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Optimization of Ferroelectret Transducers for Pulse-Echo Water Immersion Operation

Julio Quirce Aguilar[1], Tomás Gómez Álvarez-Arenas *Member, IEEE*[1]
Ultrasonic and Sensors Technologies Dept.
[1]Instituto de Tecnologías Físicas y de la Información, CSIC,
C/Serrano 144, Madrid 28035, Spain.
j.quirce.aguilar@gmail.com, t.gomez@csic.es

***Abstract*—The adaptation and optimization of polypropylene ferroelectret (FE) films as the main piezoelectric element for water immersion ultrasonic transducers is studied. One of its main features is that they present a very wide band response so they can be an alternative for certain medical applications, especially those demanding intermediate frequencies and reduced size. The main problems of using this kind of materials are the poor sensitivity and the weak bonding of the metallization to the FE film that is easily degraded when entre in contact with water. The objective of this work is to optimize FE transducers for pulse-echo water immersion, while preserving the bandwidth, by: i) protecting the surface and ii) improving the impedance matching to the water.**

Metallization degradation produced by water has been quantified, then, main materials requirements to produce matching layers for this application are reviewed and potential materials to produce them proposed. A procedure to reinforce the metallization while preserving the electromechanical film response is proposed (based on Au sputtering) and first prototypes of transducers with a single matching layer are proposed, built and characterized.

***Keywords*— Transducer, Ferroelectret, Matching Layer, Water inmersion.**

I. Introduction

The electromechanical polymeric film called ferroelectrec was introduced in the late 80's (see Refs. [1], [2] and [3]). It is a cellular polymer filled with air that can be electrically charged [4], where the cells end up comprising electric dipoles oriented along the thickness direction (see figure 1. c) that can be rather stable. Thanks to the very low elastic modulus of this cellular structure this material presents a measurable piezoelectric response. Different applications of this material have been proposed, such as air-coupled transducers [5], [6] and [7], active matching layers [8], wearable sensors [9], energy harvesting [10]. They have also been tested as transducers for water immersion and medical imaging [11], where the very wide band response obtained at intermediate frequencies and the possibility to miniaturize the transducer are quite promising features for different medical applications.

The main problems in using FE films for water immersion transducers are that the sensitivity is too low, and the FE metallization is easily degraded. This metallization is obtained by evaporation of a thin film of Al, and it has poor stability when film is bended, touched or enter in contact with water.
This fact gives rise to two main problems: i) film manipulation must be performed very carefully, ii) water immersion where water is in direct contact with the Al metalized surface is not possible as the conductivity is rapidly degraded. In both cases electrical conductivity in the outer transducer electrode is lost.
Two main solutions can be adopted to deal with this problem: i) to apply a wear plate or some impedance matching layers, ii) to apply a more resistant conductive coating. Option 1, specially the use of impedance matching layers, can be considered the most convenient, as the use of impedance matching layers is required to solve the problem of acoustic impedance mismatch between the ferroelectret film and the water. However, the Al coating can be degraded even in the process of attaching or fixing the matching layers or the wear plates, therefore, it is necessary to identify a suitable process to stabilize the outer electrode before any further manipulation.

II. Materials

The FE film used in this study is produced by the company EMFIT. Characterization of the films is performed by the non-contract ultrasonic resonant spectroscopy method presented in Ref. [12]. Thickness is 70 um, density 550 Kg/m3 and it presents a halfwave resonance at 645 kHz. One side of the film is metalized (Al) and the other one it is not. Figure 1 shows both sides and a micrograph of the cross-section, obtained by SEM of the fractured section immersed in liquid nitrogen.

