Concave 2D Ring Array Transducer for Ultrasound Visual Stimulation of the Brain

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Abstract **– Restoration of vision of blind people has been successful by implanting electrode arrays into the eyes near the retina. However, this method is invasive and may have a chance to cause surgical complications. Recently, both *in vitro* and *in vivo* studies show that ultrasound can be used to stimulate cells on the retina and subsequently stimulate the corresponding parts of the neurons in the brain to produce a perception of vision for certain blind people. Unlike implant of electrodes, ultrasound is non-invasive.**

In this paper, we studied a concave two-dimensional (2D) ring array transducer to produce high-resolution ultrasound images of objects on the retina to stimulate the brain for a perception of vision. The advantages of using concave 2D ring array transducer (20-MHz frequency or 0.075-mm wavelength, 14-mm outer diameter, 9-mm inner diameter, 18-mm curvature, a pitch of 4 wavelengths, and about 1000 elements) are that the array can fit the eyeballs better in shape, can reduce the number of transducer elements needed due to its curvature, and can avoid the heating to the lens of the eye due to the high ultrasound attenuation of the lens tissues. The high ultrasound frequency used allows a high full-width-at-half-maximum (FWHM) resolution about 0.147 mm.

Keywords – ***Visual stimulation of the brain, restoration of vision of blind people, focused ultrasound, concave 2D ring array, high frequency ultrasound, and limited-diffraction beams***

I. Introduction

Visual restoration for blind people has been studied for many years [1]-[2]. In these studies, electrode arrays are implanted near the retina in the eye to produce visual perception of electricity patterns on the electrode arrays by stimulating the cells on the retina that subsequently activate the corresponding neurons in the brain [2]. The electricity pattern on the electrode array is an image of object that normal people would see. Although this method is successful to restore vision, it is invasive and may have chances for surgical complications when implanting the electrodes into the eye, including the wiring required to produce electricity patterns.

To overcome the invasive nature of surgical implant of electrodes, ultrasound stimulation of retina of the eye has been studied by various research groups [3]-[8]. Recently, a study shows that stimulation of a point on the retina with a focused ultrasound can activate corresponding neurons (producing electrical signals) in the brain of a rat of retina degeneration *in vivo* [6]-[7]. However, these methods are based on point-by-point stimulation of cells on the retina [6]-[7].

Thus, to restore real-time vision of certain blind people with ultrasound, it is necessary to stimulate multiple points of the retina simultaneously [4][9]-[10]. To accomplish this task, it is needed to produce a device that is suitable for mounting on the eyeball and can produce a high-resolution ultrasound pattern (image) to stimulate the retina for vision perception of objects that blind people would see if they were not blind.

II. Method

In this paper, a two-dimensional (2D) ultrasound ring array transducer that is suitable for mounting on the eyes of animals such as rabbits is studied to produce ultrasound images at the retina for the visual stimulation of the brain. The ring array transducer has an outer diameter (O.D.) of 14 mm and a varying inner diameter (I.D.) from 0 to 9 mm. It is concave of a radius of 18 mm (focal length). To produce a high-resolution image, the array has a high frequency of 20 MHz, which gives a wavelength λ of about 0.075 mm in the eye. A summary of the parameters of the array is given in Table 1.

To produce an ultrasound beam pattern that is corresponding to the optical image of an object at the retina, the optical image (or the object) is first inverse Fourier transformed [11] (implemented with the fast Fourier transform or FFT [12]) based on the Fresnel approximation [13] from the wave equation [14]. Then, the ultrasound beam pattern (image) at the retina is obtained using the method [16]-[18] developed based on limited diffraction beams [19]-[22].

