Piezoceramics for High Frequency (50 to 100 MHz) Single Element Imaging Transducers*

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Abstract-The properties of transducer materials operating at high frequencies determine the level of performance which is achievable. Selection of the appropriate material can be made based on the transducer size and frequency. The properties of a number of piezoceramic materials have been experimentally determined by measuring the electrical impedance of air-loaded resonators whose thickness corresponds to resonance frequencies from 10 to 100 MHz. Materials measured include commercially available high dielectric lead zirconate titanate (PZT) and lower dielectric modified lead titanate (PT) ceramics, as well as materials which have been designed or modified to result in improved properties at high frequencies. Conclusions regarding the influence of the microstructure and composition on the frequency dependence of the properties are made based on the calculations and microstructural analysis of each material. Issues which affect transducer performance are discussed in relation to the measured properties. For larger area transducers the use of a lower dielectric constant material results in better electrical matching between the transducer and standard 50 Ω electronics. KLM model simulations show improved performance for transducers which are electrically matched.

INTRODUCTION

The use of transducer operating frequencies greater than 20 MHz has been demonstrated to provide higher resolution in both the axial and lateral directions, resulting in improved diagnostic information which can be obtained non-invasively. Ultrasound backscatter microscopy (UBM) has been shown to have many clinical applications in the 20 to 80 MHz range [1]. The design of transducers which use ultrasound at very high frequencies, between 50 and 100 MHz, has remained an engineering challenge. Work on characterizing the properties of transducer materials has been pursued. F.S. Foster et al. [2] describe the characterization of commercially available PZT materials in the 20 to 80 MHz range, useful for miniature transducers for applications such as intravascular imaging. Results show a marked decrease in the properties of commercial PZT as the operating frequency is increased. Even with reduced properties, however, the ceramic materials have been demonstrated to have higher coupling coefficients relative to polymer materials. G.R. Lockwood, et al. [3] describes a construction technique for fabricating high frequency focused transducers. The technique allows for mechanically focused transducers 20 MHz and higher to be constructed. Recent work [4] has focused on electrical matching using transmission line stubs, while treating the rest of the transducer as a 'black box' whose properties are unknown and to an extent uncontrollable.

At frequencies above 20 MHz the scale of the devices approaches the microstructural scale. There have been very few studies exploring the relationships between the microstructure and composition and the frequency dependence of piezoelectric properties for ceramic materials. Foster et al. [9] hinted that the microstructure may influence the properties. However, the materials examined were limited to commercial PZT with a similar composition and with a grain size of roughly 3 μm.

In this paper, measured properties are presented for an expanded number of commercially available materials, including lead zirconate titanate (PZT) and modified lead titanate (PT) ceramics. In addition, fine grain materials manufactured using a process described by Kim [5] which results in a submicron grain size are studied. Also, commercial materials are post processed to alter the microstructure and the high frequency properties.

The performance of piezoelectric materials is shown to vary considerably with the operating frequency. The microstructure can influence the properties, especially when the wavelength of sound in the material approaches the grain size. Porosity can also be a problem because of the tendency of sound to scatter at the interface between the high impedance continuous grains and the low impedance pores. Porosity can also lead to difficulties in poling very thin samples which are necessary for high frequency transducers, as the electrodes can short across a pore if it is large enough. In addition to microstructure, the composition plays an important role in determining the properties at high frequency. In particular, the contribution of extrinsic domain wall motion is thought to affect the piezoelectric properties at high frequencies.

With a precise knowledge of the transducer material properties it is possible to select the best material based on design requirements such as transducer area and operating frequency, and electrical impedance matching requirements. Simulations are shown which predict transducer performance. Selection of the best material based on properties and transducer dimensions is discussed. An example is given for a 2 mm diameter 50 MHz transducer designed using PT.

HIGH FREQUENCY TRANSDUCER MATERIALS

Observation of the microstructure of a variety of materials was carried out using a scanning electron microscope

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(SEM) to give in indication of the average grain size (AGS) and the level of porosity for each material. Thickness mode resonators were prepared by lapping and polishing plates to the desired thickness. For each material tested multiple samples were prepared to resonate at frequencies between 10 and 100 MHz. Not all of the materials resulted in satisfactory resonators for frequencies above 80 MHz, as sample toughness and porosity contributed to some of the materials having inadequate mechanical integrity. For each material, between three and six different sample thicknesses (i.e. frequencies) were tested, with typically two to six samples at each frequency. A gold electrode approximately 2000 Å thick was sputter deposited on each side of the samples. KLM model simulations were run to verify that this thickness would not load the high frequency samples mechanically and result in inaccurate measurements.

