The 1st Laser Display Conference (LDC'12,) Yokohama, Japan, Apr. 26–Apr. 27, 2012.

Speckle Mitigation in Laser-based Projectors

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Abstract: *The problem of laser speckle and approaches to its solution are introduced. The critical issues of performance and transmission efficiency are emphasized. The unique combination of benefits provided by DYOPTYKA's phase randomizing deformable mirror are outlined.* ***Keywords:*** *laser illumination, projection displays, speckle reduction.*

1 Introduction

Advantages of laser sources for the illumination of both large and small projection displays include: improved image *brightness*, improved power *efficiency*, improved image *contrast*, wider color *gamut*, reduced *size* of both illumination and projection optical systems, improved *depth of field*, and improved *lifetime*.

The main disadvantage of using laser sources is a potentially severe degradation of projected image quality due to the presence of a high contrast, high spatial frequency, granular pattern that seems to float in front of the projected image plane. This pattern is known as *speckle*.

Figure 1 [Top] gives an indication of the nature of the problem. The reality is much worse than can be presented in a printed image because the speckle grains can have extreme bright and dark values, the granular pattern can move with respect to stationary projected image when the observer's eye moves, and the granularity increases proportional to the distance from eye to image.

In this paper we present DYOPTYKA's technology for speckle mitigation in large and small microdisplay-based projectors such as those using TI DLP® and LCoS technology.

2 Solution approaches

Approaches to speckle mitigation include: moving projection screen; broadening laser linewidth; mutually incoherent sources of same wavelength at different angles; mutually incoherent sources of similar but different wavelengths; varying polarization; moving multimode optical fiber; moving diffuser in projection optical system; moving diffuser in illumination optical system. A theoretical analysis of the performance of several of these approaches is given in [1] and a discussion of their practicality is given in [2]. In practice more than one of these approaches is typically used in a single projector, the most common being mutually incoherent sources at different angles and a moving diffuser in the illumination optical system.

3 Moving diffuser

A moving diffuser is used to create significant variation of phase between the Airy disc-sized optical resolution elements of the projection lens, leading to the creation of sequences of uncorrelated speckle patterns which sum to a more homogeneous intensity distribution over the illuminated area. An effectively similar implementation is to use a stationary diffuser but to move the illumination beam(s) around it using a rigid tip/tilt steering mirror.

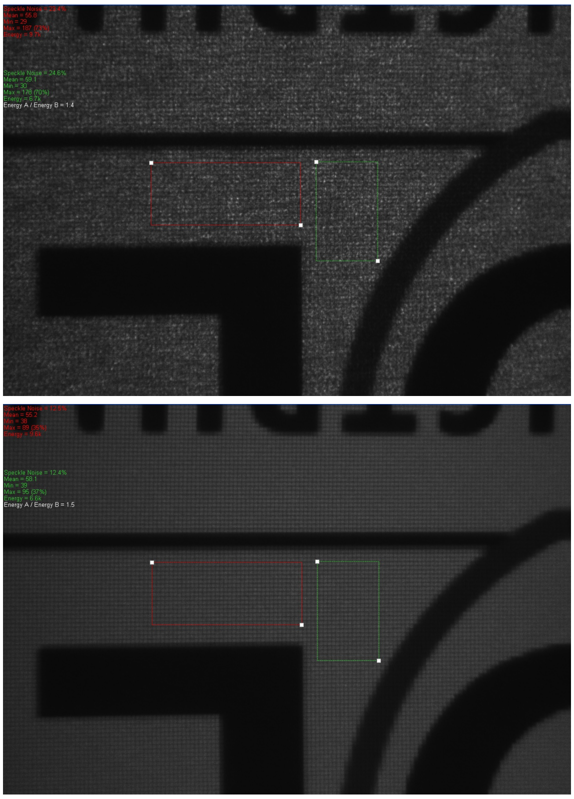

Fig. 1: [Top] TI DLP® picoprojector illuminated with a highly coherent frequency-doubled 532nm DPSS laser source, showing significant speckle. [Bottom] Reduced speckle thanks to DYOPTYKA's deformable mirror in the illumination optical system.

Important characteristics of an appropriate moving diffuser include: (i) *low diffusion angle,* since diffusion increases étendue which can lead to reduced efficiency through the optical system and reduced contrast in the image, the diffusion angle should be no greater than is necessary to vary phase between the optical resolution elements of the projection lens; (ii) *high transmission efficiency,* to minimize both energy loss and damage through absorption; (iii) *short correlation length,* to allow sequences of uncorrelated speckle patterns to be generated with a simple motion trajectory of small magnitude.

