Devolopment of Focused IVUS Transducer Using PMN-PT Single Crystal

Single-element focused IVUS transducer

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***Abstract*—The PMN-PT based high-frequency side-looking focused IVUS transducers were fabricated successfully by a mechanical dimpling technique and their performance was tested. Compared to the flat transducer, the focused transducer with 31 MHz center frequency showed superior -6 dB bandwidth (52%) and axial/lateral resolutions (29/470 µm). However, the average insertion loss of focused transducer at 35 MHz is around -21.53 dB which is little higher than that of flat one with -18.12 dB at 32 MHz. The improved imaging resolutions, especially axial resolution, can give more detailed vessel microstructure information on vulnerable atherosclerosis compared to conventional transducer. These results show that side-looking dimpled focused IVUS transducers are promising for IVUS medical imaging in vulnerable plaque diagnosis.**

Keywords—PMN-PT single crystal; focused IVUS transducer; mechanical dimpling technique; atherosclerosis

I. Introduction

Intravascular ultrasound (IVUS) is a widely used clinical imaging technique for atherosclerosis detection and diagnosis. Since it directly images the vessel wall by mounting IVUS probes on catheter tips, IVUS can provide precise vessel wall structure, lumen dimension, plaque composition and calcium content [1], [2]. IVUS imaging is based on side-looking single-element transducers which are mechanically driven by a motor to rotate inside the vessel to form a 360 degree scanning image. The center frequencies of IVUS transducers commonly used in clinic are between 20 to 40 MHz and their apertures are less than 0.8 mm limited by the size of IVUS catheters [2]. For clinical diagnosis purpose, superior axial resolution is required to evaluate the vulnerability of atherosclerosis especially the thin-cap fibroatheroma where the minimum thickness of fibrous cap is 65 um [3]. Unfortunately, as the key component of IVUS system, current commercial IVUS transducers are unfocused with narrow bandwidths and cannot provide good axial (60 µm) and lateral resolutions (300 um) due to the lack of focusing ability [4], [5]. The low axial resolution can be attributed to narrow bandwidth of transducers. These inferior resolutions, especially inferior axial resolution, would lead to some loss of detailed information about microstructures of vessel and plaque compositions. To improve these situations, building focused IVUS transducers will be an urgent task in future. Until now, three focused techniques have been adopted in fabricating the focus transducers, such as adding an extra lens, hard pressing and mechanical dimpling techniques [6] [7]. The first two techniques are difficult to be applied to IVUS transducer mainly due to the small size of transducer. Mechanical dimpling technique was first used in focusing transducer by J. Y. Dai et al two years ago [7]. It can directly form a concave surface on piezoelectric element by mechanically grinding the single crystal. The thickness of piezoelectric element along the curve surface changes continuously. This causes the piezoelectric element with multi-resonances and is in favour of the bandwidth of transducer [7], [8]. In addition, it can be used to fabricate focused transducers with small size and keep the piezoelectric element intact simultaneously [7]. Considering above mentioned, we think mechanical dimpling technique is a most promising approach to build focused IVUS transducer with broad bandwidth and high resolutions.

As we all known, either single element transducer or array transducer basically contains three components: piezoelectric element, backing layer and matching layer. The most important component is the piezoelectric element which can transmit sound waves and receive echoes reflected from tissues. Up to now, many different piezoelectric materials have been used in transducer design, [5], [6], [9]-[12] . Among them, PMN-PT single crystals are promising candidates due to their high k_t ~ 0.6, d_{33} ~ 1500 pC/N and ε_r ~ 940. For a miniaturized IVUS transducer, PMN-PT with large dielectric constant is more desirable. In this study, we demonstrated the fabrication of focused IVUS transducer using the (001)-oriented PMN-0.28PT single crystal by a mechanical dimpling technique. Their performance was characterized and compared with conventional flat transducer with similar center frequency.

