HIGH-EFFICIENCY FRESNEL ACOUSTIC LENSES

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ABSTRACT

Acoustic Fresnel lenses have emerged in recent years as an alternative to the conventional spherical lenses for focusing sound waves in applications such as acoustic microscopy. Fresnel lenses offer the advantage of near-planar geometry and, therefore, ease of fabrication compared to spherical lenses. The Fresnel acoustic lenses reported so far, however, have the disadvantage of low efficiency; only about 40% of the input signal is directed towards the focus.

In this work the design and fabrication of "binary" acoustic Fresnel lenses that offer much higher efficiencies will be described. These lenses, while being still nearly planar, have multiple phase levels to achieve phase shifts other than 0 and 180 degrees as used in conventional, two phase Fresnel lenses. Acoustic Fresnel lenses were fabricated at frequencies of about 1 MHz and 170 MHz. Measurements of the focusing efficiency and point spread function have been performed to characterize the operation of these lenses. Focusing efficiencies in excess of 80% have been achieved with these lenses. The measurements compare well to theoretical simulations.

INTRODUCTION

Scanning acoustic microscopy (SAM) has been shown to be a useful tool for imaging samples and characterizing mechanical properties of materials.[1] The acoustic lens is perhaps the most important part of a SAM because imaging with good resolution requires a diffraction limited focus. These lenses typically have diameters of a few hundred microns at UHF frequencies and mechanical grinding and polishing are the standard processes used in the fabrication of these lenses. These techniques are time consuming and expensive and alternative methods are desirable to manufacture high quality lenses at low cost. One proposed scheme is to use an isotropic etching technique in crystalline silicon for fabricating spherical lenses.[2] Although this is a batch processing technique that has potential for low cost manufacturing, it requires precision process control which may be difficult to achieve and which would increase the cost of manufacturing. Another method for fabrication of lenses was demonstrated by Yamada, *et. al.*[3-5] In this method near-planar Fresnel lenses were fabricated in quartz substrates using conventional microfabrication processes. Concentric grooves are etched into the substrate to create phase shift of 0° and 180° as the acoustic waves pass through the lens structure which creates a spherically converging wave. The results obtained with these lenses show that this technique has the potential for fabricating good quality lenses with batch fabrication. One drawback of this approach, however, is that the efficiency of these lenses is low, only 41% of the incident sound beam is focused and the remainder of the incident beam is diffracted to unwanted modes.[6]

This work describes the design, fabrication and operation of 4 phase Fresnel acoustic lenses. In higher order Fresnel lenses there are several steps made in the substrate to create several phase shift levels between 0° and 360° The resultant wave profile contains less energy in the unwanted modes. Lenses have been constructed to operate at the frequencies of 1 MHz and 170 MHz. The data obtained with these devices show that focusing efficiencies as high as 80% can be achieved with 4 phase lenses.

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BINARY FRESNEL LENSES

With the advance of guided wave optics and microfabrication technologies, new methods have emerged in recent years to fabricate devices for diffraction optics. These devices are generally termed "binary optics" and are used for several applications ranging from beam focusing to holography.[7-9] It has been shown that Fresnel type focusing lenses can be fabricated for optical applications with efficiencies approaching 100%. These lenses use multiple phase levels to better approximate the phase curvature of a spherically focusing field. It can be shown that the diffraction efficiency, η, of a multilevel diffractive lens is given by[8]

$$\eta = \left[\frac{Sin(\pi/N)}{(\pi/N)} \right]^2 \qquad (1)$$

where N is the number of phase levels. These lenses are fabricated using subsequent masking and etching steps. 2^n phase levels may be achieved for n masking steps. For example, only 3 masks are needed to realize 8 phase levels with an efficiency of 95%.

The radius of the kth phase step is given by[7]

$$r_k = \left[\left(z_o + k\frac{\lambda}{N} \right)^2 - z_o^2 \right]^{0.5} \qquad (2)$$

where z_o is the focal length and λ is the wavelength. The step size between subsequent phase levels is given by[7]

$$h = \frac{1}{Nf(1/v_l - 1/v_s)} \quad (3)$$

where f is the frequency and v_l and v_s are the velocity of sound in the liquid and the solid, respectively. Fig.1 shows the structure of a 4 phase Fresnel lens. It should be noted that that the step height produces a phase delay of 2π/N. For a 4 phase Fresnel lens this phase delay angle is π/2.

