Speckle reduction in laser-illuminated picoprojectors

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ABSTRACT

Speckle can seriously degrade image quality in laser-illuminated projection displays. Various solutions appropriate to small microdisplay-based projectors are presented. Illumination optical system and projection optical system design are discussed in order to better understand the critical constraints of size, power consumption, optical efficiency, and performance. DYOPTYKA's innovative solution, using a phase randomizing deformable mirror, is described.

Keywords: Projection displays, laser illumination, speckle reduction, LED illumination, picoprojectors.

1. INTRODUCTION

The advantages of using laser sources for the illumination of small microdisplay-based projection displays are compelling in comparison to using LEDs. They include: improved image *brightness*, improved power *efficiency*, improved image *contrast*, wider color *gamut*, reduced *size* of both the illumination source and the optical system, and improved depth of field for *focus-free* usage. These advantages lead the author and others[1] to conclude that the question is *when, not if,* laser sources will achieve widespread acceptance for this "picoprojector" application.

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 gives some indication of the nature of the problem. However 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 the stationary projected image when the observer's eye moves, and the granularity coarsens proportional to the distance from eye to image.

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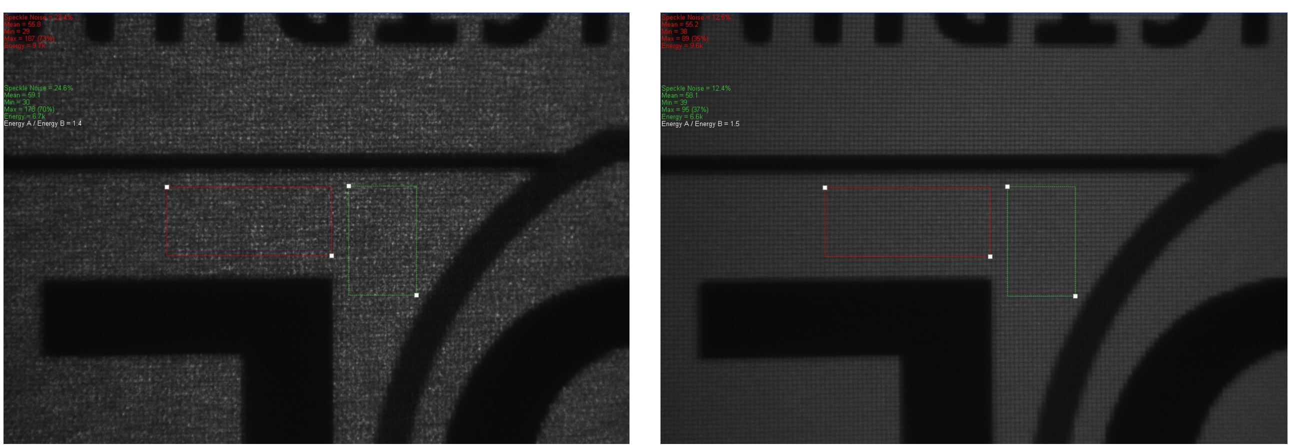

Figure 1. Extracts of imagery projected from a Texas Instruments (TI) DLP® picoprojector illuminated with a narrow linewidth frequency-doubled 532nm DPSS laser source. The left image shows significant speckle. The right image shows reduced speckle using DYOPTYKA's deformable mirror in the illumination optical system.

