Eur. Phys. J. Appl. Phys. (2016) 74: 24606
DOI: 10.1051/epjap/2015150376

THE EUROPEAN PHYSICAL JOURNAL
APPLIED PHYSICS

Regular Article

A batteryless temperature sensor based on high temperature sensitive material*

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

[1] Laboratory of Innovative Technologies, Abdelmalek Essaadi University, 1818 Tangier, Morocco
[2] Research Institute for Integrated Management of Coastal Areas, Universitat Politècnica, 46730 Valencia, Spain
[3] Polydisplinary Faculty, Hassan 1st University, 25000 Khouribga, Morocco

Received: 22 July 2015 / Received in final form: 9 November 2015 / Accepted: 12 November 2015
Published online: 3 May 2016 –

Abstract. The major challenge in wireless sensor networks is the reduction of energy consumption. Passive wireless sensor network is an attractive solution for measuring physical parameters in harsh environment for large range of applications requiring sensing devices with low cost of fabrication, small size and long term measurement stability. Batteryless temperature sensing techniques are an active research field. The approach developed in our work holds a promising future for temperature sensor applications in order to successfully reduce the energy consumption. The temperature sensor presented in this paper is based on the electromagnetic transduction principle using the integration of the high temperature sensitive material into a 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 (WGM) in the millimeter-wave frequency range. Following the results achieved, the proposed device shows a linear response to the increasing temperature and these variations can be remotely detected from a radar interrogation.

1 Introduction

Wireless sensor networks are widely used for coupling the physical and the virtual worlds. These devices present an attractive solution for a large range of environmental monitoring, distributed surveillance, control and healthcare applications [1–3]. Therefore, several techniques are currently used or under development in order to measure efficiently the physical parameters. The major challenge in wireless sensor networks is the reduction of energy consumption, which is the main factor affecting system cost and lifetime. A promising technique for measuring the physical variables without disturbing environment is using battery free sensors. Passive wireless sensor networks are very interesting candidates for measuring physical quantities in harsh environment as extreme temperature, for application requiring sensing devices with low cost of fabrication and long term measurement [4]. Because of its significant effect on our life, the temperature is the most widely sensed of all physical parameters. Passive temperature sensing techniques are therefore a field of active research and an increasing number of commercial applications is observed [5–7]. Usually, temperature sensors detect a change in a physical parameter such as resistance or output voltage that corresponds to a temperature change. In reference [8] authors perform a passive L-C sensor capable of operating in harsh environments for high temperature rotating component monitoring. Surface acoustic wave (SAW) temperature sensors take advantage of the piezoelectric effect since they convert the electrical energy into a mechanical wave using a piezoelectric substrate [9,10]. These sensors are based on involving electrically acoustic waves and then reconverting the energy of the transduced wave back into an electrical signal for temperature measurement. An interesting passive approach based on the electromagnetic transduction principle has been proposed by the authors in reference [11]. This technique has proven its efficiency in the passive remote measurement of pressure. Based on the same approach, authors in reference [12] have proposed wireless batteryless gas sensor using dielectric resonator (DR) with sensitive layer on TiO_2. The approach developed in this paper holds a promising future for temperature sensor applications, based in the integration of a temperature sensing material into passive circuit as a frequency-controlling element.

[a] e-mail: asma.bakkali@yahoo.fr

* Contribution to the topical issue "Materials for Energy Harvesting, Conversion and Storage (ICOME 2015) – Elected submissions", edited by Jean-Michel Nunzi, Rachid Bennacer and Mohammed El Ganaoui

2 Whispering gallery mode resonators for sensing applications

Over the last decade whispering gallery mode resonators have been proposed as a powerful tool for various sensing applications. This process is among the most accurate techniques established for sensing and dielectric characterization. For these resonators the total internal reflection is close to the surface and causing an evanescent field leaking out into the surrounding. The resulting resonances are high sensitive to the parameter changes of the resonator and its ambient environment. Whispering gallery modes resonators have been proposed for different applications in various publications, from temperature [13] and pressure sensing [14] to photonics and optical filters [15]. In particular, WGM resonators are optimally suited to provide temperature measurements due to their small size and appreciable resonance frequency shifts with temperature changing. This paper provides a WGM sensor as a highly sensitive platform for monitoring temperature. The principle of the WGM resonator was also applied for gas sensing using a dielectric resonator characterized by sensitive properties to the gas concentration [12]. Lead lanthanum zirconate titanate (PLZT) material, typically known as PLZT, is integrated with the WGM resonator in order to provide the temperature measurements, as the material's properties and behavior can significantly alter under temperature variations. The dielectric properties of the PLZT allow such a material to be exploited in a variety of transducer applications since it offers capabilities of operating at high frequencies and temperatures, and high chemical and environmental stability. PLZT material could have widespread use in sensor and actuator technologies. In addition to its technological and industrial uses, PLZT material will continue to provide tools and gadgets that will simplify the consumers' everyday life. With the recent drive on miniaturization of practical devices and the nanotechnology advancement, this perovskite material could be fabricated in order to exhibit transducer effects at a small enough to be useful at the nanometer resolution. The aim is to demonstrate the concept of a new temperature sensor based on the dielectric properties of this material integrated with a WGM dielectric resonator. Since the variation in temperature makes the dielectric constant of this material changing, and such modification leads to shift of the resonant frequencies of WGM resonator in the millimeter-wave frequency range. The choice of WGM and PLZT material is highly interesting since it lead to have temperature sensitive filter based on DR with a high quality factor and large temperature range.