The material properties of thickness mode plates were experimentally evaluated to determine their suitability for single element transducers operating at frequencies from 50 to 100 MHz. Materials evaluated included commercially available PZT with an average grain size in the 2.5 to 5.0 μm range and fine grain PZT materials designed to exhibit a grain size up to an order of magnitude smaller than conventional materials. The fine grain materials were studied to determine whether grain size has a dominant effect on the properties at high frequencies. Also, conventional ceramic materials are of limited use at frequencies approaching 100 MHz because the dimensions of the samples approach the grain size, resulting in not only reduced properties but also reduced structural integrity. Because of the increased number of grains across the controlling dimension, the fine grain materials provide increased strength for very high frequency samples.

Transducers made from PZT materials can have an electrical impedance which is substantially lower than 50 Ω if the area is larger than a few mm^2. Transducers with a larger radiating aperture have better lateral resolution due to a narrower beamwidth [1]. A commercial modified PT material was selected for evaluation based on its lower dielectric constant, 5 to 10 times lower than for PZT materials, which results in less capacitance and hence a higher impedance for a transducer with a larger area.

Measurements of the electrical impedance of air-loaded plate resonators were used to calculate the properties using the resonance technique. The method of the IEEE Standards [6] was used to calculate the electromechanical coupling coefficient, k_t. Several different methods of measuring mechanical losses within the plate, expressed as a mechanical quality factor, Q_m, were evaluated including the method used by F.S. Foster, et al. [2] and the method of J.-H. Ih and B.-H. Lee [7]. The calculated values were found to be equivalent between the two methods for the samples tested.

The materials tested include two commercially available high density PZT compositions, Motorola 3203HD and 3195HD (Motorola Ceramic Products, Albuquerque, NM); a high dielectric PZT composition, Ferroperm PZ21 (rep. Seacor Piezoceramics, Branford, CT); and a commercial modified lead titanate, EC97 (EDO Western, Ltd., Salt Lake City, UT). These materials all have an average grain size in the 3 to 5 μm range. In addition, two PZT compositions designed to have fine grain size were also tested, FG-0.9 and FG-0.5, the numbers referring to the AGS in μm. A group of the modified PT samples was post processed by hot isostatic pressing or HIPing. This changes the microstructure by reducing the amount of porosity.

MATERIAL PROPERTY MEASUREMENTS

The properties calculated from impedance measurements are shown in Table 1. These properties are sufficient to model the performance of transducers using a one dimensional model. Certain characteristics are desirable for transducers used for medical imaging. For instance, a high k_t favors a wide bandwidth and a low insertion loss, both of which can contribute to improved image quality. Low mechanical losses can also lead to improved sensitivity, an important consideration for high frequency applications because of the increased attenuation in the tissue at these frequencies. For larger high frequency single element transducers, a lower dielectric constant can be used to result in an electrical operating impedance which is closer to that of the pulsing and receiving electronics.

A typical data set of properties vs frequency is shown in Figure 1 for the 0.9 μm fine grain PZT. Both k_t and Q_m decrease with increasing frequency. A similar data set was prepared for each of the materials. The individual plots are not shown, although the interested reader is referred to a previous publication [8] where most of the plots can be found. The calculated properties are summarized in Table 2 for all materials. Physical properties such as transition temperature, T_c, and density, ρ, are included. Measurements of thickness mode plates operating at 20 MHz are shown, as well as the slopes calculated from linear regression analysis of the higher frequency properties. The values of the slopes can be compared between the different materials tested and conclusions drawn relating the effect of the microstructure and composition on the frequency dependence.

