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Anodic aluminum oxide-epoxy composite acoustic matching layers for ultrasonic transducer application

H. J. Fang[a,b1], Y. Chen[a,c1], C. M. Wong[a,d], W. B. Qiu[e], H. L. W. Chan[a], J. Y. Dai[a,c *], Q. Li[b], and Q. F. Yan[b]

[a] Department of Applied Physics, The Hong Kong Polytechnic University, Kowloon, Hong Kong, PR China

[b] Department of Chemistry, Tsinghua University, Beijing, PR China

[c] The Hong Kong Polytechnic University, Shenzhen Research Institute, P.R. China

[d] Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, PR China

[e] Paul C. Lauterbur Research Center for Biomedical Imaging, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China

[1] These authors contributed equally to this work.

[*]Corresponding author.

E-mail address: jiyan.dai@polyu.edu.hk

Abstract

The goal of this work is to demonstrate the application of anodic aluminum oxide (AAO) template as matching layer of ultrasonic transducer. Quarter-wavelength acoustic matching layer is known as a vital component in medical ultrasonic transducers to compensate the acoustic impedance mismatch between piezoelectric element and human body. The AAO matching layer is made of anodic aluminum oxide template filled with epoxy resin, i.e. AAO-epoxy 1-3 composite. Using this composite as the first matching layer, a ~12 MHz ultrasonic transducer based on soft lead zirconate titanate piezoelectric ceramic is fabricated, and pulse-echo measurements show that the transducer exhibits very good performance with broad bandwidth of 68% (-6 dB) and two-way insertion loss of -22.7 dB. Wire phantom ultrasonic image is also used to evaluate the transducer's performance, and the results confirm the process feasibility and merit of AAO-epoxy composite as a new matching material for ultrasonic transducer application. This matching scheme provides a solution to address the problems existing in the conventional 0-3 composite matching layer and suggests another useful application of AAO template.

Keywords:

Matching layer; AAO-epoxy 1-3 composites; ultrasonic transducer

1. Introduction

Over the past several decades, ultrasonic imaging has become a widely used technique in medical imaging and blood flow measurements, and tremendous efforts have been made to develop high-performance ultrasonic transducers with large bandwidth (bandwidth > 70%) and high sensitivity (insertion loss>-30dB) [1-3]. As we know, an ultrasonic transducer is made up of three parts including matching layers, backing layer and piezoelectric element [4], therefore, optimizing the performance of these three parts is crucial for a high-performance transducer and high-quality imaging. Among the efforts to improve transducer's performance, choosing an active piezoelectric material with high electromechanical coupling factor (>0.5) is one effective approach. For example, single crystals such as PMN-PT [5], PZN-PT [6], PIN-PMN-PT [7] and $LiNbO_3$ [8] have been implemented in fabricating high-performance transducers. Optimizing the backing material with appropriate acoustic impedance (3 to 15 MRayls) and high acoustic attenuation (-50 dB in the backing thickness at center frequency) is another approach to improve the transducer's performance. Nevertheless, optimizing the matching materials with appropriate acoustic impedance (3 to 22 MRayls for 2 or 3 quarter-wavelength marching layers) and very low acoustic attenuation (< 10 dB/mm at center frequency) is the most effective way to increase the transducer's bandwidth and sensitivity.

In this work, we propose a new matching material, the anodic aluminum oxide (AAO) template, for ultrasonic transducer fabrication. Soft lead zirconate titanate (PZT-5A) ceramic is selected as the transducer active element since it is the most widely used piezoelectric ceramic for transducer applications, and therefore, it is easy to find a benchmark to compare the transducer's performance. The PZT-5A ceramic possesses good piezoelectric properties (piezoelectric constant d_{33}>350pC/N, electromechanical coupling factor k_t ~0.5), however, since its acoustic impedance is around 35 MRayls(Z_c), while the value of human body is only 1.5 MRayls (Z_m), the mismatch between the two media will result in 84% acoustic energy reflection and reduce the amount of acoustic energy being transmitted into human body according to the equation $(Z_m-Z_c)^2/(Z_m+Z_c)^2$ [9]. This mismatching problem can be solved with one or two quarter-wavelength matching layers, and the required matching usually should have acoustic impedance in the range of 3 to 14 MRayls. However, it is difficult to find such single phase matching materials in nature, so these matching layers are usually made with a mixture of polymer and inorganic particles such as Al_2O_3 [10], CeO_2 [11], SiO_2 [12] and Ag [13]. Nevertheless, employing these 0-3 composites for high-frequencies (e.g. 10-100 MHz) transducers faces challenges such as non-uniformity, high attenuation (>20dB/mm at center frequency) [14]. This is due to the fact that the thickness of the matching layer (quarter-wavelength) becomes thinner (~ 20-200μm) when the transducer's frequency increases (>10MHz), and in addition, attenuation caused by particle scattering also increases with the increase of transducer's frequency if the particle's size is not small enough compared to the thickness of the matching layer. Although nanoparticles (Al_2O_3 particles) have been demonstrated to be a promising material for high-frequency (40MHz) matching layer application[10], a large volume fraction (>40%) of particles is difficult to be achieved in such matching layer due to the wetting problem between the particles and epoxy. Therefore, the conventional method using epoxy mixed with particles is difficult to obtain a uniform and thin matching layer (~ 20-50μm) for high-frequency transducers (>10MHz).

