Advanced Piezoelectric Single Crystal Based Transducers for Naval Sonar Applications

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Abstract - The piezoelectric, elastic and dielectric properties of PMN-PT single crystals have been evaluated for performance in high power, high duty cycle naval applications. Alternative crystal orientations, maintain high piezoelectric properties (d_{31} ~ -1000 pC/N), and allow for high height/width aspect ratio and the application of the pre-stress perpendicular to the poling direction. Modification of the composition of PMN-PT showed a 50-75% decrease in the low temperature (< 50°C) dependence of the dielectric constant. The coupling remained high (k_{33}> 0.8), and one-dimensional modeling showed only a 1-8 dB drop in the source level relative to PMN-30%PT. This is an improvement as compared to state-of-the-art, by allowing a higher drive field as a result of increased temperature stability and a higher mechanical Q.

I. Introduction

The trend towards smaller, higher power, and higher frequency sonar systems in both defense and civilian applications creates significant demand on both the electronics and sensors. Current synthetic aperture sonar systems are exploring device technology with broad bandwidth for unmanned underwater vehicles (UUV), which means with vehicles as small as 9 inches in diameter, transmit systems must be housed with limited interior volume. Tonpilz arrays are the optimum way to obtain the required acoustic pressure and bandwidth for small footprint sensors, though using traditional piezoelectrics, such as Navy Type I ceramic (PZT-4), limits the reduction in transducer size. Also, bandwidth and power capabilities are a function of the mechanical quality factor, electromechanical coupling coefficient and the drive level limits of the material.

Single crystal relaxor ferroelectrics such as $Pb(Mg_{1/3}Nb_{2/3})_{1-x}Ti_xO_3$ (PMN-PT), have shown great promise for broad bandwidth, size-limited sonar transducers. The compliance of PMN-PT is 4 to 5 times that of the ceramic, which greatly reduces the stack length for a given resonance, and the piezoelectric d_{33} coefficient is more than 6 times as large. The electromechanical coupling is also higher than PZT-4, providing a much larger operating bandwidth for a given power delivery system. Tonpilz transducers made using PMN-PT exhibit bandwidths more than double the 30% that is common in PZT devices[1].

Although the peak properties show a distinct improvement over ceramics, two key issues need to be addressed regarding real-world usage: 1) thermal and mechanical stability, and 2) lower performance due to non-ideal aspect ratio. During testing, overall source level potential was limited by the mechanical stress in the stack. Increasing the mechanical preload via the stress bolt resulted in strain and polarization non-linearities, resulting in accelerated heating and harmonic distortion. Heating also affected the dielectric properties, which show a change of over 75% in the range from 0°C to 50°C, resulting in constraints on the amplifier electronics. In certain applications, when the ring diameters were kept constant, the lower aspect ratio resulted in a 25% reduction in the electromechanical coupling coefficient (k_{eff} = 0.68) for the transducer.

These two key issues were addressed in two different sets of experiments. In the first, four different compositions of PMN-PT were grown and tested, including A-site doped and tetragonal crystals. These were tested to see if changes in the composition could significantly alter the temperature stability while maintaining the piezoelectric properties of PMN-30PT. Low-PT and tetragonal PMNT alter where on the morphotropic phase boundary the T_{rt} and T_c fall, and doping allows for a shifting of the boundary relative to PT composition. In the second set of experiments, the "32" mode was tested for mechanical and thermal stability to determine its applicability for substitution into tonpilz devices. Not only can this mode help maintain a good aspect ratio, it reduces the necessary compressive preload of the stress bolt, since the negative piezoelectric constant creates a compressive stress in the crystal when the DC bias is applied. This can reduce the nonlinear heating effects. The reduced number of glue joints in series with the vibration detection also reduces the loss and improves efficiency.

The goals of this work were to design tonpilz transducers based on novel crystallographic orientations and/or compositions of PMN-PT single crystal to optimize the performance for high drive conditions and demanding environments.

II. Methods

A. PMN-PT Tailored Compositions

Four different compositions of PMN-PT were grown using the Bridgman method. 40mm boules were oriented and sliced to obtain <001> oriented samples.

Table 1. Test parameters for PMN-PT d_{32} samples.

