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Multi-layer polymer-metal structures for acoustic impedance matching in high-frequency broadband ultrasonic transducers design

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Abstract—**Although high-frequency (⩾ 100 MHz) ultrasound has demonstrated its capability in a variety of applications, the fabrication of high frequency ultrasonic transducers with both high sensitivity and broad bandwidth remains challenging. One main reason is the mismatch of acoustic impedance between piezoelectric materials and the loading medium. Due to reliance on both specific acoustic impedance of matching materials and precise thickness control, the conventional quarter wavelength (1/4 λ) matching layer design is impractical for high-frequency transducers. Based on the transmission line theory and Mason model, we interfaced polymer-metal-polymer matching layers for transducers over 100 MHz. The modeling result comparison between transducers without matching layer and those with two conventional matching layers demonstrated that the matching performance of polymer-metal-polymer matching layers could be as good as the one of conventional matching layers. Meanwhile, unlike conventional 1/4 λ matching layer design, our design is independent on materials with specific acoustic impedance, while precise thickness control of polymer and metal can be achieved by deposition. The polymer-metal-polymer matching layers scheme paves the way to high frequency ultrasonic transducers.**

Keywords—multi-layer acoustic matching scheme, transmission line theory, Mason model, Smith Chart design, pulse-echo experiment

I. INTRODUCTION

High-frequency (⩾ 100 MHz) ultrasound has founded its way to numerous applications, such as high resolution scanning acoustic microscopy, cellular stimulation and microparticle manipulation[1-3]. However, it remains technically challenging to fabricate high frequency transducers with both high sensitivity and broad bandwidth[4-5]. In order to achieve broad bandwidth and high transmission efficiency from high acoustic impedance piezoelectric materials such as LiNbO3, PZT, and PMN-PT, an acoustic impedance matching layer is essential.

To date, conventional quarter-wavelength matching layer scheme has almost been exclusively used in piezoelectric ultrasound transducers. Both material impedance and thickness are required to be specific values. At low frequencies, both requirements were traditionally achieved as: 1) tuning the acoustic impedance of the matching layer material by mixing high impedance particles with low impedance polymer at a certain ratio, and 2) lapping it to quarter-wavelength thickness. Compared to the long wavelengths of tens to hundreds of micrometers, lapping precision of a few micrometers was tolerable. However, for high-frequency ultrasound transducers, on the contrary, the quarter-wavelength approach becomes technically impractical by lapping because thickness discrepancies of a few micrometers cause significant performance variances. Furthermore, as the wavelength shortens and approaches to the particle size for high-frequency ultrasound, the mixture properties deviate noticeably from homogenous ones, which reduce the matching performance. Homogenous materials are more preferable than the mixture of polymers and particles for a low scattering and precise thickness control through coating or deposition. Whereas in traditional matching layer design, materials with specific required impedance are rare. As a result, though high frequency (⩾ 100 MHz) ultrasonic transducers have been investigated and fabricated, sensitivity and bandwidth of them are always low due to the inappropriate matching layer design, which is merely a parylene layer (acoustic impedance 2.58 MRayl) .

Recently, multi-layer polymer-metal structures for acoustic impedance matching have been investigated to avoid reliance on specific impedance of the materials. Such multi-layer structures entail polymer and metal with different impedances, achieve a specific matching effect by tuning the thickness of each layer. Such multi-layer polymer-metal structures are effective for low-frequency transducers fabrication as well.

In this work, we implemented electromechanical equivalent circuit and microwave transmission line method[6-7] as a guidance to study the matching effect of triple-layer polymer-metal-polymer for high-frequency (⩾100 MHz) and broad bandwidth (⩾ 60%) ultrasonic transducers. The Smith chart was utilized to analyze the effective acoustic impedance as well as the reflection and transmission information. The matching performance of polymer-metal-polymer structure was compared with that of a conventional double quarter-wavelength matching layer structure with KLM modeled pulse-echo results although the quarter-wavelength matching layers are hardly realizable. Moreover, a single element transducer with 100MHz center frequency was designed and fabricated to verify the matching performance. Both the sensitivity and bandwidth were significantly improved as expected.

