INVITED PAPER *Special Section on Electronic Displays*

Speckle-Free Phosphor-Scattered Blue Light Emitted out of InGaN/GaN Laser Diode with Broadened Spectral Behavior for High Luminance White Lamp Applications

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SUMMARY Ultra-high luminance lamps emitting white light with a well-scattered blue spectrum from InGaN/GaN laser diodes and a phosphor-converted yellow spectrum show speckle contrast values as low as LED. Spectral behavior of the laser diodes is analyzed to find the reason why such low values are obtained. As a result, the PWM-driven, multi-longitudinal mode with dynamically broadened line-width is found to have a great effect on reducing speckle contrast. Despite using the lasers, such speckle-free lamps are considered to be very suitable for high-luminance and other various lighting applications.

key words: *laser diode, phosphor, lighting, speckle, spectral broadening*

1. Introduction

InGaN/GaN blue laser diodes (LDs) are quite suitable for light sources of high brightness and high luminance lamps for various applications.

In fact, there have been many challenges to realize such high brightness light sources for automotive headlamps, laser projectors, digital cinema projectors, and even for general lighting applications.

Particularly, the challenges for general lighting and LCD backlight applications are based on much greater unique features of the LDs than the conventional LEDs [1]–[5]. For example, the LDs are capable of droop-free light output up to much higher power levels with much narrower beam divergence from a much smaller area than the LEDs.

For display applications, pure spectral behavior of RGB LDs is expected to realize much wider gamut than the other light sources. Meanwhile, for the automotive headlamps and the general lighting applications, the blue LDs are utilized both for blue emission itself and generating phosphor-converted longer spectral emissions, as in the same manner as the conventional white LEDs.

The other advantage of the LDs based the above unique features is to facilitate coupling their high-power output efficiently into silica optical fibers. Therefore, we can realize a concept of remote configuration in which all the LDs and related electronic devices are arranged completely remote from the lamp structure. The ultra-high optical power transmitted through all of the fibers can be easily focused on a very small area to realize ultra-high brightness. Particularly for the white lamps using phosphors, we can focus each blue output of the fibers onto a small phosphor-coated area to ultra-high luminance and luminous flux performance.

Heat generation at the lamp is minimally limited only to optical loss, including phosphor-conversion loss for the phosphor lamps.

The authors have developed 4000–5000 lm class white lamps emitting from a very small single phosphor area, using optical fibers for separating the lamp unit from a LD light engine containing 20 pcs of InGaN/GaN high-power blue LDs and their driver circuits. (We call them “super-remote phosphor configuration”.) One of the lamps achieves the maximum center luminance as high as 140 Mcd/m^2 with luminous flux of 4050 lm [2], [4].

However, there has been a problem relating speckle noise. Laser coherence in general creates speckle noise on a detector surface including human retina when observing a light-diffusing objects illuminated by coherent light sources. The speckle noise is observed as spatial and temporal variations of intensity.

Therefore, it degrades resolution of laser displays and lighting quality of luminaires. For human eyes, speckle noise is, in most of cases, undesirable and irritating.

From a viewpoint of safety regulations, we have to comply with IEC 60825 as a laser source if it is coherent, meanwhile, IEC 62471 if it is incoherent. Particularly for lighting applications, the lamps using the phosphor-scattered LD output should be compliant with IEC 62471, as long as their measures for eye-safety risk are at the same level as the conventional light sources. As the best case scenario, if they actually lost coherence, there would be no problem to be categorized as IEC 62471.

Therefore, it is very important for high brightness lamps using LDs to measure speckle noise quantitatively. For this purpose, we utilize “speckle contrast”, as a practical measure of speckle noise or coherence. It is very popular for various types of laser displays to evaluate speckle noise of [6]–[9].

Considering the current status above, we have measured speckle contrast of our 4000–5000 lm class lamps of “super-remote phosphor configuration”. As a result, we have demonstrated that speckle contrast can be reduced down to the same value as LED, and concluded that it should be categorized as a lamp compliant with IEC 62471 rather than IEC 60825 [1]–[4].

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Such speckle-free behavior is considered to be achieved by a combined effect of multi-longitudinal mode operation of the LDs, the number of the LDs, and multiple scattering in the phosphor layers [1]–[4].