III. Results

Figs. 1(a)-1(i) show the ultrasound images of an object (the desired pattern in the upper-left corner of the figure) at the retina (the images were produced with the concave ring array and the dimensions of the images are given in the figure). In these figures, the I.D. of the ring array is 0, 6, and 9 mm from left to right respectively. From top to bottom, the pitch (the width or height of each array element) is 1.5, 4.0, and 5.6λ (corresponding to the numbers of array elements of about 7137, 1004, and 512) respectively. It is clear that as the I.D. is increased, the image quality is reduced. Also, when the pitch is 5.6λ, artifacts appear due to the aliasing caused by an inadequate spatial sampling rate. To avoid the high attenuation of the lens of the eye, 9-mm I.D. is desired. Thus, Fig. 1(f)

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(I.D. = 9 mm and pitch = 4.0λ) gives the best compromise between the image quality and the number of elements.

Fig. 2 shows a plot of the bottom 5 point objects of each of the three images in Figs. 1(d), 1(e), and 1(f). It shows that the resolution of the images is very high (the full-width-at-half-maximum or FWHM estimated from the plots is about 0.147 mm, which is very close to the theoretical FWHM 1.41λF/D = 0.136 mm calculated with Eq. (36) of [17]). However, as the inner diameter is increased, sidelobes of the image also increase, lowering the image quality, although the image resolution is slightly increased.

Figs. 3(a) and 3(b) are the amplitudes and the phases of the signals used to drive the elements of the ring array transducer to produce the image in Fig. 1(f). These figures show the quantization of both amplitude and phase of the driving signals of the transducer can be used to reduce the number of array elements, simplifying the transducer driving circuits.

Table 1. Parameters of the concave 2D ring array transducer

Parameters	Values
Frequency / Wavelength	20 MHz / 0.075 mm
Outer Diameter (O.D.)	14 mm
Inner Diameter (I.D.)	9 mm
Curvature of Array (Focal Length)	18 mm

