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Modelling and simulation of high-frequency (100 MHz) ultrasonic linear arrays based on single crystal $LiNbO_3$

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A B S T R A C T

Background: High-frequency ultrasonic transducer arrays are essential for high resolution imaging in clinical analysis and Non-Destructive Evaluation (NDE). However, the fabrication of conventional backing-layer structure, which requires a pitch (distance between the centers of two adjacent elements) of half wavelength in medium, is really a great challenge.
Objective and method: Here we present an alternative buffer-layer structure with a silicon lens for volumetric imaging. The requirement for the size of the pitch is less critical for this structure, making it possible to fabricate high-frequency (100 MHz) ultrasonic linear array transducers. Using silicon substrate also makes it possible to integrate the arrays with IC (Integrated Circuit). To compare with the conventional backing-layer structure, a finite element tool, COMSOL, is employed to investigate the performances of acoustic beam focusing, the influence of pitch size for the buffer-layer configuration, and to calculate the electrical properties of the arrays, including crosstalk effect and electrical impedance.
Results: For a 100 MHz 10-element array of buffer-layer structure, the ultrasound beam in azimuth plane in water could be electronically focused to obtain a spatial resolution (a half-amplitude width) of 86 μm at the focal depth. When decreasing from half wavelength in silicon (42 μm) to half wavelength in water (7.5 μm), the pitch sizes weakly affect the focal resolution. The lateral spatial resolution is increased by 4.65% when the pitch size decreases from 42 μm to 7.5 μm. The crosstalk between adjacent elements at the central frequency is, respectively, −95 dB, −39.4 dB, and −60.5 dB for the 10-element buffer, 49-element buffer and 49-element backing arrays. Additionally, the electrical impedance magnitudes for each structure are, respectively, 4 kΩ, 26.4 kΩ, and 24.2 kΩ, which is consistent with calculation results using Krimholtz, Leedom, and Matthaei (KLM) model.
Conclusion: These results show that the buffer-layer configuration is a promising alternative for the fabrication of high-frequency ultrasonic linear arrays dedicated to volumetric imaging.

1. Introduction

High-frequency (⩾100 MHz) transducer arrays can provide the necessary spatial resolution for the applications of skin, eye and vessel imaging, where high quality subsurface imaging is required [1,2]. A number of researchers have focused their efforts on the development of high-frequency ultrasonic phased arrays [3–6], and several different approaches are being taken such as dice-and-fill, dry etching, wet etching and so on. However, the fabrication of high-frequency (⩾100 MHz) device remains a challenge due to the technology difficulties in the fabrication of small-scale piezoelectric arrays.

Previous attempts to fabricate 100 MHz array were based on thin film (fabricated by deposition to form polycrystalline films) design ranging in thickness between 10 μm and 40 μm, which suffers from several drawbacks such as slow deposition rates, high levels of stress generated during processing which can lead to cracking of the film, and low efficiency in generating ultrasound. Far more important for the thin film design, though, is that how to realize the patterning of small-scale features within the array and to eliminate the crosstalk between different elements. Yukio Ito's group has reported 100 MHz arrays using ZnO thin films [6–9]. They fabricated a 32-element array on a sapphire focal lens with a pitch of 100 μm, in which the large pitch brought about a low resolution. The typical parameters of one element in size were 90 μm wide, 3.2 mm long, 10 μm thick. K. Shung's group has developed a 120 MHz kerfless array using 12 μm thick PZT films [10,11]. However, the crosstalk between the different elements resulted in a significant ringing because of the kerfless structure. In contrast, the single crystal design proposed here allows the sensitivity enhancement by using piezoelectric material with coupling coeffi-

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cient that is higher than that of thin films. For example, the electromechanical coupling coefficient of single crystal lithium niobate ($LiNbO_3$) is $k_t = 0.49$ when generating longitudinal waves, while those of thin films are $k_t = 0.27$ and 0.34 [10] for ZnO and PZT, respectively.

Although $LiNbO_3$ has favorable electromechanical coupling efficiency and robust single crystal structures, the fabrication of high-frequency $LiNbO_3$ arrays based on conventional configuration is still a great difficulty for the thin film etching techniques. The traditional dicing technique becomes extremely difficult to perform when the material is so thin and delicate [12,13]. So far there is no report on kerfed $LiNbO_3$ arrays in frequency higher than 100 MHz. Therefore, it is necessary to develop a novel structure to facilitate the process without affecting the performance of the array. An alternative configuration based on buffered focal silicon lens is put forward in this work. The insertion of silicon focal lens can facilitate volumetric imaging. Moreover, using silicon substrate makes it possible to integrate the arrays with IC (Integrated Circuit), which facilitates microminiaturization of electronics.

Two linear array transducers, with different dimensions and the same buffered configuration, are designed at 100 MHz to investigate the influence of different pitch sizes. The properties of conventional backing configuration are also considered for comparison. The electrical impedance, the crosstalk effect, and the acoustic characteristics of $LiNbO_3$ transducer arrays have been studied by finite element modeling (FEM). Here we use COMSOL, finite element software, to model and simulate the properties of the arrays.

