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Laser Engraved Self-focusing Piezoelectric Composite Transducer

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***Abstract*— In this paper a high frequency self-focusing piezoelectric composite ultrasound transducer using laser engraving was presented. Its center frequency is about 30 MHz and contains 11 PZT annulus, and each PZT annulus was separated by a UV engraving laser with line width of 10 μm and the kerf was filled with epoxy. The experimental results showed that it has good focusing performance and higher lateral imaging resolution than regular plan transducer. Moreover, because this self-focusing piezoelectric composite transducer was based on the precise laser engraving systems, the fabrication process was accurate and controllable.**

Keywords—focusing transducer, Fresnel half-wave band, laser engraving

I. INTRODUCTION

Focusing ultrasound transducer are widely used in many medical and industrial applications like lithotripsy[1], HIFU surgery[2], shock wave therapy in orthopedics [3], nondestructive testing[4] and so on. Common focusing transducers have acoustical lens/reflector, concave face, or array sources to focus the ultrasound energy in a specific zone[5, 6]. But it is usually hard to make the focusing transducer with micro size, short focal length or high frequency in these methods. For solving these problems, self-focusing transducers were developed[7-9], which usually pattern a Fresnel half-wave bands on the piezoelectric materials surface as the electrode. The acoustic wave generated by Fresnel half-wave sources are delayed by a multiple of a wavelength, then arrive at the focal point in-phase, constructively interfering with each other. Using this method can achieve transducers with micro size (~1-2 mm in diameter), short focal length (~350 μm) and high frequency (>100 MHz) which can be used as the ultrasonic biomicroscopy, liquid ejector and interventional imaging/therapy[7, 9, 10]. But at present this method usually use photolithography to form the Fresnel annulus on the surface of piezoelectric ceramics, and need wire lead to contact each ring separately. So the required instrument and machining accuracy for current method are quite strict. While laser engraving has several advantages compared with conventional ultrasound transducer fabrication[11-13], including micron machining precision, batch fabrication, fine structures, Non-contact, no chemical / liquid pollution, which make the possibility for Fresnel half-wave composite design and fabrication. While piezoelectric composite materials have been widely used due to their superior properties including high electromechanical coupling coefficient and low acoustic impedance[14-16]. In comparison with conventional composite transducer fabrication methods such as dice-and-fill, stacked plates or lamination techniques, micromachined piezoelectric composite transducer technology recently has become a superior method to fabricate high frequency ultrasonic transducers and arrays[17-19].

Therefore, based on recent progress on laser engraving processes and micromachined composite transducer technology, the self-focusing piezoelectric composite ultrasound transducer (FPCUT) is proposed in this paper, which using laser to etch the piezoelectric ceramic into annular rings to form Fresnel half-wave-band sources, and can avoid complicated connector and process.

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II. THEORY

Based on the concept of constructive interference of acoustic waves, a self-focusing piezoelectric composite ultrasound transducer was developed just as Fig.1 showed. The FPCUT consists of a layer of piezoelectric composite and Au electrodes on top and bottom faces of the composite. The piezoelectric composite was fabricated by etching a piezoelectric ceramic PZT into annular rings, and then filling with the epoxy. These etched PZT annular rings were Fresnel half-wave pattern on the top view.

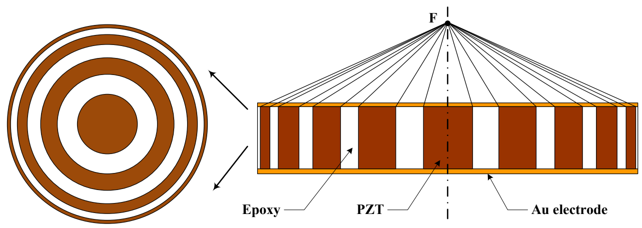

Fig. 1. Schematic of Micromachined Self-focusing Piezoelectric Composite Ultrasound Transducer

and their radius as shown in Fig.1 were special designed according to Eq. (1) [10]:

$$r_0 = \sqrt{\delta\lambda\ (F + \frac{\lambda\,\delta}{4})}$$
$$r_n = \sqrt{\frac{(2n+2+2\delta)\lambda}{2}(F + \frac{(n+1+2\delta)\lambda}{8})} \qquad (1)$$

where n=1, 2, 3 …, F is the focal length, λ is the acoustic wavelength, δ is the offset and $-1 \le \delta \le 1$.

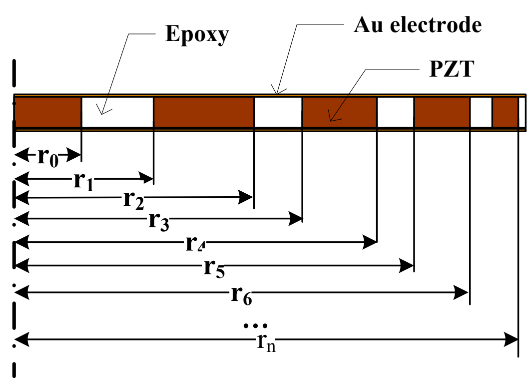

Fig. 2. The annular rings in PZT to focus the acoustic waves.

