Characterizing Ultra-Thin Matching Layers of High-Frequency Ultrasonic Transducer Based on Impedance Matching Principle

Haifeng Wang and Wenwu Cao

***Abstract*—The quarter-wavelength ($\lambda/4$) acoustic matching layer is a vital component in medical ultrasonic transducers, which can compensate for the large acoustic impedance mismatch between the piezoelectric material and the human body. At high frequencies (∼100 MHz), the $\lambda/4$ matching layers become extremely thin, and the characterization of their properties becomes very challenging. We report a method to measure the phase velocity and attenuation of ultra-thin layers using the $\lambda/4$ matching principle, in which the acoustic impedance of the thin layer is between the substrate and water. The method has been successfully used to characterize epoxy films on glass substrate. The experimental results show good agreement in the phase-velocity measurement between our proposed method and the conventional ultrasonic spectroscopy method, but the attenuation measurement is sensitive to the properties of the substrate and water medium as well as the alignment of the sample.**

I. Introduction

In order to obtain higher sensitivity and broader bandwidth, ultrasonic transducers often require one or more quarter-wavelength ($\lambda/4$) acoustic matching layers 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]. Recently, high frequency ultrasonic transducers (30–100 MHz) have become essential to further improve the quality of clinical ultrasound images [2], [3]. Because matching materials have strong frequency-dependent acoustic properties, especially at high frequencies, the knowledge of their properties at the desired operating frequency is important to high-frequency transducer design.

The methods used to characterize the matching layers can be classified into two categories: direct measurement and resonance measurement. For the direct measurement method, in which the phase velocity is determined by the time delay between two successive reflected (or transmitted) signals, and the attenuation is determined by the amplitude ratio of the signals, transducers with center frequency at least four times that of the quarter-wavelength resonance frequency are required in order to well separate the two successive signals. The other method is to measure the half wavelength resonance frequency, which is used when the two successive signals cannot be separated. The velocity is determined from the resonance frequency and the sample's thickness. For $\lambda/4$ matching layers, in either case, they are measured at the frequency at least twice of the desired operating frequency. Therefore, these measurement methods could not meet the need of characterizing the matching materials. In order to measure the properties of matching materials at the desired operating frequency, we have to fabricate thicker samples (4λ thick at least for the direct measurement and $\lambda/2$ thick for resonance method). However, for some of these materials, it is easier to make thin samples than thicker samples [4]. Most importantly, the $\lambda/4$ matching layers are very thin at high frequencies and may have different properties than thicker samples [5]. Therefore, the characterization of $\lambda/4$ matching layers becomes challenging at high frequencies due to the restriction of sample thickness and the frequency-dependent material properties.

Hadimioglu and Khuri-Yakub [4] have determined the acoustic properties of thin parylene and polyamide layers through reflection/transmission coefficients measurement. Their method also was used by Lu *et al.* [5] to characterize thin silicon-epoxy 2-2 composites. However, a constant velocity within the measurement frequency range and a relationship between the attenuation and frequency must be assumed before it is possible to perform the indirect curve fitting in their measurements.

In this paper, we report a novel method that can determine both the phase velocity and attenuation of $\lambda/4$ matching layers at exactly the desired operating frequency. Several $\lambda/4$ Epo-Tek 301 and Epo-Tek 353ND (Epoxy Technology, Inc., Bellerica, MA) epoxy layers on glass substrate were investigated by using this new method. The measured phase velocities agree well with the results obtained from thick samples ($\sim 8\lambda$) without substrate, which were obtained by the ultrasonic spectroscopy method. But the measured attenuations using the new method have large discrepancy from those obtained from thick samples. Further analysis showed that the measurement of the attenuation using the new method is very sensitive to the property variation of the substrate, propagation medium, and the alignment of the sample, causing some uncertainties in the attenuation measurements. The new method described here is particularly useful for two situations: thick

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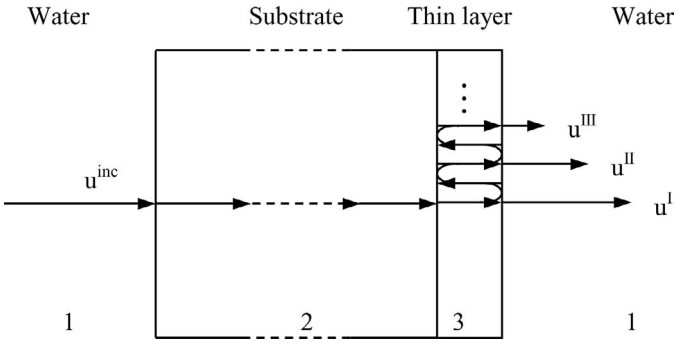

Fig. 1. Various transmitted signals from a thin layer on a thick glass substrate immersed in water.

samples cannot be made for the material so that the ultrasonic spectroscopy method cannot be used, and material properties depend on thickness, which has been observed in many thin-film samples.

