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Beam homogenization structure for a laser illuminator design based on diode laser beam combining technology

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With the rapid development of laser technology, laser as the light source of night vision illuminating can realize long-distance and clear imaging, which has been widely used in laser active illuminating field. A high-power diode laser with a wavelength of 808 nm was designed as the laser active illuminating source, and the output power of no less than 100 W was obtained by spatial beam multiplexing, polarization multiplexing, and high efficiency fiber coupling techniques. In view of the beam homogenization of illuminating source, a novel beam homogenization system based on waveguide is proposed in this work. A square spot with a horizontal divergence angle of 40°, a vertical divergence angle of 10°, and an illuminating power ratio of 4:1 was obtained by a collimating lens. Comparing with the traditional circular illuminating beam, the square illuminating beam can match the illuminating angle of CCD camera better, and the energy utilization rate is higher. In addition, by optimizing the structure of waveguide and collimating lens, the illuminating angle can be changed to meet the illuminating requirements under different conditions theoretically.

Keywords: laser illumination; spatial multiplexing; polarization multiplexing; beam homogenization; waveguide.
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1. Introduction

In recent years, with the rapid development of laser technology, various new laser active illuminating imaging systems have been developed[1-4]. Among them, the CO_2 laser with a wavelength of 10.6 μm has the advantages of better atmospheric transmission performance and safety for human eyes whereas its disadvantages are low electro-optical efficiency, large volume, and complex design of optical imaging system. The all-solid-state Nd:YAG laser has the advantages of small size and easy maintenance with a emission wavelength of 1064 nm. However, the response of conventional photodetectors is very low, so the application of solid-state lasers in this field is limited[5]. At present, the mainstream solution is to use the diode laser with an output wavelength of 808 nm/940 nm, and the biggest advantage is its high electro-optical efficiency, high reliability, small volume, and high photoelectric detector responsivity[6,7]. With infrared camera, the CCD camera or low light level (LLL) night vision system can be used for surveillance at night or 24 hours under all weather conditions[8,9].

The traditional diode laser source realizes the circular beam and uniform beam output through fiber coupling. The irradiation angle of the output laser is the same and constant in the horizontal and vertical directions. However, the homogenization of the output laser is poor[10], which has a great influence in the illuminating application. If the illuminating beam has a lot of light and dark stripes, then the central spot is particularly strong, or the edge spot is particularly weak. In the actual imaging, it will obviously produce partially clear image, partially blurred image, or even no image phenomenon, which will have a great impact on the illuminating effect. Therefore, improving the uniformity of diode laser by beam shaping is very important for the application of laser active illuminating field[11-13]. At the same time, as a circular beam source, the illumination field of view is also round, so the field of view will be missing in the four corners, which will result in incomplete collection of information. Thus, designing a square laser source is necessary.

In this paper, a diode laser illuminating source is designed. The uniformity of laser beam is improved by beam combining and beam shaping technology, and the circular to square beam conversion is realized by a waveguide. The beam size and output divergence angle can be tunable, which is beneficial to the application of laser illuminating field.

2. Experimental Simulation and Design

Laser active illuminating source usually adopts air cooling. However, the line array laser and stack packing laser need to be cooled by deionized water. Hence, they are not suitable for application in this field. In this paper, a single emitter laser is used as a unit device, and typical parameters are shown in Table 1. The advantages of this scheme include the following: no influence of thermal crosstalk between unit lasers and high operation reliability. Laser output with high power and high uniformity can be obtained through beam shaping and beam combination technology[14,15]. The divergence angle in the fast axis is usually 30°–60° and the slow axis is 8°–12° because the fast and slow axis divergence angle of the diode laser is very large. Therefore, the use of the fast axis collimation lens (FAC) and slow axis collimation lens (SAC) is necessary to reduce the laser divergence angle to facilitate the subsequent spatial beam combination and polarized beam combination.

