Published in final edited form as:
Ultrasonics. 2010 May ; 50(6): 544–547. doi:10.1016/j.ultras.2010.02.002.

High-overtone Self-Focusing Acoustic Transducers for High Frequency Ultrasonic Doppler

Jie Zhu[1,2], **Chuangyuan Lee**[3], **Eun Sok Kim**[4], **Dawei Wu**[5], **Changhong Hu**[5], **Qifa Zhou**[5], **K. Kirk. Shung**[5], **Gaofeng Wang**[1], and **Hongyu Yu**[2,6]

[1] School of Electronic Information, Wuhan University, Wuhan, Hubei 430079, P.R.China

[2] School of Electrical, Computer and Energy Engineering, Arizona State University, AZ 85287, USA

[3] Touchdown Technologies, Baldwin Park, CA 91706, USA

[4] Department of Electrical Engineering, University of Southern California, CA90089,USA

[5] Department of Biomedical Engineering, University of Southern California, CA90089, USA

[6] School of Earth and Space Exploration, Arizona State University, AZ 85287, USA

Abstract

This work reports the potential use of high-overtone self-focusing acoustic transducers for high frequency ultrasonic Doppler. By using harmonic frequencies of a thick bulk Lead Zirconate Titanate (PZT) transducer with a novel air-reflector Fresnel lens, we obtained strong ultrasound signals at 60 MHz (3rd harmonic) and 100 MHz (5th harmonic). Both experimental and theoretical analysis has demonstrated that the transducers can be applied to Doppler systems with high frequencies up to 100 MHz.

Keywords

Acoustic transducer; Self-focusing; Air-reflector; Doppler

High-frequency Doppler ultrasound has been used to detect blood flow in microcirculation. It is becoming a useful tool in preclinical cancer and cardiovascular research [1] and diagnosis of retinal vein occlusion [2], et al. Fabrication of high-frequency transducers suitable for ultrasound Doppler applications thus has been an interesting area of the research. Xu et al used a 30-MHz linear array in their ultrasound Doppler system [3]; Zhou et al fabricated a 40-MHz high-sensitivity PMN-PT based needle transducer for a pulsed-wave Doppler application [4]; Christopher et al used a 50-MHz PVDF transducer to detect blood flow in the microcirculation with a Doppler ultrasound system [5]. All of those transducers used in the Doppler systems work in thickness-mode: their physical scales are inversely proportional to their working frequency. For instance, for the PMN-PT ultrasonic transducer fabricated by Zhou et al [4], the thickness of the PMN-PT layer has to be less than 50 μm to work at a high frequency over 40 MHz. Two techniques have been used to

Contact: Dr. Hongyu Yu, School of Electrical, Computer and Engineering, School of Earth and Space Exploration, Arizona State University, Tempe, AZ, 85287, USA, Tel: 213-400-1912, Fax: 480-965-8102, hongyuyu@asu.edu.

obtain such a thickness: one is lapping a bulk ceramic down to the desired thickness, and the other is stacking up thin films [5]. But both the techniques have their own problems. Lapping piezoelectric materials may introduce defects and cracks in the device, while thin film stacking is accompanied by a large residual stress. In this work, we present a micromachined self-focusing ultrasonic Doppler transducer, and demonstrate the feasibility of producing a high-frequency ultrasound Doppler transducer with a thick bulk PZT substrate without lapping.

The self-focusing transducer mainly consists of a PZT layer and an air-reflector Fresnel lens, as illustrated in Fig. 1. The thickness of the PZT sheet is roughly 127 μm. With the PZT layer, a conventional transducer working at the thickness mode will have a fundamental resonance of 20 MHz. The PZT sheet sandwiched between two 0.1 μm nickel electrodes serves as the piezo-material, while Parylene C is used as the lens structure material. The acoustic waves produced by the PZT layer propagate into water through the Parylene C, but are reflected at the air-pockets regions. This is because the acoustic impedance of air (0.0004 MRayl) is much smaller than that (28~30 MRayl) of the PZT, while Parylene C has its impedance (2.7 MRayl) between that (1.5 MRayl) of water and that of PZT. The lens is patterned into Fresnel half-wave bands with a focal length of 1.5 mm. With the lens structure, the transmitted acoustic waves arrive at the focal point in phase, constructively interfering with each other and intensifying the acoustic pressure [6~9]. The well-focused beam will enhance the sensitivity of ultrasound Doppler.

