Air-Coupled Transducers Based on 1-3 Connectivity Single Crystal Piezocomposites.

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***Abstract*—Air-coupled piezoelectric transducers made of 1-3 connectivity PMN-PT single crystal composites (centre frequency around 1.0 MHz) were designed, built and characterized. Several matching layers configurations have been tested in order to achieve optimum sensitivity or bandwidth or both. Results are compared with those obtained from similar transducers made using 1-3 PZT ceramic piezocomposites. Both kinds of transducers exhibit similar peak sensitivities (-23 dB), but single crystal transducers present a smoother and wider frequency band (up to 89%).**

Keywords; PMN-PT single crystals, air-coupled transducers.

I. INTRODUCTION.

In spite of the large acoustic impedance mismatch between air and any solid material, air-coupled ultrasounds have been used in the past for many different applications, mainly in the fields of non destructive evaluation and materials characterization. Two main types of transducers are currently used: piezoelectric and electrostatic transducers. To minimize the effect of impedance mismatch between the piezoelectric element and the air, piezoelectric transducers make use of 1-3 connectivity composites and different configurations of matching layers (graded matching layers [1], quarter wave length ($\lambda/4$) matching layers [2], [3], or sub-wavelength matching layers [4]).

New air-coupled ultrasound applications are demanding transducers capable of operating under adverse environmental conditions, with larger bandwidths while keeping sensitivity at high values. One promising solution is the use of 1-3 connectivity single crystal composites [5], [6]. In particular, PMN-PT 1-3 composites present a relatively higher electromechanical coupling compared to conventional PZTs, this has been used in the past to improve bandwidth and overall transducer performance for contact and water coupled transducers [7]-[10]. In this paper, the use of PMN-PT 1-3 composites to fabricate air-coupled transducers is investigated.

II. MATERIALS.

A. Active materiasls: 1-3 connectivity piezocomposites.

Several 1-3 single crystal (SC) composite disks were fabricated using the dice-and-fill technique. PMN-PT single crystals (TRS Technologies Inc.), and Spurr epoxy (Polyscience, inc.), were used as the active and passive phases, respectively. A Model Basic-Dice II dicing machine (Dicing Technology Inc), equipped with a 0.008”(0.2 mm) / 0.125” (3.175 mm) (thickness/exposure) dicing blade, was used to dice PMN-PT single crystals. Various volume fractions (25-50%) were prepared by changing the width of piezoelectric elements. After backfilling the saw cuts (kerfs) with epoxy, the composites were lapped down to approximately 1 mm, which gives the fundamental thickness resonant frequency around 1 MHz. The electrical properties of fabricated 1-3 composites were then characterized using an HP4194A impedance analyzer. Relevant transducer properties of these composites are listed on Table I. For comparison purposes, 1-3 PZT ceramic fiber (CF) composite disks (Smart Materials, Germany) with a similar range of ceramic volume fraction values and a random fiber distribution have also been used. Main properties appear on Table II. In all cases, a disk diameter of 15 mm was used.

B. Passive materials: matching layers.

The type of materials used to produce the matching layers (according to the transducers design specifications –see section III-) and their impedances are listed on Table III. Fillers (like alumina or tungsten powder) are used to increase the impedance of the matrix, while glass microballoons fillers were used to decrease it.

TABLE I. PROPERTIES OF THE 1-3 PMN-PT SINGLE CRYSTAL (SC) PIEZOCOMPOSITE DISKS USED TO FABRICATE THE AIR-COUPLED TRANSDUCERS. f_m AND f_n ARE THE FUNDAMENTAL FREQUENCIES OF IMPEDANCE MINIMUM AND MAXIMUM, RESPECTIVELY.

Mnemonic	*Volume fraction (%)*	*Acoustic Impedance (MRayl)*	f_m *(MHz)*	f_n *(MHz)*
SC-1-30	26	9.97	0.89	1.48
SC-2-30	27	10.63	1.09	1.49
SC-3-30	26	10.35	0.79	1.50
SC-1-45	45	14.51	0.97	1.57
SC-2-45	45	14.57	0.93	1.47
SC-3-45	48	15.27	0.78	1.47

TABLE II. PROPERTIES OF THE 1-3 PZT CERAMIC FIBER (CF) PIEZOCOMPOSITES DISKS.

Mnemonic	*Volume fraction (%)*	*Acoustic Impedance (MRayl)*	f_m *(MHz)*	f_n *(MHz)*
CF-1-25	22	7.30	1.02	1.34
CF-2-25	22	7.30	1.02	1.33
CF-1-35	38	11.07	0.98	1.20
CF-2-35	30	9.95	0.97	1.14
CF-1-65	66	17.40	1.07	1.33
CF-2-65	71	18.40	1.02	1.26

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TABLE III. EMPLOYED MATERIALS FOR THE MATCHING LAYERS DEPENDING ON THE REQUIRED IMPEDANCE.

