Characterization of Ultra-thin Quarter-wavelength Matching Layers of High Frequency Ultrasonic Transducers

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Abstract - The quarter-wavelength (λ/4) acoustic matching layer is a vital component in medical ultrasonic transducers, which can bridge the large acoustic impedance mismatch between the piezoelectric material and the human body. At high frequencies (>50MHz), the λ/4 matching layers become extremely thin and the characterization of its properties becomes very challenging. We report a novel method to measure the phase velocity and attenuation of ultra-thin layers using the λ/4 matching principle. The method has been successfully used to measure a 14.6μm Epo-Tek 301 epoxy film on glass substrate and a 9.5μm sol-gel silicon oxide colloidal/polymer composite film on Si substrate.

I. INTRODUCTION

In order to obtain higher sensitivity and broader bandwidth, high performance ultrasonic transducers require a quarter-wavelength (λ/4) acoustic matching layer between the piezoelectric ceramic and the propagating medium. Epoxy resin, parylene and composite materials have been widely used as matching layers in the medical transducer industry for many years [1]. These materials have strong frequency dependent acoustic properties, especially at high frequencies. Therefore, time domain based ultrasonic measurement methods could not meet the need of characterizing these materials.

High frequency ultrasonic spectroscopy, a frequency domain method, has been successfully applied to determine the frequency dependent phase velocity and attenuation of these matching materials at high frequencies (25-65MHz) [2]. However, samples with thickness greater than 4λ are generally used in order to well separate the two successive transmitted signals. For some materials, it is easier to make thin film samples than making thicker samples with thickness greater than 4λ [3]. Most importantly, the λ/4 matching layers are very thin at high frequencies and may have different properties than thicker samples [4]. Therefore, the characterization of λ/4 matching layers becomes challenging at high frequencies due to the restriction of sample thickness and the frequency dependent material properties. Hadimioglu and Khuri-Yakub have determined the acoustic properties of thin parylene and polyamide layers through reflection/transmission coefficients measurement [3]. The method was also used by Lu and Smith to characterize thin silicon-epoxy 2-2 composites [4]. However, curve-fitting technique is needed in their measurements. There is also lack of convergence analysis and experimental details.

In this paper, we report a different method that can determine both the phase velocity and attenuation of λ/4 matching layers at exactly the desired operating frequency. A thin Epo-Tek 301 epoxy resin on glass substrate was first investigated by using this method. The measured phase velocity agrees well with the results obtained from thick samples, which were obtained by the spectroscopy method, but the measured attenuation using the new method is lower than that obtained from thick samples. Further analysis showed that the measurement of the attenuation using the new method is very sensitive to the property variations of the substrate and propagation medium, causing some uncertainties in the attenuation measurements. A 9.5μm sol-gel silicon oxide colloidal/polymer composite film on Si substrate was also studied.

II. MEASUREMENT METHOD

Let us consider an ultrasonic plane wave normally incident upon a thin layer on a thick substrate immersed in a fluid (water), as shown in Fig. 1. The incident wave can be expressed by

$$u^{inc} = f_0(\omega t - k_1 x) \qquad (1)$$

where ω is the angular frequency and k_1 is the wave number in water. The substrate is thick enough so that only the first transmitted signal is taken into account, while the thin layer is so thin that the multiple reflected/transmitted signals from the front and back sides of the layer are difficult to separate in

time domain. Then, the transmitted signals shown in Fig.1 may be written as:

$$u^{I}(x,t) = T_{12}T_{23}T_{31}\, f_0(\omega t - k_1(x-d_2-d_3) - k_2d_2 - k_3d_3)$$
$$= T_{12}T_{23}T_{31}\, f_0(\omega t - k_1x - (k_2-k_1)d_2 - (k_3-k_1)d_3)$$
$$u^{II}(x,t) = T_{12}T_{23}T_{31}R_{31}R_{32}$$
$$f_0(\omega t - k_1x - (k_2-k_1)d_2 - (3k_3-k_1)d_3)$$
$$u^{III}(x,t) = T_{12}T_{23}T_{31}(R_{31}R_{32})^2$$
$$f_0(\omega t - k_1x - (k_2-k_1)d_2 - (5k_3-k_1)d_3)$$
etc. (2)

Here k_i is the wave number in medium i, d_i is the thickness of medium i, $R_{ij} = (Z_j-Z_i)/(Z_j+Z_i)$ is the reflection coefficient in medium i from medium j, $T_{ij} = 2Z_j/(Z_j+Z_i)$ is the transmission coefficient from medium i into medium j, and Z_i is the acoustic impedance of medium i. In our experiments, media 1, 2, and 3 are, respectively: water, substrate, and thin polymer layer.

