Multilayer Piezoelectric Resonators for Medical Ultrasound Transducers

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Abstract--

Multilayer piezoelectric resonators were fabricated and the dependance of the electrical impedance and the coupling coefficient were measured as a function of the number of layers, for N=1,...20 layers. The magnitude of the electrical impedance followed the theoretical predicted $1/N^2$ relation, and the coupling coefficient, K_t, remained relatively constant out to N=15 layers. These cofired resonators are suitable for medical ultrasound transducers.

I. Introduction

As modern ultrasound transducer elements become smaller, the characteristic electrical impedance of the elements increases and becomes a poor match to the electrical properties of typical coaxial cables. In addition, as the number of elements in acoustic arrays increases, transducers with local integrated circuits become more attractive. Multilayer transducers are useful for both impedance and voltage control applications. For impedance control the lower electrical impedance leads to a better match to the 50 or 75 Ω existing cables. This leads to better efficiency or sensitivity, a smoother spectrum and shorter pulses. For voltage control, equivalent electrical fields may be achieved at lower applied voltage if the multilayers are connected electrically in parallel. Multilayer transducers are also an enabling step for the development of lower voltage transducers with the integration of low voltage integrated circuits such as MUX chips for linear arrays, and full custom ICs for integrated 2D arrays.

There have been recent discussions in the technical literature on the use of multilayer technology for medical imaging transducers. Saitoh et al. [1] discussed the concept of multilayers to improve the signal to noise for 1D arrays. These authors found an +8 dB improvement in the signal to noise for N=3 layer transducers. Goldberg and Smith [2] discussed the role of multilayer resonators for 2D arrays. These authors built a 3 x 43 element array with N=3 layers and showed results for the air loaded impedance, impulse response, insertion loss, cross coupling, angular response and B scan images. The work, presented here, is complementary to this published work, and is consistent with it.

The use of equal thickness multilayers for acoustic transducers is formally equivalent to using a higher dielectric constant

$$\varepsilon(N) = \varepsilon(1) N^2 \quad , \tag{1}$$

where N is the number of layers and $\varepsilon(1)$ is the dielectric constant of the starting single layer piezoelectric material. This result follows from observing that the multilayer transducer is equivalent to a multilayer capacitor. One power of N comes from the fact that there are N capacitors in parallel, and one power comes from the fact that each layer is 1/N the original thickness.

The Mason or KLM models can also be used to show that for an N layer multilayer transducer, constructed of equal thickness layers, configured with the layers acoustically in series (with alternating polarity) and electrically in parallel, the voltage and the impedance are described by the following simple relations:

$$V(N) = V(1)\frac{1}{N} \quad , \tag{2}$$

$$Z(N) = Z(1)\frac{1}{N^2} \quad , \tag{3}$$

The voltage result can be seen as discretely applying the total voltage over N equal layers, and the impedance result follows from the earlier expression for the dielectric constant. These are, also the equations that describe a transformer. Thus, multilayers can be viewed as a means to create an acousto-mechanical “self transformer”, which lowers the electrical impedance and lowers the required voltage to achieve the equivalent internal electric field. This simple model is an adequate description of an air backed piezoelectric resonator. When such a multilayer resonator is used to fabricate a complete transducer with an appropriate backing layer, front matching layer, lens and cable, these simple equations no longer are sufficient to characterize the device, and more sophisticated models are required.

II. METHODS

For these measurements, PZT-5H resonators were fabricated from cofired multilayer ceramic substrates [3] with the number of layers ranging from N=1 to N=20. The substrates were diced into samples 12x23x0.66 mm in size with 3 μm thick internal Pt electrodes, and 3000A external CrAu electrodes. These samples were then poled at 25 KV/cm at 120 C, in oil. Measurement samples were further diced to dimensions of 12x0.25x0.66 mm to mimic typical bar elements in a one dimensional phased array, and to increase the measurable impedance by reducing the area of the resonator. The typical cross sectional geometry for samples with layers N=2 and for N=3 is shown in Fig. 1. Here the difference in electrode geometry between even and odd number of layers is observed. The samples with an odd number of layers have opposite polarity external electrodes on the opposite top and bottom surfaces. The samples with an even number of layers have the same polarity external electrodes on the opposite top and bottom surfaces, with the opposing electrode on the side. A 100 μm gap was placed between the internal electrodes and the side electrode to prevent shorting or arcing during both poling and during operation.

