Different Layer Thickness Influences of a 50MHz Intravascular Ultrasound Transducer

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***Abstract*—In order to design a 50MHz intravascular ultrasound (IVUS) transducer with good pulse-echo responses, in this paper, a finite element model (FEM) was built to simulate the transducer acoustic performances with different layer thicknesses. According to comparisons of the acoustic fields and the admittance curves, the optimum thickness parameters are gained. And then, an IVUS PZT transducer with controlled layer thicknesses was fabricated and tested. The results of pulse-echo response tests shown this transducer with the optimum parameters had very good performance. The central frequency is 45.5MHz and its bandwidth was about 50% which are suitable for intravascular imaging.**

I. INTRODUCTION

Intravascular ultrasound (IVUS) is a remarkable imaging technology which provides real time cross-sectional images of coronary arteries and has become an important clinical tool for the detection and evaluation of coronary artery diseases[1]. Currently, rotating single-element IVUS transducer with center frequencies about 40MHz clinicians is widely used for clinical on the diagnosis of cardiovascular disease[2]. For improving the image resolution, transducers with higher frequencies are required. But, we also hope to get a good balance between the depth of penetration and the image resolutions.

An IVUS transducer consists of four main parts, including a piezoelectric disc, matching layers, electrodes and a backing layer[3]. The piezoelectric disc which made by piezoelectric materials with reversible electromechanical conversion ability is the core part of the transducer; Matching layers whose acoustic impedance is between piezoelectric materials' and medium's is added to the disc surface to improve the transmission efficiency rate. Backing layer is used to absorb the backward sound waves propagation and reduce the sound waves reflection, thus make the ultrasonic transducer become a single direction radiation source[4, 5]. Each of those parts' thickness plays key role on determining the transducer's performance. The electrode with the thickness of 200nm~400nm has negligible effect on the transducer's vibration and acoustic field and can be ignore.

The transducer's central frequency is constrained by structural parameters especially thickness of different layers. Building a transducer is a complex procedure, especially, an IVUS transducer. To optimize our design of a high frequency IVUS transducer, in this paper, we used a finite element analysis (FEA) to simulated study thickness influences of each layer.

Kossoff. G (1966) studied the effects of backing and matching on the performance of piezoelectric ceramic transducers just by comparing the transmit-receive results[5]. N.Guo and P.Cawley (1991) put a FEA to use on piezoelectric discs and found how a piezo disc vibrates and how to predicted its characteristic[6, 7]. Najib N.Abboud et al (1998) adopt FEM to optimize the design of ultrasonic transducers[8]. Lorenzo Spicci and Marco Cati (2011) put forward an FEA approach for optimizing and guiding ultrasound transducer manufacture, the measured performances of transducer which fabricated by this way had a good agreement with the simulation results. A KLM models was also validated[9]. Xiang Li et al (2011) proved that piezoelectric free standing film with thickness of dozens of micrometers can be used in very high frequency ultrasonic transducers, higher frequency IVUS transducer is also possibly fabricated by this way[10].

Those previous research provide a solution how to design and fabricate a proper ultrasound transducer. But few works discussed the layer thickness influences of an IVUS transducer especially very high frequency (>40MHz) IVUS transducer. In this paper, the thickness of different layers including the piezoelectric disc, matching layer and backing layer on the IVUS transducer was simulated by using a FEA model. And according to optimized thickness parameters, a sample transducer was manufactured and tested to validate our design. All the results showed that by using this FEA model to simulate an IVUS transducer and get optimized thickness parameters could help design and save fabricating time of an IVUS transducer.

II. METHODS

A. Transducer model

The transducer can be modeled as Figure 1[8]. The piezoelectric disc is used as an electromechanical converter to turn electrical signals into mechanical vibration. It can be simplified as a spring vibrator, which is working as an active component.

