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Amplitude and phase apodization caused by focusing light through an evanescent gap in SIL recorders

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ABSTRACT

High numerical aperture(NA) vector diffraction theory is used to analyze a near field optical system using a solid immersion lens (SIL). The amplitude and phase of the transmitted light through the system changes as a function of the air gap height as well as indices of refraction, incident angle, etc. We call these "amplitude apodization" and "phase apodization". The characteristics of those are done using supergaussian form. The effects of amplitude and phase apodization on irradiance are investigated for various index of refraction and air gap height.

Keywords: apodization, gap-induced aberration, evanescent coupling, characteristics, etc

1. Introduction

In optical systems the apodization of amplitude and phase degrades system performance. Phase apodization is called aberration. The focused spot-size in the recording media increases when aberrations are introduced. The peak intensity of the focused spot is also decreased by the aberrations. Amplitude apodization also decreases the peak intensity of the focused spot. Previously, we have shown the characteristics of phase apodization in solid immersion lens(SIL) systems and their effects on system performance.[1]

In this paper, we investigate the characteristics of amplitude apodization in SIL-systems. The origin and effect of the phase apodization is also studied in conjunction with amplitude apodization.

2. Theory

In SIL-systems, there is an air gap ($n_2 = 1$) between the SIL and the recording media, as shown in Fig. 1. The focused light wave is transmitted from the high index SIL to the low index air by evanescent coupling. The spot size is governed by λ/NA_{eff}, where NA_{eff} is,

$$NA_{eff} = n_{SIL} \sin\theta_m \qquad \textbf{(1)},$$

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where n_{SIL} is the index of the SIL and θ_m is the marginal ray angle emitted from the exit pupil. From Eq. (1) it can be seen that the spot size decreases with increasing SIL index as well as increasing marginal ray angle.

According to diffraction theory, the focused electro-magnetic field can be represented as a linear summation of electro-magnetic plane waves emitted from the exit pupil. By definition, the focused electro-magnetic field is the *amplitude point spread function* (APSF) of the system. Therefore the APSF can be represented as a linear sum of plane waves. In this model the plane waves making up the APSF do not just interact with the air. The plane waves interact with the air, the SIL, the disk substrate and the thin film stack on the substrate, which are together considered as thin film structure. This thin film structure is called "the system". Therefore the plane waves reflect and transmit through the system according to Fresnel's equations in p- and s- directions. Thus the effects of polarization and thin films are considered.

The direction cosine Fourier transform of the APSF, including the effects of the system, is the "*illumination system transfer function*" (ISTF). Therefore the ISTF at the exit pupil includes characteristics of the thin film.[2] The phase of ISTF is affected by the air gap height. This is called the phase apodization, or gap-induced aberration, due to the change of the phase by the air gap height. It is one kind of the instrumental aberration discussed by Chipman.[3] Here we extensively include the effects of gap induced aberration, even into the total internal reflection(TIR) region. The amplitude of the ISTF is also affected by the thin film character. This effect is called amplitude apodization.

The gap-induced aberration is also explained by the plane waves interacting with thin film structure as shown in Fig. 2. The initial phase of plane wave, ϕ_1 changes phase ϕ_3. The phase difference $\Delta\phi = \phi_3 - \phi_1$ is the aberration introduced by gap height. It is dependent upon the polarization state, index of refraction of materials (*n*), and the gap height(*h*). Mathematically, the complex phase of the transmission coefficient explains the phase apodization as shown in Eq. (2).

$$t = \frac{E_t}{E_i} = \frac{E_o' e^{i\phi_3}}{E_o e^{i\phi_1}} = t(\alpha, \beta, n_1, n_2, n_3, h) \qquad \textbf{(2)}$$

where E_t is the transmitted field and E_i is the input field. The transmitted field coefficient, t is dependent upon polarization state and the index of refraction of each layer, gap height, wavelength, etc.