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:

$$u^{inc} = u_0(2\pi ft - k_1 x), \tag{1}$$

where f is the frequency and k_1 is the wave number in water. The substrate is thick enough (at least 4λ) so that only the first transmitted signal is taken into account; 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:

$$\begin{aligned} u^I(x,t) &= T_{12}T_{23}T_{31}\, u_0\big(2\pi ft - k_1(x - d_2 - d_3) \\ &\quad - k_2 d_2 - k_3 d_3\big) \\ &= T_{12}T_{23}T_{31}\, u_0\big(2\pi ft - k_1 x - (k_2 - k_1)d_2 \\ &\quad - (k_3 - k_1)d_3\big), \\ u^{II}(x,t) &= T_{12}T_{23}T_{31}R_{31}R_{32}\, u_0\big(2\pi ft - k_1 x \\ &\quad - (k_2 - k_1)d_2 - (3k_3 - k_1)d_3\big), \\ u^{III}(x,t) &= T_{12}T_{23}T_{31}(R_{31}R_{32})^2\, u_0\big(2\pi ft - k_1 x \\ &\quad - (k_2 - k_1)d_2 - (5k_3 - k_1)d_3\big), \text{ etc.} \end{aligned} \tag{2}$$

Here k_i and d_i are the wave number and 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.

The total transmitted signal, comprising u^I, u^{II}, $u^{III} \ldots \infty$, at $x = L$ is given by:

$$\begin{aligned} u^t(L,t) &\equiv g(t) \\ &= T_{12}T_{23}T_{31} \sum_{m=0}^{\infty} (R_{31}R_{32})^m\, u_0\big(2\pi ft - k_1 L \\ &\quad - (k_2 - k_1)\, d_2 - ((2m+1)\, k_3 - k_1)\, d_3\big). \end{aligned} \tag{3}$$

Let $G(f)$ and $U_0(f)$ be the Fourier transforms of signals $g(t)$ and $u_0(t)$, respectively, a straightforward application of the shifting theorem for Fourier transforms yields:

$$\begin{aligned} G(f) &= T_{12}T_{23}T_{31}e^{-i(k_2-k_1)d_2}e^{-i(k_3-k_1)d_3}U_0^*(f) \\ &\quad \cdot \sum_{m=0}^{\infty} \left(R_{31}R_{32}e^{-i2k_3d_3}\right)^m. \end{aligned} \tag{4}$$

We define $z = R_{31}R_{32}e^{-i2k_3d_3}$, and for $|z| < 1$, $\sum_{m=0}^{\infty} z^m = \frac{1}{1-z}$ so that:

$$\begin{aligned} G(f) &= T_{12}T_{23}T_{31}e^{-i(k_2-k_1)d_2}e^{-i(k_3-k_1)d_3} \\ &\quad \cdot U_0(f)\frac{1}{1 - R_{31}R_{32}e^{-i2k_3d_3}}. \end{aligned} \tag{5}$$

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

$$h(t) = T_{12}T_{23}\, u_0(2\pi ft - k_1 L - (k_2 - k_1)d_2), \tag{6}$$

and the corresponding Fourier transform is given by:

$$H(f) = T_{12}T_{21}e^{-i(k_2-k_1)d_2}U_0(f). \tag{7}$$

Therefore, dividing (5) by (7), we get:

$$\frac{G(f)}{H(f)} = \frac{T_{23}T_{31}}{T_{21}}\frac{e^{-i(k_3-k_1)d_3}}{1 - R_{31}R_{32}e^{-i2k_3d_3}}. \tag{8}$$

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

$$k(f) = \beta(f) - i\alpha(f), \tag{9}$$

where the attenuation is given by $\alpha(f)$, and the phase velocity is given by $v(f) = 2\pi f/\beta(f)$. Therefore, we can rewrite (8) as:

$$\frac{G(f)}{H(f)} = \frac{T_{23}T_{31}}{T_{21}}\frac{e^{-i(\beta_3-\beta_1)d_3}e^{-(\alpha_3-\alpha_1)d_3}}{1 - R_{31}R_{32}e^{-2\alpha_3d_3}e^{-i2\beta_3d_3}}. \tag{10}$$

