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Finite Element Comparison of Single Crystal vs. Multi-layer Composite Arrays for Medical Ultrasound

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***Abstract*—Finite element (PZFlex; Weidlinger Assoc., New York, NY and Los Altos, CA) simulations predict that for a 2-MHz phased array element with a single matching layer, the three-layer hybrid structure [1] increases the pulse echo signal-to-noise ratio (SNR) by 16 dB over that from a single layer PZT element and −6 dB pulse echo fractional bandwidth from 58% for the PZT element to 75% for the hybrid element. Analogous finite element method (FEM) simulations of single crystal material [lead zinc niobate (PZN)-8% lead titanate (PT)] showed increased SNR by only 3.1 dB, but a −6 dB bandwidth of 108%.**

I. Introduction

TWO MAJOR goals of medical ultrasound research are increasing the SNR, for increased penetration, and the bandwidth, for improved resolution, of transducer arrays. Investigators have proposed competing technologies, which include multi-layer composite [2]–[9] versus single crystal [10]–[12] transducers to obtain increased SNR and bandwidth.

In previous work, we discussed simulation and experimental results for a multi-layer composite hybrid transducer in which one layer of 2-2 composite was on top of two bottom layers of monolithic PZT. For the hybrid array, the most significant experimental results were a 11.1-dB improvement in SNR and increased −6 dB fractional bandwidth by a factor of 1.1 compared with single layer PZT-5H transducers. Simulations predict further improvement in bandwidth by a factor of 1.4, but experimental material constants have limited results thus far [9].

Single crystal transducers are solid solutions of materials such as PZN/PT and lead magnesium niobate (PMN)/PT. The improvements reported for single crystal transducers are due to increased electro-mechanical coupling ($k_{33} \approx 0.9$), strains of up to 1.7%, and decreased acoustic impedance ($Z \approx 22$ MRayls). However, fracturing, which occurs during dicing, and the difficulty in obtaining a large enough crystal with consistent material properties complicates fabricating medical ultrasound arrays from such material. Saitoh *et al.* [11], [13] presented a single crystal transducer array (PZN-9%PT) that yielded a 5.2-dB increase in sensitivity over PZT-5A and a −6 dB fractional bandwidth of 82%.

In this paper, we describe a FEM comparison of single crystal vs. multi-layer composite vs. PZT-5H transducer arrays. SNR, bandwidth, and the "badness" criterion, which combines SNR and pulse length, previously discussed by Selfridge [14], Lockwood and Foster [15], and Mills and Smith [3], were used to evaluate these designs. "Badness" is defined as the energy in the pulse ringdown following the center of mass of the pulse (t_0) divided by the peak amplitude of the pulse squared. Badness has been normalized to a value of one for the best design in this work for comparison purposes only and not shown as an absolute evaluation parameter.

II. Methods

A. Modeling Methods

We performed FEM simulations using PZFlex to improve our hybrid array design, including two ceramic bottom layers, a 2-2 composite top layer, and a single matching layer. The software package has been validated in previous transducer development projects [3], [16], [17]. Impedance plots and pulse echo simulations were performed to compare the single crystal, multi-layer composite, and PZT control arrays. An epoxy backing ($Z =$ 3 MRayls), single matching layers optimized for each transducer, and two passive (open circuit) neighboring elements were included in the model. Fig. 1 illustrates FEM meshes of each design, but only shows one neighboring element on either side of the active elements. Material properties for PZN-4.5%PT and PZN-8%PT were obtained from Yin *et al.* [18].

Planar symmetry was used to allow modeling of only one-half the width of the transducer in azimuth, and periodic symmetry was used to model only one period of the 2-2 composite in elevation. (The unit cell was one-half of the PZT plate and the epoxy filler in elevation.) The electrode area was scaled, and the unit cell was repeated in elevation to obtain the correct electrical and acoustical results presented in this paper. Because of the symmetry, the diffraction effects in elevation are neglected, but are modeled in azimuth. Refer to the discussion by Abboud *et al.* [18] for more details about the equations that have been implemented in PZFlex. Tables I and II contain the material properties used for this paper, Tables III, IV, and V contain the mesh details, and Table VI contains the details of the array models. Ideally, 8 to 20 mesh elements per wavelength at the highest frequency of interest should be maintained. The time steps were 6.0 nS in water and 2.0 nS elsewhere for the PZT control model, 9.1 nS in water and 3.0 nS elsewhere for the hybrid model, and 3.8 nS over the entire single crystal model. By varying the mesh sizes and time steps in relation to the longitudinal velocity

