Energy Focusing Efficiency Estimation of a Multi-Level Fresnel Lens Through Surface Profile

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Received: January 02, 2018; Accepted: November 26, 2018

Abstract

A high focusing efficiency of a multi-level Fresnel lens is desired when it is designed and manufactured. How to determine the focusing efficiency becomes a problem after the Fresnel lens is fabricated. A method to estimate the focusing efficiency of the Fresnel lens basing on its surface profile is proposed. Hence, the profile of Fresnel lens fabricated shows how similar with the profile designed, which has been theoretically predicted a maximal focusing efficiency such as 40.5% and 81% for a two-phase and four-phase level Fresnel lenses, respectively. This calculation method can be applied to estimate the focusing efficiency of any surface profile of Fresnel lenses fabricated without a direct measurement of focusing efficiency. The focusing efficiency of a four-phase level Fresnel lens designed to operate at a frequency of 100 MHz of an ultrasonic ejector, which was fabricated by a two-mask process using SU-8 photoresist, approximate 60% is illustrated.

Keywords: Fresnel lens, Ultrasonic, Energy focusing efficiency.

1. Introduction

Ultrasonic ink jet printing technologies have been used to produce photographic quality prints that satisfy the demands for fine solution, high speed and more reliability of low-cost printers. Ultrasonic ejector can eject small droplets of controlled diameter from the free liquid surface by focusing high-frequency acoustic waves without nozzles, and therefore, it is favorable in fabricating print-heads. In which, ultrasonic focusing lens, which are the key components to be developed and incorporated into a novel printing system to construct a complete acoustic inkjet print-head, takes charge of focusing ultrasound generated by a piezoelectric transducer for droplet ejection. Recently, various types of ultrasonic focusing lens were investigated and fabricated such as spherical lens, reflection wall [1-3], Fresnel lens [4-7], self-focusing acoustic-wave liquid ejector [8], and a new type of lens using air as acoustic reflector which required no tight thickness control for effective focusing [9], etc.. Fresnel lenses offer advantages of planar geometry and relative ease of fabrication over other forms of the lenses. However, the geometry is critical for efficient focusing, and thus tight control of the thickness of lens elements is usually required. The design and fabrication of "binary" acoustic Fresnel lenses which use multiple-phase levels to approximate the curvature of a spherical focusing field offer high efficiencies, were carried out. Fabrication of two- and four-phase level Fresnel lenses with an operation frequency of 1 and 170 MHz, and measurement of focusing efficiency was presented. They showed that focusing efficiencies of 170 MHz two- and four-phase level Fresnel lenses are close to the theoretical values, which are about 40 and 80%, respectively. Meanwhile, the focusing efficiency of 1 MHz 4 phase Fresnel lens is significantly better than the 2 phase lens due to it can reach the theoretically predicted value of 80% [5]. [10] proposed a finite element analysis of multilevel acoustic Fresnel lens. They indicated that a high focusing efficiency about 81% is obtained for a Fresnel lens with a number of phase levels larger than four [10]. An efficiency analysis of diffractive optical lenses is reported by [11]. They proposed that the efficiency should be calculated as a weighting sum of the contributions from each region of the lens [11].

To improve the focusing efficiency of ultrasound energy, some methods to manufacture the Fresnel lens, such as two-mask, three-mask fabrication process with/without SiO_2 hard mask, using positive/negative photoresist (PR) have been developed. In this study, the surface profile of a four-level Fresnel lens working at a frequency of 100 MHz, which was fabricated by a two-mask process using SU-8 PR without SiO_2 hard mask, is used for an approximation calculation of focusing efficiency.

2. Fabrication of Fresnel lens

2.1. Fabrication process of Fresnel lens

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For focusing ultrasound at the focal plane of the lens, the parameters of Fresnel lens are related to the phase level number, working frequency, and sound velocity in the coupling medium and the lens substrate. In this study, a 100 MH_z four-phase level Fresnel lens was designed and manufactured from the silicon wafer. Therefore, the step height and maximal radial distance of the lens are h = 4.55 and r_{max} = 244 µm, respectively [12]. Since the designated parameters, the focusing lens includes four regions, in which 4-phase levels existed in each region, and it is illustrated in Fig. 1.