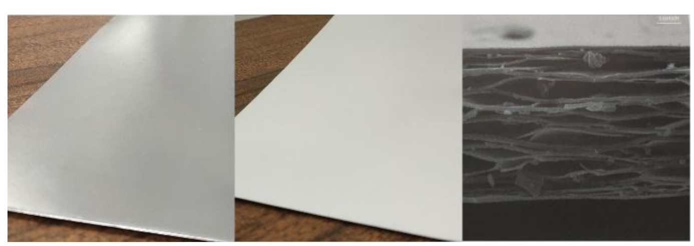

Fig. 1. Metalized side of ferroelectret (left),Non metalized side (centre), Cross-section SEM micrograph (right).

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For the matching layers and wear plate epoxy resin loaded with microspheres were used. Two kind of microspheres, were tested: the first one with density = 30 kg/m^3 and diameter 50~85 um and the second one with density = 70 kg/m^3 and diameter 15~30µm. The first one allows us to achieve lower densities (and hence lower acoustic impedances) although the diameter of the microspheres is higher, and this may limit the capability to produce thin layers out of this material and, therefore, to tune these layers to high frequencies.

Finally, to reinforce the Al electrode, gold was deposited over the Al film by a conventional sputtering technique.

III. Transducer design and fabrication.

Figure 2 shows a cross section of the proposed transducer design. The cable is welded from the SMB connector fitted on the back of the transducer (1) to the vertex of the brass cone (2) backing ending with cylindrical shape (3). The backing is glued to the housing using nonconductive epoxy (4). Then the FE film (5). is cut using a puncher to get a circular piece with larger diameter, 20mm, than the cylindrical brass backing The FE is glued with a thin film of adhesive (6) to the backing (3). To make the mass connection we place an aluminium crown (8). One matching layer/ wear plate is shown in the design (7).

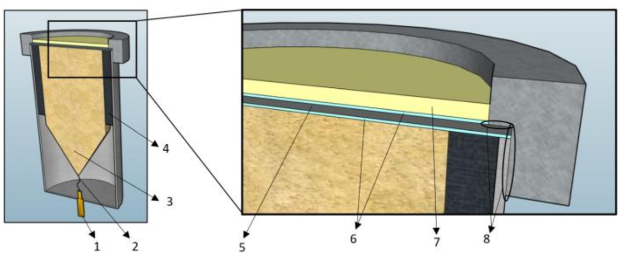

Fig. 2. Cross section view of transducer design (left) and detail of the connections (right)

IV. Matching layer design

The required impedance of each layer in a N-stack of quarter-wavelength matching layers to obtain optimum transmission is calculated by Eq. (1), where Z denotes the acoustic impedance of a layer and the subindex is the order of this layer in the stack. In this case, Z_1 is the ferroelectret layer and Z_N is water.

$$Z_n = \sqrt{Z_{n-1} Z_{n+1}}, n = 1, 2, 3, .. N \qquad (1)$$

Hence, for or one ML, the required impedance of the quarter-wavelength layer is given by Eq. (2), while for a stack of two matching layers, the required impedances are shown in Eqs. (3) and (4).

$$Z_{ML} = \sqrt{Z_{FE} Z_{water}} = 0.26M\ Rayl \qquad (2)$$

$$Z_{ML1} = \sqrt{Z_{FE} Z_{ML2}} = 0.14M\ Rayl \qquad (3)$$

$$Z_{ML2} = \sqrt{Z_{ML1} Z_{water}} = 0.46MRayl \qquad (4)$$

MLs were manufactured by mixing a low viscosity epoxy resin with microbubbles (apparent density of 30 kg/m^3). Highest possible load of microbubbles were achieved by adding a mass concentration of 12%-15%, beyond that level of load it was not possible to achieve an homogeneous mixture using conventional mixing methods. The composite is placed in a mould and let to cure for 16 h. Once cure, the sample was removed, polished and characterized by the same non-contact resonant ultrasonic spectroscopic technique. Velocity, attenuation coefficient and impedance were obtained. Velocity figure is used to calculate the thickness of the final matching layer. We always tune the matching layers to 1 MHz. Lowest achieved impedance was about 0.8 MRayl, still too high for this application. Nonetheless, the samples were used to produce and attach the matching layers to check the consistency of the whole process.