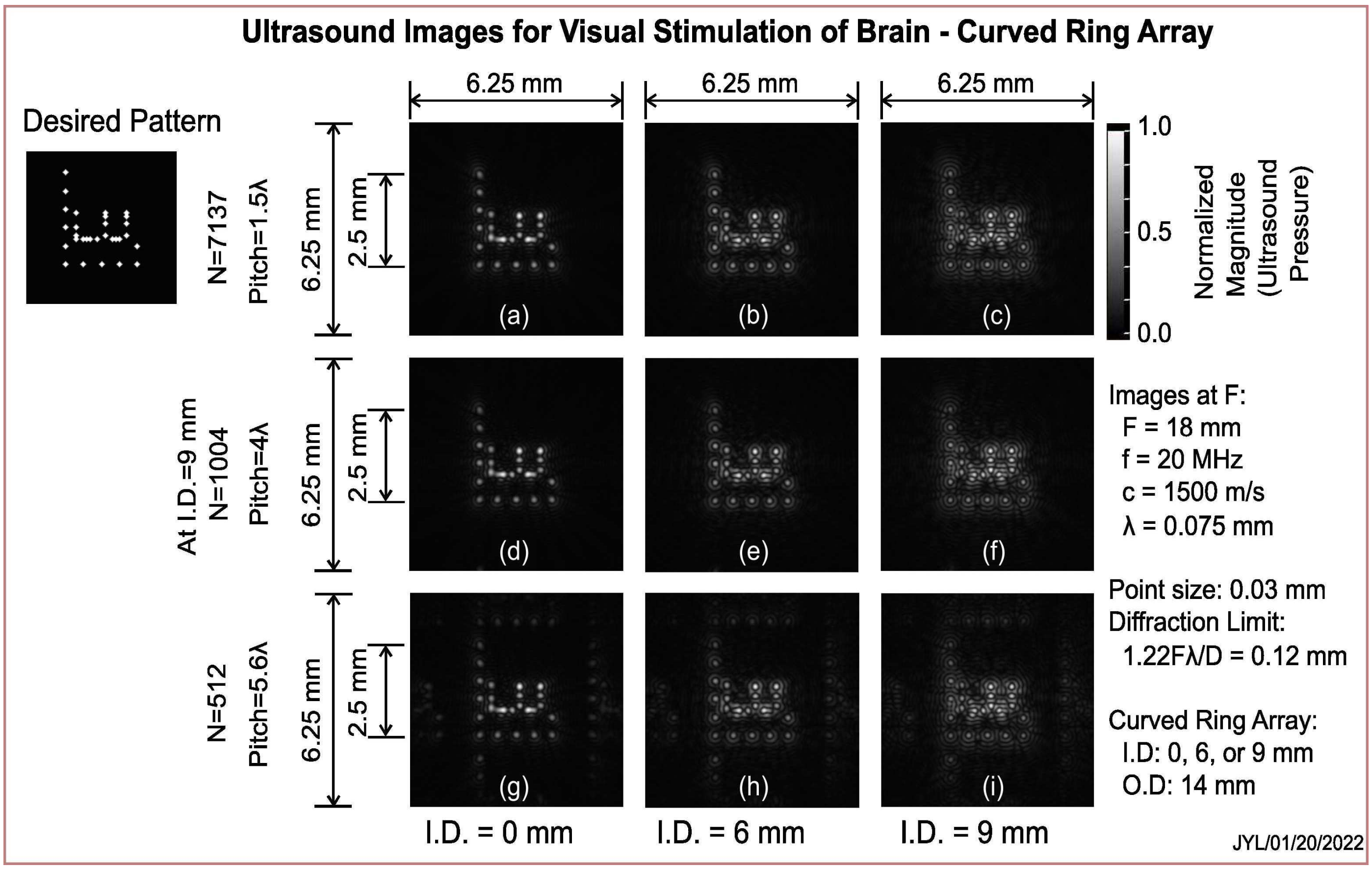

Figure 1. Ultrasound images produced at the retina for visual stimulation of the brain for blind patients to "see" the object on the upper-left corner of the figure. The object is consisting of 30 points with point size of about 0.03 mm (smaller than the wavelength of λ = 0.075 mm). The height of the object is 2.5 mm as indicated. The diffraction limit of the imaging system with the parameters used is estimated as 1.22λF/D = 0.12 mm, where D is the outer diameter (14 mm) and F is the focal length (18 mm) of the curved ring array. In the image panels ((a) to (f)), from left to right, the inner diameters (I.D.) of the curved ring array are 0 mm, 6 mm, and 9 mm, respectively. From top to bottom, the pitch sizes of the array are 1.5λ, 4.0λ, and 5.6λ, respectively. It is seen from the figure that when the pitch is 5.6λ, due to the low spatial sampling rate, aliasing occurred and ghost objects start to appear.

