Ferroelectret Transducers for Water Immersion and Medical Imaging.

Tomás E. Gómez Álvarez-Arenas and Luis Díez
Institute of Physical and Information Technologies.
Spanish National Research Council (CSIC)
Madrid, Spain
t.gomez@csic.es

***Abstract*—This paper investigates the possibility of using ferroelectret films to produce wideband ultrasonic transducers for applications in water immersion and medical imaging. Ultrasonic transducers with different sizes (apertures) were fabricated using a polypropylene ferroelectret film (0.6 MHz thickness resonant frequency) as active component. Then, they were characterized in pulse-echo operation mode in water immersion. Fabricated transducers show a useful frequency bandwidth from 0.3 to 2.5 MHz with a 6 dB relative bandwidth of 175% and minimum two-way Insertion-loss of -65 dB that depends on transducer active area. The use of matching layers to improve the Insertion loss figure is also investigated. Finally, the application of these transducers to discern between different echoes coming from layered reflectors is tested, in particular, the simple case of a rubber plate attached to a steel reflector is studied. Pulse-echo mode and both time domain and resonant frequency domain techniques have been tested and discussed, in relationship with the possibility of using this technique to determine thicknesses of the different layers in a layered reflector, which is a problem commonly found in different medical applications.**

Keywords—ferroelectret transducers; ultrasonic transducers; water immersion; pulse-echo;

I. INTRODUCTION.

Ferroelectrets are porous polymeric films with elongated pores in the film plane that give rise to a very low stiffness in the thickness direction, while stiffnesses in the plane directions are much higher and closer to that of the bulk polymer. These pores can be electrically charged, creating macroscopic electric dipoles oriented along the thickness direction. These two features (permanent and stable polarization and very low stiffness in the thickness direction) give rise to a measurable piezoelectric-like response of the film in the thickness direction as presented in [1] and [2]. These features have been used before in applications of ferroelectret (FE) films as pressure sensors, air-coupled transducers [3]-[6], skin-attachable transducers for blood pressure monitoring [7] and patch transducers for Lamb waves [8]. However, FFs have not been used before to produce water coupled ultrasonic transducers, probably for the large impedance mismatch between the FE film (0.04 – 0.08 MRayl, [9]) and the water (1.45 MRayl), for the necessity to isolate the film porous structure from the water and for the believe that the water load is too heavy for the FE film.

On the other hand, conventional piezoelectric transducers present some limitations to produce small, wideband and low frequency transducers. These transducers are of interest for materials characterization/diagnosis and medical imaging in cases where transducer size is a critical design parameter, and wide frequency band and relatively lower center frequencies are needed. This can be the case when attenuation coefficient is very large or when resonant and spectral techniques are to be used. FE films offer a significant flexibility in order to fabricate small ultrasonic transducers in the low MHz frequency range. However, the main disadvantage is that the acoustic impedance of FE is very low (< 0.1 MRayl) and so the impedance mismatch with water and human body is very large. This fact contributes to reduce both transducer sensitivity and bandwidth which can compromise the use of this technology in these cases. The purpose of this paper is to produce some FE film based transducers and test them to investigate if these transducers can be useful for water immersion and medical imaging applications.

II. TRANSDUCER MATERIALS AND DESING.

A. *Transducer materials*

The FE film employed to build the transducers was purchased from Emfit (HS03), thickness 70 μm and density 550 kg/m^3; this film presents one aluminum plated surface. The film was first characterized by the technique presented in [9]. We obtained that the first film thickness resonant frequency ($\lambda/2$) is located at 645 kHz and acoustic impedance is 0.045 MRayl. In some cases, a thin layer of Polymethyl methacrylate (PMMA) was then spin coated on the radiating surface (Al plated surface) to protect the metallization and to avoid any water percolation into the porous structure of the FF. A 5% solution of PMMA (molecular weight 950000) in Anisole has been used. To match the acoustic impedance of the transducer to the water we propose the use of quarter wavelength ($\lambda/4$) matching layers. The ideal value of the acoustic impedance (Z) for the material to build the matching layer is about 0.26 MRayl. Other requirement for the $\lambda/4$ impedance matching layer material is that it must be water resistant. For this purpose, we fabricated a low density composite made of a resin matrix and hollow spheres. Composite density (ρ) is 350-400 kg/m^3, acoustic impedance (Z): 0.4-0.5 MRayl and water absorption after24 hours < 3%. Plates were fabricated out of this composite, the thickness of the plates is set so that the plate thickness resonant frequency ($\lambda/4$) is tuned within the frequency band of the unmatched transducer.