II. Result

A. *Numerical studies of ultrasound transducers with multi-layer polymer-metal structures*

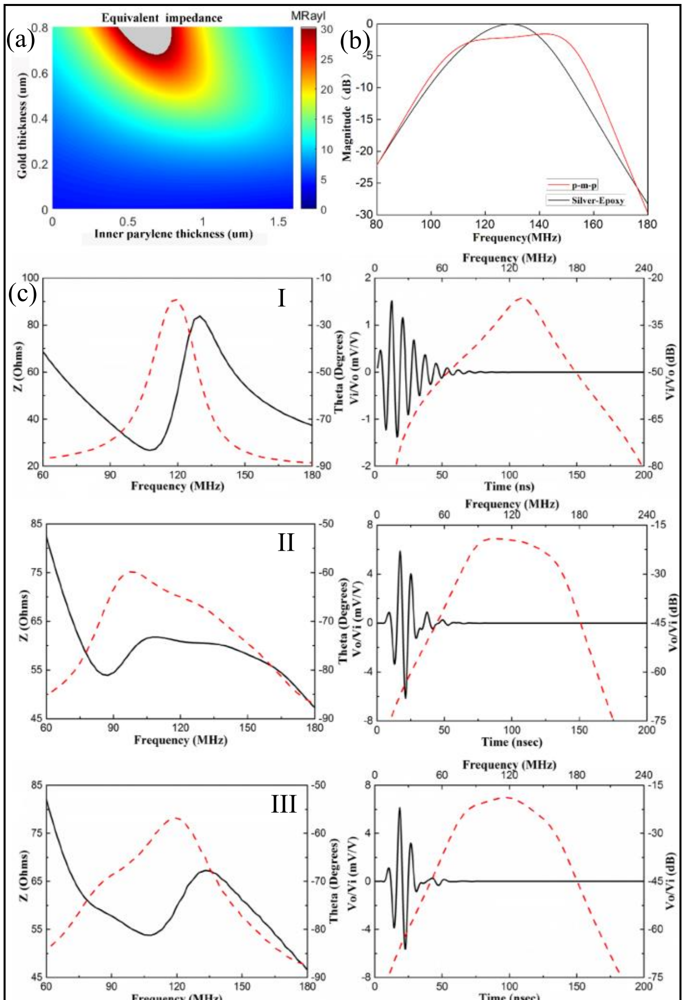

Fig.1 a)Simulation result of the equivalent impedance associated with the thickness of inner parylene and gold layers b) Simulation result of voltage transfer functions of two different matching design schemes. I)Pulse-echo modeled result with KLM model-based simulation software PiezoCAD. I) without matching layer; II) with polymer-metal-polymer matching layers; III) with double quarter-wavelength matching layers.

By earlier work[8], we set the thickness of the outer parylene layer to be around 1/4 λ, which is 4.7 μm. The effective impedance dependent on the thickness of inner parylene and gold is shown in Fig.1 a). According to the theoretical simulation, finial thicknesses of the parylene-gold-parylene layers were optimized as 0.8-0.5-4.7 μm. Besides, for conventional quarter-wavelength matching layer design, the thickness of parylene and silver epoxy was 4.7 μm and 4 μm, respectively. The voltage transfer functions of two different matching schemes are shown in Fig.1 b), the performance should be the same theoretically, however silver epoxy is not the ideal material with the specific impedance of double matching layers scheme so that the bandwidth of parylene-gold-parylene matching layers is wider than that of double matching layers at the expense of sensitivity. Krimholtz–Leedom–Mattaei (KLM) model-based software PiezoCAD (Sonic Concepts, Woodinville, WA) was utilized to simulate the transducer performance with the two acoustic impedance matching schemes. The modeled pulse-echo results were shown in Fig.1 c). As the purpose of this work was to compare performance of the two different acoustic matching schemes, attenuation in the loading medium was excluded. Also, other parameters like the transducer diameter, properties of piezoelectric element, and backing material remained the same for all the three transducer designs (Table I).

B. *Experiments on broadband ultrasonic transducers multi-layer polymer-metal matching layers*

A single element transducer with 100MHz center frequency was designed and fabricated to verify the matching performance. In the absence of the matching layer, the amplitude of the echo is 200.373 mV and the -6dB bandwidth is 36.89% (Fig.2 b). in the presence of the p-m-p structure, the magnitude of the echo increased to 791.05 mV and the -6dB bandwidth increased to 86.6% (Fig.5 c). Both the sensitivity and bandwidth were significantly enhanced as predicted.