Then, the amplitude spectrum is given by:

$$\left|\frac{G(f)}{H(f)}\right| = \frac{T_{23}T_{31}}{T_{21}}\frac{e^{-(\alpha_3-\alpha_1)d_3}}{|1 - R_{31}R_{32}e^{-2\alpha_3d_3}e^{-i2\beta_3d_3}|}. \tag{11}$$

Because $R_{31}R_{32}$ is negative when the acoustic impedance Z_i satisfy $Z_1 < Z_3 < Z_2$, the maximum value of $|G(f)/H(f)|$ occurs when:

$$\beta_3 d_3 = (n + 1/2)\pi,\ n = 0, 1, 2, \ldots \tag{12}$$

From (12), we can get the corresponding frequency $f_{\max,n}$:

$$f_{\max,n} = \left(n + \frac{1}{2}\right) \frac{v_3\left(f_{\max,n}\right)}{2d_3}. \tag{13}$$

For $n = 0$, the phase velocity of the thin layer at the corresponding frequency $f_{\max,0}$ is:

$$v_3(f_{\max,0}) = 4 f_{\max,0}\, d_3. \tag{14}$$

The frequency $f_{\max,0}$ is exactly the designed operating frequency of the transducer because the thickness d_3 is equal to $\lambda/4$ at this frequency. The attenuation α_3 at the frequency $f_{\max,0}$ can be determined from (11):

$$\alpha_3\left(f_{\max,0}\right) = \ln\left(\frac{2\xi R_{31}R_{32}}{1 \pm \sqrt{1 - 4\xi^2 R_{31}R_{32}}}\right) \Big/ d_3, \tag{15}$$

where $\xi = \left|\frac{G(f)}{H(f)}\right|_{\max} \frac{T_{21}}{T_{23}T_{31}}$. Although there are two values of α_3 matching the peak value of $\left|\frac{G(f)}{H(f)}\right|_{\max}$, only the positive value is selected here from the definition of α in (9).

III. Experimental Results

The experimental setup used in our study is the same as described in [3]. Two sets of immersion-type broadband transducers with center frequencies 40 MHz and 75 MHz, and one-way 6 dB bandwidth of 75%, are used to cover the frequency range from 30 MHz to 100 MHz. The transmitting transducer is driven by a 200 MHz computer controlled pulser (Panametrics 5052PR, Panametrics, Waltham, MA), and the signal from the receiving transducer is sampled using a digital oscilloscope (Tektronix TDS 460A, Tektronix Inc., Beaverton, OR). The sampling rate is set to 10 Gs/s to avoid aliasing. Each sampling window contains 2500 data points. To reduce the ubiquitous random errors, each measurement is averaged 64 times. The data are transmitted to a personal computer via a general purpose interface bus (GPIB). The fast Fourier transform (FFT) then is performed on the 2^{16} data points by adding zeros at the end of the signal, which gives a frequency resolution of about 0.2 MHz. The water temperature is maintained at 19.6 ± 0.1°C so that the water velocity is taken as 1481 m/s from [6].

Epo-Tek 301 and Epo-Tek 353ND epoxy resins were investigated in our experiments. For Epo-Tek 301, the two components, part A and part B (hardener) were hand mixed with a ratio of 4:1 (parts by weight) in a 30-mm diameter container. The mixture was degassed in a vacuum chamber of less than 10 mTorr until no more air bubbles were coming out of the mixture. The mixture then was cast between one mold released and one normal glass plates, and cured at room temperature for overnight. The thickness of the glass plate is 5 mm. Three thin samples were fabricated with a thickness of 14.6 μm, 10.6 μm, and 9.8 μm, respectively. The top mold-released glass plate was removed from the samples after curing. A 0.507-mm thick sample without glass substrate also was fabricated, which was cast between two mold-released glass plates, and both glass plates were removed from the sample after curing. The same procedure was applied to the fabrication of Epo-Tek 353ND epoxy resins, in which part A and part B (hardener) were hand mixed with a ratio of 10:1 (parts by weight), and the mixture was cured at 60°C for 1.5 hours. Two thin layers on glass substrate, with a thickness of 10.2 μm and 10.8 μm, respectively, and one 0.355-mm thick sample without glass substrate were prepared for the measurement.