Sample	Electric Field (kV/cm)	Prestress (kpsi)	Prestress (MPa)	Temperature (°C)
S1	10	0, 1, 2, 3, 4	0, 7, 14, 21, 28	35, 60
S2	10	0, 1, 2, 3, 4	0, 7, 14, 21, 28	20, 40, 60
S3	10	0, 1, 2, 3, 4	0, 7, 14, 21, 28	20, 40, 60
S4	20	0, 1, 2, 3, 4	0, 7, 14, 21, 28	40

The four samples consisted of PMN-PT with 28% (PMN28), 30% (PMN30) and 38% PT (PMN38), and an A-site doped PMN-30PT crystal (PMN-A). Each material was characterized by using five different aspect ratios as given in the IEEE Standards[2], and was oriented in the <001> direction for poling. All pieces were poled at room temperature using a 5 kV/cm electric field, except in the case of PMN38. Due to the hardness of the material relative to poling, it was poled at 2 kV/cm while cooling from above the Curie temperature. Resonance data were collected using an HP4194A impedance analyzer. Temperature dependence of the dielectric constant was measured between 0°C and 50°C, since that is the range of interest in sonar, though the range was increased to determine the rhombohedral-tetragonal phase transition (T_{rt}) and Curie (T_c) temperatures of the compositions.

Based on the low-field properties of the tailored compositions, one-dimensional models of tonpilz transducer elements were made to compare the basic performances of the materials. The models were modified to produce the same fundamental resonance, as well as source level. The drive fields were then compared between each composition. Electrical impedance and phase data were also extracted from each model to calculate the transducer electromechanical coupling and Q.

B. d_{32} Tonpilz Operation

The d_{32} orientation has a number of advantages, as mentioned above, though it also can provide improvements in electrical impedance matching. The proposed bar design, shown in Figure 1, allows for an easier change in impedance than the rings typically used due to the ease of thickness and length modifications.

In order to determine the dependence of piezoelectric and elastic properties of the d_{32} orientation on stress, temperature and electric field, SDECS measurements were performed by NAVSEA[3]. A 10 Hz unipolar drive was used, which was maximized at approximately 72% of the bias voltage. Crystallographically oriented <001> bars of 4x4x12 mm in size were prepared with the faces in the <110> family, one of which was sputtered with Cr/Au. An array of test conditions involving electric field, prestress and temperature were used, and are summarized in Table 1.

Elastic, dielectric and piezoelectric measurements of the d_{32} orientation were also made using resonance and direct measurements. These values were used for a finite element model of the tonpilz transducers in ATILA-GiD to determine the in-air displacement of the head mass and electromechanical coupling coefficients

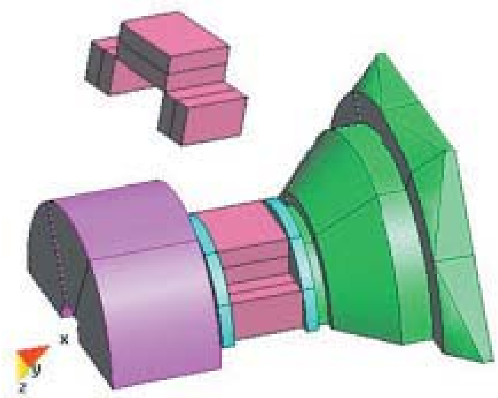

Figure 1. Stacked bar geometry shown separately and in (half) transducer assembly.

Table 2. Selected properties of Bridgman-grown PMN-PT compositions.

	30%	**28%**	**38%**	**A-site**
$K_{33}T$	7800	4366	393	5883
T_{rt} (°C)	85	104	NA	107
T_c (°C)	166	129	209	137
S_{11}^E ($x10^{-11}m^2/N$)	5.97	5.25	0.92	5.52
S_{12}^E ($x10^{-11}m^2/N$)	-0.77	-2.30	-0.16	-1.39
S_{13}^E ($x10^{-11}m^2/N$)	-4.53	-1.99	-0.47	-3.08
S_{33}^E ($x10^{-11}m^2/N$)	8.65	3.59	1.74	5.50
d_{33} (pC/N)	2280	1100	230	1504
d_{32} (pC/N)	-1060	-547	-62	-794
k_{33}	0.91	0.86	0.79	0.89
Q_m	156	164	109	209

III. Results

A. PMN-PT Tailored Compositions

Table 2 summarizes selected properties measured for each composition. Both the 28% and doped crystals show an increase of 20°C in the $T_{rt}$with minimal decreases in

