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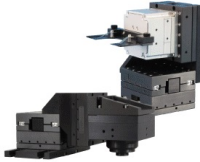
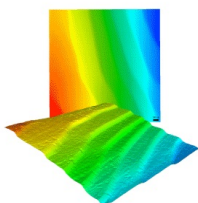
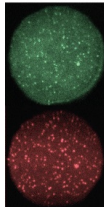
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## ABSTRACT

A new spherical vibrational energy harvesting device with an additional low power management circuit for optimizing the power transfer from the mechanical vibrations to a storage capacitor is presented. The device is devoted to underwater wireless sensor network applications due to its broadband vibrational energy harvesting, sensing, and communicating facilities. The sensing node container consists of two acrylic glass (PMMA) half-spherical shells and a Pz26 piezoelectric ring clamped between the shells. The energy harvesting, the management circuit, and communication electronics were fitted within the hollow portion of the sphere. A simulation model of the energy extraction and management system using SPICE has been developed. This simulation shows the feasibility and efficiency of the low power extraction circuit; a level of the necessary stored voltage was set at 3 V. The numerical model was validated by underwater experimental measurements; a voltage of 3 V was obtained at the terminals of a storage capacitor (47  $\mu$ F) which was sufficient to supply the communication electronics. Power harvesting performances were measured relative to the transmitter/sensor distance and the incident acoustical field excitation voltage. Finally, 175  $\mu$ W of harvested power has been measured with an excitation voltage of 8 V<sub>pp</sub> at 5 cm distance from the emitter.

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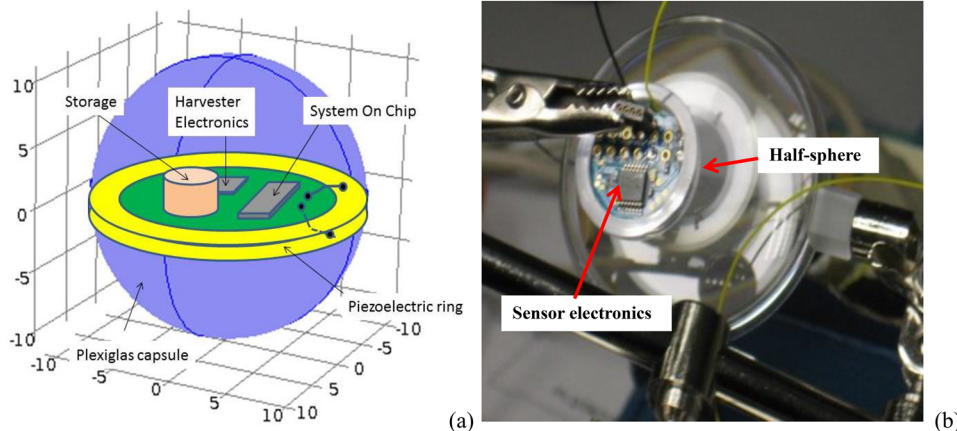
## I. INTRODUCTION

Nowadays, Underwater Wireless Sensor Networks (UWSNs)<sup>1-3</sup> is a very important domain that has attracted considerable attention due to their promising applications. It is possible to cite, for example, monitoring, tracking, and detection applications in shallow water as well as in deep oceans.<sup>4-7</sup> Moreover, acoustical waves demonstrate high efficiency in underwater environment due to their performances in propagation distance and emitting/receiving antenna characteristics.<sup>8,9</sup>

Underwater energy harvesting is devoted to the use of the ambient energy (vibration, light, and temperature) present in the environment for powering electronic devices (sensors and mobile equipment), in a way to extend their operating life and make them completely autonomous.<sup>10</sup> The problem of the underwater applications is the lifetime of electrical batteries and the danger that

batteries present to aqueous environment. In this context, energy harvesters converting ambient energy into electrical energy are promising solutions for long-term energy supply.<sup>11</sup> Ambient energy sources such as mechanical vibrations are numerous, and they are widely studied and starting to be used in UWSN applications. In underwater applications, the ultrasonic waves' energy is generated in the ocean either naturally by animals and geological activity or artificially by antennas for underwater detection, navigation, and communication.<sup>12,13</sup> More recently, much research has been done on the subject of energy autonomy and in particularly on the power supply of these underwater devices.

Generally, vibrational energy harvesting is based on resonant mechanical systems (spring-mass-damper) tuned to the frequency of the source.<sup>14,15</sup> Several physical phenomena such as the piezoelectricity,<sup>16</sup> the electrostatics,<sup>17</sup> and the electromagnetism<sup>18</sup> can be used for extraction of mechanical energy and its conversion into electrical



**FIG. 1.** (a) Structure of the spherical sensor and the hollow portion of the sphere containing the embedded electronics and (b) photo of the spherical transducer during the assembly. The electronic circuit is inserted in the hollow part of the half-sphere, and the second half-sphere (not present on the photo) was glued and sealed to form a closed spherical structure.

energy. In this work, we are presenting an energy-harvesting device based on piezoelectricity.