FAC adopts an aspheric column lens with a focal length of 0.3 mm, and the divergence angle in the slow axis is relatively small. Therefore, SAC adopts a spherical column lens with a focal length of 20 mm. Simulation is carried out by Zemax software, and the simulation results obtained are shown in Fig. 1. After beam shaping, the simulated divergence angle of the single emitter laser is 5.6 mrad (95%) in the fast axis and 10.5 mrad (95%) in the slow axis, and the corresponding spot size is 0.32 mm and 4.2 mm, respectively.

The laser parameter product (BPP) is usually used to evaluate the beam quality of diode lasers[16,17]. According to ISO-11146 standard, BPP can be expressed as

$$\mathrm{BPP} = \frac{\theta}{2} w_o, \tag{1}$$

where ω_0 represents the beam waist radius of the laser; and θ represents the far-field divergence angle of the laser, that is, BPP is the product of the beam waist radius of the diode laser and the half divergence angle of the far field. We call the minimum value of the BPP is diffraction limit. We compare the size, divergence angle, and BPP of the laser beam in the fast and slow axes before and after beam shaping. Table 2 shows that the BPP in the fast axis becomes worse after beam shaping, while BPP in

Table 1. Typical Parameters of Single Emitter Laser.

Parameters	Unit	Specifications
Center wavelength	nm	808
Center wavelength tolerance	nm	±3
Output power	W	8
Operating current	A	< 8.5
Operating voltage	V	< 2
Vertical far field 95% PIB	deg	≤ 35
Lateral far field 95% PIB	deg	≤ 12
Emitter width	μm	200
Polarization	/	TE