The gap-induced aberration exits in the angular spectrum of the ISTF, not on the image plane. Figure 3 (a) explains that the electric field at the image plane is expressed as the form of $A(x, y, z) \exp[i \times \Phi(x, y, z)]$. Here, the phase distribution, $\Phi(x, y, z)$ is not a gap-induced aberration. In Fig. 3 (b), the electric field of the ISTF is expressed as $A'(\alpha, \beta, \gamma) \exp[i \times \Phi'(\alpha, \beta, \gamma)]$, where $\Phi'(\alpha, \beta, \gamma)$ is the gap-induced aberration, because of its dependency on angular space variables. The image distribution is found by convolution of Fourier transform of $A'(\alpha, \beta, \gamma)$ and the Fourier transform of $\exp[i \times \Phi'(\alpha, \beta, \gamma)]$.

3. Characteristics of apodization

3.1. Characteristics of amplitude apodization

Changes in the amplitude of the ISTF due to system variables are called amplitude apodization. Each profile of amplitude apodization in p- and s- direction is shown for h = 100nm and n = 2.38 in Fig. 4. P-(solid line) and s-profile(dashed line) is shown. Profiles of the amplitude apodization in s-direction are investigated versus index of refraction and air gap width. S-profiles are fitted into a convenient mathematical form, called the "supergaussian ", to within maximum rms error of 1.6 %. The rms is the difference value between the original amplitude apodization and the fitted one. The supergaussian is explicitly,

$$f(\alpha,\beta) = A\exp[-(\alpha,\beta)/R]^{2N} \quad (3)$$

where A is the amplitude, R is the width, N is the shape factor. For example N = 1 results in f(α, β) having a gaussian shape in the pupil. α and β, represent the direction cosines in p-direction and s-direction of the pupil, respectively. In our example, NA_{air} is 0.7. Figure 5 displays the relevant relationship between R and A. The index of refraction varies from 1.5 (glass) to 3.1(GaP). The gap height varies from 0 to 300nm. The value of A ranges from 0.1 to 0.6 as shown in Fig. 6(a). The value of A increases as h increases for a given n. For values of n equal to or greater than 2.4 A increases linearly as h increases. The value of R ranges from 0.55 to 0.4, as shown in Fig. 6(b). The value of R decreases as h increases for a given n. For values of n equal to or greater than 2.4 R decreases linearly as h increases. The value of N ranges from 1.4 to 2.3 , as shown in Fig. 6(c). The value of N increases non-linearly for n less than 2.4. For values of n equal to or greater than 2.4, N decreases. The rms values for fitting errors are displayed in Fig.6(d). The rms value of the amplitude apodization fitting is less than 1.6%.
However, supergaussian is not good function for p-profile of amplitude apodization, as shown in Fig. 4, It behaves differently from supergaussian form.

3.2. Characteristics of phase apodization

Two dimensional distribution of the gap-induced aberration is also investigated versus n and h. Like the amplitude data, each phase profile is also fitted to the supergaussian form within maximum rms error of 2 % of λ. Therefore, the shape of the gap-induced aberration is well characterized by a supergaussian over a wide range of n and h. The A value has range of 0.1 to 0.6λ in p-profile and 0.1 to 0.4λ in s-profile, as shown in Fig 7. The A value increases as n or h increases. The A value is larger in p-direction than in s-direction. R and N values are well characterized.[1]

4. Spot width(FW1/e^2) and peak irradiance

Figure 8 shows spot width(FW1/e^2) in p- and s-direction. Amplitude-only apodization effects are displayed by dashed line. Amplitude and phase apodization are showed by solid line. The phase apodization affects significantly spot size in p-direction as shown in Fig. 8(a). Phase apodization does not affect the spot size in s-direction seriously. Maximum spot width is 0.6μm in p-direction for amplitude-only apodization case. Maximum spot width is 1.1μm in p-direction for amplitude and phase apodization.

Figure 9 shows comparison of peak irradiance for a range of 1.5 to 2.38 of n. Amplitude-only apodization gains larger peak irradiance than amplitude and phase apodization. Amplitude and phase apodization degrade peak irradiance of amplitude-only apodization. Therefore, the phase apodization reduces the peak irradiance of amplitude-only apodization. The difference between peak irradiances decreases as n increases. For n equal to 2.38, there is small difference between peak irradiances.