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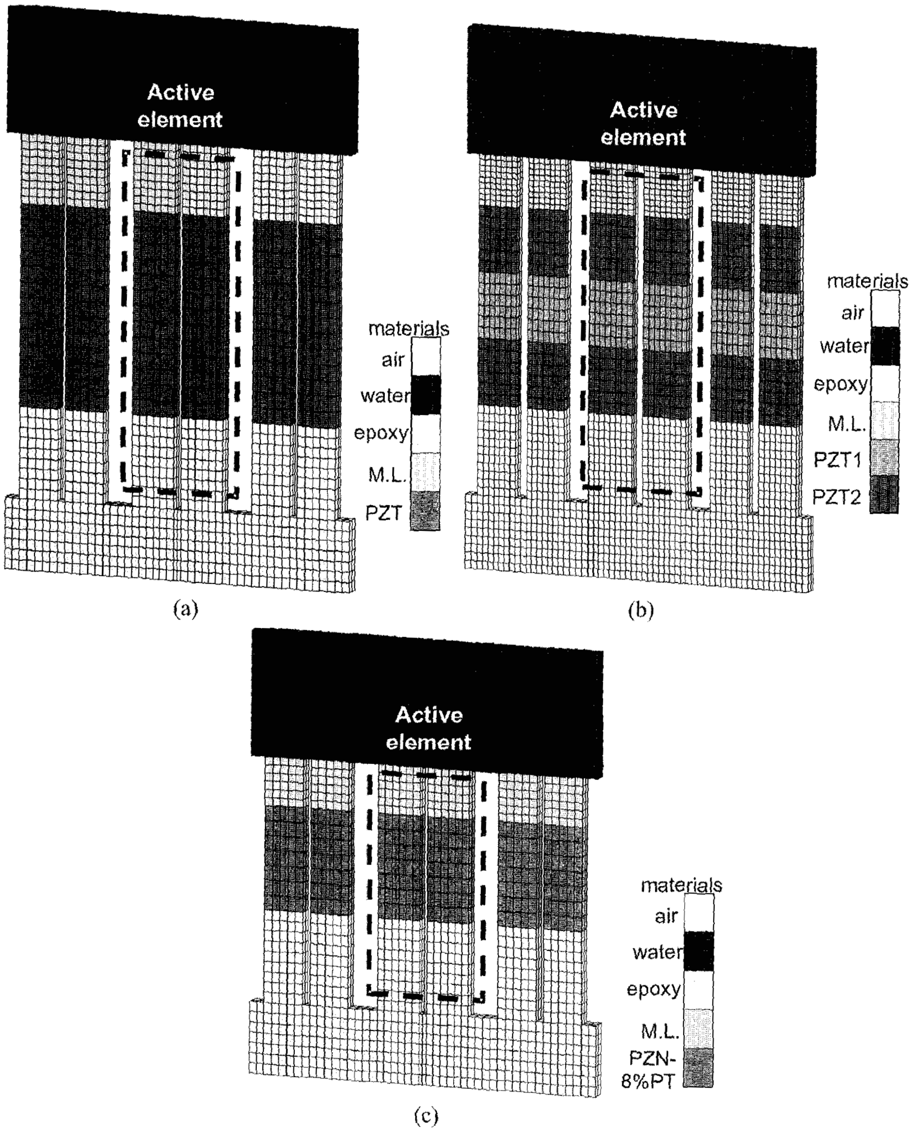


Fig. 1. FEM mesh of three elements of each array: a) PZT, b) three-layer 2-2 composite hybrid, and c) PZN-8%PT. The center element is active in each case.

of sound in each material, accuracy can be maintained, if chosen properly, while improving computational efficiency [16]. These simulations were run under Windows NT on a 450-MHz Intel Pentium® II processor and took 2 to 6 min.