In the case of energy harvesting, the direct piezoelectric effect is generally exploited by coupling a PZT (lead zirconate titanate) ceramic to a resonant structure that imposes a deformation. The vibrations of the structure induce a deformation of the piezoelectric material, thus creating its polarization. The piezoelectric energy harvesting has an advantage of high power density, wide property range, and ease of application.<sup>14</sup> They are ideal in applications that need to charge a battery and supercapacitor or to directly power remote sensor systems.

The electrical power generated by a piezoelectric transducer cannot be used directly to power electronic devices. An energy extraction circuit must be adapted and used to optimally convert the harvested energy. In most conventional cases, an AC/DC rectifier and then a DC/DC converter are used.<sup>19,20</sup> The voltages generated by a piezoelectric element are AC voltages which must be rectified (AC/DC), filtered, and level adjusted. In addition, this circuit must provide a regulation (DC/DC) of these voltages in a way to produce voltage level independent of the initial source or stress variations exerted on the piezoelectric element (i.e., impose a constant voltage on the load). The structure of the extraction circuit must take into account the electrical characteristics of the transducer such as impedance and produced voltages.

Generally, the level of energy scavenged by piezoelectric devices is not sufficient for the direct supply of electronic systems, and it is therefore necessary to store and accumulate the harvested energy in order to reach a sufficient level. The simplest and most convenient solution widely employed consists of charging a capacitor or using a rechargeable battery.<sup>21–23</sup>

Many researchers are interested in using nonlinear extraction circuits to optimize the harvested electrical power.<sup>24,25</sup> In particular, Synchronous Charge Extraction Interface (SCEI) and Synchronized Switch Harvesting Interface (SSHI) techniques were used to bring significant improvements to vibration-based piezoelectric energy harvesting systems.<sup>26</sup> In this work, we used an ultralow power boost converter (Texas Instruments BQ25504) with battery management devoted for energy harvester applications.

The purpose of the present paper is to develop and characterize a power extraction electronic circuit placed inside a spherical

piezoelectric transducer. In such a way, this device can be used as a wideband, efficient, and low-cost piezoelectric energy harvester and sensing node container for UWSNs. The sensor is illustrated in Fig. 1; it uses a clamped PZT ring as an energy converter and a spherical outer shell as a resonator. This specific configuration allows operating in a wide frequency range due to the five principal structural resonating modes distributed closely in the frequency spectrum between 10 and 60 kHz. In addition, this configuration of the sensor exhibited low directivity, which is advantageous for operation under random ambient conditions.<sup>27</sup>

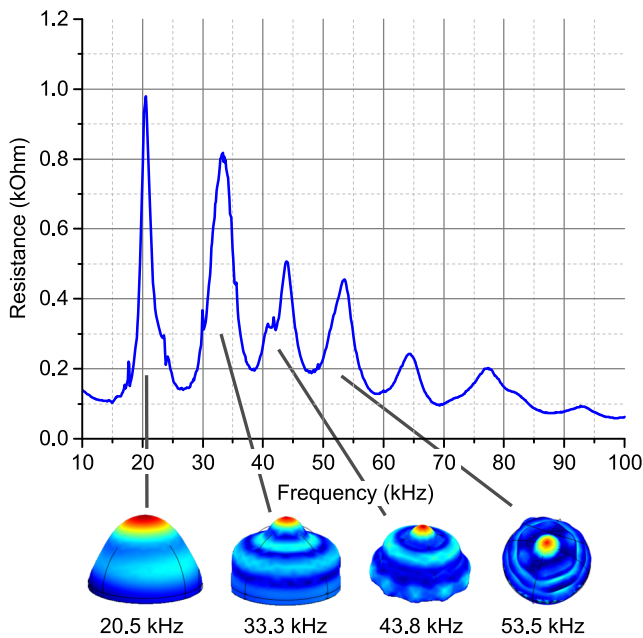
In the first part of this work, the essential properties of the spherical piezoelectric transducer are presented based on our work reported elsewhere.<sup>27</sup> These properties are relevant for interfacing the piezoelectric transducer with the power extraction circuit.

In this present work, we mainly focus on the energy extraction and storage components of the system. This system is capable to generate electrical power from ambient vibrations in order to power itself and store energy by charging a capacitor. Thus, in this part of the work, we present the implementation steps for an energy extraction circuit based on an ultralow power Texas Instruments BQ25504 booster.

