Abstract—This work presents a detection system for optoacoustic tomography based on a polymer piezoelectric sensor and a transimpedance amplifier. The results of the electrical and acoustic characterization show that the system has a large bandwidth (63 MHz), high sensitivity (1630 μV/Pa) and low equivalent noise pressure (1 Pa). The described sensor design offers an easy-to-implement and low-cost option. Moreover, the measured values suggest it is suitable for optoacoustic systems based on light emitting diodes.

Keywords: optoacoustic tomography; piezoelectric sensor; noise equivalent pressure.

I. INTRODUCTION

The main goal of optoacoustic tomography (OAT) is to obtain images from optoacoustic (OA) signals. The OA phenomenon is the generation of acoustic waves due to thermoelastic expansion caused by absorption of short optical pulses. When the OA technique is used to perform OAT, the pressure profiles generated by the optical excitation are captured with ultrasonic sensors that surround the area of interest.

An OA configuration consists of three essential elements: a light source, a detection system for capturing the acoustic waves and a system for processing the measured signals. Generally, the detection system is an ultrasonic transducer. In OAT, it is possible to classify these devices into two categories: piezoelectric (or capacitive) transducers, in which the measured electrical signal is directly proportional to the pressure; and optical detectors, which are sensitive to changes in the optical path length, induced by pressure waves [1]. The former type is the most commonly used and it is based on polymeric (broadband) or ceramic (resonant) materials. At this moment, in comparison with the optical sensors, the piezoelectric technology has higher sensitivity and lower cost. Among piezoelectric polymers, the most popular ones are polyvinylidene fluoride (PVDF) and its copolymers.

In recent years it has been attempted to replace the conventional laser sources usually used in OAT (e.g., Nd:YAG in combination with OPO, optical parametric oscillator) by schemes based on light emitting diodes (LEDs). LEDs offer a significant reduction in cost, have higher pulse rates (> 1 kHz), are significantly more stable than OPO-based light sources, and allow portable and multi-wavelength systems [2]. However, pulsed LEDs emit less energy per unit area. Therefore, to exploit the advantages mentioned above, it is necessary to have a detection system with high sensitivity, low noise and, with the same idea pursued with LEDs, inexpensive.

In a previous work [3] we detailed how to implement a broadband piezoelectric polymer sensor with linear geometry based on a thin film of PVDF. In combination with a low noise transimpedance amplifier, the transducer is suitable for the application in OAT. The method presented in ref. [3] has several advantages: ease of implementation, high repeatability, and low cost. These features make it an interesting option in order to develop systems that obtain images in real time (parallelization resorting to a detector array). When we used this transducer in the OAT system presented in ref.[4] was necessary a minimum laser energy of 1 mJ to obtain high resolution images. Nowadays, a commercial LED yields up to ~10 μJ per pulse. Therefore, the achieved sensitivity and noise equivalent pressure are not suitable for use with LED-based light sources.

In this work, we studied how to reduce the noise floor of ultrasonic sensors implemented following the method described in ref. [3]. Based on the obtained results, we apply a simple solution that significantly reduces the noise and allows the use of other transimpedance amplifier with higher gain and bandwidth; achieving a very sensitive, low-noise detection system.

The paper is organized as follows. In Sect. II we analyze the main noise source of a piezoelectric sensor following the method described in [3] and we present two solutions to increase the signal to noise ratio. Moreover, we detail the materials and methods used to characterize detection systems based on different sensors and transimpedance amplifiers. In Sect. III we compare the performance of the improved sensor with the previous one. To achieve this, we compare the responses in a bidimensional OAT and we measure the system resolution. Finally, we present the conclusions in Sect. IV.
II. DETECTION SYSTEM CHARACTERIZATION

The noise equivalent pressure (noise floor) of the detector is a most important figure of merit in OA. In OAT, a low-noise, large bandwidth detection system enables the detection of small size objects (high resolution images). As already mentioned [3] we have designed and characterized a thin film piezoelectric detector. This sensor had a rather poor signal-to-noise ratio that made it non suitable for LED illumination. The analysis of the intrinsic noise sources suggested the performance should have been better. Since the detector lacked good shielding it was possible the poor signal-to-noise ratio could be traced down to capturing stray signals.

Fig. 1 shows a picture of the polymeric piezoelectric sensors studied in this work. Sensor A consists of a PVDF film (25 μm of thickness) attached to an acrylic substrate with dimensions 30 mm x 30 mm x 10 mm. A transparent, non-conductive acrylic layer (< 1 mm thickness), placed over the detector surface prevents the acoustic coupling medium (water) from changing the dielectric properties of the PVDF thin film. The active detection area is approximately 0.7 mm \((d) \times 24 \text{ mm} \((L)\). Further technical details can be found in ref.[3]. Sensors B and C were implemented following the same method, but with an electrical shield based on conductive silver paint. It can be seen, in Fig. 1, sensor B has a window without paint around the active detection area, whilst sensor C is fully covered with paint. Even though the role and convenience of shielding are obvious, their relevance in this case will be addressed in detail.