However, the speckle contrast values measured at just above the laser threshold currents cannot be suppressed completely down to the same value as LEDs when the LDs are driven by DC-dimming.

It is important for lighting applications to keep such speckle-free behavior throughout the whole dimming range. For this purpose, it is effective to drive the LDs by PWM (Pulse Width Modulation) [3], [4].

In this work, we evaluate the spectral behavior of the LDs at various PWM dimming levels, compared with the spectral behavior of the corresponding DC dimming levels. We have found that the line-width broadening of each longitudinal mode has an additional effect on reducing speckle contrast. We also analyze the reason of the line-width broadening caused by PWM.

2. Structure

2.1 Entire LD Lighting System

Figure 1 shows a photograph of the prototype of high-brightness LD lighting system consisting of three parts, a lamp unit, a flexible metal tube including the optical fibers, and the light engine containing 20 pcs of LDs.

We have two types of the lamp structure, one is transmission type [VV], and the other is reflection type. The lamp shown in Fig. 1 is the reflection type to be explained later. The lamp unit in Fig. 1 is one of the reflection type lamps.

Figure 2 also shows its schematic structure. The light engine is a see-through drawing to explain its inside in the following subsection.

2.2 Light Engine

The high-power InGaN/GaN blue LDs made by Nichia Corporation operate up to 1.3 W at the lasing wavelength around 445 nm in multi-transverse and multi-longitudinal modes. The optical output of each LD is coupled into a step-index silica fiber with a core diameter of 100 μm via a lens unit.

2.3 Lamp

The schematic cross-section of the reflection-type lamp is shown in Fig. 3. It is the top-head structure and the fiber inlet tail structure is neglected.

The output from each fiber is incident to the periphery of a piece of unique optics for focusing the blue lights onto the YAG phosphor layer coated on a reflective heat-sink. The phosphor area has a circular shape with a diameter of 7 mm. The optics changes the direction of the input beams by internal total reflection. Then the beams are guided to the phosphor layer at the center of the optics.

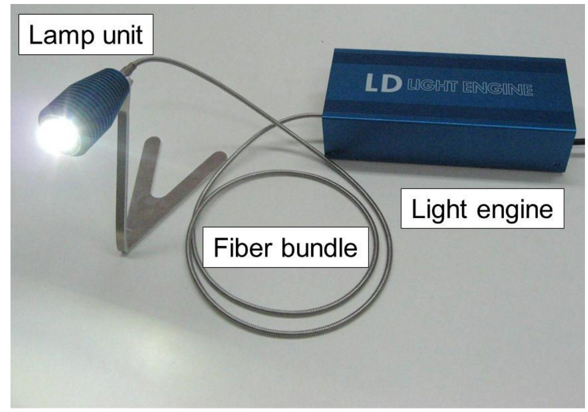

Fig. 1 Photograph of high-brightness LD lighting system.

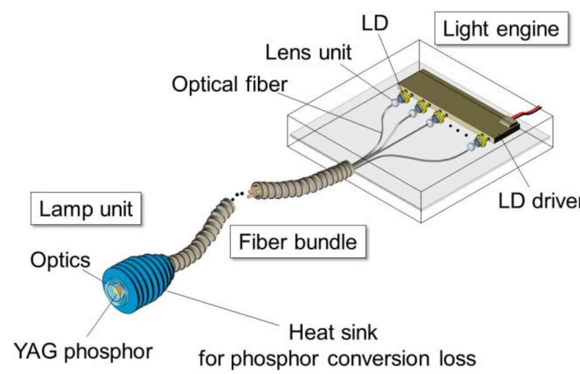

Fig. 2 Schematics of high-brightness LD lighting.

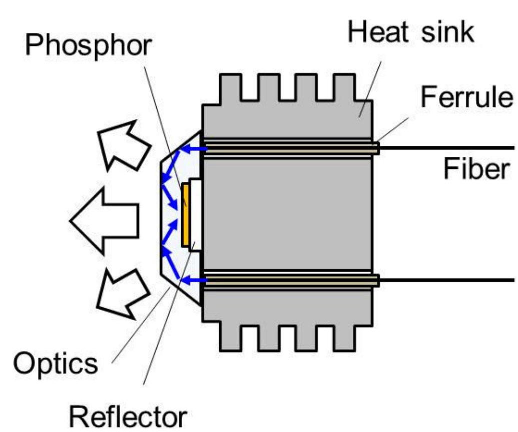

Fig. 3 Schematic cross-section of the reflection-type lamp unit.