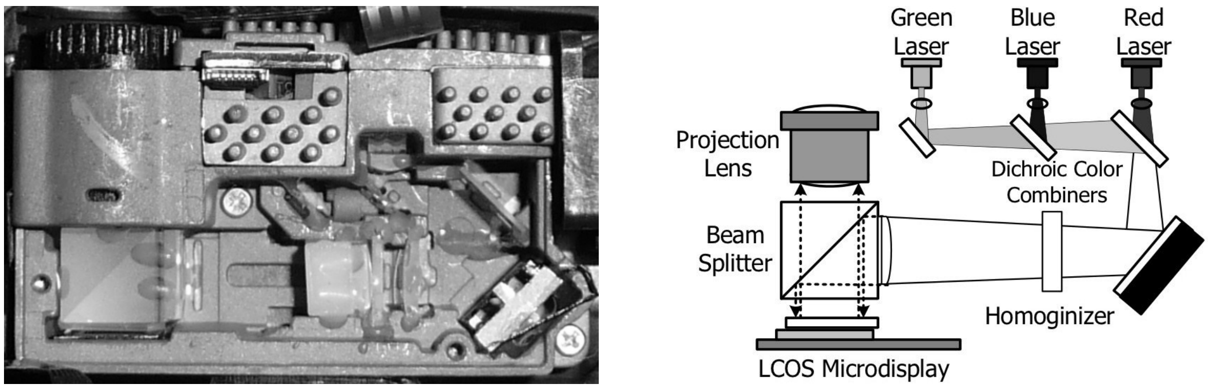

Figure 2. [Left] Laseno SMP-101 picoprojector module. Red, Green, and Blue laser sources are enclosed where cooling fins are visible. A DYOPTYKA deformable mirror prototype has been inserted at the bottom right to replace the original rigid fold mirror. [Right] Optical schematic of an LCOS picoprojector reproduced from Guttag.[1] A DLP picoprojector optical system can be similar except for mirrors or prisms in front of the microdisplay instead of the beam splitter.

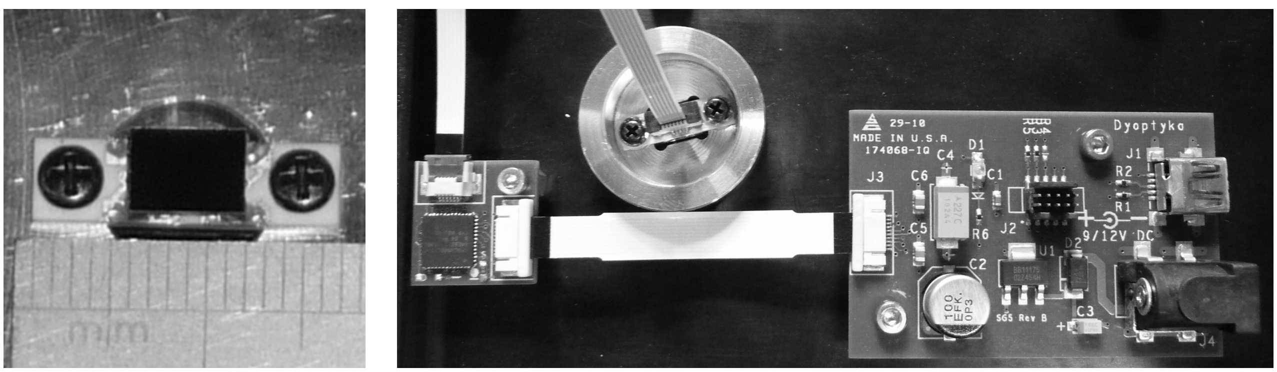

Figure 3. [Left] DYOPTYKA deformable mirror module developed for picoprojector applications. Module height is 4.5 mm. Deformable surface dimensions are 3 mm × 4.5 mm. Dielectric coating used for $> 98\%$ reflection efficiency. Power consumption < 30 mW. [Right] DYOPTYKA evaluation system comprising picoprojector mirror in a 1" optical mount, a control PCB with single PSoC controller IC, an interface PCB for 5 V or 3.3 V power supply, USB, and JTAG.

At least one laser-illuminated microdisplay-based projector has already been commercialized: the Laseno SMP-101, see Figure 2. It is an excellent proof of concept but it demonstrates the need for improved speckle reduction techniques—in particular as image brightness, hence speckle contrast, will increase through the use of more powerful laser sources.

In this paper we present a variety of speckle reduction solutions we consider practical for use in microdisplay-based projectors such as those using DLP® and LCOS technology. We conclude that DYOPTYKA's phase randomizing deformable mirror technology has a unique combination of benefits.

2. SPECKLE REDUCTION

The determinants of practicality chosen by the author are *size* and *efficiency*—which includes both the *electrical efficiency* of any active components used for speckle reduction and their *optical efficiency* because light not transmitted through the optical system to the projected image means the energy used for its generation is wasted and image brightness is reduced.

