An optical device to homogenize a laser beam

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Based on segmentation-recombination principle, a specific optical device is designed to homogenize a high-power CO_2 laser beam which is used as a heating source. A model is developed to simulate the intensity distribution of converted laser beam. The results show that the theoretical simulation is consistent with experimental record. The uniformity of converted beam spot is discussed. After modifying the optical parameters of current device, a new optical system is given, through which the uniformity of shaped beam spot is improved remarkably.

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When the thermophysical parameters of ceramic materials are measured at high temperature (2000 °C), a specific optical device (kaleidoscope) is mounted in order to homogenize the power density distribution of CO_2 laser beam which is used as a heating source. Further study on such a homogenization device[1] is needed for improving laser beam quality.

Figure 1 is the schematic diagram of this homogenization device[1] mainly composed of a square-section kaleidoscope, four flat rectangular mirrors, and two convergent lenses.

Optical parameters and reference systems used for simulation are defined in Fig. 2. The laser beam, after exiting laser device, crosses the first lens L_0 (focal length f_0) and is focused on the S point that is the center of the circular small aperture placed at the center of the square entrance of kaleidoscope. The four flat mirrors of kaleidoscope form a square-section tube with $2L$ sides and a length d_1. After going through reflections on these mirrors, beams are overlapped together at the kaleidoscope exit. The second lens L_1 (focal length f_1) images the square exit section of kaleidoscope on sample surface. This phenomenon called segmentation-recombination principle is responsible for a homogeneous power density distribution in the sample surface[2,3].

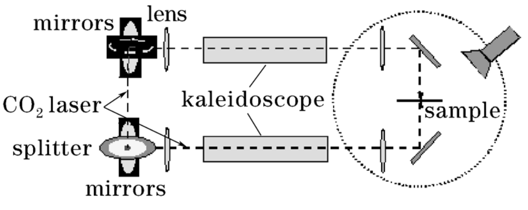

Fig. 1. Schematic of homogenization device.

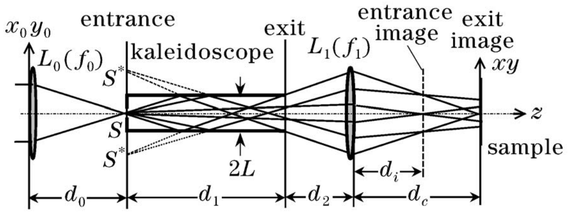

Fig. 2. Light path and optical parameters of homogenization device.

Let $U_0(x_0,y_0)=\sqrt{\frac{2P_0}{\pi\omega^2}}\exp\left(-\frac{x_0^2+y_0^2}{\omega^2}\right)$ be the complex amplitude of incident laser wave in x_0y_0 plane before L_0[4]. Here P_0 and ω are the total power and Gaussian radius of laser beam, respectively. The power density in the xy plane of sample surface is

$$\begin{aligned} I\left(x,y\right)=&\sum_{m=-N}^{N}\sum_{n=-N}^{N}\sum_{p=-N}^{N}\sum_{q=-N}^{N}F_{mnpq}\\ &\times\left|U_{mn}(x,y)\right|\left|U_{pq}\left(x,y\right)\right|\\ &\times\cos\left[\frac{2\pi}{T_{mp}}\left(x-M_i\frac{x_m+x_p}{2}\right)\right]\\ &\times\cos\left[\frac{2\pi}{T_{nq}}\left(y-M_i\frac{y_n+y_q}{2}\right)\right], \end{aligned} \tag{1}$$

where coherent factors are

$$F_{mnpq}=\begin{cases}1 & (m=p \quad \text{and} \quad n=q)\\ F_{ch}(0<F_{ch}<1) & (m\neq p \quad \text{or} \quad n\neq q)\end{cases}, \tag{2}$$

$$\begin{aligned} U_{mn}(x,y)=&\frac{1}{M_0M_c}\\ &\times U_0\left[(-1)^m\frac{x-M_cx_m}{M_0M_c},(-1)^n\frac{y-M_cy_n}{M_0M_c}\right], \end{aligned} \tag{3}$$

$$T_{mp}=\frac{\lambda(d_c-d_i)}{M_i(x_p-x_m)}, \tag{4}$$

$$\begin{cases} x_m=m\times 2L & m=0,\pm1,\pm2,\cdots,\pm N\\ y_n=n\times 2L & n=0,\pm1,\pm2,\cdots\pm N\end{cases}, \tag{5}$$

$$M_0 = -d_1/f_0, \tag{6}$$

$$M_c = -d_c/d_2, \tag{7}$$

$$M_i = -d_i/(d_1 + d_2). \tag{8}$$

After reflecting, sub-beams parted by mirrors become partially coherent due to polarization rotation. Depending on the measured contrast variations of interference fringes, an experimental value of $F_{ch} = 0.4$ is evaluated and used for the next simulations.

If the diameter of incident laser beam is D, the reflection times N can be determined by the following inequation[2]

$$N < \frac{Dd_1}{4Ld_0} + \frac{1}{2}. \tag{9}$$

For the optical system, its optical parameters are listed in Table 1, and parameters concerning CO_2 laser in Table 2. The simulation with respect to the power density distribution of converted beam spot, which is carried out through programming on a computer, is presented in Fig. 3. The comparison between simulated and experimental thermal results is given in Fig. 4. It is demonstrated that the simulated power distribution agrees with experimental results. Especially, the calculated spacing of interference fringes accords with measurement precisely[5,6]. The good agreement between prediction and measurement allows validation of the approach used for simulation.