B. Transducer desing and fabrication

Three different designs were used for the fabrication of the transducers, the only difference being the transducer size and aperture. Three different aperture were employed (all of them circular) with diameter of 22, 17 and 10 mm.

First, a ferroelectret film disk is cut from the original foil with a diameter slightly larger than the transducer aperture. The Al plated surface will be the transducer radiating surface; consequently, the non electroded surface of the FE film disk is glued to a steel back plate that is also used as one of the transducers electrodes. Hence, the FE film will present a $\lambda/2$ thickness resonance, so the expected transducer resonant frequency is 645 kHz. The plate with the FE film is then mounted on a cylindrical aluminum housing using a circular rim which is in contact with the edge of the radiating surface that is also used as electrical connection. The length of the cylindrical housing is made larger than needed to facilitate the handling of the transducers. Finally an SMB connector is fitted on the back of the transducer. Pictures of two of the 10 mm diameter fabricated prototypes are shown in Fig. 1.

The possibility of applying a thin film of PMMA on the FE film has also been investigated. The objetive is to protect the electroded surface of the FE film. The film was deposited using a spin coating system. Neither the electrode nor the FE film response were negatively affected by the PMMA film deposited by this technique.

Matching layers were fabricated as standalone thin plates that were later attached to the transducer radiating surface using a commercial gel couplant.

III. TRANSDUCER CHARACTERIZATION.

Transducers were first characterized in water immersion and in pulse-echo mode using an Olympus 5058 pulser/receiver (pulse amplitude: 900 V, gain 40 dB, damping: 500 Ω). Figs. 2-3 show the results obtained for the 22 mm aperture transducer with a steel reflector located at ~60 mm.

Fig. 1. Picture of the two 10 mm diameter prototypes of water immersion transducers using FF film (left: front face, right: rear face with SMB connector).

Figure 2 shows the received echo with a peak to peak amplitude of 200 mV and signal to noise ratio (SNR) of 42 dB. Fig 3 shows the Fast Fourier Transform (FFT) of this echo, with a peak response at 0.4 MHz and a significant sensitivity loss at 666 kHz, which coincides with the film $\lambda/2$ resonant frequency. This is the most unexpected result as peak sensitivity was expected at this frequency. Finally, the two-way insertion loss figure is calculated as the ratio of the Fast Fourier Transform (FFT) of the echo received from the reflector to the FFT of the electrical signal applied to the transducer terminals, result is shown in Fig. 4. A 40 µs rectangular temporal window was used for the FFT calculations in this case. Peak sensitivity is about -65 dB at 1.2 MHz, and 6 dB bandwidth is 175%.

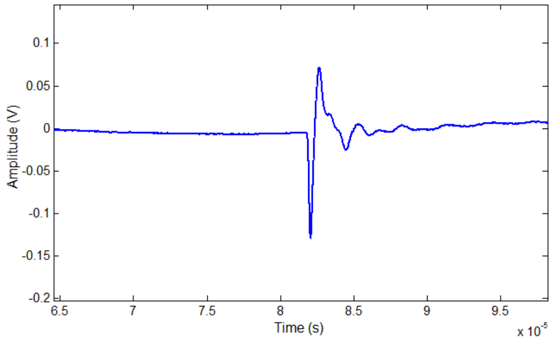

Fig. 2. Transducer impulse response response in pulse-echo mode in water immersion in the time domain.

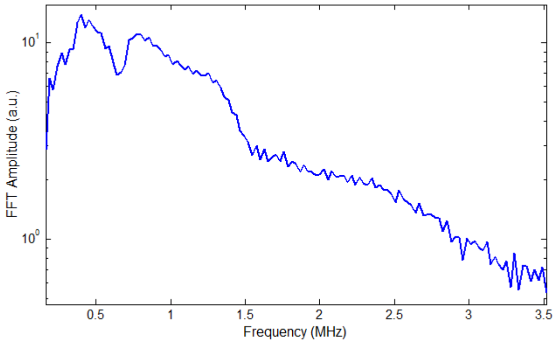

Fig. 3. FFT of the echo in Fig. 2.