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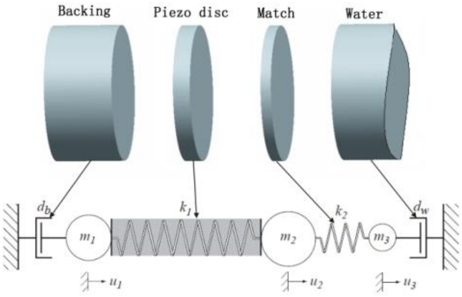

Figure 1. The coupled harmonic oscillator model.

The backing layer which absorbing the back forward vibration energy can be modeled as a damping component; The matching layer working as a driven component whose vibration can cause resonance with the piezoelectric disc and couple their own vibration modes to the piezoelectric disc can be equivalent to a spring harmonic oscillator; And the transmit medium (usually using water) with damping effect can also be modeled as a damping component.

B. *The FEA model*

A symmetry model can be built to save time and memory because of its cylinder structure. The meshing element size should be less than 1/8 wavelength (2D) or quarter wave length (3D) to insure the simulation accuracy.

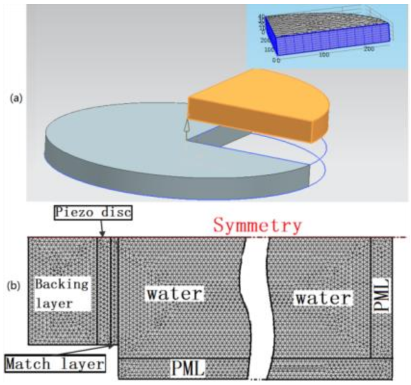

Figure 2. Transducer COMSOL FEA model (a) 3D symmetry model for vibration analysis; (b) 2D symmetry model for acoustic field analysis, PML (Perfect Match Layer) is set to simulate the infinity boundary.

The parameters of the material are very important to build an appropriate model and shall be specified. PZT-5H is selected as the material of piezo disc and Table I is the material parameters of other component.

TABLE I. Material parameters.

Material	Density (kg/m^3)	Sound speed(m/s)	Young's module	Poisson ratio
Backing	2930	1980	12GPa	0.2
Water	1000	1500	-	-
1-Match	1180	2700	3GPa	0.3
2-Match	7730	2200	10GPa	0.22

III. RESULTS AND DISCUSSION

A. *Simulation Results*

The piezo disc with different thickness had been firstly analyzed at frequency domain to gain the relationship between its resonant frequency and its thickness. The active voltage is a sine signal with amplitude of 100V. Results (in Figure 3) show that their relationship is not linear on a large scale, but on lower frequency area (below 55MHz), it is proximately linear. The curve also indicated that the thickness of PZT disc for 50MHz resonant frequency is proximately 40μm.

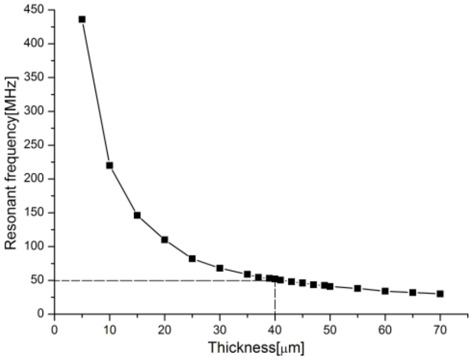

Figure 3. The resonant frequency changed by the piezo disc's thicknesses

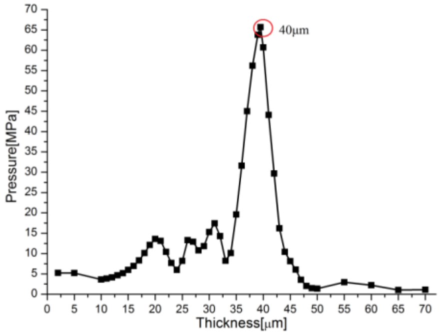

Figure 4. The acoustic pressures at the center position with 1000μm distance away from the surface of the transducer with different PZT thicknesses

To compare the acoustic pressures of the simulated transducers, the center position which 1000μm away from the surface of transducers is chosen as the measured position and simulated the acoustic fields generated by different PZT disc thicknesses. The results (in Figure 4) show that the acoustic pressure of a 40μm piezo disc is stronger than other thicknesses. So, 40μm can be certainly set as the optimum thickness of the piezo disc for the 50MHz IVUS transducer.