II. MATERIALS AND METHOD

A. IVUS Transducer Fabrication

The (001)-oriented PMN-0.28PT single crystal was used as the active material of the transducer. First, the single crystal was poled in silicone oil under an electric field of 1.5 kV/mm at room temperature for 15 min. It shows superior thickness electromechanical coupling coefficient (k_t ~ 0.6) and high piezoelectric constant (d_{33} ~ 1500 pC/N) and relative clamped dielectric constant ($\varepsilon^S/\varepsilon_0$ ~ 940). Then the single crystal was lapped to 80 μm and the Cr/Au electrode with a thickness of 500 nm was sputtered onto one side of the single crystal. A conductive backing material, E-solder 3022 (VonRoll Isola, New Haven, CT), was cured over polished side of the PMN-PT single crystal and lapped to 1.5 mm. In order to shape a focused transducer element, the opposite side of the PMN-PT single crystal was dimpled using a dimple grinder (model 656, Gatan). The focal length can be controlled by the radius of the grinding wheel. For 30 MHz transducers, the diameter of concave was about 1.2 mm. After that, the single crystal was diced and housed using Epo-tek 301(Epoxy Technology Inc., Biller-ica, MA). An electrical connector was fixed to the conductive backing using a conductive epoxy. A layer of Cr/Au was sputtered across the concave surface and housing with side opening to form the ground connection, as shown in Fig. 1. The outer diameter are smaller than 3 mm. For comparison, the flat transducer with frequency of 30 MHz and an aperture of 1.2 mm was also fabricated using the above process.

B. Transducer Characterization

The performance of all transducers was characterized in deionized water bath in pulse/echo mode. The transducer was excited by a Panametrics (Waltham, MA) model 5900 PR pulser/receiver and X-cut quartz was used as target. The experimental settings of the Panametrics unit used for the measurement are listed in Table I. The reflected waveforms were received and digitized by a 1.5 GHz oscilloscope (Wave Pro 751Zi Lecroy Crop., Chestnut Ridge, NY) with 50 Ω coupling. The fast Fourier transform (FFT) feature on the oscilloscope was used to analysis the frequency responses of the transducers from the echo waveform.

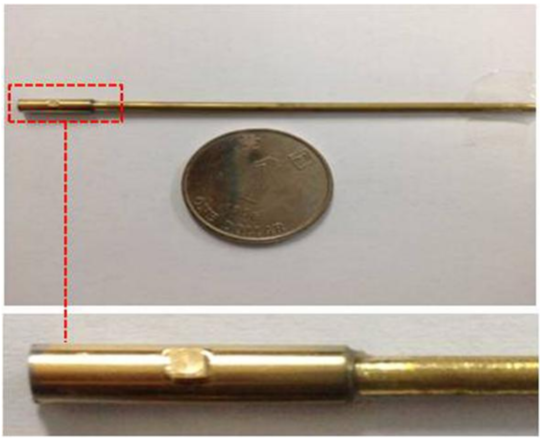

Fig. 1. Side-looking focused IVUS transducer.

TABLE I. THE EXPERIMENTAL SETTINGS OF PANAMETRICS 5900 PR PULSER/RECEIVER USED FOR PULSE/ECHO TESTING.

Parameters	Value
Pulse repetition frequency	1 kHz
Input energy	1 μJ
Damping	50 Ω
Attenuation	0 dB
Gain	26 dB
High pass filter	1 kHz
Low pass filter	200 MHz

To measure the insertion loss (IL), the transducer was excited by a tone burst of a 20-cycles sine wave with the amplitude of 2 V generated from a Sony/Tektronix (Beaverton, OR) model AFG 3251 function generator with an output impedance of 50 Ω. The voltage amplitude of the echo waveform was measured by an oscilloscope in 1 MΩ coupling mode. To evaluate the lateral and axial resolutions of transducer, a group of 30 μm diameter tungsten wire phantoms were imaged.