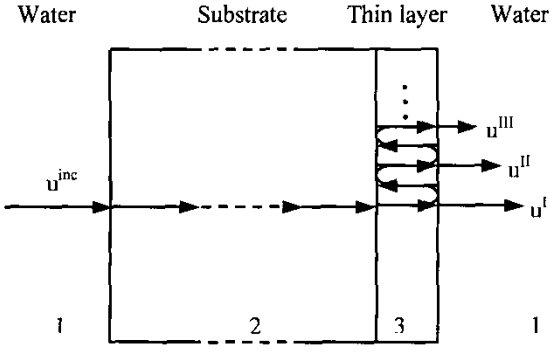

Figure 1: Various transmitted signals from a thin layer on a thick glass substrate immersed in water.

The total transmitted signal, comprising u^I, u^{II}, u^{III} ... ∞, at x = L is given by

$$u^t(L,t) \equiv g(t) = T_{12}T_{23}T_{31}$$

$$\sum_{m=0}^{\infty}(R_{31}R_{32})^m f_0(\omega t - k_1L - (k_2-k_1)d_2 - ((2m+1)k_3 - k_1)d_3) \quad (3)$$

Let $G^*(\omega)$ and $F_0^*(\omega)$ be the Fourier transforms of the signals g(t) and $f_0(t)$, respectively, a straightforward application of the shifting theorem for Fourier transforms yields:

$$G^*(\omega) = T_{12}T_{23}T_{31}e^{-i(k_2-k_1)d_2}e^{-i(k_3-k_1)d_3} F_0^*(\omega)\sum_{m=0}^{\infty}(R_{31}R_{32}e^{-i2k_3d_3})^m$$
$$= T_{12}T_{23}T_{31}e^{-i(k_2-k_1)d_2}e^{-i(k_3-k_1)d_3} F_0^*(\omega)\frac{1}{1-R_{31}R_{32}e^{-i2k_3d_3}} \quad (4)$$

When only the substrate is present in water, the first transmitted signal at x = L is

$$h(t) = T_{12}T_{23}\, f_0(\omega t - k_1L - (k_2-k_1)d_2) \quad (5)$$

and the corresponding Fourier transform is given by

$$H^*(\omega) = T_{12}T_{21}e^{-i(k_2-k_1)d_2}F_0^*(\omega) \quad (6)$$

Therefore, dividing Eq. (4) by Eq. (6), we can get

$$\frac{G^*(\omega)}{H^*(\omega)} = \frac{T_{23}T_{31}}{T_{21}}\frac{e^{-i(k_3-k_1)d_3}}{1-R_{31}R_{32}e^{-i2k_3d_3}} \quad (7)$$

For a dispersive medium, k is a complex number with the general form

$$k(\omega) = \beta(\omega) - i\alpha(\omega) \quad (8)$$

where the attenuation is given by $\alpha(\omega)$, and the phase velocity by $v(\omega) = \omega/\beta(\omega)$. Therefore, the amplitude spectrum is

$$\left|\frac{G^*(\omega)}{H^*(\omega)}\right| = \frac{T_{23}T_{31}}{T_{21}}\frac{e^{-(\alpha_3-\alpha_1)d_3}}{\left|1-R_{31}R_{32}e^{-2\alpha_3d_3}e^{-i2\beta_3d_3}\right|} \quad (9)$$

Since $R_{31}R_{32}$ is negative when the acoustic impedance Z_i satisfy $Z_1 < Z_3 < Z_2$, the maximum value of $|G^*(\omega)/H^*(\omega)|$ occurs when

$$\beta_3d_3 = (n+1/2)\pi,\ n = 0, 1, 2, \ldots \quad (10)$$

From Eq. (10), we get the phase velocity of the thin layer at the corresponding frequency $f_{max,0}$ when n=0:

$$v_3(f_{max,0}) = 4f_{max,0}\, d_3 \quad (11)$$

The frequency $f_{max,0}$ is exactly the designed operating frequency of the transducer because the thickness d_3 equals to $\lambda/4$ at this frequency. The attenuation α_3 at the frequency $f_{max,0}$ can be determined from the Eq. (10):

$$\alpha_3(f_{max,0}) = \ln\left(\frac{2\xi R_{31}R_{32}}{1\pm\sqrt{1-4\xi^2R_{31}R_{32}}}\right)/d_3 \quad (12)$$

where $\xi = \left|\frac{G^*(\omega)}{H^*(\omega)}\right|_{max}\frac{T_{21}}{T_{23}T_{31}}$.