The Fresnel lenses were fabricated to make the transducers working at their harmonic frequencies, which resulted in better resolutions without introducing any additional complication on the fabrication, especially without reducing the thickness [10]. All the harmonic transducers were built on the same 127-μm-thick PZT sheet (PSI-5A4E from Piezo Systems, Cambridge, MA), but had different lens designs to account for different wavelengths. Since the transducers are roughly symmetric in their thickness direction, only odd harmonics exist for the thickness-mode resonance. In this work, the transducers were designed for the 3rd and 5th harmonic frequencies of 60 and 100 MHz with active area of $1.76mm^2$ and $7.4mm^2$, respectively.

The fabrication process is illustrated in Fig. 2 [11]. On top of the nickel-electroded PZT sheet, 3-μm-thick photoresist was first coated and patterned as the sacrificial layer (Fig. 2(a)). After depositing and patterning 4-μm-thick Parylene C as the lens material (Fig. 2(b)), the photoresist was removed with Acetone overnight (Fig. 2(c)) through releasing holes. Another 4~5 μm thick Parylene C was then deposited to fill the released holes (Fig. 2(d)). Finally, the transducer was packaged onto a brass tube as shown in Fig. 2(e).

A set of measurements was performed to evaluate the performances of the transducers. The electrical impedance of the transducers was measured using an Agilent 4294A impedance analyzer (Agilent Inc. Santa Clara, CA), while the harmonic frequencies and their bandwidth were tested using a pulse-echo test setup [12]. In the pulse-echo test setup, a piece of quartz was immersed in a water bath as a reflecting surface at a focal distance (about 1.5 mm) of the transducer. Panametrics 5900PR (Panametrics Inc, Waltham, MA) was used as the pulser and receiver electronic unit. The echo signals were acquired and displayed with a LeCroy LC534 1GHz digital oscilloscope (LeCroy Corporation, Chestnut Ridge, NY).

Figure 3(a) shows the measured electrical impedance of the transducer working at its first, 3rd and 5th harmonic frequencies. As we can see, there is a strong resonance at 20 MHz (fundamental resonance), and two harmonic resonances at 60 MHz (the 3rd harmonic) and 100 MHz (the 5th harmonic). The measured pulse-echo response of the transducer (Fig. 3(b)) shows peaks not only at its designed operational frequency of 100 MHz (5th harmonic), but also at the fundamental (20 MHz) and 3rd harmonic frequency (60 MHz). To confirm the efficacy of the Fresnel-lens transducers, a conventional 40 MHz single element transducer with no Fresnel air-reflectors was also built and tested. The active area of the transducer is the same as the 3rd harmonic Fresnel lens transducer, which is 1.76 mm^2. As shown in Fig. 3(c), there are not 3rd and 5th harmonic peaks to be observed, though a weak second harmonic peak appears, which is likely due to the imperfect matching between the PZT and its front matching layer. Thus, unlike the conventional transducer, the Fresnel-lens transducer can be designed to produce a strong signal not only at its 5th harmonic, but also at the fundamental and 3rd harmonic frequencies. The 20% bandwidth of the Fresnel-lens transducer is not as good as the conventional one (50% bandwidth), mainly because it does not have any matching layer between PZT and water. However, bandwidth is not a major concern with Doppler transducers. This makes the Fresnel-lens transducers possible to be used in ultrasound Doppler systems with different frequencies.

The reason why the Fresnel transducer with the 5th harmonic design can also focus acoustic waves at its fundamental and 3rd harmonic frequencies (Fig. 3(b)) can be understood as follows. For the fundamental frequency of the Fresnel lens, to minimize destructive wave interference at the focal point, the path-length difference between the edges of the adjacent Fresnel rings should be $\lambda/2$ (with λ being the acoustic wavelength 2 in water). Thus, the radius ($r_{m,\,n}$) of nth Fresnel ring at the mth harmonic frequency and the focal length (F) should satisfy the following equation [13]:

$$\sqrt{r_{m,n}{}^2+F^2} - F=\frac{n\lambda_m}{2} \tag{1}$$

When the transducer is activated at the frequency of the mth harmonic frequencies with m=1, 3, and 5…, the acoustic wavelength is $\lambda_m=v/mf_0$ (with v and f_o being the acoustic-wave velocity and the fundamental frequency, respectively), and we get an equation for calculating the radius ($r_{m,\,n}$) as follows:

$$r_{m,n}=\sqrt{\frac{nv}{2mf_0}+\left(\frac{nv}{4mf_0}\right)^2} \tag{2}$$

This equation shows that when m and n are chosen to have a particular ratio between them, the radius $r_{m,\,n}$ is the same, for example, $r_{1,\,1} = r_{3,\,3} = r_{5,\,5}$, $r_{1,\,2} = r_{3,\,6} = r_{5,\,10}$, and $r_{1,\,3} = r_{3,\,9} = r_{5,\,15}$. This means that when the Fresnel lenses are designed for the 5th harmonic (Fig. 4(a)) and fundamental frequencies (Fig. 4(b)) with the same layer thickness (127 μm) and focal length (1500 μm), some parts of the rings overlap with each other, as illustrated in Fig. 4(c). Also, the rings 4 and 5 of the 5th harmonic Fresnel lens, when operating at the fundamental frequency, produce acoustic waves that are 180° out of phase than those produced by the rings 2 and 3 at the focal point. (Note that each of the Fresnel rings has about the same area, and produce about the same acoustic power.) Thus, the acoustic contributions by the rings 2, 3, 4 and 5 cancel each other out at the focal point. The remaining effective areas for the fundamental frequency from the 5th harmonic frequemcy are shown in Fig. 4(d), which can produce focused strong acoustic beams at the fundamental frequency shown in Fig. 3(b). Similarly, the pattern for the 5th harmonic can be used for the 3rd harmonic frequency as well.

In summary, high-overtone self-focusing acoustic transducers have been successfully fabricated by MEMS technology. With the Fresnel lens design, the transducers built with a bulk PZT substrate are shown to be effective at high frequencies up to its fifth harmonic (100 MHz). This device has a potential for high frequency ultrasound Doppler application.

Acknowledgments

This work has been partially supported by NIH grant # P41-EB2182.

References

1. Perrino C, Prasad S, Mao L, Noma T, Yan Z, Kim H, smithies O, Rockman H. J Clin Invest 2006;116:1547–1560. [PubMed: 16741575]
2. Michelson G, Harazny J. Ophthalmology 1997;104(4):659–663. [PubMed: 9111260]
3. Xu X, Sun L, Cannata JM, Yen JT, Shung KK. Ultrasound in Med & boil 2008;34:638–646.
4. Zhou QF, Xu X, Gottlieb EJ, Sun L, Cannata JM, Ameri H, Humayun MS, Han P, Shung KK. IEEE UFFC 2007;54(3):668–675.
5. Christopher DA, Burns PN, Starkoski BG. Ultrasound in Med & boil 1997;23:1–27.
6. Yamaha K, Shimizu H. J Acoust Soc Japan 1991;e(12):123–129.
7. Lee, C.; Yu, H.; Kim, ES. IEEE International MicroElectroMechanical Systems Conference; Istanbul, Turkey. January 22 – 26, 2006; p. 170-173.
8. Hadimioglu B, Rawson EG, Lujan R, Lim M, Zesch JC, Khuri-Yakub BT, Quate CF. Proc IEEE Ultrasonic Symposium 1993:579–582.
9. Kino, GS. Acoustic waves: devices, imaging, and analog signal processing. Englewood Cliffs, NJ: Prentice-Hall; 1987.
10. Yu, H.; Wu, D.; Lee, C.; Zhou, Q.; Kim, ES.; Shung, KK. IEEE International Ultrasonics Symposium; New York, NY. October 29–31, 2007; p. 2401-2404.
11. Lee, C.; Yu, H.; Kim, ES. Transducers ‘07, IEEE International Conference on Solid-State Sensors and Actuators; Lyon, France. June 10–14, 2007; p. 1283-1286.
12. Ritter, T. Ph.D thesis, Design, fabrication, and testing of high frequency (>20 MHz) composite ultrasound imaging arrays. Penn State University; 2000.
13. Huang D, Kim ES. J Microelectromech Syst 2001;10:442–449.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