It is worthwhile mentioning that a numerical model has been developed to validate our experimental measurements on the spherical harvester in a water tank. We were able to harvest a voltage of about 3 V, which was enough to supply the necessary power for functioning the electronics of the circuit (i.e., sensor chip and to send test code messages).

## II. SPHERICAL ACOUSTIC PIEZOELECTRIC TRANSDUCER

The shell of the proposed sensor is composed of two acrylic glass (PMMA) half-spheres. Its outer radius and thickness are 11 mm and 1 mm, respectively (Fig. 1). The active piezoelectric ring (PZT-Pz26, 1 mm of thickness) is sandwiched between the two half-spheres. This configuration with its hollow interior part provides the possibility to design a self-containing device, which can enclose all energy harvesting and communication electronics. In addition, the two half-sphere configuration allows us to isolate the electronics and the energy extraction system away from seawater for the purpose of underwater applications.



**FIG. 2.** Resistance vs frequency of the spherical shell container measured with an EIA and thumbnails of 4 first resonance modes obtained with FEM modeling for the corresponding frequencies.

In order to provide a wideband energy harvesting, several structural resonance modes of the spherical shell have been used. The spherical shell with a rigid piezoelectric disk exhibits multilobe resonance patterns in analogy with a well-studied case of a uniform spherical shell.<sup>28</sup> The piezoelectric ring was not used in its proper resonant mode; instead, the structural resonances of the entire system (sphere plus piezoelectric ring) were exploited. The spherical shell acts as a vibration amplifier around its resonances which are much lower (a few tens of kHz) than the resonance frequencies of the ring (few MHz).

The spherical transducer frequency responses were recorded with an Electrical Impedance Analyzer (EIA) Wayne Kerr 6520 in an air environment [Fig. 6(a)]. The results show that the electric impedance exhibits several resonance peaks. A Finite-Element Modeling (FEM) has been performed in order to investigate the structural shapes of the corresponding modes. Such shapes are presented in Fig. 2 for the first four resonance modes. The presence of the rigid piezoelectric ring makes the fundamental mode to be directive with the vibration maximum in the direction perpendicular to the ring. Superior resonance frequencies reveal the presence of axisymmetric modes only. The presented resonance shapes make the piezoelectric ring to oscillate mainly in the radial direction. More details on FEM modeling and spherical shell multimode vibrational behavior could be found in Ref. 27.

### III. ELECTRICAL OPTIMIZATION BY ENERGY EXTRACTION CIRCUIT

In this section, we present the architecture of the electrical energy extraction and conversion device. This extraction circuit

is based on an ultralow power high efficiency DC/DC boost converter/charger Texas Instruments BQ25504 board. The BQ25504 is a solution for the management of harvested energy that is well suited to the special needs of ultralow power applications.<sup>29,30</sup> The device is specifically designed to efficiently acquire and manage power ranging from microwatt ( $\mu$ W) to milliwatt (mW) from a variety of DC sources such as piezoelectric, photovoltaic, or thermal generators. The description and the operating principle of this circuit are detailed in Ref. 31.

#### A. Modeling of the energy extraction circuit (BQ25504)

The simulations of the energy extraction circuit used in our project were performed under SPICE using TINA-TI 9.0 software from Texas Instruments. This simulation allows us to validate the feasibility of this electrical circuit and to demonstrate its efficiency in extracting power from ambient vibrations. The complete schema of the device is presented in Fig. 3.

This system is composed of three parts:

1. The first functional block is the AC/DC converter consisting of a Graetz bridge with Schottky diodes.<sup>32,33</sup> These diodes have the particularity to be fast with a low threshold voltage: 0.3–0.4 V. The circuit is also equipped with a filter capacitor and a Zener protection diode, limiting voltage spikes to 5 V.
2. The second stage constitutes the energy treatment system (Texas Instruments BQ25504) whose operation has been described above.
3. Finally, we added a switching circuit control to activate the power supply of the sensor transmission circuit (microcontroller connected to the OUT pin) when there is enough energy stored in the extraction circuit.

For a benchtop testing of the energy extraction circuit, the piezoelectric element is replaced by a voltage generator which produces a sinusoidal voltage of 1 V amplitude ( $V_{GI}$  in Fig. 4). The rectified voltage  $V_{IN\_DC}$  at the output of the AC/DC converter reaches a maximum value around 800 mV. The two voltages  $V_{BAT}$  and  $V_{STOR}$  at the terminals of the storage capacitor ( $C_{STOR}$ ) grow from 0 V to 3 V in 2 seconds. Once the level of 3 V is attained, the output  $V_{BOK}$  goes to 1, and  $V_{STOR}$  is applied to the microcontroller driving the emitter circuit of the sensor. During the operation of this circuit,  $V_{STOR}$  and  $V_{BAT}$  voltages decreased a bit, and then, the capacitor ( $C_{STOR}$ ) recharges again involving the increase in  $V_{STOR}$  and  $V_{BAT}$  in a cyclic manner.