The following approaches create many different speckle patterns either simultaneously or sequentially over the observation period. Uncorrelated speckle patterns sum to a more homogeneous intensity distribution over the illuminated area, thus reducing speckle contrast.

Mutually non-coherent laser sources of different wavelengths. The wavelengths of typical laser primary colors (i.e. red, green, and blue) are much more saturated than the primary colors of the most common display color spaces, including HDTV. Desaturation is necessary using a weighted sum of the laser primaries to produce the primaries specified for the display color space. Since the speckle patterns for different wavelengths are uncorrelated, this achieves some speckle reduction proportional to the number of laser primaries.

In addition to the above, more than three laser primaries could be used to further reduce speckle. For example, different direct-emission green laser diodes with slightly different wavelengths could be used. Although additional laser diodes could lengthen the total optical path, length is not as critical a dimension for picoprojectors as height is.

Laser sources with increased linewidth. Since speckle arises due to the highly coherent nature of laser illumination, one means of improvement is to use sources with reduced coherence, such as the direct-emission green laser diodes under development by several manufacturers. However their approximately 2 nm linewidth is insufficient to reduce speckle to acceptable levels. It should be noted that the brightest and most power efficient green lasers available today are frequency-doubled and it is not possible to broaden their linewidth beyond about 0.1 nm.

Variation of polarization. If implemented in the illumination optical system, this is practical only for DLP® microdisplays because a constant state of polarization is required for LCOS microdisplays. Since there are only two orthogonal states of polarization, the maximum improvement in speckle contrast that can be achieved is $\sqrt{2}$.

Moving diffuser in illumination optical system. Motion of a diffusing element in the illumination optical system before the microdisplay. The purpose of moving the diffusing element is to significantly vary the phase of the coherent illumination within and between each of the Airy disc-sized optical resolution areas of the projection lens. This leads to the creation of uncorrelated speckle patterns. An effectively similar implementation is to use a stationary diffuser but to move the illumination beam around it, for example using a rigid tip/tilt beam steering mirror.

Herein we present an improved alternative to the moving diffuser approach using DYOPTYKA's technology.

3. OPTICAL SYSTEMS

Figure 4 shows an illumination optical system suited to picoprojectors where microlens arrays are used both to homogenize intensity across the illuminated field and to shape the field such that it matches the aspect ratio of a microdisplay located at the plane labelled FP. When using laser illumination, a moving diffuser located before or between the microlens arrays acts to reduce speckle, to reduce the Talbot effects that arise due to the periodicity of the microlens arrays, and to prevent damage due to otherwise perfect focus on the second lens array. The rotating diffuser shown in Figure 4 is followed by a lens to collect the diffused illumination and to direct it into the first microlens array.

A DLP® or LCOS microdisplay is used to form the pixelated image which is magnified and relayed to the screen by a projection lens. The choice of the projection lens f/# is critical because it dictates the minimum level of speckle contrast that can be achieved using a moving diffuser only. For example, an f/2.4 projection lens typically used with a DLP® microdisplay achieves a speckle contrast ratio about *half* of that achieved with an f/4.8 projection lens which could be used for focus-free operation. See Figure 5 for a worked example.

4. DIFFUSERS

A moving diffuser minimizes spatial coherence at the screen through diffusion in the illumination optical system. To minimize transmission losses, the diffusion angle should not exceed the acceptance angles of subsequent elements within the illumination and projection optical systems. This precludes the use of volume diffusers which otherwise are very effective for speckle reduction due to multiple internal scattering.