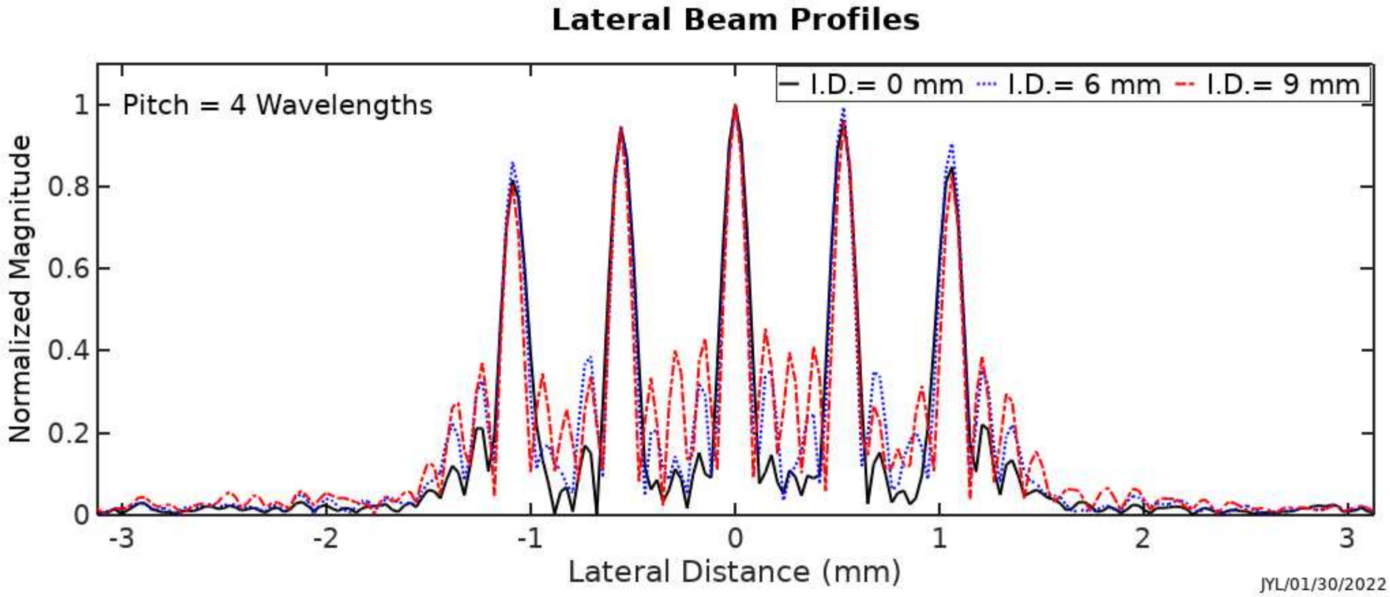

Figure 2. Line plots through the bottom 5 points of the images when the pitch size of the array transducer is 4λ to show image resolution. Black, blue, and red lines are for images obtained with I.D. = 0 mm (Fig. 1(d)), 6 mm (Fig. 1(e)), and 9 mm (Fig. 1(f)), respectively. The full-width-at-half-maximum (FWHM) image resolution estimated from the figure is about 0.147 mm, with Fig. 1(f) having a slightly better resolution but higher sidelobes.

