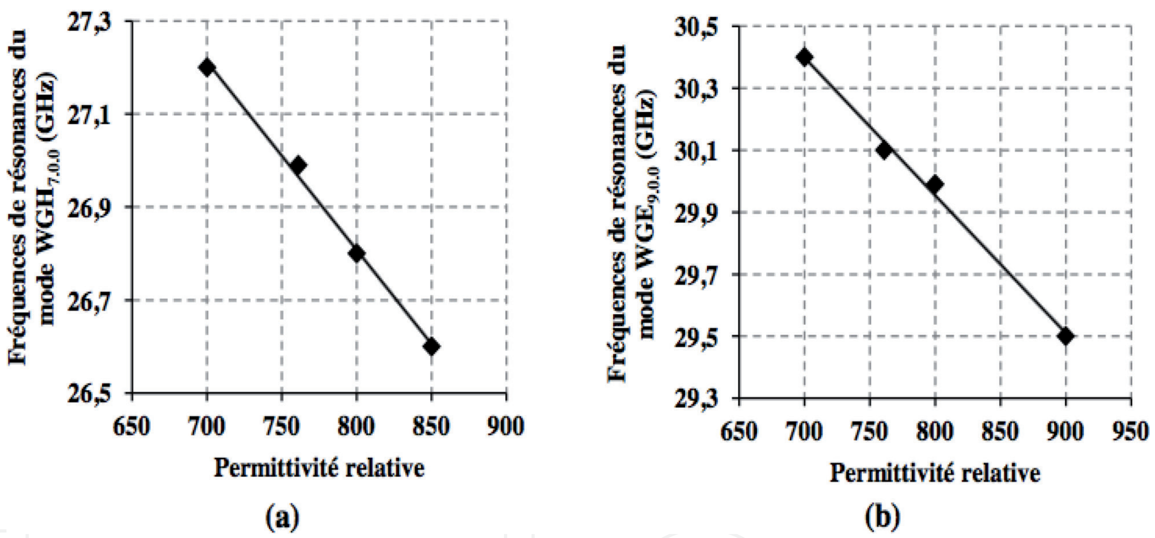

Figure 12.
Resonance frequencies as a function of PLZT permittivity: (a) $WGH_{7.0.0}$ mode and (b) $WGE_{9.0.0}$ modes.

The gallery modes in the dielectric resonator and the PLZT material are evidently used here to measure the permittivity change and deduce the temperature change. From rigorous electromagnetic numerical simulations (HFSS™), we show here that a small change in the permittivity of the sensitive material induces a large variation in the resonance frequency of the dielectric resonator gallery modes.

Based on the characteristics of the sensitive material used and the previous results, it is therefore possible to deduce the relationship between the resonance frequency of the detected gallery modes and the temperature. As a result, a linear dependence between frequency and temperature is clearly observed for all modes detected.

In other words, the relatively linear dependence between temperature and dielectric constant of the sensitive material leads to a change in the coupling coefficient between the two coplanar waveguides, and this is subsequently reflected in a shift in the resonance frequency of the system. As a result, a temperature variation usually results in a shift in the resonance frequency of the excited mode in the dielectric resonator.

7. Application of the sensor for marine fire detection

In terms of application areas, sensor networks have a potential that is revolving around many sectors of our economy and our daily lives; from environmental monitoring and preservation to industrial manufacturing, automation in the transport and health sectors, and the modernization of medicine, agriculture, telematics, and logistics. This new technology promises to revolutionize the way we live, work, and interact with the physical environment around us. Wirelessly communicating sensors with computing capabilities facilitate a series of applications that were impossible or too expensive a few years ago. Today, these tiny and inexpensive devices can be literally scattered over roads, structures, walls, or machines, capable of detecting a variety of physical phenomena. Many fields of application are then considered, such as disaster detection and monitoring, environmental monitoring and biodiversity mapping, intelligent buildings, precision agriculture, machine monitoring and preventive maintenance, medicine and health, logistics, and intelligent transport.

Today, the use of these sensors is increasingly required for supervision and safety. Industrial companies then propose wireless sensors that can inform the user about the evolution of different physical quantities, so they constitute a very fertile research axis. In addition, the development of temperature sensors has several advantages, the most important of which is safety. The current trend, given the new applications that are emerging, is to oversize sensors and make them compatible with signal processing systems in order to obtain fully integrated systems. Environmental objectives and firefighting are the most targeted applications today. The lists of applications (safety, control, analysis, comfort, etc.) and fields of application (environment, safety, medical, automotive, home automation, etc.) are very long, reflecting the great interest in the development of temperature sensors.

