Study on the noise from multiple reflections in the high power attenuation system

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The noise origin of attenuation system is explored by analyzing the wedged plate attenuator based on Fresnel transmission through two pairs of wedged plates. Multiple reflections between two surfaces of a pair of wedged plates introduce fluctuating error into the attenuation of the wedged plate attenuator and wavefront distortion of the exit laser beam. The attenuation and the radial light intensity distribution of the laser beam considering the effect of multiple reflections are calculated when the wedge space varies. And the calculation results show that wedge space between a pair of wedged plates has important influence on laser beam quality. The fluctuation of attenuation decreases but the distortion of wave-front becomes more complicated with the wedge space between the two parallel surfaces of wedged plate pairs increasing.

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When laser beam propagates through devices which have defects, dust, and hotspot, the coherent scattering from those defects or the interference of multiple reflections between two parallel planes overlapping the laser beam, will affect the light quality, and distort the wave front. The modulation on light from that noise makes light quality worse especially under the condition of high power laser, and causes many effect such as beam self-focus. The noise from defects, dust, and hotspot decreased only by improving the performance of material and processing technology. The coherent noise from multiple reflections is concerned with the structure of system or device. Therefore, it is more profitable to study on the latter[1−6].

The propagation of laser beam in high power laser attenuation system was explored to find the noise origin and analyze the influence of the noise on the light quality by discussing the noise in the wedged plates variable optical attenuator used in high power laser system commonly.

There are three fundamental interactions that can be used to attenuator optical radiation: absorption, Fresnel reflection on a surface, and interference. The attenuator must be work well under the condition of high peak and average power. Only Fresnal reflection on a surface is up to the mustard. Attenuation by absorption and interference was not consistent with the requirements for high power laser system[7].

The wedged-plate optical variable attenuator is composed with four identical uncoated fused silica wedges. In the attenuator, a certain incident angle corresponds to a certain transmission of a certain polarized light according to Fresnel reflection theory, that is to say, different incident angles correspond to different attenuations. Since uncoated glass plates are used as attenuation elements, the attenuator operates at incident energy densities limited only by the surface damage threshold of the glass. Therefore, the input power of the attenuator could be very high[7].

The amplitude transmittance (t_s or t_p) for a single surface depends upon the polarization, the ratio of the refraction indices n, and the incident angle θ_i. The transmittance for light polarized parallel and perpendicular to the incident plane is[7]

$$t_s(\theta_i, \theta_t) = 2\cos\theta_i \sin\theta_t / \sin(\theta_i + \theta_t), \quad (1)$$

$$t_p(\theta_i, \theta_t) = 2\cos\theta_i \sin\theta_t / (\sin(\theta_i + \theta_t)\cos(\theta_i - \theta_t)). \quad (2)$$

When we neglect the change of refracting index with wavefront, the amplitude transmittance only is dependent on the incident angle. Thus, controlling the incident angle accurately means controlling the transmittance of light accurately, thereby controlling the attenuation accurately. The sketch of wedged-plate optical variable attenuator is shown in Fig. 1. The working principle of the wedged-plate optical variable attenuator is shown in Fig. 2. The incident beam goes through the four glass wedged plates, there are some lights of the beam reflected on each plate surface. The beam is attenuated eight times when it exits from the attenuator. Using wedged plates in the attenuator can not only achieve total internal reflection, but also remove the influence of stray light reflected between the two surfaces of the plate, and increase the return loss of the attenuator.

In Fig. 1, the light beam from the back surface of the wedged plate deviates, and the light also displaces

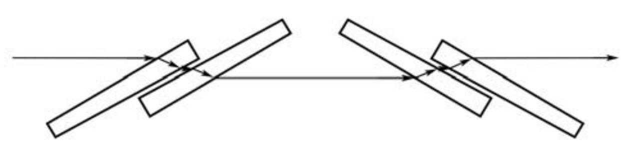

Fig. 1. Sketch of the wedged-plate optical variable attenuator.

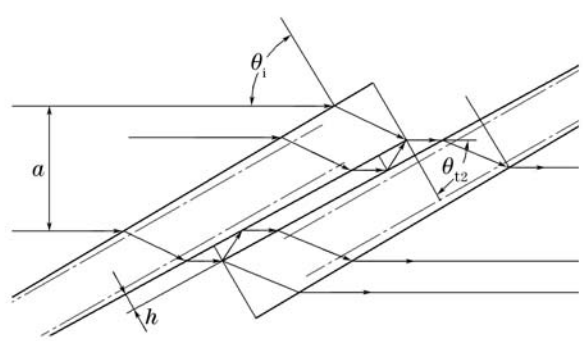

Fig. 2. Light path of the wedge pair in attenuator.