For the electrical characterization, we used the measurement method described in ref. [3]. Firstly, we measured the sensor's capacitance in the range from 10 Hz to 10 MHz with a bridge circuit excited by a synthesized signal generator. The results showed the three sensors have identical capacitance (60 pF at 10 kHz) and a dependence on the frequency that fits well with the Havriliak-Negami function [5]. Secondly, the frequency response of the system (sensor + amplifier) was determined with network analyzer at frequencies up to 200 MHz. We tested two different transimpedance amplifiers (TIA), EG&G Optoelectronics Judson PA-400 (TIA1) and FEMTO HCA-100MHz-50K-C (TIA2) with flatband gains of 4 kΩ and 50 kΩ, respectively. The detection system which combines sensor A and TIA1 has a frequency cut-off (-3 dB) of 20 MHz and 63 MHz with TIA2. Similar results (± 5 %) were measured with sensors B and C.

The acoustic characterization of the detection system was performed following the method described in ref. [6]. Fig. 2 presents the experimental setup. The piezoelectric sensor and a metallic target, used as the acoustic source, were immersed in a cylindrical cuvette (115 mm diameter x 90 mm height) filled with deionized water. A frequency-doubled Nd:YAG laser (Continuum Minilite I, 532 nm, 5 ns, 10 Hz) and a converging lens irradiated the target (copper wire). The lens focused the laser beam on the copper wire, into a spot with a diameter close to that of the wire (100 μm), thus providing a roughly spherical irradiated volume. The irradiated wire generates sub-microsecond quasi-unipolar pressure pulses. Two XYZ translation stages adjusted the position in the cuvette of the source and the piezoelectric sensor, respectively. The detection system output was digitized by an oscilloscope (Tektronix TDS 2024, 2 GS/s, 200 MHz) and processed on a personal computer. The oscilloscope trigger signal was obtained from the laser Q-Switch pulse. The laser pulse energy was measured with a pyroelectric detector (Coherent LMP10).

Figs. 3 and 4 show the response of the detection system with TIA1 and TIA2 for a pressure pulse with a peak value of 485 Pa and duration of 10 ns. In Fig. 3, it can be seen that sensors A and B have a similar sensitivity whereas sensor C has a much lower value. This is due to the sensitivity whereas sensor C has a much lower value. This is due to the silver paint layer deposited over the detection active zone that causes a
Mismatch of acoustic impedance. Assuming plane waves, the reflection coefficient between water (1500 m/s, 1 g/cm$^3$) and silver paint (2550 m/s, 6.5 g/cm$^3$) is greater than 0.8.

The plots in Fig. 4 show that the detection systems with TIA2 have a higher sensitivity but the combination sensor A + TIA2 has a very poor signal to noise ratio (SNR).

In order to study the main noise source of the detectors, we repeated the same measurements but using air as an acoustic coupling medium. This way, the captured noise is mostly electrical. Figs. 5 to 7 show the responses of the detection systems using deionized water (dashed blue line) and air (solid green line). Curiously, the noise with the detector immersed in water has always larger amplitude than in air. The results suggest the electrical properties of water play an important role. In the case of sensor A, the difference of noise amplitude between air and water is higher than the obtained values with sensors B and C. Moreover, in detector C, the difference is almost negligible. The behavior of sensors B and C with TIA1 is similar to that shown in Fig. 6. The spectrum of the signal obtained with sensor A + TIA2 in water shows a strong peak around 100 MHz (see Fig. 8). Kreyrouz and Caratelli [7] studied antennae embedded in dielectric media and found the resonance frequency strongly depends on the permittivity of the media. Since our detector resembles such an antenna, we applied the formulae derived in ref. [7] and computed, in the case of the cylindrical cuvette filled with water, a resonance frequency around 100 MHz. This value is quite inconvenient because many FM stations populate the electromagnetic spectrum in the 88-108 MHz range. The OA system determines the size of the detector and the cuvette; thus, this resonance frequency can hardly be changed. Interestingly, the otherwise desirable characteristics of a dielectric-embedded antenna, turn out to be detrimental in this case. Therefore, a good electrical shielding is mandatory if low NEP is sought. It can be seen, in Figs. 6 and 8, how the effects of this phenomenon can be reduced by shielding the detector as much as possible (~ -60 dB at 100 MHz).

Table I presents a summary of the main results obtained in this section. The detection system integrated by sensor B with TIA2 has high sensitivity, large bandwidth and a very low noise equivalent pressure (NEP) value in comparison with the detection systems studied in this work and also with other transducers reported in the literature [8]-[10]. For example, the best report in [10] presents a spectral density NEP of 0.2 mPa/Hz$^{1/2}$ (spherically focused piezoceramic, Olympus NDT panametrics), whilst our best
result (detector B + TIA2 using NEP*) amounts to 0.14 mPa/Hz^{1/2}.

