Design of Micromachined Self-focusing Piezoelectric Composite Ultrasound Transducer

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Abstract— **Based on the Fresnel half-wave band interference, a micromachined self-focusing piezoelectric composite ultrasound transducer was proposed in this paper. The theoretical analysis was deduced based on the concept of constructive interference of acoustic waves and electromechanical response of piezoelectric composites. The calculated and simulation results showed that it combined the advantages of composite transducer and plate self-focusing transducer, and can achieve high electromechanical coupling coefficient, low acoustic impedance, high intensity, short focal length and micro size. Because it was based on the micro-electromechanical systems, the fabrication process was accurate and controllable, which made it have good potential for interventional ultrasound imaging, cellular microstructure imaging, skin cancer detection and industrial nondestructive testing applications.**

I. Introduction

Focused ultrasound transducers are commonly used in many medical applications and high resolution imaging like photoacoustic microscopy [1-3]. Common focused transducers have large dimensions or acoustical lens/reflector [4, 5]. It is usually hard to make the focusing transducer with micro size, short focal length or high frequency. For solving these problems, self-focusing transducers were developed, which usually pattern a Fresnel half-wave bands on the piezoelectric materials surface as the electrode [6-9]. But this method need wire lead to contact each ring separately, so it is hard to keep every annular ring complete. Therefore, based on recent progress on PZT deep reactive ion etching (RIE) processes[10, 11]and micromachined composite transducer technology[12-14], a micromachined self-focusing piezoelectric composite ultrasound transducer (FPCUT) is proposed in this paper, which etched the piezoelectric ceramic into annular rings to form Fresnel half-wave-band sources, and can avoid complicated connector and process. Comparing other methods, this method can achieve high electromechanical coupling coefficient, high center frequency, low acoustic impedance, short focal length and micro size. These advantages make it may have great potential for medical ultrasound imaging and perhaps some treatments, industrial nondestructive testing and other fields.

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II. Design of FPCUT

Based on the concept of constructive interference of acoustic waves, a micromachined self-focused piezoelectric composite ultrasound transducer was developed. Fig.1 shows the basic structural diagram of FPCUT. It consists of a piezoelectric composite thin bulk and Au electrodes on top and bottom faces of the composite. The piezoelectric composite were fabricated by etching a piezoelectric ceramic PZT into annular rings, and then filling with the epoxy. These etched PZT annular rings was similar to Fresnel half-wave pattern on the top view just as the left part of Fig.1 shown.

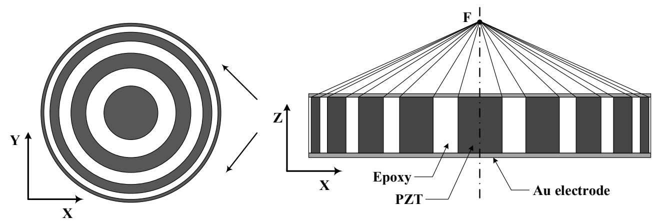

Figure 1. Schematic of Micromachined Self-focused Piezoelectric Composite Ultrasound Transducer

and their radius were special designed according to (1)[6]:

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

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

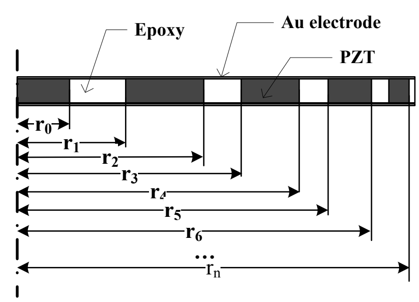

Figure 2. The etched annular rings in PZT to focus the acoustic waves

These designed annular rings made the difference in path length in a multiple of wavelength between the sources and the focal point. Therefore, when the acoustic waves arrive at the focal point, they will constructively interfere with each other, which mean that the acoustic waves generated by FPCUT will focus at the focal plane as designed.