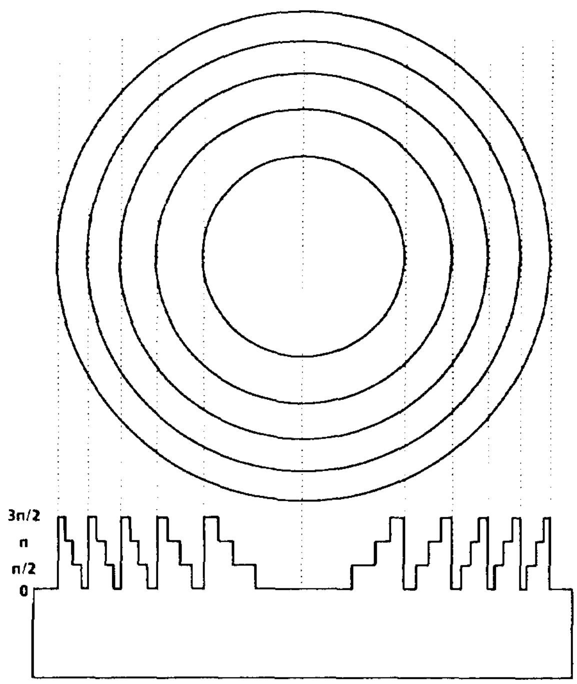


Fig. 1. Diagram of a 4 phase Fresnel lens

1 MHz FRESNEL LENSES

To test the feasibility of higher order Fresnel lenses, we first built lenses to operate at a relatively low frequency of 1 MHz. Table I shows the important characteristics of these lenses. The grooves in the aluminum base plate were made by using a precision grinding tool. Eqn 2 was used to determine the radii of curvature of the grooves. The narrowest grove width was 0.9 mm and each step was 0 5 mm high with a total lens thickness of 1.5 mm. 2 Phase Fresnel lenses with similar characteristics were also fabricated to make a comparison of the relative efficiencies. Fig. 2 shows the setup used to measure the efficiency of these lenses. The acoustic waves generated from the lens under test were detected by a spherical lens which is positioned such that the transmitting and receiving lenses are confocal. The received signal was measured as a function of the acoustic frequency. The values plotted in Fig. 3 for both 2 and 4 Phase lenses account for all other losses in the measurement system. These other losses are the one-way conversion loss of the receiving lens, the losses in the aluminum rod and water path, and the transmission loss from aluminum to water. It can be seen that the efficiency of the 4 phase lens is close to the theoretically predicted value of 80% and it is significantly better than the 2 phase lens efficiency.

Lens Material	Aluminum
Frequency	1 MHz
Substrate Thickness	15 cm
Transducer	PZT Plate
Transducer Diameter	5 cm
Lens Diameter	5 cm
Focal Length	5 cm
Smallest Ring Width	.9 mm
Step Height	0.5 mm

