TAPERED ACOUSTIC MATCHING LAYERS

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ABSTRACT

Typical ultrasonic transducers for immersion applications use one or more matching layers to increase their efficiency and bandwidth. In microwave circuits, it is common to use tapered impedance transformers to increase bandwidth. This has not been possible for acoustic transducers because of the difficulty of fabricating materials with a smoothly tapered acoustic impedance. We propose the use of silicon micromachining and vacuum impregnation to fabricate a composite material of silicon and a polymer filler. The acoustic properties of the composite are determined by the volume fraction of the silicon in the composite. By tapering the volume fraction of silicon in the direction of wave propagation, a tapered acoustic impedance results. We have fabricated a transducer operating at 5.7 MHz with a tapered acoustic matching layer and a silicon buffer layer. This transducer shows a 65% 3 dB fractional bandwidth.

INTRODUCTION

In earlier work[1], we described one use of silicon micromachining to fabricate acoustic matching layers. By chemically etching deep grooves into a silicon wafer and vacuum impregnating the grooves with a polymer, a material with adjustable acoustic properties is made. This material is a 2-2 composite of silicon and a polymer. In this paper, we extend the idea to fabricating materials with tapered acoustic impedances. We consider the design of an air backed, immersion transducer with a PZT (lead zirconium titanate) active element. Because of the impedance mismatch between PZT and water (35 and 1.5 MRayls respectively), a matching layer is used to improve bandwidth and efficiency.

The optimum matching layer would have a tapered impedance between 1.5 and 35 MRayls as shown in Figure 1. In this paper, we will describe a technique for designing such a layer. Due to limitations in fabrication, we cannot build a matching layer according to this design, however, the analysis is useful as a guide to optimum implementation.

We will also describe the fabrication of materials with a tapered acoustic impedance and the theory for predicting their properties. A transducer was fabricated using this technique, and the measured response is in excellent agreement with theoretical prediction.

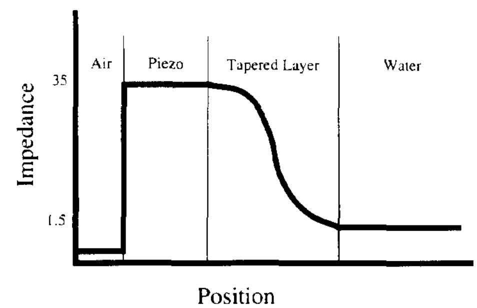

Fig. 1. Plot of impedance vs. position for a piezoelectric transducer with a tapered matching layer.

SYNTHESIZED TAPERED THEORY

The design technique for choosing the shape of an optimum taper was developed for microwave circuits by R.E. Collin[2]. In this approach, a tapered matching layer is inserted between the source and the load as shown in Figure 2. The reflection coefficient (Γ_i) at the source and matching layer interface can be written as an integral of the differential reflections at each point multiplied by the phase delay to reach the interface:

$$\Gamma_i(2\beta) = \frac{1}{2}\int_0^L e^{-2j\beta z}\frac{d(\ln \bar{Z})}{dz}dz$$

This equation for the reflection coefficient can be thought of as a Fourier transform giving the following transform pair:

$$\frac{1}{2}\frac{d(\ln \bar{Z})}{dz} = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{2j\beta z}\Gamma_i(2\beta)2d\beta$$

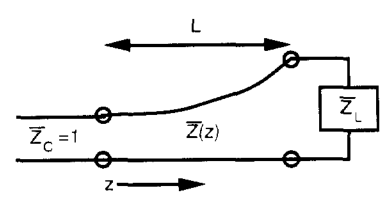

Fig.2 Transmission line model of tapered impedance layer.

Thus, by specifying a reflection coefficient, the impedance taper can be found. These equations can be simplified by making a variable substitution to a normalized form:

$$F(u) = \int_{-\pi}^{\pi} e^{-jpu} g(p) dp$$

$$g(p) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-jpu} F(u) du$$

Where, $p = 2\frac{z - L/2}{L}$, and $u = \frac{\beta L}{\pi} = \frac{2L}{\lambda}$. Thus, F(u) is a normalized reflection coefficient and can be specified as:

$$F(u) = 2\pi C \operatorname{sinc}(u) \frac{\prod_{n=1}^{N}(u^2 - m_n^2)}{\prod_{n=1}^{N}(u^2 - n^2)}$$

Where m_n are the locations of the zeros of the reflection coefficient. By taking the Fourier transform of F(u) we can represent g(p) as a Fourier series:

$$g(p) = \sum_{n=-\infty}^{\infty} a_n e^{jnp} = \frac{d(\ln \overline{Z})}{dz}$$

The Fourier coefficients are simply given by:

$$a_n = \frac{F(n)}{2\pi}$$

If we assume a triple zero at u=2, which corresponds to a taper thickness of one wavelength, F(u) is shown in Figure 3a and the resulting taper shape is shown in Figure 3b. It is important to note that this ideal taper requires a layer which varies from 1.5 to 35 MRayls. This is not achievable with the fabrication technique used in this paper. This design technique does, however, give good insight into the optimum tapered shape.