III. THEORY OF SELF-FOCUSING PIEZOELECTRIC COMPOSITE

In (1) the annular rings' radius of this self-focusing piezoelectric composite were determined by transducer focal length F and acoustic wavelength, so it is important to understand their relationship to the performance of transducer. Based on the connectivity of piezoelectric composites[16], although FPCUT is not a uniform composite, its first ceramic and epoxy ring can be considered as a 1-3 composite, while others can be considered similarly as a 2-2 composite. Then its elastic, piezoelectric and dielectric properties will be mainly decided by the piezoelectric materials volume fraction in composite according to electromechanical response of piezoelectric composites [15,16,17]. The volume fraction v of piezoelectric material in the FPCUT composite can be expressed as:

$$v = \frac{\sum_{n=0,1,\ldots,N} (-1)^n \pi r_n^2}{r_N^2} \tag{2}$$

where N is the total ring numbers in the composites, r_N is the largest ring radius.

Substituting (1) into (2), the volume fraction variation with the acoustic wavelength and focal length can be calculated:

$$v = \frac{\pi\left[\frac{n+1}{2}\left(F + \frac{\lambda(1+2\delta)}{8}\right) + \frac{\lambda n(2+n)}{16} + \delta\left(F + \frac{\lambda\delta}{4}\right)\right]}{4(n+1+\delta)\left(F + \frac{\lambda(n+1+2\delta)}{8}\right)} \tag{3}$$

Considering $\lambda = c / f$, where c is the acoustic velocity in media (~1500 m/s) and f is the frequency, then the volume fraction relationship with the transducer frequency and focal length can be plotted as Fig.3 and Fig.4 shows, respectively.

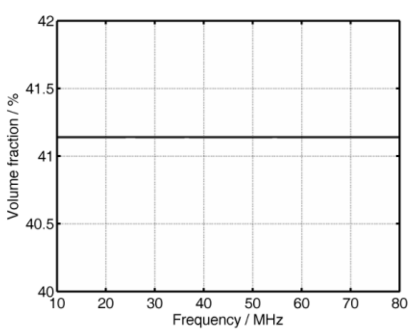

Figure 3. The ceramic volume fraction variation with the transducer frequency when the focal length was set as constant

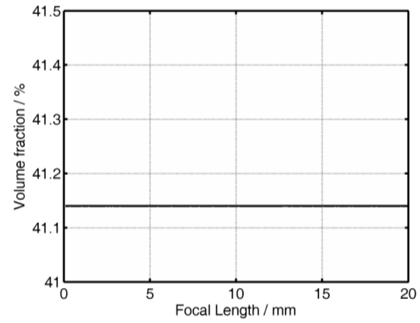

Figure 4. The ceramic volume fraction with the focal length when the frequency was set as constant

It is interesting to find that in Fig.3 the volume fraction of ceramic will not change with the frequency when the focal length was set as a constant. And in Fig.4 the volume fraction of ceramic will not change either when the frequency of the transducer was set as a constant. That is because usually the focal length is much bigger than acoustic wavelength $F >> \lambda$, (3) can be simply rewritten as:

$$v \approx \frac{\pi(N+1)}{8N} \tag{4}$$

In (4), it is obvious that the ceramic volume fraction is only depended on the total ring numbers N in composite, and independent of transducer frequency and focal length.

IV. SCHEMATIC PROCESS FLOW OF FPCUT

A Photolithography based active ion etching of PZT ceramic can be used for FPCUT fabrication, just as Fig.5 shown.