Table I. Parameters of 1 MHz Fresnel Lens

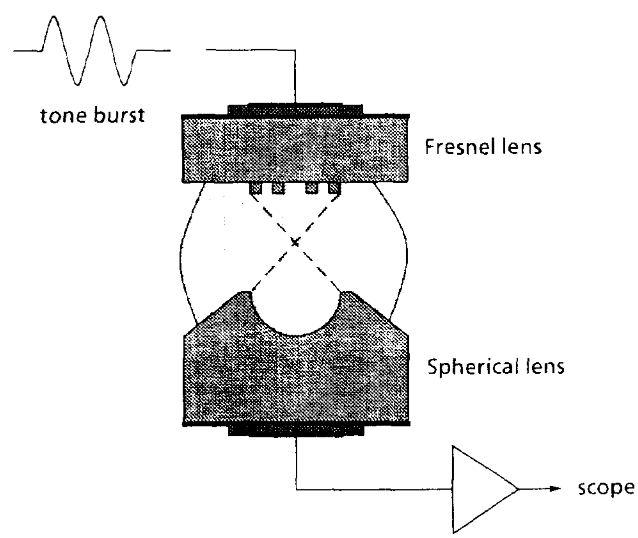


Fig. 2. The experimental setup used for measurements

4 PHASE FRESNEL LENSES AT UHF FREQUENCIES

We have also fabricated lenses to operate at UHF frequencies where the dimensions of the lenses can be measured in the micron scale and conventional IC fabrication techniques can be used to fabricate the lenses. Table II lists the parameters of the Fresnel lenses designed to operate around 170 MHz. The grooves were fabricated in the silicon substrate using a Reactive Ion Etching (RIE) process to obtain side walls as vertical as possible. The smallest dimensions of the lenses are a 5 μm groove width and a 2.7 μm step height. An SEM micrograph of a 4 phase lens is shown in Fig. 4. Two phase Fresnel lenses were also fabricated to make a comparison to the 4 phase lenses.

The measurements of focusing efficiency and focal plane field distribution were performed using a setup similar to the 1 MHz experiment. Fig. 5 displays the efficiency of the lenses as a function of the frequency after subtracting the system losses as in the 1 MHz case above. Also plotted in Fig. 5 is numerical calculations of the efficiencies of these lenses as a function of frequency. The numerical technique uses the dual

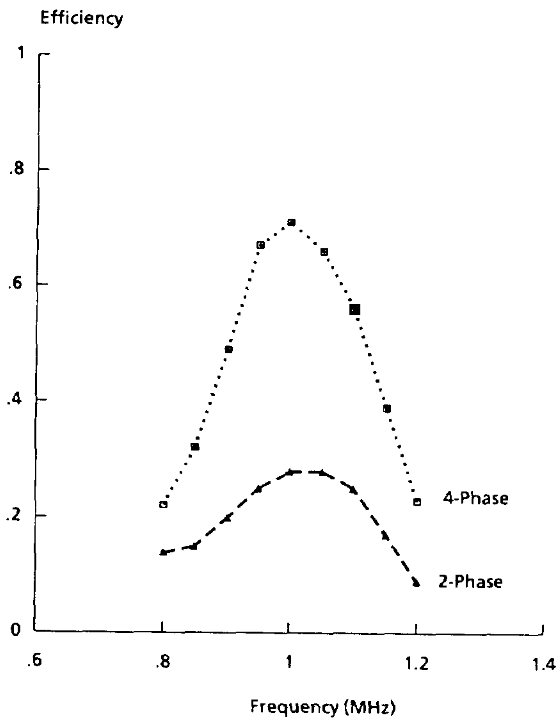
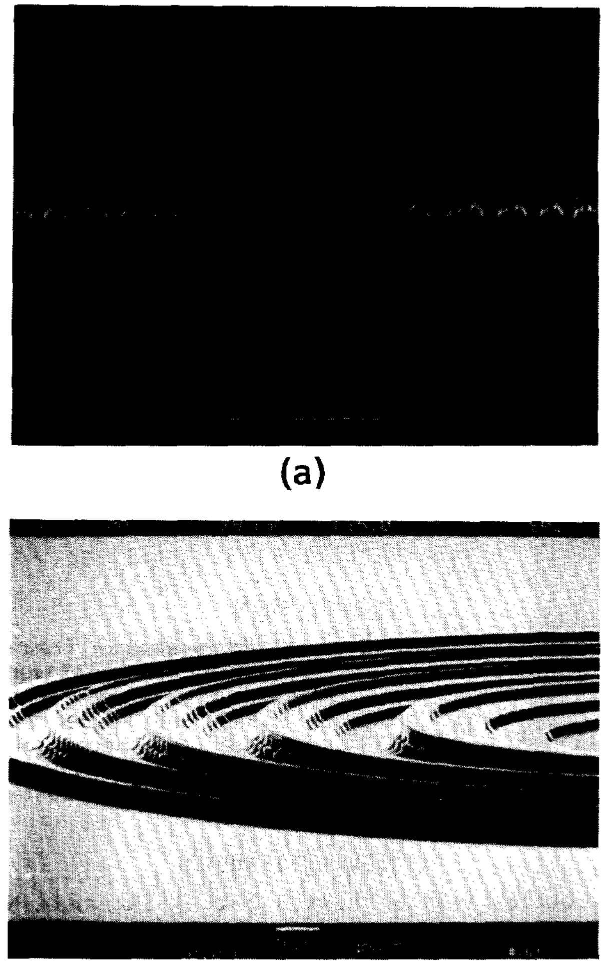