Changing the type of connectivity in the composite matching layer has been proven to be an effective way to overcome these challenges. The silicon-epoxy 1-3 and 2-2 composite matching layer fabricated by deep reactive ion etch (DRIE) has been reported for ultrasonic transducer (center frequency ~15MHz) application [14-17]. The aim of this work is to demonstrate the feasibility to use AAO template-epoxy as a 1-3 matching material in ultrasonic transducer structure. The acoustic impedance of alumina (~40MRalys) is larger than that of silicon (~20MRalys), suggesting that a wider range acoustic impedance for the AAO-epoxy composite matching layer can be achieved via changing the alumina volume fraction. The nanometer-scale pore diameter/center to center pore distance and the thickness of this 1-3 composite can be controlled by the anodization time when making the AAO template [18,19]. In this work, a relatively high-frequency (~12MHz) PZT-5A ultrasonic transducer was designed and fabricated to evaluate the efficiency of this AAO-epoxy matching material. The pulse–echo performance of this PZT-5A ultrasonic transducer with the AAO-epoxy matching layer was characterized and compared to the simulation result. In addition, the 12μm-diameter wire phantom ultrasonic image was obtained using this transducer.

2. Experimental

2.1. Design of transducer

Fig. 1(a) shows a schematic diagram of the proposed ultrasonic transducer with specific dimensions, in which the double matching layers and one backing layer are the most common combination to sandwich the transducer element. A cross-sectional scanning electron microscopy (SEM) micrograph of the AAO-epoxy 1-3 composite is shown in Fig. 1(b). It is apparent that the pore diameter of the AAO template is about 200 nm arranged in a two dimensional array, and almost all the pores of the AAO template are filled with epoxy. This demonstrates the feasibility of the filling process, making it possible for mass production of the matching layers. The PZT-5A ceramic was used as the piezoelectric element after poling under a dc field of 30 kV/cm at 120°C for 15 min in silicon oil. For the double matching layers, the optimal acoustic impedance Z_1 and Z_2 can be calculated by the following equations according to the Krimholz-Leedom-Mattaei (KLM) equivalent circuit model [20]:

$$Z_1 = (Z_c^4 Z_m^3)^{1/7} \quad (1)$$

$$Z_2 = (Z_c Z_m^6)^{1/7} \quad (2)$$

Here Z_c (34.9 MRayls) is the acoustic impedance of the PZT-5A ceramic and Z_m is the acoustic impedance of the load medium (approximately 1.5 MRayls for human body). The calculated acoustic impedance of the first (Z_1) and second (Z_2) layers are 9.1 MRayls and 2.4 MRayls, respectively. An AAO-epoxy composite with appropriate volume fraction (58%) of alumina was selected as the first matching layer. The density and sound speed of the first matching layer are 2745 kg /m^3 and 3460 m/s, respectively. A pure epoxy (Epotek 301) with the acoustic impedance of 2.8 MRayls was used as the second matching layer.
Moreover, the thickness t of each matching layer can be determined by:

$$t = \lambda/4 \quad (3)$$

where λ is the wavelength of the ultrasonic wave in the corresponding matching layer.

The backing material should have a high attenuation (-50 dB in the backing thickness at center frequency) so that it can widen the bandwidth by absorbing the ultrasonic energy radiated from the back face of the piezoelectric element and reducing the ringing resulted from reverberation of pulse. On the other hand, it will reduce the relative pulse-echo sensitivity by damping out the ultrasounds [21,22]. In order to optimize the bandwidth and signal amplitude, a mixture of Epotek 301 epoxy, tungsten powder and microbubbles with acoustic impedance of 6.5 MRayls was used as the backing layer.

