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Development of High Frequency Annular Array with a Novel Structure for Medical Imaging

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Abstract

High frequency annular arrays offer a number of advantages in medical imaging. A novel 2mm diameter, 7-element, 40MHz array using equal width elements, instead of the more conventional equal area ones, has been designed and evaluated. It showed an excellent lateral resolution (LR) with a good secondary lobe (SL) response, comparable to conventional arrays operating in excess of 70MHz, which the frequency range causes troubles in annular arrays. The novel array with strong-focusing opens a new way to improve the image quality at relatively low operating frequencies.

Keywords: annular array; high frequency; equal width; FEA

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1. Introduction

High frequency (HF) annular arrays have been developed for medical imaging applications requiring high resolution such as ophthalmology and dermatology [1, 2]. An annular array is generally designed with a number of equal area elements, which allows nearly identical phase shift and impedance for all the elements. Current annular arrays operating from 30 to 50MHz provide a lateral resolution (LR) around 100µm, and the usual way to upgrade lateral resolution is to increase the operating frequency.

However, no previous work has been found that fabricates annular arrays above 80MHz due to the high attenuation, poor penetration and contrast resolution. The frequency-dependent attenuation increases markedly beyond 40MHz. [3], which gives poor penetration– 4mm at 40MHz but 2mm at 80MHz [4]. The deterioration of contrast resolution only appears in annular arrays because of to the existence of secondary lobes (SL), which rises to an unacceptable level beyond 80MHz using the theory developed by Brown et.al [1].

To avoid very high frequency, the reduction of the f-number is an alternative showing the same positive effect on LR. The f-number of most HF transducer ranges from 2 to 4; halving the f-number could improve LR to the same degree as doubling the frequency, which also, more importantly, solves the issues of high attenuation and poor penetration. But smaller f-number (strong focusing) still shows the identical negative effect on contrast as using a higher frequency, because of the increase in SL. Thus a novel array with equal width annular elements instead of conventional equal area ones is developed. Though this structure no longer has equal impedance and phase shift which leads to the slightly complex driving and receiving circuits, it shows significant advantages in constraining the secondary lobe which is a key parameter for imaging. In our study, 40MHz, widely recognized as showing reasonable attenuation and good penetration is set as the operating frequency. F-numbers ranging from 1-2 are chosen and are expected to give even better penetration due to the strong focus. Finite Element Analysis (FEA) has proved to have very close results compared to real experiments and is used for the evaluation of the array. The results show that a strong-focused equal width annular array operating at 40 MHz is able to give the LR of 50μm with a low SL. In addition, wide bandwidth is also achieved leading to a good axial resolution.

2. Equal width annular array design

The capabilities of an imaging system are usually characterized by penetration depth and resolution (including lateral, axial and contrast). Penetration depth and lateral resolution depends mainly on the operating frequency and transducer focusing (namely f-number), as illustrated in Fig.1 using imaging theory [4, 5]. Though both finer LR and deeper penetration are achieved by strong focusing, it has yet to be applied to annular array due to another significant issue – degradation of contrast resolution i.e. increased SL amplitude.

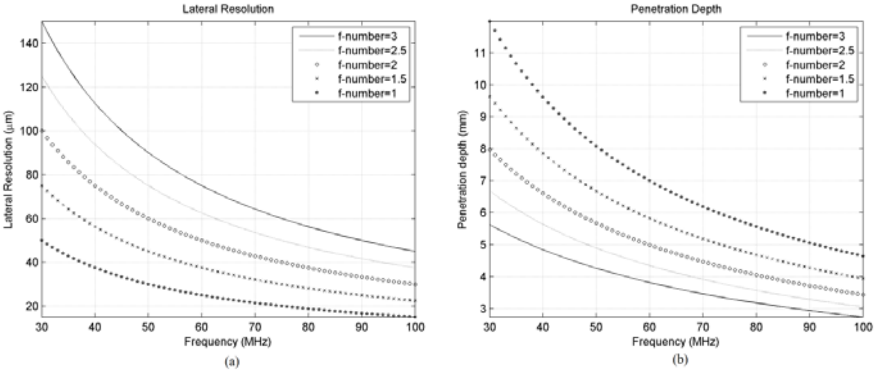

Fig. 1. (a) Lateral resolution and (b) penetration depth dependent on frequency and f-number