III. Discussion and Conclusion

The first part of discussion summarizes the core innovation of multi-layer polymer-metal structures compared with traditional quarter-wavelength matching layer scheme. It is demonstrated by Smith chart that p-m-p matching layer can achieve optimal value of acoustic impedance which leads to the high transmission efficient at a broad frequency range. While conventional double matching layer design cannot shift the impedance from edge to the center due to the lack of materials with specific acoustic impedance so that the amplitude of pressure reflection coefficient is a little higher. In addition, the p-m-p matching scheme utilizes chemical deposition to control the thickness of each layer accurately which is a breakthrough in fabrication compared to what has been published.

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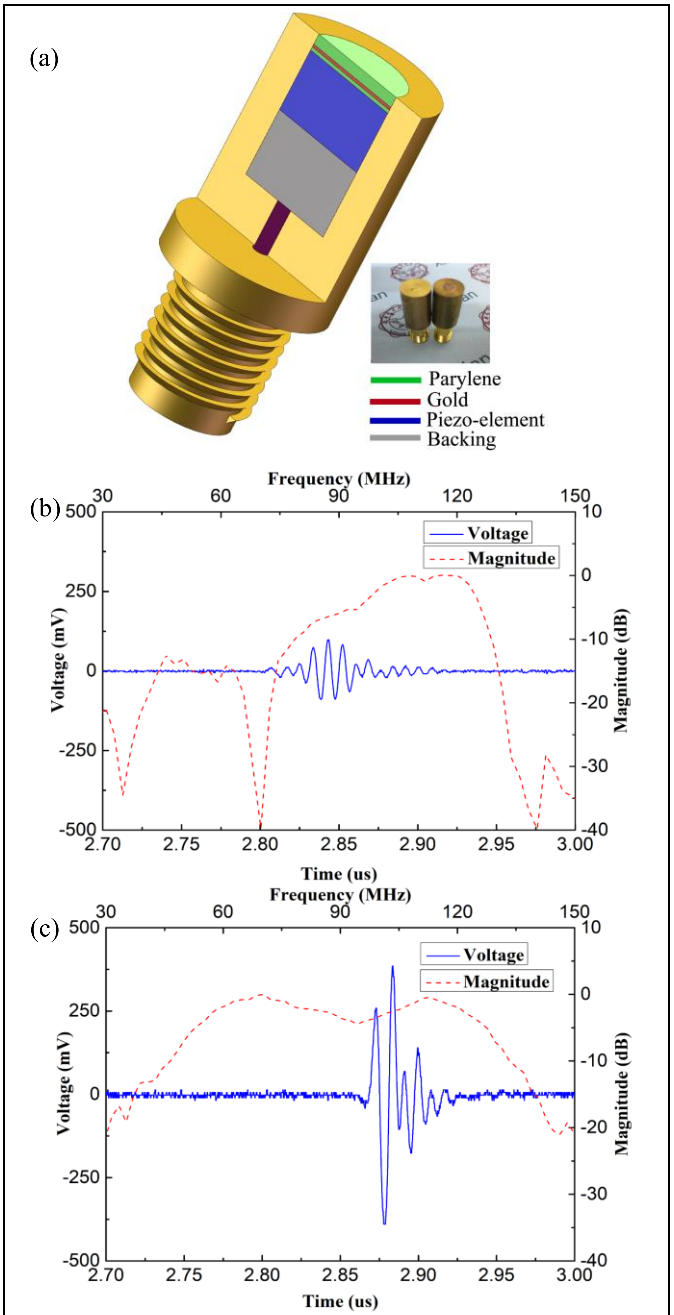

Fig.2 a) Structure and photo of the p-m-p matching transducer, the time-domain pulse/echo response and normalized frequency spectrum of b) without matching transducer and c) p-m-p matching transducer.

