Study on improvement of the laser uniformity transformation of overlapping-image waveguide cavity

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After propagating through the overlapping-image integral mirror, the interference fringe is a major factor that affects the uniformity of the image plane. In this paper, a He-Ne laser is used as light source, and the complex amplitude of the incident laser beam is modulated by an alternating electric field controlled vibrating mirror that is placed before the optical system. The experimental results show that after propagating through the overlapping-image integral mirror, not only the contrast of the interference fringes on the image plane is depressed, but also the uniformity of the intensity distribution of the transformed light beam is improved. Finally, based on the experimental results, two optical systems that can be applied to high power laser uniformity transformation are presented.

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In the study of the uniform transformation of laser intensity, the incident laser beam is divided into many sub-beams, and then these sub-beams are superposed together. This is an effectual method to obtain uniform irradiation. According to this principle, many optical devices have been developed[1−4], and this sort of device is usually called integral mirror. One of them is based on the imaging principle, which is called overlapping-image integral mirror. It can effectively depress the effect of "edge falling" (i.e. blurring and irregular boundary) at the boundary of the light spot caused by diffraction. Consequently this system has been widely used in the industry application of high-power laser[4]. However, because of the intensive coherent characteristic of laser, while the sub-beams that originate from the same incident laser beam are superposed together on the image plane, there are sharp interference fringes on the superposition pattern. How to depress the interference effect and improve the spot distribution is a challenging subject concerned with improving the performance of integral mirror[5].

The power density distribution in the interference light field relates to the amplitude and phase distribution of all coherent light beams. Thus, if the amplitude and phase distribution of each coherent light beam that reaches the observing region could be changed in real time, the power density distribution of the interference light field would vary with time. Whereas the energy absorbed by irradiated object is equal to the integral of power density with irradiating time, on the overlapping-image plane of integral mirror, the power density distribution, which is the energy superposition of the interference light wave whose amplitude and phase vary with time, can be obtained via suitably designing an optical system. Thus, the influence of interference fringe on the uniformity of power density can be restrained effectively, and the performance of overlapping-image integral mirror to homogenize light beam would be improved further. Therefore, by using He-Ne laser as light source, a set of overlapping-image device which is composed of two parallel plain mirrors (waveguide cavity) and two lenses is studied. At the same time a vibrating mirror is mounted in front of the device, so that the complex amplitude of light wave that entering the waveguide cavity can be changed in real time. Experimental test on the light wave demonstrates that after laser beam passing through the waveguide cavity, the contrast of the interference fringes in the light field on the observing plane has declined obviously after the vibrating mirror is introduced, and the uniformity of light beam on the overlapping-image plane has been ameliorated further. Based on the results, two kinds of optical systems with different structures which can be used to homogenize infrared high-power laser beam practically are presented.

Figure 1 is a schematic illustration of the experimental apparatus with a plain waveguide cavity, in which the incident laser beam is modulated by a vibrating mirror. In the figure, M_0 is a plain mirror placed at an angle of 45° to the incident beam and is in a simple harmonic vibration forward and backward about its equilibrium position. He-Ne laser beam transmitting from left to right is projected on the vibrating mirror M_0 firstly and is reflected by M_0. The reflected beam, after reflected by another 45° fixed mirror, then directs to a diaphragm M whose slit opens flatly. Subsequently the beam is focused by lens L_0 of focal length f_0 near the entrance of waveguide cavity and enters the cavity that is made of two flat rectangular mirrors placed parallel. In the cavity it goes through multiple reflections before emitting from the right-end exit of cavity. The image of light field on the cavity exit is formed by a lens L_1 placed after the cavity on the observing screen.

The above homogenizing function of the device before the vibrating mirror is introduced can be simply explained as follows: the focus of incident light formed by

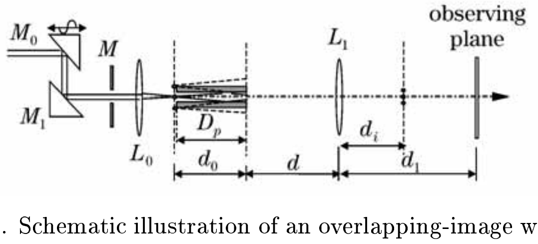

Fig. 1. Schematic illustration of an overlapping-image waveguide system with incident beam modulated by a vibrating mirror.

