VESTFOLD UNIVERSITY COLLEGE

imst
Institute of Micro and Nano Systems Technology

MASTER THESIS

SPECKLE CHARACTERISTICS OF LASER DIODES

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ABSTRACT

Laser, as the illumination source in the projector, has an intrinsic problem for high quality image. The speckle noise caused by laser coherence masks the details when the image projected on the screen. Therefore, to characterize the speckle noise of the different laser light sources becomes an important issue in developing the laser display technology.

The cheapest laser light sources, red and blue broad-area edge-emission laser diodes (BAEEL) invented in the last decades, will be characterized for future high brightness laser projector design. In this thesis, the laser emission spectrum has been measured at different operating temperatures and driving conditions. The speckle images from the laser diodes are formed on the glass diffuser screens and recorded by the CCD camera. For measuring the speckle characteristics of laser diodes, two typical measurement plans were designed, 1) the laser diodes with collimation lenses to form a small light spot in which all the light rays are roughly parallel, 2) the laser diodes without collimation lenses to get a large illumination area in the far field measurement. For the first measurement plan, we find that the speckle contrast strongly depends on the operating temperature and driving current, which can be explained by the temperature and current dependence of the emission spectrum. For the second measurement plan, three different optical-pass configurations have been setup in IMST optical lab. Under a certain measurement conditions, at specific temperature and driving current, we investigate the speckle images of the blue laser diodes in the far field, where the illumination field is a bar-shape with a large area. The speckle contrast of the different areas in the large illumination field is measured by moving the diffuser screen, by moving the diffuser screen with optical axis alignment, and by rotating the diffuser screen with optical axis alignment. The correlation of the speckle images measured in the different illumination areas is analyzed. We have observed the speckle contrasts depending on the measurement configuration. By changing the operating temperature and driving current, the speckle characteristics of the semiconductor laser diodes can be modulated; It is possible to design high brightness and low speckle noise projectors by engineering the driving scheme, temperature control, and integration configuration of the semiconductor laser diodes.

Key words: laser display, speckle reduction, speckle characterization, laser diode

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Abbreviations

LD	Laser Diode
LASER	Light Amplification by Stimulated Emission of Radiation
VCSEL	Vertical Vavity Surface Emitting semiconductor Laser
BAEEL	Broad Area-Edge Emitting-Laser diode
CCD	Charge Coupled Device
MEMS	Micro-Electro-Mechanical Systems
SD	Standard Definition
HD	High Definition
CIE	International Commission on Illumination
LED	Light Emitting Diode
LCD	Liquid Crystal Display
CRT	Cathode Ray Tube
RGB	Red, Green and Blue light
ND	Neutral Density
OD	Optical Density
LSR	Laser Speckle Reducer
CW	Continue Wave

1 INTRODUCTION

1.1 Background of the laser display

Display technology has experienced a black and white display, color display, and digital display. Color display gives us a colorful world comparing with the black and white display. While the digital display shift the display from standard definition (SD) to high definition (HD), in which the analog signal image is transferred into the digital signal image. The representative display technology in nowadays is the HD Liquid Crystal Display (LCD) with the Light Emitting Diode (LED) as the backlight, which can only present the images of less than a half color range compared with the color which can be seen by the human eyes. The use of Laser emission as the illumination light, make the display more vivid and high contrast. The laser display technology can cover 90% of the natural color gamut. Fig.1 shows the international commission on illumination (CIE) 1931 x, y chromaticity diagram for laser, LED, LCD and Cathode Ray Tube (CRT) based displays, where the chromaticity of laser displays completely covers the others[1, 2]. Briefly, the laser display technology can deliver the following advantages:

- Large color gamut due to the line spectrum characteristics
- High saturation and high contrast due to the limited straight light
- Long life due to the long lifetime of the laser sources
- Few optical components due to the purity of the laser light spectrum
- High F number optical system due to the small etendue of the laser light
- Compact size
- High optical-electrical efficiency
- Low power consumption
- Environmental friend fabrication due to the mercury free.

Based on these advantages, laser TV, Pico laser projector, laser projector for digital cinema and professional applications have been demonstrated worldwide. Commercial product such as laser TV was marketed by Mitsubishi in Northern America several years ago. Phoebusvision demonstrated 50000lm professional use projector in 2008. The Barco demonstrated its never-high brightness 66000lm laser projector in 2012. In earlier 2013 Sony broadcasted the 4000lm speckle free projector.

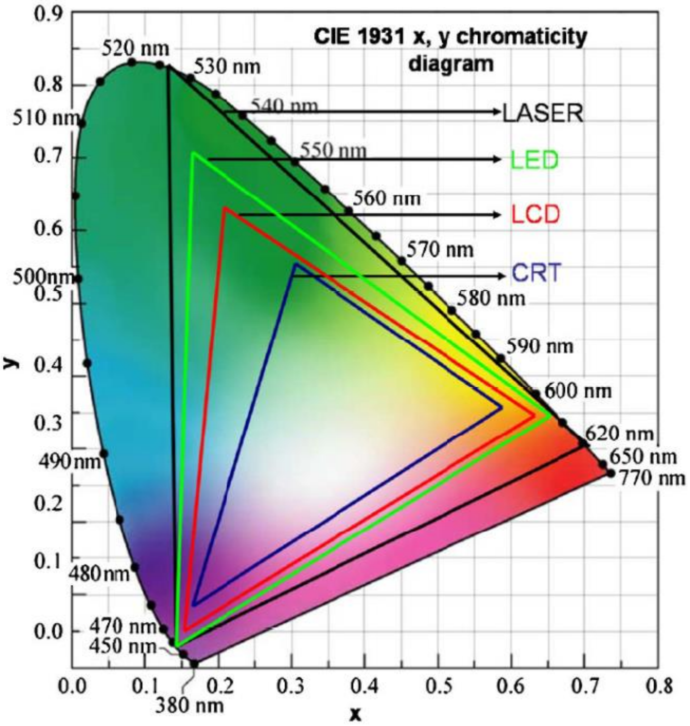


Fig. 1 The CIE 1931xychromaticity diagram for laser, LED, LCD and CRT based displays[1]

Though suggested as earlier as that the first working laser was reported in 1960, using laser to design the display devices does not make a disrupted technology due to 1) the laser sources were very expensive and the size was too big, 2) the laser speckle noise resulted from the laser temple and spatial coherence. As of today, research on laser display technology has been a focus topic for research institutes and display industries due to the solid-state and semiconductor diode lasers become widely available with an acceptable price. After the long march of several decades in developing semiconductor laser diodes, the large optical power of red and blue laser diodes have been commercialized recently.

1.2 Challenges in developing laser display technology

In the early of 1960s, by using laser source in display applications, researchers noticed that high contrast and fine scale granular structures were seen by the observer, which was defined as the laser speckle noise [3]. The speckle noise happens due to the random scattering of coherent laser radiation from the rough surface of the screen whose roughness is of the order of wavelength[4]. The scattered lights interfere with each other to generate random distribution of the intensity of light.

Speckle phenomenon is well illustrated in Fig. 2 (left), and a typical image of speckle pattern is shown in Fig. 2 (right). This speckle noise can reduce the image contrast and resolution, thus degrade the quality of the images. In the projection display, the screen must be made to be rough in order to have the wide angle observation. The speckle image will certainly be produced in such case, which can mask the projected images which cannot be enjoyed by human eyes[5]. Therefore, how to achieve low speckle noise is a major technique challenge in using the laser sources as the illumination sources for display technology. Fig. 3 and Fig. 4 show the image after speckle reduction and before the speckle reduction [6].

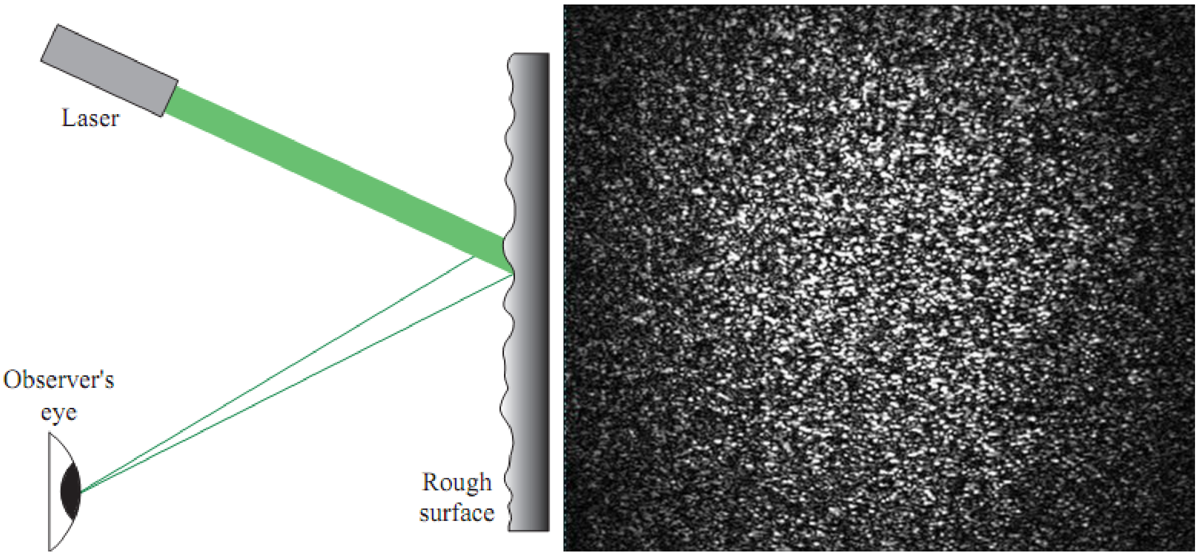


Fig. 2 Schematic presentation for physical origin of speckle phenomenon (left) and a typical speckle pattern (right).

Fig. 3 Speckle free projected image (left) and the image with speckle noise (right).