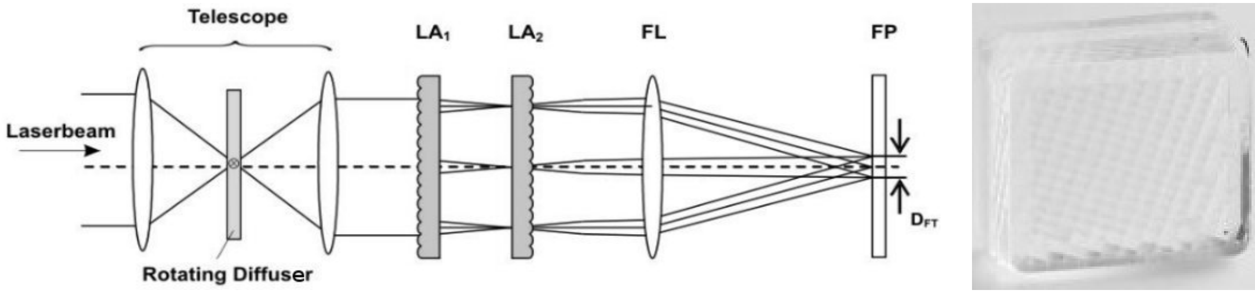

Figure 4. [Left] A typical laser illumination homogenization optical system. Schematic reproduced from Voelkel.[2] A moving diffuser, two microlens arrays, and a field lens are used to homogenize the illumination and direct it to the microdisplay plane. [Right] A close-up of a typical microlens array.

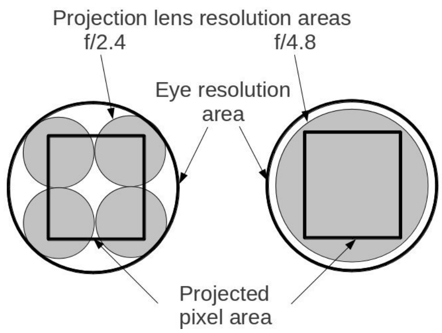

Figure 5. Using a single narrow linewidth laser source, the minimum speckle contrast ratio that can be achieved with a moving diffuser only is $C = \sqrt{(1/(d/s)^2)}$, where d is the diameter of the resolution element of the eye and s is the diameter of the resolution element of the projection lens.[3] Using $\lambda = 532\,\text{nm}$ and an image magnification of $40\times$, the diffraction-limited Airy disc diameter $s = 2.44 \times 532\,\text{nm} \times 2.4 \times 40 = 127\,\mu\text{m}$ approximately for an $f/2.4$ projection lens and $s = 254\,\mu\text{m}$ approximately for an $f/4.8$ projection lens. For a microdisplay pixel diagonal of $6\,\mu\text{m} \times 40 = 240\,\mu\text{m}$ at the screen and a viewing distance such that individual pixels are barely not resolvable, say $d = 254\,\mu\text{m}$, then $C = \sqrt{(1/(254/127)^2} = 0.5$ for $f/2.4$ and $C = 1$ for $f/4.8$. Note the relative sizes shown in the figure are approximate.

Refractive, diffractive, holographic, and reflective surface diffusers can be designed to achieve relatively low angles of diffusion (see, for example, Maradudin et al.[4]) The main problems that arise in practice are: *losses* due to unwanted higher angle scattering (see Figure 6) and the poor efficiency of anti-reflection coatings on rough surfaces; and the magnitude and complexity and of *motion* required to create sequences of uncorrelated speckle patterns over time.

Motion magnitude can be minimized by using a "cascade" of more than one diffuser at the expense of further losses and an increase in optical system length. Motion complexity is limited by the mechanical systems which can be implemented at a small scale and with low energy cost. The most common are: rotation about an axle; resonant vibrations of translational mechanisms such as tuning forks; resonant vibrations of rotational mechanisms such as a tip/tilt beam steering mirror. Since these motions are periodic, the correlation length of the diffuser must be short so that uncorrelated speckle patterns are created.

We are not aware of any diffuser design which optimally satisfies all the requirements of this application: (i) *low diffusion angle*; (ii) *high transmission efficiency*; (iii) *short correlation length*.

A microlens array pair with field lens (as shown in Figure 4) could be considered as a low angle diffuser with high transmission efficiency so it meets the first two requirements—but the periodically-distributed relatively large aperture lenslets have very long correlation lengths. Hence moving these microlens arrays results in poor speckle reduction. DYOPTYKA has developed an original solution to this problem.

