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High-sensitivity piezoelectric composite ultrasonic transducers based on Fresnel lenses for high-resolution imaging

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The development of ultrasonic transducers with higher energy conversion and transmission capabilities is crucial for medical diagnosis, smart wearable monitoring, and industrial non-destructive testing [1]. Achieving high electromechanical coupling, acoustic impedance matching, and controlled focusing of the acoustic field simultaneously remains a significant challenge. Piezoelectric materials are commonly used in underwater ultrasonic transducers for transmitting and receiving acoustic waves in a medium. However, there is often an impedance mismatch between the high acoustic impedance of piezoelectric materials and the low acoustic impedance of the surrounding medium (such as water). On the other hand, traditional focusing methods such as mechanical ball pressure and concave lenses have limitations due to the potential for damage to piezoelectric materials and their bulkiness. Recently, the use of new acoustic lenses has become a hot topic in the research of ultrasonic focusing. Melde et al. [2] used acoustic holograms to effectively control acoustic waves to achieve complex acoustic beams such as multi-point focusing. Jin et al. [3] used soft gradient refractive index metasurface lenses to produce ultrasonic focusing and vortex acoustic beams at a frequency of 200 kHz. Walker et al. [4] used acoustic metamaterial lenses to produce focused acoustic beams with high collimation and high lateral resolution at a frequency of approximately 500 kHz. Despite these advances, relatively few studies have been able to combine the performance improvement of ultrasonic transducers and applications.

In this study, we designed a 1-3-2 piezoelectric composite structure ultrasonic transducer based on a focusing high-order Fresnel lens. This method improves the acoustic transmission efficiency of the ultrasonic transducer due to gradient acoustic impedance matching (from the piezoelectric material to the water medium), further effectively combines the Fresnel acoustic focusing effect, and ultimately promotes the application of high-resolution ultrasound imaging.

Device design and fabrication. The overall device structure mainly includes a 1-3-2 piezoelectric composite element and a high-order Fresnel lens as shown in Figure 1(a). In particular, the 1-3-2 piezoelectric composite ultrasonic transducer is selected here because it has high mechanical stability and high energy conversion efficiency [5] and its design can be seen in detail in Appendix A.1. In addition, we have also considered the issue of acoustic impedance matching. The piezoelectric composite material uses a low-impedance polymer material as one of its connecting phases. This reduces the equivalent acoustic impedance of the entire piezoelectric layer by approximately 50%. This adjustment makes the acoustic impedance closer to that of the preceding medium during acoustic transmission. Figure 1(b) shows the front and side view of the 1-3-2 composite structure, from which it can be obtained that the width of 1-3-2 piezoelectric columns is 260 μm, the spacing of piezoelectric columns is 106 μm, the thickness of 1-3 parts and the ceramic substrate is 500 and 250 μm, respectively. The designed 1-3-2 piezoelectric composite structure is based on the W.A. Smith theory and the series-parallel theory of the equivalent circuit model of piezoelectric materials. The specific theoretical derivation and parameter calculation can be found in Appendix A.2. The diameter of the overall composited piezoelectric material prepared is 25 mm and the thickness of the piezoelectric layer is 750 μm. After packaging and testing, the center frequency of the ultrasonic transducer with the designed piezoelectric composite material is 2.2 MHz and the effective electromechanical coupling coefficient k_{teff} is 0.64. Finally, the Fresnel lens is designed to achieve precise acoustic focusing through a series of concentric rings that alter the phase of acoustic waves passing through the lens. The specific design theory of the Fresnel lens can be found in Appendix B.1. The lens parameters, including the

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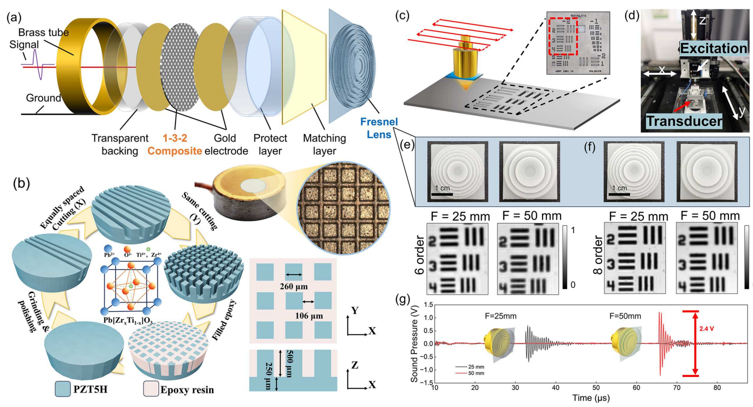