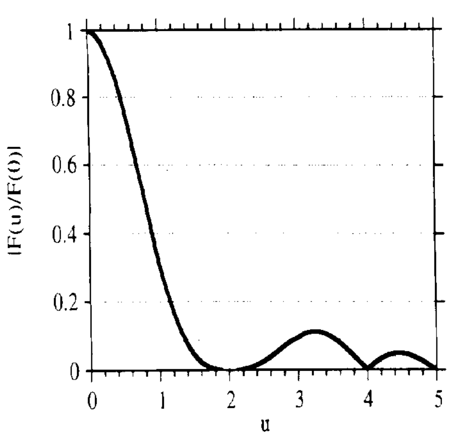

Fig.3a Plot of F(u) for the case of a triple zero at u=2, corresponding to L=λ.

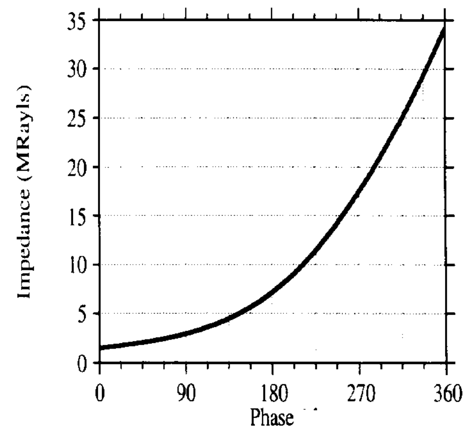

Fig.3b Synthesized Z(z) for triple zero at u=2.

FABRICATION OF COMPOSITE MATERIALS

High aspect ratio silicon structures were fabricated using a technique described by Petersen[3]. Several 3 mm thick <110> oriented silicon wafers were patterned with a grating such that the lines in the grating were parallel to the <111> planes of the wafer. Using silicon nitride as a mask and etching in hot potassium hydroxide (95°C, 11 M KOH), deep, high aspect ratio silicon structures were fabricated. At this stage, the resulting voids in the silicon can be vacuum impregnated with a polymer to result in a 2-2 composite material. The theory for the acoustic properties of these materials has been described in our previous publications[1,4]. The theoretical impedance and velocity as a function of the volume fraction of the silicon is shown in Figures 4a and 4b for reference. We use a low impedance RTV (GE RTV115) as the filler material.

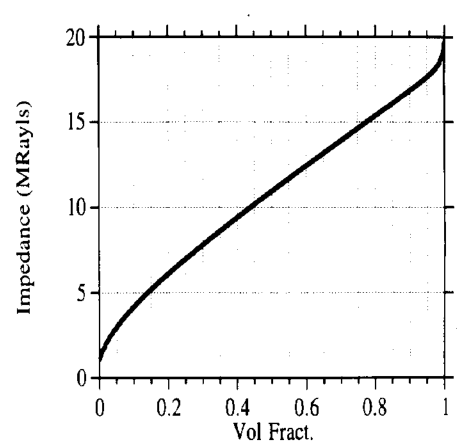

Fig. 4a Theoretical impedance vs. volume fraction of silicon for a Si/RTV 2-2 composite material.

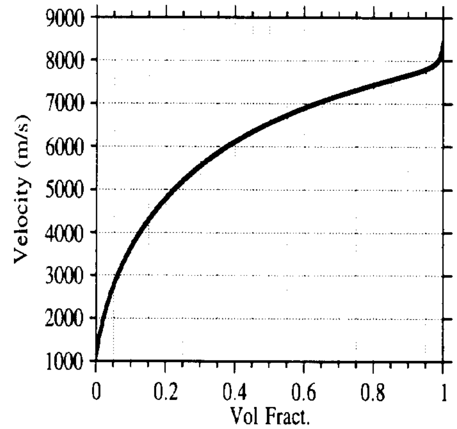

Fig. 4b Theoretical velocity vs. volume fraction of silicon for a Si/RTV 2-2 composite material.

We note that tapering the volume fraction of the silicon, yields a material with a tapered acoustic impedance. In order to achieve this tapered silicon shape, the silicon is etched in a plasma following the KOH etch. A chromium film is evaporated over the surface to act as a mask for the dry plasma etch. The chromium is evaporated onto the top surface of the wafer so that no chromium is deposited on the silicon sidewalls. The Cr acts as a mask for an anisotropic plasma etch (1:1 SF_6, Freon 115, 200 mTorr, 800 W). The resulting structure is shown in Figure 5. The volume fraction of silicon varies smoothly between zero and approximately 60% over a distance of 350 µm. By adjusting the plasma processing parameters, the precise shape of this structure can be tailored. The thickness of this layer is approximately 350 µm. Using Figures 4a and 4b, we calculate the impedance as a function of phase at 5.7 MHz for this structure. This calculation is shown in Figure 6.