III. Experimental Results

The value of the magnitude of the electrical impedance, $|Z|$, the value of the real part of the electrical impedance, R, and the value of the real part of the admittance, G, were measured using an Hewlett-Packard 4195 impedance analyzer. Representative plots of the magnitude of the electrical impedance are given in Fig. 2. Here the impedance for N=1, 3, 5, and 15 are shown for the samples diced to 12x0.25x0.66 mm dimensions. The traces were normalized in amplitude and in frequency to illustrate the change in shape with increasing layer count. The width of the traces is seen to increase and the impedance at the series resonance begins to also increase. This last change is believed to be due to the increased series resistance of the internal electrodes. There is a also a slight downward frequency shift as a function of the number of layers which is not simply accounted for by the variation in thickness of the layered samples. From this figure it is clear that the electromechanical Q of the samples is slightly reduced with the higher number of layers. Figure 3 shows a plot of the magnitude of the impedance, $|Z|$, vs., the number of layers, N for both sizes of the samples. The measurement is given by the solid dots and the $1/N^2$ prediction from Eq. (3) is given as the line with slope = 2. The vertical offset of the two curves is due to the difference in area of the two samples. Thus, the resonators appear to follow the simple $1/N^2$ impedance relationship.

The thickness coupling coefficient, K_t, was then calculated from the standard equation [4],

$$K_t = \left[\left(\frac{\pi}{2} \frac{F_s}{F_p} \right) \frac{1}{\tan\left(\frac{\pi}{2} \frac{F_s}{F_p} \right)} \right]^{1/2}, \tag{4}$$

where F_s and F_p are the series and parallel resonances, respectively. The values of F_s and F_p may be obtained from either the magnitude of the impedance, $|Z|$, or R and G. Figure 4 shows the coupling coefficient, K_t, calculated from Eq. (4) as a function of N for both sizes of the resonator samples. Here the coupling coefficient is observed to be roughly constant out to N=15 layers for this cofired structure. The vertical shift between the two sample data sets is due to the difference between a plate and a bar geometry [4].

IV. Conclusions

In conclusion, multilayer piezoelectric resonators were fabricated with layers up to N=20 from cofired ceramic PZT-5H substrates. The electrical impedance, and the coupling coefficient were measured as a function of the number of layers. The electrical impedance was seen to follow the simple $1/N^2$ prediction and the coupling coefficient was approximately constant out to N=15 layers. It appears that suitable ultrasonic medical imaging transducers can be fabricated from these structures with adequate coupling coefficient up to N=15, or about 6.4% of the resonator thickness as an internal electrode.

V. Acknowledgements

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VI. References

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FIGURE CAPTIONS

Fig. 1 Multilayer resonator structures, a) N=2, b) N=3.

Fig. 2 Representative plots of $|Z|$ for N=1, 3, 5, 15.

Fig. 3 Plot of the impedance magnitude, $|Z|$, vs. the number of layers.

Fig. 4 Plot of the coupling coefficient, K_t, vs. the number of layers.

N=2

a)

N=3

b)

