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Mitigation of beam sampling grating damage induced by upstream flaws in the final optics assembly

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Abstract. The high fluence performance of high-power laser systems is set by optical damage, especially in the final optics assembly (FOA). The flaws on the frequency converter surface can cause optical intensity intensification and, therefore, damage the downstream optical elements, such as the beam sampling grating (BSG), which is an important component in the FOA. Mitigation of BSG damage caused by flaws is discussed. Physical models are established to simulate the optical field enhancement on BSG modulated by the upstream flaw, considering both the linear and nonlinear propagation effects. Numerical calculations suggest that it is important to place the BSG in a properly selected position to mitigate the laser-induced damage. Furthermore, strict controls of flaw size, modulation depth, distance between frequency converter and focusing lens, and the thickness of the focusing lens are also significant to mitigate the BSG damage. The results obtained could also give some suggestions for damage mitigation of optical components and the layout design of the final optics assembly. [DOI: 10.1117/1.OE.56.1.011021]

Keywords: damage mitigation; flaw; final optics assembly; high-power laser; hot image.

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1 Introduction

In high-power laser systems for inertial confinement fusion[1] research, laser-induced damage[2,3] is one of the important factors that limits the maximum output power available from a solid-state laser, especially because ultraviolet damage may occur in the final optics assembly[4] (FOA). The optics damage in FOA affects the normal operation of the system and also the beam quality. It is a critical issue and a global challenge to tackle the damage problem in the FOA.

The laser damage is a complicated problem which is related to beam quality, optical components, and the environment.[5] A lot of progress[6–10] has been made corresponding to the above aspects. The current optimization design effort of the FOA is mainly about the ghost image[11] analysis and avoidance based on geometrical optics. Meanwhile, it is generally believed that upstream flaws[12] would cause enhancement of the downstream optical field based on physical optics and thereby induce damage on the downstream optics. In the FOA, a hot image caused by the flaws on the vacuum windows or the phase plate duo to the nonlinearity of frequency convertor is usually considered to be responsible for some damage sites on the focusing lens. The formation of a hot image originates from the scatter rooted in a strong background beam. After propagating a distance in the free space, the beam goes through a second-order nonlinear medium, and then an intensified holographic image of the scatter downstream is produced in a certain position. The peak intensity of the hot image may be several times larger than the initial background beam. This type of hot image is of little influence on the beam sampling grating[13] (BSG) because of the long distance between the BSG and the frequency converter. However, optical damage still occurs in the BSG, which is an important element for ultraviolet diagnosis in the FOA. The previous analysis is usually for the components used in a parallel light path.[14–16] However, the BSG is used in a convergent beam. The optical field distribution of the BSG is related to both diffractive and focusing effects. Moreover, the focusing lens is a thick component in the high-power laser system. Yet the hot image due to the nonlinearity of the focusing lens has drawn little attention. It may also be the reason why the BSG is damaged. Therefore, it is necessary and important to study the evolution of the optical field in the focusing system and find ways to mitigate the damage of the BSG.

In this paper, physical models are established to study the optical field enhancement in the BSG position modulated by upstream flaws. First, when only the linear transportation is considered, it is found that there is a local minimum of modulation degree along the propagation direction after the focusing lens. The connection of minimum modulation position with the flaw radius is given. Second, when the nonlinear effect of the focusing lens is taken into consideration, there is a peak of modulation degree and maximum intensity after the focusing lens. The peak of modulation and maximum intensity downstream is much larger than in the linear case, thus the damage risk of the BSG is much higher. Hence, it is important to place the BSG in a properly selected position to mitigate the laser-induced damage.

2 Physical Model

In the high-power laser system, a typical FOA is shown in Fig. 1, which contains the phase plate, frequency converter, focusing lens, BSG, and so on.

