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Experimental speckle evaluation of broad-area edge-emitting lasers

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ABSTRACT

The speckle characteristics of a broad-area edge-emitting semiconductor laser diode (BAEELD) in continuous wave emission regime are investigated experimentally. Performed measurements aim to assess the dependence of the speckle characteristics on spatial region of emitted light field, driving current and case temperature of BAEELD. When BAEELD operates at operating current of 550 mA and at 24 °C, the speckle in different regions from the broad-area field are measured by three different experimental configurations, including direct measurement, rotating the BAEELD, and gathering all emission by the collimating lens or two mirrors. The correlations between the speckle patterns of different regions of the broad-area field are analyzed. The results demonstrate that the speckle images measured are correlated although the BAEELD operates at different operating currents and case temperatures.

1. Introduction

Semiconductor laser diodes as light sources are becoming increasingly attractive in projection display due to their compactness, excellent electro-optical efficiency, easy scalable power by an array integration, line-spectrum, and mercury free [1–3]. However, highly coherent laser light usually leads to a granular structure masking the projected images, which is commonly known as laser speckle noise that degrades the quality of the images with large intensity fluctuations [4]. The human eye is very sensitive to intensity variations on an image, which has been extensively investigated [5–7]. So how to achieve low speckle noise is a major challenge in applications using the semiconductor laser diodes as the illumination sources.

As early as in 1970s, Dainty [8], Ohtsubo[9], Donati [10], Tiziani [11], and Goodman et al. have investigated the characteristics of laser speckle, where Goodman thoroughly explained the fundamental theory of speckle formation and its statistical properties [4]. However, mostly investigations are performed to the speckle generated from solid state or gas lasers. Recently, speckle characteristics of a vertical cavity surface emitting semiconductor laser (VCSEL) have been reported [12]. Their NIR broad-area VCSEL was droved in incoherent emission regime under pulse operation and in multimode emission under continuous wave operation. The lowest measured speckle contrast was reported at 19% in incoherent emission regime in imaging system. Kim et al., reported their measurement results for the speckle characterization of high power broad-area edge-emitting red and blue laser diodes. With a pulse driving mode, the highest speckle contrast reduction, 27.9% and 10.4%, can be achieved for their red and blue BAEELD, respectively [13].

In this article, we will focus on the speckle characteristics of BAEELD in continuous wave emission. Due to the structure of BAEELD as shown in Fig. 1, the cross section of its output beam is typically asymmetric and the beam in the fast axis is with strong angular divergence. Therefore a broad-area illumination pattern is formed in far field [14]. The characteristics of the speckle image formed by different illumination regions are investigated by using three different experimental methods, including direct measurement, rotating the light source, and gathering all light from the broad-area field by the collimating lens or two mirrors, when BAEELD operates at operating current of 550 mA and at 24 °C temperature. Furthermore, when BAEELD operates under different driving currents as well as different case temperatures, we analyze the correlation between the speckle images measured by using the central region of the illumination field of BAEELD.

2. Experimental methods and results

In this study the experimental setup to measure the speckle is shown in Fig. 2. A BAEELD used as the light source is the product of Mitsubishi ML501P73 with peak wavelength of 638 nm, typical

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0030-4026/

Fig. 1. The illumination field of an edge-emitting semiconductor laser diode.

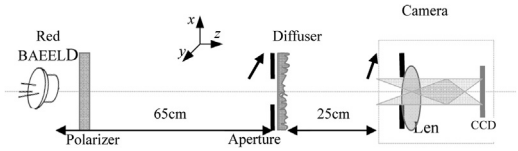

Fig. 2. Speckle measurement setup.

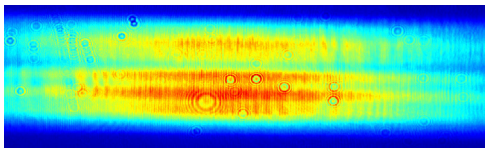

Fig. 3. Bar-shape illumination area of the BAEELD.

beam divergence (full angle, $1/e^2$) $\theta\parallel = 7.5^\circ$, $\theta\perp = 35^\circ$, and typical optical output power of 1 W. The intensity of the laser beam on the diffuser is controlled by rotating the polarizer. To maintain the same area of the diffuser in illumination, the circle aperture with the diameter of 1 cm is fixed with the diffuser which is not a fully depolarized scattering screen and has a scattering angle $=\pm 30^\circ$. After passing through the diffuser, the transmitted beam is collected by Camera lens (Pentax, C5028-M) at the distance 25 cm, and propagates to the CCD chip. The CCD chip has a 640×480 pixel array. The pixel has a dimension of $5.6\,\mu m \times 5.6\,\mu m$. The exposure time of the CCD camera is set to 30 ms to simulate the human eye integration time. The lens has focal length of 50 mm and an aperture f-number of 16. The gain of the CCD camera is set to avoid operations at over-saturation or under-saturation status. The gamma value was set $\gamma = 1$ to keep the CCD chip in the linear response region. All the measurements were carried out in the dark room to avoid the effect of ambient light. The diffuser and Camera can locate at different positions along with y-axis.