In an array structure, contrast resolution mainly depends on the level of SL, of which a level around -50dB is commonly accepted [6]. The level of SL in an equal area annular array has an approximately linear relation to EPD (Element Path Difference) [1], of which the values across all elements are identical as the result of the equal area structure. The reduction of f-number leads to the increase of EPD, which subsequently raises SL to an unacceptable level. To resolve this deadlock in annular array, a model of a 2mm aperture, 7-element, equal area annular array with strong focusing is established and investigated by FEA. It is found that the SL in the focal plane mainly depends on the inner elements; outer elements only show a nominal influence. Fig.2 compares the normalized pressure response at the focal plane achieved by the first 4 inner elements, and all elements, respectively. The pressure peak value generated by 4 elements is about 4/7 of the value from all 7 elements, which agrees with the expected linear increment. The regions identified as ‘secondary lobe’ implies that SL maintains the same level in spite of the increasing number of excited outer elements.

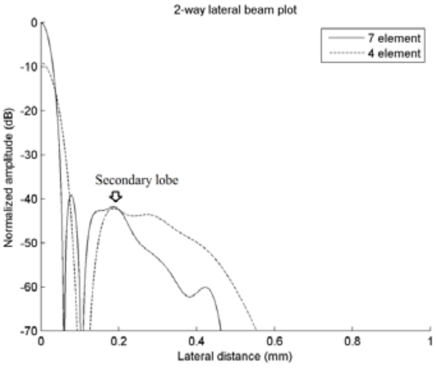

Fig. 2. Beam plot at focal plane generate by first 4 inner elements and all 7 elements, respectively

It can be assumed that decreasing the EPD values for the inner elements but increasing it for outer ones may reduce the SL which seems to be dominated by inner ones. An equal width array is proposed to set the assumption, as shown in Fig.3 and the EPD values are given in Table 1 with equivalents for an equal area array.

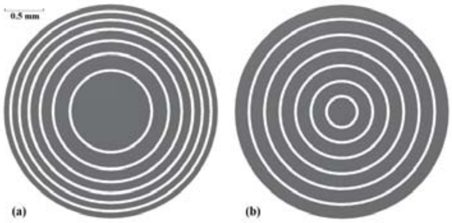

Fig. 3. Front view of (a) conventional equal area annulus (b) novel equal width annulus

Table 1. EPD value in the unit of wavelength for each equal area and equal width annular element with f-number of 1

Element number	1st	2nd	3rd	4th	5th	6th	7th
EPD in equal area annulus	0.95	0.95	0.95	0.95	0.95	0.95	0.95
EPD in equal width annulus	0.14	0.41	0.68	0.95	1.22	1.50	1.77

3. FEA evaluation

Two FEA models of 2mm diameter, 7-element, 40MHz annular arrays based on equal area and equal width structures were designed. Both arrays are focused at a focal distance of 2mm, showing the strong focusing as an f-number of 1. The pressure responses at the focal point are given in Fig.4 and comparable to each other. Bandwidths for both structures are obtained by FFT (Fast Fourier Transfer) as 22.6MHz and 18.0MHz, and leads to the axial resolution of 33.2μm and 41.7μm respectively. Though the equal width array shows slightly coarser axial resolution, this is still high quality.

