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Homogenization Without Scattering of Laser Illumination

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Abstract: *Our innovative deformable mirror technology is shown to be effective for homogenization of illumination intensity and for speckle reduction. Performance is similar to approaches that use moving diffusers but with much improved optical efficiency.*

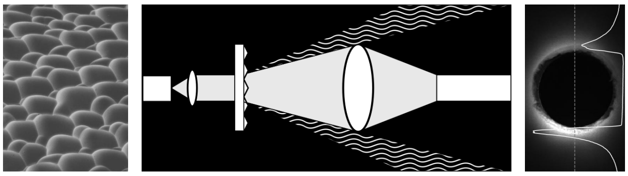

Fig. 1: [Left] Surface structure of an engineered diffuser. Although it is smooth piecewise, its slopes are discontinuous such that diffraction occurs. [Center] Typical homogenization optical system: laser diode, collimating lens, diffuser, coupling lens, integrating rod. Losses arise due to scattering by diffuser at angles higher than are accepted by coupling lens. [Right] Aperture of a beam trap positioned to accept laser light diverged approx. 6 deg by a cascade of two engineered diffusers. Plot of mean intensity in the neighborhood of the center line shows losses.

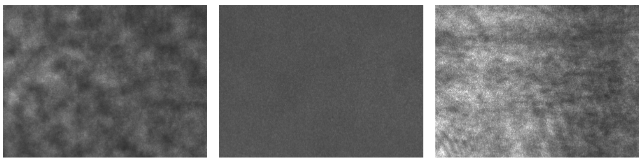

Fig. 2: Regions of field illuminated from exit face of integrating rod, with 150$\times$ magnification by $f/2.4$ projection lens, into which light from a multimode laser diode is coupled. [Left] With cascade of two engineered diffusers before light guide. [Center] Moving one of the two diffusers improves homogeneity through spatiotemporal averaging. [Right] With no diffusers before light guide, mean intensity is approx. 1.5$\times$ higher but homogeneity is poor due partially to the structure of multimode emission.

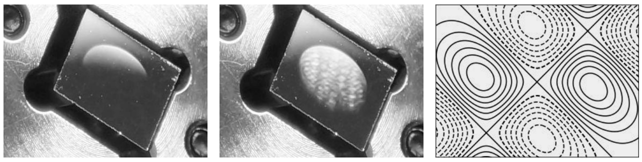

Fig. 3: [Left pair] Small deformable mirror in inactive and active states. Elliptical central region of 3mm$\times$4.5mm is actuated at hundreds of kHz to excite randomly-distributed surface deformations for angular divergence without diffraction. Reflection efficiency is approx. 99% and damage threshold is approx. 6 W. Power consumption depends on application requirements but is typically $\leq$ 100mW. [Right] Contour plot of simulated surface wave heights showing smooth transitions between regions of convex and concave curvatures. As heights change over time the curvature of each region is reversed such that directions of reflection are changed.

Fig. 4: [Left] Typical deformable mirror configuration for illumination. Light from one or more laser sources is directed into an area of several tens of mm^2, for example. Reflected light can be directed into a larger area with a smaller angle or vice-versa, in accordance with the optical invarant. [Right pair] Regions illuminated using the same deformable mirror actuated for different surface wave amplitudes such that divergence angles are approx. 2 deg and 3 deg respectively. No light is scattered outside these regions.

1 Introduction

The low étendue of laser diode emission facilitates efficient coupling into optical systems. However, in display or illumination optical systems, étendue may need to be increased to homogenize intensity and to shape the illuminated field. A moving diffuser is typically used despite the consequences for optical efficiency since even those with relatively smooth surfaces scatter light at angles such that it exits the optical system, see Figures 1 and 2.

DYOPTYKA has developed an innovative phase-randomizing deformable mirror technology [1], see Figures 3 and 4. It reduces speckle and other unwanted interference effects with excellent optical efficiency in comparison with diffusers, see Figure 5.

2 Objectives

To demonstrate how our phase-randomizing deformable mirror technology can be used for intensity homogenization without scattering for improved optical efficiency; and for the reduction of speckle contrast.

3 Apparatus

Powerful laser diodes have different structures of multimode emission and different coherence characteristics that can ef-

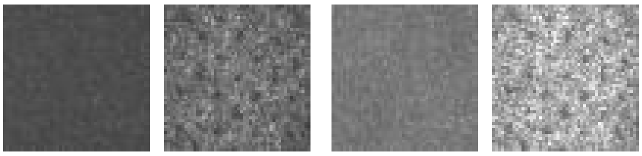

Fig. 5: [Left pair] Low-gain matt painted surface and high-gain rough metallic surface (of polarization-preserving cinema screen) illuminated with moving diffuser apparatus similar to schematic in Figure 1. Speckle contrast ratios are approx. 6% and 16% respectively. [Right pair] Same surfaces illuminated by same apparatus but without diffusers—a deformable mirror is used instead. Speckle contrast ratios are the same as with diffusers yet mean intensities are approx. $1.5\times$ higher.