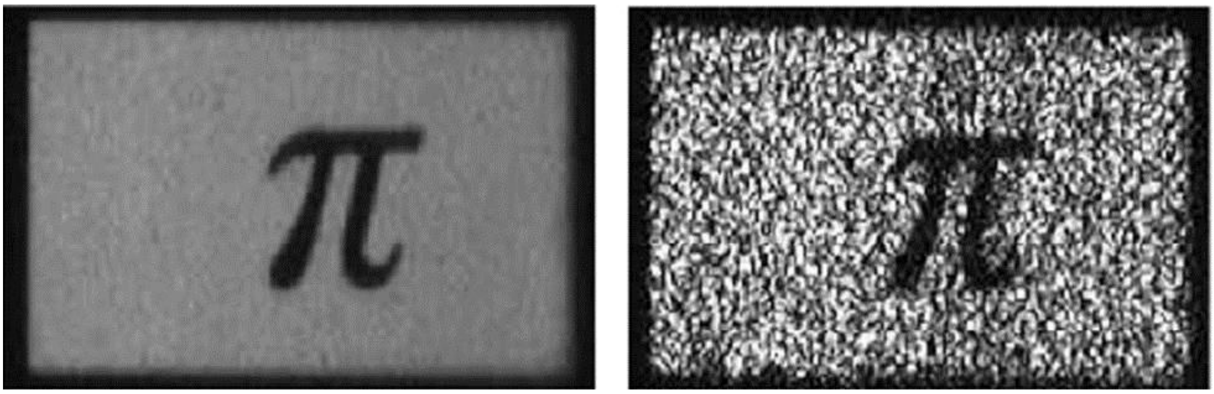


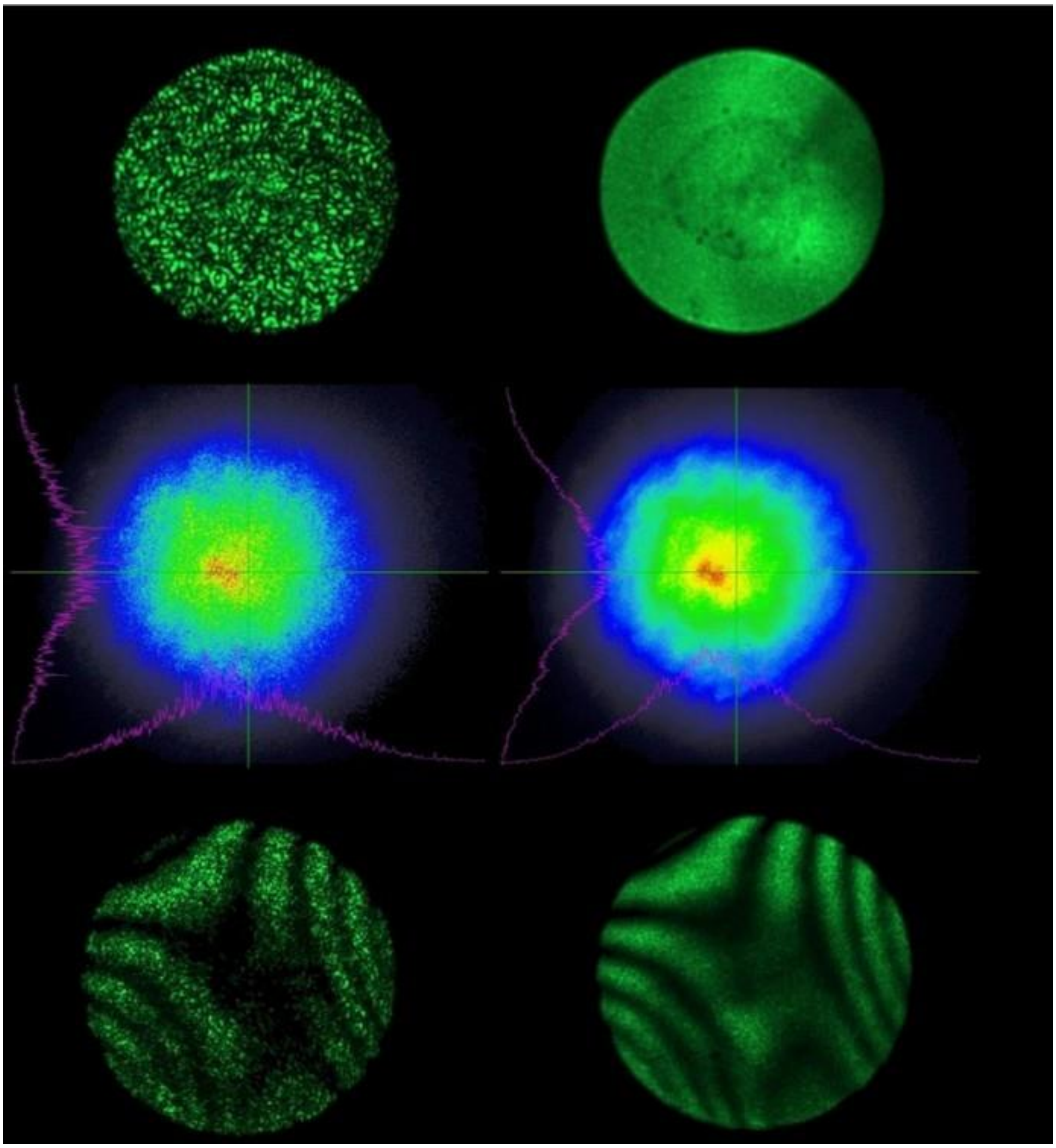
Fig. 4. Image after the speckle reduction (left) and before the speckle reduction (right)[6].

As the second challenge in developing laser display technology, both the gas lasers and the frequency doubled solid state lasers are very expensive and bulky, which blocked the possibility for commercialization of the laser display devices. The good news is that nowadays the semiconductor laser diodes have been fabricated based on the wideband gap semiconductor materials. The semiconductor diodes are much smaller and of relatively cheap price which will drop following the famous Moore's law in the years to come.

1.3 Laser speckle reduction

In order to reduce the speckle noise to emphasis the vivid image quality, a number of speckle reduction methods have been investigated. In brief, the basic principles for speckle reduction are, 1) integrating the series images in human eye integration time (typically 30s) which is partly or fully uncorrelated, 2) destroying the laser temple and spatial coherence, 3) using laser array in a certain space distribution, and 4) overdesigning the projection optics as compared with the resolution of the human eyes. As the examples, moving diffuser in the projection optical path of the projector to create partially correlated intermediate images have been widely investigated for reducing speckle in projectors [7], in which the diffuser can be random diffusers [3], or phase patterned diffusers such as Hadamard matrix [3], orthogonal array phase modulator [8], a barker like binary phase codes [9-11]. By introducing a movable screen, the series images of partially uncorrelated will also be able to be created in the eye integration time [3]. In the illumination optical path, the incident angle diversity of the light has been realized by different inventions [5, 12-14], G. M. Ouyang at HiVe used the motionless diffractive optical element to reduce the speckle of laser display [12]. The laser sources with broadband width spectrum realized via engineering the crystal for frequency doubling is the way to reduce the coherence emission. The semiconductor laser diodes in general emit multi-modes and change the centre wave length at different operating temperatures, which all benefit to the low speckle contrast in the projected images. Integrated laser diodes array with correct distance between two conjunction diodes is a good for speckle reduction. With the development of laser display technology, the speckle reduction devices have emerged time to time in last years. Dyoptyka, a company in U.K has launched its SPECKLEFREE™ series deformable mirrors for speckle reduction [13]. Optotune in Switzerland has marketed its LSR-3000 series movable diffuser droved by electroactive polymer [14]. Fig. 5 shows the two mentioned despeckle modular [13]. And Fig. 6 (b) shows the image after suppressed speckle using SPECKLEFREE mode, Fig.6 shows the image of speckle before suppressed [14]. Fig. 7 shows the images of speckle contrast before and after using LSR-3000 mode from Optotune [15]. No matter laser projector or laser television, effective speckle reduction technology has been proposed and has been able to manufacture the display prototype.

Fig. 5 The speckle suppression devices: SPECKLEFREE™ (left picture) and LSR-3000 (right picture) [13]



(a) Before speckle suppression (b) after speckle suppression

Fig. 6 Images of speckle contrast before and after using SPECKLEFREE™ [14].

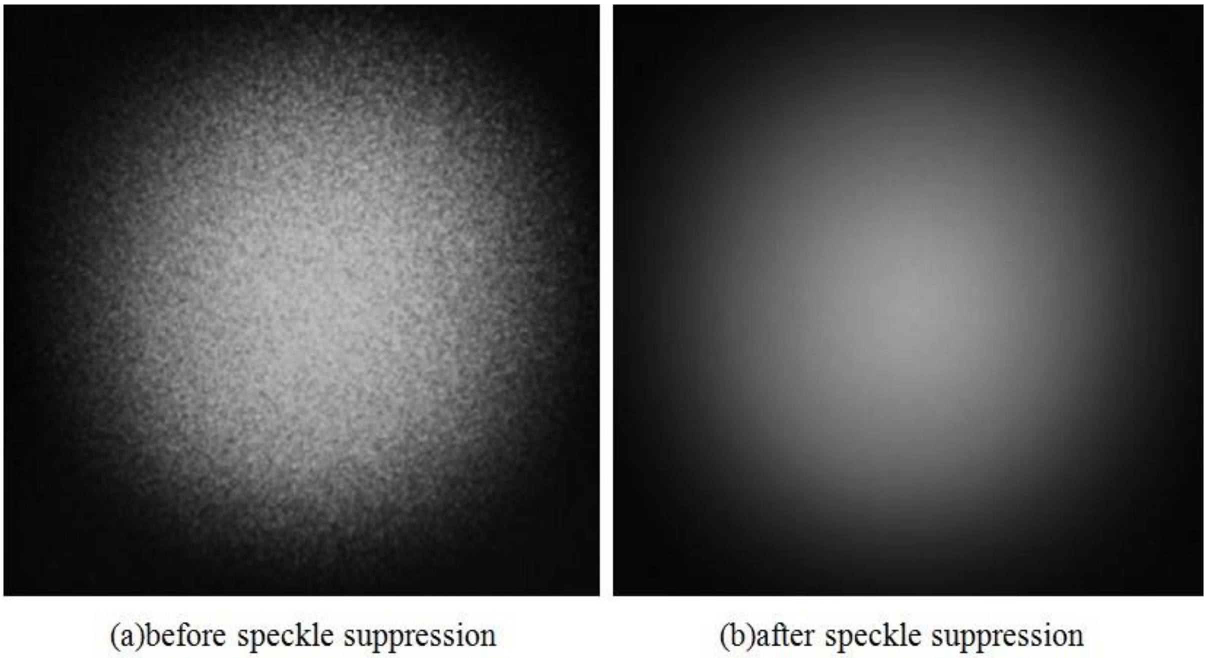


Fig. 7 Images of speckle contrast before and after using LSR-3000 [15].

1.4 Semiconductor laser diodes as the illumination sources for laser display technology

Thanks to the breakthrough made in semiconductor technology, semiconductor laser diodes emitting in the red and blue wave length now are commercial available although the power output of individual laser diode is limited for high brightness projectors. Mitsubishi sells the red laser diode with 500mW. Nichia launched the 3.6W blue laser diode. As illumination sources in the laser display technology, semiconductor laser diodes are compact and can be integrated in diodes array which has advantage of low speckle contrast. Prior to the laser diodes, the degree of the coherence and the speckle characteristics of a vertical cavity surface emitting semiconductor laser (VCSEL) have been reported [16, 17]. Under different driving conditions, VCSEL can work in, for example, the incoherent emission regime under pulse operation, and the multimode emission under continuous wave operation. The lowest speckle contrast was 19% in incoherent emission regime measured in image geometry. There is not research published in the journal about the speckle characteristics of the broad-area edge-emitting red and blue laser diodes. In order to develop a speckle free projector by using the broad-area edge-emitting semiconductor laser diodes, the speckle characteristics of such laser diodes have to be firstly investigated. In this thesis, the speckle images formed by using red and blue semiconductor laser diodes to illuminate the paper or glass screen are recorded in different optical configurations and the correlation of the images and the speckle contrast were studied.

1.5 Organization of this thesis

To present our experimental work and research results, this thesis is organized in 6 chapters.

Chapter 1 is the short introduction about the background of laser display technology. In this chapter, the advantages of laser display technology, the challenges in developing the laser display technology, and the speckle noise reduction methods are presented. The motivation and the objectives of the master project are described in brief.

Chapter 2 starts with the configuration of the laser projector display system, and then describes the experimental setup, the key elements or devices for the measurements in detail. The research plan involving different measurements are given to conclude the chapter.

Chapter 3 and Chapter 4 report the experimental results. The laser diodes emission spectrum and the speck contrast versus operating temperature and driving current are reported. The speckle images measured in different optical configurations are given for analysing the speckle characteristics of the lasers under test.

In the Chapter 5, we discuss and analyze the experimental results.

Finally, we make the conclusions in the Chapter 6.

2 Experimental Setup and devices

2.1 Laser speckle measurements

A standard way to characterize the laser speckle is to use an optical setup, in which laser light will incident onto a rough screen to create a speckle image. The image will be recorded and analyzed to determine the distribution of un-homogenous light intensity. The laser speckle usually is quantified by the speckle contrast C which is defined as the following:

$$C = \frac{\sigma}{<I>} = \frac{\sqrt{<I^2> - <I>^2}}{<I>}$$

where σ is the standard deviation of the light intensity in the speckle image, I is the light intensity, and ⟨I⟩ is the mean value of the light intensity. For a fully developed speckle image, Goodman proved that the standard deviation of the fully developed speckle intensity equals the mean value [3]. Therefore, the speckle contrast of the fully developed speckle image equals to 1, C=1. In general, the speckle image can be taken in two different optical geometries. As the first, the speckle image is taken from the free space, and the second, the speckle image is taken from the image geometry.