V. Transducer characterization.

Transducers were characterized by three different techniques: Firstly, by analyzing the surface vibration by a laser vibrometer (Polytech), that scans the transducer surface and provides surface displacement with time.

Secondly, by measuring the pulse-echo response in air, mainly to determine the integrity of the metallization and the effect of any reinforcement of this metallization.

Thirdly, by pulse-echo in water immersion. In this case, a steel reflector located at 43mm using the Olympus pulser / receiver model 5072P/R, frequency: 1 MHz, pulse amplitude: 400 V, damping 40 ohm, gain: 59 dB, Low Pass Filter: 10 MHz. Depending on the orientation of the transducer the signal response change being the biggest one when the radiating area is parallel to the steel reflector. In this work, normal incidence is used so, in order to place the transducer in the optimum position a two-axis support has been designed with two steppers controlled by Arduino UNO through MATLAB taking the amplitude signal information from the oscilloscope. The stepper model used is 28BYJ-48 with a stride angle of 5.625º/64. Figure 3 shows a schematic of the positioning device.

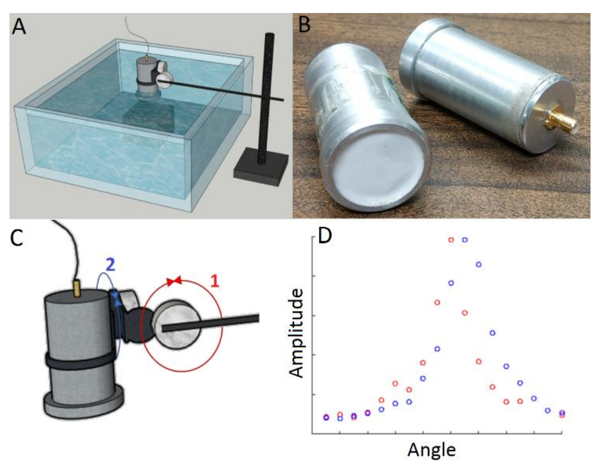

Fig. 3. Schematic representation of the experimental set-up for positioning the produced prototype transducer for water immersion pulse-echo characterization.

VI. Results and Discussion

A. Analysis of electrode degradation.

The influence of the electrode degradation in contact with water was studied and quantified. Transducers with and without matching layers/wear plates and Au reinforcement were put in water for 7 hours and the echo received from a steel reflector at 2 cm recorded. Figure 5 shows the evolution of the normalized peak to peak amplitude of the echo with time of immersion for two different cases (no protection and one matching layer). The fast degradation of the electrode of the unprotected transducer is clearly seen.

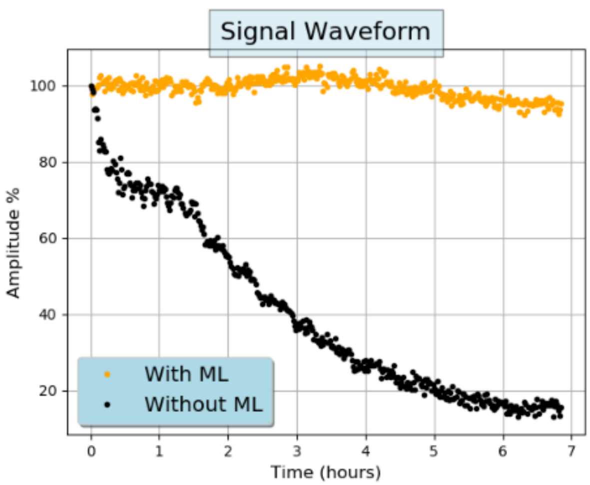

Fig. 4. Variation with time of immersion of the normalized echo amplitude for two prototype transducers: Transducer with unprotected Al metallization and transducer with one matching layer

B. Surface vibration displacement.

Mapping of the surface vibration with the laser vibrometer were performed in order to verify the homogeneous gluing of the FE film to the substrate and of the matching layers. Figure 5. shows the measured amplitude along one surface diameter. Pulse excitation where used.