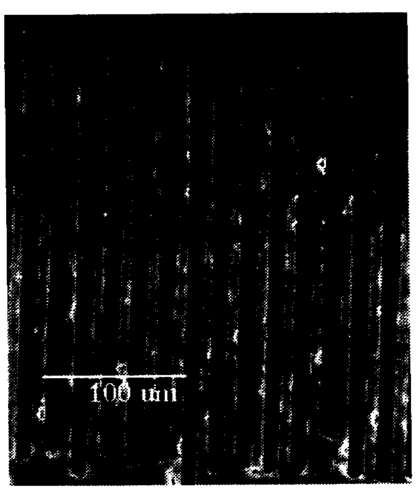

Fig.5 SEM of crossection of Si/Epoxy tapered acoustic matching layer.

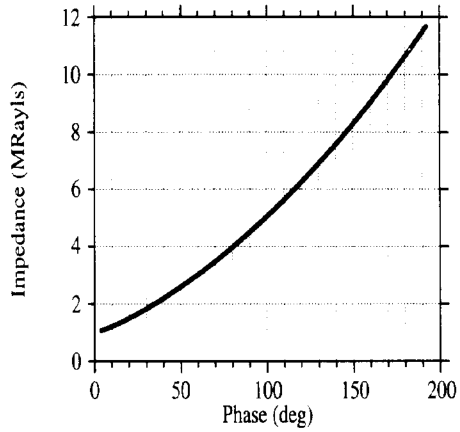

Fig.6 Impedance vs. phase for structure shown in Figure 5.

ACOUSTIC MEASUREMENT SYSTEM

We fabricated the tapered layers described in the previous section and bonded a 5.7 MHz PZT transducer to the backside of the silicon buffer layer (2.65 mm thick). The measurement system of Figure 7 was used to test the transducer. A function generator is used to excite the transducer which is immersed in water. The sound field in the water is detected using a spot poled 30 MHz hydrophone (on loan from Specialty Engineering Associates). The measurement system is shown in Figure 7.

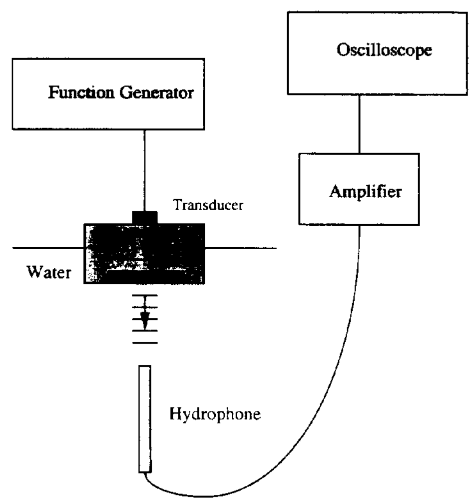

Fig.7 Schematic of measurement system.

EXPERIMENTAL RESULTS

Using the estimated impedance variation shown in Figure 6, the response of the transducer from the electrical source to water is calculated and compared to the measured response in Figure 8a. We note the excellent agreement between theory and experiment. The 3 dB one-way fractional bandwidth of this transducer was 65%. The impulse response of the transducer is also shown in Figure 8b. We note the excellent compactness and the short ring down time of the pulse.

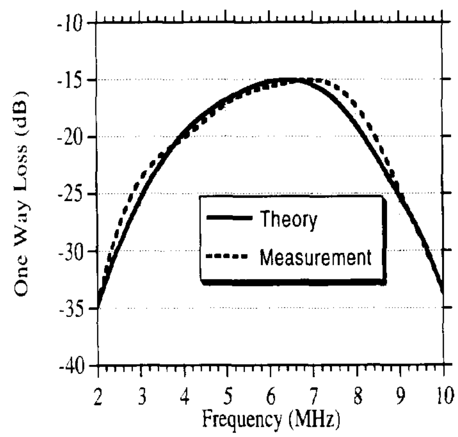

Fig.8a Measured and theoretical frequency response.

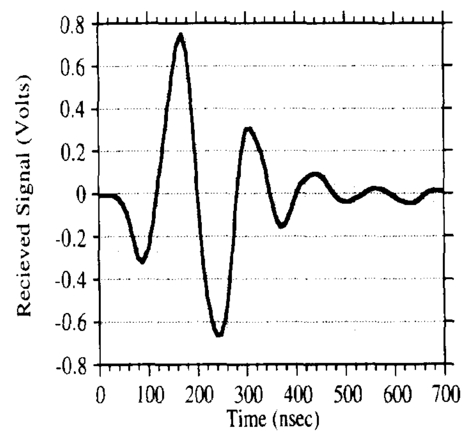

Fig.8b Measured hydrophone signal.

CONCLUSION

Silicon micromachining can be used to fabricate materials with specific acoustic impedances for matching between high impedance ceramics and low impedance media. Using a combination of wet and dry processing, tapered impedance silicon matching layers can be fabricated and used in making immersion transducers with a broad bandwidth. We believe that this technology has applications for medical ultrasound transducers, acoustic microscopy, and for efficient coupling of high frequency ultrasound into air.

REFERENCES

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