ULTRASONIC TRANSDUCERS FOR HIGH RESOLUTION IMAGING : FROM PIEZOELECTRIC STRUCTURES TO MEDICAL DIAGNOSTICS

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Abstract: The fields of medical diagnostics, namely for examination of skin, eye and blood vessels, of medical research on small animals, of cosmetics and also of non destructive testing of small parts all require very high resolution imaging techniques. Ultrasonic waves, at frequencies between 20 and 100 MHz, allow the observation of structures of several mm size with resolutions in the micrometers range. For this, specific systems including ultrasonic transducers, transmit/receive electronics and image processing and display need to be developed, since classical ultrasonic systems operate only in the 1-15 MHz range. The electroacoustic performance of transducers is one (if not the) key element of such systems. Parameters such as the centre frequency, the relative bandwidth and the loop sensitivity need to be optimised and adjusted for each application. They define both the axial resolution of the images produced and the depth of penetration, and also influence the contrast. To obtain high lateral resolution, the transducers must be focused, which implies either using a focusing lens or shaping the transducer surface. The paper describes current work on piezoelectric materials and structures, namely thick films, developed specifically for these applications. Material properties measured on different samples including thin plates, thick films on several substrates, machined bulk ceramics are presented and compared. The design of transducers using those materials identified as potentially most efficient is discussed, as well as transducer fabrication and performance.

Ultrazvočni pretvorniki za slikanje z visoko ločljivostjo : od piezoelektričnih struktur do medicinske diagnostike

Kjučne besede: diagnostika, slikanje, slikanje z visoko ločljivostjo, pretvorniki, piezo električni pretvorniki

Izvleček: Medicinska diagnostika, npr. pregled kože, oči in žil, preiskave malih živalih, raziskave v kozmetiki, kot tudi neporušno testiranje majhnih sestavnih delov, zahteva tehnike slikanja z visoko ločljivostjo. Ultrazvočni valovi s frekvenco med 20 in 100 MHz omogočajo opazovanje struktur velikosti nekaj milimetrov z mikrometrsko ločljivostjo. V ta namen je potrebno razviti posebne podsisteme, kot so ultrazvočni pretvorniki, oddajno/sprejemna elektronika, prikazovalniki in obdelava slik, saj klasični ultrazvočni sistemi delujejo le v območju 1-15MHz. Elektroakustične lastnosti pretvornikov so ključnega pomena za delovanje takih sistemov. Parametri, kot so sredinska frekvenca, relativna širina pasu in občutljivost morajo biti optimizirani in nastavljeni za vsako uporabo posebej. Le-ti definirajo osno ločljivost posnetih slik, globino prodiranja ultrazvoka in vplivajo na kontrast. Za doseganje visoke lateralne ločljivosti, moramo uporabiti bodisi zbiralno lečo ali ustrezno oblikovati površino pretvornika.

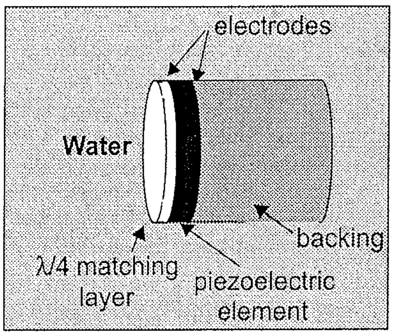
V prispevku opisujemo razvoj piezoelektričnih materialov in debeloplastnih struktur za uporabo v ultrazvočni medicinski diagnostiki. Predstavljamo in primerjamo lastnosti materialov in plastnih struktur na različnih podlagah. Komentiramo načrtovanje, izdelavo in delovanje ultrazvočnih pretvornikov, narejenih iz materialov z največjim piezoelektričnim odzivom.

1. Introduction

High frequency ultrasound devices have been developing in many fields such as electronic filters and resonators, material characterisation (acoustic microscopes), non-destructive testing and medical diagnostics. This paper will deal with ultrasonic transducers which are designed for imaging applications, and in particular for medical diagnosis in organs such as skin, eye and blood vessels, as well as for non-destructive evaluation and small animal examinations. This field has generated a great deal of research as well as commercial products, attested by many publications in both specialised and general scientific journals /1-4/. The frequency range starts around 20 MHz, and extends up to 100 MHz. The paper will first present general transducer requirements, then specific piezoelectric materials developed for high frequency will be reviewed and finally transducer fabrication and performance will be discussed (modelling and characterisation).