To optimize each design, the pulse-echo simulations were run with different matching layers, changing thickness and matching layer density, to obtain the maximum gain-bandwidth product (where gain was peak-to-peak pulse-echo amplitude, and bandwidth was −6 dB fractional bandwidth). Kerf width and sub-dicing techniques were also employed to optimize array element design. It should be noted that, throughout this paper, we assume the pre-amplifiers in receive mode are the dominant source of noise, which is a constant. Thus, increases in SNR are determined by increases in signal. We also assume the cable can be modeled as a capacitor because of the short length (cable length $\ll \frac{\lambda}{4}$ and the high impedance amplifiers in receive mode. Also, 50-Ω transmitters were used in these simulations for transmit mode.

B. Modeling Results

Table VI contains the details of the optimized design for each transducer.

As in Fig. 2, the series resonant frequency, from the PZFlex-simulated impedance plots, for both the PZT-5H

TABLE I
PZT Material Properties Used for Modeling.

	PZT-5H [19]	PZN-8%PT [18]
ρ (kg/m^3)	7820	8320
c^E_{11} (N/m^2)	1.37×10^{11}	1.11×10^{11}
c^E_{33} (N/m^2)	1.26×10^{11}	1.02×10^{11}
c^E_{44} (N/m^2)	2.23×10^{10}	6.10×10^{10}
c^E_{12} (N/m^2)	8.79×10^{10}	1.02×10^{11}
c^E_{13} (N/m^2)	9.23×10^{10}	9.97×10^{10}
c^E_{66} (N/m^2)	2.48×10^{10}	6.56×10^{10}
e_{x5} (C/m^2)	16.1	9.39
e_{z1} (C/m^2)	−9.44	−8.84
e_{z3} (C/m^2)	22.5	11.8
ε^S_{11} (F/m)	1310	2850
ε^S_{33} (F/m)	1200	579
Q (mech.)	90	90

TABLE II
Polymer Material Properties Used for Modeling. (Attenuation Is at 3.5 MHz.)

Material	Matching layer	Composite filler epoxy	Backing epoxy
ρ (g/cm^3)	varies*	1.16	1.18
v_l (m/s)	2800	2620	2470
v_s (m/s)	1300	1150	1080
α_l (dB/mm)	1.4	3.6	4.7
α_s (dB/mm)	2.9	8.3	4.7
$(\varepsilon_{33})^S/\varepsilon_0$	1	1	1

*See Table VI.

TABLE III
FEM Mesh Details for the PZT-5H Control Transducer. (The Wavelength Is Based on Bulk Acoustic Velocities.)

Material	Element size (μm)	Elements per wavelength at 2 MHz
Water	25 × 24 × 25	30 × 32 × 31
Matching layer	26 × 24 × 25	55 × 59 × 56
PZT	51 × 24 × 25	40 × 85 × 81
Backing	33 × 24 × 25	37 × 52 × 49

TABLE IV
FEM Mesh Details for the Hybrid Transducer. (The Wavelength Is Based on Bulk Acoustic Velocities.)

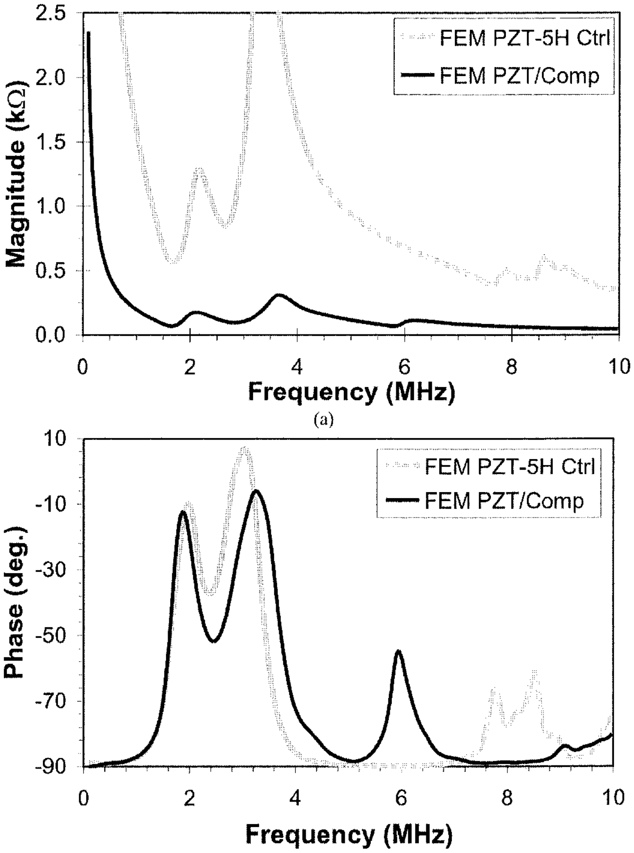
Material	Element size (μm)	Elements per wavelength at 2 MHz
Water	20 × 19 × 25	39 × 41 × 31
Matching layer	19 × 19 × 25	74 × 75 × 56
Composite polymer	37 × 19 × 25	36 × 70 × 52
Composite PZT	37 × 19 × 25	55 × 108 × 81
PZT	37 × 19 × 25	55 × 108 × 81
Backing	27 × 19 × 25	45 × 66 × 49

