1-3 COMPOSITES FOR ULTRASONIC AIR TRANSDUCERS

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ABSTRACT

There are many applications that require the use of ultrasound in air, such as robotic sensing, NDE, and gas flow measurements. Coupling of ultrasound into air from piezoelectrics is very inefficient because of the great impedance mismatch and the lack of appropriate matching materials. We present a method to manufacture low impedance materials using 1-3 air composites. This technique also required us to develop an alternative matching technique using a low impedance $\lambda/8$ section and a thin cap. We have shown that this technique works almost as well as standard $\lambda/4$ matching. A transducer was fabricated using this design technique with a one-way loss of 17 dB.

INTRODUCTION

High frequency applications of ultrasound include robotic sensing, gas flow measurements, nondestructive testing, and acoustic microscopy. Conventional techniques of generating sound in air fail at high frequencies because the large mass of the source cannot vibrate at high frequencies. Conventional methods of generating high-frequency ultrasound also fail because of the enormous mismatch of impedances between typical piezoelectrics and air. Conventional matching techniques require the use of a $\lambda/4$ matching layer. We see from Fig. 1 the effect of the impedance of this material on the one-way transduction loss. To obtain relatively good efficiency (better than 20 dB) we require a material with an impedance less than .2 MRayls .

Materials with low acoustic impedances do exist (balsa wood, sol-gel, cork, and RTV impregnated with glass bubbles). These materials, however, exhibit either large loss, large scattering, environmental instabilities, nonuniformity, or are extremely difficult to shape.

We propose to use micromachined Kapton (made by DuPont, similar to polyimide) to form 1-3 air composites.

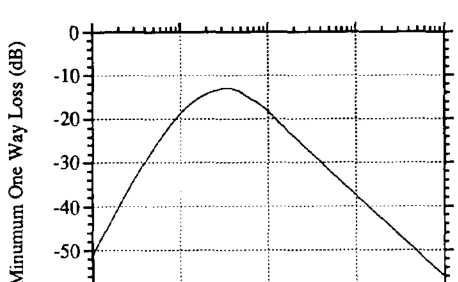

Fig. 1. One way transmission loss for a $\lambda/4$ design matching between PZT-5H and air.

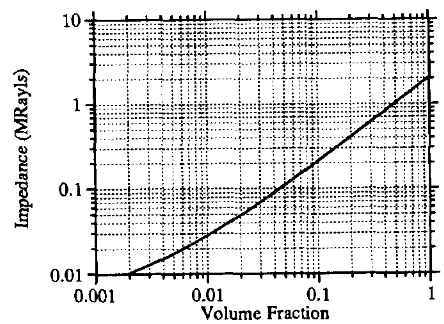

Fig. 2. Theoretical impedance of Kapton-air 1-3 composites.

1-3 AIR COMPOSITES

Using a low pressure oxygen plasma etch, Kapton can be etched with an aspect ratio greater than 20:1 . We fabricated arrays of posts on a 20 μm period with a width as small as 1 μm and a height as tall as 125 μm . The volume fraction of the Kapton determines the acoustic impedance and velocity of the material. The theoretical impedance of these materials is shown in Fig. 2 (using an analysis similar to that found in references 1 and 2). At low volume fractions, the velocity of the composite is approximately the shear velocity of the Kapton (850 m/sec).

One problem is that air has a very low viscosity that causes the air to remain stationary while the columns vibrate up and down (calculations indicate that at 1 MHz there is a 1.5 μm range where the air follows the motion of the columns). To solve this problem and to protect the fragile Kapton posts from dust and destruction, we place a thin "cap" on top of the posts.

THEORY OF $\lambda/8$ MATCHING

Because of the presence of a relatively thick "cap," we could not use the standard $\lambda/4$ matching technique since the presence of the "cap" would disturb the acoustic performance. This was solved by using a $\lambda/8$ design instead. The acoustic stack is shown schematically in Fig. 3. Two matching layers are used. Using this design, the impedance of the "cap" is not significant. The input impedance at the interface of the two matching layers is almost purely imaginary. Thus, by adjusting the thickness of the "cap," we can match the magnitude of the impedance no matter what the impedance of the first layer, the piezoelectric, or the "cap" are. The design equations for this technique are shown below. Not that the equation for Z_1 gives the optimum value, but a good match can be obtained when Z_1 differs from this value.

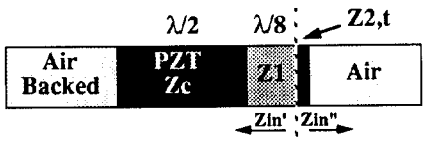

Fig. 3. Acoustic stack of λ/8 design with high impedance "cap".