### IV. EXPERIMENTAL STUDY IN A WATER TANK AND VALIDATION OF THE OPERATING PRINCIPLE

The objective of this experimental study is to validate the vibrational energy harvesting device coupled with the energy extraction circuit in real situation and to therefore demonstrate the possibility of energy autonomy of the spherical sensor. The experimental setup presented in this part allows exciting the spherical sensor from ambient vibrations in a water tank using a piezoelectric Tonpilz-type transducer of 4 mm diameter having a wide frequency band of 10 kHz–60 kHz (Fig. 5).

Initially, the spherical transducer frequency responses are recorded with an Electrical Impedance Analyzer (EIA) Wayne Kerr





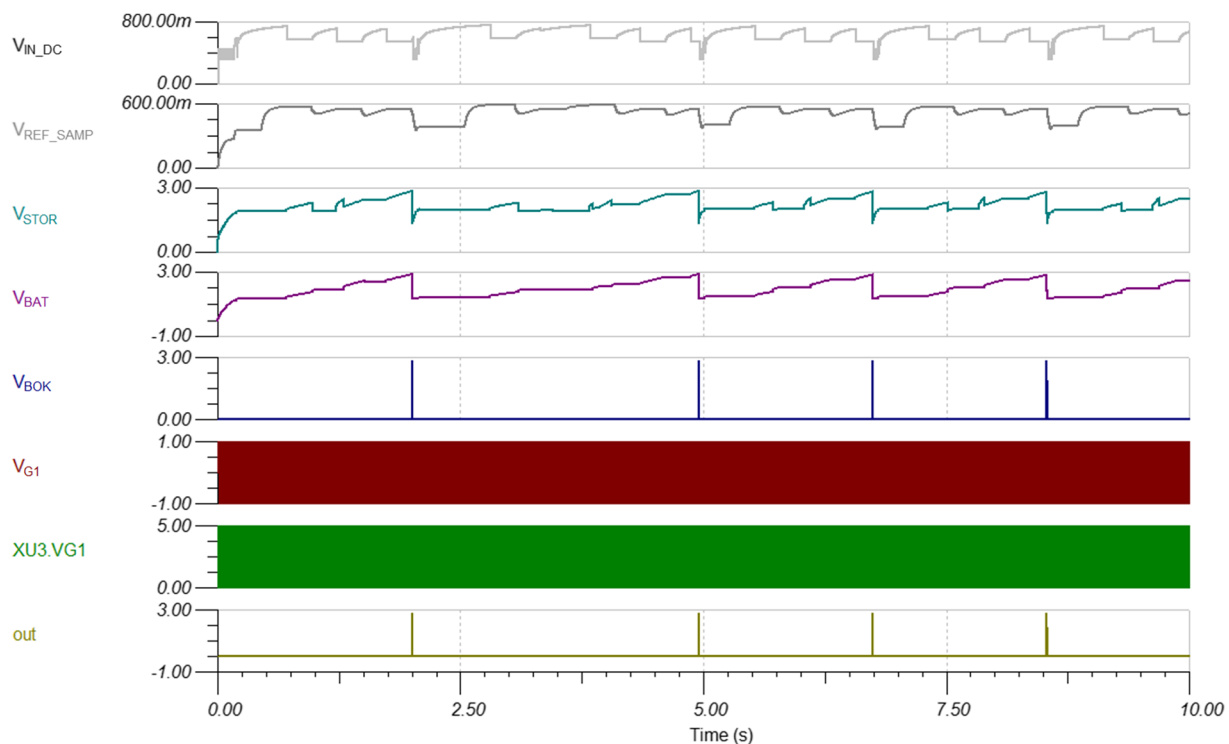


FIG. 4. Time-evolutions of different voltages in the energy management circuit.

