Phase-shifting apodizers for increasing focal depth

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We propose the use of a phase-shifting apodizers to increase focal depth, and we study the axial and radial behavior of this kind of apodizer under the condition that the axial intensity distribution is optimized for high focal depth. © 2002 Optical Society of America

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1. Introduction

Increasing focal depth has been of interest in many practical applications such as microelectronics, microscopy, medical imaging, and optical storage. Many methods have been proposed for the above purpose, such as annular aperture methods,1,2 in which focal depth is extended by obstructing the center part of light; shade mask methods,3–7 in which focal depth is extended by modulation of the amplitude transmittance over the whole pupil aperture; quasi-bifocus methods,8,9 in which focal depth is extended by the generation of bifocus with an interval of the Sparrow limit; and image-processing methods.10,11

Our aim here is to suggest the use of pure-phase, three-portion phase-shifting apodizers for increasing focal depth and to study the axial and radial behavior of this kind of apodizer under the condition that the axial intensity distribution is optimized for high focal depth.

2. Principle and Results

In this section we investigate the axial and radial behavior of the diffraction produced by a phase-shifting apodizer. The incident radiation has wavelength $\lambda$, assumed to be uniform across the exit pupil. For the three-portion phase-shifting apodizer shown in Fig. 1, the half-width ratio (HWR) (the full width half-maximum of the system with an apodizer to that of the system without an apodizer) and Strehl ratio $(S)$ of the light at the focal point of Fig. 2 can be expressed as

$$HWR = \left[ \frac{1 - 2(a^2 - b^2)}{1 - 2(a^4 - b^4)} \right]^{1/2}, \quad (1)$$

$$S = [1 - 2(a^2 - b^2)]^2, \quad (2)$$

where $a$ and $b$ are the outer radius and inner radius of the apodizer, respectively.

The axial amplitude distribution can be denoted as

$$G(u) = \sum_{j=1}^{N} \exp(i\phi_j) \int_{r_{j-1}}^{r_j} r \exp[-(1/2)iur^2]dr$$

$$= 2\int_0^b \exp[-(1/2)iur^2]dr$$

$$- \int_b^a \exp[-(1/2)iur^2]dr$$

$$+ \int_a^1 \exp[-(1/2)iur^2]dr$$

$$= \frac{2}{iu} \left( \exp[-(1/2)iub^2] - 1 - 2[\exp[-(1/2)iua^2] - \exp[-(1/2)iub^2]] \right), \quad (3)$$

where $r$ is the radial coordinate of the objective lens pupil plane and $\phi_j = \phi_j$, $j = 1, \ldots, N$ defines the phase of zone $j$ on the pupil plane. The radial position of each zone is given by $r_j = r_0 j = 0, \ldots, N$, where $r_0 = 0$. $r$ and $u$ are the simplified radial and axial coordinates in the image side, respectively.

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Thus the axial intensity distribution can be written as\(^{13}\)

\[
I(u) = 10 + 16 \sin \left( \frac{u}{4} (a^2 - b^2) \right) \\
\times \sin \frac{a^2}{4} \cos \left( \frac{u}{4} (1 - a^2 - b^2) \right) \\
- 8 \cos \left( \frac{u}{2} (a^2 - b^2) \right) - 2 \cos \frac{4u}{2} \frac{4}{u^2} \\
= \frac{1}{4} + 4(a^2 - b^2)^2 \sin^2 \left( \frac{a^2 - b^2}{4} u \right) \\
+ 2(1 - a^2)^2 \sin^2 \left( \frac{1 - a^2}{4} u \right) \\
- 2(1 - b^2)^2 \sin^2 \left( \frac{1 - b^2}{4} u \right) \\
- 2a^4 \sin^2 \left( \frac{a^2}{4} u \right) + 2b^4 \sin^2 \left( \frac{b^2}{4} u \right). \\
\]

(4)

This indicates that the axial irradiance can be expressed as the combination of light from different parts of the apodizer. The axial intensity distribution is symmetric as to the focal plane.