Various circuit models exist to simulate the behavior of the transducer including the Mason model, Redwood model and KLM model. Among them, the KLM model is more physically intuitive, and therefore, the KLM model-based simulation software Piezo CAD was used to predict the performance of the PZT-5A transducer with this AAO-epoxy matching strategy. The acoustic and piezoelectric properties of the PZT-5A ceramic were measured and summarized in Table 1. The properties of the matching and backing materials are listed in Table 2. The simulated time domain and frequency domain pulse-echo response of the PZT-5A transducer are shown in Fig. 2. The simulated results reveal that the transducer has a center frequency of 11.2 MHz and a bandwidth (-6 dB) of 70%. The PZT-5A transducer with AAO-epoxy composite matching layer was fabricated following the simulation results.

2.2. Fabrication and Characterization

The commercial AAO template (provided by Lesson Nano Technology Co., Ltd.) was first soaked in the epoxy solution (Epotek 301 diluted with acetone) in a glass beaker. To remove the air trapped inside the template, the beaker was pumped to vacuum. Then the AAO template with epoxy solution was cured overnight and lapped down to the designed thickness as the first matching layer. The second matching layer was made by casting the Epotek 301 on the first matching layer, and after curing, it was also lapped down to the designed thickness.

The PZT-5A ceramic with an active area of 2.0 × 2.0 mm^2 and a thickness of 170 μm was used as the active element of the transducer. The bottom electrode of this active element was bonded to a copper wire terminated with a BNC connector. Then, the mixture of tungsten powder/ micro bubbles/ Epotek 301 was casted on the bottom electrode and filled up the metal housing as the backing layer. A Cr/Au film with thickness of 500 nm was sputtered to make the top electrode of the PZT-5A element in contact with the metal housing serving as the ground electrode. Finally, the double matching layers were bonded to this top electrode under an external pressure with about 20000 Pa by pressing a piece of metal.

The cross-sectional morphology of the AAO template filled with the epoxy was observed with field emission scanning electron microscopy (FESEM, Jeol 6490). To evaluate the electrical performance of the transducer, the electrical impedance and phase spectra of the transducer were measured using an Agilent 4294A precision impedance analyzer. With the electric impedance plot, the corresponding effective electromechanical coupling coefficient k_{eff} can be determined as follow [24]:

$$k_{eff} = \sqrt{\frac{f_a^2 - f_r^2}{f_a^2}} \quad (4)$$

Where f_r and f_a are the resonance and anti-resonance frequencies, respectively.

The performance of the fabricated ultrasonic transducers with AAO-epoxy matching layer was evaluated by the conventional pulse-echo response method. The transducer was mounted on a holder and immersed in a water tank. A stainless steel target with thickness of 40 mm was placed in front of the transducer with a distance at the natural focal length of the transducer. During the measurement, the transducer was connected to an ultrasonic pulser-receiver (Panametrics 5900PR, Olympus, Japan). The active element was excited by an electrical impulse of 1 μJ at 1 kHz repetition with 50Ω coupling. The pulse-echo waveform was recorded by the receiving circuit of the 5900PR and displayed on an oscilloscope (Infinium 54810A, HP/Agilent, USA). The built-in Fast Fourier Transforms (FFT) math feature on the oscilloscope was used to display the frequency domain pulse-echo response. The center frequency (f_c) and bandwidth (BW) were determined from the FFT spectrum as following equation [24]:

$$f_c = \frac{(f_u+f_l)}{2} \quad (5)$$

$$BW = \frac{(f_u-f_l)}{f_c} \quad (6)$$

Where, f_l and f_u are the lower and upper -6 dB frequencies.