A part of the blue lights is converted into incoherent yellow lights there. The rest of them and the converted yellow light are mixed together and then scattered and reflected. As a result, pseudo-white light is emitted with a Lambertian radiation profile. In this so-called "reflection-type" LD lamp, the temperature rise due to phosphor conversion loss is minimized by the effective direct heat transfer to the heat-sink. Therefore, the lamp achieves the maximum center luminance as high as 140 Mcd/m^2 with luminous flux of 4050 lm (CIE1931 chromaticity: x=0.364, y=0.378). Meanwhile, the transmission-type lamp [1], [2] achieves a luminance of 30 Mcd/m^2 much lower much lower than the reflection type, limited by higher phosphor temperature caused by higher thermal resistance of the lamp structure.

3. Speckle Contrast

Speckle noise is usually undesirable and irritating for human eyes, and must be suppressed for various laser displays because it degrades their image quality, as previously explained in Sect. 1. Therefore, there have been many works to reduce speckle noise [6]–[9]. For lighting applications, speckle noise would degrade lighting quality as well.

If speckle noise of the lamp using LDs could be suppressed down to the same level as the conventional incoherent lamps, it should be categorized as a lamp rather than a laser.

We use speckle contrast, C_s, as a measure of speckle noise and/or coherence. It is mathematically defined by the following equation [8].

$$C_s = \sigma_I / J \quad (1)$$

where, σ_I is standard deviation, and J is average.

The values of C_s =100% and 0% imply a perfect coherence, and a perfect incoherence, respectively.

4. Measurement Setup

A measurement setup of speckle contrast, C_s is shown in Fig. 4. This measurement system was developed and provided by Oxide Corporation [8]. It is set in a dark room to eliminate background lights as possible.

A conventional high brightness blue InGaN/GaN LED (Philips Lumileds Luxeon Rebel, Peak wavelength: 455 nm) and one of the blue InGaN/GaN LDs used in the light engine are also set here for comparison.

As a lamp using LDs, the reflection type lamp unit is used for the measurement. The pseudo-white light generated by the LD lamp is incident to an optical filter and then only the blue spectrum is filtered out in order to eliminate the effects of incoherent phosphor-converted light.

The blue lights then illuminate a perfect diffuser screen. Finally, C_s is measured by a high performance CCD camera through a pinhole with an aperture of 0.8 mm diameter. The aperture size is determined to simulate human eyes [8], [9]. In order to measure with a full dynamic range from 0% to 100%, the CCD has a very wide range of responsivity.

The upper limit of C_s=100% is calibrated using a standard He-Ne laser oscillating in a single longitudinal mode with a very narrow line width. The lower limit is determined and calibrated to be 1.6–1.8% using a standard LED, which include run-to-run measurement errors.

Each LD of the lamp and the direct laser beam out of a LD are driven with various DC levels in the range from just above the threshold current to the operating current of 1.0 A. Here the threshold currents are around 0.15 A.

They are also driven with various PWM duty ratios, D,

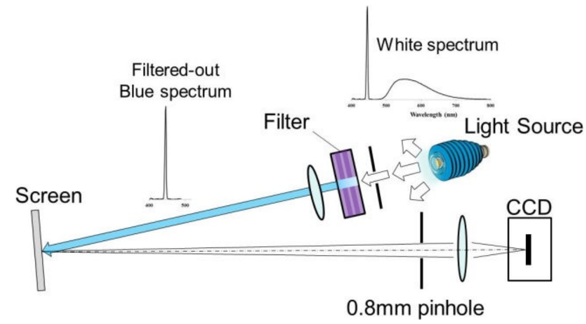

Fig. 4 Measurement setup for speckle contrast.