L_0 near the entrance plane of the cavity can be regarded as a point light source. Every reflection of internal surface of cavity leads to an equivalent mirror-image point light source. For multiple reflections, in fact the exit plane is irradiated simultaneously by multiple mirror-image point light sources which arrange longitudinally. Meanwhile only the opening of cavity is a transparent window on this plane. Corresponding to the original light wave on the exit plane, the common irradiation of multiple light sources is equivalent to the shift superposition of several wave bands that are gotten through flatly segmentalizing the original wave surface. The superposition of different parts of wave surface will improve the longitudinal uniformity of power density distribution on the exit plane. Because of the imaging effect of lens L_1, a tape-shaped light spot with quite trim boundaries will be formed on the image plane. However, owing to the spatial coherency of laser, the interference among the light waves from the array of point light sources will occur. Consequently the interference effect on the image plane is equivalent to the interference caused by the light waves emitted from an array of point light sources, which are formed while the rear focal plane of L_0 is imaged by L_1 at the distance d_i. The interference fringe will cause negative influence on the uniformity of light spot[5,6]. If the interference structure attached to the light spot can be eliminated, a quite homogeneous laser spot can be obtained along longitudinal direction on the image plane.

After the vibrating mirror is introduced, the vibration of M_0 along horizontal direction makes the position of light beam reflected by M_1 to oscillate in the vertical direction. Since the diameter of the He-Ne laser beam is very small, the spherical aberration of the lens causes the space position of the focus varying with time too. The light energy detected on the observing plane is the integral of the power distribution of interference light field with the detecting time. If the vibration period is largely shorter than detecting time, the light energy distribution with effectively weakened interference effect may be obtained.

In order to attest the theoretical analysis that the introduction of the vibrating mirror can improve the uniformity of the light spot on the observing plane, M_0 is fixed on a support that is driven by an electromagnetic exciting coil. The vibration period is selected as $T = 1/60$ s, and the alternating control current is supplied by an audio frequency signal generator. Considering the vibrating property of M_0, i.e. the velocity variation is less when it vibrates near the equilibrium position, and the velocity variation is larger as it vibrates around the peak amplitude, a diaphragm M with a 12-mm-wide horizontal slit is used to cut off the light beam near the extreme displacement up and down, so as to guarantee the light passing the diaphragm to move approximately at an even speed along the vertical direction. The photo when the light beam is blocked by M, which is taken by a charge-coupled device (CCD), and the chopping time of light beam are illustrated in Fig. 2.

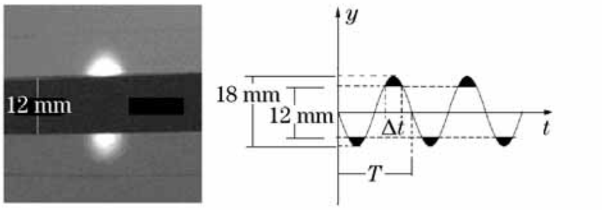

Fig. 2. The photograph and chopping time of the light beam interdicted by diaphragm M.

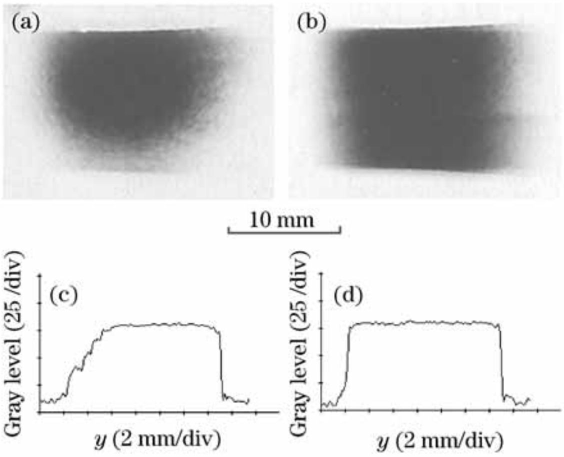

Fig. 3. (a) and (b): The light pattern of the observing plane without (a) and with (b) the vibration of the vibrating mirror. (c) and (d): The gray tone distributions along the perpendicular bisector of Figs. 3(a) and (b).