The signal received by the spherical capsule is directed to a full-wave rectifier bridge (AC/DC) with Schottky diodes, a Zener protection diode, and a filtering capacitor. The role of this block is to rectify the sinusoidal voltages produced by the piezoelectric ring and filter (pre-energy storage) and to protect the input of the harvester circuit against excess-voltages. The output voltage of the rectifier bridge ( $V_{IN\_DC}$ ) is applied to the energy treatment and management circuit (BQ25504). This circuit produces a regulated voltage on an electric charge (storage capacitor and powered circuit). Once a sufficient voltage level is attained in the capacitor  $C_{STOR}$ , it transfers this energy to the load. Finally, the sensor electronics is powered by a switching circuit that supplies the accumulated voltage ( $V_{STOR}$  in Fig. 4), whenever the signal  $V_{BAT\_OK}$  is at 1 (high logical level). In the sensor electronics, a programmed chip was used for testing the success of the operation sequence by emitting the binary code (0100).

## A. Results and discussion

An oscilloscope makes it possible to visualize the sensor signal, the emitted code  $V_{STOR}$ , and the signal  $V_{BAT\_OK}$  (Fig. 7). Figure 7(a) shows the temporal evolutions of the four variables (sensor signal voltage,  $V_{STOR}$ ,  $V_{BAT\_OK}$ , and emitted code); the sensor signal is used as the input data for the rectifier. The sinusoidal voltage generated by the piezoelectric ring has an amplitude of 3.53 Vpp. The capacitor  $C_{STOR}$  starts charging; the voltage between its terminals increases from 0 to 3.2 V [green curve in Fig. 7(a)].

During charging, the signal  $V_{BAT\_OK}$  is at 0 (low state) and the microcontroller is idle [pink curve in Fig. 7(a)]. When the  $V_{STOR}$  voltage reaches the level of 3.2 V, the signal  $V_{BAT\_OK}$  goes from 0 to 1 which allows us to validate the transfer of power to the sensor electronics. At this moment, the microcontroller is powered and the sensor emits the sample identification code [Fig. 7(b)].

The setting in operation of all the blocks of the experimental setup causes a decrease in  $V_{STOR}$  voltage and the shutdown of the microcontroller. The voltage  $V_{BAT\_OK}$  drops back to 0, and the capacitor starts a new charging cycle. During frequency scanning,  $V_{STOR}$  reaches maximum at the resonance frequencies of the sphere; consequently, the emission of the code will take place on these resonant frequencies. From this experimental device, we can harvest a sufficient level of voltage to ensure the energy autonomy of this miniaturized ultrasonic transducer.

## B. Energy balance and harvested power

In order to quantify the efficiency of energy harvesting with the spherical transducer, electrical measurements of harvested power have been performed. First, we performed several measurements at several distances between the transmitter transducer and the spherical sensor. In each case, measurements of the voltage at the terminals of the storage capacitor ( $V_{STOR}$ ) as well as the time required to reach the level of this voltage have been determined. The same measurements have been repeated with several emission voltages ( $V_G$ ) provided by the generator (5 Vpp, 6 Vpp, 7 Vpp, and 8 Vpp)