The BAEELD can emit, in a far field, approximately $8.5\,cm \times 40.9\,cm$ illumination area in x–y plane on the screen at the distance 65 cm, as shown in Fig. 3. The y-axis corresponds to the fast axis and the x-axis to the slow axis of the BAEELD. The overall output intensity of the BAEELD is made up from the superposition of all allowed transverse modes of the cavity.

2.1. Illumination angle dependence of the speckle characteristics

As the first investigation, a red BAEELD was driven in continuous-wave modal and operated with 550 mA (nearby maximum driving current in the specification) and 2.2 V at 24 °C. For speckle measurements, the different regions of the illumination field of BAEELD can be selected to shine on the fixed area of the diffuser by manually adjusting the diffuser along y axis in the range from 0 to 7 cm. In order to maintain the same observation angle, the CCD Camera and the diffuser moved together. Total $N = 15$ speckle images were captured. The speckle contrasts for individual speckle image, for the intensity sum of any adjacent two speckle images and of the first to Nth speckle images are calculated by the expression $C = \sigma_I/\langle I\rangle$, where $\langle I\rangle$ and σ_I are the mean intensity and the standard deviation of the speckle image, respectively. The results are presented in Fig. 4.

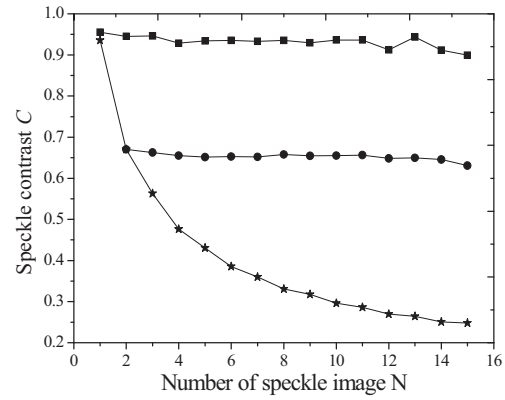

Fig. 4. Measured speckle contrast for the speckle images generated by the beam directly emitting from the BAEELD. The solid squares, circles and stars correspond to the contrasts for single frame speckle image, for adjacent two superimposed speckle images and for the superimposition of the first to the Nth speckle images, respectively.

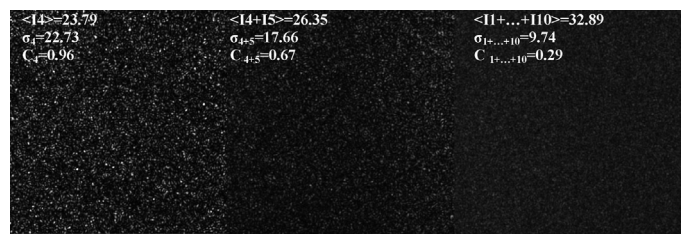

Fig. 5. The speckle images: from the left to right, the 4th speckle image, the sum of the 4th and 5th speckle images, and the sum of from the 1st to 10th speckle images.

It can be seen from Fig. 4 that apart from the random error induced by the measurement, the speckle contrast does not vary with different regions in the bar-shaped light field. The measured speckle contrast of individual speckle image is about 0.96. After two adjacent speckle images are superimposed on intensity basis, we found that the speckle contrast of superimposed image approaches to 0.7 $\left(0.96/\sqrt{2} = 0.679\right)$ and the contrast for the superimposition of the first to Nth speckle images is close to theoretical equation $C_0/\sqrt{N}$ (see the solid stars) for N independent speckle images, where C_0 is the measured contrast of individual speckle image.

As an example, in Fig. 5 we show the 4th speckle image (left), the sum of the 4th and the 5th speckle images (middle), and the sum of from the 1st to 10th speckle images (right). The intensity statistics corresponding to these speckle images with the 8-bit grayscale intensity are presented in Fig. 6.

As the second investigation, we only rotate the source along the y-axis and keep the other devices in the setup motionless to make the different regions of the illumination field from the BAEELD shine, in turn, on the same area of the diffuser, by this way we can keep the incident laser beam onto the diffuser with the same incident angle. The rotation of BAEELD is achieved by using a rotation stage with a rotating step of $\Delta\theta = 1^\circ$ within a rotating span of $\theta = 20^\circ$. Fig. 7 shows the speckle images when rotating the BAEELD by $\theta = 3^\circ$ (left), 12° (middle) and their sum on an intensity basis (right), respectively. As we can see, their speckle images are well correlated and their speckle contrasts are $C_3 = 0.954$, $C_{12} = 0.963$ and $C_{3+12} = 0.941$. For the further comparisons, the speckle contrasts calculated from the individual speckle image and the correlation coefficient between the first speckle image and others are presented in Fig. 8. All the speckle images are strongly correlation.

As the third investigation, we keep all devices motionless and add two mirrors into the optical path as shown in Fig. 9. The two beams at both sides of the illumination field that are reflected by the