3 Design of temperature sensor based on whispering gallery modes

The proposed temperature sensor design is composed of two main blocks: a temperature sensitive material and a dielectric resonator coupled with two microwave

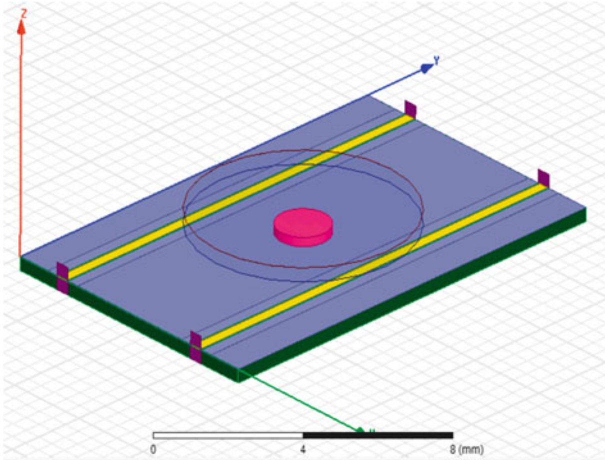

Fig. 1. Topology of the proposed sensor.

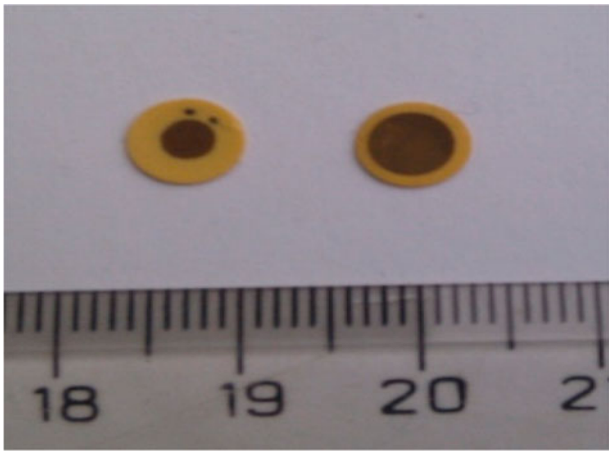

Fig. 2. Samples of the sensitive material.

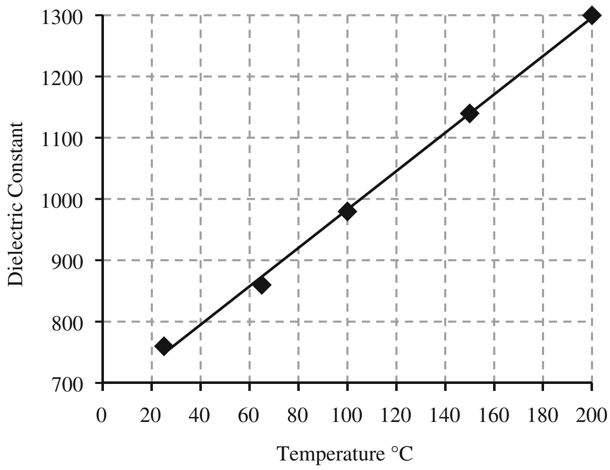

Fig. 3. Permittivity of the sensitive material versus temperature.

Table 1. Sensor parameters.

Symbol	Parameter	Value
R_{DR}	Dielectric resonator radius	3.25 mm
H_{DR}	Dielectric resonator thickness	400 μm
$\varepsilon_{\mathrm{r\ DR}}$	Dielectric resonator permittivity	80
$\varepsilon_{\mathrm{r\ Spacer}}$	Spacer dielectric constant	9.8
R_{Spacer}	Spacer radius	3.25 mm
H_{Spacer}	Spacer thickness	260 μm
W	Width of CPW signal line	300 μm
R_{Material}	Sensitive material radius	3.25 mm
H_{Material}	Sensitive material thickness	10 μm
H_{Si}	Silicon thickness	350 μm
$\varepsilon_{\mathrm{r\ Si}}$	Silicon permittivity	11.9
G	Air gap	30 μm