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for using the refracted light. The wedge pair placed parallelly compensates the deviation induced from the wedge angle, and two identical pair of such wedge pairs compensates the displacement induced from using the refracted light. The pairs of wedges were mounted on counterrotating shafts located to minimize beam displacement and deviation[7].

The lights reflected multiply by the parallel surfaces on either side of the gap interfere with the exit beam. And the interference can be removed hardly because the lights reflected multiply by the parallel surfaces are parallel to the exit light from the attenuator. The influence of the multiply reflected light is serious at extremely high attenuations[8,9].

We assume that the incident light is plane wave to simplify the calculation, the influences of the multiple reflections on the attenuation and light wave front are discussed below. Under non-normal incidence condition, the light beam is reflected multiply by the parallel surfaces on either side of wedge plate gap, and all the reflected lights are parallel to the exit beam. But the amplitude of reflected light after multiply reflecting attenuates sharply and has little influence on the exit light, and the influence of the light which reflects more than twice is neglected in calculation.

We investigate the superposition by analyzing the optical field distribution on the L plane. The lights which still parallel the propagation direction after the attenuator are

1) none reflection in two wedge pairs

$$E_1 = tA_0 \exp(i\omega t); \tag{3}$$

2) one reflection in the first wedge pair, none in the second

$$E_2 = tA_0 r^2(\theta_{t2}) \exp(i(\omega t + \delta)); \tag{4}$$

3) none reflection in the first wedge pair, one in the second

$$E_3 = tA_0 r^2(\theta_{t2}) \exp(i(\omega t + \delta)); \tag{5}$$

4) one reflection in each pair

$$E_4 = tA_0 r^4(\theta_{t2}) \exp(i(\omega t + 2\delta)). \tag{6}$$

Limited by the length of wedge overlap, only one part of the reflected light propagates through all four wedged plates. The position, where various light reached the L plane, varies. There are different superposed areas on the L plane, and the intensity of the same point changes with the incident angle varying.

One reflection by the parallel plane between wedge pairs induces a phase delay δ

$$\delta = [2h/\cos\theta_{t2} - h\tan\theta_{t2}\cos(\theta_t + 2\alpha)\sin(\theta_i)/\cos(\theta_t) \\ -h\tan\theta_{t2}\sin(2\alpha)/\cos(\theta_t)](2\pi/\lambda), \tag{7}$$

where h is the wedge spacing, θ_t is the refracted angle on the first surface of the wedged plate, θ_{t2} is the refracted angle on the second surface.

When $1 - 4s\cos\theta_i\tan\theta_{t2} > 0$, it means that the incident angle is small, light2, light3 and light4 still have the chance to overlap and interfere with each other at the L plane. There are three areas of different light intensities at the L plane. It is shown in Fig. 3.

Light1 superpose to light2 at ST segment

$$E_{ST} = E_1 + E_2, \tag{8}$$

$$x_{ST} = 2h\cos\theta_i\tan\theta_{t2}\cos(\theta_t + 2\alpha)/\cos\theta_t. \tag{9}$$

Light1, light2, light3, light4 superpose to each other at TM segment

$$E_{TM} = E_1 + E_2 + E_3 + E_4, \tag{10}$$

$$x_{TM} = a - 4h\cos\theta_i\tan\theta_{t2}\cos(\theta_t + 2\alpha)/\cos\theta_t. \tag{11}$$

Light1, light3 light4 superpose to each other at MN segment

$$E_{MN} = E_1 + E_3 + E_4, \tag{12}$$

$$x_{MN} = 2h\cos\theta_i\tan\theta_{t2}\cos(\theta_t + 2\alpha)/\cos\theta_t. \tag{13}$$

When $1 - 4s\cos\theta_i\tan\theta_{t2} < 0$ and $1 - 2s\cos\theta_i\tan\theta_{t2} > 0$, it means that the incident angle is large, light2, light3 and light4 already have no chance to overlap and interfere with each other at the L plane. There are still three areas of different light intensities at L plane. It is shown in Fig. 3.