The development of these systems generally includes a miniature, low-cost, and high-performance sensor. This is what drives our current research. Indeed, miniaturization is important to be able to easily embed autonomous systems that are increasingly distributed in networks. The cost price is of course an important factor and will be decisive for the marketing development of these sensors. The quest for performance is to make the information obtained by these sensors more reliable and affordable. This is practically interesting for the intended application: improving firefighting in marine applications.

Obviously, of all the disasters that can happen to a ship, fire is certainly the most horrible. Ashore, occupants of burning buildings can rely on fire pumps and ladders that can be on site within minutes of the first alarm signal. A ship at sea, on the other hand, must rely solely on itself in fighting the fire as in everything else, and from the first fire signal to retirement or hard-won victory, there may be no chance of a canoe rescue in bad weather.

The consequences of a fire on board a ship are always costly and sometimes tragic. It is therefore essential to have effective firefighting systems, but it is now known that conventional temperature sensors, which were widely used in the past, have significant disadvantages. The present system aims to solve this problem by using simple, autonomous, and inexpensive means. As a result, this design greatly reduces the overall energy consumption of the temperature sensor network on board ships.

To effectively control ship temperature, the use of this passive temperature sensor makes it possible to keep an eye on the temperature at all times, for long periods of time, and to alert staff in the event of a problem. If the temperature in a monitoring zone suddenly exceeds the threshold value, the sensor detects it in real time and transmits the information to the supervisor for intervention. This avoids the risk that the fire will remain ignored for a long time and therefore take on such a magnitude that any action to fight it will be too late and therefore futile.

This marine fire protection system therefore makes it possible to detect any fire risk in time, before or quickly after it is triggered, and to manage alarms in real time throughout the journey. Clearly, the deployment of such a network can provide an alarm system to detect intrusions, and it has a great advantage for long-term use on board ships without the need to charge or change the battery.

8. Conclusion

The results presented in this chapter are very encouraging: the simulation of a passive temperature sensor based on an electromagnetic transduction gave very good performances. These simulation results obtained, using previous work, allow us to consider the realization of a new high-performance temperature sensor. The optimization of this type of device was done using global electromagnetic simulations on HFSSTM including all system elements. The combination of PLZT material, dielectric resonator, and coplanar lines makes it possible to produce a narrowband filter that we excite with an electromagnetic wave at microwaves in gallery modes.

The key point of our application is based on the performance of the perovskite material and the properties of the RD gallery modes. Indeed, the dielectric resonator, covered with the sensitive material, is excited in a gallery mode that allows its oversizing with millimeter waves and its association with transmission lines in order to have a band-pass directional filter. Thus, we designed the entire 3D device on HFSS™. This software has the advantage of being rigorous and allows, a priori, taking into account all the physical and geometric characteristics of the device.

In the second part of this chapter, we have presented some of the results obtained. Several gallery modes have been observed over a wide frequency band; the Ka-band. We have therefore shown through these simulations that the measurement of the resonance frequency of a gallery mode in the dielectric resonator translates, in principle, a temperature variation with a remarkable sensitivity.

The implementation of such a device, which offers passive temperature detection, makes it possible to consider the design of a temperature sensor with high sensitivity electromagnetic transduction. The characterization of such a sensor makes it possible to evaluate the frequency in terms of geometric dispersions such as the influence of material thicknesses, and diameters will be presented in the next chapter.

Finally, our contribution provides innovative technology to meet the need to improve fire protection in maritime transport. Temperature control and traceability still require manual procedures dependent on onboard energy. The proposed system simplifies and automates relatively all these manual interventions and particularly does not require any onboard power supply. Thereafter, this firefighting device has a sensitivity of about 10 MHz/°C and allows the temperature to be controlled at any time and to react quickly in the event of a problem.

Author details

Asma Bakkali[1,2], José Pelegri-Sebastia[2]*, Youssef Laghmich[3]
and Abdelouahid Lyhyaoui[1]

1 Laboratory of Innovative Technologies, Abdelmalek Essaadi University, Tangier, Morocco

2 Research Institute for Integrated Management of Coastal Areas, Universitat Politècnica de Valencia, Valencia, Spain

3 Polydisplinary Faculty, Hassan 1st University, Khouribga, Morocco

*Address all correspondence to: jpelegri@eln.upv.es

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