III. Experimental Results

The experimental setup used in our study is the same as described in Ref. [2]. Two immersion-type broadband transducers (Panamatrix V358) with center

frequency of 50MHz are used. The transmitting transducer is driven by a 200MHz computer controlled pulser (Panametrics 5052PR), and the signal from the receiving transducer is sampled using a digital oscilloscope (Tektronix TDS 460A). The data are transmitted to a personal computer where the Fast Fourier Transform (FFT) is performed. The water temperature is maintained at 19.6±0.1°C so that the water velocity is taken as 1481m/s from Ref. [5].

Epo-Tek 301 epoxy resin was investigated in our experiments. The two components, part A and part B of Epo-Tek 301, were hand mixed with a ratio of 4:1. The mixture was degassed in a vacuum chamber of less than 10 mTorr. Then the mixture was cast between one mold released and one normal glass plates spaced 14.6μm, and cured at room temperature for overnight. The top mold released glass plate was removed from the samples after curing. A 0.507mm thick sample without glass substrate was also fabricated, which was cast between two mold released glass plates and both glass plates were removed from the sample after curing.

The thin Epo-Tek 301 layer on glass substrate was measured using the new method and the two received pulse signals g(t) and h(t) are shown in Fig. 2. The corresponding amplitude spectra $|G^*(f)|$ and $|H^*(f)|$ are shown in Fig. 3 and the spectrum ratio of $|G^*(f)/H^*(f)|$ is shown in Fig. 4, in which we found that the maximum value of 1.473 occurs at the frequency of 46.1MHz. From Eqs. (11) and (12), we can determine the phase velocity and attenuation of the thin Epo-Tek301 sample: $v = 2.69*10^3$m/s, and α = 17.2dB/mm. The density of the glass is $2.20*10^3$kg/m^3 and the phase velocity in the glass is $5.58*10^3$m/s, which was measured by the conventional pulse-echo method.

The thick sample without substrate was measured by using the ultrasonic spectroscopy method, which was developed by Sachse and Pao in 1978 [6]. The measured phase velocity and attenuation of the thick Epo-Tek 301 sample are: $v = 2.70*10^3$m/s, and α = 19.8dB/mm [2].

The phase velocity in the thin $\lambda/4$ thick sample obtained using the new method is in good agreement with that obtained in the thick sample using ultrasonic spectroscopy. The discrepancy is less than 0.5%. However, the discrepancy between the measured attenuation coefficients of the thin and thick samples is much larger, around 13%. Further numerical analysis showed that the calculation of the attenuation

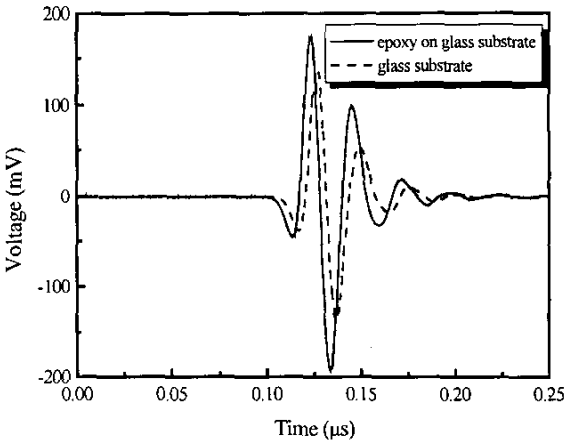

Figure 2: The signal of 14.6μm Epo-Tek 301 epoxy on a glass substrate, g(t), and the signal from the glass substrate only, h(t).

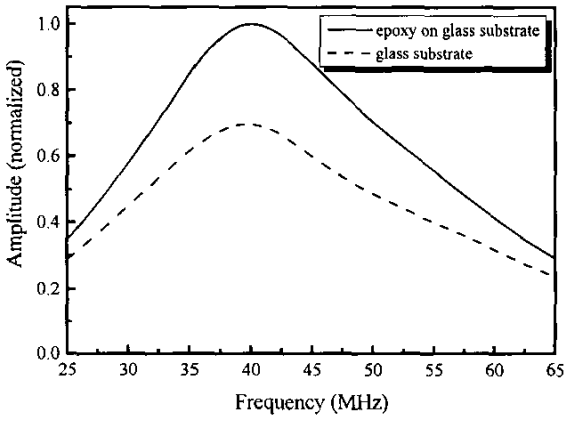

Figure 3: Amplitude spectra $|G^*(f)|$ and $|H^*(f)|$.