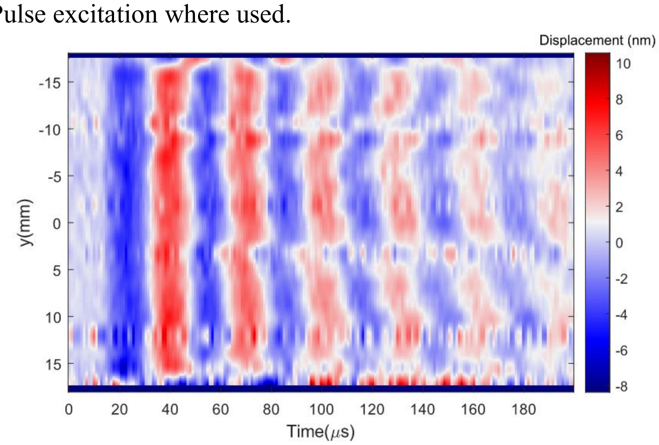

Fig. 5. Time evolution of the transducer surface displacement measured along one of the radiating surface diameters. Pulse excitation

C. Al electrode reinforcement with Au.

The stability of the electrical charge trapped in the pores of the ferroelectret film cellular structure is quite poor and easily affected by variations in temperature or ambient pressure [13]. Therefore, the ferroelectret film electrical polarization is easy lost during the process of applying another conductive coating. However, good results were obtained when an electrically conductive coating was applied to the radiating surface of the transducer before applying any wear plate or matching layers, that is, under these conditions the coating is applied directly over the Al electrode. A custom sputtering deposition system (at ISOM CSIC-UPV) was used to deposit a thin layer of gold on the Al electrode. Sputtering time was changed from 80 to 60 s to achieve different thicknesses of the Au layer. The current intensity applied was always 30 mA and the deposition was performed under a stable atmosphere of Ar after a pre-vacuum of 10^{-4} mbar. By this procedure, it was possible to achieve both a recover of the electrode conductivity (in the case of already degraded electrodes) and a full electrode integrity against contact with water or any glue employed to fix matching layers. In addition, transducer performance was not affected by the sputtering process, so we conclude that the ferroelectret polarization is no compromised during the sputtering process.

The thickness of the Au layer deposited and the preservation of the film polarization after the deposition is determined from the measurement of the spectral response of the transducer in pulse-echo mode operated in air. In the case of air-operation the ferroelectret film response corresponds to a quarter wavelength resonance and is very sensitive to any mass deposited on the front face. In particular, the thickness resonant frequency shifts towards lower values as the deposited mass increases. For a large amount of added mass there can also be a decrease of sensitivity. Clearly, any loss of trapped dielectric charge in the ferroelectret foam will show up as a decrease of the transducer sensitivity. These measurements were performed using an Olympus 5058 PR and a digital scope Tektronix 5054. Results for the transducer without Au and transducers after 30s sputtering time and 60 s sputtering time are shown in Fig 6.

Quantification of the thickness of the Au layer deposited, the measured transducer response is compared with the calculated one, where the thickness of the Au layer is used as a fitting parameter. Results are shown in Fig. 7. Comparison of figs. 6 and 7 reveals that the thickness of the Au layer sputtered is about 80 nm.

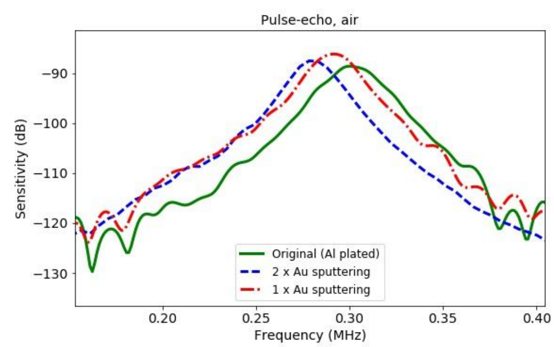

Fig. 6. Measured spectra of the pulse-echo response of the transducer in air. Original transducer and transducers with 1x 30 s sputtering of Au, and 2x 30 s sputtering of Au.