5. Conclusion

The air gap induces the amplitude and phase apodization in SIL systems due to vector diffraction effect. Amplitude apodization in s-direction is well characterized in SIL systems in terms of magnitude, width, and shape factor. The phase apodization affect the spot width significantly in p-direction. It also reduces peak irradiance.

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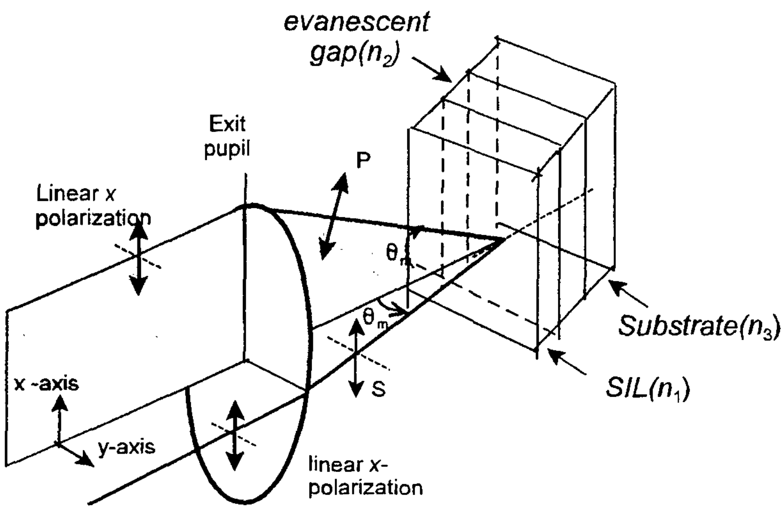

Figure 1. A diagram of the system configuration. Collimated electro-magnetic waves are focused by a lens placed in the exit pupil. The focusing electro-magnetic waves propagate to the SIL, which focuses the light to form a spot. The focused electro-magnetic wave can be described by a linear summation of plane waves.