Table 1 - Material properties of thickness mode resonators

Symbol	Description	Units
k_t	thickness coupling coefficient	
Q_m	mechanical quality factor	
v_c	longitudinal plane wave velocity	mm / μs
N_t	thickness frequency constant (= v_c / 2)	MHz·mm
ρ	density	g / cc
Z_c	characteristic impedance	Mrayl
ε_{33}^S	relative clamped dielectric permitivity	
$\tan(\delta^S)$	clamped dielectric loss tangent	
ε_{33}^T	relative free dielectric permitivity	
$\tan(\delta^T)$	free dielectric loss tangent	

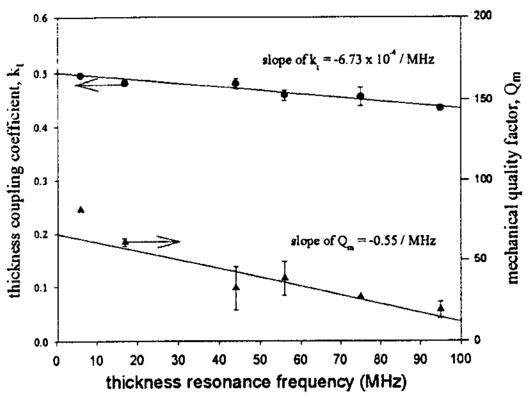

Figure 1 - Frequency dependence of k_t and Q_m for 0.9 μm fine grain PZT. Note reduced frequency dependence of k_t relative to conventional PZT.

RESULTS AND DISCUSSION

PZT Materials

PZT materials of the type tested here, i.e. PZT5 type materials, are piezoelectrically soft materials. That means that the internal dipoles or domains are easily reoriented by an applied electric field. This fact also contributes to higher coupling coefficients and dielectric constants, since domain wall motion contributes to the piezoelectric response. At high frequencies the finite activation energy and inertial mass associated with domain wall motion may lower these extrinsic contributions. A reduction in the domain wall motion contribution could explain the lower properties at high frequencies.

The data for the two high density PZT materials, both with an AGS of approximately 2.5 μm, confirms the data previously reported by F.S. Foster, et al. [2], where a slope of approximately -1.0 x 10^{-3} / MHz was reported. The microstructure and measurements for the materials show that porosity does not significantly contribute to lower properties at high frequencies for this material, since the observed porosity was very low. The frequency dependent behavior, therefore, must be explained by other factors.

SEM analysis of the high dielectric constant material, Ferroperm PZ21, revealed an AGS of 5 μm, slightly larger than for the Motorola materials. Also apparent was a higher level of porosity. The frequency dependence of k_t was very close to the Motorola materials, indicating that a small amount of porosity does not significantly affect k_t at high frequencies. The strong frequency dependence of Q_m for PZ21 leads to very high losses at high operating frequencies, similar to the other commercial PZTs. The relative clamped permitivity of 1500, highest of the materials tested, is achieved by compositionally lowering T_c to 150 °C. This results in a higher permitivity at room temperature, an important consideration for small area array elements which benefit from the higher capacitance, which can effectively lower the electrical impedance and more closely match the transducer to the pulsing and receiving electronics. For high frequency single element transducers, which can be large in area relative to their thickness, the high permitivity results in an impedance which is too low.

The fine grain PZT materials showed a similar decrease in properties at high frequencies. However, the slope of k_t vs frequency is considerably lower than for the conventional PZT materials. The AGS 0.9 and 0.5 μm materials both showed the same slope of 0.67 x 10^{-3}. Thus the frequency dependence of k_t does not seem to be improved by reducing the grain size appreciably below 1 μm. The change in Q_m with frequency, on the other hand, does show additional improvement for the FG-0.5 material which showed a slope of -0.25 / MHz, lowest of all materials tested. Therefore grain size does seem to greatly influence the frequency dependence of Q_m, even for grain sizes less than 1 μm.

The size of the domains has been shown to decrease with decreasing grain size [9]. A possible explanation for the less frequency dependent properties of the fine grain materials is that the frequency where grain size and domain effects contribute to reduced properties is increased. Thus conventional materials show reduced properties at lower frequencies owing to their larger grain and domain size, while fine grain PZT materials show a significant decrease at higher frequencies.

Table 2 - Measured properties of piezoceramic materials

					20 MHz measurements				linear regressions	
Material	Type	T_c	AGS	ρ	k_t	Q_m	ε_{33}^S	N_t	slope of k_t	slope of Q_m
		(°C)	(μm)	(g/cc)				(MHz mm)	(-10^{-3} / MHz)	(-1/MHz)
3203HD	VI	210	3.5	7.8	0.53	50	1100	2.4	1.03	0.74
3195HD	II	330	3.5	7.8	0.48	90	750	2.4	0.93	1.06
PZ21	VI	150	5.0	7.8	0.48	40	1500	2.3	1.02	0.55
FG-0.9	II	350	0.9	7.8	0.49	50	600	2.3	0.67	0.55
FG-0.5	II	350	0.5	7.8	0.46	40	1050	2.3	0.68	0.25
EC97	n/a	260	6.0	6.7	0.48	120	220	2.6	0.32	1.88
EC97-HIP	n/a	260	6.0	6.9	0.52	120	200	2.7	0.37	0.63