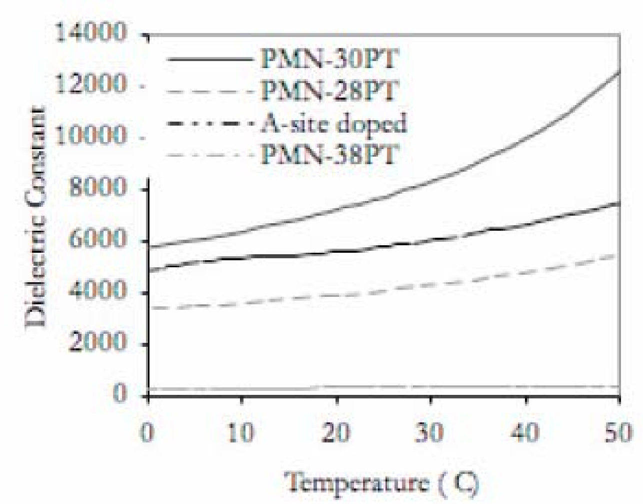

Figure 2. Dielectric properties of PMN-PT compositions from 0°C to 50°C.

Table 3. Summary of 1D model results for tonpilz transducers incorporating different compositions.

Material	SL Peak (dB)*	Crystal Length	Drive Level (dB)	Drive Field (V/mil)
PMN30	201	1	0	3.0
PMN28	200	1.39	1.1	3.4
PMN-A	198	0.83	2.9	4.2
PMN38	193	2.59	8.2	7.8

* Peak modeled at 3.0 V/mil drive field.

electromechanical coupling. This should result in more uniform properties at lower temperatures. The d_{33} and d_{31} decrease by 25-50%, though more work is being done to determine whether these materials can be driven harder to compensate for this. The low dielectric and piezoelectric constants of the tetragonal PMN are not very well suited to this application, though its high Tc shows promise for higher temperature applications.

From Figure 2, it can be seen that the dielectric constant of the doped crystal varies significantly less than the 30% crystal. All values are relative to the value at 20°C. In the range of 0°C to 50°C, it shows a change of only 37%. The PMN38 showed the least change at 33% and the PMN28 was 54%. This fits well with the increase in T_{rt} of the PMN28 and PMN-A, and increase in T_c of the PMN38.

Modeling results for the modified tonpilz elements are shown in Figure 3. A summary of the results is shown in Table 3. The source level for the PMN30 was the largest at 201 dB, for the given 1.18 kV/cm (3 V/mil) excitation. Given the nominal increases in drive level, both the PMN28 and PMN-A provided similar and source level to the PMN30. The PMN38 exhibited a significantly lower bandwidth, and despite its higher Q value, is not a desirable material for these

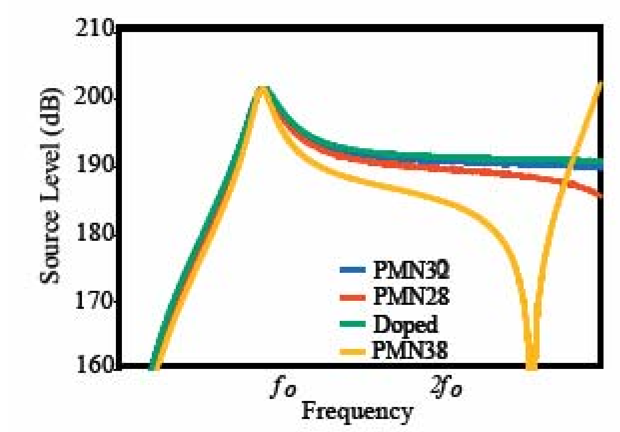

Figure 3. Source level for tonpilz models using different compositions.

tonpilz applications. It is not known what effect the higher drive levels would have on the crystals, though with the increased temperature stability, it is expected they will perform well and warrant further study.

B. d_{32} Tonpilz Operation

Table 4 shows a comparison between PMN30 crystalin the <001> and <110> poled domains. The d_{32} bar shows a piezoelectric constant 60% that of the ring configuration, and a very close effective compliance. The permittivity was half that of the ring, though the electrical impedance can be easily changed, as mentioned above.

The effect of the lower piezoelectric constant is evident in Figure 4. The head mass shows a displacement just over 1 micron, compared with 3 microns with the rings. The displacement is still more than double that of the PZT8 stack.

The SDECS measurements show that temperature and pressure have a significant impact on the field-induced phase transition. Figures 5 and 6 show the strain curves versus field for selected pressures and temperatures. At 20°C, even up to 4 kpsi the transition does not occur until near 1 MV/m. However, at 60°C and higher pressures, the transition is induced under no field. The limit in d_{33} reduces the overall compliance and source level of the resulting device. This could limit the use of the orientation in high drive applications. Operation at lower temperatures is affected little by pressure.