This technique may also be valuable in other applications where the designer has no or little choice in the impedances of the matching layers, but only on their thicknesses.

$$Z_1 = Z_c\sqrt{\frac{Z_a}{2Z_c - Z_a}}$$

$$t = \frac{Z_1 c_2 (Z_c^2 - Z_1^2)}{2\pi \upsilon_0 Z_2 (Z_c^2 + Z_1^2)}$$

where:

Z_a = Acoustic impedance of air.
Z_1 = Acoustic impedance of first matching layer.
Z_2 = Acoustic impedance of "cap."
t = Thickness of "cap."
υ_0 = Center frequency.
c_2 = Acoustic velocity of "cap."

The comparison of an optimum design using this technique is compared with the standard λ/4 technique for matching between PZT-5H and air. This is shown in Fig. 4 and we see only a slight degradation in performance.

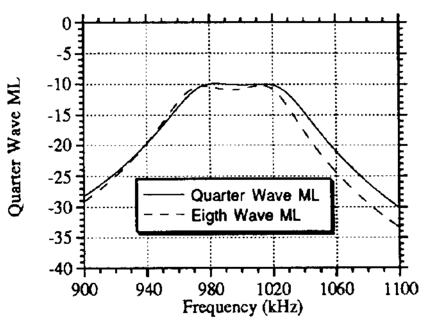

Fig. 4. Comparison of ideal performance of λ/4 and λ/8 designs for matching between PZT-5H and air at 1 MHz .

FABRICATION

The first step in the fabrication was to pattern a chromium layer on the surface of a sheet of 125 μm thick Kapton. The pattern was of 16 μm x 16 μm dots on 20 μm centers. The Kapton was then bonded to a piece of PZT-5H with a resonant frequency of 860 kHz . Then the Kapton was etched in a low pressure (60 mTorr) oxygen plasma etch. This etch was quite slow (as much as 60 hours was required).

After the arrays of posts were fabricated in this manner, a Kapton "cap" was placed on top of the posts. This "cap" was 25 μm thick with an additional 31 μm of adhesive. The "cap" was then thinned using a similar plasma etch. Periodically, the acoustic performance of the device was measured to determine when the optimum "cap" thickness was obtained. A plot of the minimum one-way loss is shown in Fig. 5.

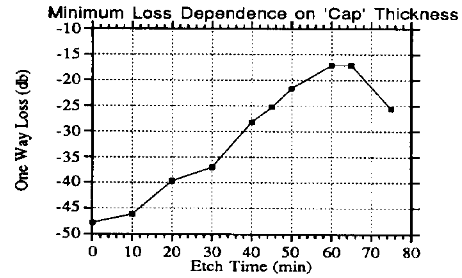

Fig. 5. Plot of transduction loss as a function etch time. ("cap" thickness starts at 56 μm and thins a rate of 18 μm/hour).

EXPERIMENTAL RESULTS

After 60 minutes of "cap" thinning, the device exhibited its best performance. The frequency response of this device is shown in Fig. 6. We also show the response of our reference transducer, a standard λ/4 design using PZT and low viscosity RTV as a matching layer. This RTV has an impedance of 1 MRayl.

We see an improvement in insertion loss of 3 dB one way and a threefold improvement in bandwidth. Theoretical analyses indicate that improve this performance by an additional 7 dB .

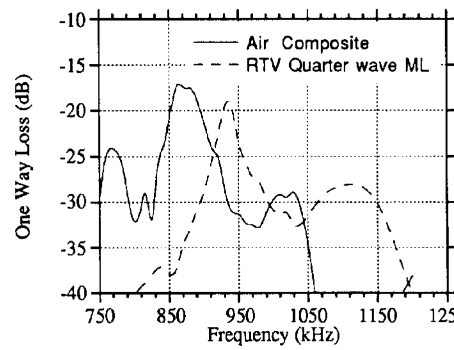

Fig. 6. Comparison of frequency response after 60 minutes of etching with reference PZT-RTV transducer.

CONCLUSIONS

We have described a new technique for the fabrication of materials for use as matching layers to couple ultrasound from piezoelectrics to air. Because of the nature of these materials, we developed a new technique for designing a matching layer that allows the presence of a high impedance cap. We demonstrated this technique and showed that we could obtain a greater efficiency than is possible with conventional materials and design. We believe that we can fabricate air transducers with as little as 10 dB one-way loss using this technique.

ACKNOWLEDGMENTS

We would like to Chung-Kao Hsieh for his analysis of the air flow around the Kapton posts, Tom Carver for his fabrication assistance, Chris Storment for his suggestion to use Kapton, and Acuson Corporation for the fellowship support of Matt Haller. This work was supported by International Business Machines on Contract No. 1339-01.

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