Referring to the definitions of related parameters in Fig. 1, the main parameters of the experimental arrangement are as follows: laser wavelength $\lambda = 0.6328$ μm, focal lengths of L_0 and L_1 are $f_0 = f_1 = 130$ mm, length of the waveguide cavity $D_\mathrm{p} = 101$ mm, window height of the cavity $2a = 5$ mm, distance between the exit of the cavity and the lens L_1 $d = 183$ mm, distance from the lens L_1 to the observing plane $d_1 = df_1/(d - f_1) \approx 449$ mm.

The holographic photographic plates are used as observing screen, and the exposure time is set as 1 second when the vibration is not introduced. In order to guarantee the equal light energy absorbed by the photographic plates in the cases of vibration and no vibration, the ratio of exposure time with vibration and without vibration is set as $T/(T - 2\Delta t) \approx 2.2$ according to the chopping time shown in Fig. 2. After the photographic plates are exposed, they are developed and fixed under the identical conditions. The light beam transforming performances of overlapping-image waveguide cavity with and without vibrating mirror are compared through observing the gray tone variation on the photographic plate.

The gray tone pictures of the light spots taken on the observing plane without and with vibration of vibrating mirror are given in Figs. 3(a) and (b), respectively. The widths of the two images are both measured to be 12.6±0.1 mm. According to imaging principle, the theoretical value should be equal to $2ad_1/d \approx 12.3$ mm, this means that the observing plane is close to the ideal image plane. The gray tone distributions along the perpendicular bisector of the two images are shown in Figs. 3(c) and (d), with the number of sampling points of 240.

It is obvious that the uniformity of the energy distribution of light spot is improved remarkably along the vertical direction by introducing the vibrating mirror. It is easy to discover that a rectangular light spot with trim boundaries and quite uniform energy distribution would be obtained on the image plane if the waveguide cavity is a rectangular cavity made of four plane mirrors[5,6] being parallel to each other per pair.

Since the wavelength of the laser is very short, the details of the interference fringes on the plate cannot be distinguished by naked eye, so we take the pictures of a tiny part in central area of Fig. 3 in virtue of measurement microscope. The pictures are shown in Figs. 4(a) and (b). The gray tone distributions along the perpendicular bisector are illustrated as Figs. 4(c) and (d). It is not difficult to appreciate that not only the contrast of interference fringes on the observing plane has declined obviously, but also the uniformity of energy distribution in local average has been improved.

The theoretical study reveals that the interference pattern on the observing plane can be described concisely through understanding the interference of an array of point light sources on the image plane imaged by lens L_1 with respect to the rear focal plane of lens L_0, and the maximal interference fringe spacing is[5,6]

$$T_{\max} = \left| \frac{\lambda (d_1 - d_i)}{2M_i a} \right|, \quad (1)$$

where M_i is the transverse magnifying power of the lens L_1 between the rear focal plane of lens L_0 and its image plane, referring to Fig. 1 it can be written as

$$M_i = -\frac{d_i}{d_0 + d}, \quad (2)$$

with

$$\frac{1}{d_0 + d} + \frac{1}{d_i} = \frac{1}{f_1}. \quad (3)$$

Let d_0 approximately equal to the length of the waveguide cavity D_p and take Eqs. (2) and (3) into Eq. (1), we can figure out $T_{\max} \approx 0.0316$ mm. In comparison with the experimental result in the Fig. 4, the theoretical calculated result accords well with the measured result.

