

Optically Efficient Directional Illumination with Homogenization of Laser Incidence on Remote Phosphor

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Abstract: A heat-sinked, more optically efficient alternative to the rotating disc laser-phosphor system is proposed. A deformable mirror is demonstrated to effect intensity homogenization, which enables temperature optimization for down-conversion efficiency, and to reduce speckle visible to the observer.

1 Background

Directional illumination, as is required for projection displays, building spotlights, and vehicular headlights, for example, needs a relatively small point source. For high luminous flux applications, remote phosphor down-conversion of incident blue wavelengths from powerful laser diodes is an effective approach because the energy from the laser(s) can be focused easily to a small spot. However, since the phosphor emission angle approaches 90 degrees, it is difficult to collect and direct the illumination with good optical efficiency. Figure 1 shows a common configuration where high angle emission is not collected by the optical system due to the separation between it and the phosphor that is rotated so as to maintain an efficient operating temperature.

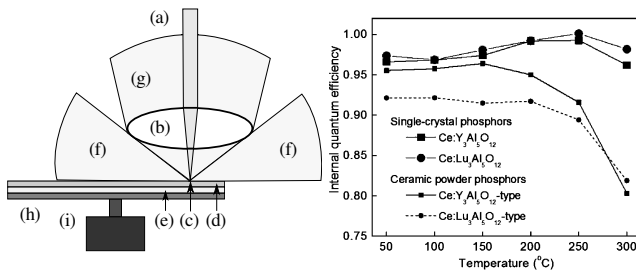


Fig. 1: [Left] Schematic of rotating disc laser-phosphor system: (a) incident blue laser illumination; (b) optical system for focusing, collection, and direction; (c) focused spot; (d) phosphor layer, typically YAG:Ce of approx. 100µm thickness; (e) reflective layer; (f) illumination lost from the optical system; (g) illumination collected and directed; (h) disc substrate, typically at least 50 mm diameter; (i) electric motor. [Right] Efficiency of various phosphor types with respect to temperature. Reproduced from [1].

The author has already proposed an alternative configuration using stationary, heat-sinked, phosphor [2]. This makes possible improved optical efficiency by reducing to zero the separation distance between optical system and phosphor. Collection and direction efficiency approaching 90% has been reported for phosphor-coated LEDs touching the entrance face of a light guide with the freeform profile of a compound parabolic concentrator (CPC) [3]. Figure 2 proposes one means of how such a light guide can be used in an optically efficient laser-phosphor directional illumination system.

An advantage of needing only a small volume of down-conversion material whose area matches the entrance face of the light guide is that it could be economic to use single crystal phosphor [1] that is more efficient and less temperature sensitive (see Figure 1 [Right]) and, in sliced and diced plate form, has excellent transparency for improved transmission efficiency of

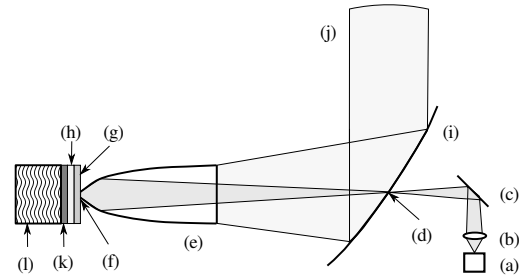


Fig. 2: Schematic of a laser-phosphor system with light guide and stationary, heat-sinked phosphor. (a) blue laser diode with highly elliptical emission; (b) focusing lens to reduce divergence at least along the fast axis; (c) fold mirror; (d) small aperture, of diameter ≤ 1 mm, for example; (e) CPC light guide; (f) entrance face of light guide, of diameter ≤ 1 mm, for example; (g) phosphor layer; (h) reflective layer; (i) reflective off-axis parabolic collimator; (j) directional illumination; (k) substrate; (l) heat-sink optimized for the application.

reflected illumination.

Of course the laser can be delivered through multimode optical fiber as in [4] and elsewhere. In addition to offering flexibility of laser diode(s) location (at the cost of optical coupling losses and additional components,) it effects reasonable homogenization of incident illumination (see Figure 3 [Left]) which is important to avoid hot spots on the phosphor that reduce emission efficiency and can cause burning. Homogeneity can be further improved (at the cost of more components and complexity) by shaking the fiber to effect inter-modal dispersion which leads to the creation of many uncorrelated speckle patterns over time, see Figure 3 [Right].

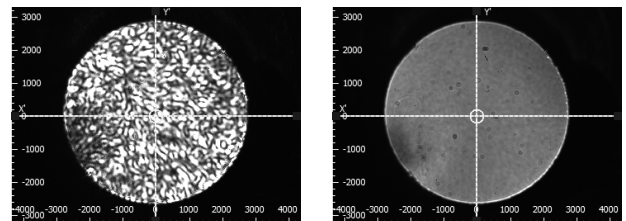


Fig. 3: [Left] Intensity distribution at face of CPC light guide into which laser has been delivered through 400 µm core diameter multimode fiber. Speckle patterns clearly visible. [Right] More homogeneous intensity distribution can be achieved through the creation of many uncorrelated speckle patterns that are integrated over time.

2 Objectives

To investigate whether good homogeneity can be effected through a CPC light guide *without* delivery through multimode optical fiber—instead using a deformable mirror (see Figure 4.) The author has already undertaken other investigations with a deformable mirror to improve homogeneity, see [5] for example. However the optical systems used (pairs of fly's eye arrays and integrating rods) were optimized for homogenization in contrast to the CPC that is optimized for collection efficiency.