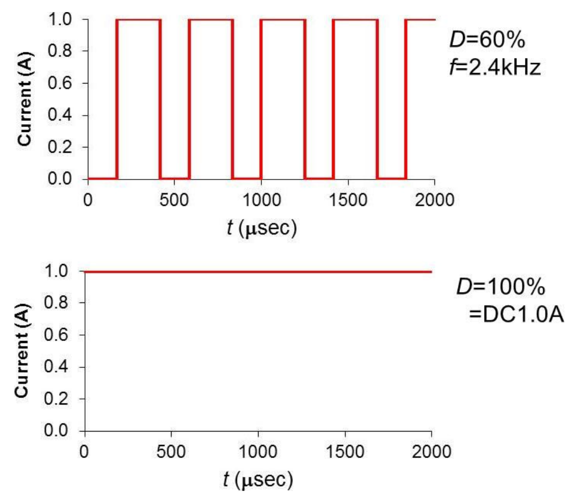

Fig. 5 Example of PWM pulse sequence.

with a pulse peak of 1.0 A, corresponding to the DC-current-equivalent dimming levels. The modulation frequency is 2.4 kHz.

The longitudinal mode behavior of one of the blue InGaN/GaN LDs is also measured changing the applied currents. We use an optical spectrum analyzer (made by ADC Corporation, Model 8341) in this spectral measurement. The LD output is directly coupled into the above spectrum analyzer. Therefore, it is independent of the speckle contrast measurements. However, the driving current levels of the LD are exactly corresponding to those of the speckle measurement.

Examples of the PWM pulse sequence are shown in Fig. 5. It should be noted that the PWM sequence corresponding to DC1.0A is a kind of NRZ (non-return to zero) continuous line exactly as the same as the DC1.0A itself. Therefore, the C_s values for both of the DC and the PWM must agree each other at DC1.0A and PWM (D=100%).

Meanwhile, the PWM pulse sequences less than D=100% are alternating RZ (return to zero) codes which includes the transient responses of pulse rise/fall.

Table 1 Measurement results of *Cs* (%) at the dimming levels of 0.16 A and 1.0 A.

Sample Under Test	DC/PWM	Dimming level (DC currents equivalent) 0.16A/*D*=16%	1.0A/*D*=100%
LD lamp	DC	11.0%	1.8%
	PWM	1.6%	1.8%
Direct LD beam	DC	74.8%	28.3%
	PWM	25.4%	29.3%
LED	DC	1.8%	1.8%

5. Results

5.1 Speckle Contrast C_s

The measured C_s values at 0.16 A (DC) and 1.0 A (DC) and the corresponding PWM duty ratios *D* for the both the LD lamp and the direct LD beam are listed in Table 1. The C_s value for the blue LED is also shown in this table for comparison.

C_s values both for the DC and the PWM must coincide at DC1.0A and PWM (*D*=100%) as in the previous section. In case of direct LD beam, the C_s =28.3% for DC1.0A and C_s =29.3% for PWM (*D*=100%).

The slight difference between them is considered to be within a measurement error. The errors tend to be larger if C_s is larger. This is because speckle is a kind of random noise.

Measured C_s values for the various dimming levels are plotted in Fig. 6 for the LD lamp and plotted in Fig. 7 for the direct LD, respectively.

As in Table 1, Fig. 6, and Fig. 7, the measured *C*s values just above the threshold current for DC-dimming are obviously higher than the values at higher dimming levels. For the LD lamp, the C_s values obtained below 0.3 A are not the same as the LED anymore. However, the *C*s values above 0.3 A are approximately as low as the LED.

Meanwhile, the measured C_s values for PWM dimming are all suppressed down to values as low as the LED.

Slightly lower value than the LED is due to the run-to-run error variation of the lower limit of the measurement system. If we change the light source, alignment must be optimized run o run. However, the relative errors through a run of the measurement just changing driving currents are very small.

As a result, it is demonstrated that PWM dimming is much more suitable than DC dimming. We can keep C_s values as low as the LED in the whole dimming range.

Compared with Fig. 6 and Fig. 7, the measurement result for the direct LD beam is quite a similar to the LD lamp except the much higher C_s values. This suggests that the major reason why we can obtain such low C_s values would be related to the characteristics of the LD itself.