TABLE V
FEM Mesh Details for the PZT-8%PT Transducer. (The Wavelength Is Based on Bulk Acoustic Velocities.)

Material	Element size (μm)	Elements per wavelength at 2 MHz
Water	25 × 24 × 25	30 × 32 × 31
Matching layer	27 × 24 × 25	53 × 59 × 56
PZT-8%PT	49 × 24 × 25	36 × 74 × 70
Backing	33 × 24 × 25	37 × 52 × 49

TABLE VI
FEM-Optimized Array Dimensions and Properties.

	PZT-5H	Hybrid	PZN-8%PT
Pitch (μm)	385	385	385
w_{kerf} (μm)	100	85	100
$w_{kerf\ (sub\text{-}dice)}$ (μm)	25	40	25
t (μm)	660	660	340
L (mm)	8	8	8
t_{ML} (μm)	230	170	160
ρ_{ML} (g/cm^3)	2.6	1.9	2.7



(a)

(b)

Fig. 2. FEM complex impedance magnitude (a) and phase (b) in water for the PZT control and the hybrid array elements.

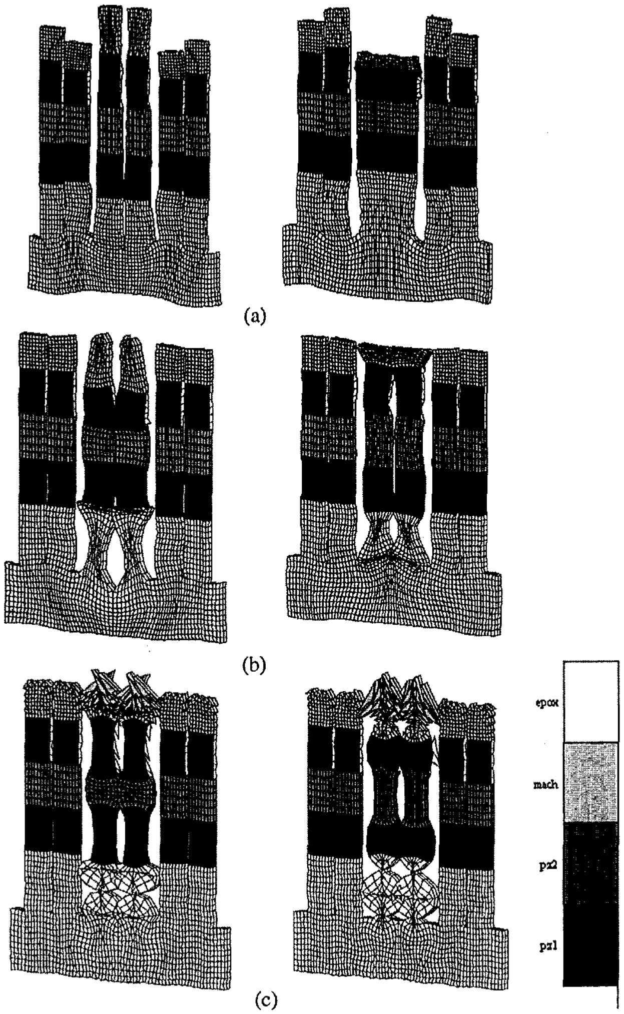


Fig. 3. Shape functions for the three layer hybrid array element at: a) 1.65 MHz, b) 3.25 MHz, and c) 5.80 MHz showing maximum (left) and minimum (right) deflection. (Note that water is not shown.)