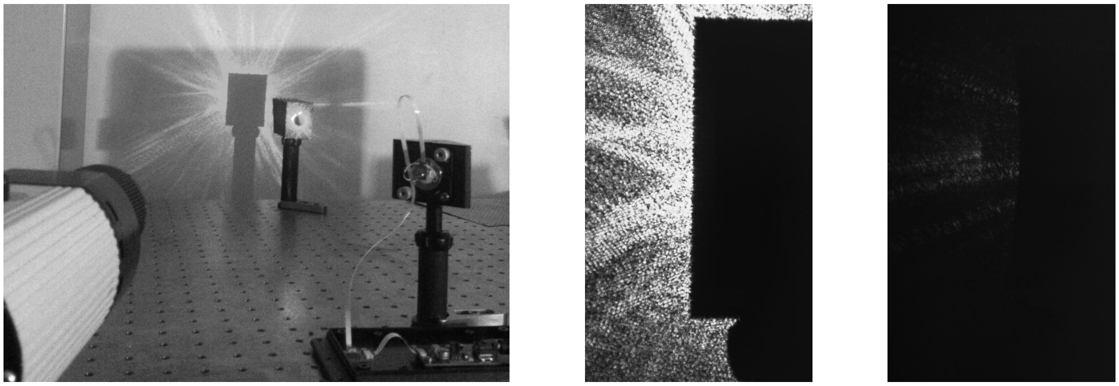

Figure 6. [Left] Apparatus for imaging the high angular scattering that arises with a 2 degree refractive circular diffuser (model EDC-2 from RPC Photonics Inc.) A beam trap is located at a distance from the diffuser such that its entrance aperture is filled. The scattered light that does not enter the aperture is easily visible on the wall. [Center] A close-up of the scattered light showing the shadow of the beam trap. [Right] No such scattering losses arise when the deformable mirror is used to diverge the beam randomly by at most 2 degrees. The small losses visible are due to diffraction at the laser beam aperture, not the deformable mirror.

5. DEFORMABLE MIRROR

We have developed a phase randomizing deformable mirror shown when active and inactive in Figure 7 [Left]. It effectively achieves, over time, randomized low angle divergence without scattering losses, see Figure 6 [Right]. It has only a small influence on beam directionality and spatial coherence, as is demonstrated by the interference fringes shown in Figure 7 [Right]. Our 4.5 mm high deformable mirror module developed for picoprojector applications is shown in Figure 3.

The continuous variation of wavefront phase effected by the deformable mirror is not normally sufficient to reduce the spatial or temporal coherence of the illumination by itself. Additional *stationary* optical elements such microlens arrays, diffusers, or a length of multimode fiber can be located before and/or after the mirror to achieve this, with the deformable mirror used to randomize the angles of illumination such that sequences of uncorrelated speckle patterns can be created at very high temporal frequencies. Its speckle reduction performance is limited only by the projection lens effective f/#, see Section 6.

For picoprojector applications where transmission efficiency is critical, the optimal solution is to have no diffuser in the illumination optical system, only the pair of microlens arrays. The deformable mirror allows the microlens arrays to play the role of efficient low angle diffusers because the randomized, non-periodic deformations compensate for the long correlation lengths of the periodic array.

Although the dielectric and/or metallic coating of the deformable mirror is highly polarization-preserving, it can be used with *stationary* quarter wave retarders, appropriately designed to be sensitive to incident angle, to scramble the polarization state of the illumination for a further $\sqrt{2}$ reduction in speckle contrast ratio with DLP® microdisplays which do not require polarization.

Typical mirror surface deformations are $\leq 1\,\mu m$ in amplitude, $\geq 1\,mm$ in wavelength, and $\leq 500\,kHz$ in temporal frequency. An electronic actuation, sensing, and closed-loop control system, implemented using a commercially-available mixed-signal 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 $40 \times 60\,mm^2$ which can tolerate $> 100\,W$ of optical power (CW.) For companion and embedded picoprojector applications our deformable mirror has an active area of approximately $3 \times 4.5\,mm^2$ with power consumption of $\leq 30\,mW$. 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 coatings and do not cause breakage. Polarization is preserved.