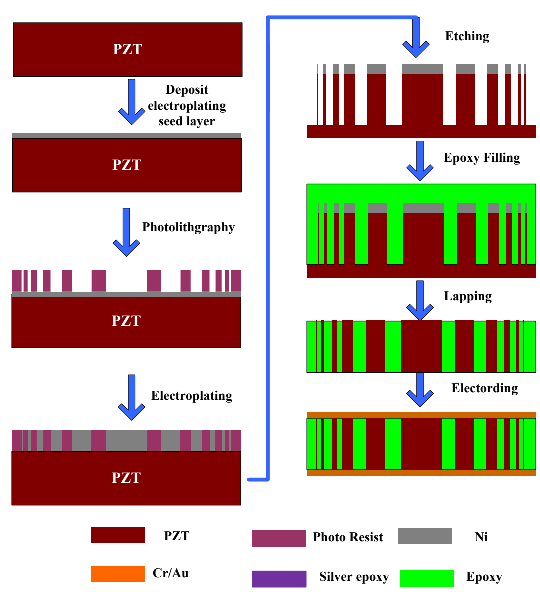

Figure 5. Schematic process flow for micromachined self-focusing piezoelectric composite

Comparing with conventional ultrasound transducer fabrication, photolithography based micromachining has several advantages, including fine structures, batch fabrication, submicron machining precision and so on [12,18], which make the possibility for Fresnel half-wave composite design and fabrication.

V. Simulation Experiments and Discussion

According to (1), a particular FPCUT with 50 MHz center frequency and 10 mm focal length was designed. It composes of PZT 5H and epoxy EPO-TEK 301. The radius of the annular rings in composite were listed in the below Tab. I. The transducer has a total 21 Fresnel half-wave annular rings, and 11 rings of which are designed as the acoustic sources. According to (4), the volume fraction of PZT in composite was 41.1%.

TABLE I. Dimensions for the 50MHz micromachined self-focusing piezoelectric composite with 10 mm focal length

Ring Order	Radius	Ring Order	Radius
r_0	551.6 μm	r_{11}	1918.7 μm
r_1	780.3 μm	r_{12}	1997.8 μm
r_2	956.1 μm	r_{13}	2074.0 μm
r_3	1104.4 μm	r_{14}	2147.6 μm
r_4	1235.2 μm	r_{15}	2218.8 μm
r_5	1353.6 μm	r_{16}	2288.0 μm
r_6	1462.6 μm	r_{17}	2355.2 μm
r_7	1564.2 μm	r_{18}	2420.6 μm
r_8	1659.7 μm	r_{19}	2484.4 μm
r_9	1750.2 μm	r_{20}	2546.7 μm
r_{10}	1836.3μm	Thickness	37 μm

According to (4), and similar method based on the electromechanical response of piezoelectric composites[15,17], the parameters of above self-focusing piezoelectric composite can be calculated as electromechanical coupling coefficient of 0.67, piezoelectric coefficient of 580 pC/N, acoustic impedance of 15.1 MRayl, and center frequency of 50MHz.

Furthermore, a COMSOL simulation experiment was performed to verify this FPCUT model. As an example described above, the simulated FPCUT composes of PZT 5H and epoxy EPO-TEK 301, the propagation medium is water. The material properties are presented in Tab. II.

TABLE II. Key material properties of PZT-5H and EPO-TEK 301

PZT 5H			
ρ (kg/m^3)	7500	d_{31} (pC/N)	-274
s_{11}^E (10^{-12}m^2/N)	16.5	d_{33} (pC/N)	593
s_{33}^E (10^{-12}m^2/N)	20.7	c_{11}^E (10^{10} N/m^2)	12.7
ε_{33}^T	3400	c_{33}^E (10^{10} N/m^2)	11.7
ε_{11}^T	3130	e_{31}^{ES} (C/m^2)	-6.62
		e_{33}^{ES} (C/m^2)	23.3
EPO-TEK 301			
ρ (kg/m^3)	1500	Possion's ration	0.35
Young's modulus (Pa)	3.6×10^9	Isotropic Structural loss factor	0.05

The ring radius and thickness of FPCUT were listed as Tab. I. When the transducer is excited with a burst of RF signal, the acoustic distribution field was showed as Fig.6. It is clear that the generated acoustic waves converged to the focal point, and then diffracted after the focal point. The energy of the focal area is obviously stronger than else area. Fig.7 is the simulated acoustic intensity distribution on the focal plane. It is easy to find that the focal point is extremely small, and the area of FWHM (full width at half maximum) is about 0.25 mm^2. At the focal point (x=0, y=0) the intensity reached its maximum which is much stronger than other areas.