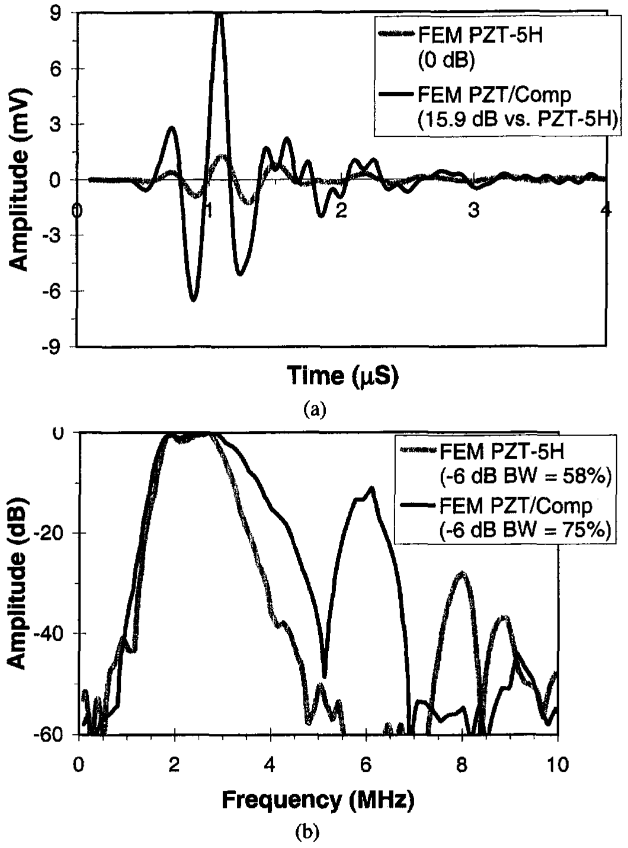


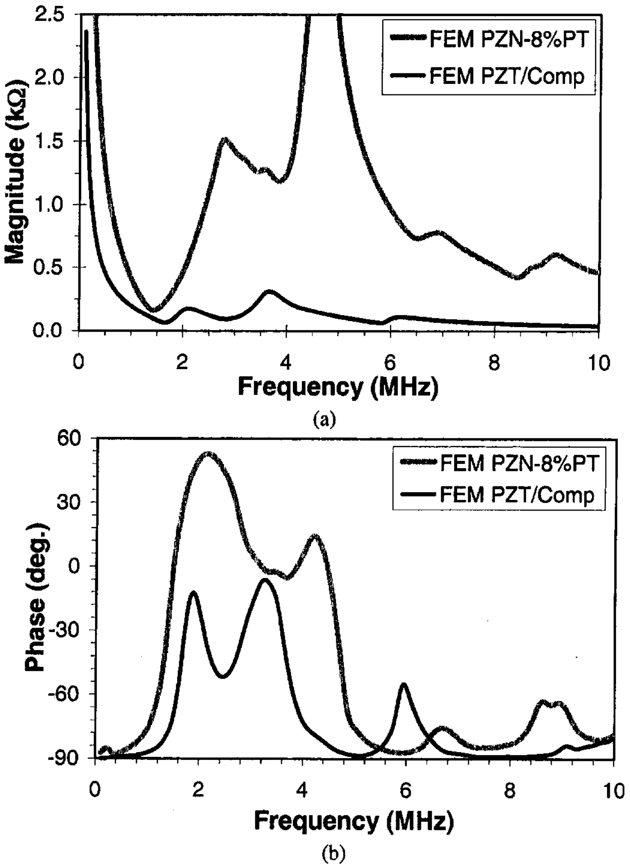
Fig. 4. FEM pulse-echo results a) pulse and b) spectra for the PZT control and hybrid array elements in water.

control and the hybrid array elements was 1.7 MHz with a magnitude of 560 Ω for the PZT control element and 69 Ω for the hybrid element. The single layer resonance in the hybrid element appears near 6 MHz, and, for both array elements, the third harmonic of the thickness resonance is between 7 and 10 MHz. Shape functions at 1.65, 3.25, and 5.80 MHz are illustrated in Fig. 3 to confirm the cause of each resonance. In Fig. 3(a), the main mode of oscillation is in the thickness direction. Fig. 3(b) shows the thickness mode resonance coupled with a bending mode of the element, and Fig. 3(c) illustrates the single layer resonance of the multi-layer stack coupled with shear modes in the backing and matching layers.