To analyze the optical field characteristics on the BSG in the FOA, we have built a simplified model of the FOA, as

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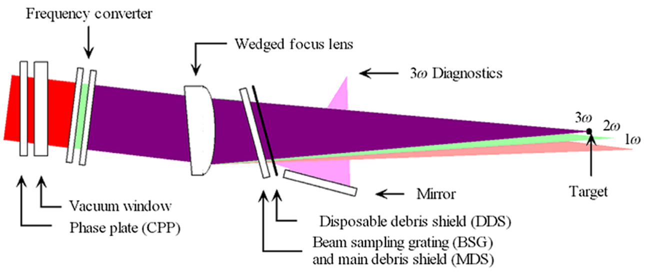

Fig. 1 Schematic diagram of an FOA.

shown in Fig. 2. The laser passes through the frequency converter, the focusing lens, the BSG, and finally focuses on the target. In reality, there are flaws or defects, such as contamination particles on the frequency converter. The flaws will induce modulation into the whole beam. Due to diffraction and nonlinear effects, the optical intensity will be enhanced, which may cause the BSG damage. Here, we are mainly concerned about the optical field at the front surface of the BSG. The parameter d is the distance between the lens and the BSG. The parameter d_1 is the distance between the frequency converter and the lens. The parameter f is the focal length of the lens.

The input optical filed of a high-power laser is usually a super-Gaussian beam, which can be described as

$$E_1(x,y) = E_0 \exp\left[-\left(\sqrt{\frac{x^2+y^2}{\omega_0^2}}\right)^N\right], \tag{1}$$

where E_0 is the average amplitude of the super-Gaussian beam, ω_0 is the beam waist, and N represents the order of the super-Gaussian beam.

Although the flaws on optical elements are various, they can be divided into two kinds according to their influence on the optical field, phase and amplitude types. Here, we mainly study the influence of the phase type flaws as they would cause a bigger impact than the amplitude flaws.[16] Phase flaws on the optical surface are usually symmetric, similar to the Gaussian-like distribution, whose transmittance function can be expressed as follows:

$$t_p = \exp\left[i\Delta \exp\left(-\frac{x^2+y^2}{a^2}\right)\right], \tag{2}$$

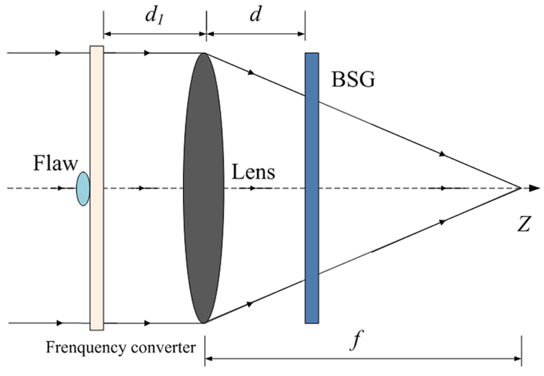

Fig. 2 Simplified model of an FOA.

where t_p denotes the transmittance of the phase type, Δ denotes the modulation depth of the flaw, and a denotes the radius of the flaw. It is found that flaws existing in the present system are mainly the size of micrometers. Then the optical field E_2 at the rear surface of the frequency converter can be described as $E_2 = E_1 * t_p$. After propagating a distance of d_1, the optical field E_3 at the front surface of the lens can be calculated according to Fresnel diffraction integral theory. The transmission function of the focusing lens is $\exp[-jk(x^2+y^2)/2f]$, where k is the wave number in vacuum. When the nonlinear effect of lens is considered, the optical field designated as E_4 at the rear surface of the lens can be obtained based on the nonlinear paraxial equation as follows:

$$\nabla_\perp^2 + 2jk_0\frac{\partial E}{\partial z} = -\frac{2k_0^2}{n_0}\Delta nE, \tag{3}$$

where k_0 is the wave number in the medium with the refractive index n_0 and $\Delta n = \gamma I$ is the nonlinear refractive index variation compared to n_0. The parameter γ is the nonlinear index coefficient of the nonlinear medium. The parameter I is the optical intensity. After the propagation of a distance d, the optical field at the surface of BSG can be obtained by Fresnel diffraction integral theory.