2.1.1 Objective Speckle

The following Fig.8 shows the free space measurement configuration, where the speckle image is taken by the photo film or detector arrays such as CCD chips in a distance away from the rough screen. The speckle image on one point of film or one pixel of the detector array is formed by the waves scattered from different points of screen, which interfere with each other at the detecting point [18].

In such a measurement configuration, with a fixed light spot dimension the distance of the detector from the screen will determine the average size of the speckle grain. Care must be taken in configuring the measurement setup to assure that the speckle size will be much bigger than the pixel of the detector, so that the spatial average of the speckle intensity will not happen on the pixel of the detector.

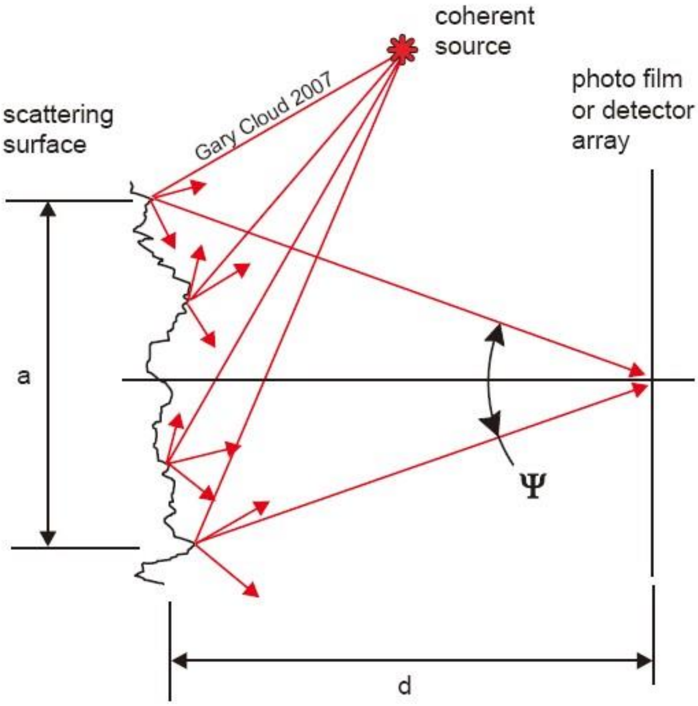


Fig. 8 Schematic plot of the objective speckle measurement

2.1.2 Subjective Speckle

The Fig. 9 displays the configuration for the image geometry measurement, where the speckle image is taken by the photo film or detector arrays such as CCD chips in a distance away from an image lens which is placed between the detector and the rough screen. The converging waves scattered from single point of the rough screen have traveled various path lengths and interfere each other to produce a particular brightness at the convergence point, which in this configuration is the detecting point [18].

In such a measurement configuration, with a fixed aperture of the image lens the distance of the detector from the image lens will determine the average size of the speckle grain. Similar to the objective speckle measurement, the speckle size must be assured to be much bigger than the pixel of the detector, so that the spatial average of the speckle intensity will not happen on the pixel of the detector.

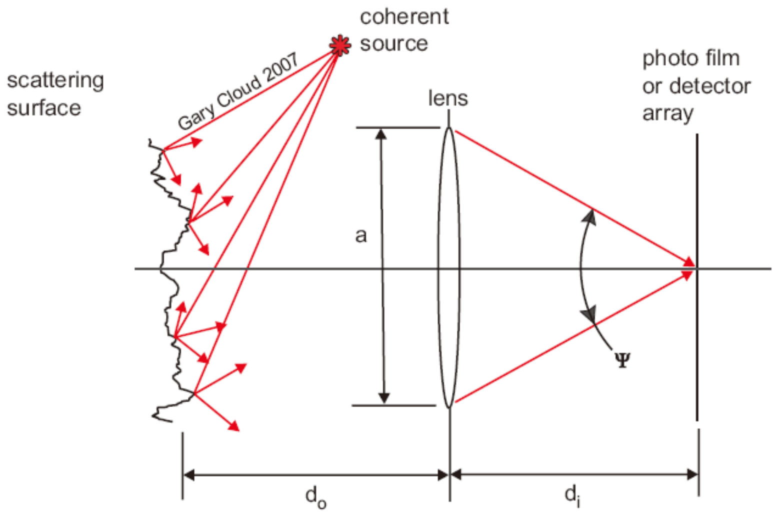


Fig. 9 Schematic plot of the subjective speckle measurement

2.1.3 Laser Speckle measurement setup

In our study, both the objective and the subjective speckles were measured with the general configuration as shown in Fig. 10, where the objective speckle was measured with the CCD camera without the lens, and the subjective speckle was measured with the CCD camera mounted with a lens.

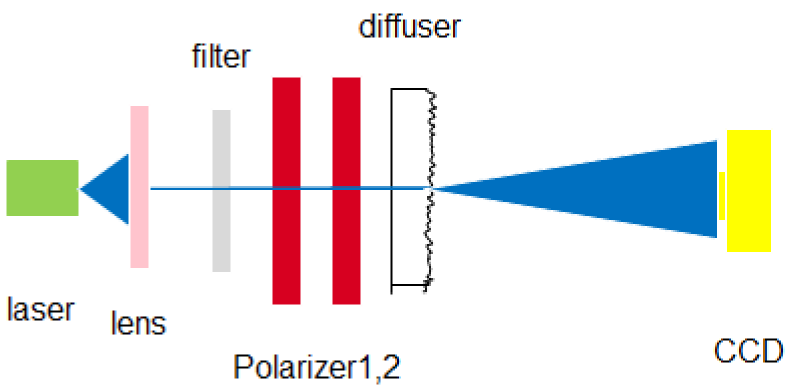


Fig. 10 Optical scheme for the speckle measurement setup in this thesis

(1) Filter

To control the light power onto the detector without changing the laser light spectrum, absorptive neutral density (ND) filters from company EO are selected in the setup. We have ordered the ND filters with optical density (OD) ranging from 0.15 to 2.5, see Fig. 11. For the high power blue laser diode, the OD of 2.5 is used in the experiment.

Fig. 11 The filter in our laboratory

(2) Polarizer

In the optical path configuration, the polarizer is also used to modulate the laser power onto the detector so that the detector will not work beyond the dynamic range. Two polarizers can be required in some cases in order to get proper light intensity. Fig. 12 shows two 42 mm Circular polarizers from Thorlabs in the experiment.

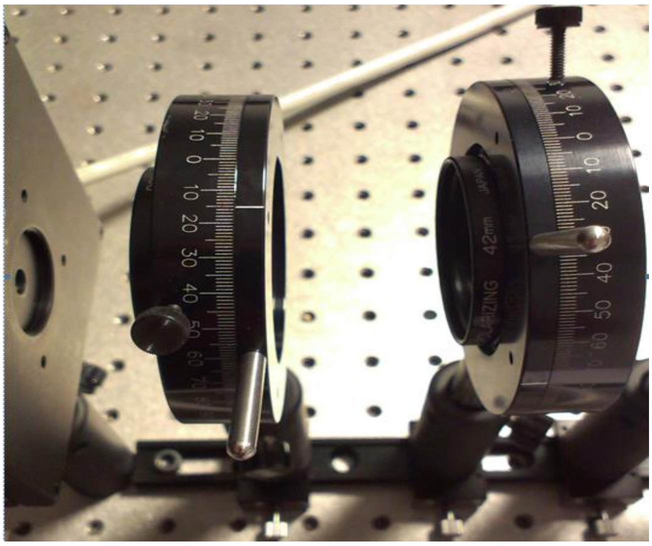


Fig. 12 Polarizer used in the experiment

(3) Diffuser and Aperture

In our experiment, two type of the screen were used for creating the speckle image. One is glass made random diffuser, and another is the standard printing white paper. The random glass diffuser is with the size: $50mm \times 50mm$ and has a 120-grid sandblast. In order to define the same area of the diffuser to be used to create the speckle image in the different optical field, an aperture is fixed onto the diffuser. The aperture is made of a black paper punched with a circular hole in the center. Fig. 13 shows the diffuser with aperture mounted on the optical table.

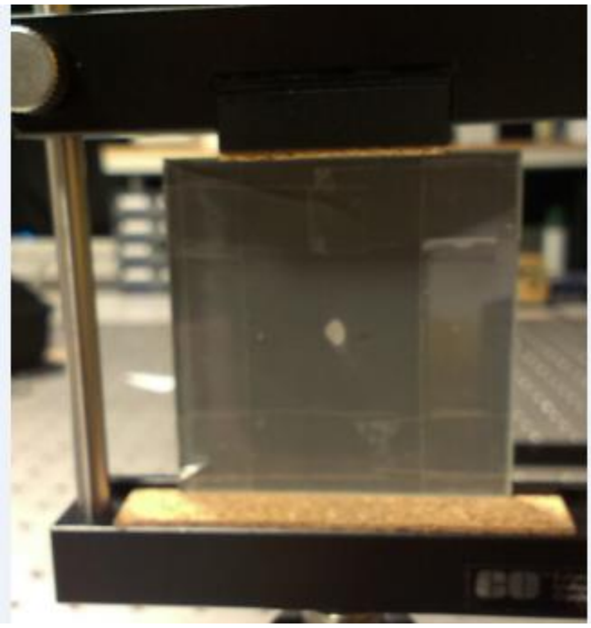


Fig. 13 Diffuser with aperture used in experiment

(4) CCD

The CCD sensor is DMK21AU04 from IMAGINGSOURCE, which is used in the setup. The CCD has a 640 ×480 pixel array, and the pixel size is 5.6 μm × 5.6 μm. The CCD was connected with a computer for date management and image reproducing. Fig.14 shows the picture of the CCD mounted on the optical table.

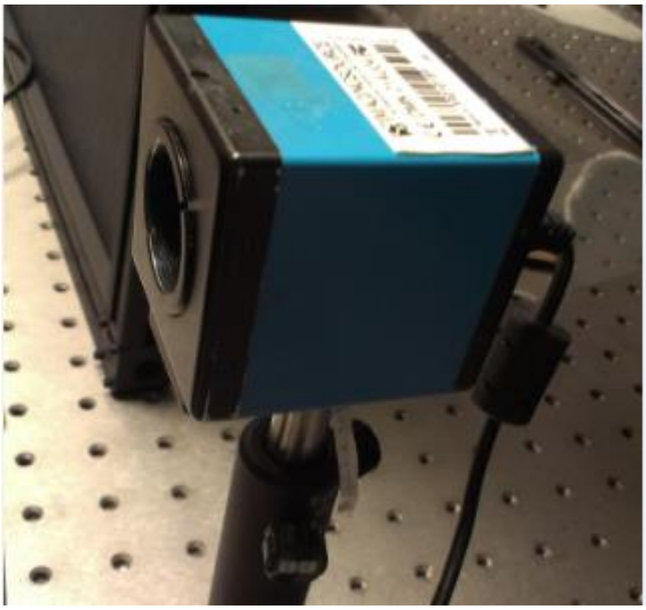


Fig. 14 CCD is provided in the laboratory

2.2 Laser diodes for the measurements

The DCI (digital cinema initiative) color gamut is the largest color gamut specified for any kind of display systems. The laser wavelength must be carefully selected to cover the completely DCI color gamut (DCI 2007 [19]). Table 1 shows the minimum and maximum wavelengths usable to satisfy this requirement. For the reference, a laser projector developed by E&S company for satisfying the DCI [20] uses the laser wavelengths are also listed in the Table 1.

Table 1: Laser wavelength to completely cover the DCI 2007 color gamut

Color	Minimum	Nominal	Maximum	E&S
Red	616	630	650	631
Green	523	532	545	532
Blue	455	462	468	448

In this thesis, we will focus on the investigation of commercial available red and blue semiconductor laser diodes which are a broad-area edge-emitting device. The specifications of the blue and red LDs are shown in Table 2 &3.

