Temporal evolutional acoustic pattern generated by a 3D printed Fresnel lens-focused transducer

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***Abstract*—The controlled coupling of acoustic field has the potential to address grand scientific challenges for biological imaging, particle manipulation, therapy and intervention. However, current technologies have limited flexibility and poor control over acoustic pattern generated by a given transducer design. We report a Fresnel lens-focused ultrasonic transducer for generating excited signal dependent acoustic pressure patterns. A 3D-printed Fresnel lens is bonded to a 5 MHz ultrasonic transducer built using conventional technology. The normalized intensity maps of the acoustic pressure fields from the Fresnel lens-focused transducer under various cycle numbers of excited signal were characterized. The results demonstrated that under different cycle excitation, a temporal evolution acoustic intensity at various longitudinal locations along the focus can be generated and controlled by a 3D printed Fresnel lens focused ultrasound transducer. It suggests a simple way for acoustic pattern control which can have broad application in the future.**

Keywords—temporal evolutional acoustic pattern, 3D printed Fresnel lens, finite element simulation, ultrasonic transducer

I. INTRODUCTION

Ultrasonic wave can induce various effects, e.g. radiation force, cavitation, thermal effects, on the biological tissue at points where ultrasound focused, providing promising tools for imaging, crystallography, particle tweezing, cellular stimulation and theranostic application [1-3]. Better control of the ultrasound beam is of paramount importance for various applications, especially at low frequency range as it can penetrate deeper inside the tissue and even in the brain through the skull [4-5].

With the advanced ultrasound beam control strategies established in recent years, mainly by using multi-element arrays for phase modulation and correction, satisfied diffraction limited focusing can be achieved [6]. Although effective, it is expensive and requires complicated electronics. Single element focused transducer is a great alternative. Recently, 3D-printed holographic acoustic lens has been demonstrated to be able to generate designed acoustic fields from a single element transducer [7]. However, it is limited flexibility and poor temporal control over acoustic pattern generated by the given transducer design.

We report a Fresnel lens-focused ultrasonic transducer for generating excited signal dependent acoustic pressure patterns. Fresnel zone theory was used to design the size of the lens, the shape of the lens for a 5MHz plane transducer. A 3D-printed Fresnel lens is bonded to a 5 MHz ultrasonic transducer built using conventional technology. FEM and experimental characterizations were performed. The presented study has the potential to address grand scientific challenges for biological imaging, particle manipulation, therapy and intervention..

II. RESULT

A. *Numerical studies of ultrasonic transducer with Fresnel lens*

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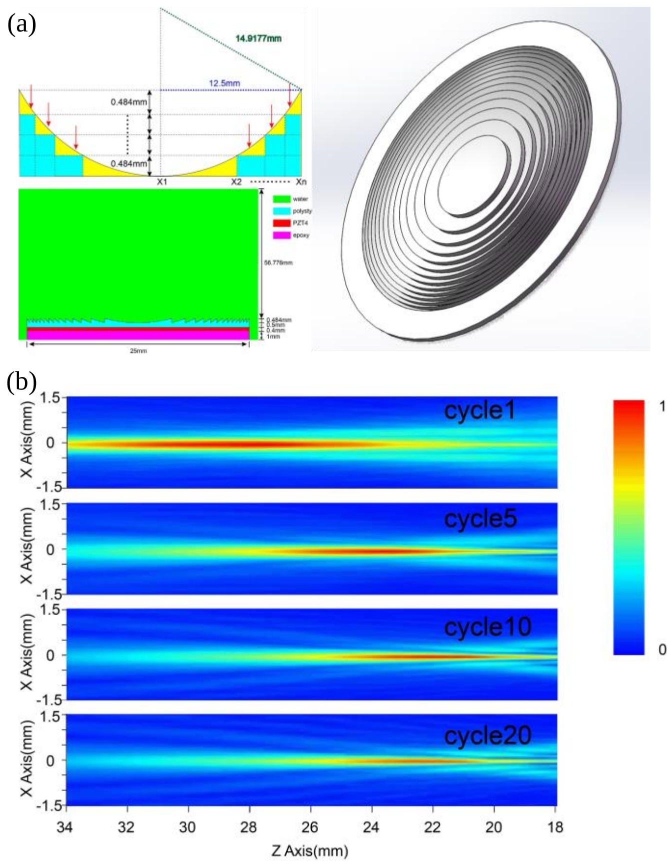