2. Transducer requirements

The classical single-element transducer is composed of a piezoelectric plate or disc poled along the thickness direction, whose thickness defines the resonance frequency of the device (Figure 1). The piezoelectric element (typically a ferroelectric ceramic), has an acoustic impedance (*i.e.* around 33 MRa) much higher than biological tissues (close to that of water, *i.e.* 1.5 MRa). This large difference leads to poor acoustic matching and low axial resolution. Consequently, other layers are added to this active layer. First, on its rear face, a thick layer is bonded (backing) /5/. It serves as a mechanical support for the active element, but acoustic energy flows by the rear face. The closer the backing acoustical impedance is to that of the active layer, the more energy is lost. The consequence is a lower sensitivity but a higher axial resolution. The attenuation coefficient and the thickness of the backing layer must be sufficient so that no energy can be radiated back to the active layer, which would produce parasitic echoes. Secondly, on the front (*i.e.* between the piezoceramic and the propagation medium), a matching layer is used. Its design is optimised in order to increase the transfer of energy from the active layer to the tissues /6/ /7/. The thickness of this matching layer is generally around a quarter-wavelength at the resonance frequency, and its acoustical impedance is intermediate between those of the piezoceramic and tissues. The use of a matching layer thus improves the sensitivity of the transducer. Moreover, since the acoustical energy can better flow towards the tissues, the duration of acoustical resonance in the active layer is decreased. Consequently, the matching layer also improves axial resolution. Influence of these two elements on the impulse and frequency responses transducers is shown in Figure 1 and a trade-off has to be found for each application. The active layer is typically a PZT-based material, while matching layers and backings are polymer-based.



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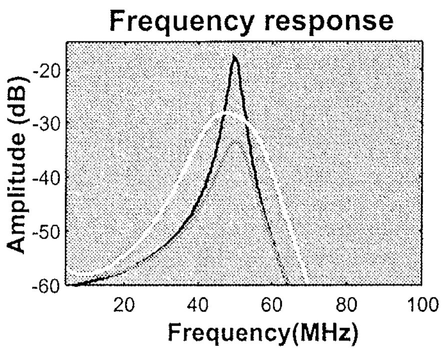

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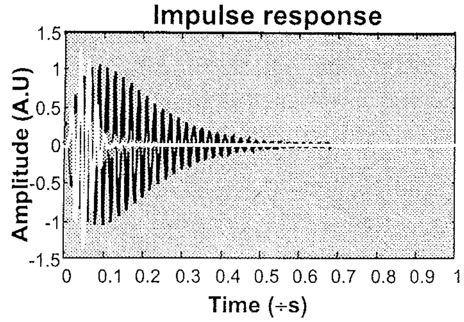


(c)

Figure 1: (a) Classical diagram of a single-element transducer.
(b) and (c) Frequency and impulse responses of: black line: piezoelectric element (water on front face and air on rear face), grey line: piezoelectric element+backing, white line: with matching layer.

The radiation pattern of a focused single-element transducer is defined by the size of the active element (D) and the focal distance (F) (Figure 2). In the case where a lens is used for focusing, (F) can be deduced from the lens curvature (R_C) and the sound wave velocities in the lens and propagation media (Figure 3).

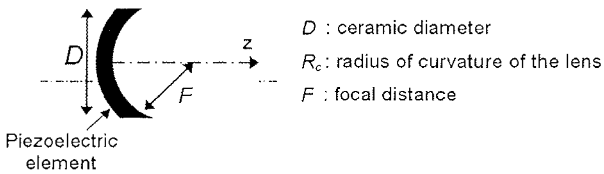


Figure 2: Shape-focused transducer.

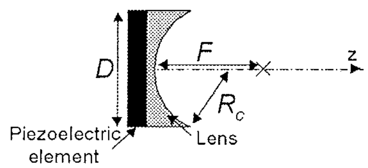


Figure 3: Lens-focused transducer.

Lateral resolution is linked to the width of the acoustic beam and is optimum at the focal distance. Approximate expressions of this lateral resolution ($R_{lateral}$), depth of field (DOF) and axial resolution (R_{axial}) for a spherical shape transducer are defined (eq. 1). The ratio between the focal distance and the diameter of the piezoelectric element, called the f-number ($f_{\#}$), allows to define the trade-off between lateral resolution and depth of field. λ is the wavelength at nominal frequency and BWR_{-6dB} is the relative bandwidth at -6dB.