Table 2: Typical Optical / Electrical Characteristics of the blue LD

Item	Symbol	Absolute Maximum Ratings	Unit
Forward Current	If	1.2	A
Optical Output Power	Po	1.5	W
LD Reverse Voltage	Vr (LD)	5	V
Storage Temperature	Tstg	-40～85	˚C
Operating Case Temperature	Tc	0～33	˚C

Initial Electrical/Optical Characteristics

Item		Condition	Symbol	Min	Type	Max	Unit
Optical Output Power		If=1.0A	Po	0.75	1.00	-	W
Dominant Wavelength		If=1.0A	λd	440	-	455	nm
Threshold Current		CW	Ith	150	-	300	mA
Slope Efficiency		CW	η	0.8	-	1.8	W/A
Forward Voltage		If=1.0A	Vop	4.0	-	6.0	V
Beam Divergence		If=1.0A	θ //	5	12	25	°
Full Angle (1/e2)			$\theta \perp$	30	40	50	°
Emission point Accuracy	Angle	If=1.0A	$\Delta\ \theta \perp$	-5	-	5	°

Table 3: Typical Optical / Electrical Characteristics of the red LD

Item	Symbol	Absolute Maximum Ratings	Unit
Threshold Current	Ith	174	mA
Operating Current	Iop	307	mA
Optical Output Power	Po	150	mW
Peak wavelength	λp	636.8	nm
Beam Divergence	θ //	4.2	°
Full Angle (1/e2)	$\theta \perp$	35.3	°
Temperature Controller	Tc	25	°C

To well control the operation temperature of the LDs, the LD under test will be mounted on the TCLDM9 diode mount from Thorlabs shown in Fig.15. The LD under test can be quickly and easily changed in the mount. It is as simple as inserting the laser diode into the socket according to the imprinted pin assignment. The LD then can be fasted by the clamp ring. The temperature and current control units are also depicted in the Fig.15. By using such a setup, we are able to control the temperature with 0.1% accuracy and the current with 1% accuracy.

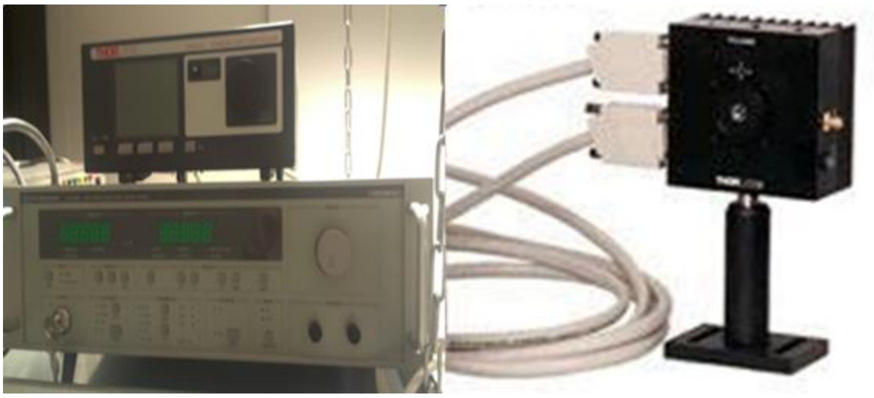


Fig. 15 Temperature and current controller connected with the laser mount

2.3 Experimental plans

In this part, we are going to describe the strategic experimental plans for characterizing both the spectrum and the speckle of the red and blue laser diodes.

2.3.1 The emission spectral measurement of the Laser diode

For the first, the spectrum of the LD will be characterized by using the setup shown schematically in Fig. 16.

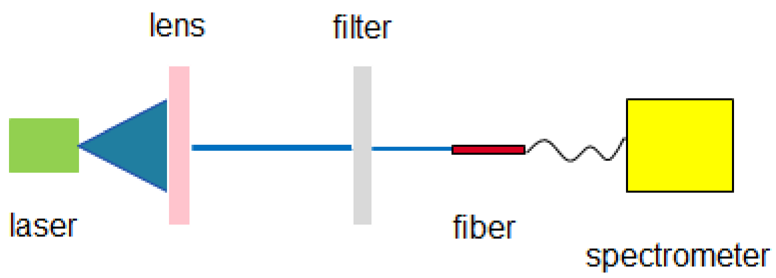


Fig. 16 The schematic plot for characterizing the emission spectrum of the LD

In this setup, the laser emission after a collimation lens passes through the filter, fiber-optic and was measured by the fiber-spectrometer, Ocean Optics HR4000 Spectrometer, which is a versatile high-resolution spectrometer. The HR4000 has a 3648-element CCD-array detector from Toshiba that enables optical resolution as precise as 0.02 nm (FWHM). The HR4000 is responsive from 200-1100 nm, but the specific range and resolution depend on the grating and entrance slit choices. The spectrum intensity for the laser diode is too high to measure. In order to reduce the light intensity, we add the ND filter in the setup to have a proper spectral measurement.

2.3.2 The speckle measurement for the collimated laser diodes

As the first step, the objective and subjective speckles were measured for the same LD. With the correct setup parameters, we confirmed that the speckle contrasts are the same for both the objective and subjective speckles. Therefore, through our all experiments the objective speckle is measured to reduce the use of the lens attached to the CCD camera.

For obtaining the speckle characteristics of the LD, the first measurement scheme was designed for collimated LD. One polarizer is used in case of the red LDs, see Fig. 17. The speckle contrast of red LD is investigated by changing the operating temperature and driving current.

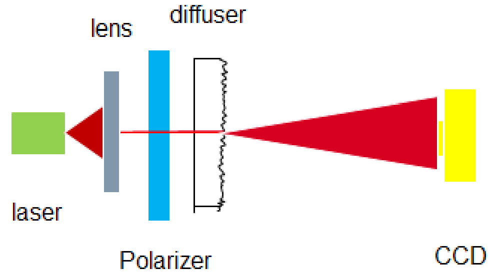


Fig. 17 The schematic of speckle contrast measurement setup for the collimated red LD

In the case of measuring the collimated blue LDs, the filter and two polarizers are used to adjust the power onto the CCD camera because of the large optical power emitted from the blue LD, see Fig.18. Similar to the measurement above for the red LDs, the speckle characteristics of the blue LD are also studied by changing the operating temperature and driving current.

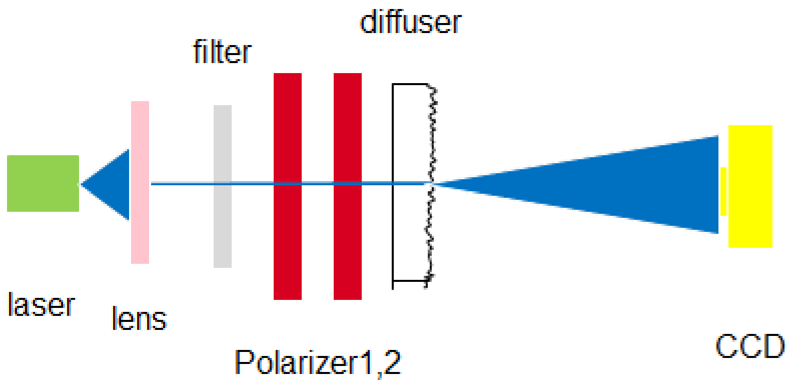


Fig. 18 The schematic of speckle contrast measurement setup for the collimated blue LD

2.3.3 The speckle measurements along the illumination area of the laser diodes

The second measurement scheme was designed to measure the correlation degree of the speckle images from the different illumination area of the LDs, see Fig. 19. The LD without collimation, illuminates a large area as a bar shape in the far field. The different illumination areas from the LD are selected step by step to shine on the same area of the diffuser. The speckle images are measured in each step.

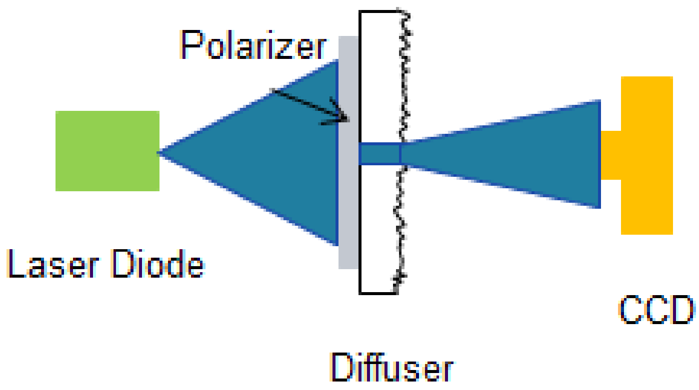


Fig. 19 The schematic of speckle contrast measurement setup for the un-collimated blue LDs

Three different measurement methods are applied in this measurement scheme. For the first method, the illumination area is selected by manually moving the diffuser attached with the aperture along the illumination field, while the polarizer and CCD moved together with the diffuser, see Fig. 20.

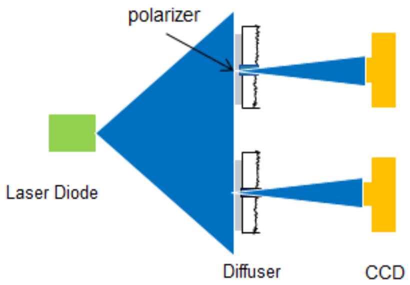


Fig. 20 Polarizer, Diffuser and CCD move together along the illumination field, [M1]

For the second method, the illumination area is selected by manually moving the diffuser attached with the aperture along the illumination field, while the polarizer and the CCD camera will be aligned in the optical axis as shown schematically in Fig. 21.

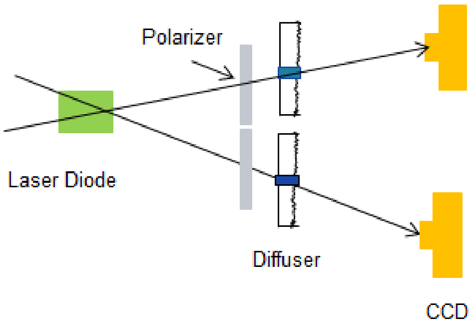


Fig. 21 Moving polarizer, diffuser, and CCD camera aligned with the optical axis, [M2]

As the third method, the illumination area is selected by manually rotating the fixed set of polarizer, CCD camera and diffuser attached with the aperture around the LD, in which the polarizer, diffuser and CCD camera do not change their relative position. The configuration of the measurement is schematically shown in Fig. 22.

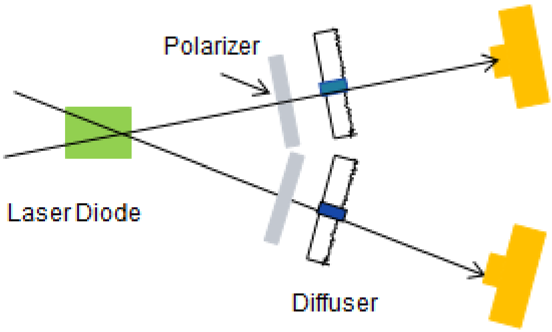


Fig. 22 The schematic plot for rotating the set of the polarizer, diffuser and CCD camera around the LD

3 Measurement results for the emission spectrum of the blue laser diode

The laser speckle strongly depends on the coherence of the laser source. The frequency doubling solid state laser sources emit pure mode of the laser beam in a high degree of coherence, which has been characterized to be able to form a fully speckle image. The semiconductor laser diodes in general will not be able to emit pure mode laser beams [21, 22]. Because of the working principle of the semiconductor laser diodes, the operating temperature will significantly affect the wave length of the emission comparing with the frequency doubling solid state laser source, as well as the driving condition can change the emission spectrum of the semiconductor laser diodes from a few modes to multi-modes. Therefore, to understand the speckle characteristics of the semiconductor laser diodes, their spectra are measured as the first step.

3.1 The temperature dependence of the spectrum

The blue laser diode was drove in a continuous-wave mode with a constant current of 1 A. The emission spectra of the blue laser diode were measured when the operating temperature is changed from 20℃ to 50℃. The results are presented in Fig. 23.