For analysis of the near-field optical beam quality, we define the modulation degree M as

$$M = \frac{I_{\max}}{I_{\text{avg}}}, \tag{4}$$

where $I_{\max}$ represents the maximum intensity and I_{avg} represents the average intensity. In the real optical field, M is larger than 1. When M is decreasing, the near-field is more uniform, which means better beam quality and smaller probability of damage.

3 Simulation and Analysis

For simulation, the parameters are chosen according to the high-power laser facility in our laboratory. The wavelength is 351 nm, the focal length is 2.2 m, and the distance d_1 is 0.6 m. The super-Gaussian beam shape of the 12th order was used as the input beam with a waist of 0.6 cm and average intensity of 3 GW/cm^2, which is the design point of 9 J/cm^2 at 3 ns. The sampling region is divided into 1024 points. One-dimensional calculation is carried out to save the computing time. The beam modulation characteristics and optical field enhancement downstream caused by upstream flaw in the target system are discussed.

3.1 *Linear Propagation*

When only the linear propagation effect is considered, the influence of flaws on the beam modulation of the downstream BSG is investigated. As shown in Fig. 2, the BSG is placed after the focusing lens with a distance of d. At a specific distance d, we can simulate the optical intensity distribution and get the corresponding modulation degree and maximum intensity. When the flaw radius a is 300 μm and the modulation depth Δ is $\pi/2$, the modulation degree and maximum intensity of the optical field at different distances d away from the lens are shown in Fig. 3. We can see that the maximum intensity grows with the distance d due to the

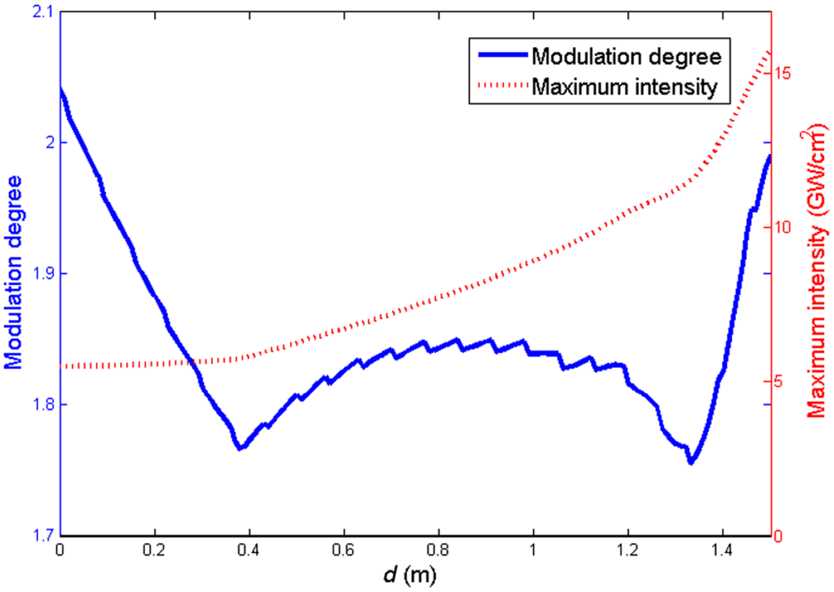

Fig. 3 Modulation degree and maximum intensity as functions of distance *d* when the flaw radius *a* is 300 μm and the modulation depth Δ is $\pi/2$.

focusing effect without an inflection point. However, there is a minimum of the modulation degree (1.76) when *d* is 0.39. When the modulation degree *M* is bigger, it means a more uneven field distribution, which will more easily induce the optical damage due to the self focusing effect. Therefore, we can choose to put the BSG in a position with a smaller modulation and smaller intensity to mitigate the damage issue. Actually, there are two minimal modulation degrees at distances of 0.39 and 1.33 m. Due to the focusing effect, the optical intensity of 1.33 m is obviously much stronger than that of 0.39 m. Therefore, we will choose to put the BSG at the distance of 0.39 m.