$$f_{\#} = \frac{F}{D}, \qquad R_{lateral} \approx \lambda \times f_{\#},$$

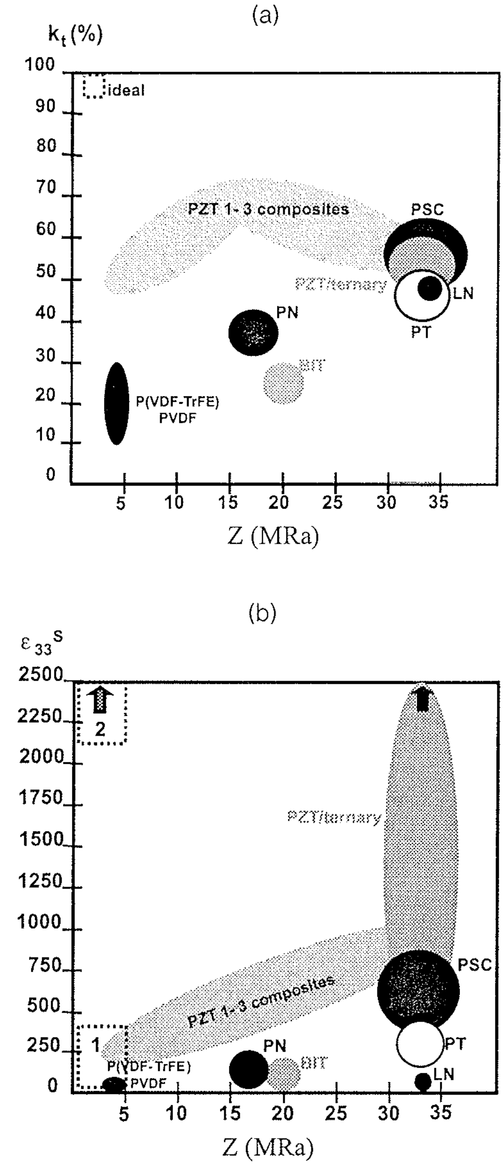
$$DOF \approx 7\lambda \times f_{\#}^2, \qquad R_{axial} \approx \frac{\lambda}{2BWR_{-6dB}} \qquad (1)$$

The resolutions and depth of field can change of several orders of magnitude according to frequency. High frequencies lead to high resolutions but, due to increase of attenuation in tissues, the depth of penetration in the explored medium is reduced. The acoustical properties of the explored medium as well as of the driving electronics also influence imaging performance /4//8/.

For typical fixed values for medical imaging as the centre frequency at 50 MHz (i.e. a f-number of 2.5, a focal distance at 7.5 mm, a relative bandwidth (-6dB) at 60%), the corresponding diameter D is at 3 mm, the thickness of the piezoelectric element (ceramic) is around 45 µm, the axial and lateral resolutions are respectively around 30 and 75 µm, and the depth of field around 1.3 mm. These resolutions correspond to those generally required for skin imaging.

3. Piezoelectric materials

For the piezoelectric material, in particular for medical applications, two of the most important material parameters are the effective electromechanical coupling coefficient k_{eff} of the main vibration mode used and the acoustic impedance Z_{ac}. The k_{eff} factor represents the piezoelectric activity of the material in the considered mode of vibration, in other words the capability of the material to convert electrical energy into acoustical energy (or vice-versa) in a short time; it should of course be as high as possible. This factor depends not only on the material properties but also on the geometry of the active element. In medical imaging applications, all vibration modes are longitudinal, *i.e.* the displacements are in the poling direction which defines the thickness dimension. For large plates or discs (thickness much lower than lateral dimensions), the thickness coupling factor k_t is used. For bars or pillars (thickness higher than lateral dimensions), the factor is k_{33}. For the intermediate case of an array element (one small and one large lateral dimensions with a thickness value between them), k'_{33} factor is defined /9/. The value of the dielectric constant also has an important role on the electrical matching. Figure 4 represents values of the thickness mode coupling factor (k_t) versus the acoustic impedance (Z_{ac}) for a wide range of available piezoelectric materials. It can be observed that no material allows to obtain both high coupling and low acoustic impedance (ideal area on Figure 4). The best trade-off must be found among these materials. For almost all medical transducers applications, PZT piezoceramics are used because of their high coupling factor, even if their acoustic impedance is high, since this can be compensated for by using acoustic matching layers in the transducer structure. For a given application, properties such as dielectric constant and grain size allow to choose a specific material reference. A large range of properties can be found from relatively low (a few hundred) to very high (a few thousand) relative dielectric constants with grain sizes from one to ten micrometers. For large area devices such as single element transducer, a moderate dielectric constant allows good electrical matching to cables and electronics (which are typically at 50 to 80 ohms) (area 1), while array elements require much higher dielectric constants (area 2).

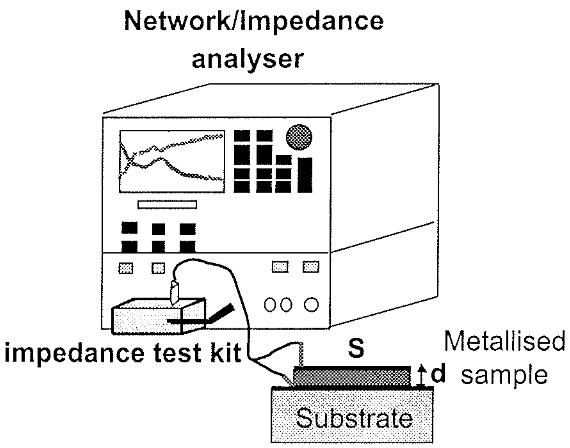


PZT: Lead zirconate titanate, **PT**: Lead titanate, **PN**: Lead metaniobate, **BIT** : Bismuth titanate, **PSC** : Piezoelectric single crystals, **LN** : Lithium Niobate, **PZT 1-3 composites** : PZT and polymer

Figure 4: (a) Electromechanical coupling factor in thickness mode (k_t) and (b) Dielectric constant at constant strain versus acoustical impedance for a wide range of piezoelectric materials.