Finally, in order to verify the repeatability of the method, of type B and we obtained similar results (± 10 %).

![Fourier spectrum of noise of sensors + TIA2.](image)

**Fig. 8. Fourier spectrum of noise of sensors + TIA2.**

**TABLE I**

| Sensor A | Sensor B | Sensor C |
|----------|----------|----------|
| Sensitivity (μV/Pa) TIA1 | TIA2 | TIA1 | TIA2 | TIA1 | TIA2 |
| Bandwidth (MHz) | 20 | 63 | 19 | 62 | 20 | 60 |
| NEP (Pa) in water | 24 | 260 | 13 | 3.0 | 7.0 | 22 |
| NEP (Pa) in air | 3.4 | 30 | 0.8 | 2.5 | 6.0 | 20 |
| NEP* (Pa) in water | 4.0 | 43 | 0.20 | 1.1 | 0.90 | 3.0 |
| NEP* (Pa) in air | 0.50 | 3.5 | 0.10 | 0.40 | 0.80 | 3.0 |

III. APPLICATION TO OAT

In order to compare the performance of the detection systems I (sensor A + TIA1) and II (sensor B + TIA2), we used them in the 2-D OAT described in ref [4]. Fig. 9 shows the experimental setup scheme. The sensor and the sample were immersed in a control volume filled with deionized water. The water temperature was measured with a calibrated thermocouple. This makes possible to determine accurately the speed of sound in water. A Nd:YAG laser with second harmonic generation (Continuum Minilite I, 532 nm), 5 ns pulse duration, 10 Hz repetition rate and pulse energy less than 1 mJ , was used as the light source. A diverging lens adapts the diameter of the laser beam to a size larger than the sample, trying to achieve an homogeneous illumination. The ultrasonic detector was fixed and pointed to the center of the rotating sample stage using a XYZ translation stage. Phantoms were fixed on the sample stage and rotated (Newport PR50CC) through 360 degrees. Full view data (360 degrees) minimizes the effect of a limited view detection [11]. OA signals were recorded every degree and, at each angle, averaged 64 times.

The sample consists of a transparent film embedded in agarose gel. On the film was drawn the pattern (Fig. 9) with a laser printer. The pattern is a set of pairs of black disks (100 μm of diameter) at different distances. The agarose gel was prepared with 2.5 % (w/v) agarose in distilled water. First, a cylindrical base of the agarose gel with a diameter of 15 mm and a height of approximately 25 mm was prepared. Then, the object (transparent film) was placed in the middle of the cylinder and fixed with a few drops of the gel. Finally, another layer of gel with a thickness of 1 mm was formed on top of the sample object.

The projections of the initial pressure distributions into the xy plane were obtained using the backprojection algorithm described in ref. [12].

![OAT system scheme used to assess the detection system performance.](image)

**Fig. 9. OAT system scheme used to assess the detection system performance.**

![Reconstructed image for the detection system integrated by sensor A and TIA1.](image)

**Fig. 10. Reconstructed image for the detection system integrated by sensor A and TIA1.**

![Reconstructed image for the detection system integrated by sensor B and TIA2.](image)

**Fig. 11. Reconstructed image for the detection system integrated by sensor B and TIA2.**
Figs. 10 and 11 present the reconstructed images for the detection systems I and II. From the figures and taking into account the separation between the discs, the resolutions of the systems I and II are 195 ± 10 μm and 100 ± 10 μm, respectively.

IV. CONCLUSION

In this work we studied how to reduce the noise floor of a piezoelectric sensor presented in a previous paper [3]. It was found that the sensor in conjunction with the acoustic coupling medium (water) behaves as a resonant dielectric antenna. This phenomenon limits the performance of the system because it helps capturing unwanted signals. From the analysis of the tests, a silver-paint based electrical shield was deposited on the detector. As a result, the new sensor has very low noise. This improvement allowed the optimal use of a TIA with high gain and large bandwidth. The result was a broadband detection system (~60 MHz), high sensitivity (~1600 μV/Pa) and very low equivalent noise pressure (~1 Pa). Moreover, the system performance was tested in a 2-D OAT obtaining better resolution.

The improved detection system offers an easy-to-implement, high repeatable and low-cost option that is suitable for LED-based OAT. Furthermore, the sensor size can be increased in order to obtain images of larger samples using the method detailed in ref. [13], which permits increasing the active detection area without reducing the bandwidth or the sensitivity. Moreover, the sensitivity of the system can be increased by using a focused transducer [14], which can be implemented simply by adjusting the sensor’s substrate shape.

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