waveguides in coplanar topology (CPW). The main element is the lead-lanthanum-zirconate-titanate material as shown in Figure 2. The dielectric property of this ceramic presents a dielectric constant variable with the temperature changes. This material, e.g., Figure 3, offers excellent dielectric properties with temperature dependent permittivity value. Results obtained from literature indicated that the temperature is a linear function of the sensitive material dielectric constant [16,17]. As described in Figure 1 the temperature device includes a WGM dielectric resonator, covered by the sensitive layer, used to detect the temperature variations, placed between two parallel CPW lines, used for electromagnetic wave traveling. WGM dielectric resonators provide many advantages over the conventional dielectric resonators, particularly at millimeter-wave frequency band. Some of these advantages are given as follow:

- Dimensions larger than the conventional modes with controllable size.
- Good suppression of spurious modes, because the propagation constant along the z-axis is quite small.
- Very high quality factor, as the radiation losses are negligible.
- High level of integration: the height of the resonator can be smaller making it easier to integrate.

Parameters values of the temperature sensor are listed in Table 1.

In order to ensure a relevant detection range, the radar technology reader was considered for the temperature sensor interrogation. The use of radar interrogation for a RF transduction passive sensor presents an innovative solution. This paper addressed the measurement of temperature using WGM resonators based on PLZT material using the frequency shift of the resonance modes in response to changes in the external environment. In order to measure the temperature in Ka band, a prototype of FMCW radar was fabricated in the context of the thesis performed by Chebila [18]. The device is responding to temperature sensor criteria in terms of required operating frequency wireless communication over a range greater than 20 m. The radar principle consists on sending an electromagnetic wave flow to the sensor, which returns an echo with power amplitude depending on the measured temperature. The modulation technique of this radar and its architecture based around a voltage-controlled oscillator (VCO) facilitated its realization and adjustment. The radar performed in 2011 is a frequency modulated continuous radar (FMCW), used in the Ka band around 30 GHz. This HF radar will serve also to detect the distance measurements of the temperature sensor. The signals received by the reader must therefore provide information about the distance between the radar and sensor in addition to the temperature value. In conclusion, this radar meets three important parameters for remote reading: its range is greater than 20 m, working on a frequency compatible with the proposed sensor and contains an identification system cells within a network.

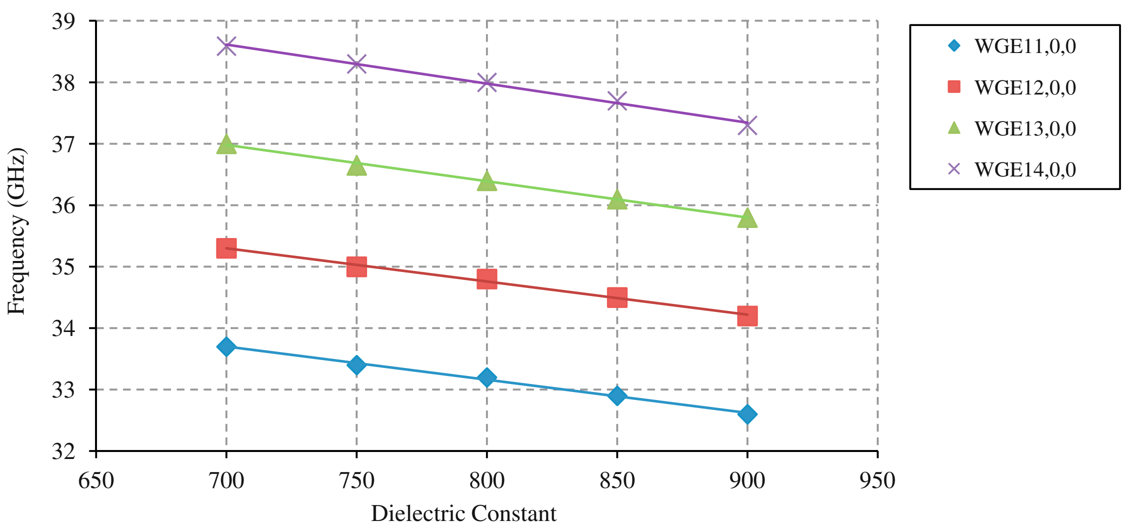

Fig. 4. Frequencies versus dielectric constant for $\mathrm{WGE}_{11,0,0}$, $\mathrm{WGE}_{12,0,0}$, $\mathrm{WGE}_{13,0,0}$ and $\mathrm{WGE}_{14,0,0}$ modes.

