Speckle reduction for illumination with lasers and stationary, heat sinked, phosphors

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Abstract

DYOPTYKA's innovative solution for the reduction of speckle noise in projection displays, using a phase-randomizing deformable mirror, is shown to achieve effective speckle reduction in an illumination system where at least one of the color primaries is a laser which is also used to excite fluorescence of other wavelengths from a volume of stationary, heat-sinked, phosphor. It is also shown how incident illumination is more evenly distributed on the phosphor which reduces very high localized temperatures to avoid burning.

1 Background

Until laser sources with all the appropriate characteristics for high luminance projection displays (i.e. green wavelengths, optical power, wall-plug efficiency, broad spectral linewidth) become commercially available, market demand for long-lifetime solid state illumination sources is being satisfied using semiconductor laser diodes to excite fluorescence from phosphors.

A common approach is to direct the laser illumination onto a phosphor-coated highly-reflective disc which is rotated to avoid continuous illumination of a single patch of phosphor which causes burning (see Figure 3 [Bottom.]) Some systems also use the lasers for one of the color primaries (typically blue.) In this case the rotating disc also reduces laser speckle due to temporal variation of surface diffusion and volume scattering in the phosphor.

An alternative approach to prevent burning is to keep the phosphor stationary and to cool it with a heat sink. This enables use of increased laser powers for higher luminance and also reduces the size of the system in the height dimension. However, for system designs using lasers for one or more of the color primaries, it does not provide effective speckle reduction.

DYOPTYKA has developed an innovative technique for speckle reduction [1, 2, 3, 4]. It does not require a moving diffuser—instead it uses a deformable mirror which can be actuated at hundreds of kHz, see Figure 1.

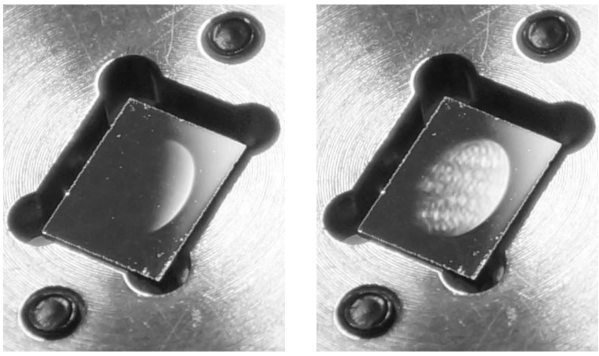

Figure 1: DYOPTYKA's miniaturized deformable mirror with elliptical active area of 3.0 mm by 4.5 mm and dielectric stack coating for high reflection efficiency. [Left] Deformable mirror inactive. [Right] Deformable mirror active, showing the randomly-distributed surface deformations which lead to the generation of uncorrelated speckle patterns.

2 Objectives

The objective of this study are: (i) to determine how the deformable mirror can be used to reduce objective and subjective speckle [5] in a projection display optical system where lasers are used for one or more of the color primaries and laser-excited phosphor is used for the other; (ii) to determine how the deformable mirror can be used to reduce very high localized temperatures on the phosphor to avoid burning.

3 Apparatus

The apparatus used to undertake experimentation is shown and described in Figures 2 and 3.

It should be noted that a relatively thin layer, approx. 100 µm, of YAG:Ce phosphor was used. There were two reasons for this choice: (1) better heat transfer through the thin layer into the heat sink than through a thicker layer; (2) although we found that the volume scattering which arises