The properties of the fine grain materials at frequencies less than 20 MHz are slightly lower but comparable to the commercially available materials. This is consistent with previous conclusions [9] which explained the decrease in terms of a reduced domain wall mobility due to clamping at the grain boundaries and a reduced number of domain orientations within an individual grain. The reduced frequency dependence results in better properties at high frequencies. Another important advantage of the fine grain materials is their ability to be formed into very thin resonators. The minimum plate thickness achievable for the conventional materials was about 24 μm, while by using the same technique for the fine grain materials plates as thin as 13 μm were made, corresponding to resonance at 150 MHz.

The dielectric constant of the fine grain materials was similar to the conventional materials. Thus while the high frequency properties are slightly better, the high dielectric constant effectively limits the fine grain materials to miniature single element and array applications where the small element area dictates the use of a higher dielectric material for electrical impedance matching. Fine grain PZT materials offer great promise for high frequency array applications in particular because the element width and spacing are necessarily close to the grain size of conventional materials.

PT materials

The lead titanate material tested was EC97. The grain size of this material was the largest of all the materials tested, with an average of about 6 μm and some grains approaching 10 μm. Also evident from SEM analysis was a fairly high level of porosity. The size of the domains is also quite large, being visible at magnifications where the domains of PZT are not apparent. The fracture characteristics show a mix of transgranular and intergranular fracture. Despite its large grain size, the material was fairly easy to process into very thin plates. The minimum plate thickness achieved for a 1 cm diameter disk was 24 μm.

The measured k_t at low frequencies was found to be approximately 0.5, comparable to the PZT materials. Considering the relatively large grain size, it is interesting to note the very low slope of k_t vs frequency (-0.32×10^{-3}) which resulted in an extrapolated k_t of 0.45 at 100 MHz. This slope was the lowest of all materials tested despite the grain size being the highest, indicating that grain size is not the dominant contributor to reduced properties at high frequencies. The low slope of k_t vs frequency can be attributed to a lower contribution of the properties from extrinsic effects which tend to be reduced at high operating frequencies. Domain wall motion in particular appears to be an important factor in determining the frequency dependence of k_t. Since PT materials in general have a reduced domain wall mobility relative to the PZT materials, it is not surprising that the frequency dependence of k_t is reduced. Thus even though both the grain and domain sizes are larger than for the PZT materials tested, the lower contribution from extrinsic effects makes the frequency dependence less for the PT materials.

The Q_m at low frequencies was highest among all of the materials evaluated, although there was a large variation in measurements from sample to sample at low frequencies. It is believed that the inconsistent measurements are linked to incomplete mixing or some other processing deficiency which leads to areas of inhomogeneous properties within the samples. In fact, areas of varying opacity were evident in the very thin samples, indicating that the composition varies spatially through the samples. The high value of Q_m at low frequencies can again be ascribed to the low degree of domain wall mobility which is present in PT materials, as domain losses dominate internal loss in PZT materials [10]. The slope of Q_m vs frequency for EC97 was highest of all materials tested, resulting in a low Q_m of about 10 at 80 MHz. This is believed to be a result of the fairly high degree of porosity present in the material. Due to the large impedance mismatch at the ceramic-pore boundary, the scattering from a pore will be much greater than for a large grain. This scattering leads to significant attenuation of the sound within the material and thus a lower Q_m. The effect is most severe when the wavelength in the material approaches the size of the pores, as is the case at frequencies approaching 100 MHz.

The relative clamped dielectric permitivity, ε_{33}^S, was 220, typical for this type of material. This is an advantage for some high frequency single element transducers in terms of electrical impedance matching, particularly for transducers more than a few mm^2 in area. The reduced dielectric constant results in a higher electrical impedance and better matching to standard 50 Ω electronics for larger area transducers, as discussed later.