The main propose of simulation of three different transducers by KLM model is to estimate the size of piezoelement of transducers. As we can see from Fig.1 c), the electrical impedance is around 50Ohms at operating frequency with the size of 1.5mm*1.5mm so that the transducer can match the internal resistance of power source. Another aim is to obtain the acoustic performance of conventional double quarter-wavelength matching design. With the frequency increasing to 100MHz. it is difficult to lap it to the quarter-wavelength thickness and the performance of matching layer is reduced since the thickness of matching layer shortens and approaches to the particle size. It can be found that the sensitivity and bandwidth of transducer are significantly improved by either double matching design or p-m-p scheme. The sensitivity is increased from -56.4dB without matching layers to -44.2dB with matching layers and the bandwidth is increased from 29.3% to 62.8% respectively

As the final point of discussion, the acoustic performance of p-m-p structures is experimentally demonstrated and some drawbacks of transducers are pointed out. As predicted, the magnitude of echo and the -6dB bandwidth, which are two critical standard for diagnostic imaging, increased to 791.05mV and 86.6% respectively. However, there are still some drawbacks of transducer. The spectrum analysis of echo signal shows that there are two peaks at 75MHz and 115MHz respectively, which lies in the constant error (0.5um) of parylene chemical deposition equipment. The thickness of inner parylene layer (0.8um) cannot be accurately controlled, leading to an extra phase drift and thus the other peak of acoustic energy in spectrum appears. There are some solutions to this problem such as adjusting the operating temperature of the device, using more sophisticated techniques (semiconductor process) or seeking other materials for fabrication.

In conclusion, we demonstrated that triple layer polymer-metal-polymer structure enables an acoustic matching layers design for the high-frequency broad bandwidth ultrasonic transducer. Theoretically, the polymer-metal-polymer matching layers performed almost as good as the double quarter-wavelength matching layers for over 100 MHz transducer design presented in our modeling work. For practical considerations, it bypasses the fabrication limitations of the traditional matching methods in high frequency transducers. The polymer-metal-polymer matching layer design pioneers a new path to developing an effective matching strategy for high-frequency transducers.

IV. METHODS

A. Transmission line theory and Mason model

The microwave transmission line method was applied as guidance for polymer-metal-polymer structure design and the electromechanical equivalent circuit, namely Mason model was extended to verify the performance of ultrasonic transducers. Each ultrasonic vibration layer was equivalent to a section of circuit, and the microwave impedance matching network methodology was applicable to the multi-layer transducer design. High transmission efficiency and low reflection coefficient can be achieved by tuning the matching network.

The electromechanical equivalent circuit model contains two acoustic terminals with their common terminals connected to the electric transformer. The voltage transfer function derived from this model can be the criterion of the performance of matching layers and the microwave impedance matching network methodology was utilized to simplify the calculation. The equivalent input impedance and the reflection coefficient can be achieved and adjusted by tuning the matching network. To illustrate the feasibility of our multi-layer polymer-metal structures for acoustic matching propose, Smith chart was utilized to illustrate the equivalent impedance and the reflection coefficient. The matching loci in the Smith chart explicitly demonstrate the matching effect. The center of the chart is the matched point with 100% transmission while the circle edge means 100% reflection. The phasor from the origin (center) to a position in the Smith Chart represents the reflection coefficient, length of the phasor indicating the amplitude of the reflection and the direction indicating the phase. With each layer added in sequence, the loci shift clockwise as a circle with centers on the horizontal middle line and the position dependent on the impedance of the material. Meanwhile, the impedance can be directly read from the chart. As both reflection information and the impedance information are plotted in the same chart, the reflection information can be directly converted from and to the impedance value. With matching layer added in sequence, the impedance was shifted from the edge to the center for both matching schemes, indicating that the impedance was matched in both cases. The two loci presented two examples of the matching scheme, which resulted in similar bandwidth and transmission efficiency.

B. Experimental setup and measurements

The electrical impedance was measured by WK6500B 1J65120B impedance analyzer (Wayne Kerr Electronics, UK), The acoustic performance was characterized by conventional pulse-echo experiment carried out in distilled water. The acoustic echo was received and analyzed by an Ultrasound Pulser/Receiver (DPR 500, USA).

C. Numerical calculations

Krimholtz–Leedom–Mattaei (KLM) model-based software PiezoCAD (Sonic Concepts, Woodinville, WA) was utilized to simulate the transducer performance with the two acoustic impedance matching schemes The materials used for the PiezoCAD simulation are listed in Table I.

Table.I Material properties used in transducer designs

Material	Function	c [m/s]	ρ [kg/m3]	Z [MRayl]
$LiNbO_3$	Piezo-element	7360	4688	34.5
Parylene	Matching layer	2350	1100	2.58
Gold	Matching layer	3240	19700	63.8
Silver-epoxy	Matching layer	1900	3860	7.3
water	Front load	1540	1000	1.54

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