Measurements of the complex electrical impedance as a function of frequency allow the dielectric, mechanical and electromechanical properties to be obtained by a fitting process /9-11/. The set-up is composed of a network analyser with its impedance test kit and a spring clip fixture to make electrical contacts with the electroded piezoelectric material (Figure 5(a)). These contacts have a great importance in particular at high frequency, since to stay in free resonator condition, their sizes must be very small in comparison with the size of the measured sample and the forces applied must not disturb the resonance mode. Figure 5(b) shows the typical resonance of a PZT disk made by tape-casting which has an antiresonant frequency around 50 MHz. At high frequency, the piezoelectric element is often deposited on a substrate during the fabrication process (Figure 5(a)) and the experimental electrical impedance depends on this substrate. With an electrical equivalent circuit, such as KLM which is well adapted to multilayer structures (electrodes, piezoelectric layer and substrate), and knowing all the acoustic properties of electrodes and substrate, the fitting process allows to obtain the properties of the piezoelectric layer (Figure 4 (c))/12/ /13/.

(a)



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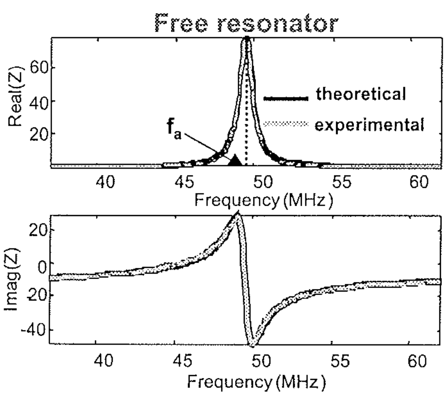

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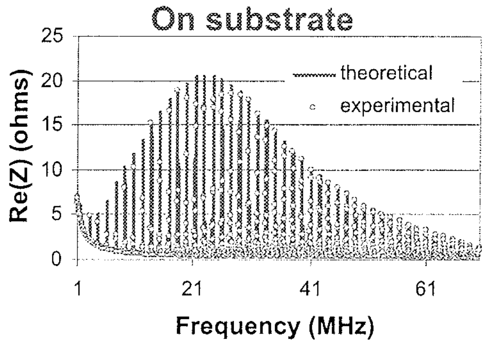


Figure 5: (a) experimental set-up for electrical impedance measurements, (b) experimental and theoretical complex impedance (fit) of high frequency piezoelectric disk in free resonator conditions, (c) experimental and theoretical impedance (real part) (fit) of high frequency piezoelectric thick film on alumina substrate.

Typical parameters characterised are the following:

- Resonant (f_r) and antiresonant (f_a) frequencies which correspond respectively to maximum of real admittance and real impedance;
- The thickness coupling factor (vibration corresponding to a thickness mode) can be calculated with

$$k_t = \sqrt{\frac{\pi}{2}\frac{f_r}{f_a}\cot\left(\frac{\pi}{2}\frac{f_r}{f_a}\right)} \qquad (2)$$

- The longitudinal wave velocity $v = 2df_a$ (d: thickness of the piezoelectric sample) (3)
- Dielectric constant ε is obtain from the capacitance C_0 after resonance and dimensions;
- Mechanical quality factor (or mechanical losses δ_m)

$$Q_m = \frac{f_a}{\Delta f} \qquad (4)$$

where Df corresponds to the frequency width at half the maximum resistance;

- Dielectric losses appear as an offset on resistance curves, the measurement can be made at twice the anti-resonant frequency and they can change with frequency.

Piezopolymers such as PVDF or copolymers /14/ /15/ can be purchased as films with thickness of one to a few tens of microns which can be directly used for high frequency applications. Their coupling factors are relatively low (between 15 and 30%) and relative clamped dielectric constant is low (around 5). These two last properties tend to give a relatively low sensitivity and the electric matching is difficult. But their acoustic impedance is low and close to that of tissues (between 4 and 5 MRa), so acoustic matching is not indispensable (Table 1).