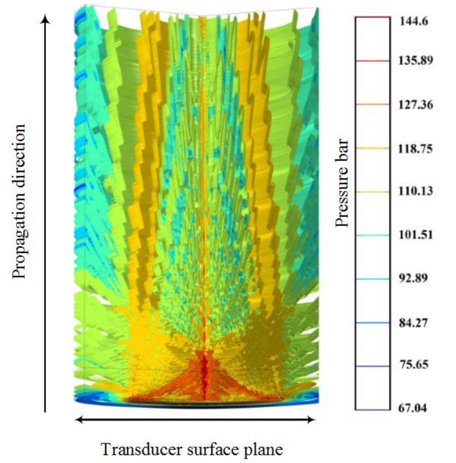

Figure 6. The simulated 3-D acoustic field distribution of FPCUT with 10 mm focal

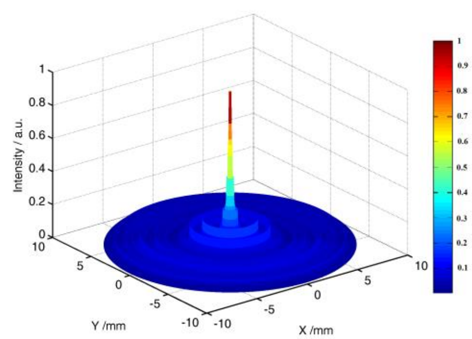

Figure 7. Acoustic intensity distribution of FPCUT on the focal plane

In Fig.8 the spatial distribution was obtained in the focal plane in radial direction with the acoustic focus as the point of origin. The measurement beam width is about 0.5 mm, and the peak pressure is about 141.4 MPa when the excitation voltage is 120 V. According to the diagnostic acoustic output display standard recommended by American Food and Drug Administration (FDA), the derated global maximum acoustic output should not exceed 190 W/cm^2. If we do not use pulse with very high repetition frequency, the output of FPCUT can be controlled under this safety level. While in other areas the average pressure intensity is less than 10 MPa. Therefore, the focusing performance of FPCUT is quite well.

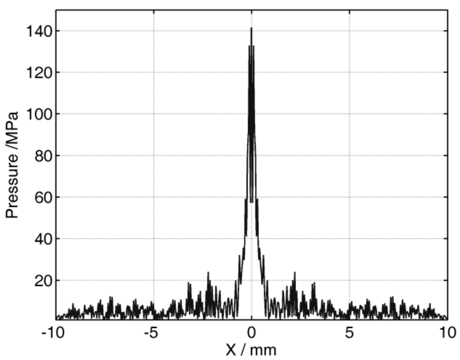

Figure 8. Radial pressure distribution in the focal plane

Based on above results, it is believed that this self-focusing piezoelectric composite transducer was able to be used as a micro HIFU transducer, which was able to be inserted in the blood vessel for plaque breaking, or it can be used as surface ultrasonic imaging with high resolution, like skin diagnose, eye cornea / ciliary body inspection and so on.

VI. CONCLUSIONS

A method for micromachined self-focusing piezoelectric composite ultrasound transducer design and analysis was developed to gain high intensity, high concentration, and high frequency ultrasound wave with micro size transducer. According to the theoretical analysis, the volume fraction of ceramic in FPCUT is only depended by the total ring numbers N in composite, and independent of frequency and focal length. This feature makes design of FPCUT much easy. The COMSOL simulation results prove the feasibility of FPCUT, and indicated that FPCUT is a quite good focused transducer with concentrated focal region size about 0.5 mm in width, and high peak pressure as 140 MPa, which may be used in medical imaging, treatment and other applications.

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