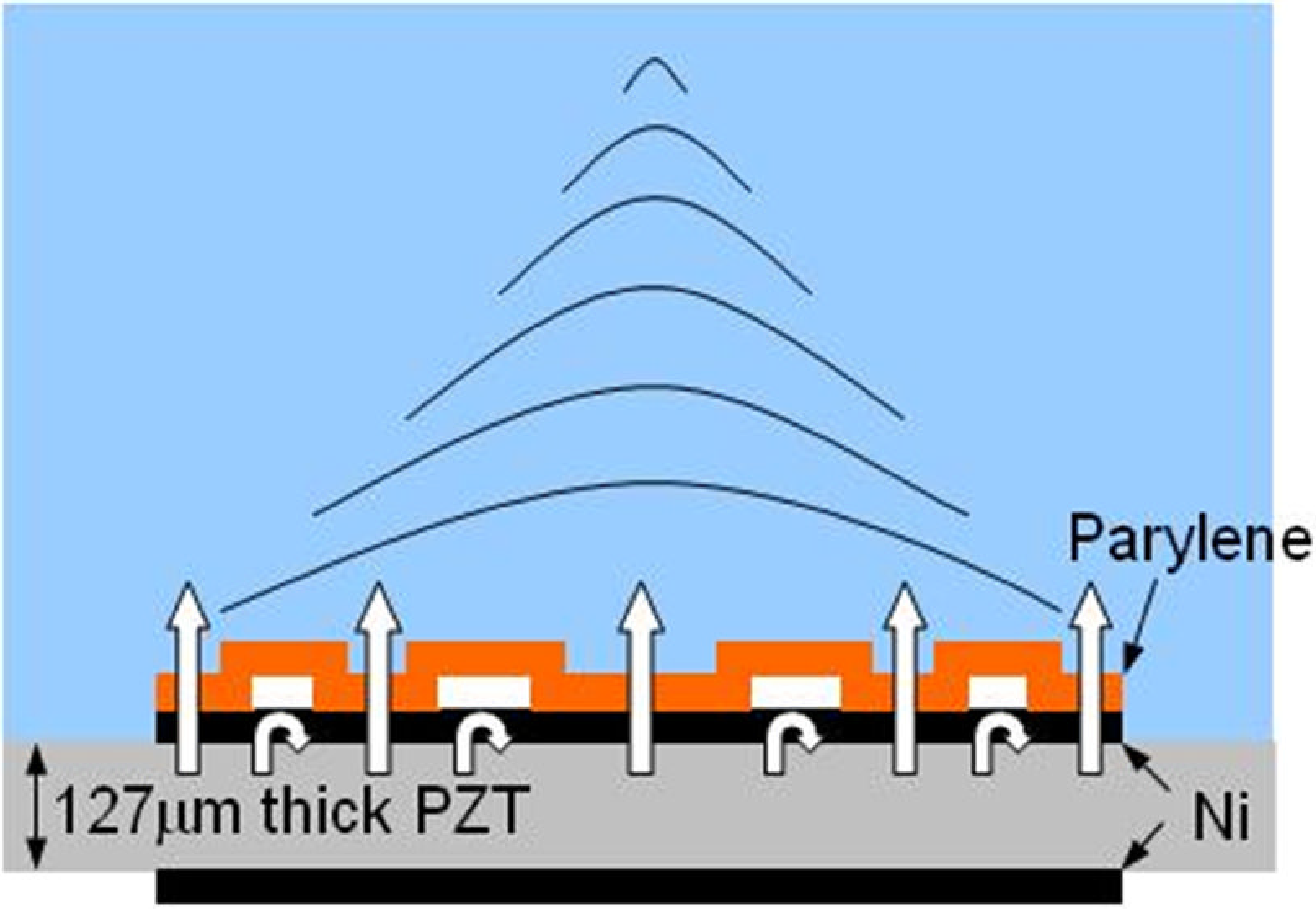

Figure 1.
Cross-sectional view of the transducer with the acoustic Fresnel lens employing air-reflectors