The two-way insertion loss (IL) represents the ratio of the output power of an ultrasonic transducer to the input power from the driving source. It can be obtained by connecting the transducer to a function generator (8116A, HP/Agilent, USA). After the transducer was excited by a sinusoidal tone burse of 20-cycle with a constant voltage of V_i at f_c, the peak amplitude V_o of the echo was measured using the oscilloscope with 1MΩ coupling. Then the two-way insertion loss can be calculated from the following equation [24]:

$$IL = 20 \ \log(\frac{V_o}{V_i}) \quad (7)$$

A single channel imaging platform was employed to evaluate the performance of the designed transducers [25–26]. The platform provides the bipolar pulse excitation with MOSFET pair (TC6320, Supertex Inc., Sunnyvale, CA) configurations. The center frequency and amplitude of the pulses are 12 MHz and 96 Vpp respectively. The gain of the imaging receiver is set to 47 dB with a dynamic range of 51 dB. The echo data were acquired by a 12 bit, 200 MSPS analog-to-digital converter (ADC). A field programmable gate array (FPGA) component was employed for image processing including the band-pass filter, Hilbert transform, envelope extraction. Afterwards, the ultrasound data was transferred to a computer through a high speed universal serial bus (USB) interface.

3. Results and discussion

In Fig 1(b), it is found that the nanofibers of epoxy are twisted under an internal stress and peeled off from the template. The volume fraction of alumina φ in this composite can be calculated using the rule of mixtures [27]:

$$\rho = \rho_a \times \varphi + \rho_e \times (1 - \varphi) \quad (8)$$

where ρ, ρ_a and ρ_e are the densities of the 1-3 composite, alumina and epoxy, respectively. The theoretical volume fraction of alumina based on the size and density of pores is calculated to be 58%. It is worth mentioning that the composite matching material based on alumina powder and epoxy with a high volume fraction alumina (>40%) is very difficult to be achieved, since air bubbles trapped in the mixture cannot be removed easily from the viscous mixture. While one can see that, with AAO template as used in our work, the volume fraction of alumina in the composite can easily reach more than 50%. Practically, the volume fraction of alumina can be further increased by reducing the pore size or the mesh number, leaving a plenty of room for further increasing the acoustic impedance for multilayer matching scheme where relatively larger acoustic impedance (>10 MRayls) for the first matching layer is needed.

The frequency-dependent electrical impedance and phase angle are shown in Fig. 3, where the resonance frequency (f_r) and anti-resonance frequency (f_a) derived from the thickness vibration mode are 12.5 MHz and 14.5 MHz, respectively. From this result, the effective electromechanical coupling coefficient can be calculated to be 0.51 based on Eq. (4).

The pulse-echo response of the transducer was measured in a water tank at room temperature.

Figs.4 (a) and (b) are the pulse echo response and FFT spectrum of the fabricated PZT-5A single element transducer with AAO-epoxy matching layer. The measured center frequency of the transducer is found to be 11.6 MHz, which is close to that of the designed value. With the AAO-epoxy composites as the first matching layer, the transducer yields a bandwidth (-6 dB) of 68% and the two-way insertion loss of -22.7 dB. The experimental result is within 2% discrepancy to the simulated result, and the performance of the transducer with AAO-epoxy matching layer can compete with the commercial transducers (bandwidth ~60% at 10M Hz) [28]. This suggests that the AAO-epoxy 1-3 composite can act as an efficient matching layer. For comparison, the performance of a 15MHz transducer with silicon-polymer 1-3 composite matching layer was given, and it's -6dB bandwidth is 50% [14], which is relatively lower than that of AAO-epoxy matching layer transducer (68%).

Besides the pulse-echo performance, a wire phantom including tungsten wires arranged with different steps was used to evaluate the image performance. Fig. 5 shows the ultrasonic image of the wire phantom captured by the fabricated PZT-5A transducer. From the image information, the axial and lateral resolutions (-6dB) of this transducer were acquired to be 192.5μm and 810μm, respectively.

4. Conclusion

The 1-3 composite material consisted of epoxy nanofibers filled in AAO template has been demonstrated to be an effective matching layer material for ultrasonic transducers. A ~12 MHz PZT-5A ultrasonic transducer with this AAO-epoxy matching layer has been fabricated and characterized. Very good performance of the transducer, i.e., a low insertion loss (-22.7 dB) and a broad bandwidth of 68%, have been obtained. The coincidence between the measurement and simulation shows that the AAO-epoxy is an effective matching layer, and this value is better than that of the silicon-polymer matching layer transducer (bandwidth~50%). The results confirm the applicable feasibility of this new matching material. Moreover, due to the tunability of acoustic impedance of the AAO templates, this approach has potential for matching layer application which can meet the requirements of different transducers.

Acknowledgments

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Table 1. Properties of PZT-5A ceramic.