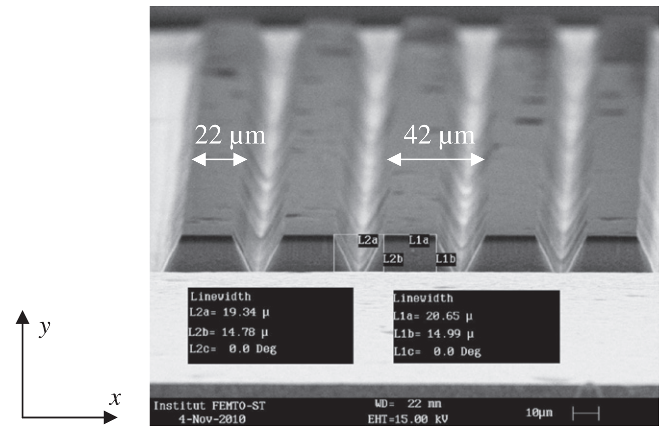

Fig. 1. SEM image of $LiNbO_3$ 36°/Y-cut array etched by RIE (Reactive Ion Etching) technology (thickness: 33 µm).

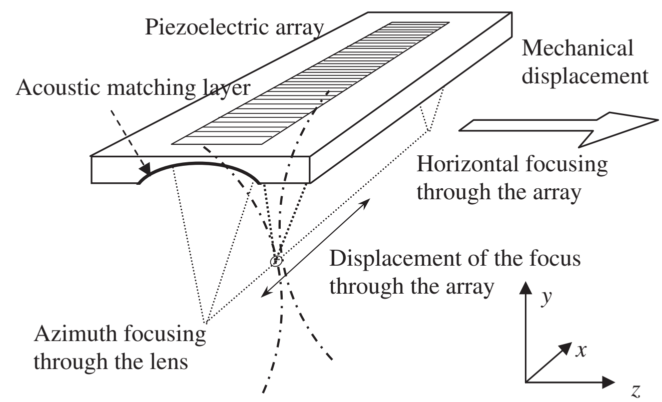

Fig. 2. Schematic diagram of linear array on silicon lens for volumetric imaging.

2. Design of the transducer arrays

The traditional configuration of the array transducer is the backing-layer structure where the wave is emitted directly into water using mechanical matching and the backward propagating wave is scattered by the rough backing surface of the silicon substrate (see Fig. 3c). The spatial resolution along x-axis can be controlled by the linear phased array.

Ideally, the pitch (p) should be limited to half wavelength in water to avoid grating lobes ($p \leqslant 7.5$ µm, the wavelength in water is 15 µm at 100 MHz). As a result, the kerf width (d) should be smaller than 7.5 µm. For such kind of full-kerfed array, the kerf etching with high aspect ratio ($h/d > 33$ µm/7.5 µm) is required. But it is impossible to fabricate such small features in the piezoelectric arrays using state-of-the-art technologies. We have investigated that the smallest pitch of 42 µm could be obtained for a full-kerfed single crystal lithium niobate array with a thickness (h) of 33 µm. Fig. 1 is the SEM image of the lithium niobate ($LiNbO_3$) 36°/Y-cut array etched by RIE (Reactive Ion Etching) technology. As shown in Fig. 1, all kerfs are grooved in a V-shape with 75° vertical angle. The width of the etched kerf is a function of its depth because of the crystalline structure of $LiNbO_3$.

The goal of this work is to develop a full-kerfed linear array for volumetric imaging application with an acceptable resolution. Here, an alternative configuration based on a buffered silicon lense, as shown in Fig. 2, is put forward to avoid the difficulties in the high depth/width aspect ratio etching. A buffered silicon layer is placed between the piezoelectric array and a matching layer (SU-8 composite), which allows the wave to propagate in water through silicon and the matching layer. This results in a much smaller aspect ratio thanks to the much larger velocity of sound in silicon (At 100 MHz, the wavelength in Si (λ_{Si}) is 84 µm, then the pitch is half of this value, 42 µm). Moreover, the spatial resolution along z-axis can be controlled by the silicon focal lens. The spatial resolution along x-axis can be controlled by the linear phased array. To investigate the influence of pitch size for this configuration, another buffer-layer array of different dimensions ($p = 7.5$ µm) is also considered here which is shown in Fig. 3b. The widths of the element of Fig. 3a and b are 22 µm and 5.5 µm, respectively. To study the effect of buffer layer, a conventional structure (see Fig. 3c) is designed with the same array parameters as Fig. 3b but without Si buffer layer. In order to obtain higher sensitivity and broader bandwidth transduction, the thickness of the matching layer must be in quarter wavelength thick and the acoustic impedance is $Z_m = \sqrt{Z_f Z_s}$ for the buffer structure (or $Z_m = \sqrt{Z_f Z_{piezo}}$ for the backing structure) [14,15]. The matching material considered in this study is an SU-8-based nano-composite (mixed with nano-powder of TiO_2), the acoustic impedance of which could be arbitrarily adjusted to meet the required values [16].

3. Results and discussion

COMSOL, a commercial finite element tool, is used to model and simulate the properties of the transducer arrays. 3-Dimensional (3-D) simulation consumes quite a lot of memory and time. Thus we simplify the 3-D model to 2-D simulation in x–y plane to investigate the properties of the array. The simulation process and materials properties can be found in Appendix at the end of this paper.

3.1. Focusing acoustic field

Numerical results for continuous wave beam focusing are given in Fig. 4a–c, where the pressure modulus represents the acoustic field in fluid and the total displacement represents the acoustic