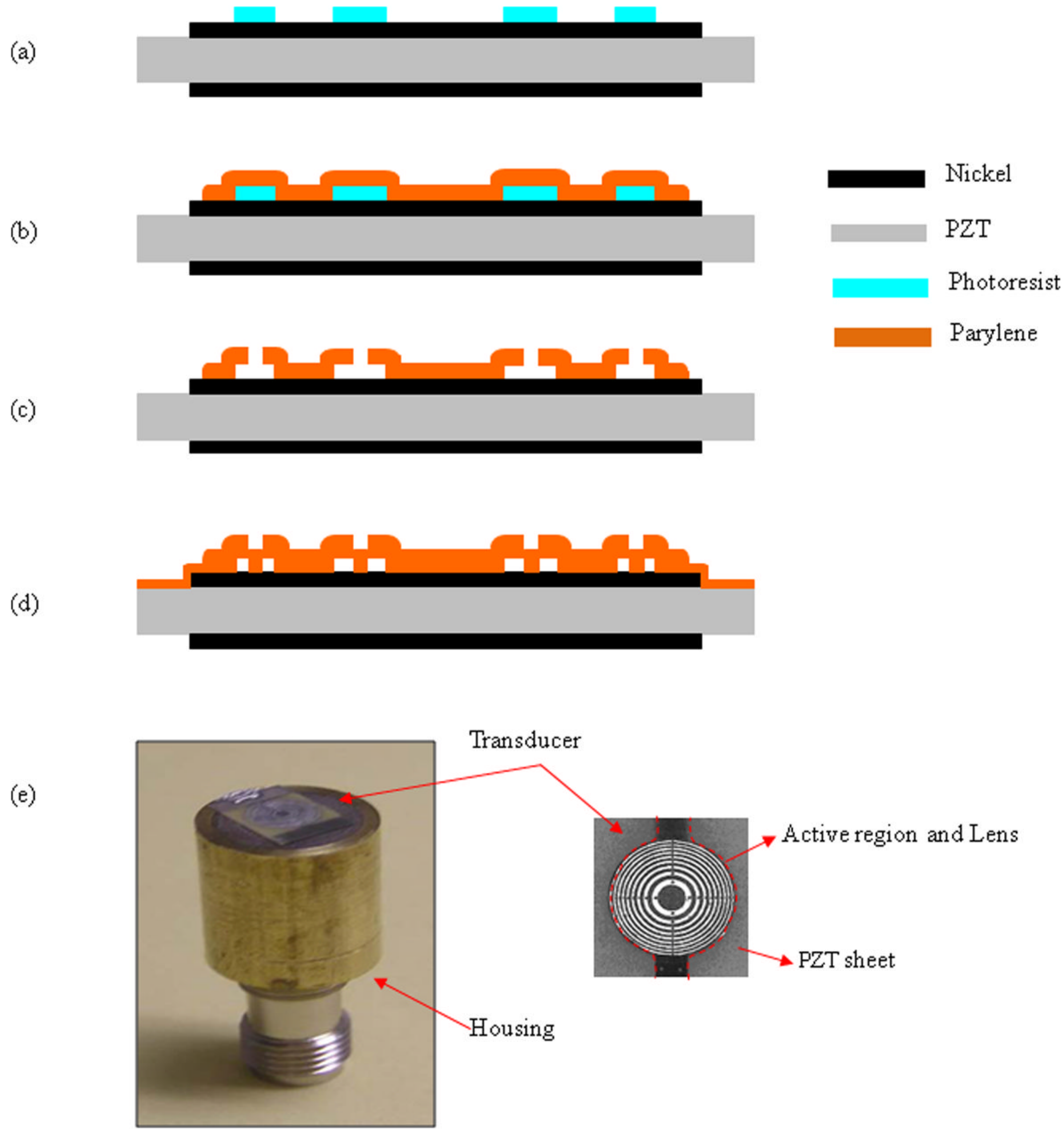

Figure 2.
Fabrication and packaging of the transducer

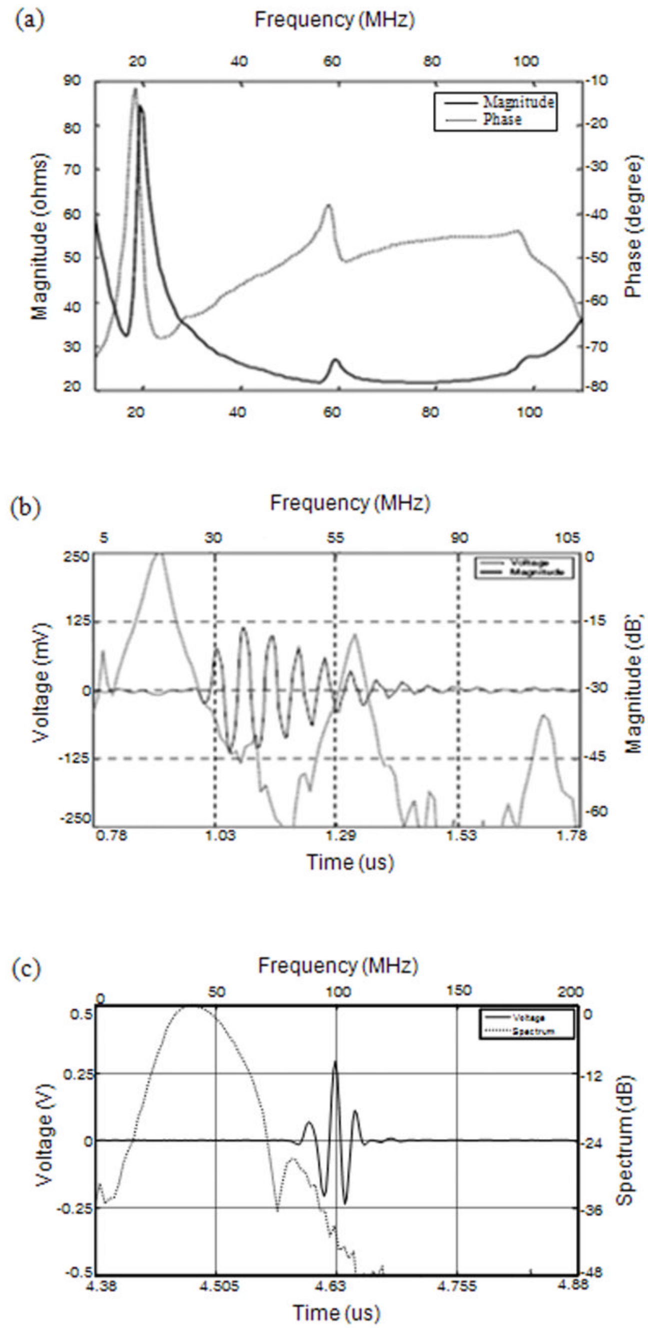

Figure 3.

Testing results: (a) Measured electrical impedance of the 5th harmonic transducer (b) Measured pulse-echo responses and frequency spectrum of the 5th harmonic transducer (c) Measured