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High-Frequency Homogenization of Laser Illumination Through Stationary Multimode Optical Fiber

Fergal Shevlin
DYOPTYKA, 7 Westland Court, South Cumberland St., Dublin 2, Ireland.
Phone: +353-85-1423747; Email: fshevlin@dyoptyka.com

Abstract: *Our innovative deformable mirror technology is shown to be effective for homogenization of illumination intensity, and for minimization of speckle, when used with a short length of multimode fiber and within a short camera exposure period.*

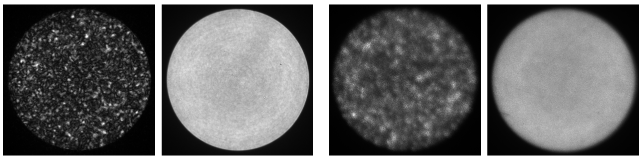

Fig. 1: Circular core; approx. 26× magnification of real image. [Left pair] Exit face; Deformable mirror inactive and active; Speckle contrast ratio $C_S = 58.9\%$ and 5.3% respectively. [Right pair] Volume scatterer; Deformable mirror active and inactive; $C_S = 28.9\%$ and 5.8% respectively. [Both pairs] With deformable mirror inactive, laser power was reduced to minimize sensor saturation by bright speckle grains.

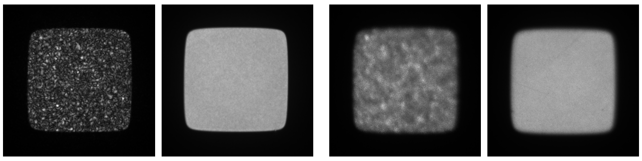

Fig. 2: Square core; approx. 26× magnification of real image. [Left pair] Exit face; Deformable mirror inactive and active; $C_S = 47.5\%$ and 3.6% respectively. [Right pair] Volume scatterer; Deformable mirror active and inactive; $C_S = 18.1\%$ and 4.6% respectively. [Both pairs] With deformable mirror inactive, laser power was reduced to minimize sensor saturation by bright speckle grains.

1 Introduction

When laser emission is coupled into multimode optical fiber, intensity at the exit face suffers from a highly irregular spatial distribution as can be seen in figures 1 and 2 [left]. One approach to homogenization is to shake the fiber to effect change in distribution such that it sums to a more even intensity over the sensor exposure period. Concerns include dynamic fatigue in fiber and length of fiber required.

An alternative approach which does not require any movement of the fiber is described herein. It uses an innovative phase-randomizing deformable mirror technology developed by DYOPTYKA, see figure 3, which has been shown to reduce speckle and other unwanted interference effects in many applications [1] with excellent optical efficiency [2] and at very high frequencies [3].

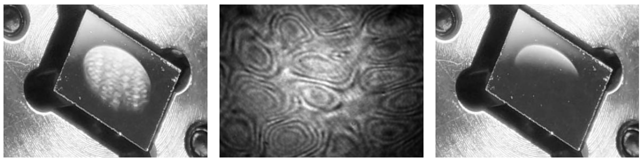

Fig. 3: [Left] Deformable mirror active. Randomly-distributed surface deformations are excited at very high frequencies in the 3 mm×4.5 mm elliptical region. Reflectance ≤ 99% and damage threshold >1 Wmm^{-2} for wavelength-appropriate mirror coatings. [Center] Microscope interferometer image showing fringes resulting from actual mirror deformations. [Right] Mirror inactive with near planar surface.

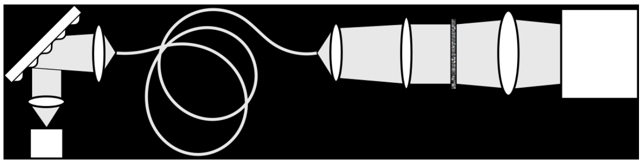

Fig. 4: DPSS laser source, CW, λ=532 nm; collimating lens for approx. ⌀1 mm beam; deformable mirror operating at 1.5 MHz, approx. 3° full-angle divergence; coupling lens f=4.51 mm arranged for approx. 10× angular and $1/10\times$ size magnification; multimode optical fiber, length 2 m, coiled and stationary, N.A.=0.39, ⌀200 µm circular core or □150 µm square core; collimating lens f=7.86 mm; focusing lens f=200 mm; real image plane and optional volume scatterer; imaging lens f=55 mm, $f/2.8$, focused to real image plane; camera with pixel size approx. □12 µm at real image plane, exposure period 20 µs.

2 Objectives

To demonstrate how our deformable mirror technology can be used with a short length of stationary multimode fiber for homogenization of illumination intensity during a short camera exposure period; and for the reduction of speckle generated by a scattering object.