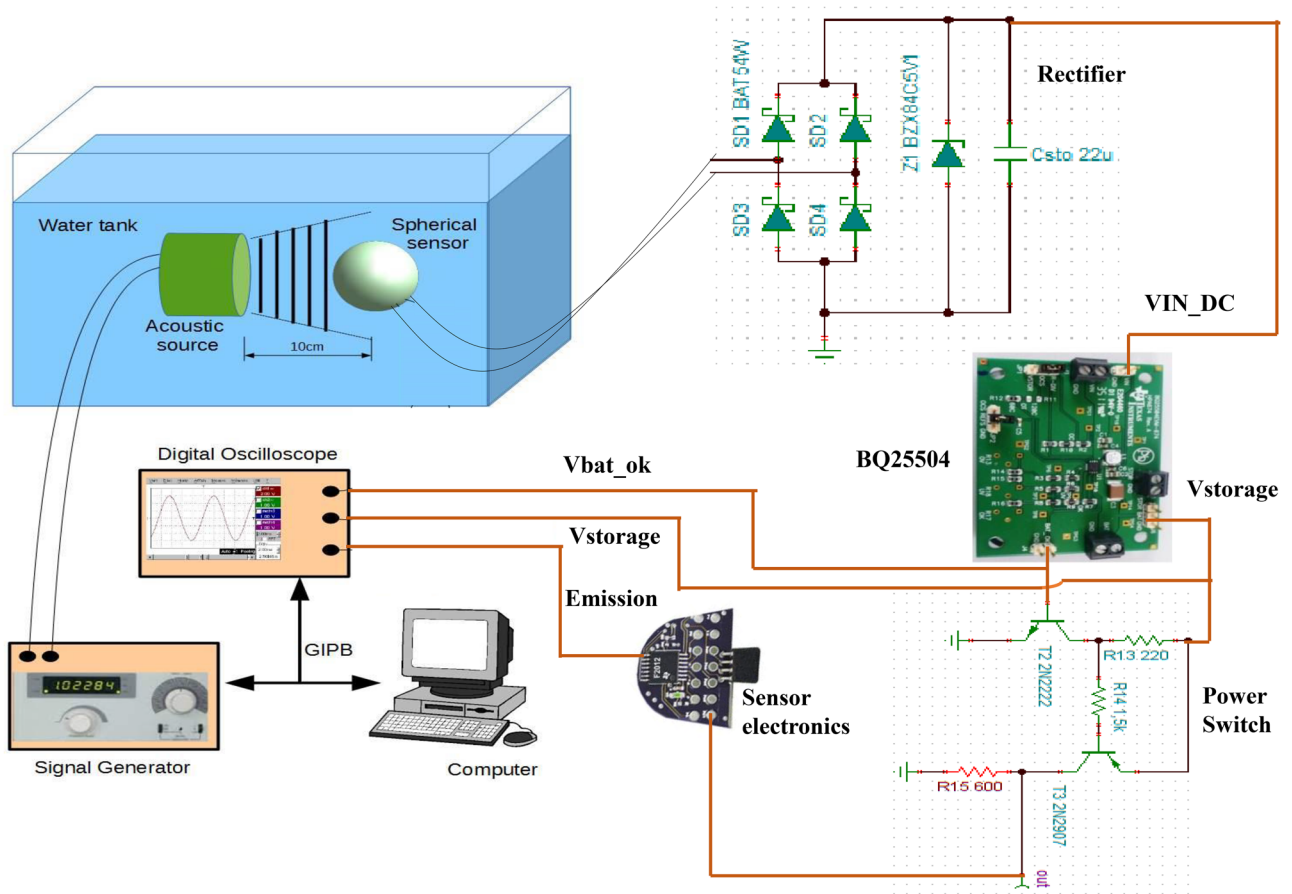
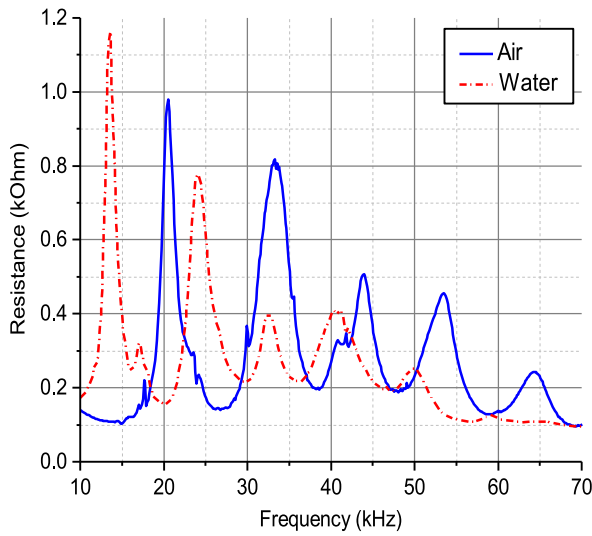
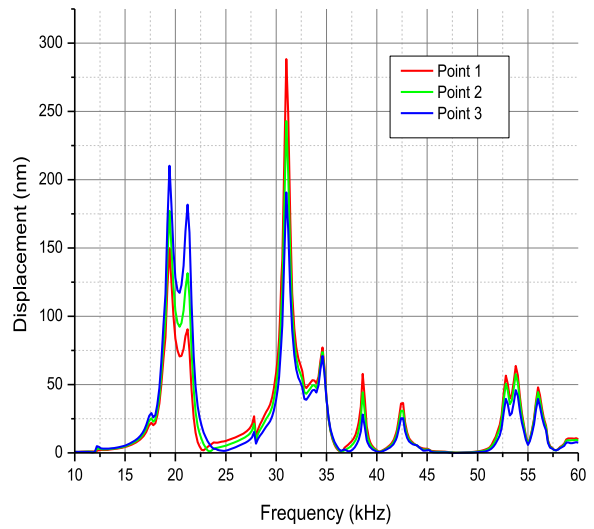


FIG. 5. Complete experimental setup of vibrational energy harvesting.



(a)



(b)

FIG. 6. (a) Real part of electrical impedance vs frequency for the spherical transducer and (b) displacement of the acoustic source.