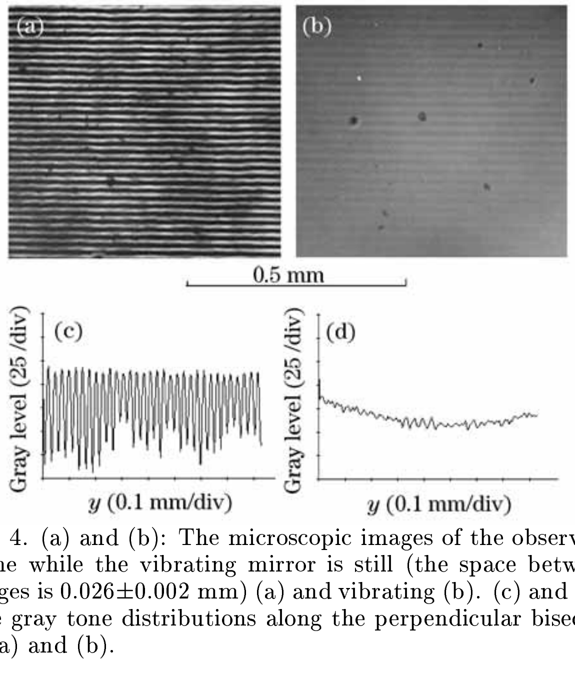

Fig. 4. (a) and (b): The microscopic images of the observing plane while the vibrating mirror is still (the space between fringes is 0.026±0.002 mm) (a) and vibrating (b). (c) and (d): The gray tone distributions along the perpendicular bisector of (a) and (b).

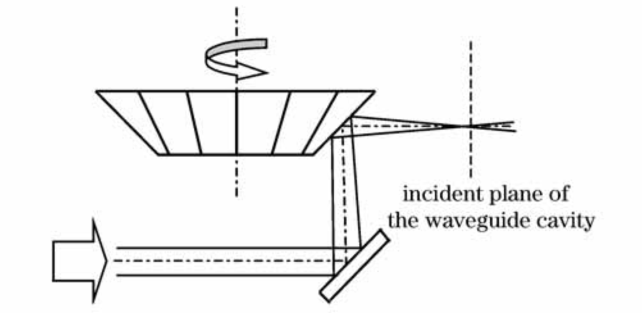

Fig. 5. Arrangement for modulating the light beam with rotational reflecting mirrors.

It should be pointed out that, the purpose of our experimental study is only to confirm that the optical system performance can be improved by changing the complex amplitude of the incident light in real time. Even though good results are obtained, the presence of the diaphragm M will lower the efficiency of the light power utilization. This is not suitable for laser application in industry that needs to decrease the laser power loss particularly. To solve this problem, we put forward two sorts of practical devices as follows.

Figure 5 show an arrangement in which the vibrating mirror is replaced by rotating reflecting mirrors. As shown in the figure, the laser beam transmitting from left to right is focused by a concave mirror and projected toward the rotating reflecting mirrors turning at a high speed. The rotating reflecting mirrors device is made up of many flat mirrors attached onto a 45° angle pyramid. When the pyramid rotates around its axis at a high speed, the focus point of the reflected light beam will move on a spatial surface that is approximately a plane[5]. Take the approximate plane as the incident plane of the waveguide cavity, the complex amplitude of the light wave entering cavity can be changed in real time, thus the same function to weaken the interference effect as the vibrating mirror is accomplished. For the case of Fig. 5, if the waveguide cavity behind is composed of two plane mirrors, the internal reflecting surface of the cavity should be arranged to parallel to the paper plane. If the waveguide cavity is constructed from four plane mirrors and has a square-section, the cavity should be turned so that the scanning direction of the focus point formed by the reflected light from the rotating mirrors accords with the direction of the diagonal of the square-section cavity exit. Thus, the effect to weaken the intensity of interference fringe produced by two light waves in perpendicular directions is accomplished. It is not difficult to find that, the composite optical system consisting of the rotating mirrors and the waveguide cavity can utilize the incident light energy sufficiently. Especially when the lens is replaced by the reflecting mirror with the same function, the optical system, which is made of metal material, is easy to cool, therefore it is able to homogenize the high-power laser beam further effectually.