Table 1: Main properties of a P(VDF-TrFE) piezoelectric copolymer film.

material	$\varepsilon_{33}^{S}/\varepsilon_0$	v_l (m/s)	k_t (%)	δ_e (%)	δ_m (%)	Z (MRa)	ref
P(VDF-TrFE)	4.1	2380	29	6.9	4.0	4.6	[16]

$\varepsilon_{33}^{S}/\varepsilon_0$: clamped dielectric constant; $\mathbf{v_l}$: longitudinal wave velocity; $\mathbf{k_t}$: thickness coupling factor; δ_e: dielectric losses; δ_m: mechanical losses; **Z**: acoustic impedance;

The second main and determinant advantage is the flexibility of the film which allows a direct focusing and avoids the addition of a lens (Figure 6). Even with a relatively low (k_t), these materials are widely used for high frequency transducer fabrication in the range of from 20 MHz to over 100 MHz.

(a)

(b)

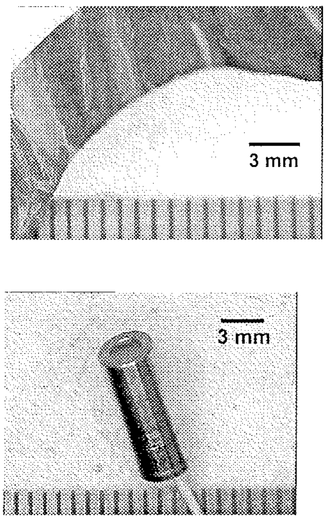


Figure 6: (a) Copolymer sheet and (b) high frequency copolymer based transducer.

Ceramic thick films are a very promising alternative. Many processes are possible and have been developed /17/ such as screen-printing, tape-casting, spin or dip coating processes and spray techniques /15/ /18/ /19/ /20/ /21/ to make piezoelectric thick films (few tens of microns). The three first ones are widely used techniques, in particular for imaging applications. In each case, the samples (generally circular shape) are made directly in final shape and avoid machining, namely lapping, which can represent a critical step where micro-cracks or breakdown can appear. The tapes can be used to manufacture thin self-supported disks as shown on Figure 7.

(a)

(b)

c)

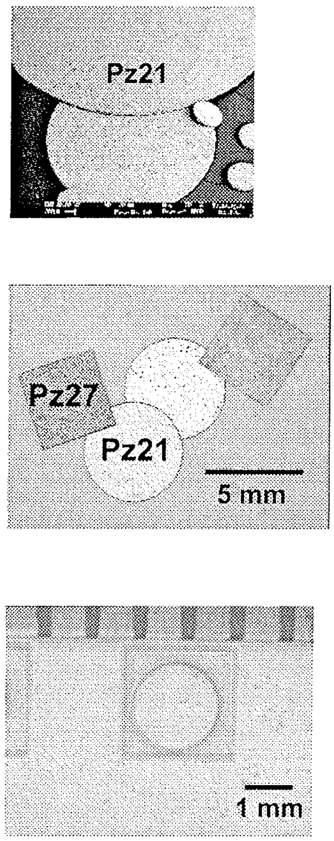


Figure 7: Tape-casted self supported disk photographs. (a) (b) from Ferroperm piezoceramics (Denmark), (c) from Laboratoire de Céramique (EPFL, Switzerland)

Table 2 summarises several representative characteristics of self-supported samples where properties are slightly lower than those of bulk ceramics (in particular k_t) but their actual performance allow to integrate these elements in transducers which deliver satisfying properties.

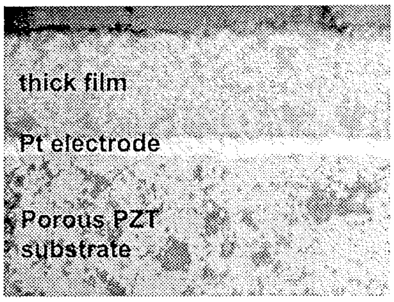
Table 2: Properties of self supporting samples made by tape-casting.

Materials	$\varepsilon_{33}^{S}/\varepsilon_0$	k_t (%)	f_a (MHz)	ρ (kg/m^3)	δ_m (%)	ref
Pz21 (PNNZT)	1920	43	33.9	7420	4.7	[22]
Pz29 (PZT)	1035	35.5	34.1	6900	6.0	[22]
PZT	675	43	46	-	3.6	[23]

$\varepsilon_{33}^{S}/\varepsilon_0$: clamped dielectric constant; $\mathbf{k_t}$: thickness coupling factor; $\mathbf{f_a}$: antiresonant frequency; ρ: density; δ_m: mechanical losses.

The substrates used for the deposited thick films can be used in two ways. First, the substrate can be chosen to be used directly as a backing for the transducer /24/. Many conditions are necessary for this in terms of sintering temperature (for the thick films) and acoustical properties for the transducer. Porous PZT can be a good choice (Figure 8(a)). This method leads to an integrated device. Secondly, the substrate can be chosen only as an intermediate material. For example, The PZT thick film is deposited on an aluminium substrate (Figure 8(b)) /25/. On the other side, epoxy resin loaded with Ag powder is added as the future backing. Finally, the Al substrate is etched and a new electrode is deposited on the front face of the thick film. This method allows to optimise the choice of these two materials for the future transducer. For these two cases, properties of the piezoelectric thick films are given in Table 3 where the performance obtained can be relatively high, but the reproducibility remains an important problem to be solved. Moreover, the choice of the bottom electrode material and thickness can also greatly influence the final properties.