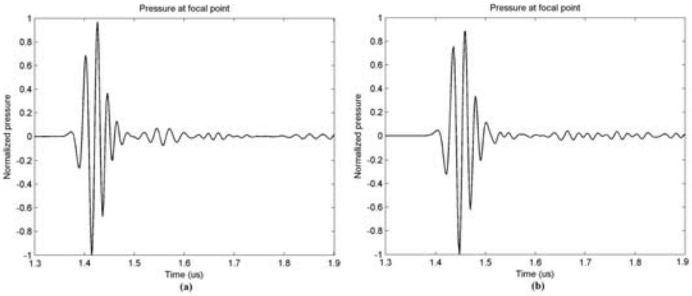

Fig. 4. Pressure responses at focal point of (a) equal area array; (b) equal width array

Fig.5 shows the imaging performance expressed as a beam plot at the focal plane, illustrating the advantage of the novel structure with fine LR and low SL. A1mm aperture, 7-element, 40MHz equal area annular array focused at 2mm showing f-number of 2 is also modeled as being representative of conventional focused arrays. All of the data are detailed in Table 2. The calculated LR by imaging theory [5] and SL by EPD theory [1] of a 70MHz equal area array are also given for further comparison.

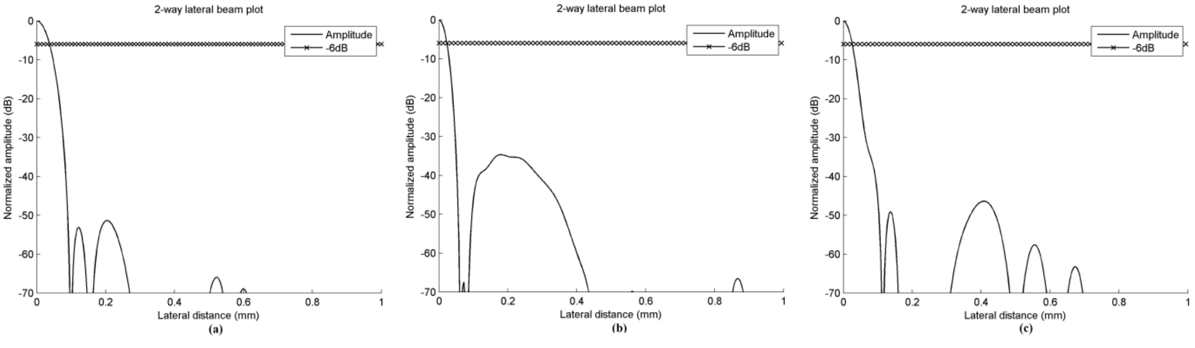

Fig. 5. Beam plot at focal plane of (a) equal area array with f-number=2, (b) f-number=1; (c) equal width array with f-number=1;

Table 1: Comparisons of the two structures at same focal distance, f_0 – resonant frequency, *F* – focal distance, *D* – diameter, *f/#* – f number, *LR* – lateral resolution, *SL*- secondary lobe.

Array	f_0 (MHz)	F (mm)	D (mm)	f/#	LR (µm)		SL (-dB)	
					by calculation	by FEA	by calculation	by FEA
Equal area (Fig5.a)	40	2	1	2	75	74.4	62.5	53.1
Equal area (Fig5.b)	40	2	2	1	37.5	45.4	33.1	34.7
Equal width (Fig5.c)	40	2	2	1	--	51.6	--	49.1
Equal area	70	2	1	2	42.9	--	40.6	--

The difference between calculated and FEA values are close to each other, implying the correctness of the FEA models. The novel equal width annular array shows good LR with sufficient low SL, which is also much improved over the equal area structure with strong focusing or higher frequency. The method of using strong-focusing can be realized by an equal width structure annular array giving fine LR and reduced sidelobes, instead of moving to higher frequencies with the associated complexities.

4. Conclusion

The reduction of f-number is proposed as an advanced method to improve penetration depth and LR at relatively low frequencies. But there is a disadvantage in that there is a deterioration of contrast resolution or SL which prevents its application in conventional equal area annular arrays. An equal width annulus structure has been proposed to address this problem. The FEA results illustrate that sufficient low SL is achieved by the equal width structure with comparable axial and lateral resolution to conventional designs using either strong-focusing or very high frequency. It can be concluded that equal width annular arrays can improve image quality without necessitating an increase in frequency.

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