In this study, a feasible fabrication of Fresnel lens using two masks associated with two etching steps was proposed. A two-mask fabrication process employing SU-8 in the lithography was applied with the purpose of addressing the difficulty of non-uniform photoresist coverage because of the high aspect ratio (ratio of the feature height to its width) of the lens. The fabrication processes of acoustic focusing lens are carried out by two cycles corresponding to two different masks. In the first cycle fabrication processes, the Si substrate is etched with the depth of 2h, where h is the step height of Fresnel lens. And then, the wafer is aligned and exposed with 2^{nd} mask and repeated the same processes with the depth of Si etching h in the second cycle.

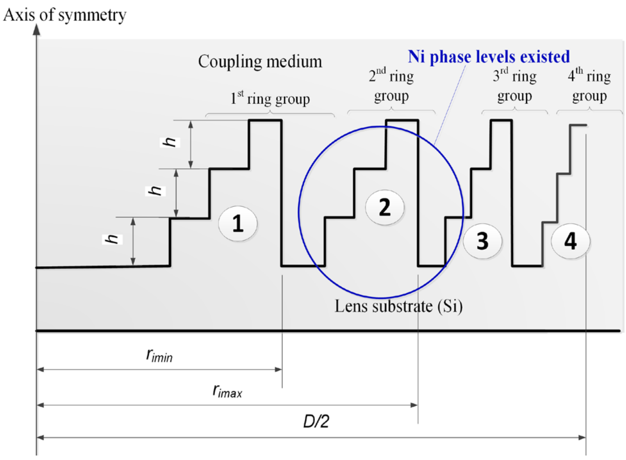

Fig. 1. Designated profile of Fresnel lens; h denotes step height; D is diameter of the Fresnel lens.

2.2. Achievable result analysis

A high focusing efficiency of the Fresnel lens is expected. However, this paper presents an estimation of the efficiency basing on data of surface profile measurement. In general, focusing efficiency, which is also called the first-order diffraction efficiency, of an N-phase-level Fresnel lens can be theoretically predicted as

$$\eta_N = \left[\frac{\sin(\pi / N)}{\pi / N} \right]^2 \quad (1)$$

This equation is used to predict the ideal value of the efficiency. However, there are several factors, which affect the efficiency, must be considered in the calculation because it may lead to a lower total efficiency. In which, errors in the fabrication process may contribute a major reduction of the efficiency. In additions, the losses when passing through the Fresnel lens, the medium, etc. will also result in a lower overall efficiency.

Besides, the total efficiency should be considered as a weighting sum of local efficiencies of each region constructing the lens because the number of phase levels existed in these regions may differ from the design. If the influence of lateral dimension of surface profile is only taken in account, the efficiency can be written as [11]

$$\bar{\eta} = \sum_{N_i} \gamma_{N_i} \eta_{N_i} \quad (2)$$

where, γ_{N_i} and η_{N_i} are the weighting coefficient and the efficiency of a region that N_i phase levels existed, respectively.

Assuming plane-wave transmission through the lens, the contribution of each region N_i phase levels existed is given by the relative area of the lens. So, the efficiency coefficient can be calculated by equation as follows [11]

$$\gamma_i = \frac{\int_{r_{i\min}}^{r_{i\max}} r dr}{\int_0^{D/2} r dr} = \frac{4}{D^2}\left(r_{i\max}^2 - r_{i\min}^2\right) \quad (3)$$

where $r_{i\max}$ and $r_{i\min}$ bound the region N_i phase levels existed; D is diameter of the lens. Basing on the designated parameters, the limitation and weighting coefficient of each region of the lens are listed in Table 1.

Table 1. Parameters of N_i phase levels existed-regions of a Fresnel lens.

