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# Numerical and experimental investigation of kerf depth effect on high-frequency phased array transducer

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ABSTRACT

*Background:* High-frequency ultrasonic transducer arrays are essential for high resolution imaging in clinical analysis and Non-Destructive Evaluation (NDE). However, the structure design and fabrication of the kerfed ultrasonic array is quite challenging when very high frequency (⩾100 MHz) is required.

*Objective and method:* Here we investigate the effect of kerf depth on the performances of array transducers. A finite element tool, COMSOL, is employed to simulate the properties of acoustic field and to calculate the electrical properties of the arrays, including crosstalk effect and electrical impedance. Furthermore, Inductively Coupled Plasma (ICP) deep etching process is used to etch 36°/Y-cut lithium niobate ($LiNbO_3$) crystals and the limitation of etching aspect ratio is studied. Several arrays with different profiles are realized under optimized processes. At last, arrays with a pitch of 25 μm and 40 μm are fabricated and characterized by a network analyzer.

*Results:* Kerf depth plays an important role in the performance of the transducer array. The crosstalk is proportional to kerf depth. When kerf depth is more than 13 μm, the array with crosstalk less than −20 dB, which is acceptable for the real application, could provide a desired resolution. Compared to beam focusing, kerf depth exhibits more effect on the beam steering/focusing. The lateral pressure distribution is quantitatively summarized for four types of arrays with different kerf depth. The results of half-cut array are similar to those of the full-cut one in both cases of focusing and steering/focusing. The Full-Width-at-Half-Maximum (FWHM) is 55 μm for the half-cut array, and is 42 μm for the full-cut one. The 5-μm-cut array, suffering from severe undesired lobes, demonstrates similar behaviors with the no-cut one. ICP process is used to etch the 36°/Y-cut $LiNbO_3$ film. The aspect ratio of etching profile increases with the kerf width decreasing till it stops by forming a V-shaped groove, and the positive tapered profile angle ranges between 62° and 80°. If the mask selectivity does not limit the process in terms of achievable depth, the aspect ratio is limited to values around 1.3. The measurement shows the electrical impedance and crosstalk are consistent with the numerical calculation.

*Conclusion:* The numerical results indicate that half-cut array is a promising alternative for the fabrication of high-frequency ultrasonic linear arrays. In fact, the minimum pitch that could be obtained is around 25 μm, equivalent to a pitch of 1.6$\lambda$, with a kerf depth of 16 μm under the optimized ICP parameters.

## 1. Introduction

The need for improved imaging resolution has prompted intensive studies in developing high-frequency transducer arrays, which can provide the necessary spatial imaging resolution for specialized applications in medical imaging [1,2], such as the imaging of skin, eye and vessel [3–5]. So far, a variety of high frequency (50–100 MHz) arrays with different materials and structures have been demonstrated [6,7]. However, structure design and fabrication of the ultrasonic array is still more challenging when very high frequency (⩾100 MHz) is required.

Structure design and the effect of the material are two critical factors for high-frequency transducer arrays. A number of researchers have focused their efforts on the development of high-frequency (⩾100 MHz) ultrasonic phased arrays. Recently, Shung's group has reported a 120 MHz kerfless array using 12 μm thick PZT films [8,9]. This kerfless linear ultrasonic array can provide a simplified alternative to arrays built using composite elements. However, the crosstalk between the adjacent elements results in a significant ringing because of the kerfless structure. Thus, such a design is limited in use to conventional linear array

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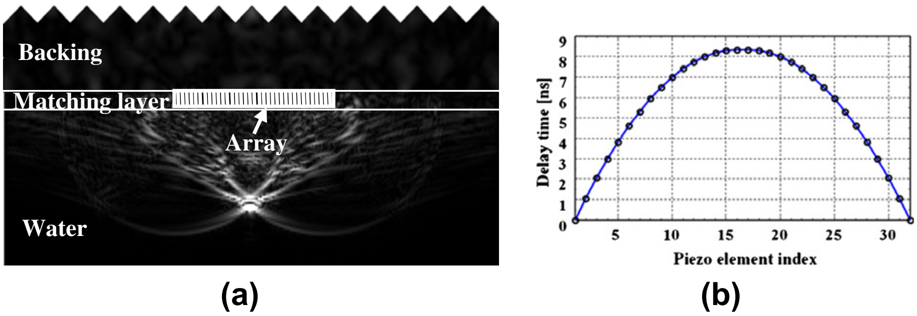

**Fig. 1.** Designed array structure and simulated focusing field in impulsion wave: (a) principle of focusing transducer array and (b) Delay time for a 32-element array.

imaging, where the acoustic beam is not steered. To reduce the crosstalk and provide as good performance as possible, mechanical isolation between elements is necessary. Moreover, a smaller pitch should be taken within the limits of the process capability as far as possible for the sake of high resolution. Ito's group has reported 100 MHz arrays using ZnO thin films [10–13]. They fabricated a kerfed linear array on a sapphire focal lens with a pitch of 100 μm, in which the large pitch brought about a low resolution.