Fig.1 a)The designed specification of the Fresnel lens-focused ultrasonic transducer. b)the focal depth was determined from the acoustic pressure patterns by PZFlex simulaiton

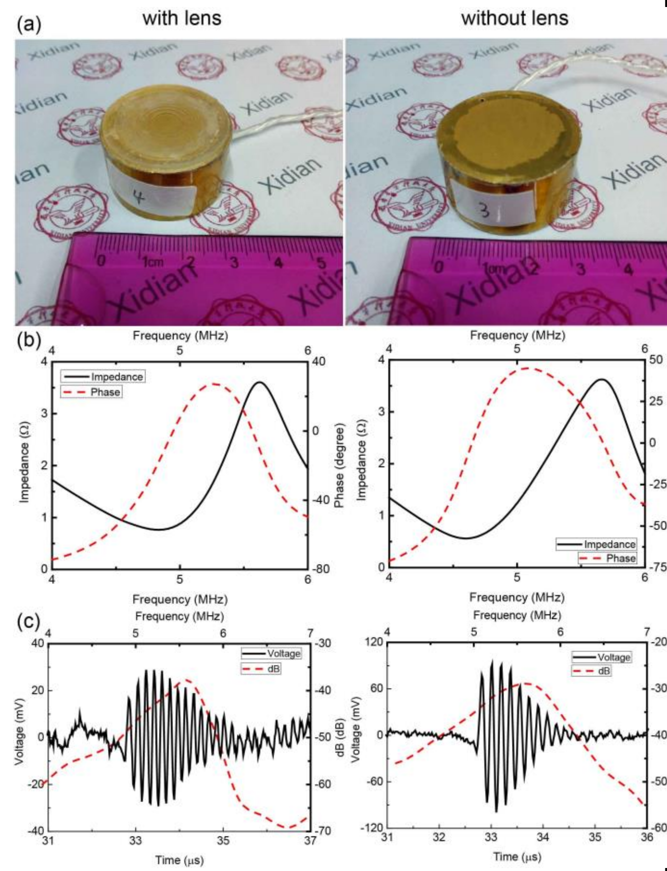

Fig.2 a)the transducer with and without Fresnel lens; b) the frequency dependence of electrical impedance and phase plots of the transducers with and without Fresnel lens; c) the measured pulse-echo waveform with normalized frequency spectrum.

Fig.1 shows the designed specification of the Fresnel lens-focused ultrasonic transducer (Fig.1a) In the simulation, the focal depth was determined from the acoustic pressure patterns (Fig.1b) As can be seen, the acoustic pressure patterns of the device changes with the cycle numbers of excited signal. The focal depth was obtained from the PZFlex simulation assuming a value of 1490 m/s for the speed of sound, and changes from 28.2mm to 22.28mm when the cycle numbers increase from 1 to 20. The -6 dB beam widths of the device with 1, 5, 10, 20 cycles determined to be 0.86mm, 0.62mm, 0.5mm and 0.5mm, respectively. From the simulation results, it can be observed that the Fresnel lens-focused transducer has a tight focus, and the focus characters change with the excitation signal.

B. Experiments on Fresnel lens-focused ultrasonic transducer

Fig.2 (a) shows the transducer with and without Fresnel lens and Fig.2 (b) displays the frequency dependence of electrical impedance and phase plots of the transducers with and without Fresnel lens. The resonant frequency and corresponding impedance were determined from the plots to be 5.28 MHz and 1.8 Ω with lens and 5.1 MHz and 0.58 Ω without lens, respectively. The measured pulse-echo waveform with normalized frequency spectrum is shown in Fig.2 (c). The center frequency is 5.46 MHz with lens and 5.48 without lens, and the -6 dB bandwidth was measured to be 11.54% with lens and 18.98% without lens.