	Region 1	Region 2	Region 3	Region 4
r_{min} (µm)	0	119.40	170.10	209.8
r_{max} (µm)	119.4	170.10	209.80	244
γ_i	0.24	0.25	0.25	0.26

Errors in fabrication process may determine the number of phase levels existed in each region. And it will also affect the local focusing efficiency. Hence, the local efficiencies of a four-, three-, and two-phase level regions estimated by Eq. (1) are about 81, 68, and 40.5%, respectively.

To get a more accuracy efficiency, the influence of the etching depth is needed to account. To be convenient in calculation, we consider the "cross-section area" of each valley covered by the surface profile is cross-section area of the region N_i phase level existed. We propose a new coefficient i_i defined as a ratio of cross-section area of the region of fabricated surface profile and the corresponding area of the designated surface profile. Hence, i_i is called as an identity coefficient.

$$i_i = \frac{A_{i-fab}}{A_{i-des}} \quad (4)$$

$$\text{Or } i_i = \frac{A_{i-des}}{A_{i-fab}} \quad (5)$$

where, $A_{i\text{-}des}$ and $A_{i\text{-}fab}$ denote the cross-section area of the i^{th} designated and fabricated regions, respectively. Hence, the overall efficiency can be written as

$$\overline{\eta} = \sum_{N_i} i_i.\gamma_{N_i}.\eta_{N_i} \quad (6)$$

In actual fabrication, the profile of Fresnel lens may include 4-phase level in all 4 regions of the surface profile or 2-, 3- phase level in the outermost regions. For convenience in a comparison of the surface profile of fabricated Fresnel lens and the expectation value, we may classify some achievable results in the fabrication as follows.

2.2.1. Four-phase level in the whole surface profile of Fresnel lens

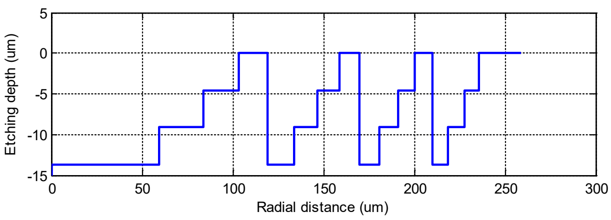

Fig. 2. Four-phase level in the whole surface profile of Fresnel lens

This is the ideal case when the whole surface profile of Fresnel lens is shaped with four-levels. Fig. **2** illustrates an achievable profile of the lens in this case. In fact, there are many factors that may affect the fabrication process and its surface profile. However, if the ideal profile can be made, we can easily see that the focusing efficiency can reach the maximal value. The identity coefficient i_i will become 1 if the fabricated profile is the same as the ideal one. In the fabrication process, some errors are always existed, so the measurement of cross-section area is still needed. The focusing efficiency can be expressed as:

$$\overline{\eta} = \sum_{N_i} i_i.\gamma_{N_i}.\eta_{N_i} = 0.81 * \sum_{N_i} i_i.\gamma_{N_i} \quad (7)$$

Obviously, if the fabricated profile is the same as the ideal profile, Eq. (7) becomes:

$$\overline{\eta} = 0.81 * \sum_{N_i} i_i.\gamma_{N_i} = 0.81 * 1 * \sum_{N_i} \gamma_{N_i} = 0.81 * 1 * 1 = 0.81 \quad (8)$$

2.2.2. Four-phase level in the innermost region, three-phase level in the other regions of the surface profile of Fresnel lens

The largest feature size is in the center area of Fresnel lens. Thus, obtaining a 4-phase level is easier than other regions. Hence, the three outer regions of the profile of the fabricate Fresnel lens may not exist with 4-phase level. The three-phase level obtained in these regions, which is illustrated in Fig. **3**. Therefore, the focusing efficiency can be considered as:

$$\overline{\eta} = \sum_{N_i} i_i.\gamma_{N_i}.\eta_{N_i} = 0.81 * i_1\gamma_1 + 0.68 * \sum_{N_i} i_i.\gamma_{N_i} \quad (9)$$