To gain high focal depth, we perform some mathematics as was done in Ref. (8). When \(u = 0\),

\[
\frac{d^2I(u)}{du^2} = - \frac{1}{2} - 2(a^2 - b^2)^4 - (1 - a^2)^4 \\
+ (1 - b^2)^4 + a^8 - b^8 = 0. \tag{5}
\]

Solving this equation, we have two curves that satisfy our demand, which are shown in Fig. 3. Figure 4 shows the axial intensity distribution for different values of inner radius \(b\) and outer radius \(a\). The solid curve corresponds to the system without the apodizer. The values of \(b\) and \(a\) of the curve with \(b = 0.22\) and \(a = 0.927\) are a pair of values taken from curve 2 of Fig. 3. The values of \(b\) and \(a\) of the other three curves are taken from curve 1 of Fig. 3. Figure 5 shows the corresponding radial behavior for each curve in Fig. 4. The solid curve corresponds to the system without the apodizer. It is easy to see that the spot size of the two curves for \(b = 0.28\) and \(b = 0.3\) in Fig. 5 are smaller than that without the apodizer. The spot size of the two curves for \(b = 0.22\) and \(b = 0.82\) in Fig. 5 are larger than that without the apodizer. But not all the values in curve 1 of Fig. 3
satisfy our demand. When the inner radius $b$ is within the interval of $0.3 < b < 0.44$, the intensity at the point where the focal plane intersects with the axis decreases with the increase of $b$. When $b$ is within the interval $0.44 < b < 0.60$, the intensity at the point where the focal plane intersects with the axis is near zero, which results in a bifocus. When $b$ is within the interval $0.60 < b < 0.82$, the intensity at the point where the focal plane intersects with the axis increases with the increase of $b$. Figure 6 shows the axial intensity distribution for three pairs of $b$ and $a$ when $b$ is within the interval of $0.3 < b < 0.82$. Further discussion as to the generation of bifocus is beyond the scope of this paper. What we are also concerned about are the half-width ratio and Strehl ratio. For each pair of inner radius $b$ and outer radius $a$ in curve 1 and curve 2 of Fig. 3, we have calculated the corresponding HWR and Strehl ratio, which are shown in Figs. 7 and 8. In Fig. 7, when the inner radius $b$ is within the interval of $0.5 < b < 0.66$, the HWR is zero, which means there is no peak value in the center of the curve in the radial direction. When the inner radius $b$ is smaller than 0.5, the HWR is smaller than 1, which means the resolution of the beam is higher than that without the apodizer. When the inner radius $b$ is within the interval of $0.66 < b < 0.9$, the HWR is bigger than 1, which means the resolution of the beam is smaller than that without the apodizer. The Strehl ratio decreases to an extremely low value when $b$ is within the interval of $0.4 < b < 0.6$. In Fig. 8, when the inner radius $b$ is within the interval of $0 \leq b < 0.34$, the HWR is bigger than 1, and when $b$ is within the interval of $0.34 \leq b < 0.38$, the HWR is smaller than 1.

3. Experiment

An experiment has been successfully performed with an objective lens of N.A. = 0.85 and a laser wavelength of 0.5145 μm. The apodizer is made of K9 glass through a solid etching method. The inner radius $b$ and outer radius $a$ are 0.27 and 0.54, respectively. The radius of the exit pupil is 3.373 mm. So the actual size of the inner radius and outer radius are 0.9107 and 1.8214 mm. The refractive index of K9 glass is 1.52007. To generate phase $\pi$, we need the etching depth to be 494.6 nm. We tested the etching depth with an Alpha-Step 500 step; the tested depth is 492.1 nm, so the error rate is 0.5%. The light throughput of this apodizer is 92% if the reflection of the two surfaces is taken into consideration. The light throughput could be improved through coating methods. We used a fiber tip mounted onto
a three-dimensional nanoscanning piezoelectric transducer tube as the detector to test the intensity distribution near the focus. The detected light intensity was transformed into electronic current, amplified by a photomultiplier tube, and then processed by a computer. Figure 9 shows the axial intensity distribution of the original system and the calculated, tested, and expected results. If we take the width at which the intensity drops to 80% of the peak value as the focal depth, the focal depth of the original system is 0.712 μm, the calculated focal depth is 2.04 μm, the tested result is 2.05 μm, and the expected focal depth is 2.29 μm. The tested focal depth agrees very well with the calculated result; the error rate is less than 0.5%. The expected axial intensity distribution is calculated with \( b = 0.27 \) and \( a = 0.547 \).

4. Conclusion

In summary, we have proposed to use pure-phase, three-portion phase-shifting apodizers to gain high focal depth. Mathematic method is used to gain all the values of the inner radius and the outer radius that satisfy our requirement of high focal depth. The light from different portions of the apodizer offset each other in the peak intensity, which results in a high focal depth. An experiment was performed, which agrees well with the theoretical prediction.

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