The EC97 material was post processed with a heat treatment in order to improve the properties for high frequency transducers. The resulting material is referred to as EC97-HIP. The process referred to is hot isostatic pressing, or HIP, and consists of heating the samples to a high temperature such as 1000 degrees C at a high isostatic pressure such as 13.8 MPa (2000 psi). The result of the pressure and heat is a reduction in pore size and an increase in the density [11]. Both 6.0 and 0.6 mm thick samples were processed to determine if sample thickness influenced the results. All samples were repoled at 110 degrees C with a field of 50 kV/cm applied for 10 minutes in a fluourinert bath.

From SEM analysis of the EC97-HIP material it was evident that porosity had been reduced significantly. For the samples tested the density increased ~4% relative to the non-treated samples. The k_t increased slightly to a value of 0.52 measured at 50 MHz, higher than for the PZT materials. This increase can probably be attributed to the decrease in porosity. The HIP treatment and the associated decrease in porosity had an even more profound effect on Q_m, with a value of about 100 being measured at 98 MHz. This is significantly higher than the best PZT which showed a Q_m of about 20 in this range. In fact the Q_m for EC97-HIP is almost equivalent at 98 MHz to the highest Q_m of the PZT materials measured at 20 MHz, which was 120 for 3195HD. This is also convincing evidence that losses due to domain wall motion do contribute to a lower

Q_m for PZT materials, and that PT materials, owing to reduced extrinsic contributions, are inherently less lossy at high frequencies. The difference between EC97 and EC97-HIP also seems to suggest that porosity is a significant contributor to mechanical loss for PT type materials.

TRANSDUCER DESIGN BASED ON PROPERTIES

The influence of the material properties on the response of single element transducers was determined by use of the KLM model [12], which was custom implemented in Mathcad using the transfer matrix approach [13]. The measured material properties shown in Table 2, in addition to the front and rear mechanical termination conditions and the transducer area, are sufficient to model transducer operation. The connecting cable impedance and length can also strongly influence the transducer response. Selection of the best material can be made based on the modeled performance characteristics, such as the pulse echo waveform amplitude and pulse length. The electrical impedance of the transducer is particularly important in determining transducer performance.

Simulations were run using the measured 50 MHz properties for 3203HD and EC97. A 2 mm diameter transducer was loaded with water on the front and a 5.4 Mrayl material on the back. Results for the real and imaginary parts of Z_{ein} are shown in Figure 2 for high density PZT. The peak in the real part is less than 10 Ω, considerably lower than the 50 Ω impedance of the electronics. Results are shown in Figure 3 for EC97. The peak, 56 Ω, can be seen to be higher and much closer to 50 Ω than the PZT transducer.

Simulated waveforms for the two transducers driven by a monocycle pulse with an amplitude of 14 v peak to peak from a 50 Ω source impedance and loaded by a 50 Ω receive impedance show the effect of electrical impedance matching on the pulse echo response. The PZT transducer waveform, shown in Figure 3, can be seen to have a long pulse length. The PT transducer response, shown in Figure 4, can be seen to have a higher signal amplitude and a shorter pulse length, both of which contribute to improved image quality. These results are similar to those obtained by G.R. Lockwood, et al. [4] for a similar PZT transducer with an electrical matching network. The matched electrical impedance of the PT transducer facilitates energy transmission between the transducer and the electronics without the need for a matching network, resulting in improved transducer performance.

CONCLUSIONS

The piezoelectric properties of transducer materials operated at high frequencies can be significantly different than those at low frequencies. An experimental investigation determined the properties of a number of materials operated as thickness mode resonators at frequencies between 10 and 100 MHz. Results showed that conventional PZT materials have significantly reduced properties at high frequencies, most likely as a result of decreased extrinsic or domain wall motion contributions. New fine grain PZT materials have been demonstrated to have less frequency dependent properties, particularly the mechanical loss. This behavior is believed to be due to a shifting of the extrinsic reduction phenomenon to a higher frequency.

The PT class of materials were found to have properties which behaved markedly different than PZT materials at high frequencies. The frequency dependence of k_t was found to be less for EC97 than for even the fine grain PZT, despite the fact that EC97 has an AGS over an order of magnitude larger. Coupling coefficients close to 0.5 were measured at 80 MHz. This shows that composition plays a more significant role than grain size in determining the frequency dependence of k_t. While the EC97 showed high losses at frequencies close to 100 MHz, the same material which had undergone a HIP treatment showed much lower losses as a result of the decreased porosity. Thus it appears that the frequency dependence of Q_m is also affected by not only grain size and porosity, but also by composition. PT materials, possibly due to reduced extrinsic contributions, suffer less of a decrease at high frequencies than do PZT materials, despite a larger grain size. Mechanical losses are considerably lower for the PT materials in the 50 to 100 MHz range, with a Q_m of nearly 100 being measured at 98 MHz.