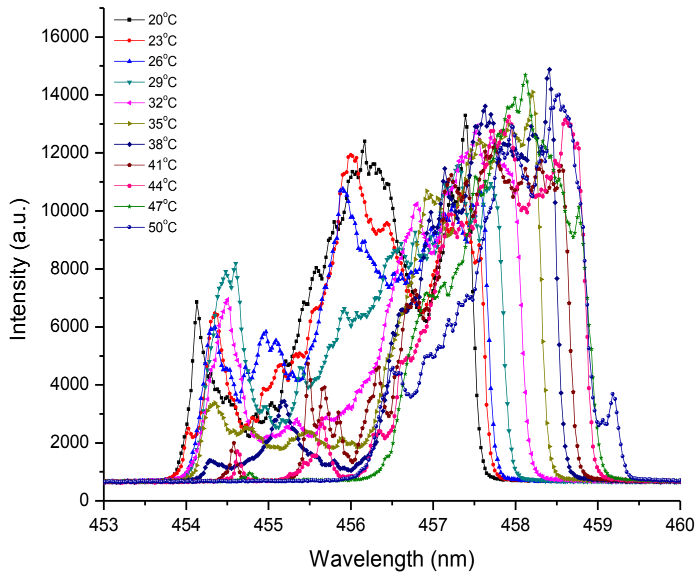


Fig. 23 The emission spectrum versus the LD operation temperature

For clearance, three typical spectra at different temperatures are shown in Fig. 24.

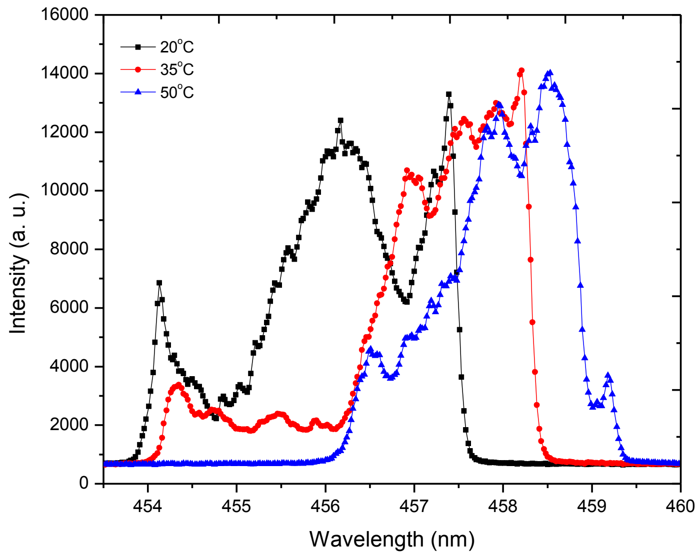


Fig. 24 The emission spectrum versus the LD operation temperature

Both figures indicate the clear dependence of the emission spectrum on the laser operating temperature in the range of from 20 ℃ to 50 ℃. With the temperature increasing, the wavelength drift occurs and the band width becomes narrow at high operation temperatures.

3.2 The driving current dependence of the spectrum

At the fixed 20℃operating temperature controlled via Thorlabs laser mount, the emission spectrum was measured under the driving current changed from 150 mA to 1150 mA. The results are presented in Fig. 25.

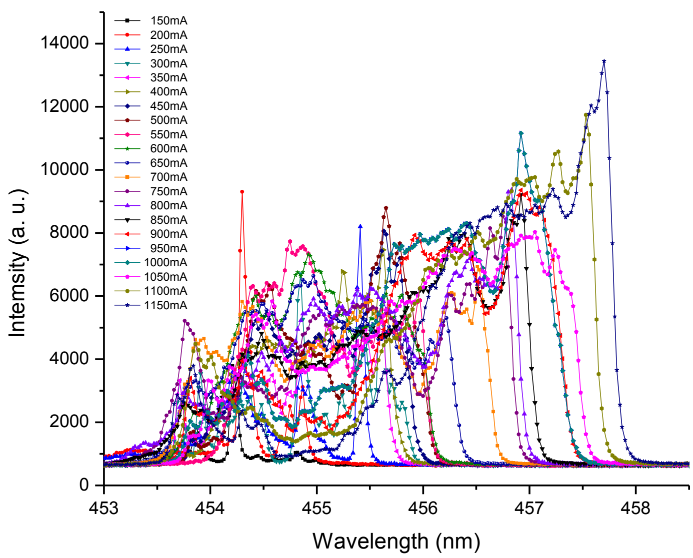


Fig. 25 The emission spectrum versus the LD driving current

For clearance, three typical spectra at different temperatures are shown in Fig. 26.

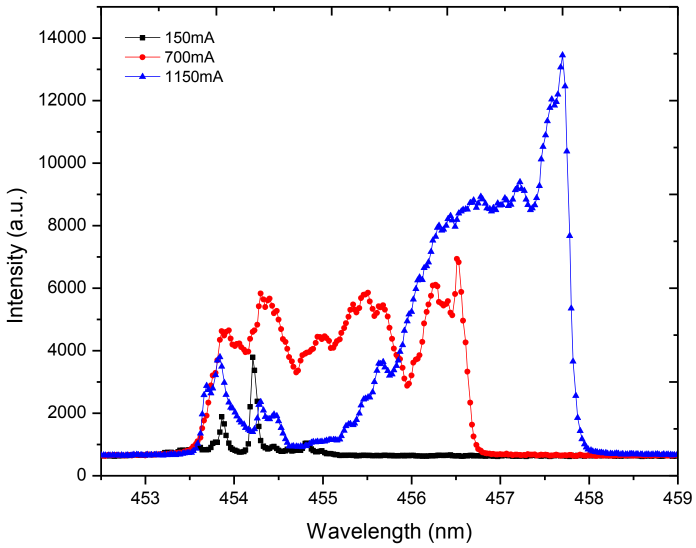


Fig. 26 The emission spectrum versus the LD driving current

Both figures indicate the clear dependence of the emission spectrum on the driving current which determines the operation mode of the laser diode. At the low driving current, the total number of modes is much less when the driving current increases. As the driving current increase, the wavelength drift occurred and the band width of the emission becomes wider.

4 Speckle measurements of the laser diodes in free space geometry

After confirming the equal results from the measurements of the objective and subjective speckles, in this thesis, all experiments have been configured with the free space geometry measurement for the speckle characterization.

4.1 The speckle contrast of the red laser diode

By following the schematic measurement scheme introduced in the section 2.3.2 of Chapter 2, see Fig. 17, the picture below presents the real lab setup. In order to avoid the speckle contrast measurement error which is caused by environmental light, all measurements is made under the darkness.

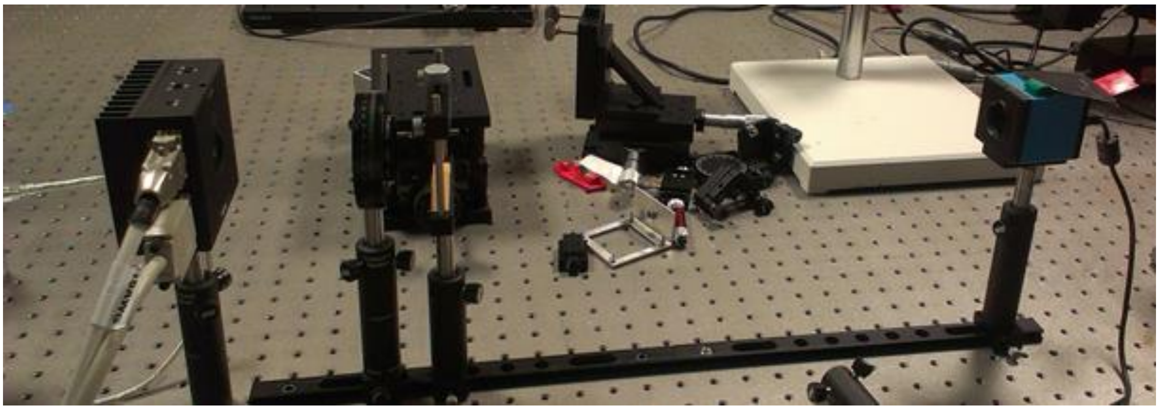


Fig. 27 Image of the lab setup for the experiment with collimated LDs

The collimated red laser diode is used in this experiment. The laser beam quality, measured 50 cm away, after the collimation is given in Fig. 28. The beam passes through polarizer and the glass diffuser, after that, the beam propagates and falls on the CCD camera. The speckle image is recorded by the CCD camera and the speckle contrast is calculated by MatLab.

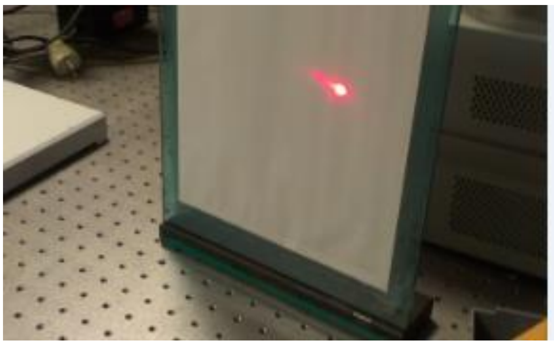


Fig. 28 Image of collimated red laser beam on the screen

The exposure time of the CCD camera is set to 30 ms to simulate the human eye integration time. The gain of the CCD camera is set to avoid the CCD camera working in an over-saturation or under-illumination status. The gamma value was set γ =1 to keep the CCD chip in the linear response region.

4.1.1 The operating temperature dependence of the speckle contrast

When the operating temperature is changed from 5℃ to 15℃ under the driving current of 200 mA, the speckle contrasts are listed in Table 4. The speckle contrast as a function of operating temperature is shown in Fig. 29. The reason for the speckle contrast limited by 0.75 is due to the glass screen partially depolarization [3].

Table 4: The speckle contrast at different operating temperatures: I=200mA

Temperature (℃)	Speckle contrast
5	0.6493
6	0.6399
7	0.6573
8	0.6603
9	0.6410
10	0.6641
11	0.7240
12	0.7375
13	0.7487
14	0.7501
15	0.7479

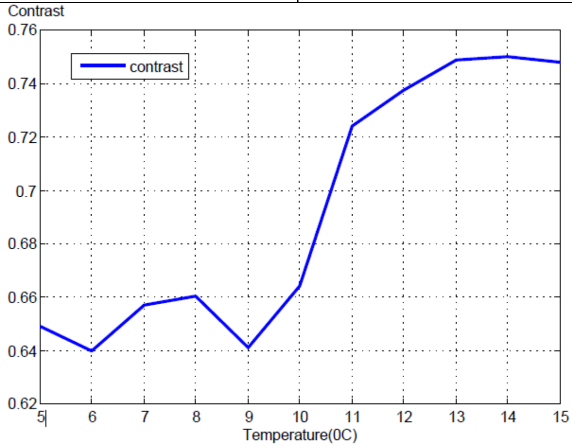


Fig. 29 The plot of speckle contrast depends on operating temperature: I=200(mA)

4.1.2 The driving current dependence of the speckle contrast

For the speckle contrast versus the driving current, the measured results at the operating temperature of 5℃ when the driving current is changed from 180 mA to 300 mA are presented in Table 5. The speckle contrast as a function of driving current is shown in Fig. 30.