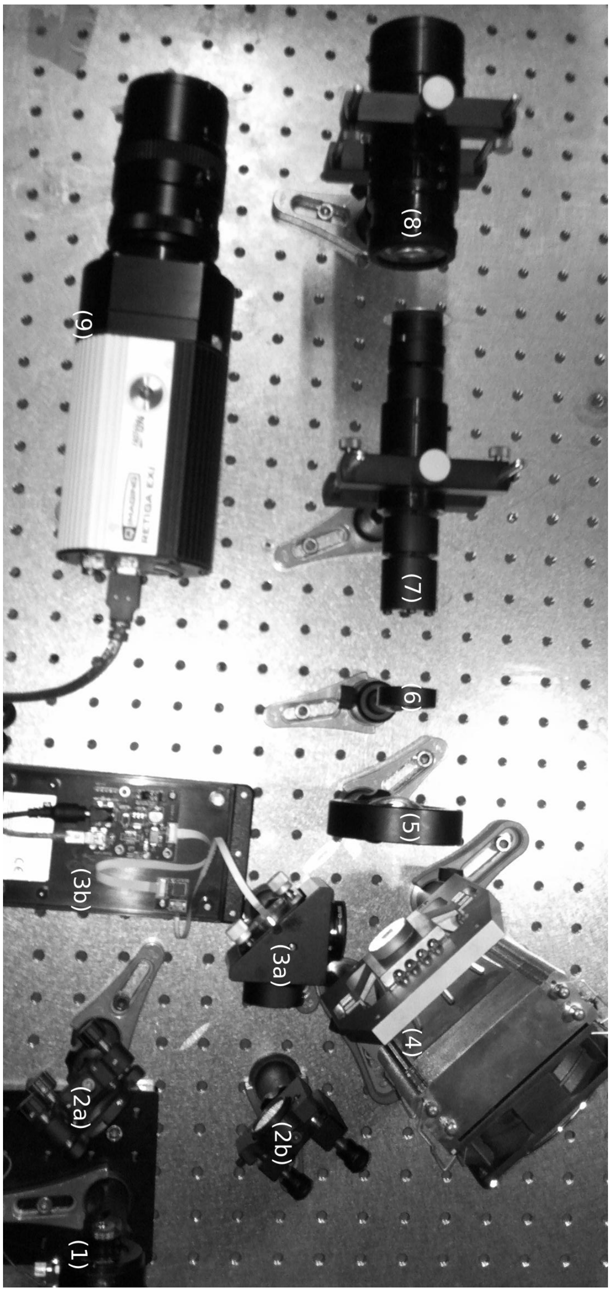

Figure 2: Illumination and projection apparatus: (1) Nichia NDB7875 approx. 445 nm blue laser diode with (pseudo-) collimating lens operated in CW to emit approx. 1 W optical power; (2a,b) fold mirrors; (3a) DYOPTYKA uDM-1.6 deformable mirror in tip/tilt kinematic mount; (3b) DYOPTYKA Rev. 5D control electronics for laboratory usage, operating at a base actuation frequency of approx. 400 kHz; (4) Stationary phosphor and heat sink, see Figure 3; (5) Condenser lens arranged for f/2.4 illumination; (6) Thorlabs FL441.6-10 bandpass filter to allow transmission of laser illumination only; (7) Rectangular glass rod for illumination homogenization; (8) Projection lens from DLP projector arranged to project exit face of glass rod; (9) Camera. A paper screen (see Figure 6) located at approximately 1 m distance is not shown.

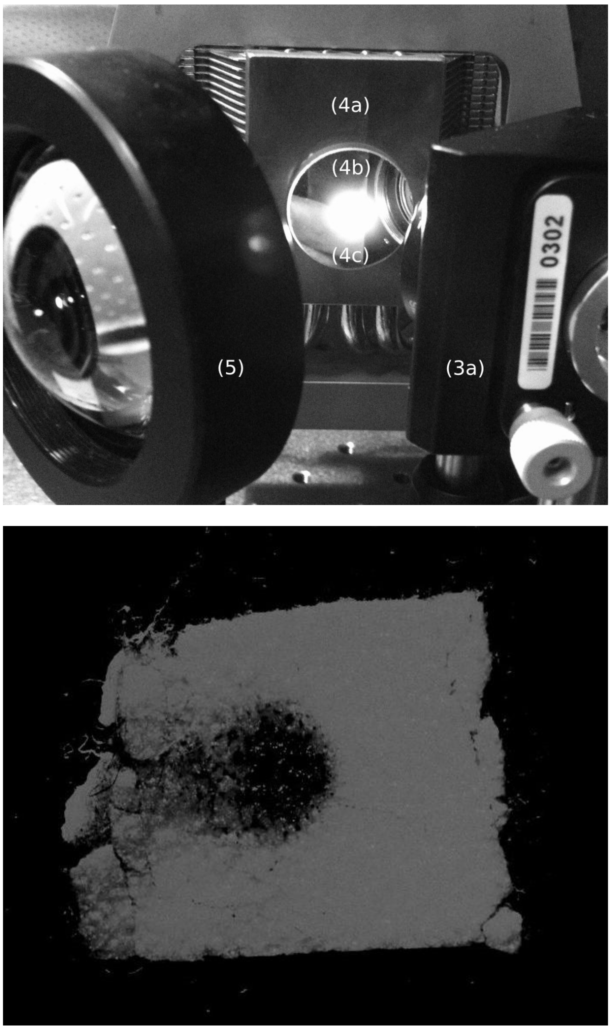

Figure 3: [Top] (4a) heat-sink with cooling fins and rear-mounted fan; (4b) protected aluminum mirror; (4c) Phosphor fluorescence under excitation by laser. [Bottom] YAG:Ce phosphor patch of dimensions approx. $7\,\mathrm{mm} \times 5\,\mathrm{mm} \times 100\,\mu\mathrm{m}$ glued to mirror (4b.) Burn damage was due to hot spots from irregular modal distribution of laser diode when deformable mirror was inactive.

in a thicker layer is very effective at reducing the coherence of the laser illumination, it was at the cost of greatly reduced transmission efficiency of the laser wavelength with a consequent increase in heating of the phosphor.