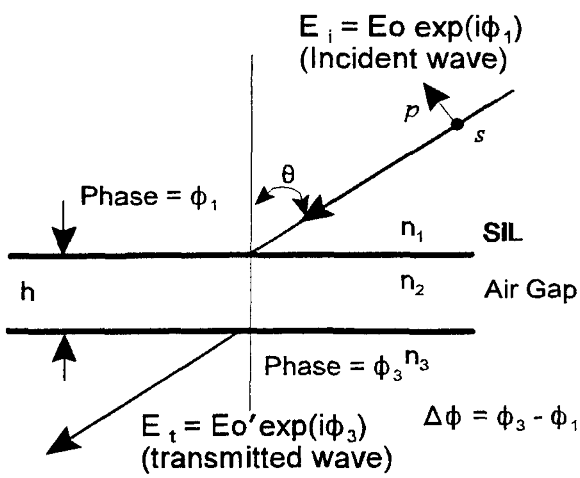

Figure 2. Explanation for the phase change

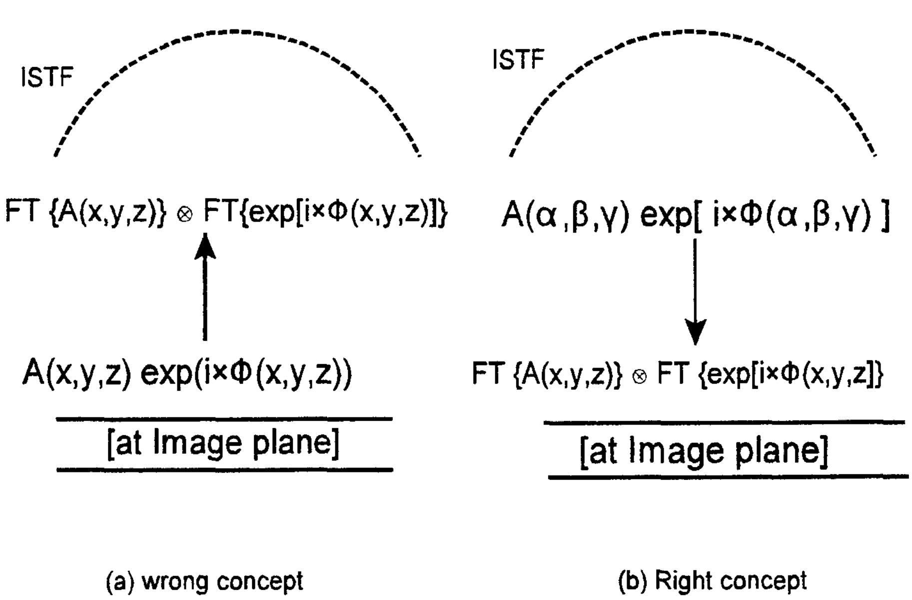

Figure 3. Right understanding for the gap-induced aberration

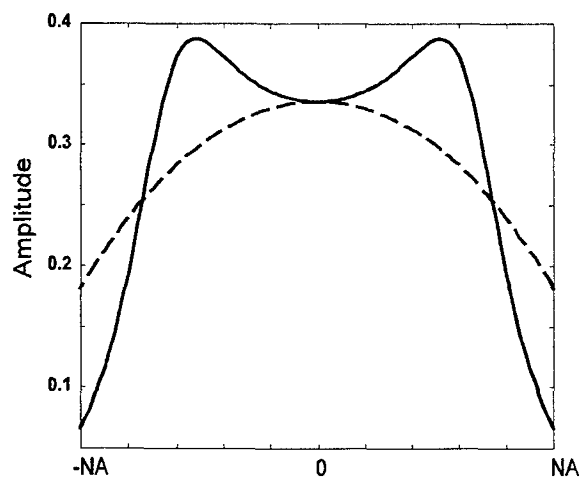

Figure 4. P-and s-profile of amplitude apodization in SIL system. n1/n2/n3 = 2.38/1/2.38. NA (air) = 0.7. P-profile is represented by solid line. S-profile is represented by dashed line.

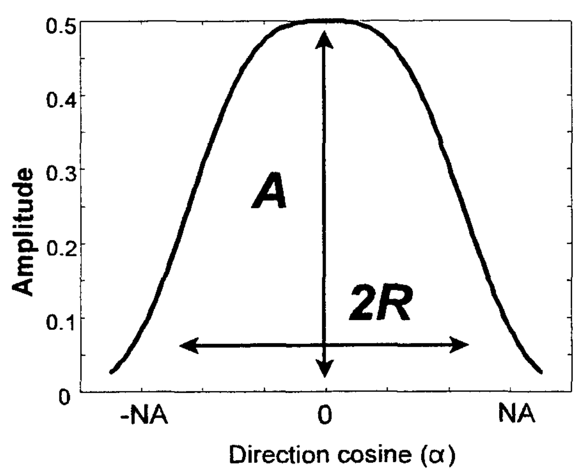

Figure 5. Supergaussian form. A represent amount of amplitude, R shows the width.