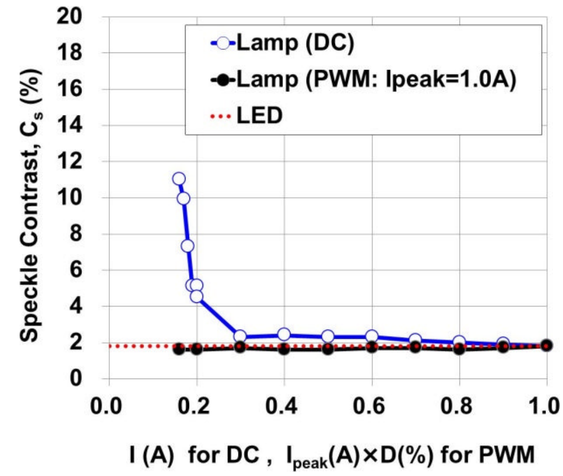

Fig. 6 Plot of Cs for the LD lamp (DC and PWM).

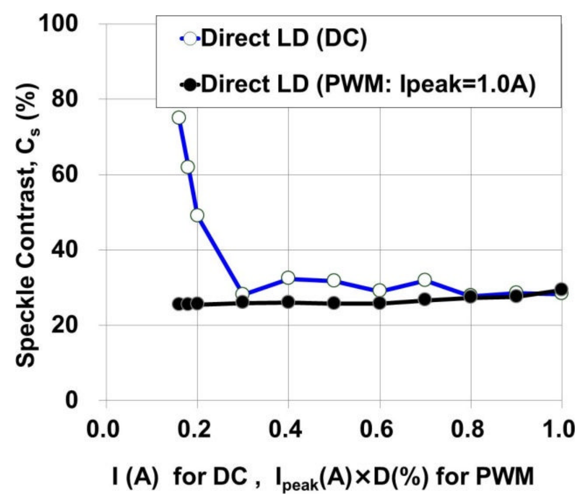

Fig. 7 Plot of Cs for the direct LD (DC and PWM).

We have to analyze the reasons for obtaining such low speckle contrast more in detail. A big difference between the DC and the PWM is a transient behavior of the pulse rise/fall.

To analyze the transient effects, we have to use a PWM sequence with lower pulse peak. It is difficult to obtain significant differences if we use the PWM sequence with a pulse peak of 1.0 A. This is because we obtain only the lowest C_s values around the lower measurement limit in the whole dimming range for the pulse peak of 1.0 A.

If we use a PWM sequence with a pulse peak of 0.2 A, it was expected from Fig. 6 to have a C_s value around 5% at *D*=100%. Therefore, we plot the C_s values for PWM-dimming with a pulse peak of 0.2 A in Fig. 8. The PWM-dimming with a pulse peak of 1.0 A is also plotted for comparison. As in Fig. 8, for lower duty ratio *D*, the pulse-top width decreases and the effect of the transient pulse rise/fall becomes more dominant. It is obvious that the transient behavior has a great effect on reducing speckle contrast C_s.

5.2 Spectral Behavior

Temporal coherence is closely related to the spectral behavior of laser sources. To analyze the transient effects more in detail, we evaluate the spectra of one of the LDs.

Figure 9 shows the spectra of the direct beam from the LD at the dimming levels of 0.16 A, 0.2 A, 0.4 A, 0.6 A, 0.8 A, and 1.0 A. The spectra in the upper are for the DC dimming. Those in the lower are for the PWM dimming. The time sequence of driving current for each spectrum is also shown just below it.

We have already known that the spectra for the DC1.0A and the PWM (D=100%) coincide each other. As in the upper spectral group in Fig. 9, the LD operates in a semi-single longitudinal mode at lower current levels for DC dimming. Then the spectral envelope becomes broader from 0.4 A. The fine spectral structure of each line spectrum of the multi-longitudinal mode behavior is still distinguishable. At 0.8 A, the spectral envelope splits off and has a double-peaking profile. The line-width of each mode looks broader at 1.0 A.

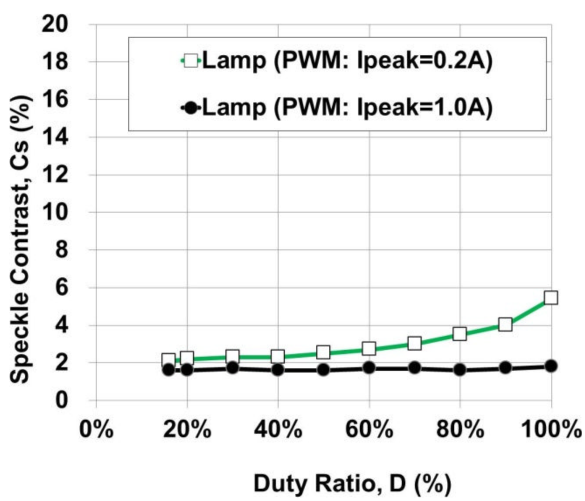

Fig. 8 Plot of Cs for PWM with a pulse peak of 0.2 A.

