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Design of a Novel High Frequency Ultrasound Annular Array

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Abstract

The design of a novel 50MHz 7-elment annular array is described. Equal-width electrodes are deposited on the rear face of piezoelectric layer to form a kerfless array, instead of mechanical cutting. Compared with equal-area designs, much better performance is achieved by the novel design. The cross talk is down to -20dB, the -6dB bandwidth and insertion loss are 41% and 18dB, respectively. The pulse responses are largely improved compared with conventional kerfless annular arrays. Furthermore, no pre-focus lens for the central element is required in this array, promising simplified fabrication.

Keywords: annular array; kerfless; high frequency; ultrasound;

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1. Introduction

High frequency annular arrays offer a number of advantages over linear-phased arrays [1, 2]. The inherent axial symmetry of annular array results in the requirement of far fewer elements than linear-phased array. It not only reduces the cost of electronics since fewer channels are needed, but also leads to larger area element providing high-quality imaging. The annular arrays are often designed that each element has the same area. The equal-area constraints achieve approximately same electrical impedance and the same phase shift across every element. There has been much research into array fabrication by cutting concentric rings into a piezoelectric substrate to create a series of annular elements. However, this situation leads to unwanted lateral modes. Because the widths of outer elements are decreased to maintain the equal-area condition, the width of the outermost element eventually becomes comparable to its thickness, resulting in the lateral mode coupling into the operating bandwidth of transducer. A solution to this is presented by Morton [3] by depositing patterned electrodes instead of cutting the piezoelectric substrate. With no grooves between adjacent elements, the lateral mode can be avoided in the outer elements. The fabrication is also simplified due to no mechanical cutting. However, it is generally believed that the cross talk in the kerfless array is very severe resulting in significant ringing. As a result of this, these arrays have not had a significant amount of research effort, and applications have been limited.

In this paper, the behavior of a conventional equal area annular kerfless array is investigated. In addition, a novel annular kerfless array with geometry based on equal-width elements is presented and this is shown to offer the potential for performance benefits. The insertion loss, bandwidth, cross talk and pulse response in focusing for both geometries are investigated by finite element analysis (FEA), a method showing very close results to real experiments. The results from the novel annular arrays are comparable to most sophisticated high frequency ultrasound transducers. It implies the feasibility of kerfless annular array in high frequency imaging with far simple fabrications, and experiments are being planned to verify this.

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2. Investigations on equal area annular kerfless array

The FEA model of a 50MHz, 2mm-diameter and 7-element equal area annular array using PZT-5H was created by using a software program, Ansys 11.0. A patterned electrode is deposited on the rear face of the PZT layer with 10μm grooves. Suitable epoxies are chosen as matching and backing layers. The central, middle (4 th element counting from axis centre), and outermost elements are selected as the representatives of annular elements. Fig.1 shows the impedance spectrum of these three elements, a decreasing trend is clearly visible. It can be ascribed to the increase of effective electrode width due to the electrical fringing effect, which is also contributes to cross talk.

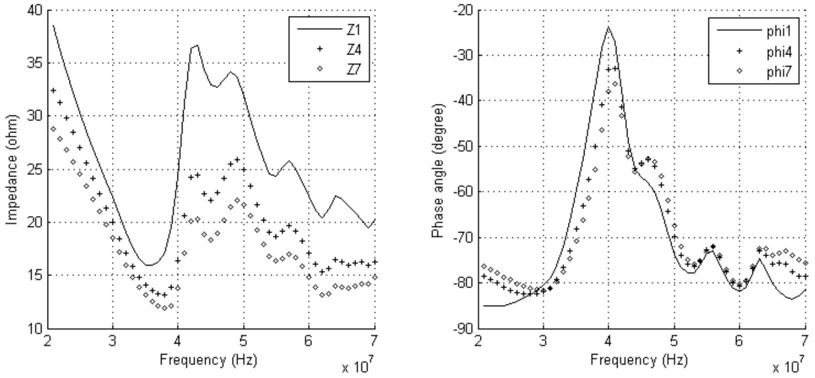

Fig. 1. Impedance spectrum of three elements (a) Impedance amplitude; (b) phase angle

Table 1 lists the insertion loss (IL) and bandwidth (BW) of the three elements, showing good performance. However the reduction of the central frequency is unwanted. This results from the decreasing impedance from inner to outer elements, which in turn leads to the mismatch of the tuning network (based on 1D KLM model [4]) for the outer elements.