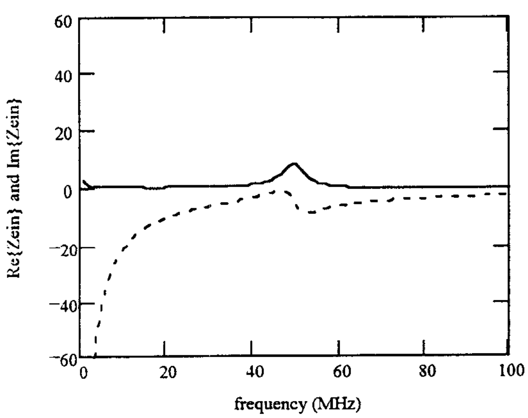

Figure 2 - Modeled impedance for 2 mm diameter 50 MHz PZT transducer. Note the peak in the real part is considerably less than 50 Ω.

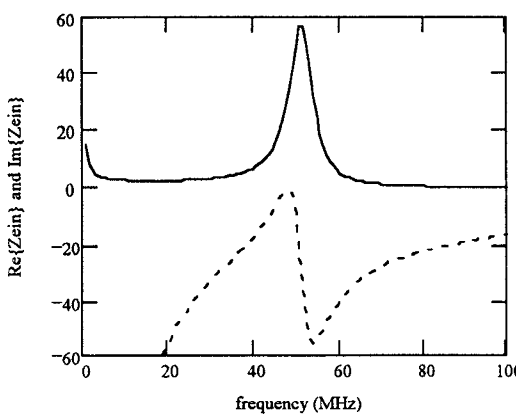

Figure 3 - Modeled impedance for 2 mm diameter 50 MHz PT transducer Note the peak in the real part is more closely matched to 50 Ω.

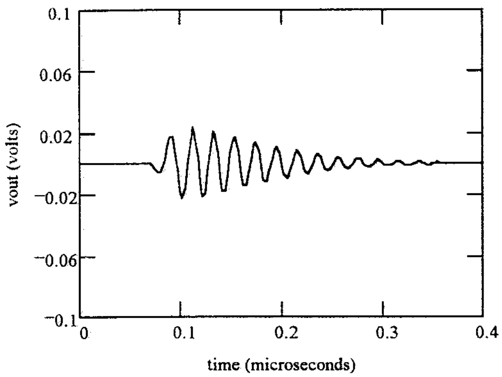

Figure 4 - Simulated pulse echo waveform for 2 mm diameter 50 MHz PZT transducer. Note the low sensitivity and long pulse length.

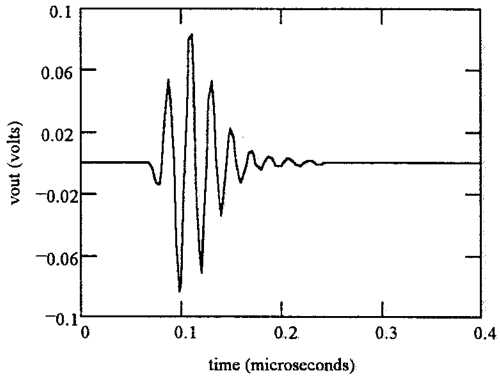

Figure 5 - Simulated pulse echo waveform for 2 mm diameter 50 MHz PT transducer. Note the higher sensitivity and shorter pulse length.

Simulations using the measured properties showed that the lower dielectric constant of the PT material can result in the electrical operating impedance of the transducer being more closely matched to 50 Ω. The simulated waveform for a 2 mm diameter PT transducer showed higher amplitude and shorter pulse length than for a PZT transducer with the same dimensions. It is possible to closely match the electrical impedance of the transducer to the electronics without the need for a matching network by considering the dielectric properties of the piezoelectric material in conjunction with the transducer area.

For transducers with a very small area relative to their thickness, PZT materials can result in close electrical matching between the transducer and electronics. This is particularly true for miniature high frequency single element transducers useful for applications such as intravascular imaging. High frequency arrays, where the elements are extremely small, will also require the high dielectric constant of PZT materials. For applications where the transducer area is larger, the PT materials can increase performance due to not only improved piezoelectric properties but also closer electrical matching.

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