For PWM dimming, the spectral envelope is kept broad in the whole range of dimming. It should be noted that the line-width of each mode seems much broader than that for DC dimming. Multi-longitudinal mode operation occurs even if dimming levels are low.

This is because the pulse peak of the PWM dimming is up to 1.0 A. At least, at the pulse peak at each dimming level, spectral behavior similar to the DC1.0A is coming up. Addition to the stable multi-longitudinal mode operation, the line-width broadening stably occurs because each pulse always includes large transient rise and fall.

To analyze the transient effects, we make a comparison between the DC1.0A (equal to PWM: D=100%) and the PWM: D=95%. In Fig. 10, the spectra for the DC1.0A and the PWM (D=95%) are shown together with their current sequences. The PWM (D=95%) is chosen because of its RZ pulse code, whereas NRZ continuous line for the DC1.0A. The input power levels for the both are very close each other. Therefore, we can clearly pick up the effect of the transient responses of the transient pulse rise/fall.

As shown in Fig. 10, the envelope spectral profiles for the both sequences look quite similar. However, the fine spectral structure of each longitudinal mode still observed for the DC1.0A is not clearly observed for the PWM (D=95%). This implies that the dynamic behavior of the

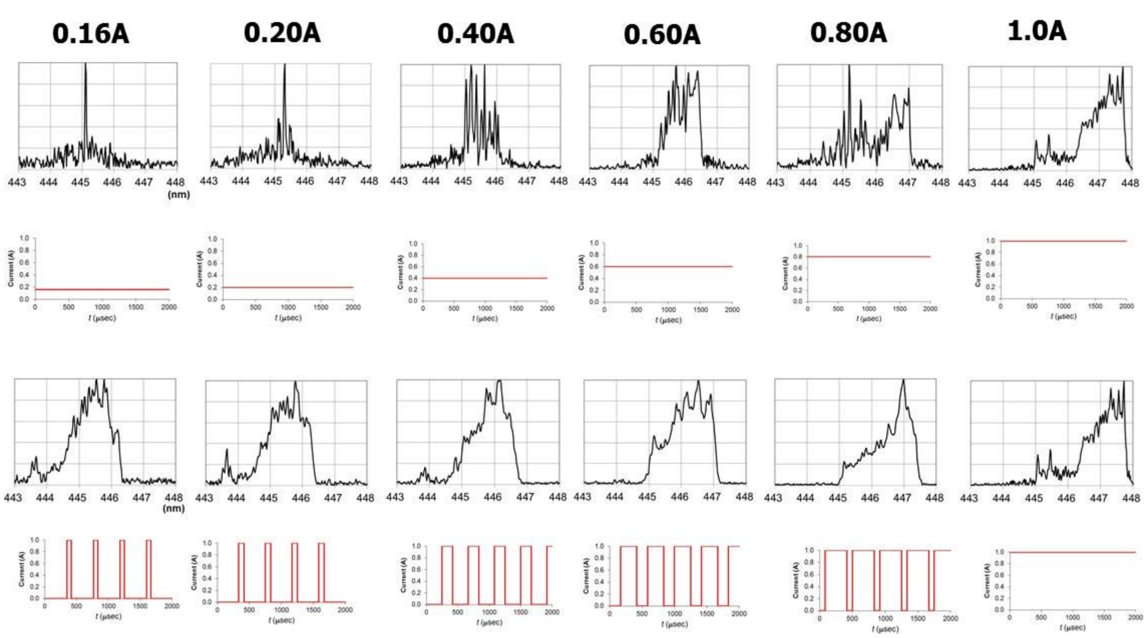

Fig. 9 Spectral behavior of one of the LDs for various dimming levels. (Upper: DC dimming, Lower: PWM dimming)