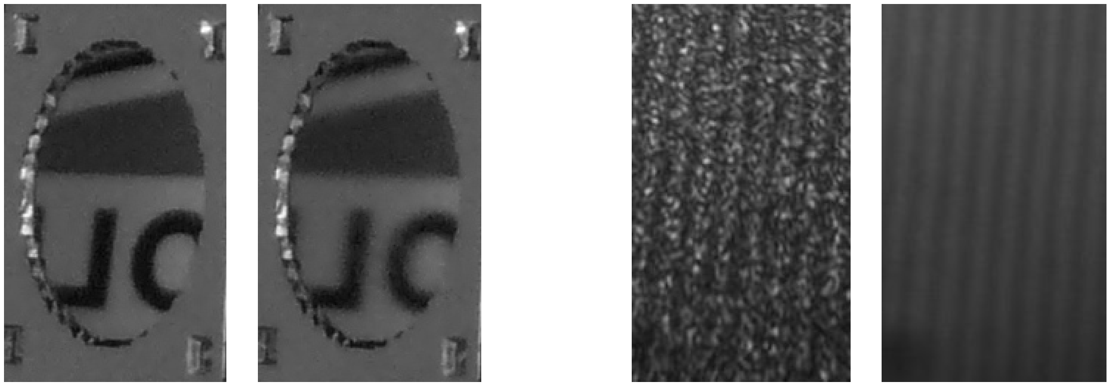

Figure 7. [Left] A deformable mirror prototype showing a reflection of some text when inactive and when active with approximately 0.5 degrees randomized divergence—showing the reflection blurred. [Right] Fringes from a Michelson interferometer with a deformable mirror in the common path before the split into two arms, when inactive and when active. These fringes demonstrate that beam directionality and coherence are preserved with the deformable mirror, i.e. it does not act as a diffuser to scatter illumination.

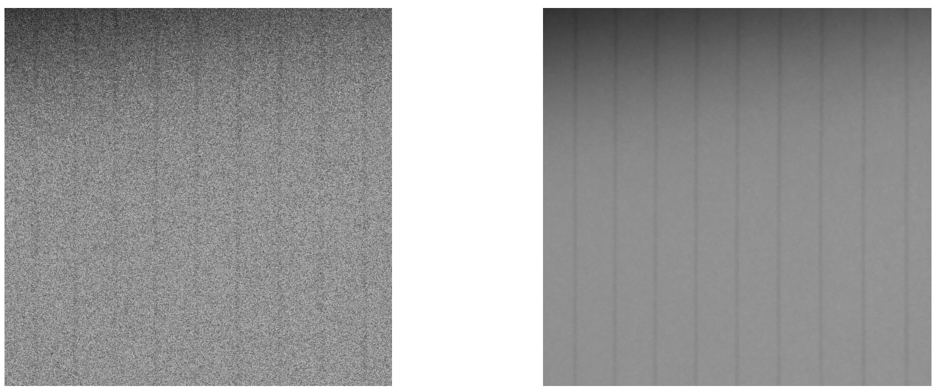

Figure 8. [Right] A sheet of writing paper located directly after a diffuser illuminated with a narrow linewidth frequency-doubled 532nm DPSS laser and imaged with camera lens at a fast f/#. [Left] The same scene but with a deformable mirror active before the diffuser. With no projection optical system after the diffuser a very low speckle contrast ratio can be achieved.

6. PERFORMANCE

Accurate evaluation of speckle contrast ratio must take into account all projection and viewing parameters. This makes it difficult to compare the performance of different systems. In acknowledgement of this, some standardized apparatus and procedures for speckle measurement have been proposed, e.g. by Gollier.[5]

The difference between speckle contrast visible in Figure 1 and Figure 8 is due mainly to there being no projection lens in the latter. Such significant differences arising due to variations in apparatus discourages us from quoting absolute speckle contrast ratios. We feel that side-by-side comparisons are more meaningful.

Figure 9 shows comparative imagery from an unmodified commercially available picoprojector whose projection lens effective f/# is about f/4.8 and the same model modified to include a prototype DYOPTYKA deformable mirror. Since the optical resolution of the projection lens is close to the pixel size, the speckle contrast ratio is higher than for the picoprojector shown in Figure 1 whose effective f/# is about f/2.4.