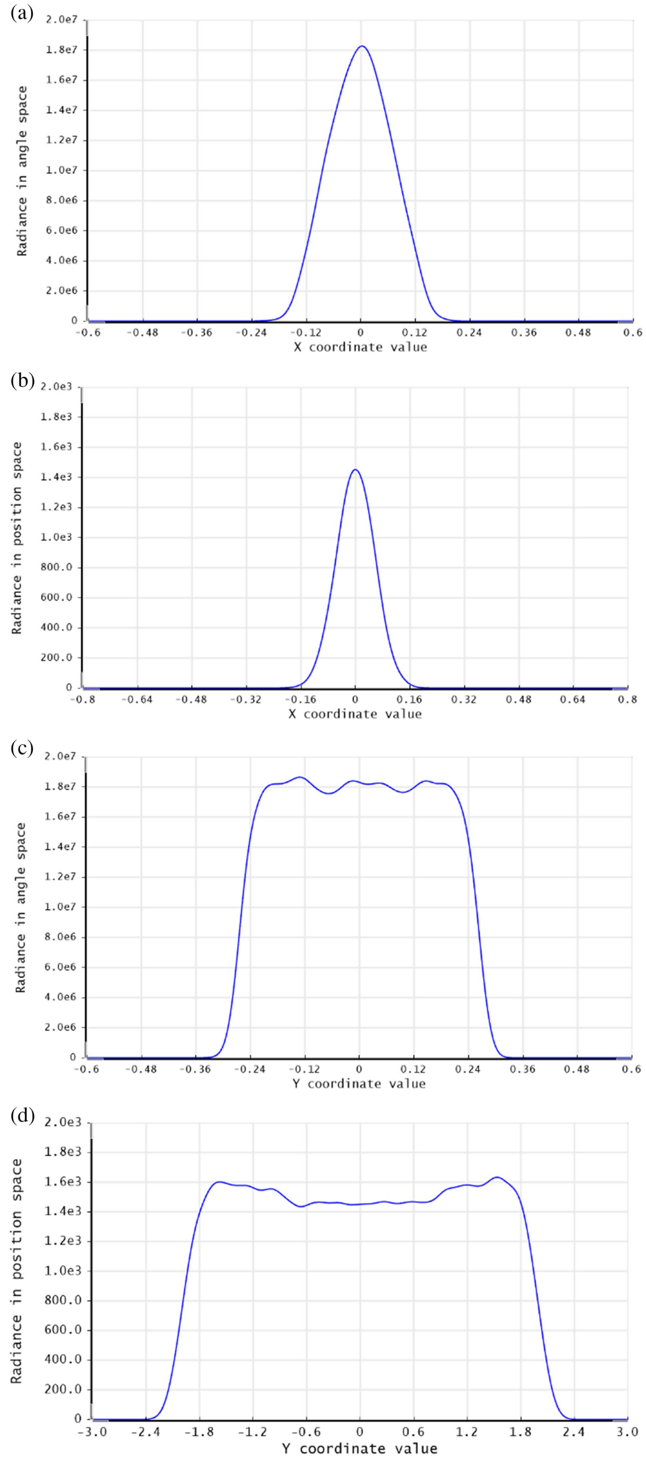

Fig. 1. Divergence angle and beam size of single emitter laser after collimation. (a) Fast axis divergence angle; (b) fast axis beam size; (c) slow axis divergence angle; (d) slow axis beam size.

Table 2. Beam Quality of Diode Laser before and after Collimation.

Parameters	$2\omega_0$/mm	θ/mrad	BPP/(mm·mrad)
Before collimated in fast axis	0.0015	612.5	0.23
After collimated in fast axis	0.32	5.6	0.45
Before collimated in slow axis	0.2	210	10.5
After collimated in slow axis	4.2	10.5	11.0

the slow axis changes slightly. Although the beam quality is still unbalanced, it can be further optimized by beam combining technology.

Beam combination is a process of homogenizing BPP in fast and slow axes. The BPP in the slow axis is much larger than that of the fast axis, so it is necessary to make the BPP in the fast and slow axes close by stacking beams in the fast axis. To obtain high power laser output, several single emitter lasers are combined by spatial beam combination and polarized beam combination. As shown in Fig. 2, the optical path is simulated and analyzed by Zemax software. The divergence angle in the fast axis is calculated to 8 mrad when considering the installation and adjustment error. A total of 10 single emitter lasers are used as a group, and the beams are stacked in the fast axis direction through spatial combination, in which the step spacing is 0.5 mm. In the end, the beam size in the fast axis direction is 5 mm, and the BPP is 10 mm·mrad, which is close to the BPP of the slow axis laser beam. To achieve the design requirements of high power, the "half wave plate +PBS" combination method is adopted to integrate the laser beam of another 10 single emitter lasers through polarization beam combination technology, and the power density is doubled while maintaining the beam quality. The laser beam after beam combination is shown in Fig. 3(a). We use the focusing lens to couple the combined laser into the fiber with a core diameter of 200 μm and NA 0.2 to homogenize laser beam, the corresponding beam quality is about 20 mm·mrad, and the beam spot after fiber is shown in Fig. 3(b).

The diode laser through beam shaping and coupling into the optical fiber can play the role of laser uniformity, but for the

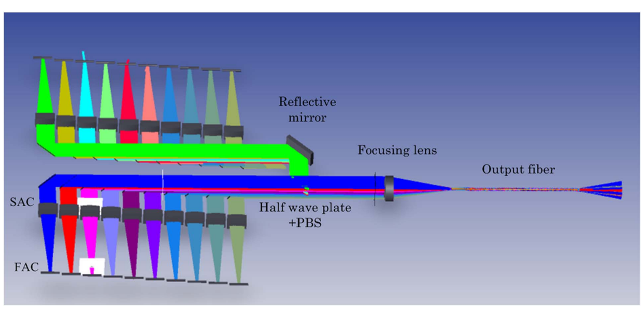

Fig. 2. Schematic of the beam combination structure.