Fig. 4 shows the simulated pulse-echo results. The PZT control element had an amplitude of 2.5 mV, a −6 dB bandwidth of 58%, and badness of 11.7. The hybrid element echo amplitude was 16 mV, a −6 dB bandwidth of 75%, and a normalized badness of 1. Thus, the hybrid array had increased echo amplitude of 15.9 dB, increased bandwidth by a factor of 1.29, and decreased badness by a factor of 11.7 compared with the PZT-5H transducer.

The complex impedance results for the PZN-8%PT versus the hybrid transducer are in Fig. 5. In this case, the series resonant frequency for the single crystal transducer was 1.4 MHz with a magnitude of 160 Ω compared with 69 Ω for the hybrid element. The third harmonic of the thickness resonance is between 6 and 10 MHz.

Fig. 6 shows the simulated pulse-echo results for the single crystal transducer versus the hybrid design. The PZN-8%PT element had an amplitude of 3.6 mV, a −6 dB bandwidth of 108%, and a normalized badness of 5.4. Thus, the single crystal element had an increased echo amplitude of 3.1 dB, increased bandwidth by a factor of 1.86, and decreased badness by a factor of 2.2 compared with the PZT-5H control element. These results appear consistent with the experimental results obtained by Saitoh *et al.*, where PZN-9%PT yielded a 5.2-dB increase in sensitivity over PZT-5A and a −6 dB fractional bandwidth of 82% [11].



(a)

(b)

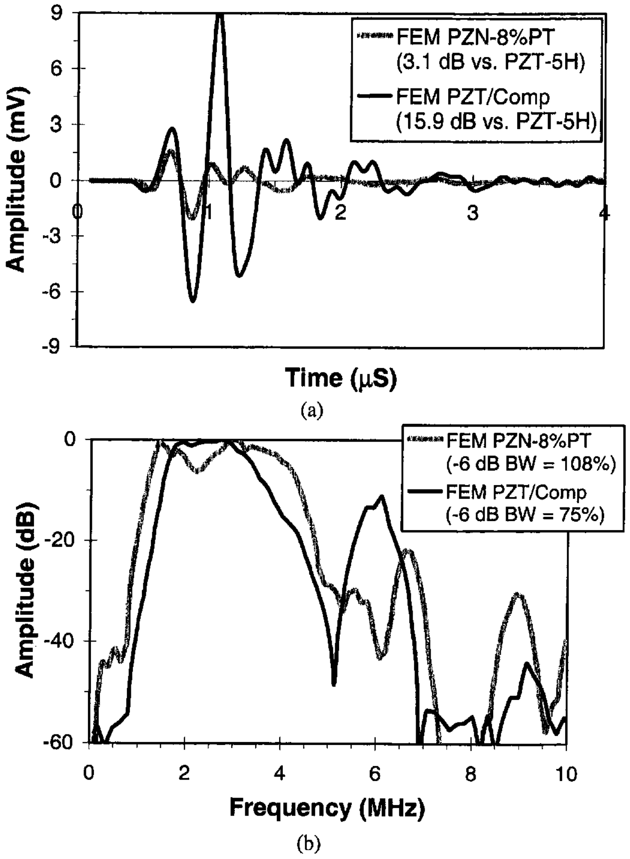
Fig. 5. FEM complex impedance magnitude (a) and phase (b) in water for the PZN-8%PT and the hybrid array elements.

TABLE VII
Summary of FEM Results.

	PZT-5H	Hybrid	PZN-4.5%PT	PZN-8%PT
Z_S (Ω)	350	44	250	160
SNR (dB)	0	15.9	2.3	3.1
−6 dB BW (%)	58	75	88	108
Normal badness	11.7	1	5.6	5.4

III. Discussion

This paper has presented a finite element comparison, summarized in Table VII, of phased array transducers using PZT-5H versus a multi-layer composite hybrid versus a single crystal. The FEM simulations predict that a hybrid three-layer transducer array, where the outer most layer is a PZT/polymer composite, is superior to PZT-5H and at least comparable with single crystal transducer arrays. We used SNR, bandwidth, and the badness parameter as measures of performance. With the exception of the bandwidth of the single crystal transducer, the hybrid array was superior in each case.



(a)

(b)

Fig. 6. FEM pulse echo results a) pulse and b) spectra for the PZN-8%PT and hybrid array elements in water.

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