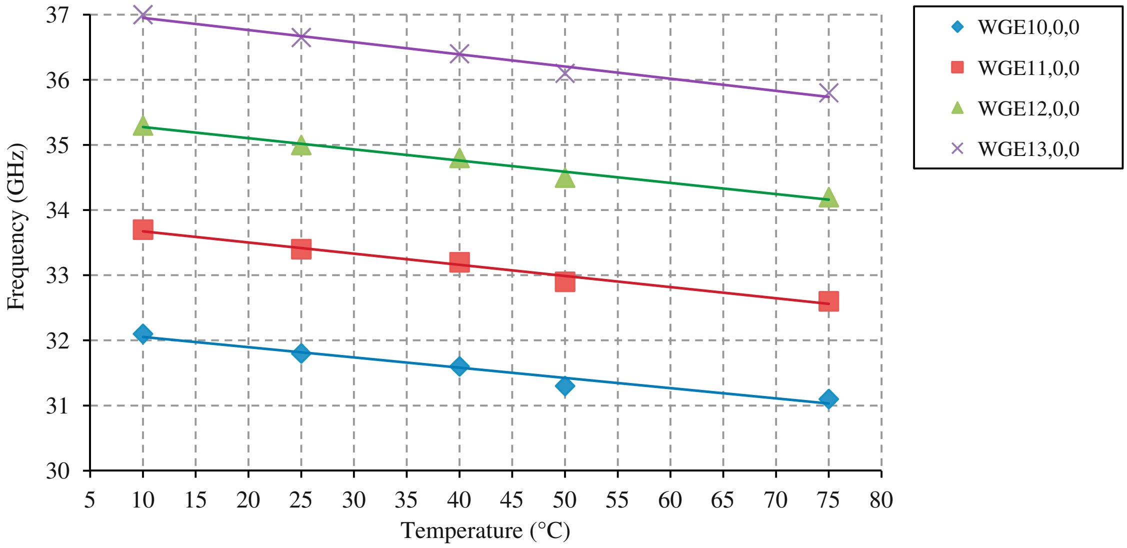

Fig. 5. Resonance frequency versus temperature for $WGE_{10,0,0}$, $WGE_{11,0,0}$, $WGE_{12,0,0}$ and $WGE_{13,0,0}$ modes.

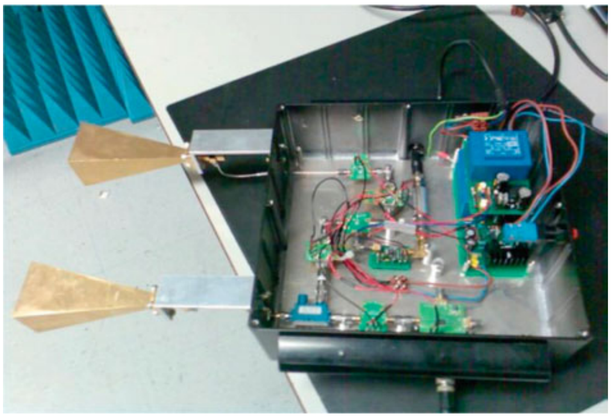

Fig. 6. FMCW radar [21].

4 Results and discussion

Full wave electromagnetic simulations have been performed for the proposed temperature sensor. Figure 4 shows the simulated resonant frequencies versus values of the sensitive material permittivity from 700 to 900, for $WGE_{11,0,0}$, $WGE_{12,0,0}$, $WGE_{13,0,0}$ and $WGE_{14,0,0}$ modes. Based on the results achieved and the variation of sensitive material with the temperature changes, the variation of frequency versus temperature can be deduced. The resonant frequencies as a function of the temperature is reported in Figure 5, in order to verify the sensor linearity between the two parameters: frequency and temperature. For $WGE_{10,0,0}$, $WGE_{11,0,0}$, $WGE_{12,0,0}$ and $WGE_{13,0,0}$ modes, variations of resonant frequencies versus temperature are almost linear decreasing functions. Other modes have been observed and presented interesting results are published in references [19,20].

For the wireless communication with the sensor, the FMCW radar can be used in order to detect small variations from an antenna loaded by whispering.

The radar, as shown in Figure 6, is planned to satisfy the wireless communication over a range greater than 20 m [21].

The sensor behavior is very interesting as a wireless passive system and the results proved that the resonator-based sensor system is very functional and useful for remote measurements of the temperature variations.

5 Conclusion

The proposed temperature sensor detects the resonant frequency of a dielectric resonator correlated with the temperature ambient via the temperature sensitive material. This concept needs an efficient dielectric resonator along with a circuit to replace the need for batteries. Therefore, the material property serves as a basis to develop wireless high-temperature sensors. By performing full-wave simulations using high frequency structure simulator, performances provided by the sensor can be deduced. The temperature-sensing device presents a powerful tool for many interesting applications since it offers very low power consumption and provides environmentally friendly temperature measurements.

This research was supported in part by EMMAG Program, 2014, funded by the European Commission.

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