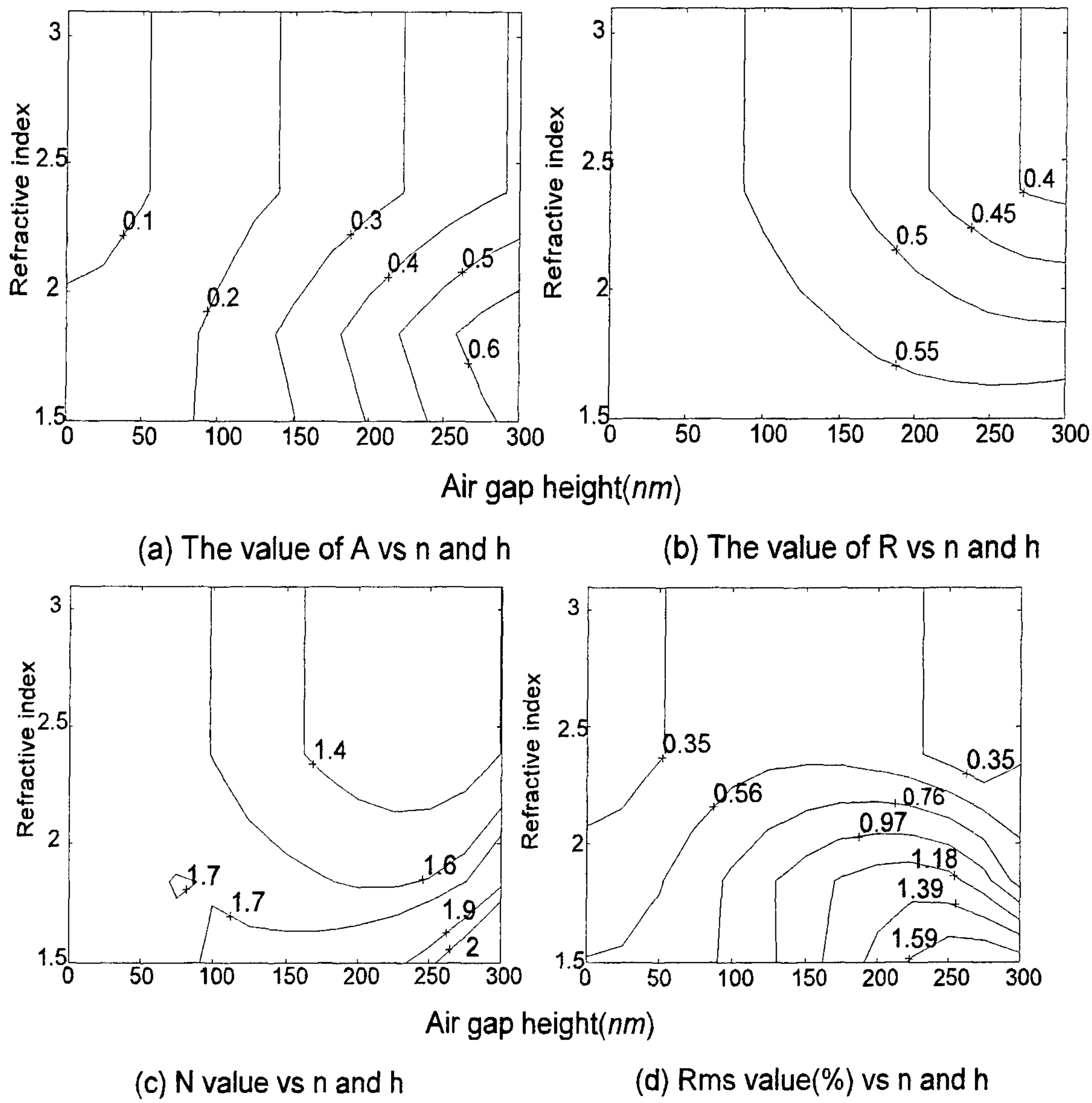

Figure 6. (a) The value of A of amplitude apodization in s-direction vs n and h (b) the value of R of amplitude apodization in s-direction vs n and h. (c) The value of N of amplitude apodization in s-direction vs n and h (d) Rms value of amplitude apodization fitting errors in s-direction vs n and h