3 Apparatus

Details are provided in figure 4. Both circular core and square core multimode fiber were used. A low-power lens focused a real image of the fiber exit face onto a plane

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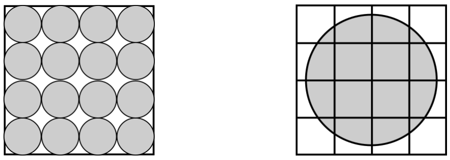

Fig. 5: [Left] When sensor pixel region on scattering surface is larger than the diffraction-limited spot size of the illumination optical system then minimum $C_S = 1/\sqrt{n}$ for n spots [4]. [Right] In high-resolution imaging, sensor pixel regions are typically smaller which precludes spatial averaging of uncorrelated speckle patterns within the region for reduction of C_S.

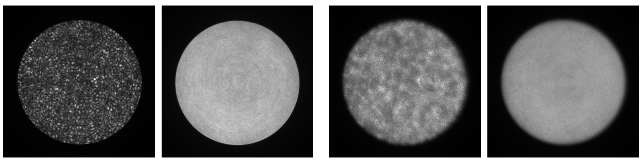

Fig. 6: Circular core; approx. 24× magnification of real image. [Left pair] Exit face; Deformable mirror inactive and active; $C_S = 41.0\%$ and 5.6% respectively. [Right pair] Volume scatterer; Deformable mirror active and inactive; $C_S = 16.8\%$ and 5.2% respectively.

where a volume scatterer could be placed.

The scatterer was a thin sheet of fluoropolymer with a smooth surface since roughness makes it difficult to distinguish speckle from surface in high resolution imagery. Scattering angle was approx. 20°.

4 Homogeneity

The exit face imagery shown in the left pairs of figures 1 and 2 demonstrate relative improvements in speckle contrast ratio [4] of over 90% with deformable mirror active. Square core homogeneity is visibly better than that of the circular core which is consistent with there being better mode mixing.

The volume scatterer imagery shown in the right pairs of the aforementioned figures demonstrate a lower relative improvement due to effect of scattering on intensity distribution and the generation of finer grain speckle.

5 Resolution

Relationships between sensor pixel regions and illumination optical system spot size are presented in figure 5. To investigate the effect of smaller spots in high resolution imaging, illumination magnification was reduced by moving the collimator closer to real image plane and refocusing.

Figures 6 and 7 show the imagery acquired. With deformable mirror active, there were only small differences in speckle contrast ratio between higher and lower magnifications. However with deformable mirror inactive, speckle contrast ratios were significantly reduced relative to those of the higher magnification configuration. This will be investigated further.

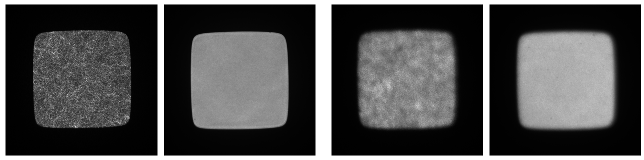

Fig. 7: Square core; approx. 24× magnification of real image. [Left pair] Exit face; Deformable mirror inactive and active; $C_S = 31.9\%$ and 3.8% respectively. [Right pair] Volume scatterer; Deformable mirror active and inactive; $C_S = 14.9\%$ and 4.4% respectively.

6 Coupling efficiency

Efficiency of coupling from deformable mirror into the optical fiber, and its temporal stability, were not measured during this experimentation. However efficiency of $> 95\%$ has been reported to us by customers. This is made possible by there being no high-angle scattering from the smooth deformations on the mirror surface. All reflected light is within a cone of small angular extent (3° in the case of the mirror used in this experimentation) which can be collected by the coupling lens of practical focal length.

7 Conclusions

Excellent homogeneity and speckle reduction has been demonstrated within 20 µs which was the shortest exposure period supported by the camera. Similar performance can be expected within even shorter periods since our technology has already been demonstrated to be effective within the duration of individual pulses as short as 6 ns in different configurations of illumination optical system.

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

[2] Shevlin, F., "Homogenization without scattering of laser illumination," in [*The 8th Laser Display and Lighting Conference (LDC '19)*], The Japan Society of Applied Physics, Yokohama, Japan (April 2019).

[3] Shevlin, F., "Speckle reduction within nanosecond-order pulse widths for flash lidar applications," in [*The 9th Laser Display and Lighting Conference (LDC '20)*], The Japan Society of Applied Physics, Yokohama, Japan (April 2020).

[4] Goodman, J., [*Speckle phenomena in optics*], SPIE, second ed. (2020).