Materials for Acoustic Matching in Ultrasound Transducers

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Abstract - Acoustic impedance (Z) and fabrication issues for matching layers in high frequency transducers were identified. Guided by a density/impedance relationship established for various polymers, glasses, ceramics and metals, few monolithic materials with Z in the range of 6 - 9 MRayls were found. Composites of gold- and silver-polymer resulted in the desired impedances, however, with increased attenuation. Issues of microstructural scale, homogeneity and particle size effects were noted including issues of percolation behaviour for conducting composites. UsingPiezoCad, the effect of matching layer thickness and impedance variation of a 100 MHz transducer were modeled.

I. INTRODUCTION

Acoustic backing and matching layers are essential for high performance ultrasound transducers owing to the large impedance mismatch between the piezoelectric element (e.g. ~ 37 MRayls) and tissue (Z = 1.5 MRayls). Using transmission line theory, Collins (1955) reported that constructive reinforcement of acoustic waves would occur when the thickness of the matching layer was 1/4 of the wavelength \( \lambda \) [1]. Using the KLM model, Desilets et al. also determined optimum impedance values for single and multiple matching layers for ultrasound transducer, as reported in Table 1.

The use of matching layers in high frequency ultrasound, defined herein as ~ 30 - 100 MHz, is also expected to enhance transducer performance. In contrast to conventional low-frequency (2 - 7.5 MHz) devices, however, numerous issues must be addressed. First, the ability to fabricate ultra-thin layers is problematic with projected thickness tolerances on the order of a few microns; secondly the issue of scale, i.e. specifically for composites where the layer thickness is on the order of the microstructural features giving rise to acoustic non-homogeneity and scattering; and thirdly, percolation behaviour specifically for conducting composites; and lastly the intrinsic increase in attenuation with increasing frequency.

It was the purpose of this work to review the various issues of matching layers for high frequency applications. The study employs both modeling methods and the search for novel monolithic and composite materials.

<table>
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<tr>
<th>KLM model</th>
<th>( Z_p^{1/3} Z_l^{2/3} )</th>
<th>4.3 MRayls</th>
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<td>Single layer</td>
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<th>Double layer</th>
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<td>( Z_p^{4/7} Z_l^{3/7} )</td>
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<td>( Z_p^{1/7} Z_l^{6/7} )</td>
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Table 1: Matching layer impedances for LiNbO₃ transducer [2]

II. OVERVIEW OF ACOUSTIC IMPEDANCES

As presented in table 1, materials with acoustic impedances Z ranging between 2 and 10 MRayls are desired for single and double-layer matching schemes. In our search for suitable candidates for matching layers, the impedance of various materials, including polymers, ceramics, glasses, and metals, were reviewed. It was found that there was a correlation between the magnitude of Z in relation to bulk density as presented in figure 2a. This figure was expanded and replotted in figure 2b, where it can be clearly seen that there are very few monolithic materials in the range of 6 - 9 MRayls, with polymers readily filling the...
need in the 2 – 3 MRayls regime. From the density/impedance relationship, various materials with densities ranging from 1,500 kg/m³ to 3000 kg/m³ were identified and their acoustic impedances determined, including AlN, Si₃N₄, BN, glasses, marble, etc. Included in figure 2, again no monolithic material appears suitable for the first layer of a double layer matching scheme.

Figure 2a: Acoustic impedances of polymers, glasses, ceramics and metals as a function of bulk density after [3], [4], [5] and this work

Figure 2b: Acoustic Impedances of materials with densities up to 3500 kg/m³

From the above, it becomes evident that for matching layers, one must incorporate composites, as utilized extensively today. In terms of acoustics, the composite, being comprised of two or more materials, must appear homogeneous in the frequency range of interest (see Fig. 3). That is, the microstructural scale of the individual components should be on the order of < 1/10 λ, or deleterious effects such as excessive attenuation would arise.

Figure 3: Fabrication issues of composites

An example of a currently used material is a silver-loaded polymer-composite being also electrically conducting, allowing it to be multifunctional as the ground plane. In addition to scale, issues of particle size in relation to percolation, i.e. the volume fraction filler Vc at which conduction occurs, can be altered [6]. In addition to the particle size effects on percolation, submicron conducting particles such as Ag, may result in non-conducting composites due to readily oxidized surfaces.

The acoustic impedance of various filler-polymer composites investigated for both matching and backing materials, the latter distinguished by high attenuation (> 50 dB/mm) is summarized in figure 4. As found for the monolithic materials, a general relationship between density and impedance is observed. The large degree of scatter within the data is probably associated with the issues summarized in figure 3, including segregation, inhomogeneity and size effects.

Also included in figure 4 are results of composites prepared in this work, including gold-polymer composites. The use of gold particles (~ 0.8 – 1.5 microns) was selected owing to its inherent inertness to oxidation, thus
allowing elevated conductivity even if nanoparticles would be required. Other candidate materials include silver, carbon, titanium-diboride and palladium-silver.

FIGURE 4: Acoustic impedances of composites including Au, Ag and W-polymer, etc. after [3] and this work.

Figures 5a and 5b present the percolation behavior of gold- and silver- composites. As presented, percolation occurs at 12 and 14 Vol%, respectively. To assure both conductivity and desired impedance, one must take into account factors that effect percolation including particle size and homogeneity of the particle distribution in the polymer matrix.

III. FABRICATION ISSUES

Thickness
In addition to the magnitude of impedance, additional issues of layer thickness and varying impedance remains. In this section, these parameters and their impact on transducer performance were modeled. Using PiezoCad, the performance of a ~100 MHz (LiNbO3) transducer was modeled as a function of matching layer thickness, relative to a 1/4 λ, as shown in Figure 6. As presented for a single matching layer of 7.5 MRays, the model confirmed enhanced performance at 0.25 (or ¼ λ) for center frequency, bandwidth, insertion loss, and pulse length, parameters commonly employed in evaluating transducer performance. Based on the model, a standard Ag-polymer composite matching layer, with a thickness of 10 microns and a tolerance of ± 1 micron would be required to maintain optimum transducer performance.
Impedance magnitude

Using a $1/4 \lambda$ matching layer as above, the figure of merit (as defined by peak to peak sensitivity x bandwidth) was plotted in figure 7 as a function of impedance magnitude as it deviates from the set value of 7.5 MRayls. As presented, transducer performance is less sensitive to impedance magnitude than found for thickness.

Figure 7: Transducer figure of merit of sensitivity as a function of matching layer impedance

IV. SUMMARY

An overview of acoustic impedances ($Z$) and fabrication issues for matching layers in high frequency transducers was presented. A nearly linear relationship between density and $Z$ for polymers, glasses, ceramics and metals was established. Guided by this relationship, materials with densities in the range of 1500 – 3000 kg/m$^3$ were identified and characterized for potential candidates with $Z$ in the range of 6 – 9 MRayls. In addition to monolithic materials, both conducting and non-conducting composites were investigated. Issues of microstructural scale, homogeneity and particle size effects on percolation behavior were noted. Examples of gold- and silver-polymer composites were presented. In addition to the magnitude of $Z$, issues of layer thickness and impedance variation on performance was modeled using a 100 MHz LiNbO$_3$ transducer.
Acknowledgments
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V. REFERENCES


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