Table 1. IL and BW of three equal-area elements, *fc* – central frequency

Element	Central	Middle (4th)	Outermost
IL (dB)	18.0	19.4	20.3
fc (MHz)	44	40.5	39
BW (%)	68.2	66.7	71.8

More importantly, cross talk is further investigated in the time domain. A mono-cycle sinusoidal pulse signal is applied to the elements. As an example, the 4th element is excited as representative due to its middle position. Table 2 lists cross talk at its adjacent elements - the level of cross talk is found to be as large as -7.8dB.

Table 2. Cross talk in adjacent elements when 4th element is excited

Element	1st	2nd	3rd	5th	6th	7th
Cross talk (dB)	-10.1	-17.8	-12.3	-7.8	-12.9	-20.3

From Table 2, cross talk is seen to decrease with distance from the excited element. An unexpected ringing was seen (-10dB) about 300ns after the pulse signal. This time is related to the shear wave propagation across the element surface. The shear waves lead to the interference in the centre element due to the axis-symmetric structure. Fig 2 demonstrates the shear wave effect in the central element when phased signals are applied to achieve focusing.

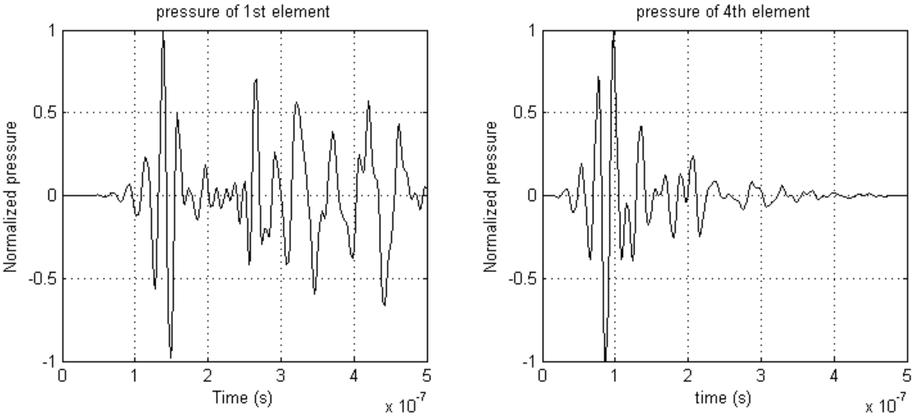

Fig 2. Pressure outputs in 1st and 4th elements in equal-area array by phased pulse signals

The pulse response of 4th element is good and of reasonable length; the tail is acceptable and should be diminished further by the application of a Gaussian signal. However, the central element shows significant unwanted ringing. The source of this ringing is due to the large vibration from the strong thickness extensional (TE) mode in the very large central element, generating significant shear mode amplitude. Furthermore, a pre-focus lens is required in the large central element, which is not easy to fabricate with precise curvature at high frequency and also results in limitations of dynamic focusing.

3. Novel equal-width annular kerfless array

It is observed that cross talk and central element ringing are the two major concerns in the conventional equal area kerfless annular array. The decreasing impedances may also lead to some difficulties in the tuning network. In the kerfless array, the electrode broadening is regarded as a main factor of cross talk [5, 6]. The extent of electrode broadening in each element is similar. Increasing the size of the grooves between adjacent electrodes may be a potential solution. In terms of the ringing in the central element during focusing, we believe that the decrease of the width of central element can improve the performance, since the relatively narrow central element has a less strong TE mode which may reduce the wave interference.

The realization of a narrow central element makes the equal-area condition infeasible, thus a novel equal-width annular array is proposed. Besides the narrow central element, the increase of electrode kerfs is also achieved. The novel array is still a 7-element, 2mm-diamter and 50MHz array, but with equal width element of 100μm and equal grooves of 50μm between them. PZ34 provided by “Ferroperm” is selected to replace traditional PZT-5H for several reasons. The low dielectric loss of PZ34 allows good electrical matching to the standard circuit resistant (50Ω). The resistance of each equal-width element is close to 50Ω (except the central one). PZ34 also has a high thickness coupling factor and shows a better quality factor. Furthermore, it’s the material with lowest Poisson ratio, which will reduce the shear wave amplitude. Though equal-width array elements obviously have different impedances, the tuning still can be realized by setting independent networks for each electrode.. Based on this analysis, a novel annular array was presented and demonstrated with good performance as shown below.