A model with different thickness single match layer is secondly set up. Their admittance curve and acoustic field are compared. Figure 5 shows the acoustic pressure in the measured position of transducers with different thicknesses of a single match layer, which are changed from 1μm to 20μm.

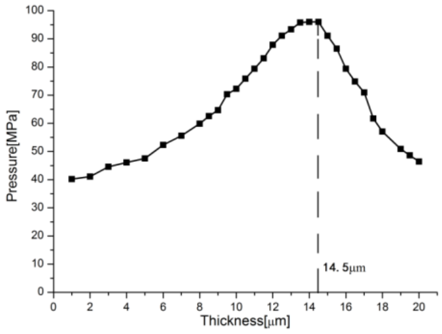

Figure 5. The acoustic pressure at the measure position with different thicknesses of the first match layer.

The results in Figure 5 indicated that when the thickness of the first match layer is 14.5μm, the acoustic pressure was strongest. And 14.5μm also closely approximates to quarter acoustic wave length of 50MHz frequency, which was thought as the perfect thickness of a match layer by using the KLM model[11].14.5μm can be set as the designed thickness of the first match layer.

In the situation of a transducer with double match layers, the same method could be used .The thickness of the second match layer was simulated while the other conditions are fixed. Figure 6 is the pressure of different thicknesses of the second match layer at the measured position. The thickness of the second match layer was set from 1μm to 20μm.According to Figure 6, the strongest acoustic pressure happened when the second match layer thickness is 11.5μm. As we know, that the quarter wave length of the second match layer is 11μm. So, we believe that 11.5μm can be set as the optimum thickness of the second match layer.

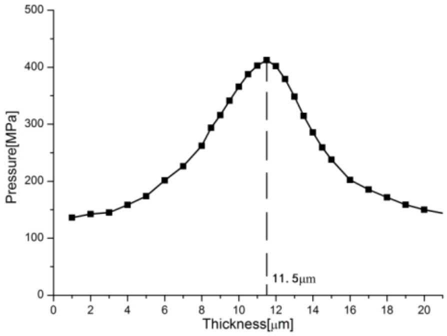

Figure 6. The acoustic pressure at the measure position with different thicknesses of second match layer.

To investigate the influences of backing layer whose thicknesses is changed from 10μm to 400μm. The pressure at the measure position and the backing end point were plotted. In Figure7, the pressure at the measure positions hardly changes by the different backing layer's thicknesses. But the pressure at the end point of backing layer differs a lot as the thickness change of the backing layer. On the curve, the weakest pressure occurs at 260μm.So the suggested thickness of the backing layer can be set as 260μm.

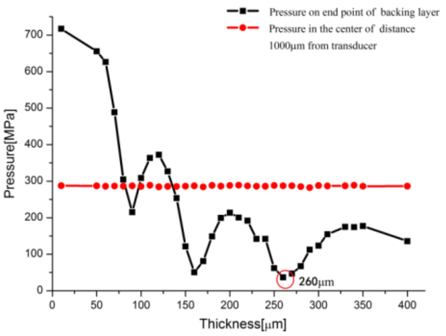

Figure 7. The acoustic pressure at the measure position and the end point of backing layer changed with different thicknesses of the backing layer.

For a summary, the optimum thickness parameters for 50MHz IVUS transducer are listed as Table Ⅱ.

TABLE II. The optimum thickness parameters

Constituent part	Optimum thickness (μm)
Piezo disc	40
First match	14.5
Second match	11.5
Backing	260

Based on the instructional data on Table Ⅱ, the admittance character of the transducer is as Figure 8. Its global acoustic field with the optimum parameters is also shown on Figure 8.