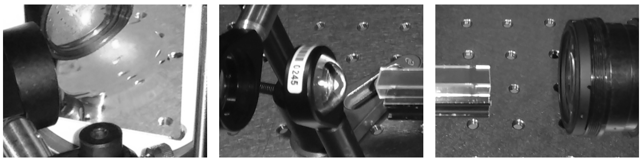

Fig. 6: Elements of experimental homogenization and projection apparatus. [Left] Prototype large deformable mirror with approx. 200 W damage threshold, oriented at 45°, reflecting approx. ⌀15 mm beam expanded from 532 nm DPSS laser; $f = 50$mm, ⌀30 mm lens positioned close to deformable mirror to collect light from approx. ⌀15 mm region. [Center] $f = 20$ mm, ⌀25 mm aspheric lens positioned to direct light into $6 \times 8\text{mm}^2$ entrance face of integrating rod. [Right] Exit face of integrating rod and DLP® projection lens with stop added to approximate $f/2.4$.

fect homogenization performance. Hence a highly coherent laser source with a near-Gaussian beam profile was chosen for the purposes of experimentation. Its beam was expanded to approx. ⌀15 mm such that is was similar in diameter to the combined emission from multiple powerful laser diodes.

A prototype large deformable mirror with a high laser damage threshold was used. Due to a fabrication error it had a distorted surface figure—the effect of which is seen in the following section. Large diameter lenses were used to couple into an integrating rod of length 50 mm. In an alternative configuration, three such rods were positioned next to each other for length 150 mm.

A projection lens was used to form a magnified image of the exit face at a distance of approx. 2 m. See Figure 6 for further details.

4 Homogeneity

The homogeneity of intensities shown Figures 7 and 8 are certainly improved through the action of the deformable mirror. That their mean intensities are the same supports the assertion that no light is scattered from the system.

It can be seen in Figure 8 that intensity distribution across the field is not perfect. Likely explanations include mirror surface figure distortion and misalignment of the aspheric lens used for coupling into the integrating rod.

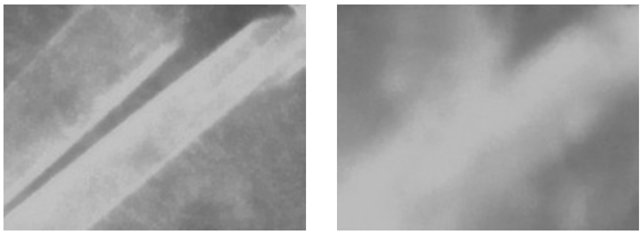

Fig. 7: Regions of field illuminated through integrating rod of length 50 mm. Mean intensities are approximately the same. [Left] Prototype large deformable mirror inactive. Distortions of its surface result in highly irregular intensity distribution. [Right] Deformable mirror active. Its surface wave amplitudes are insufficient for good homogeneity.

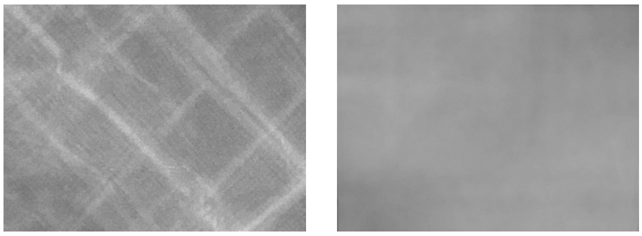

Fig. 8: Regions of field illuminated through integrating rod of length 150 mm. Mean intensities are approximately the same. [Left] Prototype large deformable mirror inactive. Longer light guide achieves more global distribution of irregularity. [Right] Deformable mirror active. Its surface wave amplitudes are sufficient for good homogeneity.

Although it was not measured with this particular apparatus, we are confident from previous experimentation that speckle contrast ratio is reduced by the deformable mirror to the same level as by a moving diffuser, see Figure 5.

5 Conclusions

Homogenization without scattering has been demonstrated. Our understanding is that surface waves on the deformable mirror result in spatially-distributed randomized angular divergence that makes the illuminated region appear as an extended source that fills the entrance face of the integrating rod better than point-like sources. The smooth transitions between surface waves, whose wavelengths are longer than those of the light, do not result in diffraction. Movement of surface waves further improves homogenization by directing light along different optical paths such that standing interference patterns do not arise. This movement also acts to reduce speckle contrast.

[1] Shevlin, F., "Phase randomization for spatio-temporal averaging of unwanted interference effects arising from coherence," *Applied Optics* **57**(22), E6–E10 (2018).

[2] Goodman, J., [*Speckle phenomena in optics*], Roberts and Company, Colorado, USA (2007).