pulse-echo responses and frequency spectrum of the conventional transducer without the Fresnel air-reflector lens

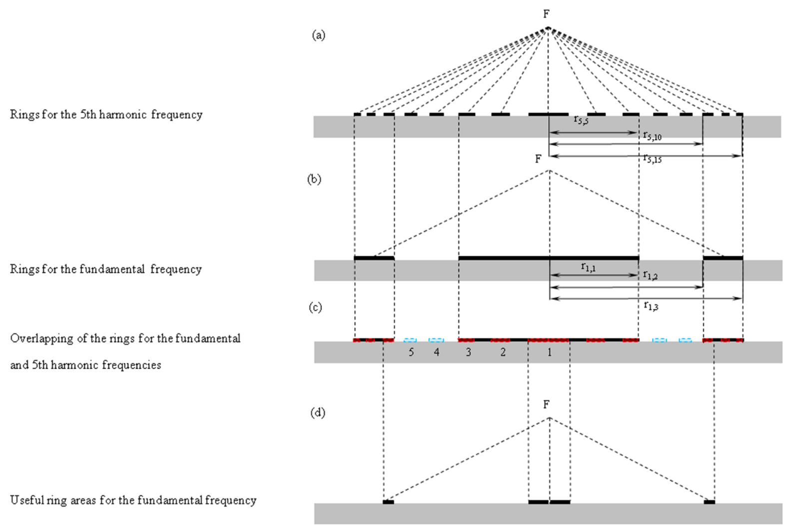

Figure 4.

Fresnel rings for the 5th and fundamental frequencies. For both frequencies, the focal length as well as the substrate thickness is chosen to be the same.