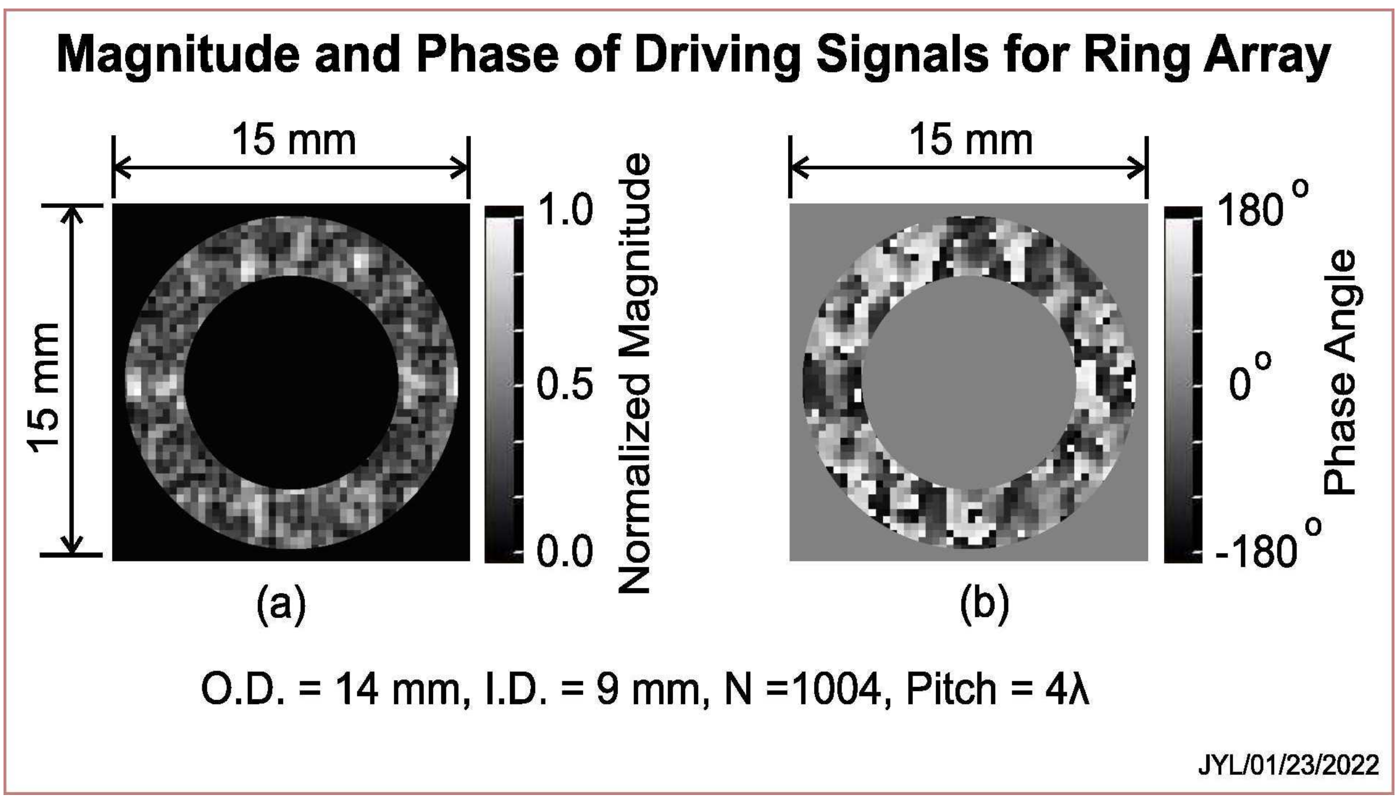

Figure 3. Driving signals for the elements of the curved ring array transducer to produce the image in Fig. 1(f). The O.D. and I.D. were 14 mm and 9 mm respectively. The pitch and the number of elements of the ring array were 4λ and 1004 respectively. (a) Normalized magnitude of the signals for each element. (b) Phase of the signals for each element.

IV. DISCUSSION

From the results, it is seen that as the diameter of the inner ring increases, the quality of ultrasound beam pattern (image) is reduced. However, for animal such as the rabbit, an inner diameter of about 9 mm is necessary to avoid the lens area where the ultrasound attenuation is high and thus heating of the lens may be a risk. Thus, there is a compromise between the image quality and the diameter of the inner ring of the array transducer. Also, because the array transducer has a concave shape, it can be a better fit to the shape of the eyeball and reduce the phase errors when forming the ultrasound beam pattern (image) at the retina, resulting in a reduced number of transducer elements needed since a larger size of the elements of the array transducer can be used. A smaller number of array elements will reduce the complexity of the hardware that is used to drive the transducer since the number of transmitter channels is reduced.

It is worth to note that because the Fresnel approximation [13] is used, the Fourier method used is only suitable for paraxial beam patterns (images). I.e., the quality of images is higher near the beam axis. As the size of image increase, distortions can be seen near the edges of the images.

The images in Fig. 1 were obtained at a flat surface. However, the bottom of the eye at the retina is curved. Since the focal distance of the concave array is fixed, the retina curvature may increase the quality of images near edges [17].

It is noticed that using the Bessel beams and X waves [19] given in Eqs. (25) and (26) of [17], one could design ultrasound beam patterns that will stay in focus within their large depth of field using the method in [23]. Or, using a zeroth-order Bessel beam (n=0 in Eq. (25) of [17]), one could form ultrasound beam patterns by directly adding a shifted version of the beam. However, the high sidelobes of the Bessel beams may reduce the quality of images.

V. CONCLUSION

A high-resolution ultrasound pattern can be produced with a concave 2D ring array transducer for the visual stimulation of the brain. The large pitch (4.0λ) and thus a smaller number of transducer elements can be used because the curvature of the ring array is the same as the focal length of the array. The ring array can avoid the heating of the eye lens that has a high ultrasound attenuation.

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