Table 5: The speckle contrast at different driving currents: T=5℃

Current(mA)	Speckle contrast
180	0.7477
190	0.6945
200	0.6644
210	0.6268
220	0.5959
230	0.5900
240	0.5806
250	0.5866
260	0.5446
270	0.5728
280	0.5538
290	0.5765
300	0.5671

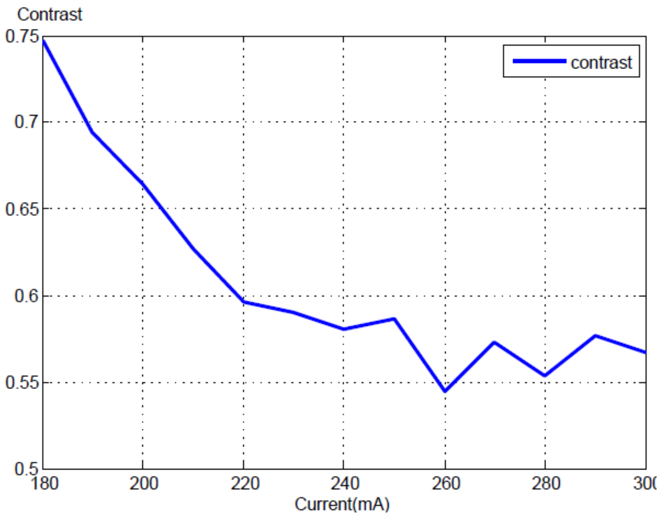


Fig. 30 The plot of speckle contrast depends on operating temperature: T=5℃

4.2 The speckle contrast of the blue laser diode

Following the measurement configuration descripted in the section 2.3.2 of Chapter 2, the lab setup for the speckle contrast measurement of the blue laser diode is given in the following picture.

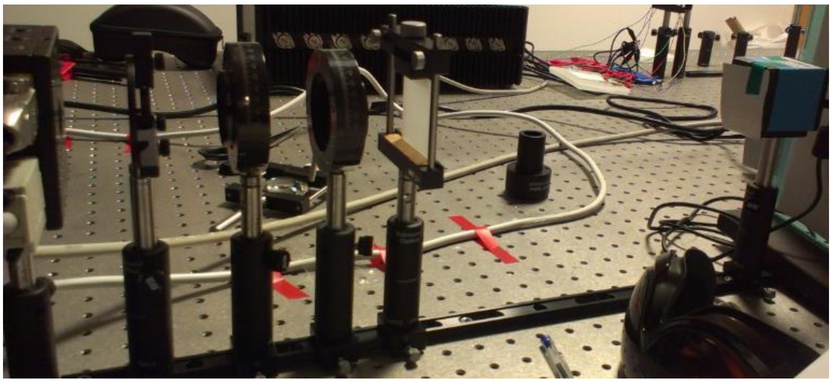


Fig. 31 The picture of the lab setup for the experiments with the blue LDs

Similar to the measurement procedures for the red LDs, the speckle contrast versus the operation temperature and the driving current are reported in the next two paragraphs.

4.2.1 The operating temperature dependence of the speckle contrast

For the blue LDs, the speckle contrasts were measured when the operating temperature is changed from 20℃ to 50℃ under the driving current of 1 A. The results are listed in Table 6. The speckle contrast as a function of operating temperature is shown in Fig. 32.

Table 6: The speckle contrast at different operating temperatures: I=1A

Temperature(℃)	Speckle contrast 1st time	Speckle contrast 2nd time
20	0.2987	0.3006
23	0.2980	0.2977
26	0.2996	0.2995
29	0.3026	0.3044
32	0.3077	0.3092
35	0.3154	0.3183
38	0.3198	0.3142
41	0.3154	0.3131
44	0.3172	0.3151
47	0.3178	0.3170
50	0.3178	0.3170

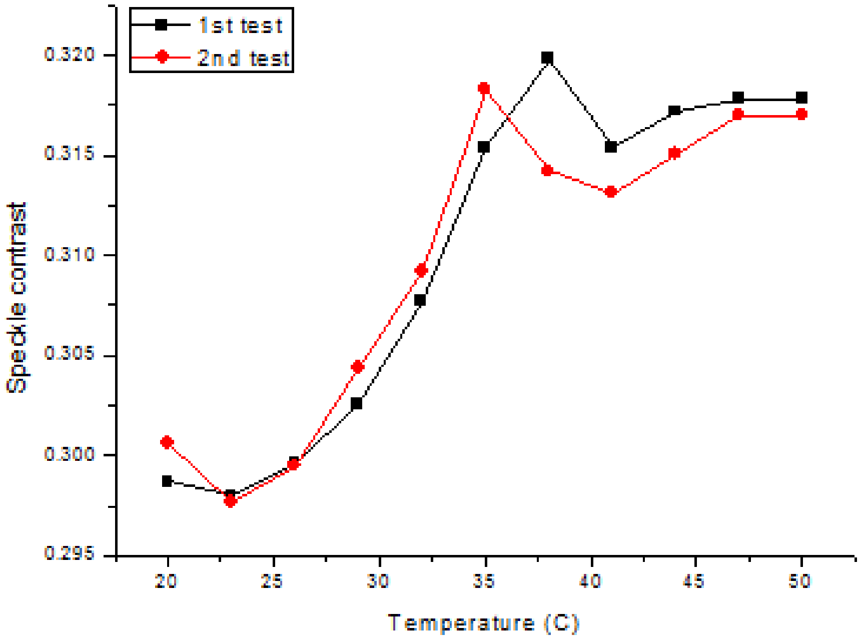


Fig. 32 The speckle contrast versus the operating temperature: I=1(A)

4.2.2 The driving current dependence of the speckle contrast

The driving current dependence of the blue laser diode was measured with the current changes from 150 mA to 1200 mA at the operating temperature of 20℃. The results are shown in Table 7. The speckle contrast as a function of driving current is shown in Fig. 33

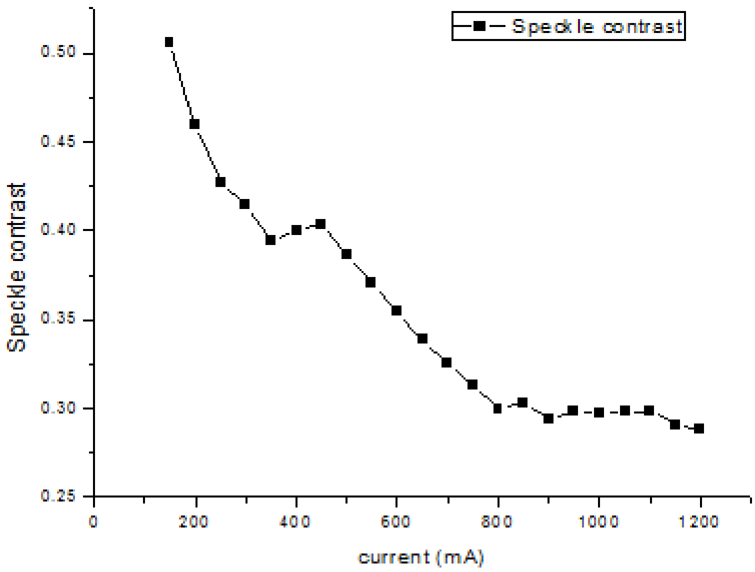


Fig. 33 The speckle contrast versus the driving current at T=20℃

Table 7: The speckle contrast at different driving currents: T=20℃

Current [mA]	Speckle contrast
150	0.5060
200	0.4594
250	0.4265
300	0.4145
350	0.3938
400	0.4004
450	0.4035
500	0.3860
550	0.3707
600	0.3545
650	0.3387
700	0.3251
750	0.3133
800	0.2998
850	0.3031
900	0.2943
950	0.2984
1000	0.2975
1050	0.2980
1100	0.2985
1150	0.2908
1200	0.2887

4.3 The speckle characteristics in the far field illumination of the blue LD

The far field illumination area of the blue laser diode driven at current of 200 mA and at operating temperature of 25℃ is given in Fig. 34. At the distance of 30 cm, the illumination field is of the bar shape 220 mm×20 mm.

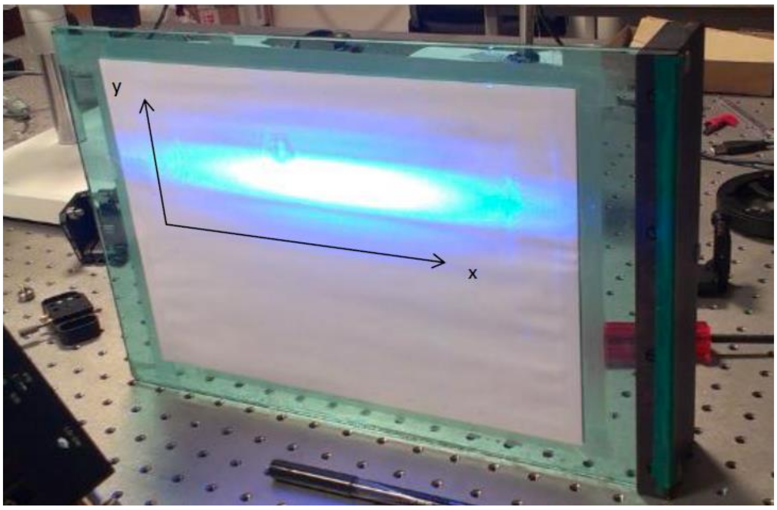


Fig. 34 The far field illumination area of the blue LD

The different illumination areas were selected to develop the speckle image at the same position of the diffuser defined by the aperture. The results are reported below for the different measurement methods M1, M2, and M3.

4.3.1 The speckle characteristics along illumination field by moving CCD together with the diffuser

Fig. 35 is the picture of the lab setup to realize the schematic optical path configuration described in the section 2.3.3 of Chapter 2, see Fig. 20. The illumination area is manually selected by moving the diffuser along x direction in the range from 0 to -42 mm. In order to maintain the same observation angle, the polarizer, diffuser and CCD moved together in each measurement step. Table 8 lists the speckle contrast measured in x direction, the record data are plotted in Fig. 36.

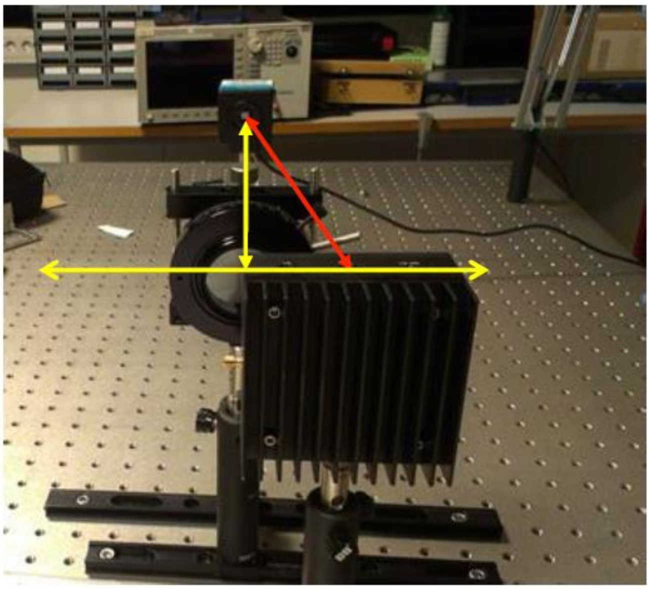


Fig. 35 The measurement setup for the speckle of the far field illumination, (M1)

Table 8: Speckle contrasts measured along the x direction

No.	Position	Average speckle contrast*
1	(0,0)	0.8352
2	(-3,0)	0.8124
3	(-6,0)	0.8015
4	(-9,0)	0.7749
5	(-12,0)	0.7297
6	(-15,0)	0.7098
7	(-18,0)	0.7067
8	(-21,0)	0.6702
9	(-24,0)	0.7026
10	(-27,0)	0.6884
11	(-30,0)	0.6649
12	(-33,0)	0.5971
13	(-36,0)	0.6230
14	(-39,0)	0.5270
15	(-42,0)	0.5874