Here, the optical field evolution is controlled by both the diffraction and the focusing effects. The diffraction effect would decrease the modulation degree while the focusing effect would increase the modulation degree. Therefore, there will be an extremum of modulation degree. The size dependences of distance for minimum modulation are analyzed as shown in Fig. 4. When the radius is bigger, the distance away from the lens for minimum modulation is also longer. This means bigger flaws have a wider affected region. By noting that, the shortest safe distance for the BSG and the lens is decided by the radius of flaws on the frequency converter. To design a compact FOA, the size of the flaw on the optical element must be strictly controlled. For example, when the distance *d* is 0.4 m, the flaw radius allowed on the frequency converter should be smaller than 300 μm [see Fig. 4]. In turn, for a typical flaw size of 200 to 300 μm, the distance between the lens and the BSG should be longer than 0.4 m. Therefore, it is very important to place the BSG in a suitable location to avoid damage.

For a given distance ($d = 0.4$ m) and flaw radius ($a = 300$ μm), Fig. 5 shows how the beam modulation degree changes with the modulation depth Δ. Although the BSG is placed in the location with the smallest modulation, the optical field modulation degree could exceed the allowable upper limit (1.8) due to the increase of the initial

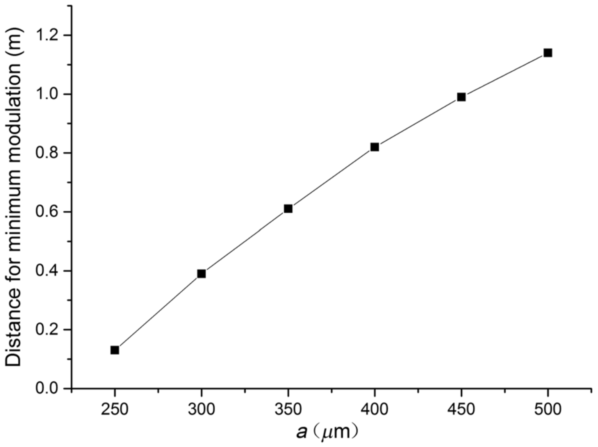

Fig. 4 Size dependences of distance for minimum modulation when the modulation depth Δ of flaw is $\pi/2$.

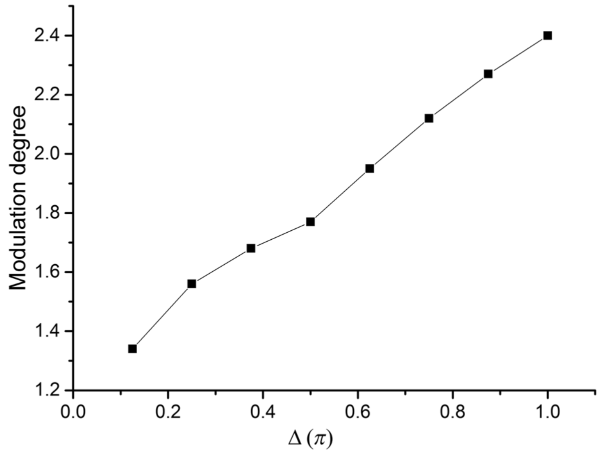

Fig. 5 Modulation degree versus initial modulation depth for a given distance $d = 0.4$ m and flaw radius $a = 300$ μm.