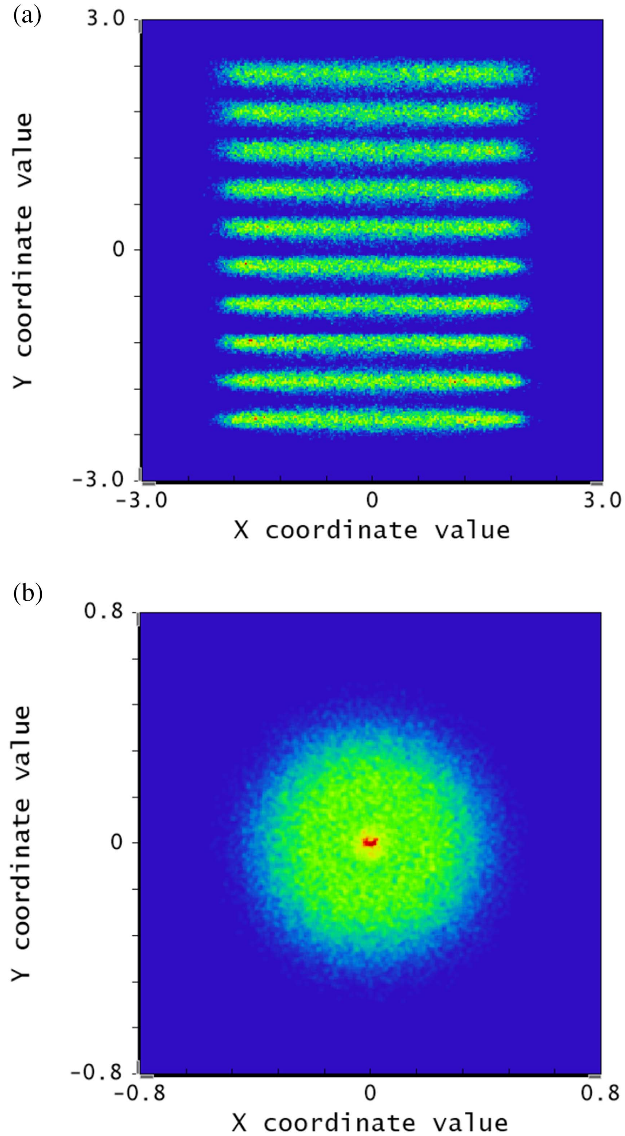

Fig. 3. Laser beam distribution (a) after beam shaping and space combining and (b) after fiber coupling.

illuminating source, light and dark stripes will become more obvious with the increase in transmission distance, and the beam uniformity will worsen. Therefore, a novel structure for laser beam homogenization is designed in this paper. The laser is radiated from the fiber and then passes through a waveguide to uniform the light again. In addition to uniform laser beam, the use of waveguide can also realize the conversion of circular to square beam. The length and width characteristics of the output laser can be controlled by the length and width ratio of the output port of the waveguide. Combined with the shaping lens, the irradiation angle can be changed. The schematic diagram of the optical path structure is shown in Fig. 4. In this paper, we take the uniformity of the spot and the structure size of the system into consideration. When the waveguide size is smaller, the number of laser reflection is larger, and the distribution of laser beam from

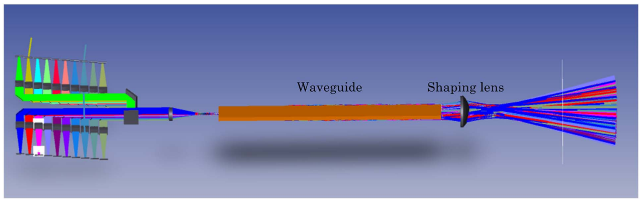

Fig. 4. Diagram of the light path structure.

waveguide is more uniform. The size of the adopted waveguide is 2 mm×8 mm×120 mm, and the output beam at 0.1 mm behind the waveguide is 2 mm×8 mm (Fig. 5).

To meet the practical application, the use of the beam expanding lens is necessary to change the beam divergence angle. In this paper, the horizontal divergence angle after beam expanding is approximately 40°, the vertical divergence angle is about 10°, and the ratio is 4:1 (Fig. 6).