Relative permittivity $\varepsilon_{33}^{S}/\varepsilon_0$	850

Electromechanical coupling coefficient k_t	0.51
Density ρ (kg /m^3)	7760
Longitudinal velocity c (m/s)	4500
Frequency constant(Hz·m)	1900
Acoustic impedance Z_a (MRayls)	34.9

Table 2. Basic material parameters of materials used in the transducer.

Material	Use	ρ (kg /m^3)	c (m/s)	Z_a (MRayls)
AAO-epoxy	Matching layer 1	2745	3460	9.5
Epotek 301	Matching layer 2	1048	2640	2.8
Tungsten powder/micro bubbles/Epotek 301 [23]	Backing layer	3570	1820	6.5

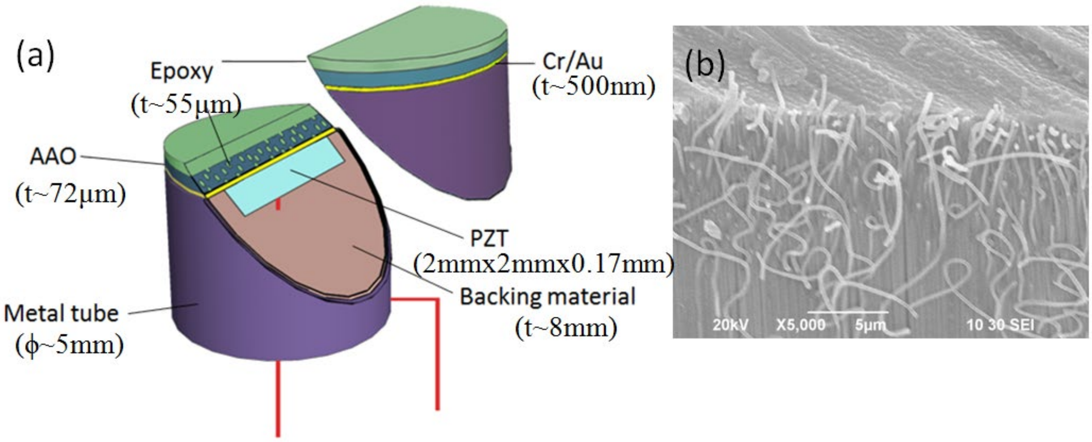

Fig. 1. (a) Schematic diagram of the designed PZT-5A transducer and (b) cross-sectional SEM of AAO-epoxy 1-3 composite.