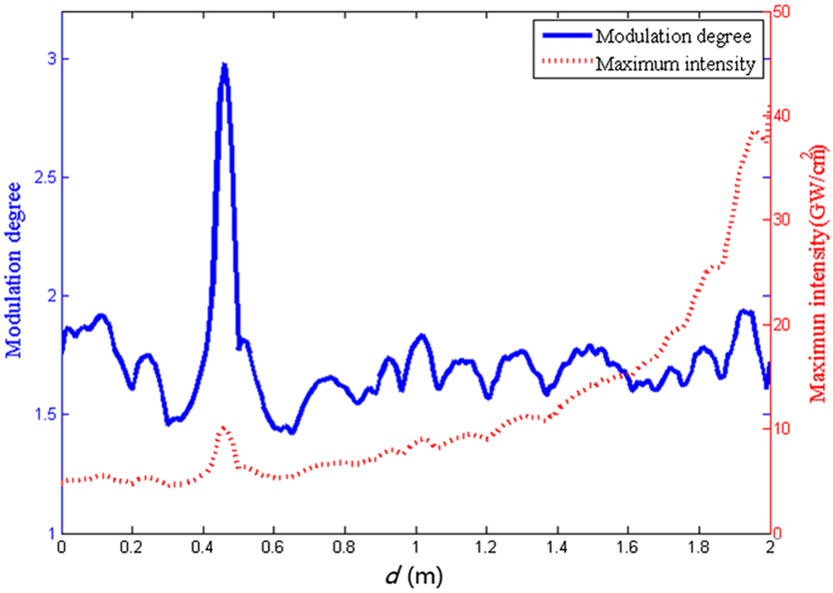

Fig. 6 Modulation degree and maximum intensity versus distance d when the thickness of the media $L = 80$ mm, refractive index $n_0 = 1.48$, the nonlinear index coefficient[2] $\gamma = 3.1 \times 10^{-7}$ cm^2/GW, input intensity is 3 GW/cm^2, flaw radius a is 50 μm, and the modulation depth Δ is $\pi/2$.

modulation depth. To suppress the damage caused by near-field quality degradation, the initial flaw modulation depth should be controlled below $\pi/2$.

3.2 *Nonlinear Propagation*

In fact, the nonlinear effect becomes more and more pronounced with the increase of the laser fluence for a high-power laser facility. In the FOA, the thickest optical component is the focusing lens, which is made of fused silica. Here, we take the focusing lens as a nonlinear media to investigate the optical field evolution and enhancement in the focusing system. The parameters of the nonlinear media are taken as follows: the thickness of the media $L = 80$ mm, refractive index $n_0 = 1.48$, and the nonlinear index coefficient[2] $\gamma = 3.1 \times 10^{-7}$ cm^2/GW.

Based on the split-step Fourier method[17] and Fresnel diffraction theory, the influence of flaws on the beam modulation of the downstream BSG is investigated. When the flaw radius is 50 μm and the modulation depth is $\pi/2$, the modulation degree and maximum intensity of the optical field at different distances d away from the lens are shown in Fig. 6. It can be seen that there are modulation and maximum intensity peaks along the propagation direction when the nonlinear effect of the focusing lens is taken into account. The modulation or intensity peak for nonlinear propagation is much bigger than the one for linear propagation. What is more, as mentioned above in Sec. 3.1, the BSG can be placed at 0.4 m or a longer distance away from the lens to avoid the impact of the flaw with a radius less than 300 μm. However, when the nonlinear effect is considered, even a flaw of 50 μm can cause a peak modulation and intensity at a distance of 0.46 m away from the focusing lens. If the BSG is placed in this position, it will definitely be damaged.

A sharp increase of modulation degree and maximum intensity is observed at the distance of 0.46 m (Fig. 6). When d is 0.46 m, the spatial profile of the laser intensity is shown in Fig. 7. The maximum intensity is 10.1 GW/cm^2, and the modulation degree is 2.98. This peak is a nonlinear holographic hot image,[16] which is caused by the nonlinear interaction of scattered light by the flaw and the background light. It will be fatal for the BSG. Hence, the influenced range of the hot image needs to be excluded from the selection of the BSG location.

Thus, the location of the peak modulation and intensity is very important. We define the distance between the peak location and the lens as parameter d_2. For further consideration, the influence of the flaw radius on the distance d_2 and the maximum intensity is analyzed, as described in Fig. 8. We can see that when the radius is less than 150 μm, the maximum grows with the increase of the radius. When the radius is larger than 150 μm, the maximum decreases with the increase of the radius. However, the distance d_2 is insensitive to the change of the radius. This is due to the nonlinear characteristics of the hot image. The hot image location