It should also be noted that a single laser diode was used. This makes speckle reduction more challenging than in a system where multiple diodes are used. Although sufficient angular separation between multiple sources can lead to speckle reduction, the cost is increased complexity and reduced transmission efficiency in the illumination optical system. Hence there are clear benefits to using as few sources as possible.

The only difference in apparatus between when the deformable mirror is active and inactive is the

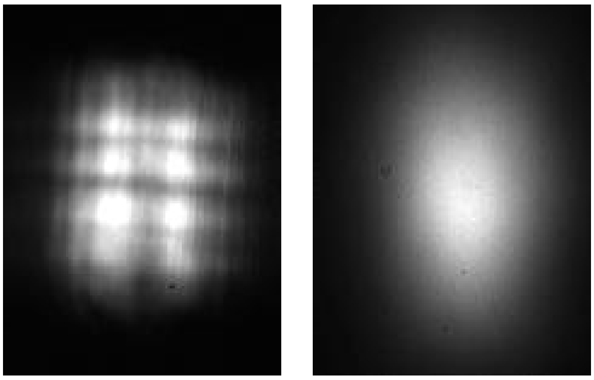

Figure 4: [Left] Thorlabs BC106-VIS beam profiler image of laser diode emission collimated and focused at infinity with simple lenses. Area is approximately 1.5 mm × 1.0 mm. Irregular intensity distribution is apparent. [Right] Beam profiler image of the same laser diode emission but reflected from the deformable mirror and focused with a positive lens into an area of similar size. To enhance visibility these images have different dynamic ranges.

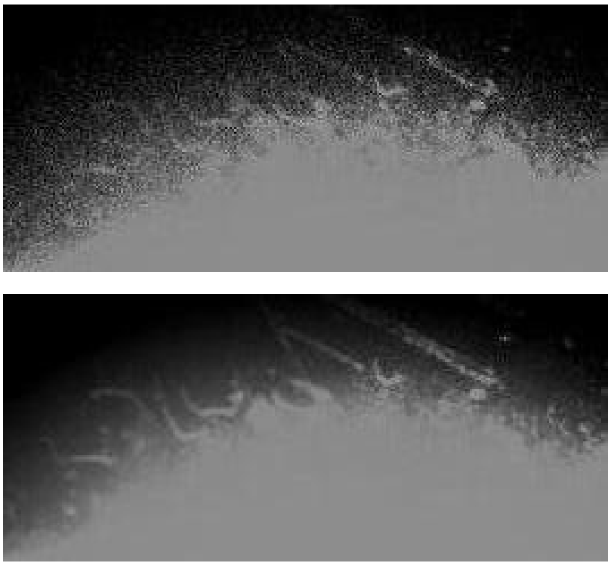

Figure 5: [Top] Emission and reflection from phosphor patch with deformable mirror inactive. Speckle arising from laser illumination is visible in the non-saturated periphery; [Bottom] With deformable mirror active state, speckle is not visible.

addition of a positive lens to focus the illumination diverged by the active deformable mirror into an area similar to that when inactive. The mirror can be controlled such that divergence is as little as approx. 0.5° full angle.

4 Results

Figure 4 shows the effect of the deformable mirror redistributing the laser illumination at a high temporal frequency. The benefit of this redistribution is to eliminate hot spots where heat accumulates faster than it can be transferred into the heat sink—which leads to burning, as can be seen in Figure 3 [Bottom.] Figure 7 shows imagery which quantifies the differences in temperature on the phosphor patch.

Figure 6 shows the effect of the deformable mirror on the objective speckle in the projected image. A significant reduction is achieved. Projection and camera magnifications and f-numbers were not chosen to observe subjective speckle from the screen, but reduction was visible to the eye of the observer. Some reduction of subjective speckle can be seen in Figure 5.

5 Originality

It is the author's understanding that this is the first demonstration of significant speckle reduction in an *optically efficient* projection display illumination system with lasers and stationary, heat-sinked, phosphors. As has been mentioned in Section 3, a thick layer of phosphor can achieve a significant reduction of coherence through volume scattering but optical efficiency is poor. The elimination of hot spots to prevent burning can also lead to improved optical efficiency since the étendue of the phosphor emission is reduced through having a smaller illuminated area than would otherwise be necessary.