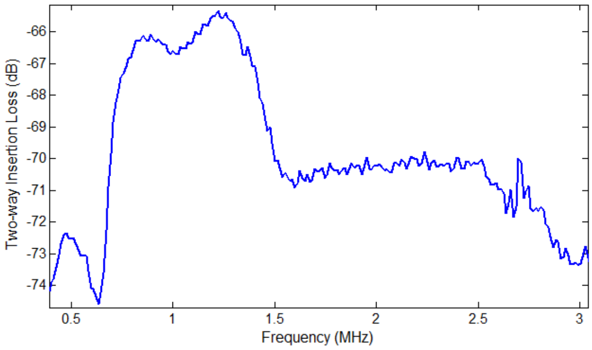

Fig. 4. Two-way insertion loss vs frequency.

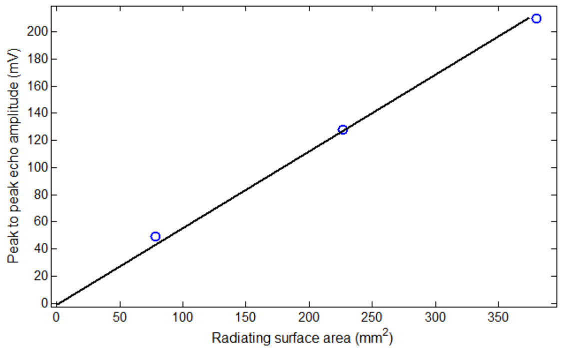

Fig. 5. Peak to peak amplitude of the reflected echo vs transducer radiating surface area for the three different transducer desing tested (transducer circular aperture and diameter of 22, 17 and 10 mm, respectively). Solid line represent a liner fitting.

Similar results were obtained with the 17 and 10 mm aperture transducer, with the only difference that the smaller the aperture, the smaller the received peak to peak echo amplitude. Figure 5 shows the variation in the echo peak to peak amplitude with the FE film section for the three different transducer sizes studied: 22, 17 and 10 mm. These measurements were obtained using the same pulser/receiver configuration as before and a steel reflector located at 32 mm from the transducer.

By attaching the matching layer to the transducer radiating surface we obtained no improvement in the transducer sensitivity or in the echo peak-to-peak amplitude. Different matching layers, tuned to different frequencies within the transducer band (0.7-1.5 MHz) were produced, but no improvement was observed in any case.

IV. APPLICATION TO PLATE MEASUREMENTS IN PULSE-ECHO MODE.

Pulse-echo measurements were repeated by attaching ruuber plates of different thicknesses to the steel reflector in order to determine the possibility to discern between the echoes coming from the two different interfaces (rubber /water and rubber / steel) both in the time and in the frequency domain. This can be used either to determine ultrasound velocity in the plate or plate thickness which is a problem commonly found in materials characterization and in medical diagnosis, like in the case of cornea and artery wall thickness measurements. Measurements in the time domain require that pulse length must be smaller than the time of flight in the rubber plate, while measurements in the frequency domain require that some orders of the rubber plate thickness resonances appear within the transducer frequency band. A rubber plate with an acoustic impedance close to that of the water was selected in order to test the efficiency of the transducers to detect the small reflection coming back from the water / rubber interface. Ultrasound velocity in the rubber plates is 1550 ± 50 m/s and density 1120 kg/m^3.

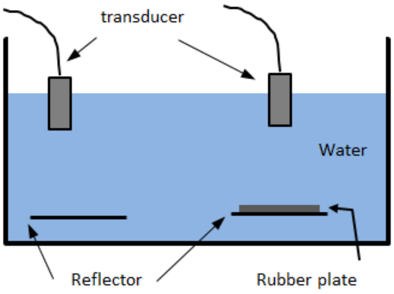

Fig. 6. Schematic representation of the experimental set-up.