Impedance range (MRayl)	***Materials***
0.1-0.5	Polymeric membranes [2], [3], [11], [12].
0.5-1.0	Calcium carbonate powder aggregates [13].
1.0-2.5	Silicone rubbers (with and without fillers).
2.5-5.5	Epoxy resins or polyurethanes (with and without fillers).

III. TRANSDUCERS DESIGN, SIMULATION, AND FABRICATION.

All transducers were designed with an external λ/4 matching layer made of a polymeric membrane [2], [3], [11] (acoustic impedance: 0.05 MRayl, attenuation coefficient at 1.0 MHz: 850 Np/m). Two or three intermediate matching layers were used between the piezocomposite disk and the membrane. Materials for the matching layers are selected to meet the acoustic impedance value (Z_i) given by [11] and [14]:

$$Z_i = \left(Z_C^{(n+1-i)} Z_M^{i}\right)^{1/(n+1)}, \qquad (1)$$

where n is the number of intermediate matching layers layers, and Z_C and Z_M are the acoustic impedances of the piezocomposite and the polymeric membrane, respectively. Required impedance values for the intermediate matching layers range from 0.11 up to 5.5 MRayl, depending on the number of layers and on the impedance of the 1-3 piezocomposite. Employed materials are listed on Table III.

Transducer response is theoretically estimated by calculating the amplitude of the wave potentials in each material layer. Towards this end boundary conditions, accurate material properties and pertinent constitutive equations are considered. Concerning the number of layers, simulations results are shown in Fig. 1. The best sensitivity is obtained with two matching layers, but much broader bandwidths are obtained with three and four matching layers with a reduction of the sensitivity of about 8 dB. Therefore, designs with three or four matching layers are preferred.

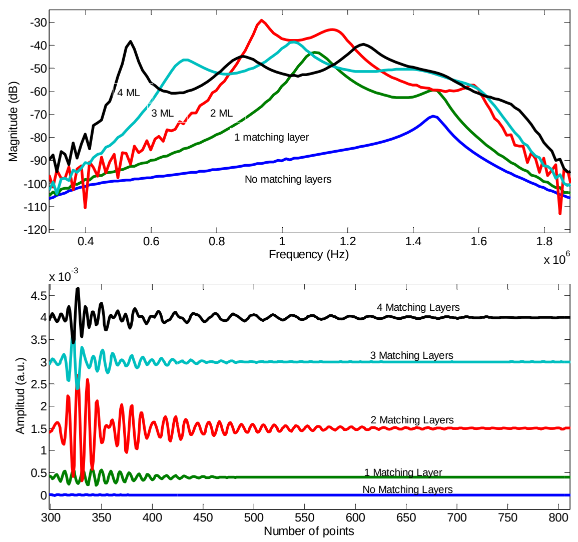

Figure 1. Calculated frequency band and signal in the time domain for pitch-catch operation. Separation between transmitter and receiver 10 mm.

Figure 2. Prototype transducers for efficient air-coupled operation. Transducer aperture: 20 mm

In addition, simulation results show that the resonant frequency of the matching layers are to be tuned to f_m to get maximum sensitivity, while they are to be tuned to $(f_m+f_n)/2$ to get maximum bandwidth.

Transducers are designed so that the matching layers can be easily removed, so different configurations can be tested. Three cases have been tried: 1) Three matching layers tuned to f_m, 2) three matching layers tuned to $(f_m+f_n)/2$, and 3) four matching layers tuned to $(f_m+f_n)/2$. Some of the fabricated prototypes are shown in Fig. 2.

IV. TRANSDUCERS CHARATERISATION.

Transducer performance was examined under two different operating conditions, corresponding to pulse-echo and through transmission modes of operation. In the pulse-echo mode, an aluminum reflector was located at 25 mm, while in through transmission the airgap between transmitter and receiver was 17 mm. A 5058 Panametrics pulser/receiver was used. Spike amplitude was set to 400 V, and gain was 0 dB and 20 dB for through transmission and pulse-echo measurements, respectively. The received signals were digitized and Fast Fourier transforms extracted using a Tektronix 5052 digital oscilloscope, with the acquisition mode set to high-res. Electrical signal applied at transmitter terminals was also displayed on the oscilloscope.