* note: the average is done for 5 measurements

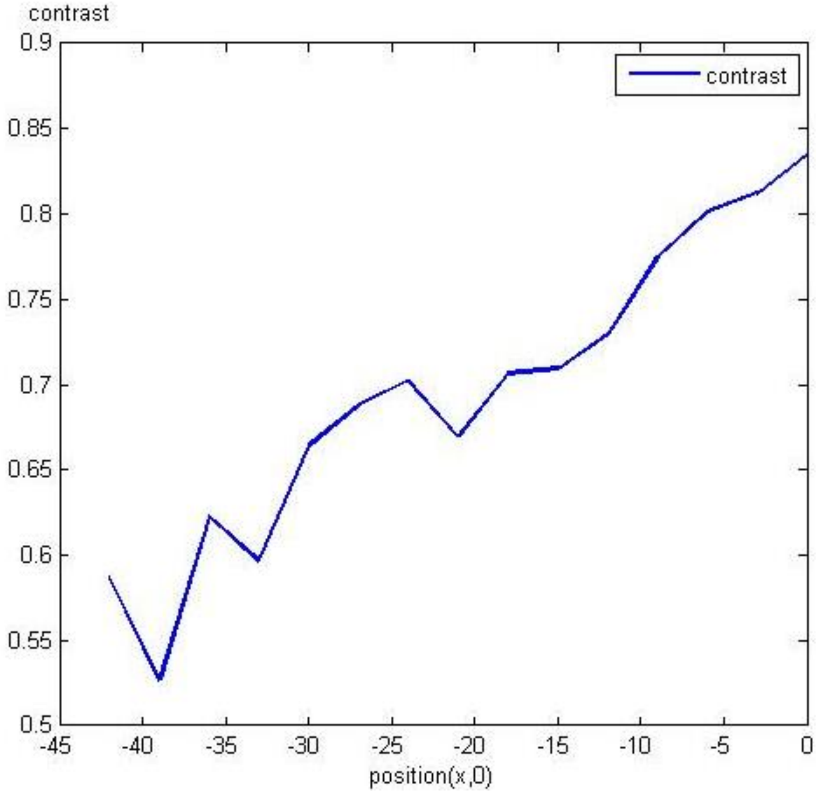


Fig. 36 The speckle contrast along the x direction of the far field illumination, (M1)

4.3.2 The speckle measurement along the illumination field by moving the fixed diffuser with optical axis alignment

Fig. 37 is the picture of the lab setup to realize the schematic optical path configuration described in the section 2.3.3 of Chapter 2. The illumination area is manually selected by moving the diffuser along the x direction in the range from -30 to 30 mm and the y direction in the range from -9 to 9 mm. In the picture, the relative position of the polarizer, the diffuser and the CCD camera is displayed to show the alignment with the ray direction. Table 9 gives the speckle contrasts measured along the x direction, which are plotted in Fig. 38. Table 10 gives the speckle contrasts measured along the y direction, which are plotted in Fig. 39.

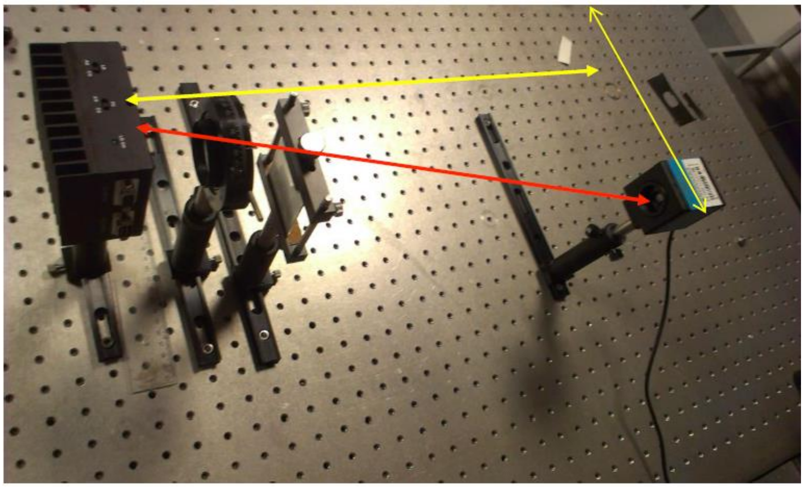


Fig. 37 The image of the lab setup for the speckle measurement in the far field illumination 2, (M2)

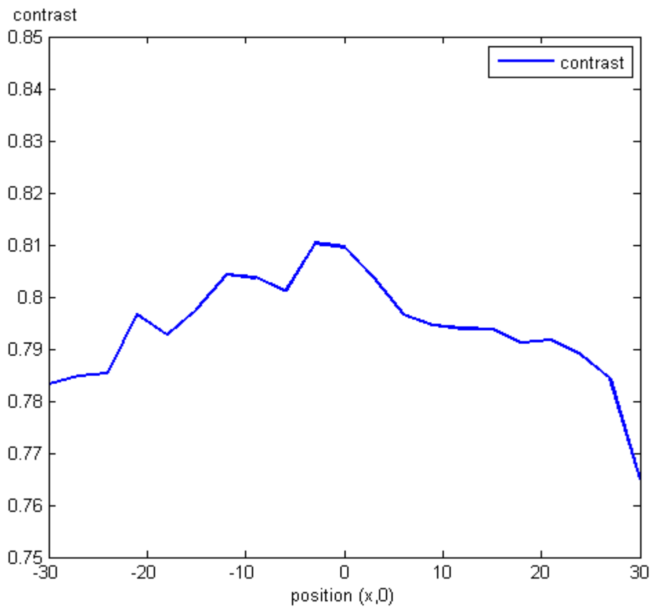


Fig. 38 The speckle contrast measured along the x direction from (-30, 0) to (30, 0), (M2)

Table 9: The speckle contrasts measured along the x direction

No.	Position	Average speckle contrast*
1	(30,0)	0.7649
2	(27,0)	0.7843
3	(24,0)	0.7890
4	(21,0)	0.7919
5	(18,0)	0.7914
6	(15,0)	0.7939
7	(12,0)	0.7940
8	(9,0)	0.7947
9	(6,0)	0.7967
10	(3,0)	0.8039
11	(0,0)	0.8097
12	(-3,0)	0.8104
13	(-6,0)	0.8012
14	(-9,0)	0.8038
15	(-12,0)	0.8044
16	(-15,0)	0.7977
17	(-18,0)	0.7928
18	(-21,0)	0.7968
19	(-24,0)	0.7855
20	(-27,0)	0.7849
21	(-30,0)	0.7833

* note: the average is done for 5 measurements

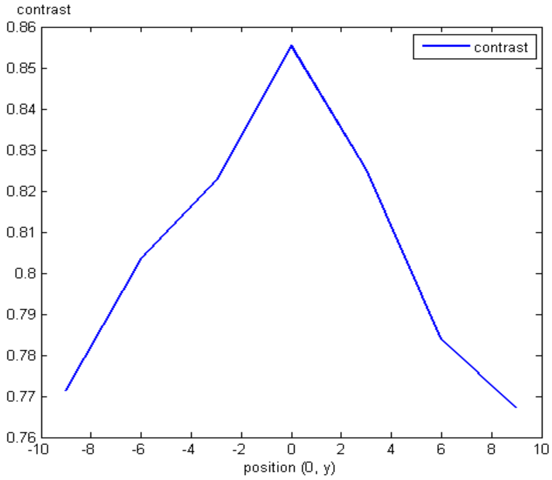


Fig. 39The speckle contrasts measured along the y direction from (0, -9) to (0, 9), (M2)

Table 10: The speckle contrasts measured along the y direction

No.	Position	Average speckle contrast*
1	(0,9)	0.7674
2	(0,6)	0.7841
3	(0,3)	0.8253
4	(0,0)	0.8555
5	(0,-3)	0.8228
6	(0,-6)	0.8038
7	(0,-9)	0.7714

* note: the average is done for 5 measurements

4.3.3 The speckle characteristics along illumination field by rotating the set of the diffuser and CCD around the LD

The lab setup in Fig. 40 indicates the last measurement configuration. The illumination area is manually selected by rotating the set of the polarizer, the diffuser and the CCD camera around the laser diode to keep the polarizer, the diffuser and the CCD camera all perpendicular to the incident light. The equivalent displacement of the diffuser along the x direction is in the range from -30 to 30 mm. Table 11 lists the speckle contrasts measured along the x direction, which are plotted in Fig. 41.

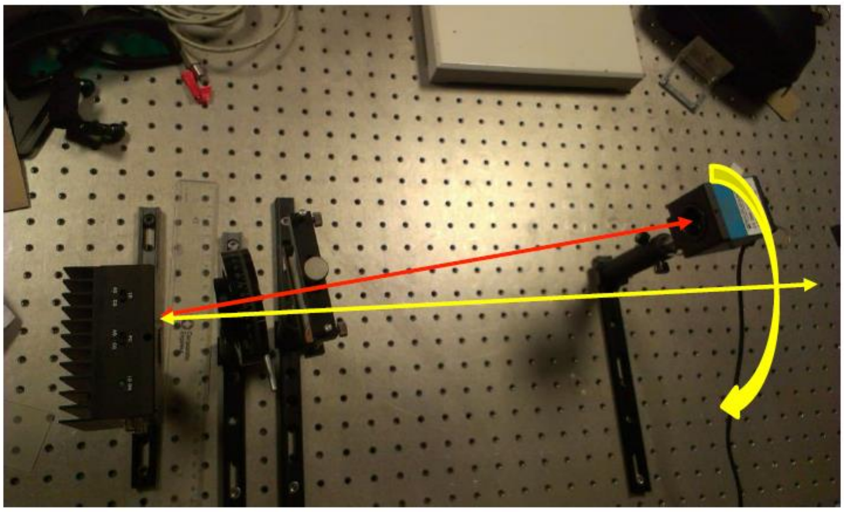


Fig. 40The image of the Lab setup for the speckle measurement in the far field illumination, (M3)

Table 11The speckle contrasts measured along the x direction

No.	Position	Average speckle contrast*
1	(30,0)	0.8320
2	(27,0)	0.8278
3	(24,0)	0.8347
4	(21,0)	0.8286
5	(18,0)	0.8341
6	(15,0)	0.8319
7	(12,0)	0.8314
8	(9,0)	0.8322
9	(6,0)	0.8318
10	(3,0)	0.8304
11	(0,0)	0.8367
12	(-3,0)	0.8274
13	(-6,0)	0.8308
14	(-9,0)	0.8356
15	(-12,0)	0.8316
16	(-15,0)	0.8304
17	(-18,0)	0.8282
18	(-21,0)	0.8347
19	(-24,0)	0.8302
20	(-27,0)	0.8315
21	(-30,0)	0.8338

* note: the average is done for 5 measurements

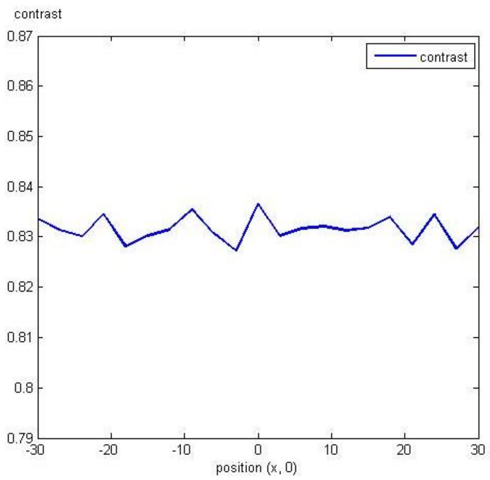


Fig. 41The speckle contrasts alone the x direction from -30 to 30mm, (M3)

5 Analysis and Discussions on the experimental results

5.1 Beam coherence across the broad area edge-emitting semiconductor LDs

Before the semiconductor laser diodes were available for laser display technology, the frequency doubling solid-state laser sources were intensively investigated for speckle free display applications. The high degree of the coherence, pure emitting mode and extreme narrow waveband (line spectrum characteristic), of such laser sources brought huge challenge for speckle reduction. In last years, the speckle characteristics of the semiconductor VCSEL were reported [16, 17]. Depending on the driving condition, such as CW or pulse driving, the VCSEL can work in very different regimes in which the spectra, such as emitting modes, the wave bandwidth, and the center wave length, change clearly. It was discovered that the coherence degree of the beam across the emitting area reduces due to the area distribution of the emitting modes [17]. In our investigation on the speckle and spectrum of the semiconductor laser diodes, we use different approaches to measure the coherence of the laser beam. By measuring the speckle images developed with the different illumination areas in the far field, we are able to calculate the correlation coefficient between the speckle images.