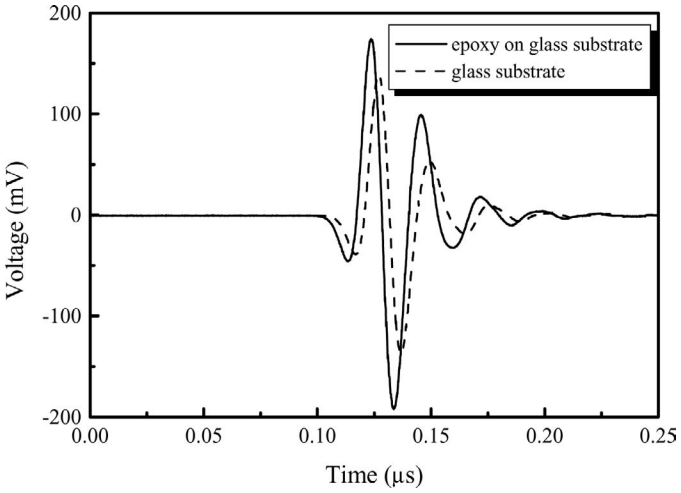

Fig. 2. The signal of 14.6-μm Epo-Tek 301 epoxy on a glass substrate, $g(t)$, and the signal from the glass substrate only, $h(t)$.

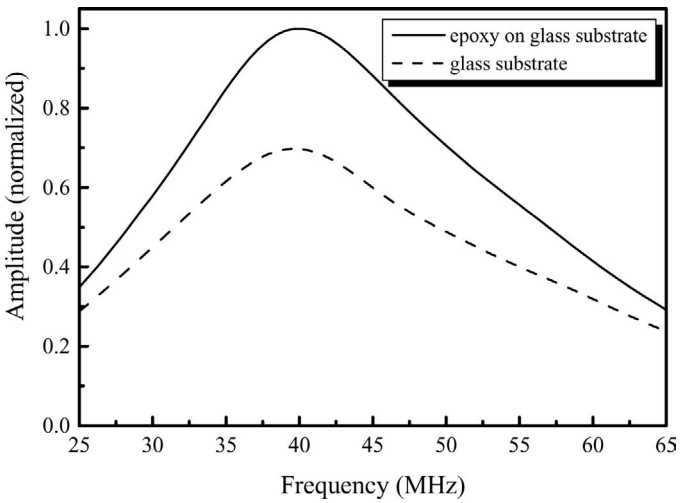

Fig. 3. Amplitude spectra $|G(f)|$ and $|H(f)|$.

The Epo-Tek 301 layers on the glass substrate were first measured by using the new method. Fig. 2 shows the two received pulse signals, $g(t)$ and $h(t)$, for the 14.6-μm sample on glass substrate, respectively. 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. One can find that the maximum value of 1.473 occurs at the

TABLE I
MEASUREMENT RESULTS OF EPO-TEK 301 EPOXY.

Thickness (μm)	14.6		10.6		9.8	
Frequency (MHz)	46.1		64.8		70.4	
	v (m/s)	α (dB/mm)	v (m/s)	α (dB/mm)	v (m/s)	α (dB/mm)
New method	$2.69 * 10^3$	17.2	$2.75 * 10^3$	24.0	$2.76 * 10^3$	26.3
Ultrasonic spectroscopy	$2.70 * 10^3$	19.8	$2.72 * 10^3$	27.9	$2.73 * 10^3$	31.0

TABLE II
MEASUREMENT RESULTS OF EPO-TEK 353ND EPOXY.

Thickness (μm)	10.8		10.2	
Frequency (MHz)	63.9		68.0	
	v (m/s)	α (dB/mm)	v (m/s)	α (dB/mm)
New method	$2.76 * 10^3$	15.1	$2.77 * 10^3$	16.0
Ultrasonic spectroscopy	$2.79 * 10^3$	12.4	$2.80 * 10^3$	13.2

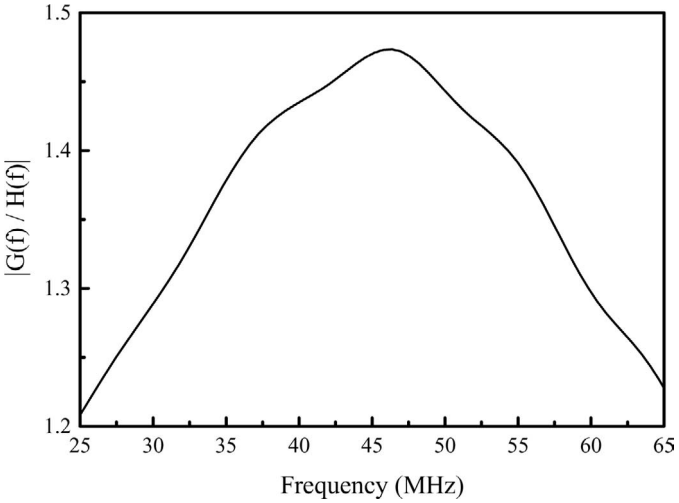

Fig. 4. The spectrum of $|G(f)/H(f)|$ ratio.