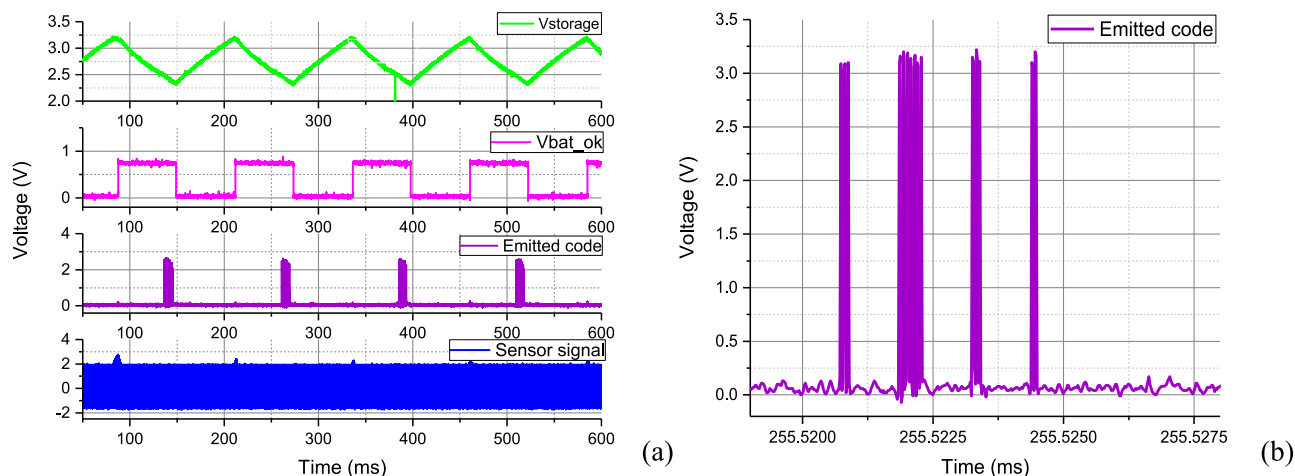


FIG. 7. (a) Internal signals of embedded electronics of the spherical sensor and (b) code emission.

(see Table I). In all the studied cases, the sufficient level of  $V_{STOR}$  ( $\sim 3$  V) to supply the sensor has been accumulated. The energy stored in the charged capacitor ( $C_{STOR} = 47 \mu\text{F}$ ) is about  $E_{STOR} = 21 \mu\text{J}$ . The energy density of this harvester depends on the maximum harvested voltage level and on the storage capacitor. The energy density of our harvester which has a node volume of  $5.6 \text{ cm}^3$  was estimated to be  $3.75 \mu\text{J}/\text{cm}^3$ . The electric powers harvested as function of excitation voltage  $V_G$  and distance are presented in Table I.

When the applied voltage level  $V_G$  increases at constant distance between the transmitter and the sensor, the amplitude of the signal received by the spherical sensor increases and the charging time of the capacitor decreases. As a result, the electrical power harvested becomes more and more important. Taking the case where the distance is 5 cm, for  $V_G = 5$  Vpp: the charging time is

280 ms, and the power is  $75 \mu\text{W}$ , while, in the case of  $V_G = 8$  Vpp, the charging time is 120 ms, and the harvested power is  $175 \mu\text{W}$ .

We can also notice that for a sensor-transmitter distance of 20 cm, the  $V_{STOR}$  reaches a level of 2.1 V and 2.6 V after a long duration for  $V_G = 5$  Vpp and  $V_G = 8$  Vpp, respectively. In this case, the energy stored in the capacitor was not sufficient to power the microcontroller and the recognition code was not emitted.

Figure 8 illustrates the traces of the harvested powers vs sensor-transmitter distance for the different amplitudes of the emitted generator voltage ( $V_G$ ). As shown, the power decreases with the increase in the distance and it increases as well with the increase in the emission amplitude.

TABLE I. Electric powers harvested at different distances between the transmitter transducer and the spherical sensor. The estimated harvested power for each case is printed in bold character.

5 Vpp	Distance (cm)	5	8	10	15	18	20
	$V_{storage}$ (V)	3	3	3	2.9	2.9	2.1
	Time (ms)	280	300	340	480	540	No emission
	<b>Power (<math>\mu\text{W}</math>)</b>	<b>75</b>	<b>70</b>	<b>62</b>	<b>43</b>	<b>38</b>	
6 Vpp	Distance (cm)	5	8	10	15	18	20
	$V_{storage}$ (V)	3	3	3	3	2.9	2.2
	Time (ms)	200	280	300	460	500	No emission
	<b>Power (<math>\mu\text{W}</math>)</b>	<b>105</b>	<b>75</b>	<b>70</b>	<b>45</b>	<b>42</b>	
7 Vpp	Distance (cm)	5	8	10	15	18	20
	$V_{storage}$ (V)	3.1	3	3	3	2.9	2.5
	Time (ms)	180	250	300	320	360	No emission
	<b>Power (<math>\mu\text{W}</math>)</b>	<b>116</b>	<b>84</b>	<b>70</b>	<b>65</b>	<b>58</b>	
8 Vpp	Distance (cm)	5	8	10	15	18	20
	$V_{storage}$ (V)	3.2	3	3	3	3	2.6
	Time (ms)	120	200	260	300	320	No emission
	<b>Power (<math>\mu\text{W}</math>)</b>	<b>175</b>	<b>105</b>	<b>80</b>	<b>70</b>	<b>65</b>	

