MINIATURE HIGH FREQUENCY ARRAY TRANSDUCERS BASED ON NEW FINE GRAIN CERAMICS

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ABSTRACT

New fine grain ceramics have been developed for high frequency applications (i.e. 15 to 50 MHz). Modified lead titanate (MPT) and lead zirconate titanate (PZT) ceramics are prepared by either hydrothermal synthesis or hot isostatic pressing. Their fabrication is described, as well as results of microstructure analysis, which include pore size and grain size distributions.

The thickness mode piezoelectric, elastic and dielectric constants are measured and used as inputs for the design of 20 MHz linear array transducers with 32 elements of less than 100 μm width. The manufactured arrays are characterized in pulse echo operation and their centre frequency and bandwidth are compared to theoretical predictions. Finally, the radiation pattern of an element is measured and the effect of inter-element coupling is discussed. Performances are compared to those of PVDF-based transducers in view of intravascular imaging applications. The bandwidth is slightly lower but the sensitivity is much higher than those of PVDF devices. This is explained on one hand by higher coupling coefficients and on the other hand by lower electrical input impedances due to higher dielectric constants.

INTRODUCTION

Recently, high frequency ultrasonic imaging has been used in a number of applications. For medical examinations of superficial structures, such as the skin [1] and the anterior part of the eye [2], resolutions in the order of 100 μm are needed. In the case of intravascular imaging [3], the transducers must be small enough to penetrate into blood vessels of a few millimeters diameter. Such ultrasonic systems are also of interest for nondestructive testing of surface layers or small structures, in particular for the integrated circuit industry. Most imaging systems operating at frequencies over 15 MHz use a single-element transducer based on piezoelectric polymers or ceramics. Piezoelectric single crystal transducers, which are commonly used in acoustic microscopy, have rarely been integrated in real-time imaging probes because of their large size and weight. Systems based on array transducers have been developed for intravascular imaging, most of which use piezoelectric polymers. The sensitivity of such transducers is poor. This is due to both low coupling coefficients of polymers and to high electrical impedances induced by the very low dielectric constants of such materials.

The aim of this work is to develop piezoelectric ceramic array transducers operating at frequencies higher than 15 MHz. Thus the requirements are a fine grain size (<2 μm) and a low porosity. A modified lead titanate (MPT), characterized by a low planar coupling, and a lead zirconate titanate (PZT), characterized by a very high dielectric constant, were chosen. Microstructure analysis and electroacoustic measurements are performed before the materials are used to fabricate 20 MHz linear array transducers. Electrical, pulse-echo and radiation pattern characterizations are carried out and results are compared to theoretical predictions and to standard technology performances.

CERAMIC PREPARATION

Modified lead titanate

A hydrothermal synthesis process was used to obtain the P:T(5 m) powder with composition (Pb0.98Sm0.02)(Ti0.98Mn0.02)O3. The precursor for synthesis was prepared as described previously [4], by adding a mixed nitrate solution containing lead, samarium and manganese to a stirred suspension of TiO2 powder. After adjusting the pH to 10 with NaOH, the precursor was placed into an autoclave and synthesized at 290°C under 6MPa for 10 hours. The powder was then collected, washed repeatedly and dried in an oven at 80°C.

The powder was pressed into plates with dimensions 20 x 20 x 1.5 mm³ using a pressure of 95 MPa. The plates were sintered at 1200°C for 2 hours and then lapped to give parallel faces. Poling conditions were 100°C and 5KV/mm during 10 minutes.

Lead zirconate titanate

The PZT ceramics are prepared by a mixed oxide process [5] using a standard powder (Pz-21 from FERROPERRN, Denmark). After calcination the powder was milled for 2 hours to obtain a particle size of 0.4 μm. A binder was added and the powders were pressed into plates as for MPT. Sintering was carried out at 1240°C during 1 hour.
The plates were then hot isostatically pressed without encapsulation, at 1000°C, with a pressure of 50 MPa for 1 hour. The atmosphere was a mixture of 20% O2 and 80% Ar. Heating and cooling rates were 600°C/hour. The plates were lapped and poled as standard Pz-2.