Two rubber plates (1.05 and 2 mm thick) where attached to the steel plate reflector (see Fig. 6) using a commercial ultrasonic coupling gel and the received echo was recorded as it was done before. In this case, we used the 22 mm diameter transducer. Received echoes are shown in Fig. 7. Now, the echo is composed of two main contributions: the echo coming from the water / rubber interface (first arrival) and the echo coming from the rubber / steel interface (see Fig. 7), which appear delayed a time we denote as Δt. In both cases, the echoes coming from the water / rubber and the rubber / steel interfaces appear separated in the time domain so that it is possible to measure Δt, we obtained: 1.4 µs and 2.5 µs. Assuming a velocity of 1550 ± 50 m/s in the rubber, plate thickness can be estimated from the ultrasonic measurements: 1.085 ± 0.035 mm and 1.94 ± 0.06 mm, respectively, that agrees well with nominal values.

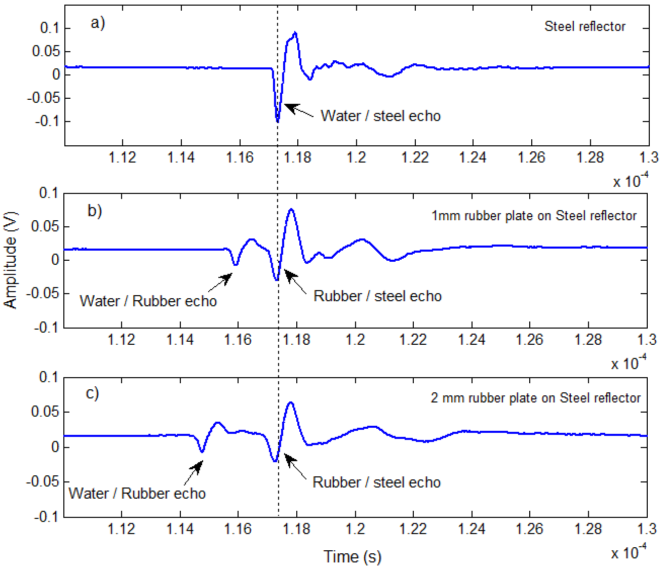

Fig. 7. Received echo from: a) the steel reflector, b) the 1 mm rubber plate placed on the steel reflector c) the 2 mm thick rubber plate on the steel reflector.

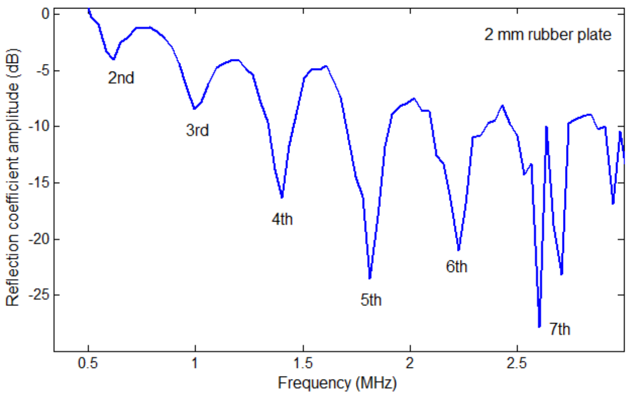

Fig. 8. Amplitude of the reflection coefficient of the 2 mm thick rubber plate attached to the steel reflector (normalized to the amplitude of the echo received from the steel reflector without the rubber plate).

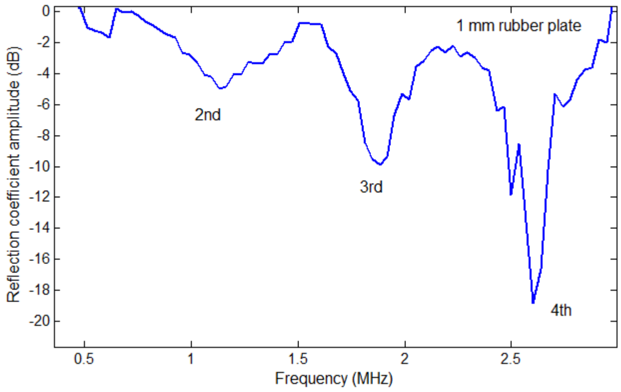

Fig. 9. Amplitude of the reflection coefficient of the 1 mm thick rubber plate attached to the steel reflector (normalized to the amplitude of the echo received from the steel reflector without the rubber plate).