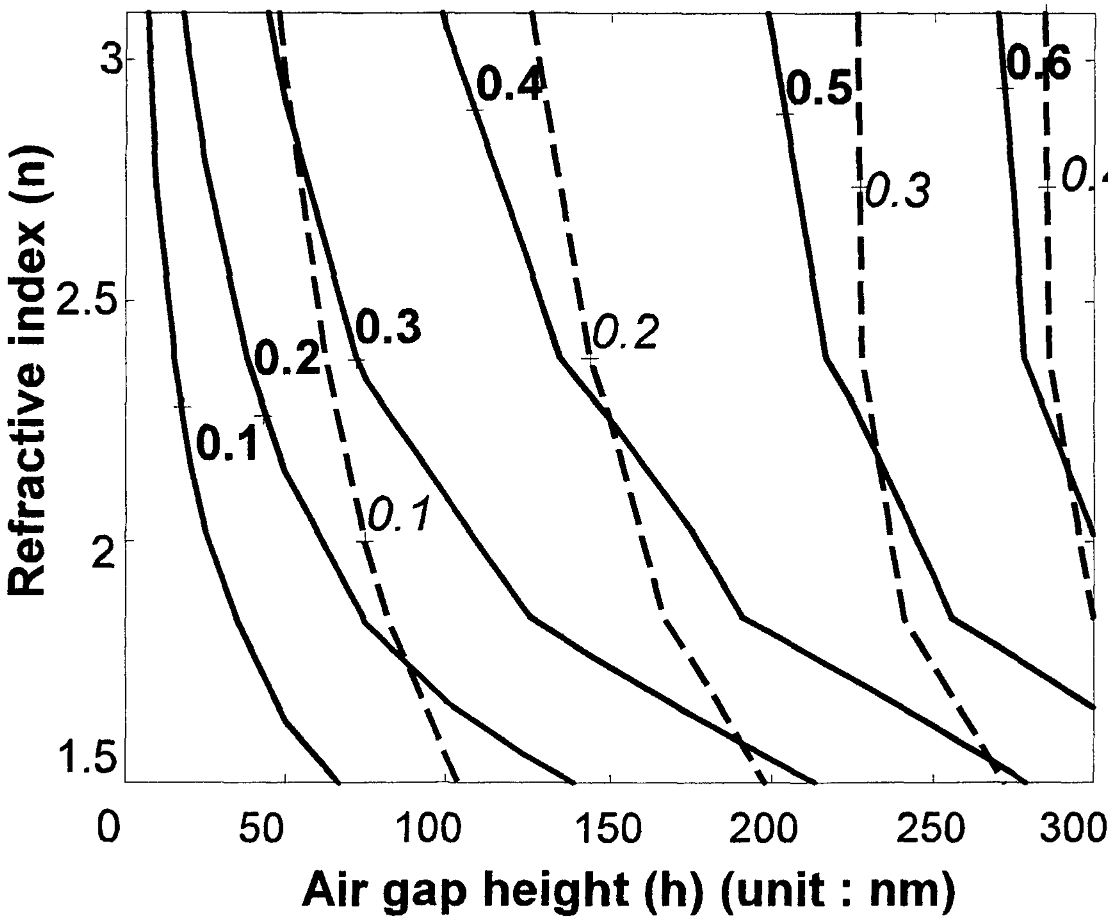

Figure 7. The A value of phase apodization vs n and h. Solid line represent p-direction, while dashed line does s-direction in the pupil