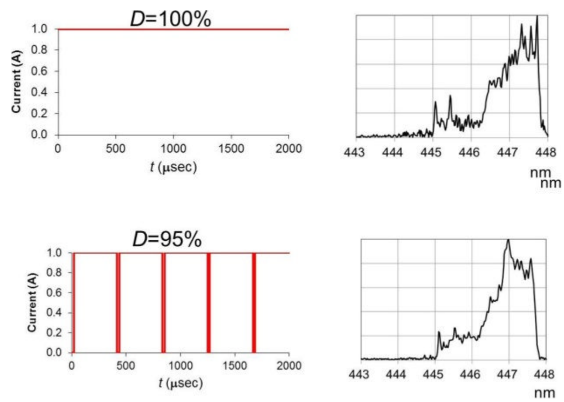

Fig. 10 Spectral comparison between DC1.0A and PWM (D=95%).

pulse transients cause much stronger line-width broadening of each longitudinal mode.

6. Discussion

6.1 Spectral Effect

Here we discuss why spectral broadening occurs.

For dynamic analysis of spectral behavior of multi-longitudinal mode operation of the LDs, we have to start with rate equations.

However, it is difficult to solve rate equations for the both multi-transverse and multi-longitudinal modes strictly. It is too complicated to solve them because too many rate equations corresponding to the number of the both modes are needed. For example, the number of the longitudinal modes estimated to be several of tens as in the DC spectra in Fig. 9.

Therefore, for simplicity, we consider the spectral broadening of single mode, neglecting complicated interactions among the modes.

The rate equations for single mode are simply expressed as follows.

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_n} - GS$$
$$\frac{dS}{dt} = \Gamma\left(G - \frac{1}{\tau_n}\right)S + \beta\frac{N}{\tau_n} \tag{2}$$

where, N is the carrier density, S is the photon density, I is the applied current, e is the electron charge, V is the volume of the active region, τ_n is the carrier lifetime, τ_p is the photon lifetime, Γ is the optical confinement factor, β is the spontaneous emission factor, G is the gain coefficient.

The dynamic wavelength shift of single longitudinal mode can be analyzed using the rate Eq. (2). It is well-analyzed in the field of optical communication systems, known as "wavelength chirping" expressed as the following equation.

$$\lambda(t) - \lambda(0) = \Gamma\frac{\lambda(0)}{n_{eff}}\frac{dn}{dN}\{N(t) - N(0)\} \tag{3}$$

where, λ is wavelength, n_{eff} is effective refractive index of the active region, and dn/dN is differential refractive index expressing a change rate of the refractive index when carrier density N changes. The refractive index of the active region changes by the free-carrier plasma effect. The variables, $N(t)$ and $\lambda(t)$ are time-dependent functions. $N(0)$ and $\lambda(0)$ are the initial values.

Rapid increase of carrier density in the active region of the LD at the pulse rise/fall of PWM dimming will cause a change of refractive index. The carrier-induced refractive index change of the active layer will then cause a change of lasing wavelength. As a result, the pulse rise and fall cause a line-width broadening.

For higher carrier density, chirp-induced line-width broadening becomes larger as in Eq. (3). Therefore, higher applied currents cause larger line-width-broadening.

As in Fig. 9, even for DC dimming, the broadening to some extent occurs at 1.0 A, which is larger than lower DC currents. It is considered to occur because the mode power is exchanged interactively from mode to mode even if there are no intentional pulse transients. Such interaction must be analyzed by many of rate equations for multiple modes, which we have skipped for simplicity.

The longitudinal modal spacing is approximately given by,

$$\Delta\lambda \approx \frac{\lambda^2}{2n_{eff}L} \tag{4}$$

where, L is the cavity length. The chromatic dispersion term is neglected for simplicity.

Assuming, $L = 1$ mm, $\lambda = 450$ nm, $n_{eff} = 2.4$, the mode spacing of the blue LD is estimated to be 0.042 nm. This value well agrees with actual modal spacing in Fig. 9.

If we assume, $dn/dN = 5.5\,\text{nm}^3$, $\Gamma = 0.2$, $N(t) - N(0) = 10^{18}\,\text{cm}^{-3}$ and $10^{19}\,\text{cm}^{-3}$, the wavelength chirp $\lambda(t) - \lambda(0)$ calculated using Eq. (3) is approximately 0.2 nm for $10^{18}\,\text{cm}^{-3}$ and 2 nm for $10^{19}\,\text{cm}^{-3}$, respectively.