(a)



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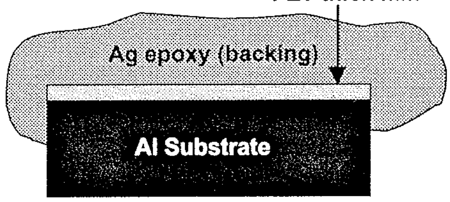

Figure 8: (a) Cross section of optical microscope photograph of screen-printed PZT thick film on Porous PZT substrate from JSI - Slovenia, (b) screen-printing with intermediate substrate.

Different types of piezocomposites have also been developed for high frequency applications /26-41/ , namely 1-3 connectivity including fibres and hollow spheres, as well as curved films.

4. Transducer fabrication and performance

4.1. Transducer fabrication

A fabrication technique, described by Lockwood *et al.* /42/, has allowed to increase significantly the sensitivity of focused transducers, for centre frequencies around 50 MHz, compared to the more classical polymer-based devices. This method has been applied to both ceramic and single crystals. First, bulk ceramic is bonded on a malleable substrate (typically conductive epoxy layer). Ceramic is then lapped to required thickness (generally few tens of microns). The third step is the lapping of the substrate generally to around 100 microns and machining of the structure to final diameter. The two-layer composite is then heated and pressed into a spherically shaped well. The diameter of the well is the focal distance of the transducer. The shell is cooled and removed from the well. Finally, an attenuating backing is added. Two possibilities exist for focusing. The first is the use of a spherically-shaped active element (Figure 9(a)), the second is the addition of lens (Figure 9(b)).

4.2. Transducer performance: overview of published results

The two next Tables (Tables 4 and 5) give an overview of published results on high frequency transducers using materials and/or process described in previous sections. Table 4 specifies essentially the characteristics (fabrication process, dimensions or material used) while Table 5 gives the corresponding performance such as bandwidth and sensitivity /44/ /33/ /45/ /25/ (if authors give these values). Concerning the sensitivity, the comparison between values is not always possible since the definition used by different authors is not identical.

Table 3: Properties of screen-printed samples on different substrates.

material	process	substrate	e (μm)	$\varepsilon_{33}^S/\varepsilon_0$	v_l (m/s)	k_t (%)	δ_e (%)	δ_m (%)	Z (MRa)	ref
PZT/PGO	Screen-printing	PZT	35.5	334	3240	47	4.7	4.8	-	[24]
PZT/PGO	Screen-printing	Al_2O_3	39	342	3940	39.7	2.0	1.5	-	[24]
PZT	Spin coating	Al	20	220	3950	24.4	-	-	21.8	[25]

e_{33}^S/ε_0: clamped dielectric constant; v_l: longitudinal wave velocity; k_t: thickness coupling factor; δ_e: dielectric losses; δ_m: mechanical losses; **Z**: acoustic impedance.

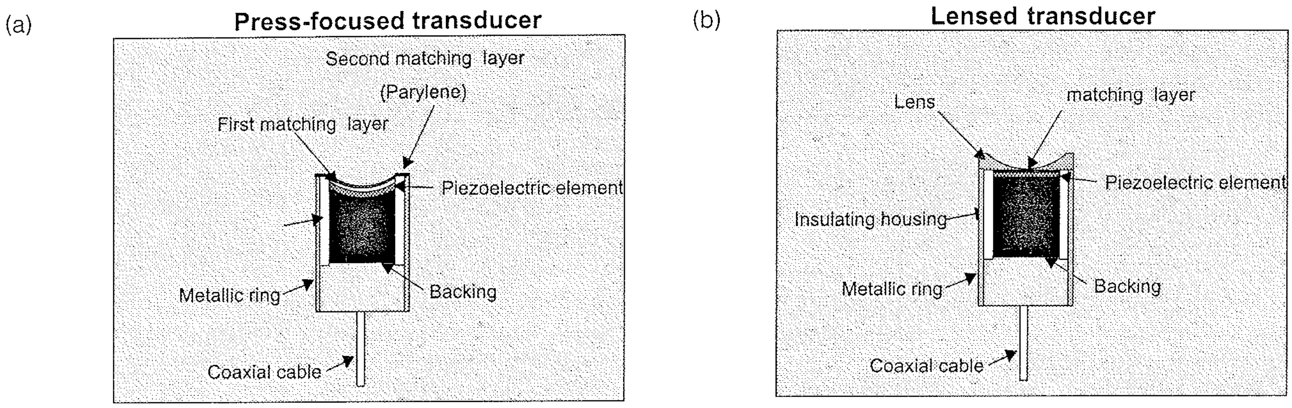

Figure 9: Cross-sections of schematic representation of press&lens-focused transducers.