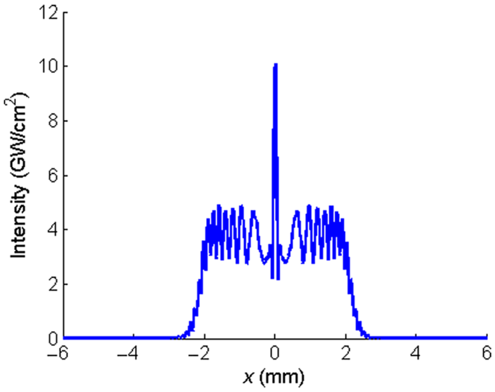

Fig. 7 Spatial profile of the laser intensity at the distance d of 0.46 m when the thickness of the media $L = 80$ mm, refractive index $n_0 = 1.48$, the nonlinear index coefficient[2] $\gamma = 3.1 \times 10^{-7}$ cm^2/GW, input intensity is 3 GW/cm^2, flaw radius a is 50 μm, and the modulation depth Δ is $\pi/2$.

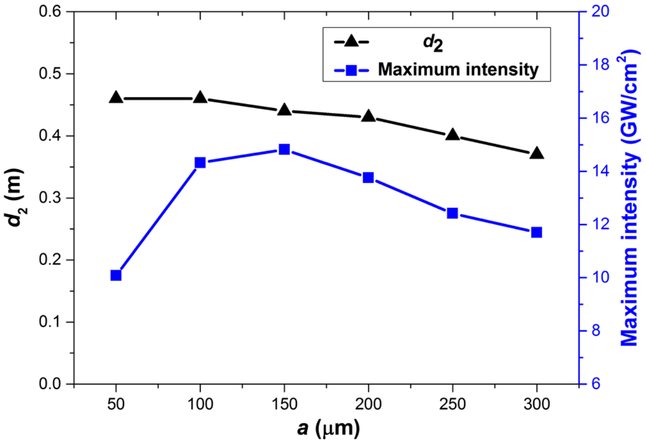

Fig. 8 Distance d_2 and maximum intensity versus flaw radius when the modulation depth Δ of flaw is $\pi/2$.

should be related to the position of the flaw, which is similar to the relationship between the object and the image in geometrical optics.

Thus, the influence of distance d_1 between the frequency converter and the lens on the distance d_2 and the maximum intensity is also analyzed, as plotted in Fig. 9. The peak location d_2 increases with the distance d_1. The maximum intensity also grows with the increase of the distance d_1. This is mainly because of the focusing effect. We can see that the BSG location selection is also limited by the positional relationship of other optical elements in the FOA. In other words, it is also a choice to change the distance between the frequency converter and the lens to mitigate the BSG damage at a given distance d.

At last, the influence of lens thickness on the peak modulation degree is also investigated. For a 50-μm flaw, when $d_1 = 0.6$ m and $d_2 = 0.46$ m, the result is shown in Fig. 10. With the increase of the lens thickness, the optical modulation degree undergoes an exponential growth, which is consistent with the B-integral theory.[18] When L is reduced to 40 mm, the peak modulation degree can be brought down to 2 or less. To control the growth of the optical modulation, it is needed to reduce the thickness of the nonlinear media as much as possible, especially for the focusing lens. If the lens thickness can be limited to less than 30 mm, the optical field enhancement caused by nonlinear effect will be largely suppressed.

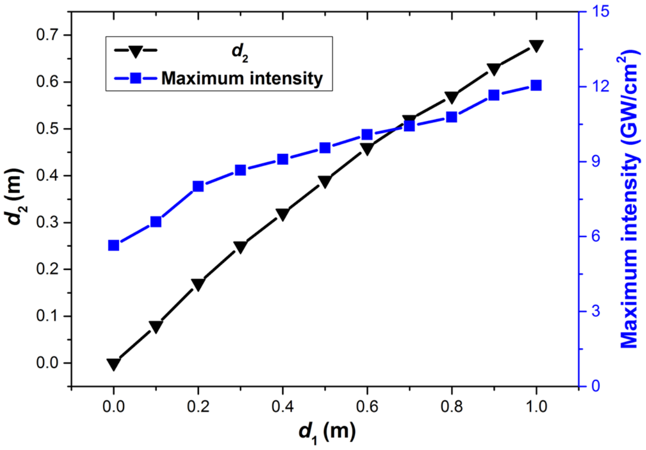

Fig. 9 Distance d_2 and maximum intensity versus distance d_1 when the flaw radius a is 50 μm and the modulation depth Δ is $\pi/2$.