The normalized intensity maps of the pressure fields from the Fresnel lens-focused transducer with different cycle numbers of excited signal are shown in Figs.3 (a)-3(d). The focusing effect of the Fresnel-lens is very evident, which is indicated by the focal spots in Figs. 3(a)-3(d). The maximum pressure amplitude of the wave from the Fresnel lens-focused transducer was 0.7MPa

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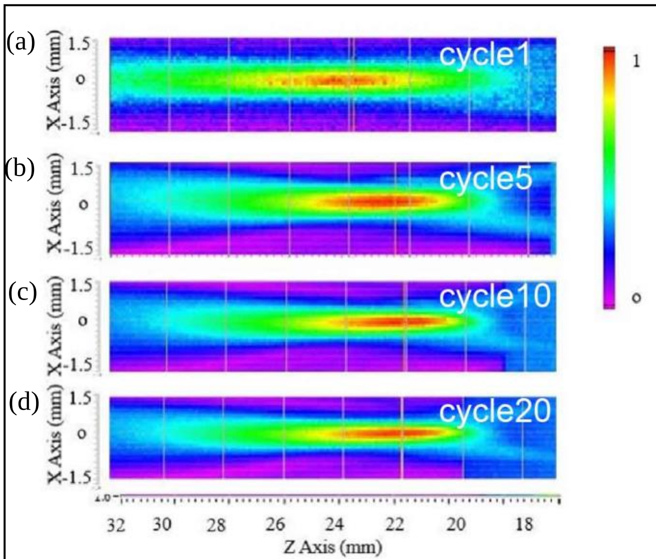

Fig.3 a)-d) the normalized intensity maps of the pressure fields from the Fresnel lens-focused transducer with different cycle numbers of excited signal.

Furthermore, referring to the intensity maps in the x-z plane in Figs. 3(a)-3(d), it could be seen that the focal spot shifted closer to the lens surface when the excited cycle numbers increased, which was similar to that found in simulations. The tendency of focal length changes with different numbers of excitation pulses agrees well with that in simulation shown in Fig.1(b). The differences of simulation and experiment may be because of the cycle numbers. To explain the differences, we received and displayed the echo from the Fresnel lens-focused transduce, as can be seen, even the excited signal has only on cycle, the received signal exist several cycles due to the performance of transducer.

III. Discussion and Conclusion

We report a Fresnel lens-focused ultrasonic transducer for generating excited signal dependent acoustic pressure patterns. A 3D-printed Fresnel lens is bonded to a 5 MHz ultrasonic transducer built using conventional technology. The normalized intensity maps of the acoustic pressure fields from the Fresnel lens-focused transducer under various cycle numbers of excited signal were characterized. The experimental results demonstrated that the focal depth changed from 23.8 mm to 21.9 mm when the cycle numbers of excited signal increased from 1 to 40, and remained unchanged after 10 cycles, which is agree with the simulation results. These results demonstrated that under different cycle excitation, a temporal evolution acoustic intensity at various longitudinal locations along the focus can be generated and controlled by a 3D printed Fresnel lens focused ultrasound transducer. It suggests a simple way for acoustic pattern control which can have broad application in the future.

The controlled coupling of acoustic field has the potential to address grand scientific challenges for biological imaging, particle manipulation, therapy and intervention. Current technologies have limited flexibility and poor control over acoustic pattern generated by a given transducer design. Ahmet et al, have demonstrated that using a Fresnel lens can focus 25 kHz acoustic waves to manipulate small particles. It is shown that there is standing waves between transducer and acoustic lens which can reduce the output energy [8]. To obtain a tunable focus acoustic lens, non-linear acoustic lens has been designed and showed to be used at low frequency range of 0.1-180 kHz, which works for high energy applications [9]. The presented study bound the ultrasound transducer with centre frequency at 5 MHz with the lens which can eliminate the standing wave. The diffraction limited focal patterns can be adjusted by turning the excitation time course. It is promising for various application in biomedicine.

IV. Methods

A. *bvbFabrication of the Fresnel lens-focused ultrasonic transducer*

The 5 MHz ultrasonic transducer was built using conventional technology using PZT-4 as piezoelectric material, and Epoxy (Tec 301) as backing layer. The diameter of the transducer is 25 mm. The transducer was bonded with a Fresnel lens (VeroClear Resin: speed of sound, c=2424 m/s, density, ρ=1180 kg/m3, acoustic impedance, Z=2.86 MRayl, and attenuation, α=5.5 dB/cm) that was 3D-printed using a Stereolithography Apparatus (SLA) printer (Form 2, Formlabs, MA, USA) with a print-layer thickness of 25 µm. The lens profile was chosen to produce a focus at 38 mm from the surface using the geometric Fresnel lens design rules described by Mori et al [RF Mori]. Acoustic Fresnel lenses exploit the fact that the phase is cyclical (modulo 2π); for instance, in the frequency domain, a phase of 3π is the same as that of π. The thickness of the lens at each point is set to introduce a specific phase delay to create a focal point at the target. Since the phase is kept between 0 and 2π radians using the modulo operation, the lens acquires the characteristic shape of a Fresnel lens. In this way, a lens gets compressed into a thinner format, which results in lower attenuation compared to a regular lens and enables closer focusing.