Table 4: Overview of published results on high frequency transducers (part 1).

Material	e (μm)	f_c(MHz)	shaping	$F_\#$/F (mm)	Z_b(MRa)-material	Z_{m1}(MRa)-material	Z_{m2}(MRa)-material
P(VDF-TrFE) [16]	17	34	prefocused	2.7/6	15 – Ag epoxy	no	no
PVDF[33]	9	48.1	prefocused	2-3/-	3.15 –pure epoxy	no	no
$LiNbO_3$ crystal [44]	-	78	prefocused	2/-	5.9 – Ag epoxy	7.3 – Ag epoxy	2.6 - parylene
$LiNbO_3$ crystal [33]	60	44.5	Lens (epoxy)	2-3/-	5.9 – Ag epoxy	7.3 – Ag epoxy	no
$LiNbO_3$ crystal [45]	-	200	prefocused	1.15/0.8	4.3 – Ag epoxy	no	no
PT ceramic [33]	32	45.1	prefocused	2-3/-	5.9 – Ag epoxy	3- parylene	no
Fiber composite [34]	32	31	prefocused	-/17.5	Porous polymer	no	no
PT hollow sphere [41]	70-90	39.8	-	-/1.43	6 - Ag epoxy	parylene	no
PZT thick film [25]	-	72	prefocused	-/2.8	Ag epoxy	no	no

e: thickness of the piezoelectric material; f_c : transducer centre frequency; **F**: focal distance; $F_\#$: f-number; Z_b: acoustic impedance of the backing- corresponding material; Z_{m1} and Z_{m2}: acoustic impedances of the first and second matching layers - corresponding material;

In these nine high frequency transducers, a wide range of centre frequencies is observed (between 31 and 200 MHz). The press-focused process is essentially used. A majority of transducers have been designed to have a f-number between 2 and 3. With PT hollow sphere, this f-number is lower. For backing material, epoxy loaded with silver particles is mainly used. For matching layers, technology takes a very important place and generally only one matching layer is added. These matching layers are often in parylene which allows uniform and repeatable deposition of controlled-thickness layers.

In accordance with properties of piezoelectric materials, $LiNbO_3$ and PT based single-element transducers deliver best performance corresponding to a good trade-off between resolution and sensitivity. Press-focused process delivers better performance than lens-focused process /44/. Attenuation due to various lens thickness decreases

Table 5: Overview of published results of high frequency transducers (part 2).

Material	D (mm)	tuning	BW (%)	AR (μm)	LR (μm)	IL (dB)
P(VDF-TrFE) [16]	2.2	no	70	51	-	-
PVDF [33]	3	no	118	-	-	-45.6
$LibO_3$ crystal [44]	3	yes	73	-	-	-13.5
$LiNbO_3$ crystal [33]	3	yes	74	-	-	-21.3
$LiNbO_3$ crystal [45]	0.7	-	22	12	14	-18
PT ceramic [33]	3	yes	47	-	-	-23.7
Fiber composite [34]	5	no	118	-	-	-29.3
PT hollow sphere [41]	2	no	33	-	-	-20.1
PZT thick film [25]	1	no	52	20	295	-46

D: Aperture; **tuning**: addition or not of a self inductor and a transformer; **BW**: bandwidth at -6dB; **AR**: axial resolution (-6dB); **LR**: lateral resolution (-6dB); **IL**: Insertion loss.

the sensitivity (around -6dB for $LiNbO_3$ transducers /44/) even if bandwidth is slightly increased.. Finally, the transducer ($LiNbO_3$ based) with two matching layers (Ag epoxy and parylene) gives, as expected, the highest performance.