Table 1. Optical Parameters of Homogenization Device

d_0 (mm)	d_1 (mm)	L (mm)	d_2 (mm)	d_c (mm)	f_0 (mm)	f_1 (mm)
127	200	5	254	254	127	127

Table 2. Laser Parameters

Laser Output Power, P_0 (W)	Gaussian Radius of Laser Beam, ω (mm)	Coherent Factor, F_{ch}
200	5	0.4

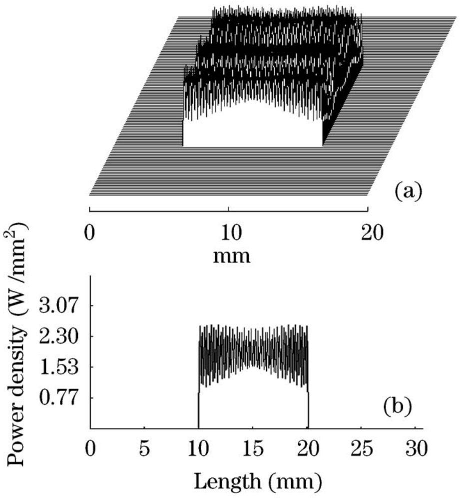

Fig. 3. Simulation of power density distribution of converted beam spot.

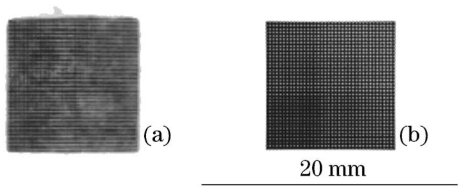

Fig. 4. Comparison between (a) experimental and (b) simulated thermal results.

It can be noticed that the converted square beam spot with sharp edges shows the local drastic variation of power density due to interference, though it is uniform on average. To appraise the uniformity of converted beam spot in which there are noticeable interference fringes, a synthetic criterion can be introduced as

$$I_f = (I_{\max} - I_{\min})T_{\max}, \tag{10}$$

where $T_{\max} = \frac{\lambda(d_c-d_i)}{2L|M_i|}$ is the maximal spacing of interference fringes. It means the maximal power fluctuation within unit length in the normal direction of fringes. Obviously, the smaller the value is, the more uniform the converted beam spot is. Combining Eqs. (1), (3), (4), and (7), the proportional relation can be obtained as

$$I_f \propto \frac{d_1}{2L} \times \frac{1}{M_0^2} \times \frac{1}{M_c}. \tag{11}$$

Thus, by increasing M_0 and M_c, or decreasing $\frac{d_1}{2L}$, the uniformity of converted beam spot can be improved further.

Keep incident laser beam and converted beam spot size

Table 3. Optical Parameters of Optimized Optical System

d_0 (mm)	d_1 (mm)	L (mm)	d_2 (mm)	d_c (mm)	f_0 (mm)	f_1 (mm)
50	54.35	3.5	187	267.14	50	110

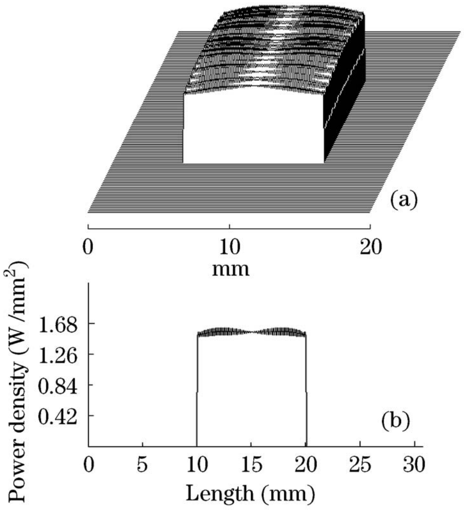

Fig. 5. Power density distribution of converted beam spot after optimization.

the same. Simultaneously, the reflection times $N = 1$ is not changed either, so as to suppress the contrast of interference fringes. Through modifying the optical parameters of the device, a new optical system is got (see Table 3). Correspondingly, the power density distribution of final beam spot converted by the optimized optical system is presented in Fig. 5. In addition, it is evident that the distribution in y direction is the same as it because of the symmetry of optical system.

Calculation shows that the uniformity of converted beam spot is improved remarkably, comparing $I_f = 0.46$ before optimization with $I_f = 0.039$ for new optical system. Meanwhile, for evading energy loss, the lens L_1 must be larger in size.

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References

1. J. Li, *The Laser Diffraction and Heat Reaction Calculation* (in Chinese) (Science Press in China, Beijing, 2002) p.288.
2. Z. Fan, J. Li, C. Li, and K. Ma, Chin. Opt. Lett. **3,** 24 (2005).
3. A. Delmas and J. C. Li, International Journal of Thermophysics **24,** 1427 (2003).
4. J. Li, Q. Zheng, D. Lin, Y. Qin, and C. Li, J. Optoelectronics·Laser (in Chinese) **13,** 767 (2002).
5. J. Li, Chin. J. Lasers (in Chinese) **28,** 1120 (2001).
6. J. Li, J. Merlin, Y. Qin, Q. Zheng, and Y. Fu, Opt. Eng. **42,** 3545 (2003).