Two-way insertion loss (IL) was calculated as the ratio of the measured voltage across the receiver transducer terminals (V_R) to the applied voltage across the transmitter transducer terminals (V_T).

$$IL = 20log_{10}\left(\frac{|FFT(V_R)|}{|FFT(V_T)|}\right), \qquad (2)$$

The peak transducer sensitivity (SNS), was calculated taking into account the contribution of the ultrasound attenuation in the air-gap:

$$SNS = \max(IL) + 20log_{10}e^{\alpha t}, \qquad (3)$$

where t is the total distance travelled by the ultrasonic signal in the air gap and α is the attenuation coefficient, calculated by $\alpha = 1.84 \times 10^{-11} \times f^2$, were f is the frequency [12]. For many air-coupled applications the frequency band of the two way Insertion Loss with a signal to noise ratio over 20 dB is a good estimation of the usable frequency bandwidth

TABLE IV. TRANSDUCERS PERFORMANCE IN PULSE-ECHO.

Active element	*Peak sensitivity (dB)*	*f_c (MHz)*	*Matching layers conf.*	*Relative bandwidth (%)*
CF-25	-39	1.12	3L, f_m	66
CF-35	-32	0.89	3L, f_m	33
CF-65	-33	0.88	3L, f_m	34
	-37	0.83	3L, $(f_m + f_n)/2$	69
SC-30	-50	0.82	3L, f_m	66
SC-45	-39	0.83	3L, $(f_m + f_n)/2$	89
	-32	0.92	3L, f_m	66
	-37	0.96	4L, $(f_m + f_n)/2$	39

where, f_c.: transducer centre frequency, 3L: three matching layers, 4L: four matching layers, f_m: matching layers tuned to f_m, and $(f_m + f_n)/2$: matching layers tuned to $(f_m + f_n)/2$.

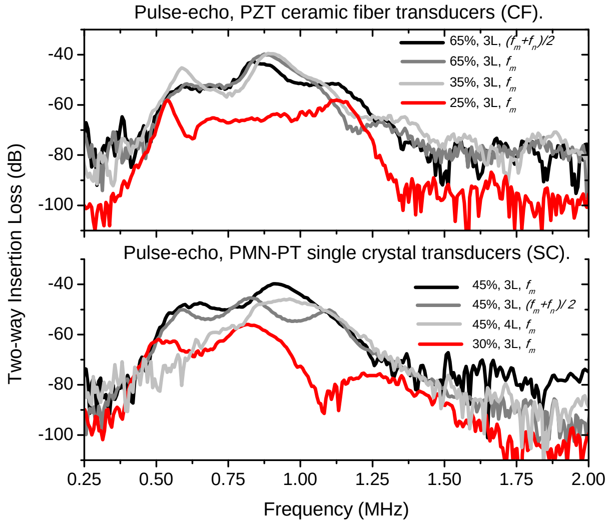

Figure 3. Two-way Insertion Loss of the air-coupled transducers made with the 1-3 connectivity in Table III.

A. Pulse-echo results.

Table IV summarizes the results. Maximum sensitivity of -32 dB was achieved with both SC (45%) and CF (35% and 65%) composites with three matching layers tuned at f_m. In spite of the relatively lower acoustic impedance, the lowest volume fraction composites present the poorest performance. The widest bandwidth (89%) was achieved with the SC composite with three matching layers tuned at $(f_m + f_n)/2$. Addition of a fourth matching layer does not present any advantage. This can be produced by the increased technical complexity of introducing and additional matching layer. Fig. 3 presents measured two-way IL vs. frequency for the cases shown in table IV.

B. Through transmission (pitch-catch) results.

Table V summarizes the results obtained in through transmission mode of operation. Sensitivities are better than those obtained in pulse-echo because now it is possible to tune the frequency bands of transmitter and receiver. The best sensitivity (-22 dB) was obtained with CF-65, being similar to the best sensitivity yielded by the SC transducer (-23dB).

TABLE V. PERFORMANCE IN THROUGH TRANSMISSION MODE.

Active element	*Peak sensitivity (dB)*	*Frequency (MRayl)*	*Matching layers conf.*	*Relative bandwidth (%)*
CF-65	-27 -28	0.89 1.09	3L, $(f_m + f_n)/2$	75
	-22 -27	0.88 1.05	3L, f_m	75
CF-35	-29 -28	0.85 1.14	3L, $(f_m + f_n)/2$	71
	-24 -29	0.85 1.15	3L, f_m	69
SC-45	-25 -23	0.83 1.07	3L, f_m	82
	-25 -25	0.89 1.07	4L, $(f_m + f_n)/2$	83
	-28 -26	0.91 1.25	3L, $(f_m + f_n)/2$	86

However, bandwidths are always broader and smoother for SC transducers. The broadest bandwidth (86%) was attained by the SC-45 composite and three matching layers.

As in pulse-echo mode, the use of four matching layers, does not represent a clear advantage. Two-way insertion loss measurements versus frequency are shown in Fig. 4. Fig. 5 shows the received signal in the time domain for three of the best configurations. Signal shape is close to the calculated response (see Fig. 1). The measured SNR is 39 dB, 44 dB and 45 dB for SC-45, CF-65 and CF-35, respectively.