Therefore, the acoustic waves generated by these adjacent annular sources arrive at the focal with a multiple of wavelength λ delay due to the difference in path length between the sources and the focal point. Then the acoustic waves arrive at the focal point in-phase, constructively interfering with each other, which mean that the acoustic waves generated by FPCUT will focus at the focal plane as designed.

III. DESIGN AND FABRICATION

A prototype transducer was made to verify this FPCUT model. According to Eq. (1), a particular FPCUT with 30 MHz center frequency and 3.5 mm focal length was designed. The radius of the annular rings in composite were listed in the below Table 1. The transducer has a total 21 Fresnel half-wave annular rings, and 11 rings of which are designed as the acoustic sources.

Table 1. Dimensions for the 30 MHz self-focusing piezoelectric composite transducer with 3.5 mm focal length

Ring Order	Radius	Ring Order	Radius
r_0	421.8 μm	r_{11}	1490.1 μm
r_1	597.7 μm	r_{12}	1553.6 μm
r_2	733.3 μm	r_{13}	1615.1 μm
r_3	848.3 μm	r_{14}	1674.6 μm
r_4	950.1 μm	r_{15}	1732.5 μm
r_5	1042.6 μm	r_{16}	1788.9 μm
r_6	1128.2 μm	r_{17}	1843.9 μm
r_7	1208.2 μm	r_{18}	1897.6 μm
r_8	1283.7 μm	r_{19}	1950.2 μm
r_9	1355.5 μm	r_{20}	2001.8 μm
r_{10}	1424.2 μm	Thickness	56 μm

A process based on a UV engraving laser (wavelength: 355 nm, line width: 10 μm, pulse duration: <20 ns, Pulse Repetition rate: >40 KHz) was used for FPCUT fabrication. Because limited by the power of laser, the Fresnel annulus can not be completed in one time. So first a set of marker lines was etched a depth of a few microns on the surface of the PZT wafer by the UV engraving laser. Then the laser was controlled to perform repeated etching in these kerf areas until the depth of 80 μm was engraved. The final etched Fresnel annulus piezocomposite was showed in 4. After laser engraving, the annular kerfs of etched PZT wafer were next filled with the epoxy *EPO-TEK 301-2*. The epoxy was cured at 80°C for 3 hours. The wafer was then lapped on one side until the PZT anulus were exposed. The wafer was then flipped over for the second side lapping until the final thickness was achieved. Both sides of the resulting Fresnel annulus composites were then sputtered with a layer of 10 nm Cr and 100 nm Au as the electrodes. Then a layer of conductive silver epoxy E-Solder 3022 was applied to the composite as the backing material in a PTFE (Poly tetra fluoroethylene) mold. After curing at 65°C for 3 hours, the sample was diced into an individual piece. Then it was placed in a needle housing, the center core and mesh wire of a 46 AWG coaxial wire were connected to the piezocomposite surface and backing layer respectively with silver conductive. The gap between the transducer and the stainless steel needle was filled in by an insulating epoxy. It was poled under 10 KV/cm at room temperature for minutes prior to characterization.

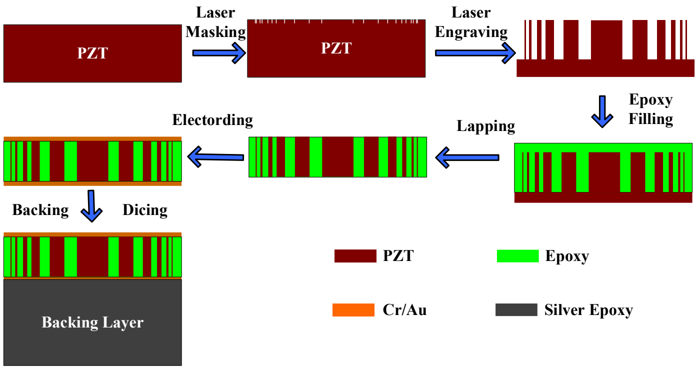

Fig. 3 Schematic process flow for micromachined self-focusing piezoelectric composite