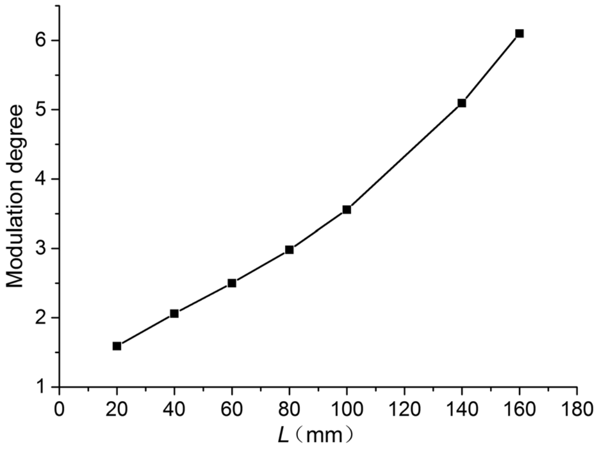

Fig. 10 Modulation degree versus thickness of the lens when the flaw radius a is 50 μm and the modulation depth Δ is $\pi/2$.

4 Discussion

This paper is focused on how to mitigate the BSG damage by the optimization design of the system, which is one part of the FOA designs. When we want to design an FOA, the configuration must first be selected. Meanwhile, it is necessary to avoid damage problems as much as possible. In this case, the layout of the optical components in the FOA is a very important aspect. We can first get a rough layout by ghost image analysis based on geometrical optics. Then it is necessary to adjust the optical element arrangement according to the analysis based on diffractive optics and nonlinear optics because the optical element should not be placed in the position with stronger light intensity or singularity. That is the meaning of the analysis in this paper.

According to the simulation and analysis, we present two main approaches to mitigate the optical damage. First, reduce the possible maximum intensity existing in the whole beam path. This can be achieved by the control of the flaw and the thickness of the nonlinear media. The optical elements should go through the flaw measurement and control before they are put online. Second, when an area of very strong light is inevitable, the optical elements should be placed outside the strong area. Take BSG for example, given the distance between the lens and the frequency converter and the focal length of the focusing lens, we can calculate the position of the hot image and find a position with smallest intensity or modulation to place the BSG. We can also see that the layout of the optical element is closely related to the actual system parameters. By the way, the improvement of input beam quality in FOA is also an important aspect of the damage mitigation, i.e., a problem of the upstream system, which is not involved here.

5 Conclusion

To conclude, the beam modulation characteristics and optical field enhancement downstream caused by an upstream flaw in the target system are investigated. First, when only the linear transportation is considered, it is found that there is a valley of the modulation degree after the focusing lens.

The minimum modulation position is affected by the flaw size. The modulation degree grows with the increase of the initial modulation depth. Secondly, when the nonlinear effect of the focusing lens is considered, the peak maximum intensity and modulation downstream is much bigger than the one for the linear situation. And the damage risk of the BSG at these positions is much higher too. The peak modulation position is related to the distance between the frequency converter and the focusing lens. The exponential growth of the modulation degree with the thickness of the lens is also demonstrated. From the above analysis, we can conclude that it is important to place the BSG in a properly selected position with lower modulation and intensity to mitigate the laser-induced damage. Strict controls of flaw size, modulation depth, distance between frequency converter and focusing lens, and the thickness of the focusing lens are also significant to mitigate the BSG damage. The approach to mitigate damage, in this paper, is not limited to the BSG, but is also suitable for other elements in the FOA and even for the entire laser path. The results may be helpful for the design of the FOA and the damage mitigation.

Acknowledgments

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