Figure 6 shows a comparison between calculated through transmission insertion loss (already shown in Fig. 1) with the correspondent measured values (already shown in Fig. 4) for two different cases. For the SC and three matching layers case, there is a perfect match that reveals that the fabricated design is very close to its ideal realization. However, for the four matching layers in the transmitter and three in the receiver, there is a significant deviation of the experimental data from the theoretically calculated values. This can be to the increased practical complexity of fabricating a transducer with four matching layers with the required impedance and resonant frequency.

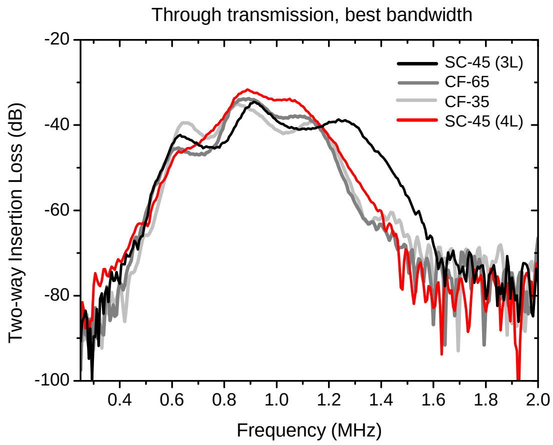

Figure 4. Two-way Insertion Loss. Optimum bandwidth configuration.

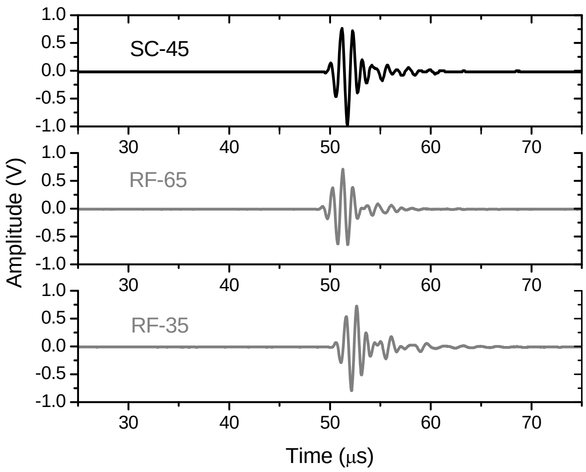

Figure 5. Impulse response in through transmission mode. Pulser: 5078 Panametrics; pulse amplitude: 400 V; gain: 0 dB; separation: 17 mm.

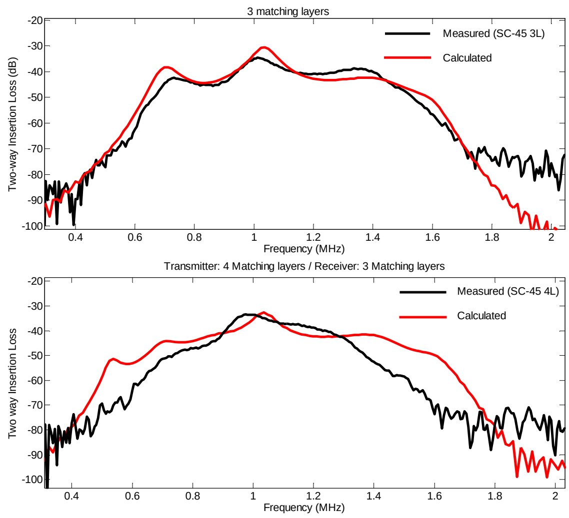

Figure 6. Measured and calculated frequency bands of the SC transducer with two different matching layers configurations in pitch-catch configuration.

V. CONCLUSIONS.

Several air-coupled transducers using 1-3 connectivity PMN-PT single crystal composites, have been designed, manufactured and characterized. Similar transducers, but using 1-3 connectivity PZT ceramic fiber composites, have also been produced for comparison purposes.

In pulse-echo operation mode, sensitivity of both types of transducers is similar (-32 dB), but larger frequency bandwidths were achieved with the SC composite (89%). In through transmission, sensitivity of the CF and SC transducers is similar (-22 dB and -23 dB, respectively), but relatively broader bandwidths are yielded by the SC composites (86% compared with a 75% for CF).

Transducers built with the composite disks with the lowest volume fraction of piezoelectric material (CF-25 and SC-30) resulted in a relatively poorer performance and yielded very irregular frequency bands. However, little difference was observed between the transducers produced with 65% and 35% volume fraction CF. This suggests that the benefit of a lower acoustic impedance of composites with lower volume fractions (better matching to air) is somehow compensated by a lower piezoelectric response. Finally, techniques to efficiently increase the number of matching layers have to be further investigated so that full benefit of the relatively broader bandwidth of 1-3 PMN-PT composites (that theoretical models predict) can be obtained.

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