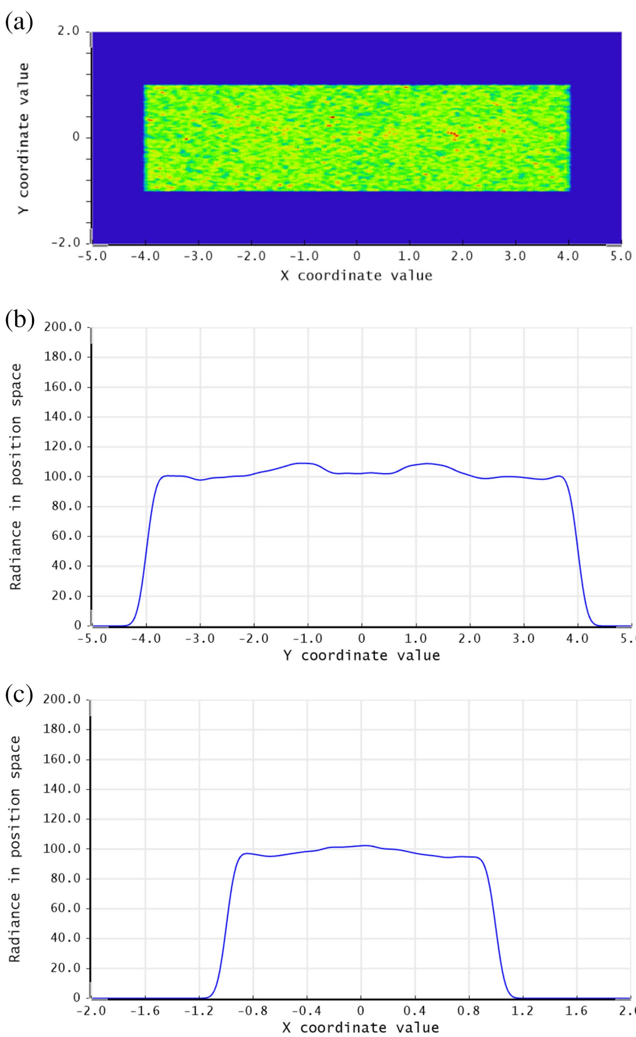

Fig. 5. (a) Laser beam distribution after homogenization; (b) horizontal beam size; (c) vertical beam size.

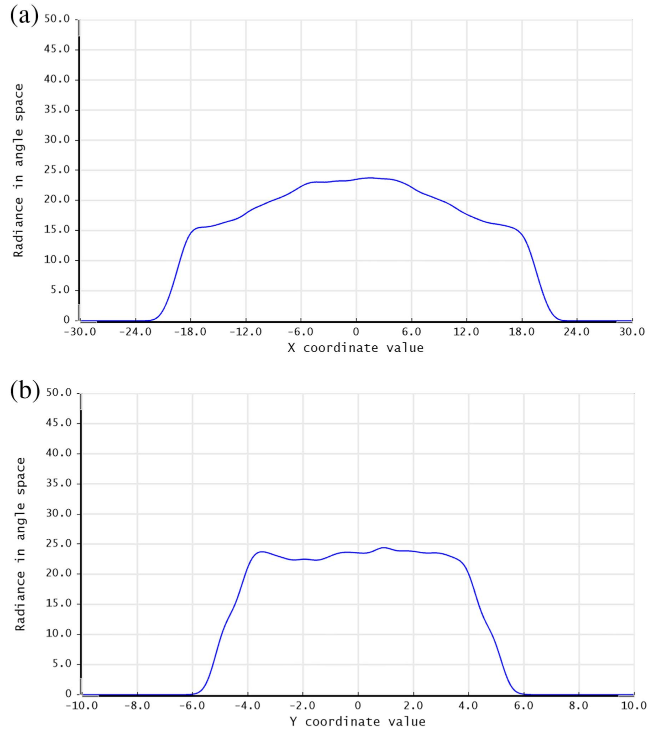

Fig. 6. Divergence angle after beam shaping: (a) horizontal direction; (b) vertical direction.