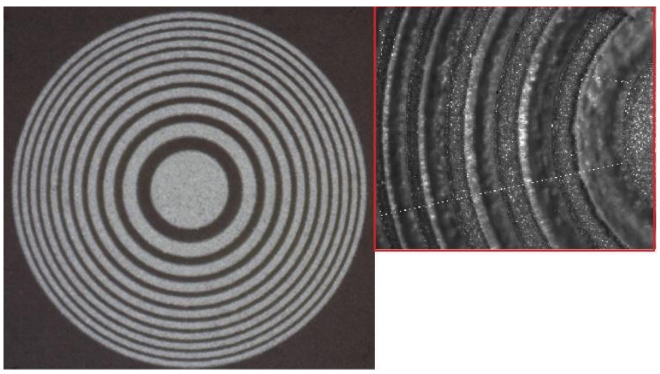

Fig. 4 Photographs of the engraved Fresnel annulus piezocomposite

IV. Experiment

A DPR500 (pulse amplitude: 90 V, gain: 0 dB, filter: 5~300 MHz, RPF: 200 Hz, JSR Ultrasonics, USA) was used as the pulser-receiver to measure the center frequency, -6 dB bandwidth and pulse-echo amplitude of the fabricated FPCUT. The pulse echo response was measured by recording the reflection from a quart polyethylene plastics flat placed at 3.5 mm in front of the transducer. The measured center frequency is 27 MHz, the –6 dB bandwidth is 50.37%, and the pulse half width is 58.8 ns just as **Error! Reference source not found.** shows. And the transducer pulse echo amplitude was measured as 51.5 mV with 50 Ω coupling impedance setting.

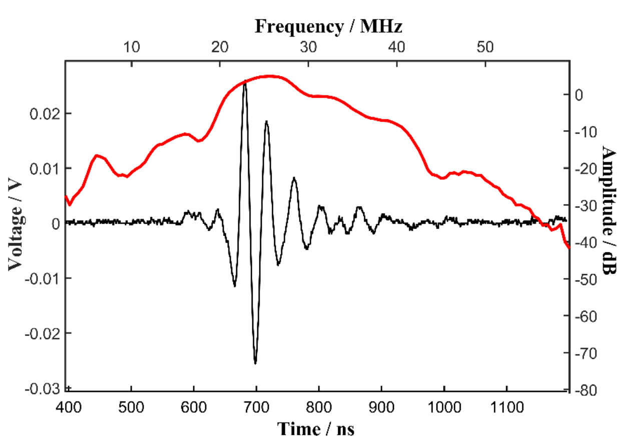

Fig. 5 The pulse-echo waveform and frequency spectrum of fabricated FPCUT transducer

The acoustic distribution was measured by a scanning system UMS III (scan step resolution 0.001 mm, Precision Acoustics Ltd, Dorchester, UK). The hydrophone measurement step size was 50 µm. The acoustic intensity distribution of this fabricated transducer along Z axial was measured as Figure 1. For avoiding the collision between the tested hydrophone and transducer, the recorded data was beginning at 1 mm away from the transducer. The measured focal length along the axial direction is 3.7 mm, which is very closed to the designed focal length 3.5 mm.

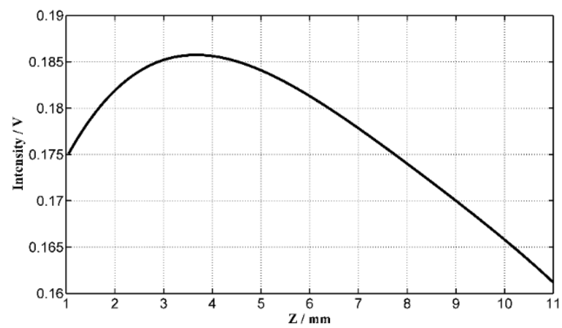

Fig. 6 The measurement acoustic intensity of fabricated FPCUT along Z axis

The transducer's acoustic intensity distributions in the focal plane (X-Y plane) were then scanned as Figure 7. It is easy to find that at the focal point (x=0, y=0) the intensity reached its maximum which is much stronger than other areas, and the diameter of the focal point (@-6 dB) is about 100 µm, which indicate that the transducer can achieve a higher lateral resolution and SNR image than usual flat ones.

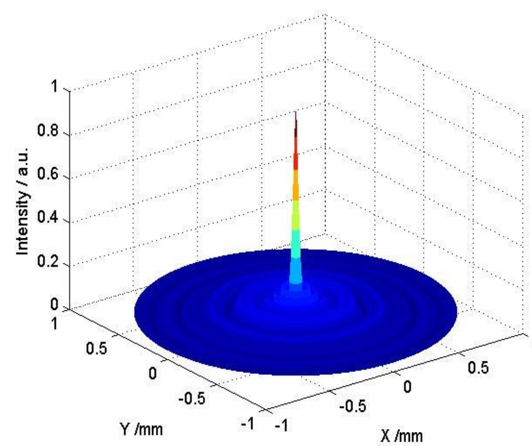

Fig. 7 Measured acoustic intensity distribution of fabricated FPCUT

V. Conclusion

A method for self-focusing piezoelectric composite ultrasound transducer design and analysis was developed to gain high frequency, wide bandwidth, low acoustic impedance, high intensity, and focusing ultrasound wave with high machining accuracy. High frequency self-focusing piezocomposite ultrasound transducer was successfully fabricated using a UV laser engraving technique. Compared with the conventional transducer, the fabricated FPCUT exhibits high lateral resolution of about 100 µm and high SNR imaging. With the progress and promotion of laser technology and laser cutting technology, including femtosecond lasers, smaller line width, higher energy and et al., it shows that the laser engraving technique has high potential in fabricating high-frequency piezocomposite and focusing transducer for medical imaging and industrial applications. More details can be found in our forthcoming journal paper[20].

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