As for the equal area array, table 3 lists the values of IL and BW in the central, middle, and outermost element, which are excited separately. Both IL and BW show good results. Compared with the PZT-5H equal area array, the BW is slighted reduced, however, a consistent centre frequency is seen and should provide a good pulse shape in the operating frequency range. Independent tuning networks are realized by coaxial fiber and transformers.

Table 3. IL and BW of three equal-width elements, *fc* – central frequency

Element	Central	Middle (4th)	Outermost
IL (dB)	18.3	17.4	17.4
fc (MHz)	44	43.5	43.5
BW (%)	40.9	43.7	43.7

Table 4 displays the cross talk in adjacent elements when only the 4th element is excited. The level of cross talk is largely diminished and is down to -20dB, which compares favorably to diced arrays [7]. Though the central element still shows slight interference and ringing, it is not a significant factor in this case. The novel structure and new material do affect and improve the performances of the kerfless annular array.

Table 4. Cross talk in adjacent elements when 4th element is excited

Element	1st	2nd	3rd	5th	6th	7th
Cross talk (dB)	-19.8	-34.0	-25.4	-21.8	-38.0	-46.6

The ultimate goal for the annular array is to achieve dynamic focus. Different phase shifts are applied into every element in the array. Fig 4 shows the pressure pulse response of 1st and 4th element respectively during focusing. The pressure obtained in 4th element is a good shape; a slightly long tail appears due to the small decrease in BW. More importantly, the ringing in central element is largely improved; only a small amount of influence due to interference can be seen, the tails can be improved by Gaussian signals as mentioned above. Both of two pulse responses are quite good by the excitations of mono-cycle sinusoidal signal. The expected behaviors of this novel array have been achieved very well.

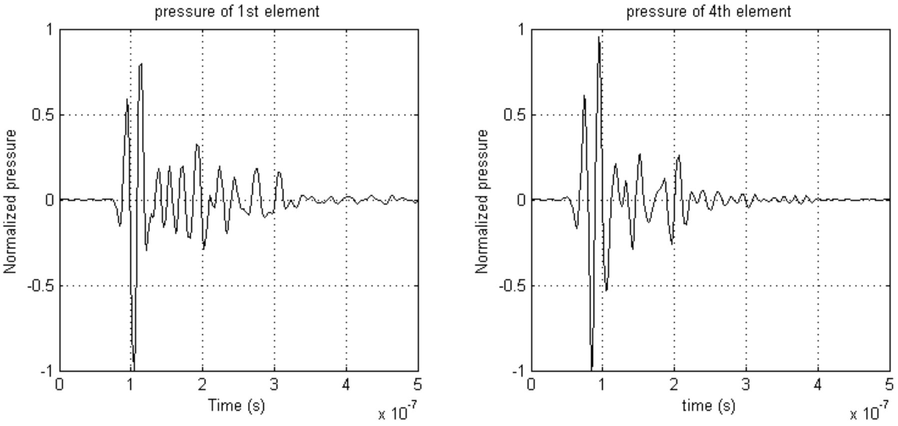

Fig 4. Pressure outputs in 1st and 4th elements in equal-width array by phased pulse signals

In addition, further improvement may be potentially introduced in this novel equal-width array. Since the central element has a significantly larger impedance compared to the other elements, its tuning is feasible but not very easy. It is feasible to design arrays with no central electrode. Initial results obtained by FEA show no evidence of central pressure and good pulse responses. But the influence on the focusing performance by removing the central element has yet to be determined.

4. Conclusion

The novel equal width array is demonstrated to show a low cross-talk, reasonable IL and BW, and also with a reduction in the unwanted ringing in the centre element compared with a conventional equal-area kerfless array. The fabrication of this type of array is not difficult; the realization can be done by using traditional screen printing and accurate electrode sputtering. No central pre-focused lens is required, which not only provide good dynamic focusing, but also further simplifies the fabrication. Though the requirements of the electrical matching network in the equal width kerfless annular array is more complex, the advantages of this structure outweigh the disadvantages, and work is progressing to characterize such a device.

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