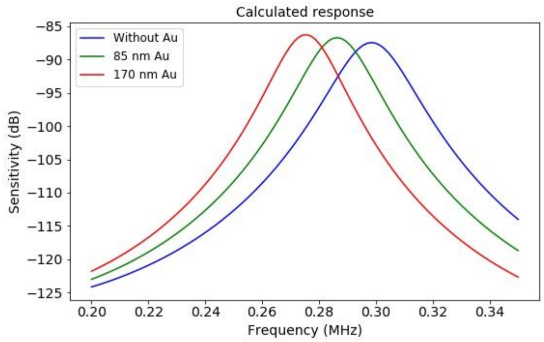

Fig. 7. Calculated spectra of the pulse-echo response of the transducer in air with different layers of Au deposited .

D. Influence of matching layers.

In addition to provide a protection to the outer electrode, matching layers are expected to improve sensitivity and modify bandwidth. Although achieved matching layer materials impedance is still very large, it is of interest to determine how do they affect the transducers.

Figure 8 shows a comparison of a transducer with and without matching layer.

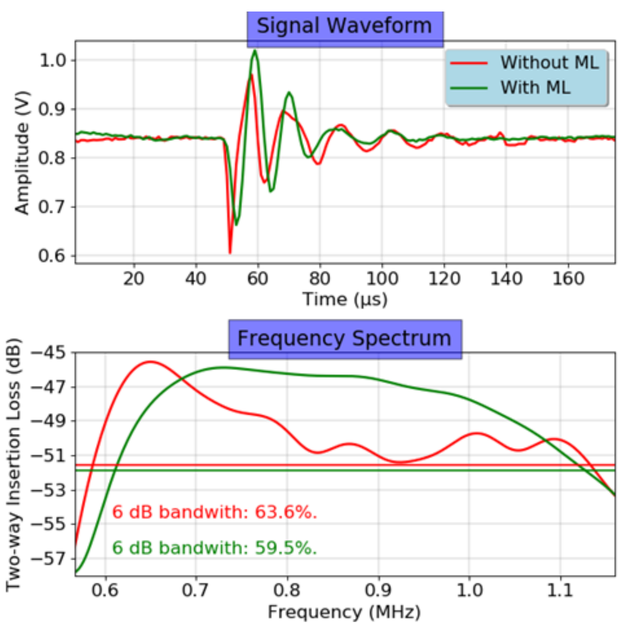

Fig. 8. Measured pulse-echo response in water immersion of transducers with and without matching layer. Up: impulse response. Bottom Spectra. The +40 dB Gain in the pulser receiver are not considered in the figure, so actual peak sensitivity is about -96 dB.

VII. CONCLUSIONS

The main drawbacks to use ferroelectret transducers in water immersion are the poor sensitivity and the poor stability of the transducer response. In this paper, we have verified that this poor stability is due to the Al electrode degradation when it enters in contact with water. Several prototypes of ferroelectret based transducers for water immersion have been produced and tested. Laser vibrometry scanning of the radiating surface revealed a quite homogeneous response that validates the fabrication routes employed for this prototype. Moreover, we have shown that it is possible to the deposit an extra layer of Au (by sputtering) whose effect on transducer response is minimal but that provides efficient protection of the Al electrode. Finally, the requirements for matching layer have been reviewed and some materials have been fabricated trying to meet these requirements by using syntactic foams. However, achieved impedances are still well beyond the expected values. Nonetheless, prototype transducers have been built employing these matching layers and it has been possible to improve the frequency band, though no significant improvement of the sensitivity has been achieved.

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