Table 4. Properties of PMN-PT single crystals.

Property	PMN-PT		PZT-8
	d_{32} bar	d_{33} ring	
K^T_{33}	3721	7800	1000
d_{33} (pC/N)	901	1981	220
d_{31} (pC/N)	-431	-921	-90
d_{32} (pC/N)	-1188	-921	-90
Compliance ($x10^{-12}$ m^2/N)	s_{11}^E=57.4	s_{33}^E=67.7	s_{33}^E=13.9

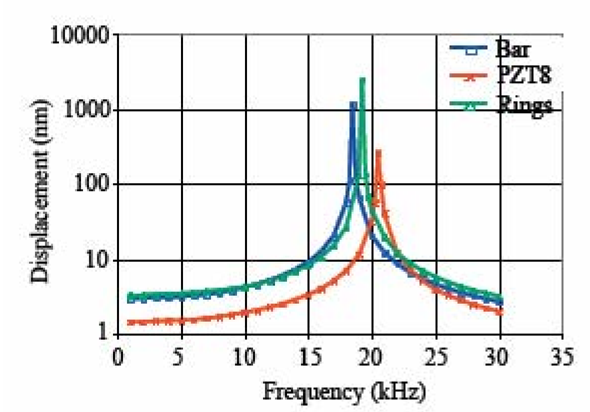

Figure 4. Comparison of in-air displacement of tonpilz head modeled using PZT8 or PMN-PT.

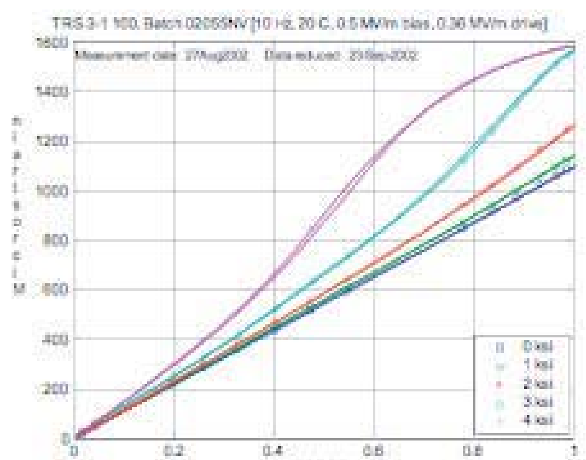

Figure 5. Polarization and strain vs field for selected values of temperature and prestress for <110> poled PMN-PT.

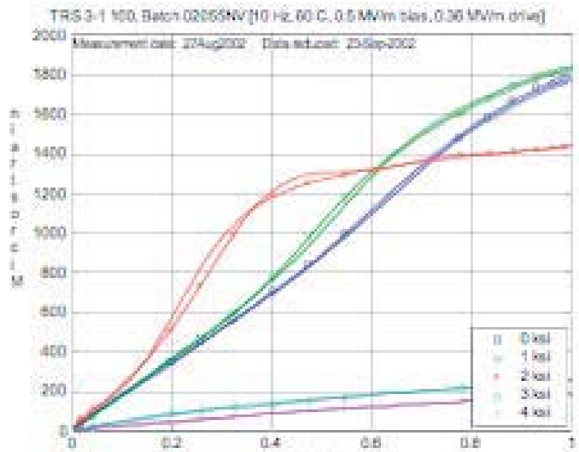

Figure 6. Strain vs field at 60°C for different pre-stresses. Field is in MV/m.

IV. Discussion and Conclusions

The performance characteristics of tonpilz transducers have been limited due to nonlinear effects that heat the transducer, temperature dependence of the properties, and a non-ideal aspect ratio during direct substitution of stacks. Tailoring the composition and/or changing the orientation show promise for overcoming these limitations.

The data show that the dielectric constants of the tailored materials change 50-65% less than PMN30 over a 50°C range. Modeling shows that similar bandwidth, source level and center frequency can be attained by the PMN-A and PMN28 compositions, though it is currently unknown what effects the higher drive fields will have on the material properties. The bar tonpilz design and d_{32} operation has several advantages over the ring design, since the capacitance can be easily modified and the pre-stress is orthogonal to the poling direction. However, the increased effect of temperature and prestress on the field-induced transition point does reduce the efficacy of the orientation for high drive applications.

V. Acknowledgments

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VI. References

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