This implies that the line-width broadening due to the dynamic wavelength shift (chirp) completely cover the modal spacing. In fact, we cannot observe the fine mode structure in the spectra for the PWM dimming. As a result, such line-width broadening is considered to occur due to multi-mode operation including mode-to-mode interactions, and the transient behavior of pulse modulation greatly enhances the broadening. Such dynamic spectral behavior of the LDs has a great effect on reducing speckle contrast C_s.

6.2 Superposition Effect

Another contribution to reducing speckle contrast C_s is the number of the LDs. This superposition effect is well-known and is expressed as follows [10].

$$Cs \propto 1/m^{1/2} \tag{5}$$

where, m is the number of LDs.

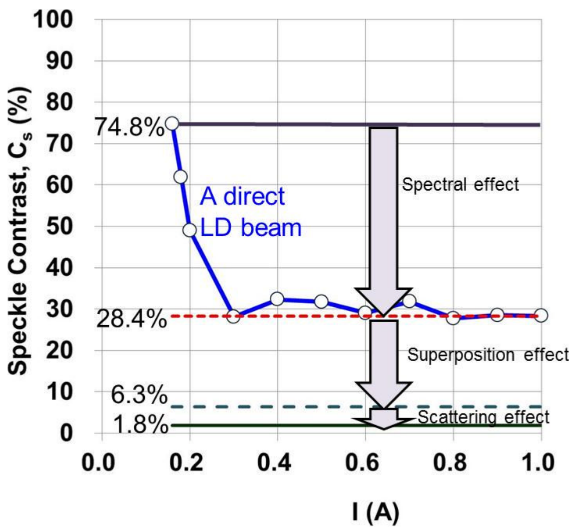

Fig. 11 Quantitative analysis of the three major effects on reducing C_s.

The lamp systems usually use 20 pcs of LDs. Therefore, C_s reduces down to 22.4% of that using only one piece of LD. Actual spectral behavior is a result of supposing the spectral behaviour of each LD shown in the previous subsection.

6.3 Additional Scattering Effect

Both of the spectral and the superposition effects are not sufficient for reducing C_s as low as the LED level.

In fact, the multi-mode effect reduces C_s down to around 28% from 75% for single use of LD. The superposition effect using 20 pcs LDs is 22.4% as in the above discussion. Therefore, the total reduction of C_s by the both effects is estimated to be 6.3%, not reaching the perfect reduction of C_s down to 1.8%. We have to consider additional effects for explaining the perfect reduction of C_s. (These quantitative analysis is shown in Fig. 11.)

We consider that multiple scattering by the phosphor layer and the other lamp structure is the additional effect. First of all, the depolarization effect by scattering reduces C_s by $1/\sqrt{2}$, reaching 4.5%. However, we have to still consider furthermore. The further effects of the multiple scattering by the phosphor layer will be discussed more in detail in our future work [11].

7. Conclusion

Ultra-high luminance lamps emitting white light with a well-scattered blue spectrum from InGaN/GaN laser diodes and a phosphor-converted yellow spectrum are expected for various lighting applications.

We have measured speckle contrast of the blue scattered light out of such lamps using the blue laser diodes for evaluating lighting quality relating laser coherence.

Speckle contrast as low as a LED is obtained except just above the threshold current for DC dimming. We have also found that PWM dimming is very effective to overcome the relatively high speckle contrast close to the threshold in the case of DC dimming.

In this work, we have analyzed the reason why PWM-dimming is capable of suppressing speckle contrast so effectively. Spectral behavior of the laser diodes is also analyzed in detail for this purpose.

As a result, multi-longitudinal mode operation of the laser diodes with dynamically broadened line-width is found to have a great effect on reducing speckle contrast. Particularly, at the transient pulse rise/fall, rapid increase of carrier density in the active region of the LD causes a change of refractive index. The carrier-induced refractive index change then cause a line-width broadening via wavelength chirp.

The rest of the effects for obtaining the perfect reduction of speckle contrast down to the LED level are also analyzed quantitatively. The superposition effect of using many lasers, and the scattering effect in the phosphor layer are discussed briefly. The scattering effect will be more in detail in our future work.

The LD lamps using blue LDs are quite suitable for high-brightness lighting applications without any lighting quality degradation by speckle noise. They should be categorized as "lamps" in IEC 62471 rather than "lasers" in IEC 60825 because they are actually incoherent due to their completely speckle-free capability.

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