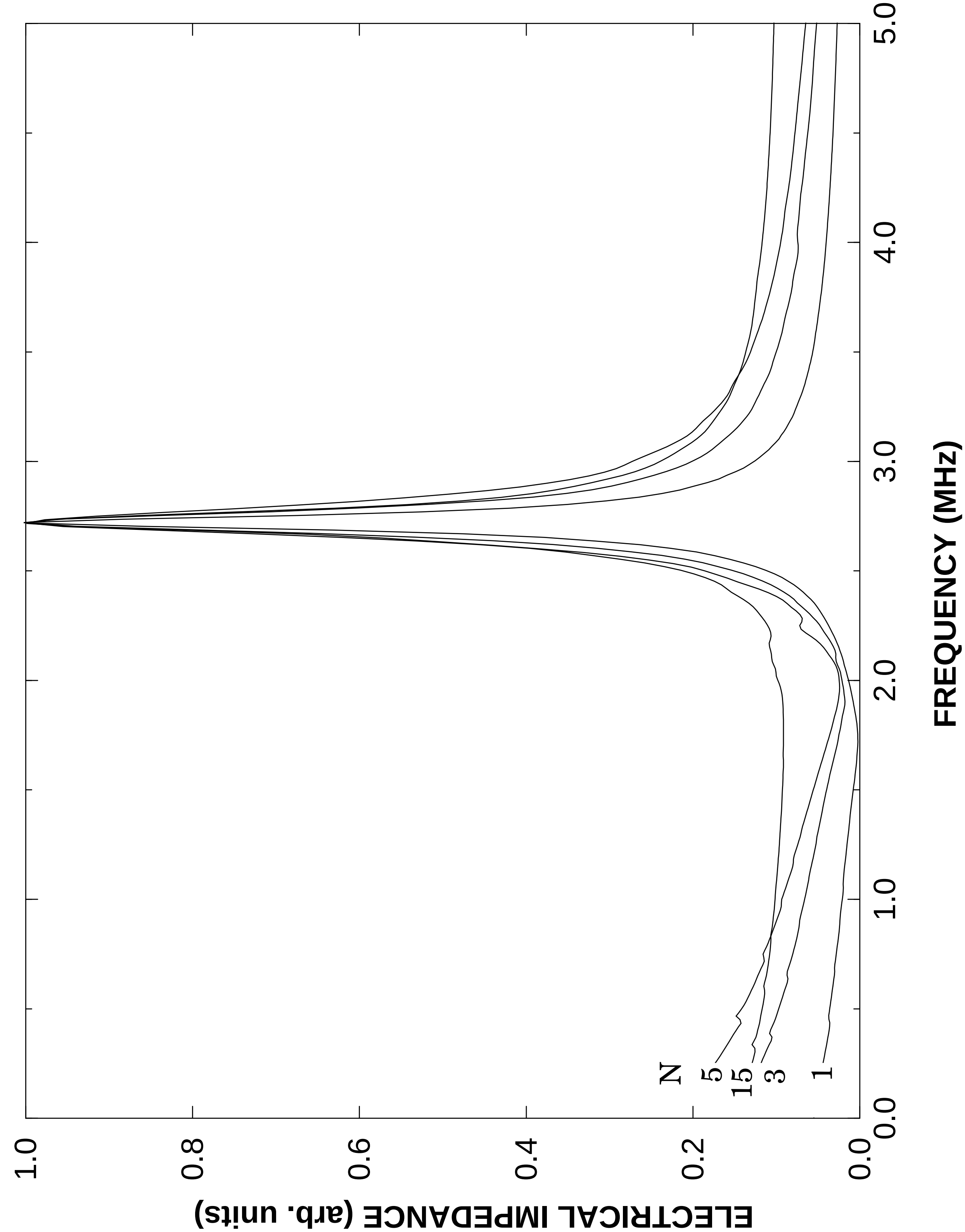

Figure 1: Representative plots of |Z| for N=1, 3, 5, 15R

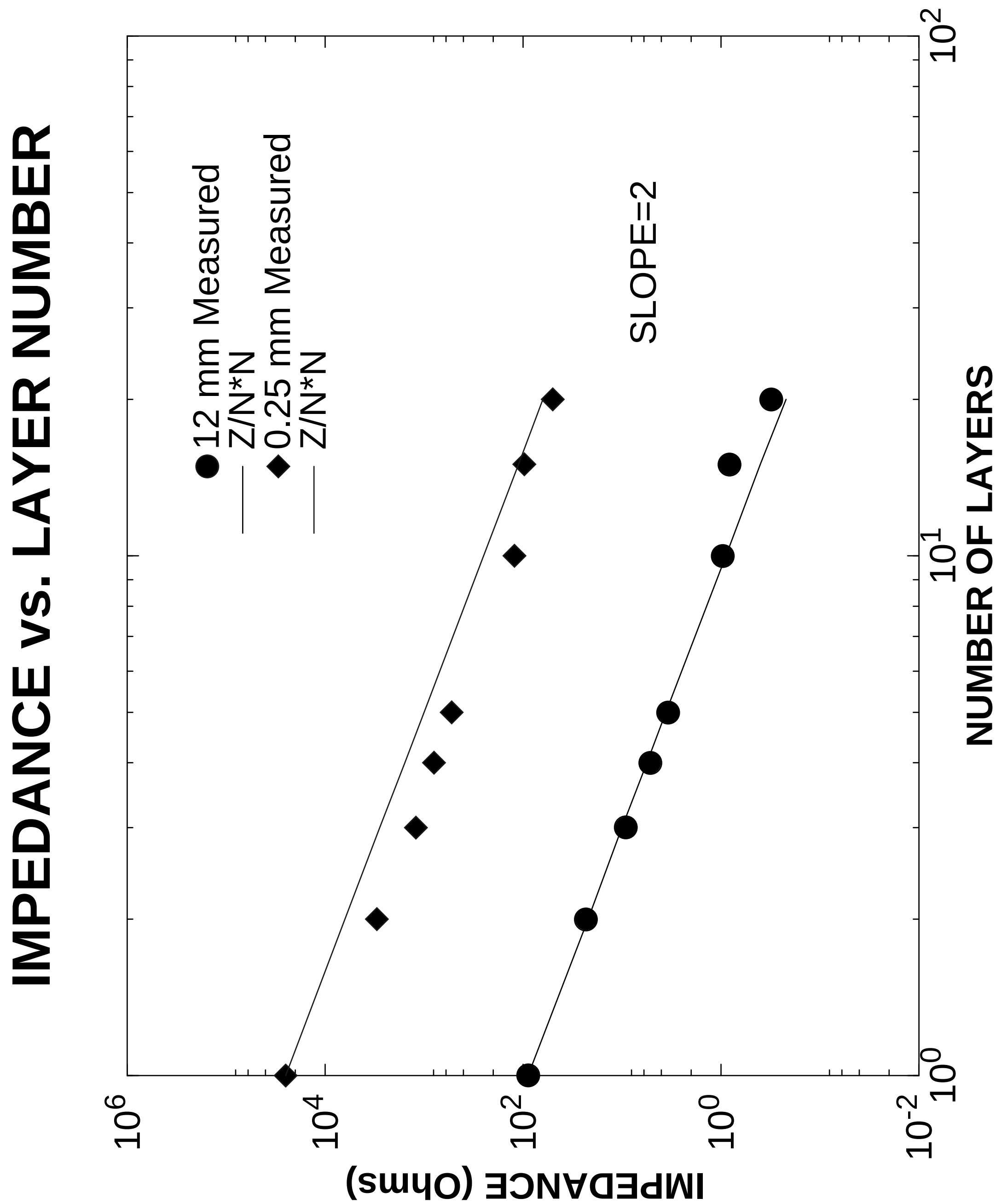