Light1 superpose to light2 at ST segment

$$E_{ST} = E_1 + E_2, \tag{14}$$

$$x_{ST} = a - 2h\cos\theta_i\tan\theta_{t2}\cos(\theta_t + 2\alpha)/\cos\theta_t. \tag{15}$$

Only Light1 at TM segment

$$E_{TM} = E_1, \tag{16}$$

$$x_{TM} = 4h\cos\theta_i\tan\theta_{t2}\cos(\theta_t + 2\alpha)/\cos\theta_t - a. \tag{17}$$

Light1, light3, light4 superpose to each other at MN segment

$$E_{MN} = E_1 + E_3 + E_4, \tag{18}$$

$$x_{MN} = a - 2h\cos\theta_i\tan\theta_{t2}\cos(\theta_t + 2\alpha)/\cos\theta_t. \tag{19}$$

When $1 < 2s\tan(\theta_{t2})\cos(\theta_i)$, the light reflected by the second wedge beyond the first wedge length cannot reach the second wedge. Therefore, there is only light1 at the L plane; the reflected light has no influence on the light.

The schematic of experimental setup is shown in Fig. 4. At first, we placed the first surface of the first wedged plate vertical to the horizon to make the incident angle

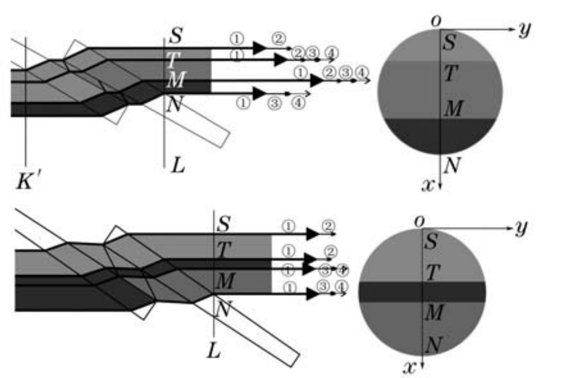

Fig. 3. Light intensity distribution on L plane. (a) $1 - 4s\cos\theta_i\tan\theta_{t2} > 0$; (b) $1 - 4s\cos\theta_i\tan\theta_{t2} < 0$, and $1 - 2s\cos\theta_i\tan\theta_{t2} > 0$.

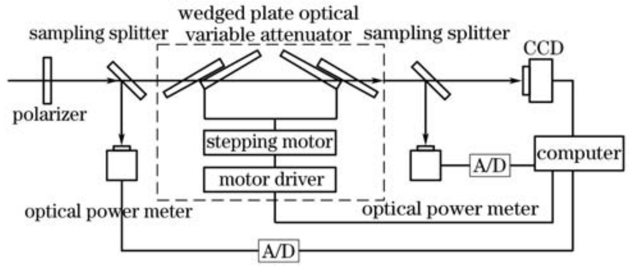

Fig. 4. Schematic of experimental setup.

zero. The polarized light transferred by a polarizer, is sampled by a sampling splitter before entering the attenuator and sampled by another sampling splitter after passing throgth the attenuator. Then an optical power meter gets the incident light intensity and another gets the exit light intensity, the values converted by A/D converter are transferred to a computer. The light intensity distribution measured by a charge coupled device (CCD) is also transferred to the computer. After receiving the values from two optical power meters and the CCD, storing the data, the computer begin to send a signal to the motor driver, and then the driver sets a pulse to the stepping motor. The stepping motor revolves a certain angle. And the computer receives new data from the measuring apparatus for new incident angle. After the stepping motor revolves a critical angle, we can draw the curve of the attenuation and the light intensity distribution at the exit plane with different incident angles[4,7,10]. Then we change the wedge space, and do the process again. We get some curves of attenuation and the light intensity distributions with different incident angles under the condition of different wedge spaces. From the curves, we can study the influence of the noise on the attenuation and light intensity distribution when the wedge space varies.

Supposing the incident light beam with beam diameter of 3 mm, wavelength of 650 nm, the glass wedge made by clown glass ($n = 1.51637$) with wedged angle of 1°, we simulate the influence of noise by using Matlab. The relationship of the attenuation and light intensity distribution at the exit plane of the attenuator are gotten, when the wedge spaces are 3, 30, 300 μm, respectively.

The curves of attenuation versus incident angle considering interference by the reflected light are shown in Fig. 5, when the polarization plane of the incident light is perpendicular to the incidence plane. And Fig. 6 shows the light intensity distributions along the x axis.