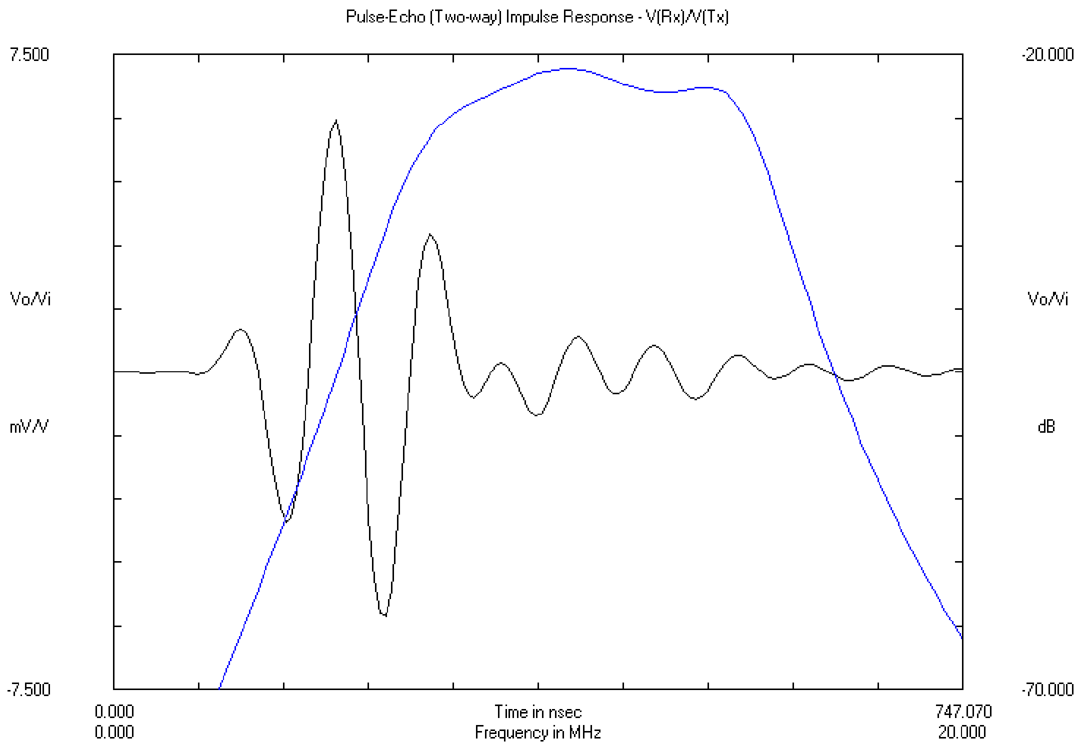

Fig. 2. Simulation of the pulse-echo response of the PZT-5A transducer.

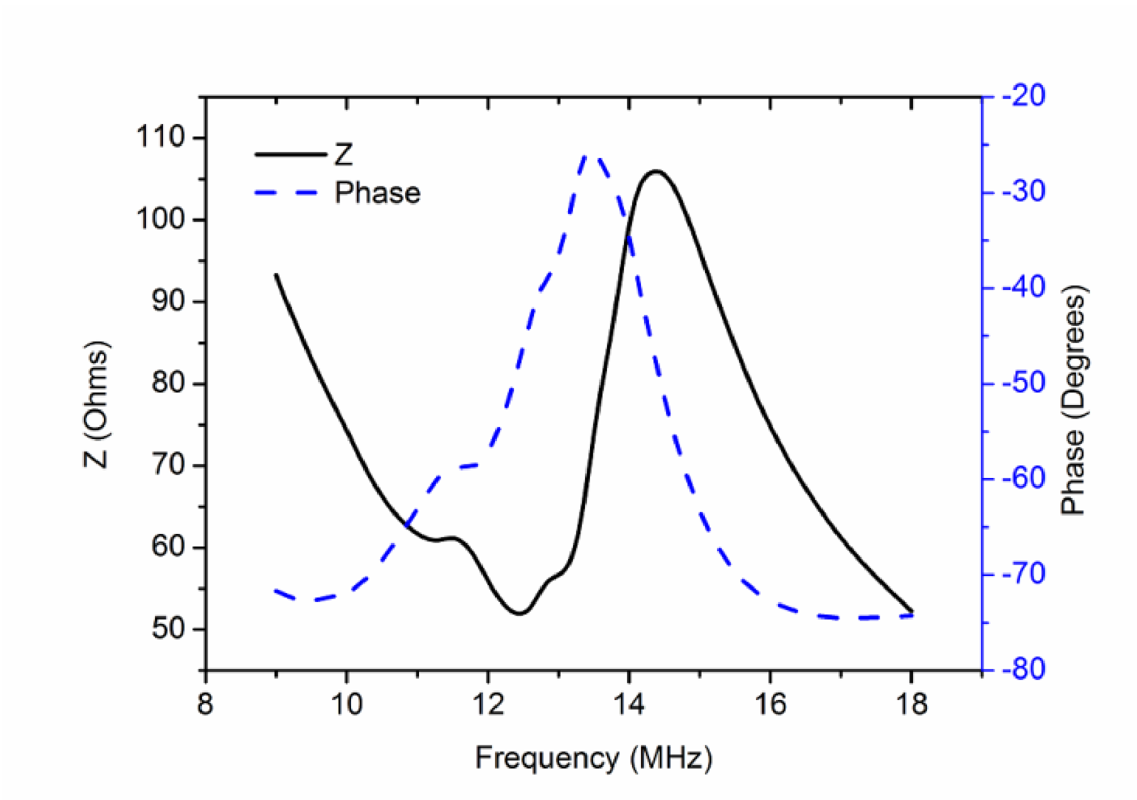

Fig. 3. The impedance and phase angle spectra of the PZT-5A transducer.