For an ideal profile, the efficiency can be estimated as:

$$\begin{aligned} \overline{\eta} &= 0.81 * 1 * \gamma_1 + 0.68 * 1 * \sum_{N_i} \gamma_{N_i} \\ &= 0.81 * 0.24 + 0.68 * (0.25 + 0.25 + 0.26) \quad (10) \\ &= 71.1\% \end{aligned}$$

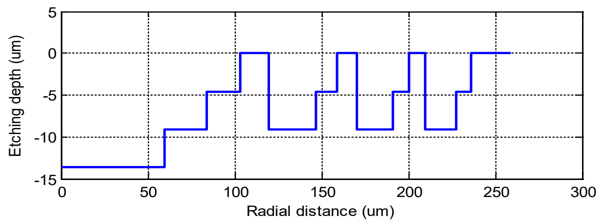

Fig. 3. Four-phase level in the innermost region, three-phase level in the other regions of the surface profile of Fresnel lens

2.2.3. Two-phase level in the whole surface profile of Fresnel lens

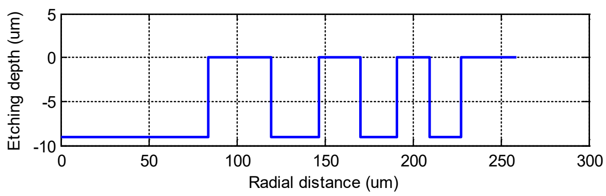

Fig. 4. Two-phase level in the whole surface profile of Fresnel lens

In the fabrication process of Fresnel lens, after the first etching completed, the surface profile can be obtained as shown in Fig. **4**. For some reasons that the second etching is not successful or cannot be made, so the surface profile is considered as a two-phase level. The calculation of focusing efficiency is much easier, but it is lower than other kinds of profile. In this case, the focusing efficiency can be considered as:

$$\bar{\eta} = \sum_{N_i} i_i \cdot \gamma_{N_i} \eta_{N_i} = 0.41 * \sum_{N_i} i_i \cdot \gamma_{N_i} \quad (11)$$

For an ideal profile, we can get the efficiency as

$$\bar{\eta} = 0.41 * 1 * \sum_{N_i} \gamma_{N_i} = 0.41 * 1 * 1 = 41\% \quad (12)$$

2.2.4. Four-phase level in the two innermost regions, 3-phase level in the two outermost regions of the surface profile of Fresnel lens

As known, the etching rate depends on feature size and etching depth of a pattern. A larger feature size will result in a larger etching rate; it may cause a deeper trench when compare with another smaller feature in the same pattern. The situation will also occur when the Fresnel lens is fabricated. Hence, a larger etching rate and deeper trenches can be formed in the regions 1 and 2 because their larger feature sizes in comparison to other regions. The achievable surface profile can be shaped including a four-phase level in the two innermost regions and 3-phase level in the two outermost regions. An illustration of this case is shown in Fig. **5**. The focusing efficiency can be considered as:

$$\bar{\eta} = \sum_{N_i} i_i \cdot \gamma_{N_i} \eta_{N_i} = 0.81 * (i_1\gamma_1 + i_2\gamma_2) + 0.68 * \sum_{N_i} i_i \cdot \gamma_{N_i} \quad (13)$$

For an ideal profile, the efficiency can be calculated as:

$$\bar{\eta} = 0.81 * (0.24 + 0.25) + 0.68 * (0.25 + 0.26) = 74.37\% \quad (14)$$

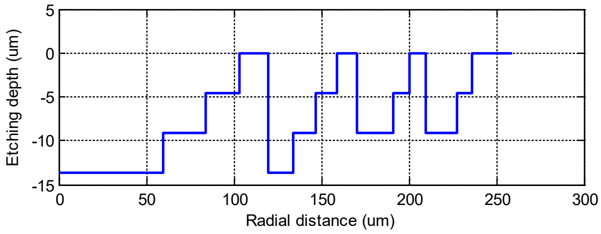

Fig. 5. Four-phase level in the two innermost regions, 3-phase level in the two outermost regions of the surface profile of Fresnel lens