3. Results and Discussion

In this paper, the operating current of the illuminating laser source is adjusted within the range of 0–8 A, and the *P-I-V* curve is shown in Fig. 7. When the operating current is 8 A and the voltage is 36.07 V, we obtain a 139.5 W power laser output. For 808 nm single emitter laser with unit output power of 8 W, 160 W laser output can be achieved after 20-channel beam combination theoretically. The output power is lower than the theoretical value after beam combination because of four reasons. (1) In the process of space beam combination, the height of the ladder is 0.5 mm, and the edge laser beam is blocked more

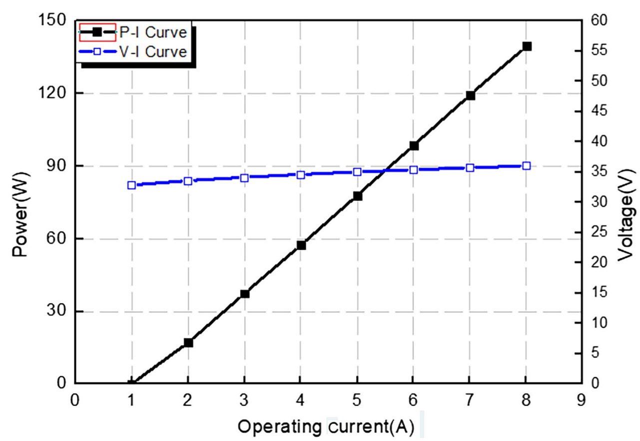

Fig. 7. *P-I-V* curves of laser illuminator.

or less in the actual installation and adjustment process. (2) The lenses in the optical path are coated with anti-reflection film, and the transmittance is 99%–99.8%, so a certain loss occurs. (3) The linear polarization degree of laser chip itself cannot reach 100% TE polarization or TM polarization, but usually is 95%–98%. In the process of polarization combination, TE polarization or TM polarization incident at an angle of 45°, compared with the ideal case incident at the Brewster angle, there is a certain angle error, so the loss will be generated. (4) Power loss will occur in the process of fiber coupling and waveguide coupling. When several processes are accumulated, the actual output power is lower than the theoretical output power.

The intensity distribution of the laser beam is evaluated in terms of uniformity. $I_{\max}$ and $I_{\min}$ represent the maximum and minimum intensity distributions, respectively. Uniformity can be expressed as[18]

$$U = 1 - \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}. \tag{2}$$

Figure 8 shows the illumination laser diagram. The uniformity of the beam under different operating currents is tested experimentally, and the results are obtained. Figure 9 shows that with the increase in operating current, the laser beam uniformity maintains good stability, and a uniformity of 90.4% can be maintained, thereby guaranteeing the effect of laser illuminating.

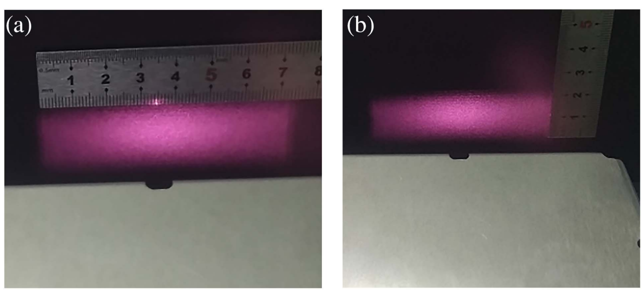

Fig. 8. Physical image of laser beam (a) horizontal direction (b) vertical direction.

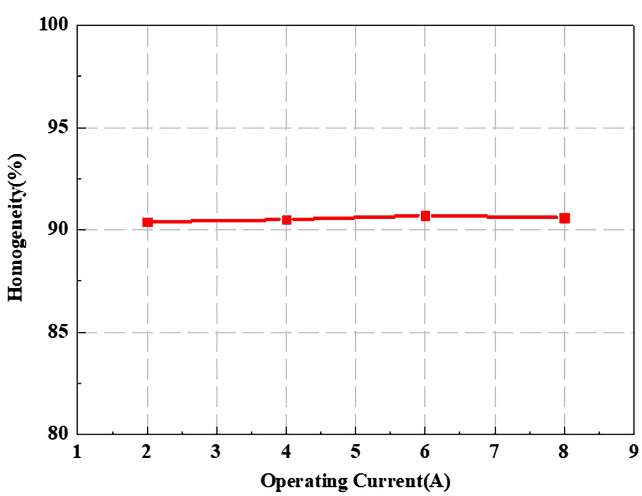

Fig. 9. Homogeneity of laser beam with varying operating current.