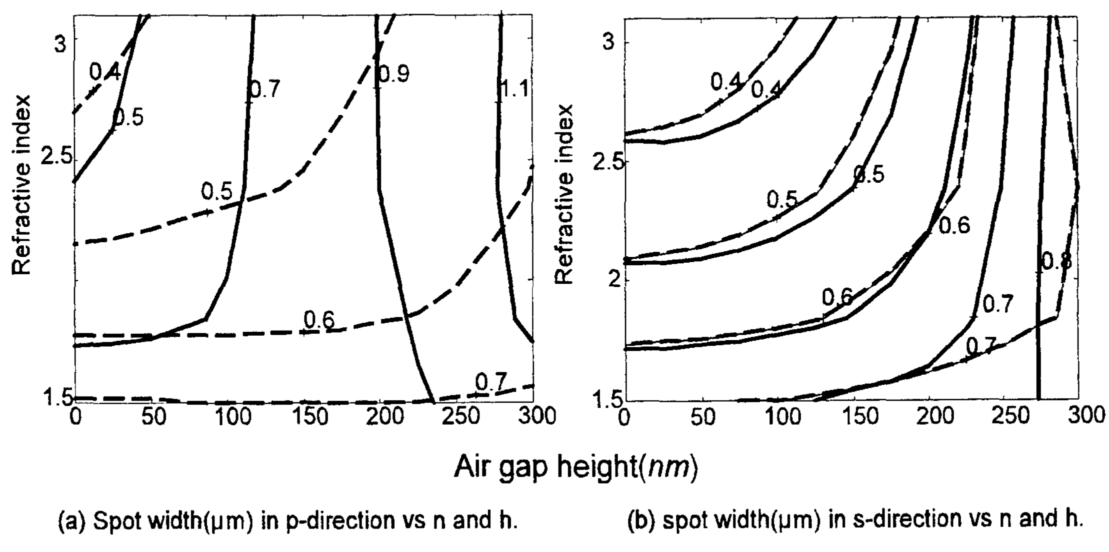

Figure 8. (a) Spot width in p-direction vs n and h. (b) Spot width in s-direction vs n and h. Solid line represent the both amplitude and phase apodization case. Dashed line represent amplitude-only apodization.

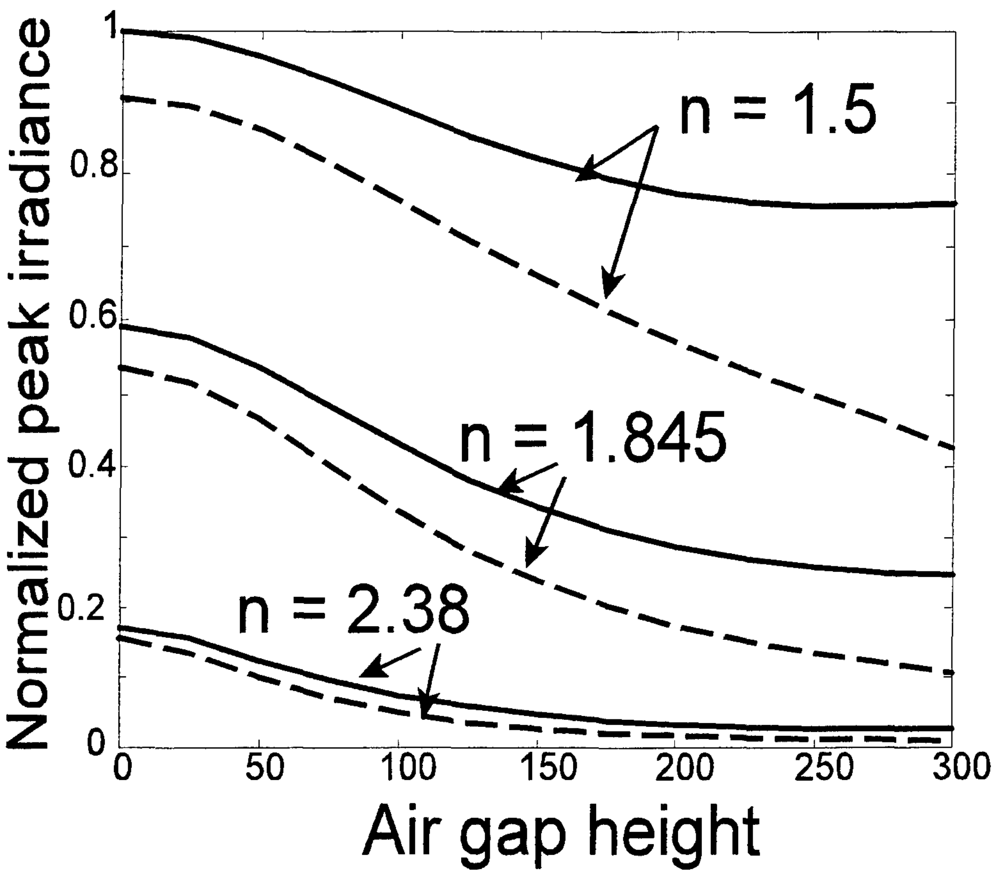

Figure 9. Comparison of peak irradiance for a range of 1.5 to 2.38 of n. Solid line represent peak irradiance for amplitude-only apodization. Dashed line represent peak irradiance for amplitude and phase apodization.