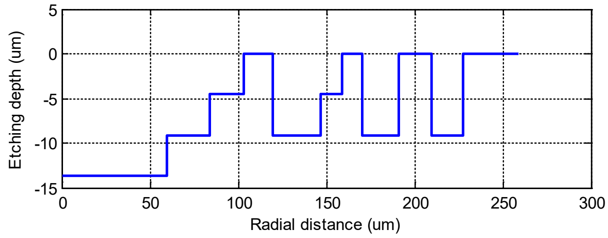

Fig. 6. Four-phase level in the innermost region, 3-phase level in the second region, 2-phase level in the two outermost regions of the surface profile of Fresnel lens

2.2.5. Four-phase level in the innermost region, 3-phase level in the second region, 2-phase level in the two outermost regions of the surface profile of Fresnel lens

Similar with reasons analyzed above, an achievable profile of the lens fabricated may include a four-phase level in the innermost region, 3-phase level in the second region, and 2-phase level in the two outermost regions. Fig. **6** shows a surface profile of the lens in this case. Thus, the focusing efficiency can be estimated as:

$$\bar{\eta} = \sum_{N_i} i_i \cdot \gamma_{N_i} \eta_{N_i} = 0.81 * i_1\gamma_1 + 0.68 * i_2\gamma_2 + 0.41 * \sum_{N_i} i_i \cdot \gamma_{N_i} \quad (15)$$

For an ideal profile, we can write:

$$\bar{\eta} = 0.81 * 1 * 0.24 + 0.68 * 1 * 0.25 + 0.41 * 1 * (0.25 + 0.26) = 57.35\% \quad (16)$$

2.2.6. Four-phase level in the innermost region, 3-phase level in the second region, 2-phase level in the third region, and no phase level existed in the outermost region of the surface profile of Fresnel lens

A worse situation for the fabrication if the four levels Fresnel lens is only manufactured with a four-phase level in the innermost region, 3-phase level in the second region, 2-phase level in the third region, and no phase level existed in the outermost region, which is illustrated in Fig. **7**. It will result in a lower focusing efficiency than expectation. The focusing efficiency can be determined as:

$$\bar{\eta} = \sum_{N_i} i_i \cdot \gamma_{N_i} \eta_{N_i} = 0.81 * i_1\gamma_1 + 0.68 * i_2\gamma_2 + 0.41 * i_3\gamma_3 \quad (17)$$

For an ideal profile, the efficiency can be estimated as:

$$\bar{\eta} = 0.81 * 1 * 0.24 + 0.68 * 1 * 0.25 + 0.41 * 1 * 0.25 = 46.69\% \quad (18)$$

3. Results and disscution

The Fresnel lens has been fabricated by applying a two-mask process using SU-8 PR. The surface profile and the SEM (Fig. **8**) of the lens have been measured to evaluate the fabrication quality. Fig. **9**(b) illustrates the surface profile of the fabricated lens, which is placed together with the designated profile to make a comparison. Hence, the four-phase level is not formed in the two outermost regions, it can be explained that the etching rate in these regions is smaller than the inner regions because of their smaller trench widths. This phenomenon can be called the "loading effect" [13] when a deep etching taken in regions with different widths. Therefore, the fabricated profile of the Fresnel lens can be considered as it includes two regions with 4-phase levels and two others with 3-phase levels corresponding to regions 1, 2, 3, and 4, respectively. In additions, the "cross-section area" is considered to compare with the relative designated one. And, the identity coefficients, therefore, are also estimated. These paramters are listed in Table 2.

As mentioned in the achievable results section, the ideal efficiency can approach 74%. In comparison with the ideal efficiency, the identity and weighting coefficients of the fabricated lens are determined basing on the measurement data of surface profile. Hence, the boundary of each region is determined by two parameters, which are r_{i_min} and r_{i_max}. Table 3 shows the weighting coefficients determined from experiment data.