Figure 1 (Color online) (a) Structure of the 1-3-2 composite ultrasonic transducer with Fresnel lens; (b) preparation and image of the transducer; (c) C-scan system schematic; (d) imaging device diagram; (e) 6th-order Fresnel lenses with 25 and 50 mm focal lengths; (f) 8th-order Fresnel lenses with 25 and 50 mm focal lengths; (g) echo signals at maximum amplitude using 6th-order Fresnel lenses.

number of rings (order), ring spacing, and thickness, were optimized to ensure efficient focusing at the target frequency. Fresnel lenses with orders of 4, 6, and 8, and focal lengths of 25 and 50 mm respectively, were fabricated via 3D printing using GR rigid resin. The designed frequency of the lens was matched to the center frequency of the transducer (2.2 MHz) to ensure compatibility. A 1 mm thick substrate was also added as a matching layer to optimize acoustic energy transmission and reduce reflection losses. The specific design and preparation process of the Fresnel lens can be found in Appendix B.2.

Results and discussion. To verify the acoustic performance (especially focusing characteristics) of the 1-3-2 types piezoelectric composite transducer based on a high-order Fresnel lens, we conducted the acoustic field test using needle hydrophone to measure the sound pressure distribution generated by the ultrasonic transducer in the water tank (see Appendix C.1 for specific experimental steps). Since the ultrasonic transducer has a wide operating frequency range, we focus on pressure map within the effective bandwidth of 1.2 to 3.0 MHz. The specific experimental acoustic field distribution and comparison results are detailed in Appendix C.2. Figure C2 shows the experimental sound pressure distribution generated by six different Fresnel lenses in the frequency range of 1.8–2.6 MHz, where the sound pressure intensity has been normalized. To better show the frequency response of ultrasound transducers with different orders Fresnel lenses, Figures C2(c), (f), and (i) give the maximum sound pressure intensity distribution at each frequency (1.8, 2.0, 2.2, 2.4, 2.6 MHz). Although the sound pressure intensity decreases when the frequency deviates from the center frequency by 2.2 MHz, it remains above 0.5 (i.e., greater than −6 dB) within the test range of 1.8–2.6 MHz. The above experimental results not only show that the device has the ability to focus the sound beam, but also exhibits effective lateral resolution at different frequencies, which demonstrates its good broadband focusing characteristics. To further evaluate its performance in ultrasound applications, we conducted C-mode ultrasound imaging experiments and imaging plate detials are provided in Table C1. Figure 1(c) shows the schematic with the red-arrow scanning path and the red-dotted-box resolution plate (key part). Figure 1(d) is the imaging device diagram. The imaging area for C-mod is −2 group, lines 2–4, and results are in Figure 1(e). As the Fresnel order increases, imaging improves with better contrast and lateral resolution. Figure 1(f) shows the 6th- and 8th-order, 25 and 50 mm designed focal-length Fresnel lenses for imaging. The echo signals of ultrasonic transduer with two focal-length lenses at focusing positon are shown in Figure 1(g). This study realizes high-resolution focused imaging of a composite ultrasonic transducer based on a broadband Fresnel lens. It demonstrated its acoustic beam focusing capability in the 1.8–2.6 MHz broadband through hydrophone testing, and ultrasonic imaging performance through C-mode imaging. Three sets of comparable Fresnel lens ultrasonic transducers have been selected for performance evaluation and comparison, and the results are shown in Table C2. The combination of Fresnel lens and composite transducer in this work can not only focus the acoustic beam in a frequency band, but also significantly improve the resolution of the ultrasound imaging, providing a new solution for high-performance transducer.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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