We are aware of no diffuser design which optimally satisfies all of these criteria. Figure 2 [Left] gives an indication of the significant losses that can arise due to high angle scattering from a low angle refractive microlens diffuser considered to be efficient [3]. Further losses arise due to the less than optimal anti-reflection surface coatings achievable on

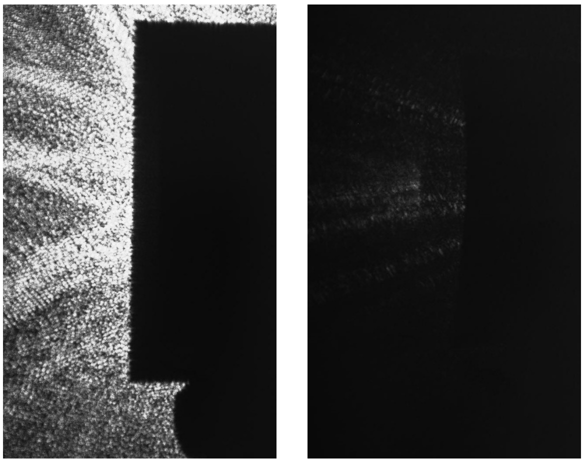

Fig. 2: [Left] Scattering losses arising from a 2 degree circular refractive diffuser where a beam dump has been located to have an acceptance angle of 2 degrees. [Right] No such scattering losses arise with a deformable mirror diffusing the beam randomly by at most 2 degrees.

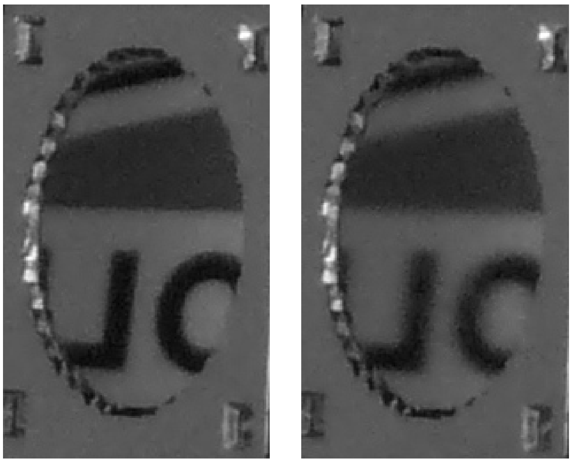

Fig. 3: [Left] Deformable mirror when inactive, showing reflection of some text. [Right] Deformable mirror when active with approximately 0.5 degree randomized divergence, showing blurred reflection of text.

its small microlenses with high surface curvatures.

Low angle diffusion with good transmission efficiency can be achieved using much larger diameter microlenses arrays with lower surface curvatures, as used in so-called fly's eye illumination homogenization optical systems. However because these arrays are periodic with long correlation lengths, it is a challenge to move them in such a way as to create sequences of uncorrelated speckle patterns. DYOPTYKA has devised an original solution to this problem.

4 Deformable mirror

We have developed a phase randomizing deformable mirror, shown when inactive and active in Figure 3. It effectively achieves low-angle diffusion without scattering losses, as can be seen in Figure 2 [Right]. It should be noted that the small losses visible are due diffraction at the laser beam aperture, not the deformable mirror. Maximum diffusion angles between approximately 0.5 degrees and 5 degrees can be maintained reliably.

The continuous variation of wavefront phase effected by the deformable mirror is normally not sufficient to reduce the spatial or temporal coherence of the illumination by itself. An additional *stationary* optical element such as a large diameter microlens array or a length of stationary multimode optical fiber can be located after the mirror to achieve this, with the deformable mirror used to randomize the incident angles of illumination such that sequences of uncorrelated speckle patterns are created at very high temporal frequencies.

5 Performance

The results in a projection display can be effective, as seen in Figure 1 [Bottom]. Speckle contrast ratios of $\leq 3\%$ can be achieved under optimal imaging conditions.

When the effective f/# of the projection optical system is very high, as in a wide-angle RPTV, and/or the image magnification of the projection optical system is very high, as in a digital cinema projector, then any speckle mitigation technique based solely on the reduction of *spatial* coherence in the illumination optical system will be of limited effectiveness. In this case the use of a length of multimode optical fiber after the deformable mirror leads to improvement since it additionally reduces average *temporal* coherence. Very high fiber coupling efficiency can be achieved since there is no high angle scattering.

6 Technical details

Typical mirror surface deformations are $\leq 10\,\mu$m in amplitude, ≥ 1 mm in wavelength, and ≤ 500 kHz in temporal frequency. An electronic actuation, sensing, and closed-loop control system, implemented with a single system-on-a-chip IC, is used to make highly randomized distributions of deformations.

For digital cinema projectors we have built deformable mirrors with active areas of approximately 40×60 mm^2 which can tolerate > 100 W of optical power (CW.) For companion microprojectors and those to be embedded in other devices such as cell phones we have built deformable mirrors with active areas of approximately 3×4.5 mm^2 with power consumption of ≤ 30 mW. Using dielectric mirror coatings it has been possible to achieve $\geq 98\%$ reflection efficiency across the range of visible wavelengths. Piezoelectric actuators with lifetime ratings of $\geq 100\,000$ h are used. Surface deformations are within the limits of elastic deformation of the mirror substrate and do not cause breakage. Polarization is preserved.

7 Conclusions

Our phase randomizing deformable mirror has a unique combination of benefits regarding speckle-reduction *performance*, optical *efficiency*, *manufacturability*, *reliability*, and *size*. Further details about the technology and its applications are provided in the recent longer paper by author [2].

References

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