CERAMIC CHARACTERIZATION

Microstructure analysis

The microstructures of these materials were examined by scanning electron microscopy. The ceramics were polished and thermally etched. Porosity measurements were made on polished surfaces and the grain size distributions were determined from thermally etched samples. Measurements were made using software based on IMCO 10 system (Kontron Electronic GMBH 1990) on, typically, 10 images for porosity measurements and on a total of 1000 grains for grain size determination. The grain sizes were calculated as equivalent diameters to a circular shape from the measured areas. Results are summarized in Table I and figures 1 and 2 represent micrographs of MPT and PZT respectively.

Table I: Microcharacterization results.

<table>
<thead>
<tr>
<th>Material</th>
<th>Average grain size (µm)</th>
<th>Std. dev. grain size (µm)</th>
<th>Average pore size (µm)</th>
<th>Porosity rate(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPT</td>
<td>1.8</td>
<td>1.4</td>
<td>5.1</td>
<td>8</td>
</tr>
<tr>
<td>PZT</td>
<td>1.8</td>
<td>0.9</td>
<td>7.8</td>
<td>1</td>
</tr>
</tbody>
</table>

Electroacoustic measurements

These measurements were carried out on discs machined out of plates at least 24 hours after poling. The relative permittivity \( \varepsilon_{33} \) and dielectric losses \( \tan \delta \) at 1 KHz were measured using an LCR meter. The piezoelectric \( \varepsilon_{33} \) coefficient was measured using a Berlincourt meter. The longitudinal velocity \( V_L \), coupling coefficients \( k_l \) and \( k_p \) were determined from electrical impedance curves measured on a HP 4195A impedance analyzer, according to IEEE standards [5]. The dielectric constant \( \varepsilon_{33} \) was determined at twice the thickness resonant frequency. Table II summarizes the results for both ceramics.

Table II: Electromechanical properties of ceramics.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \varepsilon_{33} ) (( \times 10^5 ))</th>
<th>( \tan \delta ) (%</th>
<th>( \varepsilon_{33} ) (pC/N) (m²/N)</th>
<th>( k_l ) (%)</th>
<th>( k_p ) (%)</th>
<th>( Z ) (MΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPT</td>
<td>182</td>
<td>1.1</td>
<td>412</td>
<td>40</td>
<td>48</td>
<td>5600</td>
</tr>
<tr>
<td>PZT</td>
<td>5020</td>
<td>1.8</td>
<td>2070</td>
<td>4050</td>
<td>44</td>
<td>450</td>
</tr>
</tbody>
</table>

MODELLING AND DESIGN OF ARRAYS

Electroacoustic behaviour

A model based on the KLM equivalent circuit [7] in which we have included frequency-dependant losses was used to calculate input electrical impedances, 50 Ohm loop sensitivity and -6 dB bandwidths of transducers.

Radiation patterns

Elementary and 32 element aperture radiation patterns were calculated by a Huygen’s principle-based model we have developed [8]. It considers the array as a single line of point-sources and point-receivers, and consequently is limited to lateral radiation patterns. Electrical cross-coupling can be taken into account through an apodisation factor affected to the neighbours of the considered element.

Array structure

The transducer consists in 32 elements with a pitch of 100 µm and an aperture of 30 µm. They are linear arrays and their transverse elevation is 3 mm. No mechanical focusing has been included. The transducer consists of a ceramic plate on a loaded epoxy backing and with an epoxy quarter wave-length layer, designed for acoustical matching to water, on the front
face. The elements are created by cutting through the matching and ceramic layers. An attenuating polymer material is then used to fill the gaps between the elements.

**CHARACTERIZATION OF ARRAYS**

Input electrical impedances are measured using the same analyzer as previously. The curves shown here are those obtained when the front face of the element is coupled to water.

The pulse-echo response of an element is measured in water using a large stainless steel flat reflector placed at 4 mm of the transducer's front face. A Panametrics 5052PR (35 MHz bandwidth) is used to generate pulses and to amplify echoes which are sampled by a digital scope (100 MHz bandwidth) and transferred to a micro-computer for frequency response determination. A 10 μH inductor is connected in parallel with the element under test to compensate for the imaginary part of the input impedance.