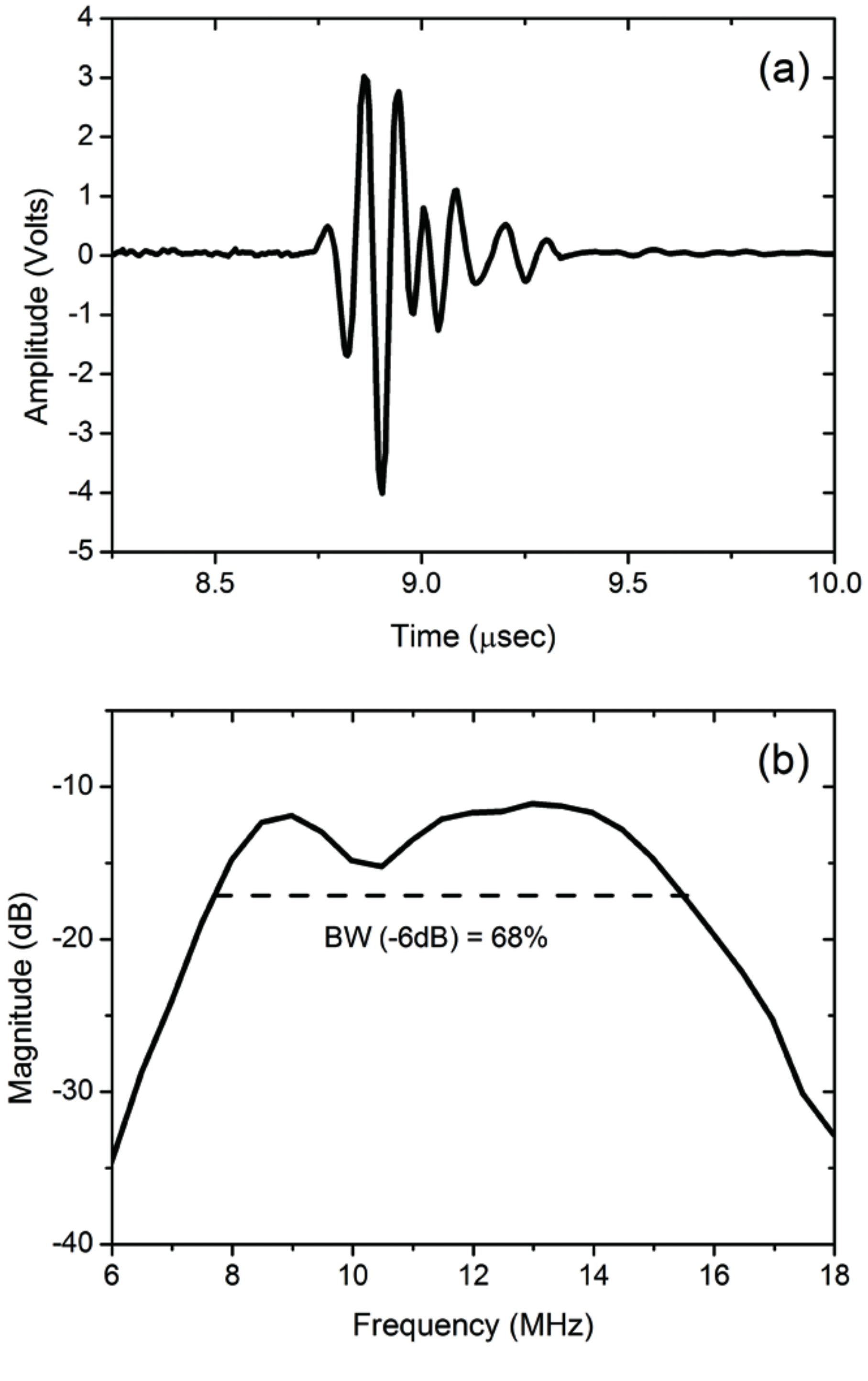

Fig. 4. (a) Pulse-echo waveform and (b) frequency spectrum of the fabricated transducer.

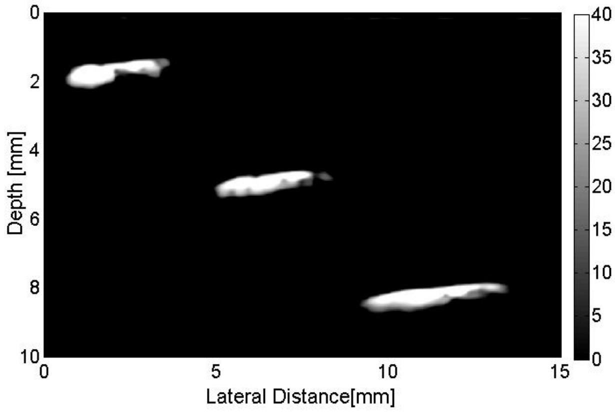

Fig. 5. Wire phantom image captured by the PZT-5A transducer