Regarding the effect of the materials, previous attempts to fabricate high frequency (100 MHz) ultrasonic transducer array were based on thin film (fabricated by deposition to form polycrystalline films) design ranging in thickness between 10 μm and 30 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 coupling efficiency in generating ultrasound. In contrast, the single crystal lithium niobate ($LiNbO_3$) design proposed here allows the sensitivity enhancement with coupling coefficient that is about two times higher than that of thin films [10]. Several different approaches to fabricate the $LiNbO_3$ kerfed arrays are being taken such as dice-and-fill [14], interdigital pair bonding technique [15], and so on. However, it is difficult to fabricate linear arrays at frequencies higher than 100 MHz using those methods because the pitch is very small. There is no hitherto report on kerfed $LiNbO_3$ arrays at frequencies higher than 100 MHz. MEMS (Micro Electronic Mechanical System) etching technology brings new possibilities in the development of high frequency array transducers due to its abilities in performing small-scale features. Among a wide variety of etching methods, Inductively Coupled Plasma (ICP) deep etching has been used in etching $LiNbO_3$ thin films. Recently, The FEMTO-ST lab and Wehrspohn's group have made a lot of progress in deep etching X-cut, Z-cut, Y-cut and 128°/Y-cut $LiNbO_3$ crystals [16,17].

When using $LiNbO_3$ to realize the high-frequency (100 MHz) kerfed transducer array, the etching depth ($h$) of $LiNbO_3$, $\frac{1}{2}\lambda$, should be 33 μm, which is determined by the working frequency. To avoid the grating lobes, the pitch ($p$) should be limited to half wavelength in water ($p \leqslant 7.5$ μm, the wavelength in water is 15 μm at 100 MHz). Therefore, the kerf width ($d$) should be smaller than 7.5 μm. For a full-kerfed array, the etch profile with high aspect ratio ($h/d > 33$ μm/7.5 μm) is required. The ratio is so great that the ICP deep etching process would be inefficient, and maybe result in the end-stop at the undesired kerf depth, which is unacceptable for fabricating high-frequency arrays.

In this work, we explore the limitation of the high aspect ratio ICP deep etching under optimized process parameters and study what role the kerf depth plays in the transducer array. 36°/Y-cut $LiNbO_3$ linear arrays with different sizes are realized by means of ICP process. COMSOL, finite element software, is chosen to model and simulate the properties of the arrays. Acoustic beam characteristics, crosstalk effect, and electrical impedance of $LiNbO_3$ transducer arrays have been studied by Finite Element Method (FEM).

## 2. Design and fabrication

### 2.1. Linear array design

The 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. The lateral spatial resolution can be controlled by the linear phased array. To focus the ultrasonic beam, time delays are applied to the elements to create constructive interference of the wave fronts. Each element radiates a spherical wave at a specified time. Fig. 1a shows the principle of the focusing transducer array. Fig. 1b is the delay time applied to the 32-element array.

The design of the array structure is shown in Fig. 2. 36°/Y-cut $LiNbO_3$ single crystal is chosen as the active piezoelectric material for its favorable electro-mechanical efficiency and robust single crystal structure. The center frequency of the device is chosen to be 100 MHz based on the $LiNbO_3$ film with a corresponding thickness of 33 μm. Silicon substrate has the ideal acoustic impedance for use as a backing layer, but resonance in the low-loss, semiconductor crystal makes it necessary to use a more lossy substance. Thus, a thickness of 300 μm silicon with rough backside is chosen as the backing layer. Additionally, in order to obtain higher sensitivity and broader bandwidth transduction, the thickness of the matching layer must be in a quarter-wavelength thick. The matching material considered in this study is an SU-8-based nano-composite (mixed with nano-powder of $TiO_2$), of which the acoustic impedance could be arbitrarily adjusted to meet the required values [18]. 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

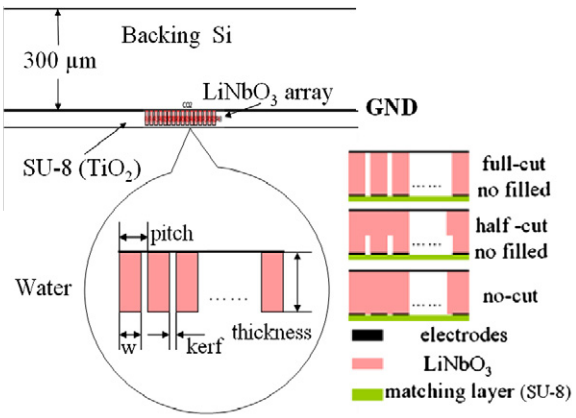

**Fig. 2.** Structure of the phased array transducer.