Elementary transverse radiation patterns are measured using similar equipment. The reflector is placed at 8 mm of the transducer, which corresponds to a typical focal distance for a 20 MHz transducer. A polar scan is obtained by rotating the transducer around its front face.

**RESULTS AND DISCUSSION**

**Input impedance**

Figures 3 and 4 show respectively the theoretical real and imaginary parts of the input impedance of one element of a PZT-based array. Figure 5 shows the corresponding experimental results. One can observe similar shapes for these curves. Differences in values of impedance are due partly to the fact that our model assumes that only thickness vibrations occur. Since the width of elements is here in the same order than the thickness, this assumption in not correct. Indeed a lateral vibration mode appears at a frequency of approximately 14 MHz and can be observed on the real part of the experimental impedance.

![Figure 3](image)

Figure 3 : Theoretical real part of the input impedance of an element of the PZT-based array.

![Figure 4](image)

Figure 4 : Theoretical imaginary part of the input impedance of an element of the PZT-based array.

![Figure 5](image)

Figure 5 : Experimental real and imaginary parts of the input impedance of an element of the PZT-based array.

**Pulse-echo response**

The theoretical frequency response, in 50 Ohm environment, of a PZT-based element is shown in figure 6. The maximum sensitivity is obtained at 20 MHz and corresponds to a value of -17 dB whereas the -6 dB bandwidth is 8 MHz (43% of the -6 dB centre frequency). The experimental time and frequency responses are shown in figure 7. The -6 dB center frequency is 20 MHz and the -6 dB bandwidth is 16.8 MHz. This large experimental value of bandwidth, compared to theoretical predictions, is due to the lateral vibration mode already observed on impedance curves at 14 MHz. The time response is also significantly perturbed by this low frequency vibration which appears in the second part of the signal.

**Radiation patterns**

Theoretical radiation pattern of one element (considered to be 100 μm wide) taking into account a -24 dB electrical coupling between two neighbouring elements is shown in figure 8. This value of coupling corresponds to a network analyser measurement. The -6 dB angular directivity is then 26 deg. The experimental angular resolution, from the measured curve of figure 9, is 25 deg. These results are in close agreement. Finally a prediction of the radiation pattern of a 22
element aperture with electronic focusing at 8 mm is shown in figure 10. A grating lobe at a level of -51 dB appears at an angular position of 38 deg.

Figure 6: Theoretical sensitivity of an element of the PZT-based array.

Figure 7: Experimental time and frequency pulse-echo responses of an element of the PZT-based array.

Figure 8: Theoretical transverse radiation pattern of an element of the PZT-based array.

Figure 9: Experimental transverse radiation pattern of an element of the PZT-based array.

Figure 10: Theoretical transverse radiation pattern of a 32 element aperture of the PZT-based array with electronic focusing at 8 mm in water.
CONCLUSION

We have developed two new fine grain ceramics (MPT and PZT) for operation at frequencies higher than 15 MHz. The average grain sizes are between 1 and 2 μm and a hot isostatic pressing allows to obtain low porosity rates for the PZT composition. A 20 MHz linear array transducer with an element width of 80 μm is manufactured using the PZT ceramic. Its elementary electrical input impedance is more than an order of magnitude lower than that of an equivalent PVDF-based transducer, which allows a much better electrical matching to a 50 Ohm environment. This feature, combined with low insertion losses, induces a 50 Ohm loop sensitivity at least 40 dB higher than that of a PVDF-based array.

The radiation pattern shows an angular directivity of 25 deg., which is sufficient for focusing at distances in the order of 8 mm in water.

Because of technological difficulties, it has not yet been possible to manufacture an array using the MPT ceramic. Theoretical modelling predicts that sensitivity should be lower than for PZT, but the low lateral and planar coupling coefficients should reduce the effect of the lateral vibration in the elements. Consequently, the angular directivity should be increased and the pulse-echo response duration decreased.

In the future, the PZT composition will be optimized in terms of thickness coupling coefficient in order to obtain even higher sensitivities.

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REFERENCES