Based on the electro-photo effect, if a kind of electro-optical crystal with desired characteristics with respect to the laser being transformed can be found out, the vibrating mirror M_0 can be replaced by this crystal. The

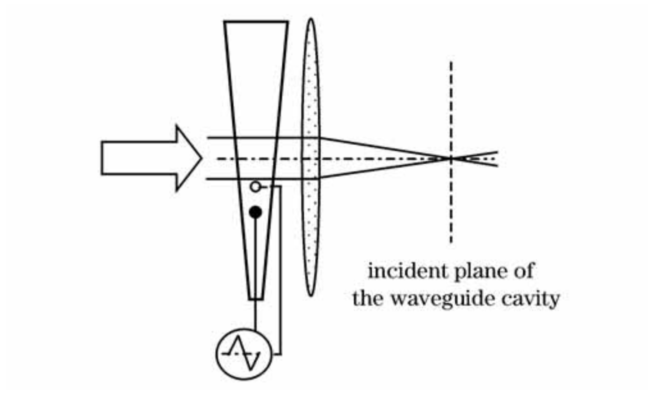

Fig. 6. Arrangement for modulating the light beam with an electro-optical crystal.

principle schematic that the laser beam entering waveguide cavity is modulated by an electro-optical crystal is shown in Fig. 6. In the figure the laser beam propagating from left to right is modulated by a wedged electro-optical crystal according to the transverse electro-photo effect of the crystal[7]. Both sides of the crystal are coated with thin conductive film, and a saw-tooth modulating voltage is applied. The oscillating direction of the light wave passing through the cavity is along the vertical direction, and the focus point of light beam formed by the lens also oscillates along the vertical direction linearly. So it is not difficult to conclude that an optical system, which can utilize the incident light energy sufficiently and achieve better performance of light beam homogenization, can be developed likewise, while the focal plane of lens is used as the incident plane of the waveguide cavity.

In the research of laser industry applications, the high-power laser uniformity transformation is an important subject that has been studied to obtain homogeneous laser irradiation. For a long time, to divide a laser beam into many sub-beams and then to superpose them again, there has been an important method to obtain uniform laser irradiation. One method is called overlapping-image integral mirror, in which the images of the divided wave bands are superposed together and the diffraction effect of the divided wave bands can be weakened obviously, not only the light spot with trim boundaries can be obtained, but also the energy distribution distortion of the light field caused by diffraction can be eliminated effectively, finally the light spot whose energy distribution is very close to the distribution according with geometry optics is obtained. A homogeneous laser spot is very important to exactly control the laser distribution in the area of the treated materials and is quite convenient to theoretical analysis of thermal interaction between laser and materials. If the interference effect is not taken into account, the light spot uniformity obtained by means of the overlapping-image integral mirror usually is one scalar level better than the non-overlapping-image integral mirror[3]. In the laser heat treatment to metal, the influence of dense interference fringe on the thermal acting can be ignored[8]; therefore, the performance of overlapping-image integral mirror is better than the non-overlapping-image optical system. However, when the thermal conduction of materials is poor or the laser irradiating time is very short, the interference effect caused by light wave superposition will always affect the local uniformity of the light spot. How to eliminate the effect of the interference fringe on the uniformity of the light beam and to futher improve the performance of overlapping-image integral mirror has been a puzzle for researchers.

The simulation research and the numerical analysis presented in this paper denote that, as long as the detecting time of laser is one scalar level longer than the vibration period, the interference effect can be remarkably depressed. But in fact, the presence of the diaphragm will reduce the utilizing efficiency of light energy in experiment. For the practical application, using the rotating mirror modulation scheme or electro-optical crystal modulation scheme can make full use of light energy. In industry application of laser heat treatment, the equivalent thermal acting time is usually at the level of several seconds[9], even though the equivalent time is shorter than 10^{-2} second, it is easy to achieve that the rotating mirrors with tens of reflecting surfaces reach the required rotating speed, so as to get the modulation period on light beam shorter than 10^{-3} second. For the electro-optical crystal, the response time may be as short as 10^{-10} second[7]. As soon as the electric-optical crystal that is suitable for the used laser can be found, the modulation to the laser beam will meet basically all applications involved in the applied study. Therefore, by mounting proper light modulating device in front of the overlapping-image integral mirror and changing the complex amplitude of the light wave before entering the optical system in real time, the contrast of the interference fringes on the image plane can be reduced remarkably, and the performance of the overlapping-image integral mirror can be improved further. The two optical systems presented in this paper can be used as the reference for developing practical optical system.

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