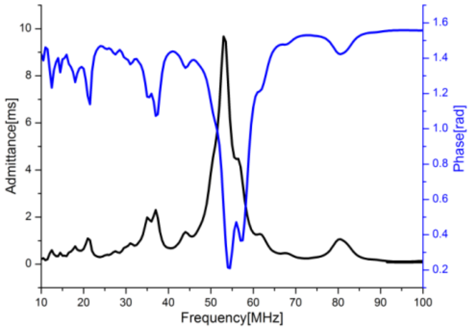

Figure 8. The admittance curve of the transducer, the black line is the admittance curve and the blue line is the phase of admittance.

Figure 8 shows that this transducer's central frequency is slightly higher 50MHz. There is other small secondary frequency occurs on the admittance curve making the curve not smooth as a typical piezoelectric admittance curve[12]. Figure 9 is the acoustic pressure field generated by the transducer; the sound field shows that the near field is very complex and turbulent and cannot be used. But its far field is quite typical; its main lobe is very obvious and has strong pressure while its side lobe can also be observed but very small compared to the main lobe.

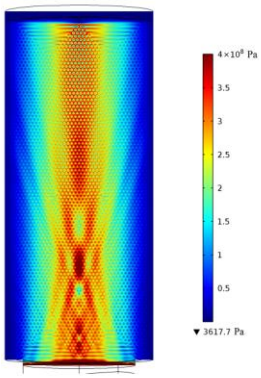

Figure 9. The acoustic field of the IVUS transducer.

B. The test results

Based on Table Ⅱ, an IVUS transducer was fabricated. Figure 10 is a photo of the IVUS transducer we house made

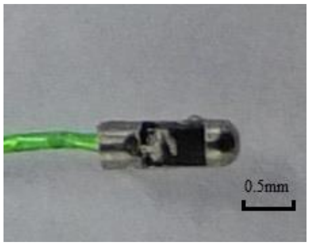

Figure 10. The IVUS transducer sample.

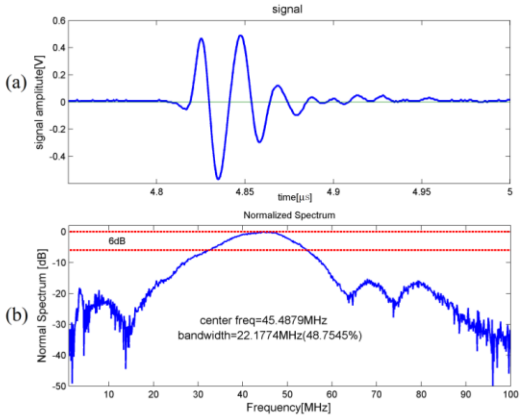

Figure 11. The transducer's pulse-echo result. (a) The echo signal. (b) The echo signal's spectrum.

The sample IVUS transducer is tested through pulse-echo method. Figure 11 showed its pulse-echo signal and spectrum. The echo signal can last just a few circles with high amplitude, while its aftershock wave is very weak and just lasts a very short time. Those results prove that the transducer can have a rather high axial resolution and good sensitivity. According to its spectrum curve, transducer's center frequency is 45.5MHz 5MHz which is very close to the designed central frequency. The difference between the simulation and experiment test could be the fabrication error like lapping thickness control and so on. Its bandwidth is 48.7545% which is quite good for intravascular imaging.

IV. CONCLUSIONS

Using the numerical FEA simulation method to assist designing a 50MHz IVUS transducer is performed in this paper. By comparing the acoustic field characters on the main lobe and its admittance characters, the optimum thickness parameters are gained. The optimum thickness of the piezo disc, the first match layer, the second match layer and backing layer are 40μm, 14.5μm, 11.5μm and 260μm. Based on the simulation results, an IVUS transducer sample is built and then tested. Its pulse-echo result indicated the transducer with the optimum parameters has rather good performance.

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