B. *Experimental setup and measurements*

The frequency dependence of the electrical impedance (both magnitude and phase) of the transducers was measured using WK6500B 1J65120B impedance analyzer (Wayne Kerr Electronics, UK).

Pulse-echo response measurements were performed in distilled water, with the transducer connected to a JSR Ultrasonics DPR 500 (Imaginant, Pittsford, NY) pulser/receiver and excited by an electrical impulse at 200 Hz repetition rate and 50 Ω damping. The energy involved was 12.4 µJ and no gain was applied. The echo response was captured and displayed on an oscilloscope (RTE 1104, ROHDE&SCHWARZ, Germany), with the built-in fast

Fourier transform (FFT) feature used to compute the frequency spectrum of the pulse-echo response. An X-cut quartz plate was used as a reflector.

Acoustic pressure maps were acquired using a 3D ultrasound intensity measurement system (UMS3, Precision acoustics, Dorchester, UK) The Fresnel lens-focused transducer and a needle hydrophone (SN2010, 0.5 mm probe, Precision Acoustics, Dorchester, UK) were placed opposite each other in degassed water. The transducer was driven at the center frequency using a function generator combined with RF power amplifier (A075, E&I, Rochester, N. Y. USA). The voltage applied to the transducer was 30 V. Signals from the hydrophone were captured by a digital oscilloscope (DSOX3024A, Agilent, USA), then plotted in pseudo-color using MATLAB code.

C. Numerical calculations

Simulations of acoustic wave propagation in water media and in Fresnel lens structures were carried by using a finite-element analysis software (PZFlex, Weidlinger Associates, Los Altos, CA).

The PZFlex simulation sets the thickness of the PZT ceramic to be 400 μm with the corresponding center frequency of 5 MHz. 10mm Epoxy was set as the backing layer. During the simulation process, the piezoelectric material was connected in series to a 50 Ω resistor, and the transducer was excited with different cycles of a sinusoidal signal: an excitation frequency of 5 MHz, and a driving voltage of 1 V peak-to-peak. The materials used for the PZFlex simulation are listed in Table I.

Table I. Materials used for the PZFlex simulation

Material	Function	c (m/s)	ρ (kg/m^3)	Z (MRayl)
PZT-4	Piezoelectrics	4600	7500	34.5
VeroClear Resin	Lens	2424	1180	2.86
Water	Front load	1490	1000	1.49
Epoxy	Backing layer	2080	2849	5.92

REFERENCES

[1] Szabo T L. Diagnostic ultrasound imaging: inside out[M]. Academic Press, 2004.

[2] Wells P N T. Biomedical ultrasound[J]. Academic, London Google Scholar, 1977.

[3] Napoli A, Scipione R, Cannata R, et al. MR-Guided Focused Ultrasound Treatment[M]//Management of Bone Metastases. Springer, Cham, 2019: 263-271.

[4] Carpentier A, Canney M, Vignot A, et al. Clinical trial of blood-brain barrier disruption by pulsed ultrasound[J]. Science translational medicine, 2016, 8(343): 343re2-343re2.

[5] Leinenga G, Langton C, Nisbet R, et al. Ultrasound treatment of neurological diseases—current and emerging applications[J]. Nature Reviews Neurology, 2016, 12(3): 161.

[6] Kyriakou A, Neufeld E, Werner B, et al. A review of numerical and experimental compensation techniques for skull-induced phase aberrations in transcranial focused ultrasound[J]. International Journal of Hyperthermia, 2014, 30(1): 36-46.

[7] Melde K, Mark A G, Qiu T, et al. Holograms for acoustics[J]. Nature, 2016, 537(7621): 518.

[8] Cicek A, Korozlu N, Kaya O A, et al. Acoustophoretic separation of airborne millimeter-size particles by a Fresnel lens[J]. Scientific reports, 2017, 7: 43374.

[9] Donahue C M, Anzel P W J, Bonanomi L, et al. Experimental realization of a nonlinear acoustic lens with a tunable focus[J]. Applied Physics Letters, 2014, 104(1): 014103.