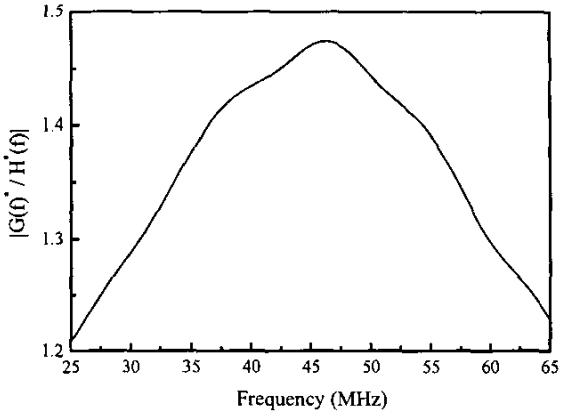

Figure 4: The spectrum of $|G^*(f)/H^*(f)|$ ratio.

using the new method is very sensitive to the properties of the substrate and water. For example, 1% change in the acoustic impedance of water could result in 8% change in the attenuation calculation in the new method, but only produce 0.4% change in the ultrasonic spectroscopy method. Since the phase velocity in water varies with the degree of purity and the reported book value did not specify the degree of water purity, we performed a direct measurement of the velocity in our water medium. Our measured value is 1473 m/s, slightly lower than the cited book value from Ref. [5]. The corresponding attenuation α_3 in the thin sample is then changed to 18.2dB/mm if using our measured water velocity, but α_3 is still 19.8dB/mm for the thick sample, so that the discrepancy is reduced to 8%. Since the $\lambda/4$ matching layers are very thin, the difference in the attenuations does not make much contribution to the final amplitude of the ultrasonic wave when it is used in the ultrasonic transducers. In our experiments, the value of $|G^*(f)/H^*(f)|$ is 1.473 when the attenuation is 18.2dB/mm, and 1.463 when the attenuation is 19.8dB/mm, which means that the difference is only 0.7%. It is therefore very challenging to achieve high accuracy attenuation measurements.

Silicon oxide colloidal/ polymer composite films were also studied. Silicon propoxide $[Si(OC_2H_5)_4]$ was firstly hydrolyzed by dropping it into a mixture of H_2O, C_2H_5OH and HCl, the solution was stirred at room temperature for two hours. Then the silicone was added into the solution to form homogeneous composite solution with high viscosity under stirring. Ethanol was added to achieve desired concentration. The mixture solution was deposited onto silicon substrate by spin coating at 2000 rpm for 30 seconds. The substrate was then placed on a hot plate at 100°C to evaporate the solvent. Each layer film is about 2-3 μm thick. The process was repeated to achieve the desired thickness of films after placed the sample into oven at 150°C for aging. The measured velocity of a 9.5μm thick sol-gel silicon oxide colloidal/polymer composite film on Si substrate is 2460 m/s.

IV. CONCLUSION

A novel method is established to characterize thin quarter-wavelength matching layers for high frequency ultrasonic transducers at the exact operating frequency. The method has been applied to study the 14.6μm Epo-Tek 301 epoxy resin, and 9.5μm thick Silicon oxide colloidal/ polymer composite film. The measured phase velocity is in good agreement with that obtained in thick sample by using ultrasonic spectroscopy method. On the other hand, the measured attenuation in the new method is very sensitive to the properties of the substrate and water, causing some uncertainties in the attenuation measurements.

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REFERENCES

[1] K. K. Shung and M. Zipparo, "Ultrasonic transducers and arrays", IEEE Engineering in Medicine and Biology, Vol. 6, pp. 20-30, 1996

[2] H. Wang, T. Ritter, W. Cao and K. K. Shung, "High frequency properties of passive materials for ultrasonic transducers", IEEE Trans. on Ultrason., Ferro., and Freq. Contr., vol.48, pp.78-84, 2001

[3] B. Hadimioglu and B. T. Khuri-Yakub, "Polymer films as acoustic matching layers", IEEE Ultrasonic Symp., pp. 1337-1340, 1990

[4] X. M. Lu, T. L. Rhyue, N. Tea and L. S. Smith, "Transducer material characterization by transmission coefficient measurement", IEEE Ultrasonic Symp., pp. 1061-1064, 1998

[5] V. A. Del Grosso and C. W. Mader, "Speed of sound in pure water", J. Acoust. Soc. Am., vol. 52, no. 5, pp. 1442-1446, 1972

[6] W. Sachse and Y. H. Pao, "On the determination of phase and group velocities of dispersive waves in solids", J. Appl. Phys., vol. 49, no. 8, pp. 4320-4327, 1978