Temperature sensor tag based on supercavity mode of dielectric resonator

Ildar Yusupov\textsuperscript{1,5}, Dmitry Filonov\textsuperscript{2,5}, Pavel Ginzburg\textsuperscript{3}, Mikhail Rybin\textsuperscript{1,4}, Alexey Slobozhanyuk\textsuperscript{1,5}

\textsuperscript{1}Department of Physics and Engineering, ITMO University, Saint Petersburg 197101, Russia.
\textsuperscript{2}Center for Photonics and 2D Materials, Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia
\textsuperscript{3}School of Electrical Engineering, Tel Aviv University, Tel Aviv 69978, Israel
\textsuperscript{4}Ioffe Institute, Saint Petersburg 194021, Russia.
\textsuperscript{5}Sirius University of Science and Technology, Sochi 354340, Russia

E-mail: ildar.yusupov@metalab.ifmo.ru

Abstract. This paper presents a wireless temperature sensor design based on the excitation of a high-Q supercavity mode in a dielectric resonator. Narrow resonance bandwidth improves sensor performance enabling accurate temperature measurements. The sensor consists of a half split ceramic cylinder attached to a metal sheet. The resonator parameters which lead to the excitation of a supercavity mode were obtained numerically. When the ambient temperature increased continuously from 23 to 120°C the notable shift of the resonant frequency was experimentally demonstrated.

1. Introduction

Wireless sensing techniques are widely used in modern industrial and civil technology systems. Current devices make it possible to determine with high accuracy the parameters of the environment, or the parameters of specific components as part of a complex industrial system [1]. In harsh environmental conditions, the use of chipped technologies requires complicated solutions due to the presence of silicon components. Thus, chipless design of tags promises greater perspectives [2]. The absence of a chip allows chipless sensors to be integrated into systems where the use of silicone components is impossible. Chipless sensors are known to use to determine pressure [3], humidity [4], structural health monitoring systems [5], and many others. Such sensors represent a resonator or a set of resonators, which response allows assessing the change in the state of the object on which the chipless tag is placed. Chipless sensors are especially common in temperature monitoring systems. They can be based on dielectric substrates [6] or with the use of ceramic resonators. Ceramic materials were shown to be effective as RFID tags, which can be miniaturized and can have a relatively high reading range [7].

Nowadays there are several examples of exploiting ceramic resonators as a chipless tag for temperature sensing [8]. The operation principle of such sensors is based on the shift of resonant frequency of dielectric resonator fundamental mode due to heating. High-quality (Q) resonances can significantly increase the efficiency of the sensing tag. Narrow resonance bandwidth simplifies the reader operation and allows high accuracy measurements.
The proposed temperature sensor concept is based on a similar principle reported earlier in Refs. [9] and [10]. The main difference is the use of dielectric resonators supporting a supercavity mode. The observation of supercavity modes has been already shown for optics [11], and recently it was experimentally demonstrated for microwave range [12]. This property of a ceramic cylindrical resonator allows us to obtain responses with Q factor above $10^4$. The structure of the proposed chipless sensor is shown in figure 1a. It consists of half a dielectric cylinder placed on a metal screen. The cylinder parameters are optimized to maintain the supercavity mode. The resonator is excited by a loop antenna connected to a vector network analyzer. The loop antenna is oriented along the x-axis. The obtained reflectance spectra are used to measure the ambient temperature.

2. Supercavity mode of dielectric resonator

Supercavity modes are realistic counterpart of an ideal mathematical concept of bound states in the continuum [13]. Supercavity modes can be sustained even by a single dielectric resonator due to the destructive interference of a pair of leaky cylinder modes with the same far-field profiles [11]. Adjusting for the destructive interference condition occurs by changing the aspect ratio of the cylinder resonator.

A numerical simulation using CST Microwave Studio was carried out to determine the parameters of the high-quality resonator. The requirement for the appearance of a supercavity mode is the ratio of the cylinder radius to its height as $r/h = 0.7$. As a result, the obtained parameters of the resonator: radius $r = 15$ mm, height $h = 21.42$ mm, permittivity $\varepsilon = 506$, loss tangent of ceramics $\tan\delta = 0.0004$. The optimized cylinder was cut in half and placed on the perfect electric conducting boundary. The result of numerical simulations is shown in figure 1b. The spectrum of the reflectance obtained by the loop antenna has a narrow resonance of -23 dB at 859.6 MHz. The inset shows the distribution of the absolute value of the magnetic field amplitude at the resonance. This distribution of the electromagnetic field is typical for the supercavity mode [12]. A change in the dielectric constant of the ceramic material leads to a shift in the resonance frequency of the mode under study. As the radius to height ratio remains constant, such a change of permittivity does not affect the supercavity mode parameters.

![Figure 1](image_url)

**Figure 1.** (a) Configuration of the proposed temperature sensor. Dielectric resonator with the shape of half-cylinder attached to a metallic ground plane. The resonator is excited by a loop probe connected to a vector network analyzer. The probe position is marked as a yellow star. The probe axis is oriented along the x-axis. (b) Numerically simulated and measured reflection coefficient of the resonator. Inset shows the magnetic field amplitude of supercavity mode.