Despite speckle reduction being limited by the projection lens, we observed that the system with the deformable mirror had noticeably improved image quality. On further investigation we found this was almost entirely due to a significant reduction of speckle arising from scattering from across the whole illuminated field, as is measured with the camera lens highly defocused. We also observed this speckle pattern moved with a dif-

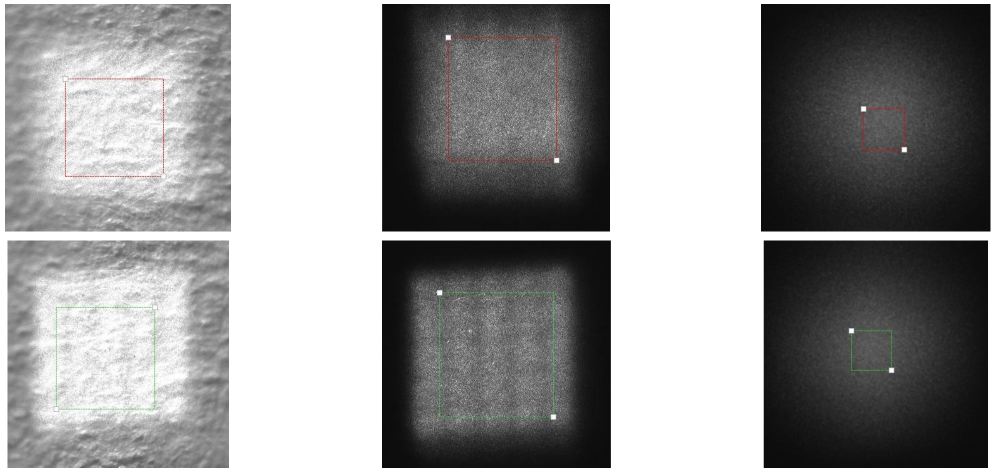

Figure 9. [Top row] A 5 × 5 group of pixels projected from a Laseno SMP-101 picoprojector onto a sheet of writing paper. Imaged with high magnification. [Bottom row] A 5 × 5 group of pixels projected from another Laseno SMP-101 picoprojector modified to include a DYOPTYKA deformable mirror (as shown in Figure 2). [Left] Camera pixel saturation precludes speckle contrast analysis; [Center] As in left image but with camera exposure period reduced. Difference in image quality likely due to misalignment of projection lens. [Right] As in center image but with camera lens defocused.

ferent velocity to its counterpart at the screen in response to head movement. This has an effect on subjectively evaluated image quality disproportionate to what is quantitatively evaluated.

7. CONCLUSIONS

DYOPTYKA's phase randomizing deformable mirror has a unique combination of benefits regarding speckle reduction *performance*, optical *efficiency*, *manufacturability*, *reliability*, and *size*. We are increasingly confident that our technology provides the most *effective* and most *practical* alternative to moving diffusers in laser-illuminated picoprojectors.

Until laser sources with broader linewidths become sufficiently powerful and energy efficient, we suggest using approximately f/2.4 projection lenses. Although they need to be focused at close projection distances, the improvement in image quality due to the lower speckle contrast is significant. This should be in addition to color primary weighted averaging, and polarization variation if possible. This will enable the use of narrow linewidth laser sources, for example the frequency-doubled 532 nm ones which are sufficiently powerful, efficient, and commercially available today, in picoprojectors much brighter than are possible with LEDs.

APPENDIX A. FURTHER READING

The advantages of laser illumination for picoprojector applications have been well documented in the literature. See, for example, Guttag et al.[1] A recent review of laser-illuminated displays in general is given in Chellappan et al.[6] and a discussion of the potential for high power Digital Cinema-type projectors is given in Janssens et al.[7] An excellent treatment of speckle, its applications, and a variety of mitigation techniques is given by Goodman.[3] Another publication by this author briefly describes how the performance of DYOPTYKA's technology can be further improved using a length of multimode optical fiber to reduce average temporal coherence as well as spatial coherence in projection displays large enough to accommodate some fiber.[8]

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