Figure 1: Plot of the impedance magnitude vs. the number of layers

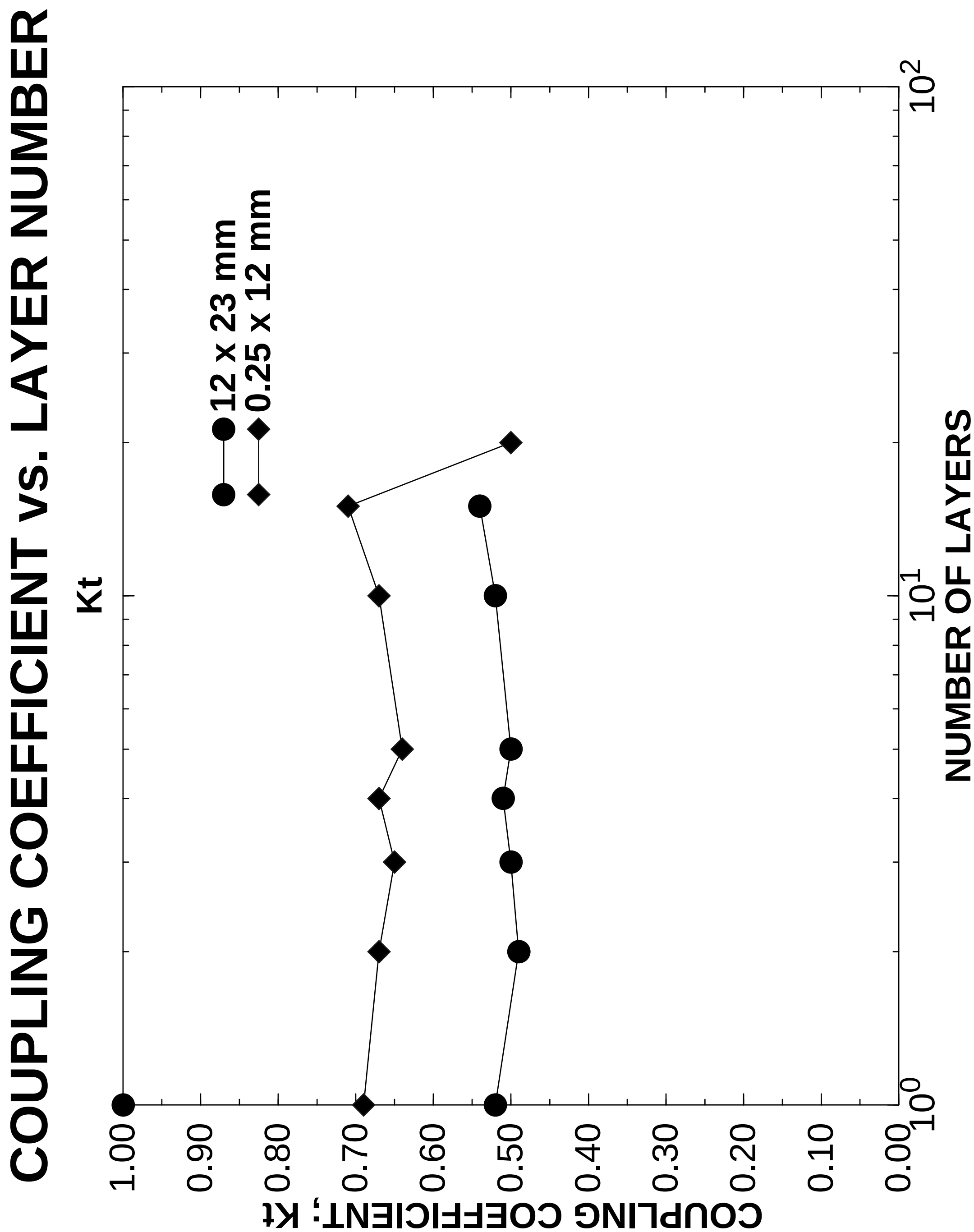

Figure 1: Plot of the coupling coefficient, Kt, vs. the number of layers.