III. RESULTS AND DISCUSSION

The pulse/echo response and frequency spectra for the flat and dimpled focused transducers are shown in Fig. 2. The center frequency (f_c) and -6 dB bandwidth (BW) can be acquired from the frequency spectra according to the following formulas [4].

$$f_c = (f_l + f_u)/2\,, \tag{1}$$

$$BW = (f_u - f_l)/f_c\,, \tag{2}$$

where f_l and f_u are the lower and upper -6dB frequencies, respectively. For the flat transducer, the lower -6dB frequency is 25 MHz and the upper -6 dB frequency is 34MHz. According to the formulas (1) and (2), the center frequency and -6 dB bandwidth of flat transducer are 30MHz and 27%, respectively. Compared with the flat transducer, the lower and upper -6 dB frequencies of the dimpled focused transducer are 23 MHz and 39 MHz, respectively. The calculated center frequency is 31 MHz which is slightly higher than that of flat one. The -6 dB bandwidth is 52% which is almost twice higher than that of the flat transducer, see the Table II. The broad bandwidth can be attributed to the multi-resonances caused by continuous change of thickness along the curve surface of the dimpled piezoelectric element. The axial resolution can be calculated from the full-width-at-half-maximum (FWHM) of pulse/echo response [5]:

$$\text{Axial resolution} = \text{FWHM} \times \text{speed of sound} / 2, \tag{3}$$

where speed of sound is assumed to be 1500 m/s. For the focused transducer, the value of FWHM is 38 ns, thus the axial resolution was calculated to be 28 μm which is better than the flat transducer (axial resolution = 53μm). After compensation for attenuation caused by water and reflection from quartz target, the insertion loss was calculated from the equation [4]:

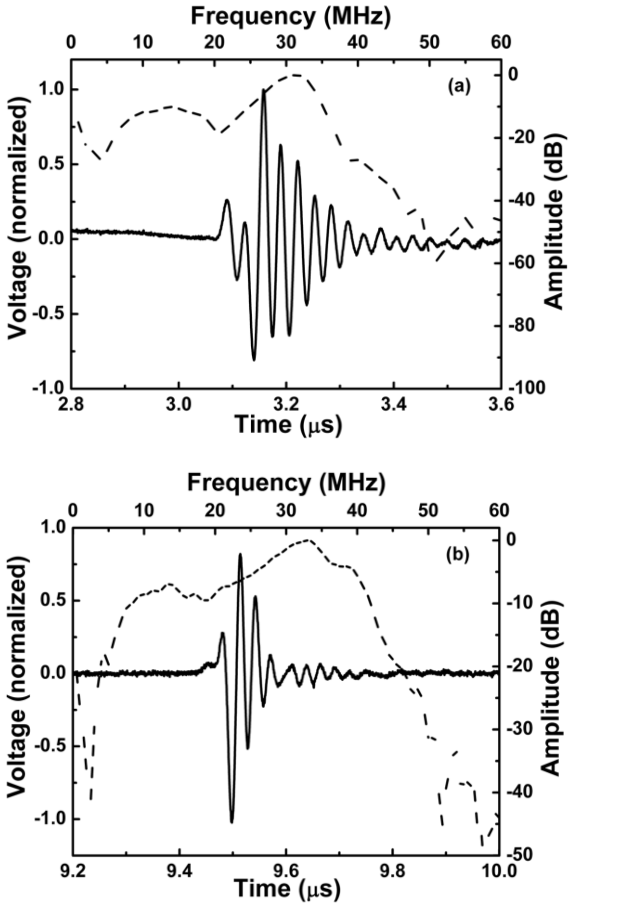

Fig. 2. The pulse/echo response and frequency spectra for the (a) flat and (b) focused transducers.