frequency of 46.1 MHz. From (13) and (14), we calculated the phase velocity and attenuation of the thin Epo-Tek 301 sample to obtain: $v = 2.69{*}10^3$ m/s and $\alpha = 17.2$ dB/mm. The density of the glass substrate is $2.20 * 10^3$ kg/m^3, and the phase velocity in the glass was measured to be $5.58 * 10^3$ m/s. Similarly, the other Epo-Tek 301 and Epo-Tek 353ND thin samples on glass substrate also were measured, and the results are shown in Table I and Table II, respectively.

We like to emphasize that the phase velocity of the sample cannot be determined by the time-of-flight, Δt, between the signals $g(t)$ and $h(t)$. In our experiments, if we take the time shift between the first positive peak of the $g(t)$ and $h(t)$ in Fig. 2 as Δt, then it will result in an incorrect phase velocity of $2.39 * 10^3$ m/s. The interference of overlapping signals causes large uncertainties in the determination of the true signal maximum in the direct measurements.

The thick Epo-Tek 301 and Epo-Tek 353ND samples without substrate were measured by using the ultrasonic spectroscopy method. Sachse and Pao [7] developed the through-transmission ultrasonic spectroscopy to determine the dispersion relation in dispersive solids in 1978. It has been the main tool to characterize solid materials with strong frequency dependent properties [8], [9]. Recently, we successfully extended this method to characterize transducer materials at frequencies up to 110 MHz [10], [11]. The measured phase velocity and attenuation of the thick Epo-Tek 301 and Epo-Tek 353ND samples without substrate at the frequencies of interest are also listed in Tables I and II.

The phase velocities in the $\lambda/4$ samples obtained using the new method are in good agreement with that obtained in the thick samples using ultrasonic spectroscopy. The discrepancy is about 1%. However, the discrepancy between the measured attenuation coefficients of the thin and thick samples is much larger (>10%). Further analysis showed that calculation of the attenuation using the new method is very sensitive to the properties of the substrate and water, as well as the alignment of the sample.

For example, 1% change in the acoustic impedance of water could result in an 8% change in the attenuation calculation of the 14.6 μm Epo-Tek 301 sample in the new method, but it may produce only a 0.4% change in the ultrasonic spectroscopy method. Because 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 [6]. The corresponding attenuation α in the 14.6-μm sample is then changed to 18.2 dB/mm if using our measured water velocity, but α is still 19.8 dB/mm for the thick sample, so that the discrepancy is reduced to 8%. Because the $\lambda/4$ matching layers are very thin, the difference in the attenuation 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 18.2 dB/mm, and 1.463 when the attenuation is 19.8 dB/mm, which means that the difference is only 0.7%. It also is observed that the attenuation measurement is very sensitive to the alignment of the sample. In our measurement, 1° rotation could result in a 10% difference in the attenuation for the 14.6-μm Epo-Tek 301 sample. Therefore, it is very challenging to achieve high accuracy attenuation measurements. However, the capability to accurately measure the ultrasonic wave velocity is very useful as one could use it to probe the elastic properties of thin and thick films.

IV. Conclusions

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 Epo-Tek 301 and Epo-Tek 353ND epoxy layers on glass substrate, with thickness ranging from 9.8 μm to 14.6 μm. The measured phase velocity is in good agreement with that obtained in thick samples by using the ultrasonic spectroscopy method. However, the measured attenuation in the new method is very sensitive to the properties of the substrate and water, as well as the alignment of the sample, causing some uncertainties in the attenuation measurements. Although indirect velocity measurements on thin films had been performed by Hadimioglu and Khuri-Yakub [4], the new method is the first method ever reported so far that allows direct measurement of phase velocity and the attenuation in such thin samples.

Acknowledgments

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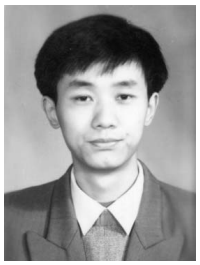

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