The interference between these two echoes give rise to a set of thickness resonances of the rubber plate (f_n) that are located at v/(4t) × (2n-1), where n = 1, 2, 3, 4, ...

Measured amplitude spectrum of the reflection coefficient for the 2 mm thick rubber plate are shown in Fig. 8. Resonances (2nd to 7th order) are located at: 612, 993, 1404, 1815, 2226 and 2602 kHz, so obtained thickness of the rubber plate from these ultrasonic measurements is 1.93 ± 0.02 mm.

Measured amplitude spectrum of the reflection coefficient for the 1 mm thick rubber plate are shown in Fig. 9. Resonances (2nd to 4th order) are located at: 1.13, 1.883, and 2.602 MHz, so obtained thickness of the rubber plate from these ultrasonic measurements is 1.033 ± 0.008 mm.

V. DISCUSSION AND CONCLUSIONS.

Results obtained show the possibility to produce ultrasonic transducers for water immersion applications based on ferroelectret films. The 6 dB pulse-echo bandwidth of the transducer without matching layers is very large (175%) which allows for a good spatial resolution and wide spectrum analysis. Resonances between 0.5 and 2.7 MHz have been observed in rubber plates, which can be used for a characterization of the properties of the plate or to generate an ultrasonic image.

The peak-to-peak echo amplitude varies linearly with the area of the FE film. This feature has to be considered if small transducers are to be designed and build.

The use of matching layers presented no advantage. The reason is probably due to the layer of gel coupling between the FE film and the matching layer. Future designs will consider the possibility to fabricate the matching layer directly on the FE film so that this gel coupling layer is avoided. Finally, the transducers present a reduced insertion loss figure at low frequencies and at 650 kHz. It is expected that these features could be improved by using a better electrical matching between the transducer and the pulser/receiver.

REFERENCES

[1] K. Kirjavainen, Electromechanical film and procedure for manufacturing the same, US Patent No. 4654 546, 1987.

[2] G. M. Sessler and J. Hillenbrand, “Electromechanical response of cellular electret films,” *Appl. Phys. Lett.*, vol. 75, no. 21, p. 3405, 1999.

[3] M. Wegener, E. Tuncer, W. Wirges, R. Gerhard-Multhaupt, M. Dansachmuller, S. Bauer-Gogonea, R. Schwodiauer, and S. Bauer, “Ferroelectrets: highly anisotropic electrically charged polymer foams for electromechanical transducer applications,” *IEEE Ultrason. Symp. 2004*, vol. 62, no. c, pp. 1138–1141, 2004.

[4] J. Döring, J. Bartusch, U. Beck, and A. Erhard, “EMFIT Ferroelectret Film Transducers for Non-Contact Ultrasonic Testing,” in *ECNDT*, 2006, pp. Tu.1.7.1, 1–10.

[5] J. L. Ealo, J. Camacho, C. Fritsch, F. Seco, and J. Roa, “A fabrication procedure for airborne ultrasonic phased arrays based on cellular electromechanical film,” *2008 IEEE Ultrason. Symp.*, pp. 891–894, Nov. 2008.

[6] T. E. G. Álvarez-Arenas, “Air-coupled piezoelectric transducers with active polypropylene foam matching layers,” *Sensors (Switzerland)*, vol. 13, no. 5, pp. 5996–6013, 2013.

[7] E. Hyun, S. Noh, C. Yoon, and H. C. Kim, “Patch type integrated sensor system for measuring electrical and mechanical cardiac activities BT,” in - *2014 9th IEEE Sensors Applications Symposium, SAS 2014, February 18, 2014 - February 20, 2014*, 2014, pp. 94–96.

[8] T. E. Gómez Álvarez-Arenas. " Patch transducers based on ferroelectret films for Lamb and Surface waves generation and reception " in *International Workshop on Acoustic Transduction Materials and Devices.* Pennsylvania State Univ. 10-12 May 2016.

[9] T. E. Gómez Álvarez-Arenas, H. Calás, J. E. Cuello, a. R. Fernández, and M. Muñoz, “Noncontact ultrasonic spectroscopy applied to the study of polypropylene ferroelectrets,” *J. Appl. Phys.*, vol. 108, no. 7, p. 074110, 2010.