$$IL = 20\log_{10} V_o/V_i + 1.9 + 2.2\cdot 10^{-4}\cdot 2d\cdot f_c^{\,2}, \qquad (4)$$

where V_i and V_o are input and output voltage amplitudes, respectively; d is the distance from the transducer to the quartz target in millimeters. The signal loss resulted from transmission into quartz was compensated by 1.9 dB and due to attenuation in water was compensated by 2.2×10^{-4} dB/mm$\cdot$ MHz^2. However, the *IL* of focused transducer is increased to -21.53 dB at 35MHz compared with flat transducer (*IL*= -18.12 dB at 32 MHz), as shown in Table II. The focused transducer exhibited a higher insertion loss and a lower sensitivity than the flat transducer because of the multi-resonances and lager *f*-number. Figs. 3(a) and (b) show the images of 30 μm wire phantom from the flat and focused transducers, respectively. The lateral resolution of focused transducer obtained from -6 dB envelope widths was 470 μm

TABLE II. MEASURED TRANSDUCER PERFORMANCE.

Properties	Flat Transducer	Focus Transducer
Center frequency (MHz)	30	31
Aperture (mm)	1.2	1.2
-6dB Bandwidth	27%	52%
Insertion Loss (dB)	-18.12	-21.53
Axial Resolution (μm)	53	28
Lateral Resolution (μm)	510	470

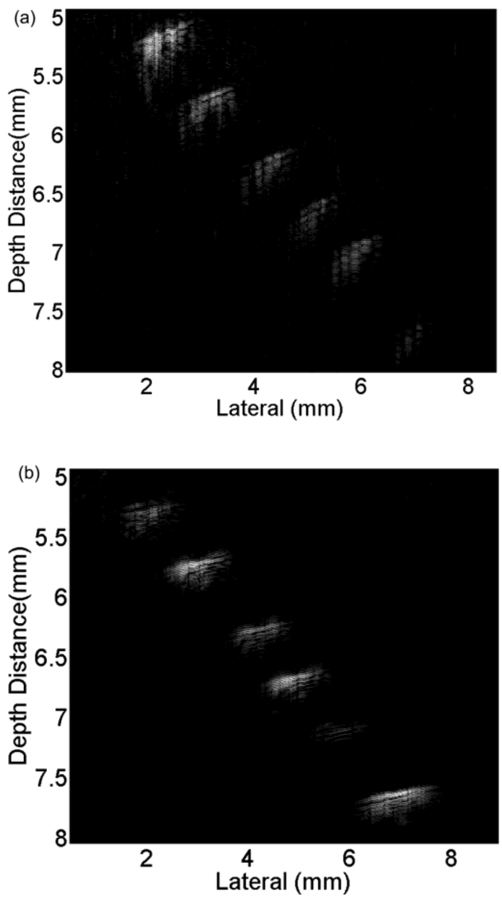

Fig. 3. The images of 30 μm wire phantom from the (a) flat and (b) focused transducers.

which approximately agreed with the theoretical value determined by the following formula [5]:

$$\text{Lateral resolution} = \text{wavelength} \times f\text{-number} \qquad (5)$$

The actual measured *f*-number was around 10 which was larger than the design value of 6. Compared with the flat transducer (lateral resolution = 510 μm), the lateral resolution of focused transducer was improved in some degree. In the future work, in order to further improved lateral resolution, we will design and fabricate the focused IVUS transducer with smaller size and *f*-number.

IV. CONCLUSIONS

The PMN-PT based high-frequency side-looking focused IVUS transducers were fabricated successfully by using mechanical dimpling technique and their outer diameter are smaller than 3 mm. The center frequency and the -6 dB bandwidth measured using the pulse/echo method are about 31 MHz and 52%, respectively, superior to flat one with 30 MHz, 27%. The average insertion loss at 35 MHz is around -21.53 dB which is little higher than that of flat one with -18.12 dB at 32 MHz. The -6 dB axial and lateral resolution of the focused transducer obtained by imaging the 30 μm wire phantom are also higher than that of flat one. The improved imaging resolution gives more detailed vessel microstructure information on vulnerable atherosclerosis compared to conventional ones. These results show that side-looking dimpled focused IVUS transducers are promising for IVUS medical imaging in vulnerable plaque diagnosis.

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