We can find that phase-difference δ varies with the incident angle from the simulated and calculated results above, and then the multiple beam interference results in that the curve of attenuation fluctuates around the theoretic curve without interference. When the wedge space closes to wavelength, the reflected lights have large influence on the attenuation. Especially at high attenuation, the transmission of light1 is small, yet the influence of the reflected lights grows larger with the proportion of the reflected light in exit light increasing. As shown in Fig. 5(a), when the incident angle closes to the critical angle the attenuation difference even reachs ±20 dB. And the reflected lights arrives at the second wedged plate only in small incident angle with a large wedge

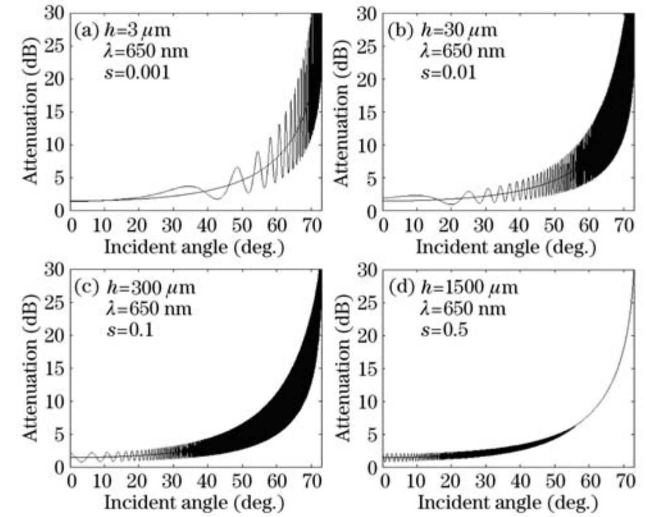

Fig. 5. Curves of attenuation versus incident angle (s light) with different wedge spaces.

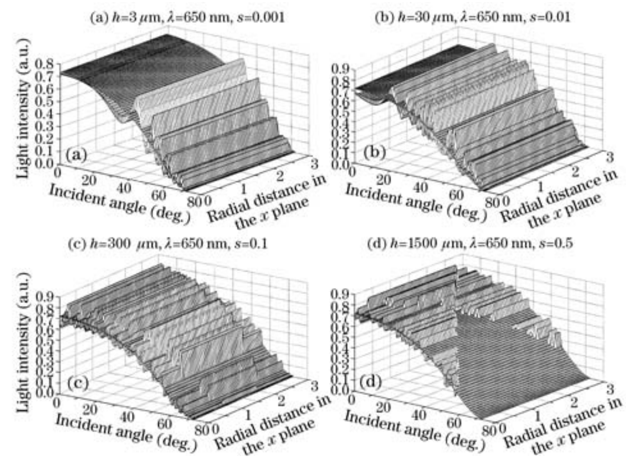

Fig. 6. Curves of light intensity distribution along the x axis (s light) with different wedge spaces.

space, limited by the length of wedge overlap. Therefore, the influence of reflected light on attenuation was reduced by enhancing wedge space. Then we examine the distribution of the light intensity at L plane. The different superpositions of different beam at L plane induce to a step radial distribution of light intensity. When the wedge space h is close to wavelength, $x_{\mathrm{MN}} = x_{\mathrm{ST}} = 2h\cos\theta_{\mathrm{i}}\tan\theta_{\mathrm{t2}}\cos(\theta_{\mathrm{t}} + 2\alpha)/\cos\theta_{\mathrm{t}}$ is small, thus the radial distribution of the light intensity is even to a certain incident angle, as shown in Fig. 5(a). But $x_{\mathrm{MN}} = x_{\mathrm{ST}} = 2h\cos\theta_{\mathrm{i}}\tan\theta_{\mathrm{t2}}\cos(\theta_{\mathrm{t}} + 2\alpha)/\cos\theta_{\mathrm{t}}$ grows large with the increase of the wedge space h. Then the step radial distribution of the light intensity is growing clear to a certain incident angle. When the wedge space h increases to a certain value, the radial distribution of the light intensity is obviously different with different incident angle. It is clearly shown in Fig. 6(d).

In conclusion, from the simulation above, it is shown that the multiply reflected light superposed on the light beam in attenuation system induces to multiple beam interference, and the interference results in the fluctuation of the curve of the attenuation, and the distortion of the wave front of the exit beam. And the impact degree of the coherent noise on the attenuation and the wave front of the exit light beam is decided by the interior structure of the attenuator (the distance between the parallel surfaces in wedge pair): increasing the wedge space can decrease the influence of multiple reflection on the attenuation, but complicate the distribution of light intensity on the beam section at the same time. It is proved that the influence of this kind of noise on light beam quality can be reduced by optimizing the structure of the attenuator.

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