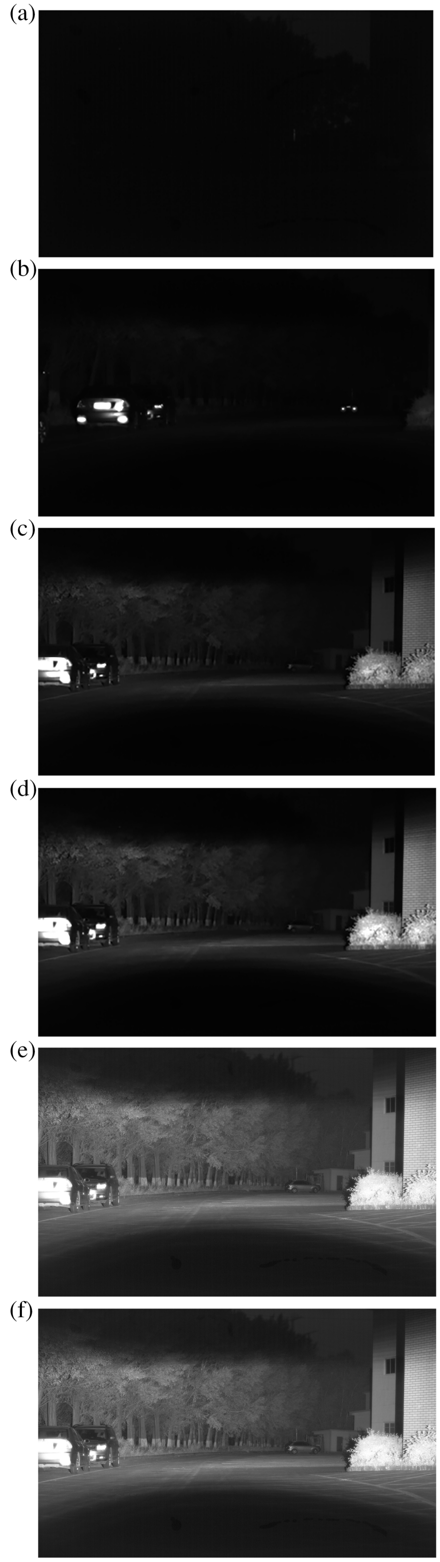

Fig. 10. Illuminating effect of diode laser with varying operating currents: (a) current 0 A; (b) current 2 A; (c) current 4 A; (d) current 6 A; (e) current 7 A; (f) current 8 A.

Finally, a night vision illuminating test is performed outdoors. Combined with computer image acquisition system, the beam of the diode laser output is captured by CCD. By changing the operating current, the laser power of the illuminating source is improved, and the images at 100 m are obtained (Fig. 10). CCD camera cannot detect any image information without an illuminating laser. With the increase in operating current, the image gradually becomes clearer. The illuminating beam presents a relatively regular rectangle, and the brightness within the illuminating range is very high and reaches the expected design goal.

4. Conclusion

In this paper, an 808 nm diode laser illuminating source with an output power of 139.5 W is developed by beam shaping, spatial beam multiplexing, polarization beam multiplexing, and fiber coupling technology. The illuminating beam is homogenized by fiber coupling and waveguide, and the conversion of circular to square beam is realized. The beam uniformity under different operating currents is greater than 90%, and the feasibility of the scheme is verified by field test. The square beam output with arbitrary length and width ratio can be realized by setting the size of the waveguide, and the horizontal and vertical divergence angles can also be changed by beam expanding lens. The diode laser illuminating source and the beam homogenization system provide conditions for the application of night vision illuminating source under different conditions.

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