A further objective was to observe whether there is any reduction in speckle visible to an observer due to coherence of the blue wavelengths in the illumination.

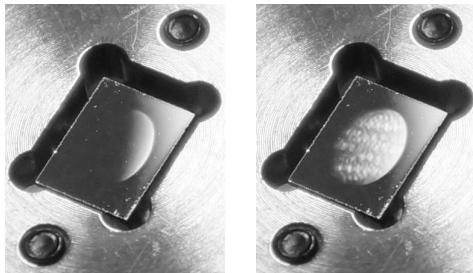


Fig. 4: DYOPTYKA's small deformable mirror in inactive and active states. Elliptical central region of 3mm×4.5mm is actuated at hundreds of kHz resulting in randomly-distributed surface deformations which achieve angular divergence, inter-modal dispersion in light guides, and the generation of uncorrelated speckle patterns. Reflection efficiency is approx. 98% and damage threshold is approx. 5 W. Power consumption depends on application requirements but is typically ≤100mW.

3 Apparatus and Results

To observe homogeneity, the optical path was made similar to the incident path of Figure 2 but with a deformable mirror as the fold mirror and a beam profiler camera at the entrance face of the CPC, see Figure 5. The camera imagery is shown in Figure 6. It is clear that homogeneity is greatly improved through the action of the deformable mirror. Further improvement should be possible by optimizing mirror divergence angle such that the light guide directs more illumination towards the edges of the entrance face.

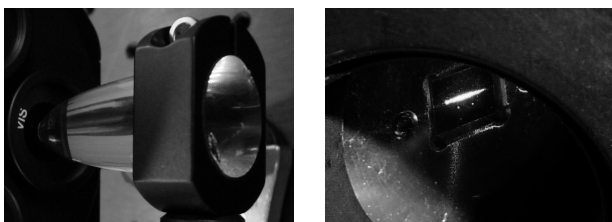


Fig. 5: [Left] Circular glass CPC (Edmund Optics model #65-442,) positioned such that its 5 mm dia. entrance face is in front of the sensor of a beam profiler camera (Thorlabs BC-106-VIS.) [Right] Deformable mirror (DYOPTYKA model uDM) on which is visible the elliptical emission of a 450 nm laser diode with 1 W optical power (Roithner LaserTechnik.) An $f=4.51$ mm aspheric focusing lens was positioned close to the diode to limit divergence.

To observe speckle, the optical path was made similar Figure 2 but with deformable mirror, planar CPC light guide, and a sheet

of paper instead of a parabolic collimator, see Figure 7. With deformable mirror inactive, a certain granularity was discernible. This reduced significantly with deformable mirror active.

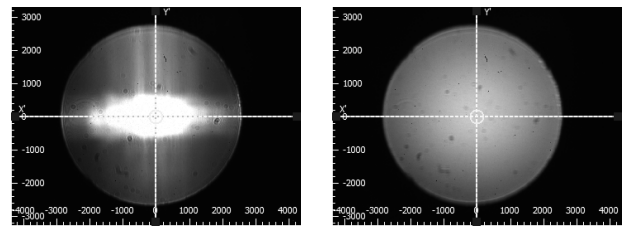


Fig. 6: [Left] Deformable mirror inactive: most incident energy within 15% of CPC entrance face area. Intensity distribution within this area is not at all homogeneous due to modal structure of laser but it cannot be seen here because sensor is saturated. [Right] Deformable mirror active: improved homogeneity.

4 Conclusions

Our deformable mirror has been demonstrated as an alternative to optical fiber for homogenization of incident illumination to avoid hot-spots and to allow heat-sinking optimized for efficiency of down-conversion material. Furthermore, it has been observed to reduce speckle. This motivates further steps towards thorough evaluation of our proposal for a more compact and more optically efficient alternative to the rotating disc laser-phosphor system for high luminous flux directional illumination applications.

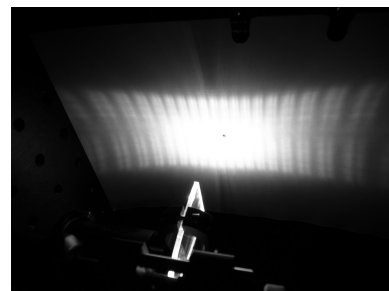


Fig. 7: Custom-made PMMA planar CPC positioned such that its 5×1mm² entrance face touches a strip of heat-sunk YAG:Ce phosphor. Its planar nature results in images of its exit face at various intensities on the paper sheet. This was to facilitate human observation because a superimposed single image was too bright.

- [1] Villora, E. G. et al., "Single-crystal phosphors for high-brightness white lighting," SPIE, International Society for Optics and Photonics (February 2016). DOI: 10.1117/2.1201602.006288.
- [2] Shevlin, F., "Speckle reduction for illumination with lasers and stationary, heat sunked, phosphors," in [International Display Workshop/Asia Display, (IDW/AD'13)], Institute of Image Information and Television Engineers (ITE), Society for Information Display (SID) (December 2013).
- [3] Fournier, F. et al., "Optimization of freeform lightpipes for light emitting diode projectors," *Applied Optics* **47**(7), 957–966 (2008).
- [4] Maemura, Y. et al., "A reflection-type white light source using blue laser diodes with high luminance of 1500 cd/mm²," in [The 4th Laser Display and Lighting Conference (LDC '15)], The Japan Society of Applied Physics, Yokohama, Japan (April 2015).
- [5] Shevlin, F., "Optically efficient homogenization of laser illumination," in [International Display Workshop (IDW '15)], Institute of Image Information and Television Engineers (ITE), Society for Information Display (SID) (December 2015).