The first discovery in the speckle measurements, see Fig. 20 and Fig. 36, we find that the speckle contrast decreases gradually from 0.83 to 0.66 from the illumination center to the side. Note that the maximum speckle contrast 0.83 is caused by the glass diffuser which is not a fully depolarized. Using the MatLab we make the compound speckle image via any two conjunct speckle images. We find that the composed speckle image has a reduced speckle contrast to the level as the superposition of the two independent speckle images. By now, it appears that 1) the beam emitted from the side of LD has lower coherence comparing the center beams because of the low speckle contrast of the speckle image developed by the side illumination area; 2) the speckle images from the different illumination areas in the far field of the LD emission are independent from each other as reported by Zhang et al[23].

The first conclusion above which is not reported in [23], actually reminds us for building up more measurement configurations as a double check. From previous master student Li's work [24], we learned that the position of the camera away from the center of the scattered light by the glass diffuse can cause the measurement error, which normally results in a reduced speckle contrast. Therefore, the measurement shown in Fig. 21 was performed. In this way, we are able to align the CCD camera in the beam direction. The results are shown in Fig. 38 and Fig. 39, which show that the speckle contrast decreases from 0.81 to 0.77 along the x direction, and 0.86 to 0.77 along the y direction. Ignoring the random noise from the measurements, we can conclude by the improved measurement configuration that the coherence degree of the beam may not depend on the location of the beam emitting area. However, the compound speckle image from any two conjunct speckle images still reveals the uncorrelation of the speckle images.

By measuring the collimated laser diodes, see Fig. 28, we achieved the speckle contrast equal to 0.76 which cannot be explained by [23]. By the collimation, the spread beams from different emitting area of the LD will folded together and illuminate a small area on the diffuser, thus we can say that the speckle image developed by the collimated beam is an equivalent compound speckle image of many speckle images developed by the beams emitted from the different emitting areas. In case that the speckle images are independent of each other for the beams emitted from the different emitting areas, the speckle contrast of their compound speckle image will be much smaller than 0.76. From this measurement results, we have to solve the challenge issue. What is the reason for that the compound speckle image from any measured two conjunct images has reduced speckle contrast in our two measurement schemes.

Examining the measurement setup in Fig. 20 and Fig. 21, we notice that when the diffuser moves along the far field illumination area, the angle of the incident light to the diffuser normal direction will changes step by step for each measurement. As discussed in the first chapter, the angle diversity is one of important technology for speckle reduction in laser illumination optics. As illustrated in Fig. 42, the different incident light beams 1 to 3 will see a different roughness of the same screen.

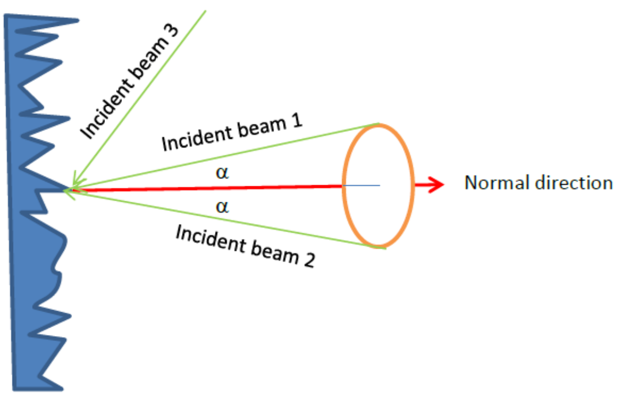


Fig. 42 Illustration of the surface roughness seen by different incident beams

According to Goodman's book [3], the speckle image developed on the screen by the different beams will have different characteristics due to the difference of the equivalent roughness of the screen. Although the beams 1 and 2 have the same incident angle, but rotated into the different direction, the inside construction of the speckle image will also rotated accordingly. Understanding above discussion and analysis, we designed the experimental configuration shown in Fig. 22, in which the set of the polarizer, the diffuser and the CCD camera will keep to align with the center of the scattered light which is in the normal direction of the diffuser surface. The measurement results are shown in Fig. 41. The speckle contrasts are almost the same around 0.83. Meanwhile the speckle contrast of the compound speckle image by any two conjunct speckle images does not change except the random measurement noise. The results can give a good answer to the challenge question arisen above.

As the conclusion of this paragraph, the coherence of the beam does not change along the emitting area; the speckle images developed by the different illumination areas in the far field are well correlated with each other, which is against the previous report results from Zhang et al [23]. We believe that from microscopy point of view the coherence of the beam emitted from different position of the LD may change point-by-point such as the reported results by reference [16], but the far field illumination experiments do not lead the same conclusion, which can be resulted from the average effect of a large number of the microscopy areas.

5.2 The speckle characteristics of the broad area edge-emitting Semiconductor LDs

5.2.1 Temperature dependence

For the red and blue laser, the results from Fig. 29 and Fig. 32 demonstrate that the speckle contrast increases sharply when the operating temperature increasing, but tends to saturate when the operating temperature increases above 13℃ for the red LD and 35℃ for the blue LD respectively. The discussion of this result will start with studying the basic working principle of the semiconductor LDs.

The working principle of the semiconductor laser diodes can be very briefly illustrated by the following pictures Fig. 43 and Fig. 44, which were given in our ELN4000 lecture [25]. The band-gap structure for the energy states, the stimulated photo generation, and the resonance in the cavity, will compose the base for the laser diode emission.

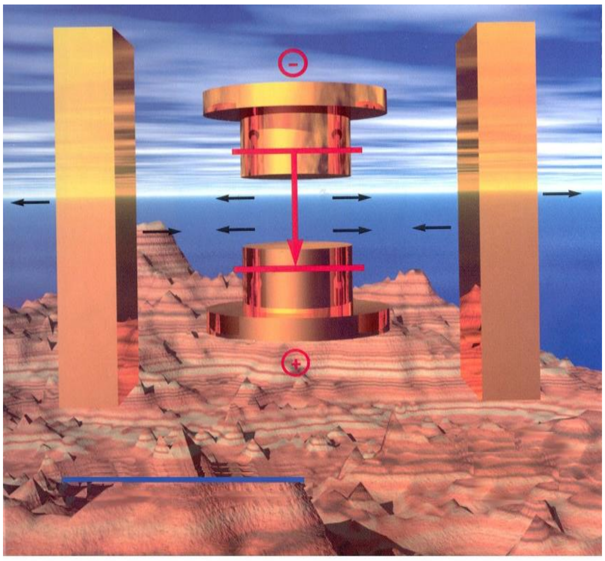


Fig. 43 Illustration of the basic working principle for semiconductor laser diode

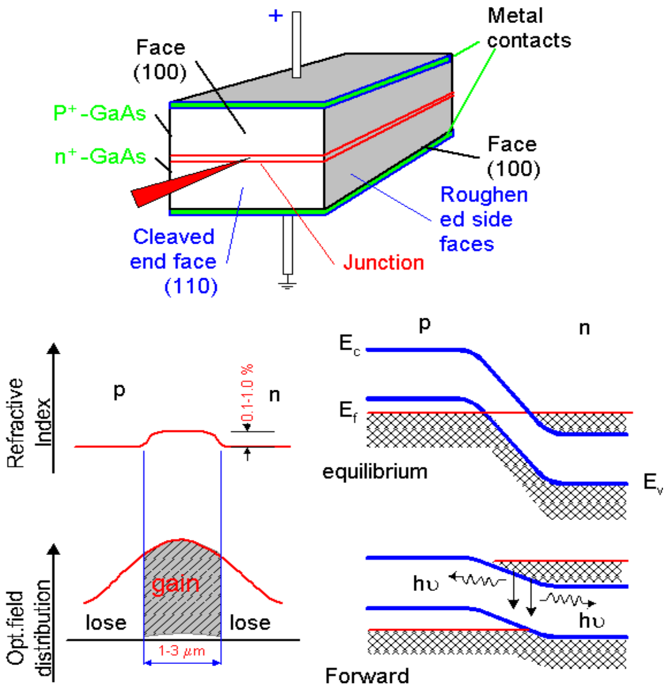


Fig. 44 Structure for a typical homojunction semiconductor edge-emitting laser diodes

From above figures, we can see that the small cavity in the LD can be strongly affected by the operating temperature due to the thermal expansion of the material. The resonance of the photons in the changed cavity will result in the wave shift of the LD emission. The emitting modes will certainly modulated by the temperature at the emitting junction. With the spectrometer available in our optical lab, we have measured the blue laser diode spectrum versus the operating temperatures. The results reported in section 3.1 show the clear wave spectrum shift and the change of the mode distribution in the spectra are revealed in Fig. 23 and Fig. 24. By increasing operating temperature, the number of the emitting modes which contribute to the intensity of the emission increases significantly, although little change in the bandwidth is observed. At low operating temperatures, the emission intensity clearly is dominated by a few emitting modes. Therefore, the degree of the light coherence will be much high at the low temperature comparing to that at the high temperatures. As the conclusion, by changing the operating temperature of the semiconductor LDs, the speckle characteristics of the LDs can be changed. At our driving current condition, the speckle contrast reduces when the LDs works at low temperatures.

5.2.2 Driving current dependence

For the red and blue laser, the results from Fig. 30 and Fig. 33 demonstrate that the speckle contrast reduces obviously when the driving current increasing, and tends to stable when the driving current increases above 250 mA for the red LDs and 800 mA for blue LDs respectively. The wave spectrum versus the driving current is measured and reported in section 3.2. We can find that wave spectrum shift and the change of the mode distribution in the spectra are revealed in Fig. 25 and Fig. 26. By increasing driving current, the number of the emitting modes which contribute to the intensity of the emission increases significantly. Meanwhile, we observed that the bandwidth of the spectrum at the large driving current increase comparing to that at the low driving current. At low driving current, the emission intensity clearly is dominated by a few emitting modes. Therefore, the degree of the light coherence will be much high at the low driving current comparing to that at the high driving current. As the conclusion, by driving the semiconductor LDs with different scheme, the speckle characteristics of the LDs can be changed. At our measurement condition (at 20 ℃), the speckle contrast can vary from 0.5 to 0.3.

5.3 Operating semiconductor LDs for low speckle noise in projector design

Following the analysis and discussions above, we can see that the speckle characteristics of the semiconductor laser diodes strongly depend on the operation conditions. The coherence of the beam is certainly lower than the frequency doubling solid-state laser sources. Due to the LDs are compact, the array integration for the high brightness projector becomes possible, which also results in a low speckle noise display due to the independence of each LD in the array. By pulse drive mode or variable CW drive within human eye integration time, the number of the emitting modes and the distribution of the modes will vary in the time consequence, thus the speckle contrast of the speckle image developed on the screen can be reduced due to the compounding the partially uncorrelated series speckle images. In addition, due to the temperature can determine the emitting spectrum of the LDs, we can design a substrate of distributed temperatures for the integrated LDs array. In such a way, the diversity of the spectrum at the same time will be created for the LDs array in operation, which will again reduce the speckle noise in addition.

6 CONCLUSION

In this thesis work, we have developed several experimental optical configurations to investigate the speckle characteristics of the semiconductor broad-area edge-emitting laser diodes. The spectrum of the semiconductor laser diodes has been measured versus the operating temperature and the driving current. The speckle images developed on the screen by the different areas in the far field illumination of the semiconductor laser diodes have been measured using the different optical configurations. Our results and the analysis show the following conclusions. The coherence of the beam does not change along the emitting area of the semiconductor laser diode, the speckle images developed by the different illumination areas in the far field are well correlated with each other, which is against the previous report results from Zhang et al [23]. We believe that from microscopy point of view the coherence of the beam emitted from different position of the LD may change point-by-point; In the far field illumination, average effect of the microscopy areas in a macro area do not lead the same conclusion for the coherence change along the emitting position; By changing the operating temperature and driving current, the speckle characteristics of the semiconductor laser diodes can be modulated; It is possible to design high brightness and low speckle noise projectors by engineering the driving scheme, temperature control, and integration configuration of the semiconductor laser diodes.

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