And therefore, the focusing efficiency is estimated by following expression:

$$\bar{\eta} = \sum_{N_i} i_i.\gamma_{N_i}\eta_{N_i} = (0.96*0.2279+0.76*0.2546)*0.81$$
$$+(0.78*0.2489+0.74*0.2668)*0.68 = 0.6002 \approx 60\%$$

This value is much smaller than that of the ideal profile, which is about 74.4%. It is easy to understand because of the fabrication errors resulted from the fabrication process as mentioned in the previous sections.

Table 2. Cross-section areas of designated and fabricated profile of Fresnel lens

	Region 1	Region 2	Region 3	Region 4
Designated Area(μm^2)	1.123*10^3	369.14	232.91*	198.48*
Fabricated Area (μm^2)	1.17*10^3	281.9	182.7	147.15
Identity coefficient γ_i (%)	96	76.37	78.45	74.14

*) areas calculated from 3 levels only

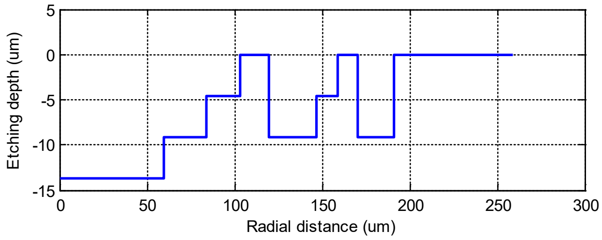

Fig. 7. Four-phase level in the innermost region, 3-phase level in the second region, 2-phase level in the third region, and no phase level existed in the outermost region of the surface profile of Fresnel lens.

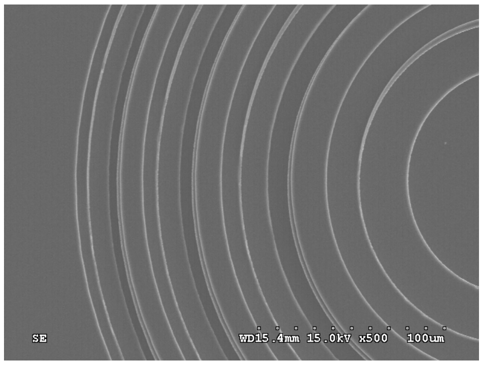

Fig. 8. Fresnel lens fabricated by a two-mask process using SU-8 PR

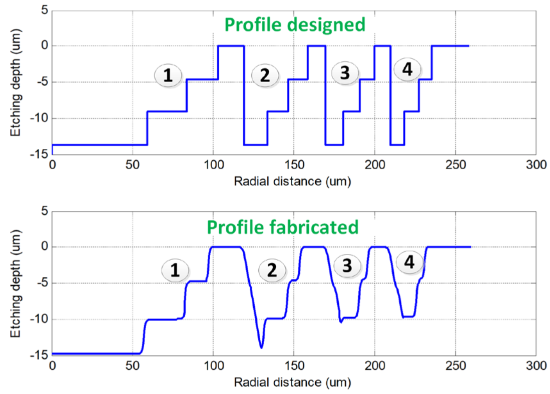

Fig. 9. Designated and fabricated profile of 4-phase level Fresnel lens

Table 3. Weighting coefficient of each region of the fabricated lens

	Region 1	Region 2	Region 3	Region 4
$r_{i\ min}$ (μm)	0	116.47	169.01	207.72
$r_{i\ max}$ (μm)	116.47	169.01	207.72	243.46
Weighting coefficient i_i (%)	22.79	25.46	24.89	26.68

4. Conclusion

The achievable energy focusing efficiency of a four-phase level Fresnel lens has been analized through its surface profile. Experimental estimation of focusing efficiency of a 100 MHz four-phase level Fresnel lens of an ultrasonic ejector, which was fabricated by a two-mask process employing SU-8 PR, approximate 60% is illustrated. The estimation is used to investigate the influence of a multi-level Fresnel lens geometry on its focusing efficiency, in which the ideal efficiency is calculated basing on the scale theory for optics.

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