Fig. 3. Measured efficiency vs frequency for 2 and 4 phase lenses at 1 MHz

Lens Material	<111> Silicon
Frequency	165 MHz
Substrate Thickness	1.4 mm
Transducer	Thin-film ZnO
Transducer Diameter	300 μm
Lens Diameter	300 μm
Focal Length	300 μm
Smallest Ring Width	5 μm
Step Height	2.8 μm

Table II. Parameters of 170 MHz Fresnel Lens

Hankel transform technique for calculation of the focusing eficiency. Again, the measured conversion efficiencies are close to the theoretical values within the noise level of the experiment. Plotted in Fig. 6 is the relative intensity of the received signal as the receiving lens is translated along the focal plane of the transmitting lens. The full-width at half maximum of the signal is 17 μm which is approximately twice the wavelength at 170 MHz. It should be noted that the detected signal in this experiment should be the convolution of the point spread functions of the two lenses. The data in Fig. 6 shows that the Fresnel lens focuses the signal to a diameter less than 2 λ. An independent measurement of the point spread function of the receiving lens will be performed to predict the Fresnel lens charecteristics more accurately from Fig. 6


(a)

(b)

Fig. 4. (a) and (b) Scanning electron micrographs of a 4 phase silicon Fresnel lens

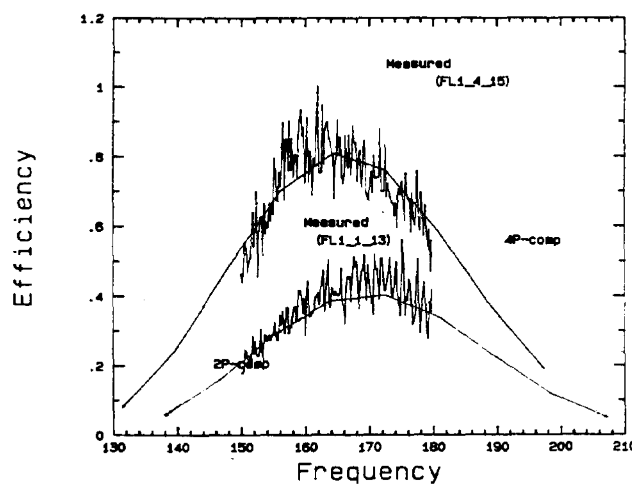


Fig 5. Measured efficiency vs frequency for 2 and 4 phase lenses at 170 MHz

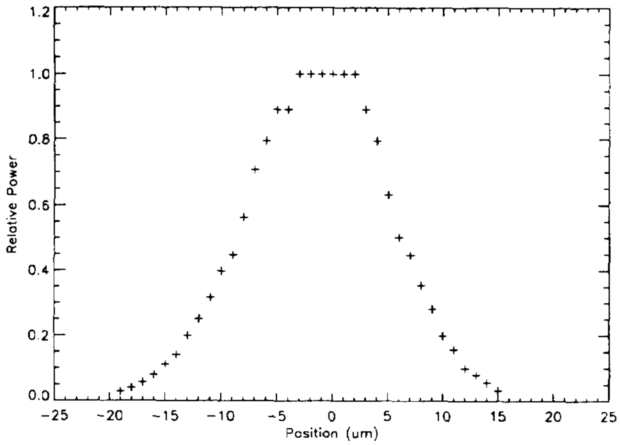


Fig. 6 Received signal vs receiving lens position for the 4 phase Fresnel lens

CONCLUSION

We have developed 4 phase binary acoustic Fresnel lenses to operate at UHF frequencies. The lenses were fabricated in crystalline silicon using a simple 2-mask microfabrication technique. The focusing efficiency of these lenses is near 80% and is close to the theoretically predicted value. The efficiency is a factor of two better than the value for 2 phase Fresnel lenses as anticapated from theory.

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