6 Impact

Optimized heat-sinking of stationary phosphors should enable innovation in the design of laser-phosphor hybrid illumination optical systems. One benefit is that a smaller number of more powerful laser sources can be used. Another benefit due to the very high speed of operation of the deformable mirror is that short, high power, laser pulses could be used with a relatively low repetition frequency to allow the phosphor to cool between pulses.

References

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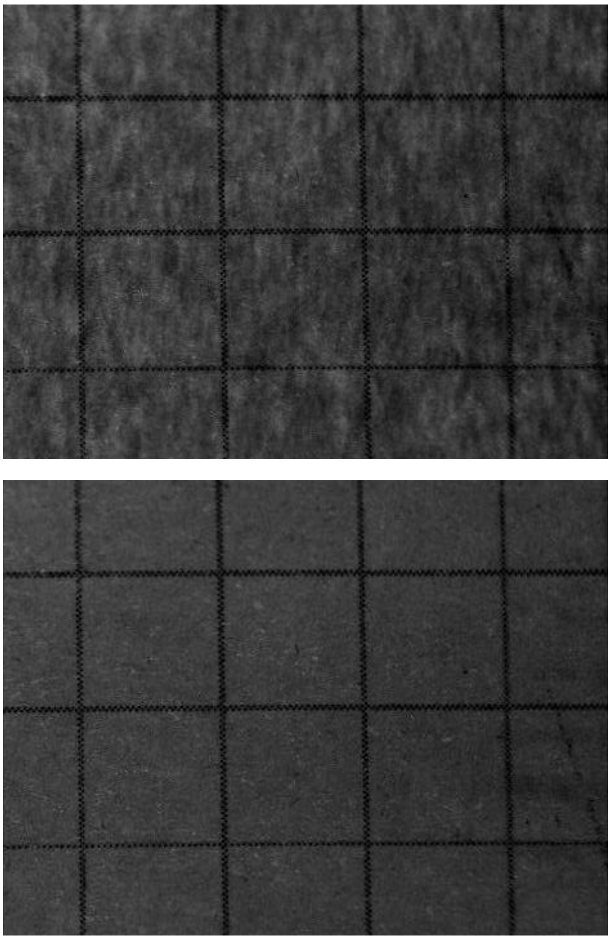

Figure 6: Paper screen with printed grid illuminated with laser blue wavelength only through projector apparatus. [Top] With deformable mirror inactive, although some subjective speckle is visible to the eye of an observer, objective speckle is dominant on the screen. This arises due to the surface diffusion and volume scatting in the phosphor. If the phosphor patch is moved gently by hand, the objective speckle pattern can be seen to move. [Bottom] With the deformable mirror active, although a greatly reduced amount of subjective speckle is still visible to the eye of the observer, the objective speckle on the screen is virtually eliminated.

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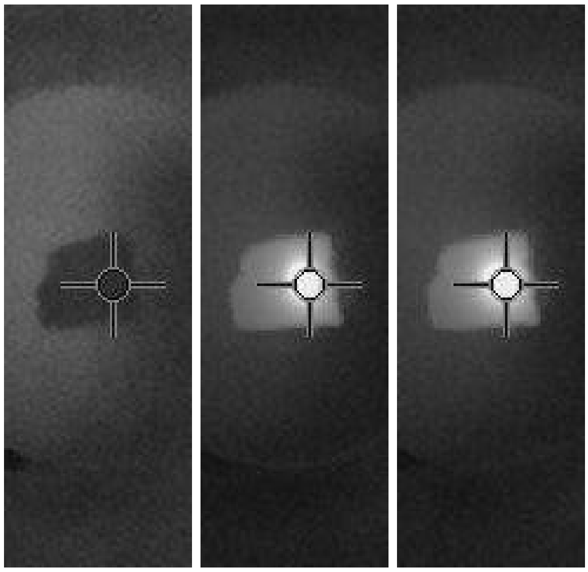

Figure 7: [Left] Thermal infrared image of phosphor patch acquired with FLIR i7 camera with a f=76.2 mm ZnSe lens used as a macro. With no laser illumination, the camera indicated a temperature for the targeted region of 30.9 °C. [Middle] With laser illumination active and the deformable mirror inactive, the camera indicated a temperature for the targeted region of 119 °C. [Right] With laser illumination active and the deformable mirror active, the camera indicated a temperature for the targeted region of 100 °C. Illumination intensity was deliberately kept low to avoid burning with deformable mirror inactive. To enhance visibility these images have different dynamic ranges.