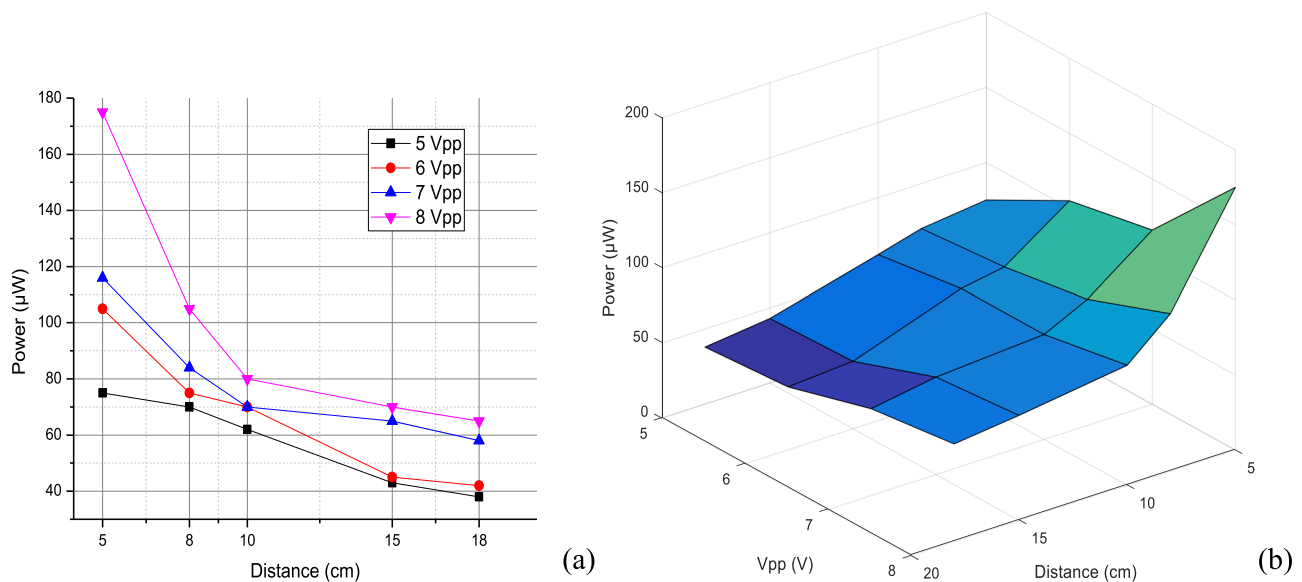


FIG. 8. (a) Harvested powers vs sensor-transmitter distance and (b) 3D power-distance-Vpp graphic.

## V. CONCLUSION

In this paper, an experimental study of piezoelectric energy harvesting from an acoustic spherical transducer was carried out. The device consists of a piezoelectric ring sandwiched between two half-spheres. The electronics embarking the sensor's components is positioned in the hollow portion of the sphere. We presented the experimental validations of the complete vibrational energy harvesting technique with an extraction and management circuit of the harvested power.

The simulation model of the energy extraction circuit shows the feasibility and efficiency of this circuit. A voltage generator has been used as the equivalent of a piezoelectric ring producing a sinusoidal voltage applied to the power management system in order to charge a storage capacitor. A voltage of 3 V at the terminals of the storage capacitor was sufficient to power the microcontroller and issue a code by the transmission system.

Furthermore, we tested the energy autonomy of the spherical sensor in a real environment; underwater analysis shows that the frequency band of the spherical transducer in the receiver mode is in the range of 10–60 kHz. The measurements were made with all the elements of the harvesting and storage circuit (Texas Instruments BQ25504) coupled with the embedded electronics of the spherical sensor. According to the simulation results, average voltage value about 3 V is obtained to power the electronics and to send a programmed code to the transmitter system of the sensor. Finally, an energy balance was performed to quantify the level of scavenged power as a function of distance and transmission voltage. For a distance of 5 cm, 175 µW is obtained with an emission amplitude of 8 Vpp.

The perspectives of this work are designing a transducer by introducing the energy extraction circuit in the hollow part of the sphere and the miniaturization of sensor geometric dimensions in

order to be suitable with biomedical applications or applications in the field of recognition of a bioacoustic signature.

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