3. Experimental demonstration

We performed experimental studies to demonstrate the temperature sensing effect. The experimental setup is shown in figure 2a. Half of the ceramic resonator with the parameters specified above was
placed on a metal sheet with dimensions of 30x30 cm². The loop probe connected to the vector network analyzer was placed near the ceramic resonator, and the reflection coefficient was measured. Figure 1b shows a comparison of the numerically obtained and measured reflection coefficients. Both spectra are in an excellent agreement; the small deviation is explained by the inaccuracy of determining the exact parameters of the cylinder.

Let us describe the results on the demonstration of the temperature dependence of the resonant frequency. The ceramic resonator was heated with an air solder, and the temperature was controlled by a thermocouple sensor connected to the multimeter. Figure 2b depicts selected spectra corresponding to temperatures of 23, 40 and 80°C. The complete responsibility of the resonant frequency shift to ambient temperature from 23 to 120°C is shown in figure 2c. The resonant frequency gradually increases from 856 to 1115 MHz almost with linear temperature dependence.

Figure 2. Experimental demonstration of resonance frequency shift due to increased ambient temperature. (a) Photo of the experimental setup. (b) Reflection spectra for temperatures of 23 (red curve), 40 (green) and 80°C (blue). The arrow shows direction of the resonance shift. (c) Measured resonance frequency versus temperature.

4. Conclusion
We have demonstrated the passive wireless temperature sensor’s operation based on the dielectric resonator supercavity mode’s resonant frequency shift. The proposed sensor has simple construction consisting of the half split ceramic cylinder attached to the metal sheet. The supercavity mode has been excited by the loop antenna and the spectra of the reflection coefficient have been measured. In the experiment we have confirmed the shift of the resonant frequency with the ambient temperature increasing continuously from 23 to 120°C. The future work will demonstrate the operation of the proposed sensor tag over broader temperature ranges. The far-field interrogation of the sensor using a directional antenna will also be investigated in the future.
Acknowledgments

The numerical and experimental results were supported by the Russian Foundation for Basic Research (Grant No. 20-37-51011). Materials for the experiment were supported by Russian Science Foundation (Grant No. 21-79-30038).

References

[1] L. Da Xu, W. He, and S. Li, “Internet of things in industries: A survey,” *IEEE Trans. Ind. Informatics*, vol. 10, no. 4, pp. 2233–2243, 2014
[2] V. Mulloni and M. Donelli, “Chipless RFID sensors for the internet of things: Challenges and opportunities,” *Sensors (Switzerland)*, vol. 20, no. 7, 2020
[3] C. Schuster, P. Schumacher, M. Schusler, A. Jiménez-Sáez, and R. Jakoby, “Passive chipless wireless pressure sensor based on dielectric resonators,” *Proc. IEEE Sensors*, vol. 2017-Decem, pp. 1–3, 2017
[4] Y. Feng, L. Xie, Q. Chen, and L. R. Zheng, “Low-cost printed chipless RFID humidity sensor tag for intelligent packaging,” *IEEE Sens. J.*, vol. 15, no. 6, pp. 3201–3208, 2015
[5] S. Dey, R. Bhattacharyya, S. E. Sarma, and N. C. Karmakar, “A Novel ‘Smart Skin’ Sensor for Chipless RFID Based Structural Health Monitoring Applications,” *IEEE Internet Things J.*, vol. 8, no. 5, pp. 1–1, 2020
[6] X. Y. Guo, G. C. Wan, Y. M. Gao, and M. S. Tong, “A Novel Temperature Sensor Based on Chipless RFID Tags,” no. 4, pp. 1–3, 2021
[7] D. Dobrykh et al., “Long-range miniaturized ceramic RFID tags,” *IEEE Trans. Antennas Propag.*, 2020
[8] M. Schüßler, C. Mandel, B. Kubina, and R. Jakoby, “Realization concepts for chipless wireless temperature sensing,” *Sensoren und Messsyst. 2014 - 17. ITG/GMA-Fachtagung*, pp. 1–6, 2013.
[9] C. Mandel et al., “Dielectric ring resonators as chipless temperature sensors for wireless machine tool monitoring,” *2017 11th Eur. Conf. Antennas Propagation, EUCAP 2017*, pp. 3912–3916, 2017
[10] B. Kubina, M. Schusler, C. Mandel, A. Mehmood, and R. Jakoby, “Wireless high-temperature sensing with a chipless tag based on a dielectric resonator antenna,” *Proc. IEEE Sensors*, pp. 4–7, 2013
[11] M. V. Rybin et al., “High- Q Supercavity Modes in Subwavelength Dielectric Resonators,” *Phys. Rev. Lett.*, vol. 119, no. 24, pp. 1–5, 2017
[12] M. Odit, K. Koshelev, S. Gladyshev, K. Ladutenko, Y. Kivshar, and A. Bogdanov, “Observation of Supercavity Modes in Subwavelength Dielectric Resonators,” *Adv. Mater.*, vol. 33, no. 1, pp. 1–7, 2021
[13] M. Rybin and Y. Kivshar, “Supercavity lasing inflation identified,” *Nature*, vol. 541, pp. 164–165, 2017.