4.3 Comparison of transducer performance.

Electroacoustic behaviour of transducers includes electrical input impedance that will govern energy transfer between the imaging system and the transducer, pulse-echo response whose amplitude is linked to sensitivity and duration to axial resolution, and frequency response equal to the Fourier transform of pulse-echo response, which defines centre frequency and bandwidth. All these curves can be predicted with the assumption of single axis vibration, using equivalent electrical circuits such as KLM /10/ /46/ or others /47/. All transducer layers are taken into account as well as electrical elements such as electrical matching and cables. Finite element methods are also available /48/ /49/ in cases where no assumptions can be made on acoustic modes. Acoustic radiation patterns allow to define lateral resolution, which is high when lateral beam dimensions are low, and acoustic noise level (the off-axis power level measured in dB using the on-axis power level as a reference). The appearance of side lobes tends to increase acoustic noise level. Lateral resolution is responsible for image sharpness and low parasitic lobe levels ensure the absence of artefacts in the lateral direction. Radiation pattern calculations can be performed by applying Huygen's principle (*i.e.* the transducer surface is assumed to be a series of point-sources, and the pressure radiated at any point is the sum of pressures radiated by each of the point-sources /50/). For simple geometry (circular, annular or rectangular transducers), analytical results have been derived (impulse diffraction theories), and allow more efficient calculations /51/ /52/. Five different piezoelectric materials have been retained for comparison: P(VDF-TrFE) copolymer, $LiNbO_3$ single crystal, lead titanate ($PbTiO_3$) ceramic, soft PZT ceramic and finally PMN-PT single crystal. For these simulations, three parameters have been fixed: the transducer centre frequency (50 MHz), the active area of the piezoelectric element (diameter of 3 mm) and the length of the 50 ohms coaxial cable (1.5 m). One matching layer is considered. A self inductor and a transformer are also taken into account. Table 6 gives all the parameters of piezoelectric materials used for the simulations (values from literature).

The optimisation of transducer performance allows to determine the characteristics /43, 53-56/ of the matching layer (acoustical impedance and thickness), backing (acoustical impedance), value of the self inductor and ratio of the transformer. The performance results are specified in Table 7. These simulations do not take into account focusing by a lens. Impulse responses are represented in Figure 10. Due to low k_t, the P(VDF-TrFE) based transducer delivers a low sensitivity. The results for the $PbTiO_3$, soft PZT and single crystal (PMN-PT) are similar. The electrical matching allows to compensate for the difference in dielectric constants. The $LiNbO_3$ single crystal delivers a similar bandwidth but a lower sensitivity since the dielectric constant is much lower than that of the three previous materials.

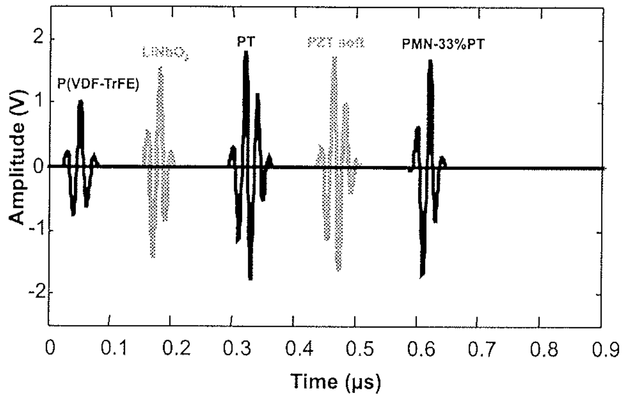

Figure 10: Electroacoustic responses of the five simulated transducers.

5. Conclusion

PZT-based thick films are very promising for high frequency ultrasonic transducer applications since their electromechanical properties are high and they are compatible with backing materials. Their performance has been demonstrated in non focused configurations, and current work aims at obtaining curved films in order to focus the beam without use of a lens.

Table 6: Piezoelectric material parameters for high frequency transducer simulations.

Material	k_t (%)	$\varepsilon_{33}^S/\varepsilon_0$	ρ (kg/m^3)	v_l (m/s)	δ_e (%)	δ_m (%)	Z (MRa)
P(VDF-TrFE) [16]	33	4.1	1932	2380	6.9	4.0	**4.6**
$LiNbO_3$ crystal [33]	**49**	28	4640	7340	0.1	0.01	34.1
PT ceramic [33]	**49**	**200**	6900	5200	0.9	0.83	35.9
PZT soft ceramic [57]	50	800	7900	4390	2.5	2.7	34.7
PMN-33%PT [58]	**62**	712	8060	4645	-	-	37.4

k_t: thickness coupling factor; $\varepsilon_{33}^S/\varepsilon_0$: clamped dielectric constant; ρ: density; v_l: longitudinal wave velocity; δ_e: dielectric losses; δ_m: mechanical losses; **Z**: acoustic impedance.

Table 7: Design and performance parameters of high frequency single element transducers.

Material	e (μm)	Z_b(MRa)	Z_{m1}(MRa)	e_{m1}(×λ/4)	tuning	BW(%)	IL(dB)
P(VDF-TrFE)	22.4	1.2	2	1.5	Yes	71	26
$LiNbO_3$ crystal	69.6	4.5	4	1.2	Yes	70	23.4
PT ceramic	51.0	4.3	4.3	1.2	Yes	53	19.7
PZT soft ceramic	43.1	4	4.2	1.2	Yes	54	20.6
PMN-33%PT	44.3	2.7	4	1.0	Yes	68	22

e: thickness of the piezoelectric material; Z_b and Z_{m1}: acoustic impedances of the backing and matching layer; e_{m1}: thickness of the matching layer normalised by a quarter-wavelength; **tuning**: addition or not of a self inductor and a transformer; **BW**: bandwidth at -6dB; **IL**: Insertion loss

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