Speckle Mitigation in Laser-Based Projectors

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What does speckle look like?
Can speckle be reduced?
How can speckle be reduced?

**Speckle pattern averaging approaches:**

- Move diffusing screen where a real image is formed.
- Move diffuser in illumination optical system.
- Move waveguide/fiber in illumination optical system.
- Vary polarization if possible.
- Multiple laser sources of same wavelength but at different angles.
- Multiple laser sources of similar but different wavelengths.
- Desaturation of laser primaries.

**Laser linewidth broadening approaches:**

- Drive laser at threshold and/or pulse.
- Use diode sources if/when they become practical, e.g. for Green.
Laser Primaries and Display Color Spaces

Figure reproduced from Guttag.
Most effective single approach: Moving Diffuser

- Creates many different optical paths of different lengths through the illumination optical system.
- Can minimize spatial coherence at screen.
- Movement creates many different speckle patterns over time.
- Can be used in a scanning projector but requires speed and focus.
But moving diffuser usually isn't enough

Minimum speckle contrast from a single coherent source proportional to: eye resolution / projection lens resolution.

Multiple different approaches used to overcome this limit.

Figure inspired by Goodman.
Diffuser motion complexity limited by mechanical system implementation: easiest motions are *periodic*---no good for speckle reduction---so diffuser needs short *correlation length*.
Diffuser types for speckle reduction

Optimal characteristics:

- Low diffusion angle.
- High transmission efficiency.
- Short correlation length to minimize required motion.

Randomized microlens arrays probably best conventional solution:

Figures reproduced from Voelkel.
Randomized microlens array problems

- Higher angle scattering losses.
- Sub-optimal anti-reflection coating.
- Correlation lengths $>>$ 100 um.
What are the important characteristics of a speckle reduction solution?

- **Speckle reduction performance**
- **Optical efficiency**
  - for picoprojectors: brightness, power consumption.
  - for Cinema projectors: brightness, damage threshold.
- **Size**
  - for picoprojectors: 4.5 mm target height.
  - for LCD backlights: also needs to be small.
- **Power consumption**
  - for picoprojectors in particular
- **Reliability**
- **Cost**
Dyoptyka solution: phase randomizing deformable mirror

- Randomized divergence, controllable from 0.5 to 5 deg. approx.
- No high-angle scattering losses.
- Minimal motion required, e.g. < 1 um.
- Polarization preserved.
Randomized divergence: 0.5 deg. max.
Randomized divergence: 1.5 deg. max.
Randomized divergence: 2.0 deg. max.
Randomized divergence: 2.5 deg. max.
Randomized divergence: none.
Randomized divergence: non-diffusing.

Deformable mirror active in initial path of Michelson interferometer. Fringes formed in re-combined path:

Beam **directionality** and **coherence** preserved!
Use with large aperture periodic microlens array to create diverse optical paths

Performs better than moving randomized microlens array:

- No higher-angle scattering losses.
- Better anti-reflection coatings on larger microlenses.
- Only motions required are < 1 μm deformations of mirror surface.
Use before or between microlens arrays

... or optical fiber, or LCD backlight plate, or any optical element that supports multiple optical paths
Miniaturized versions available

- 4.5 mm high with active area 3.0 mm x 4.5 mm.
- > 99% efficiency dielectric coating for R, G, B.
- < 30 mW power consumption at 5V or 3.3V.
- 10 mm x 10 mm control electronics PCB.
Speckle Reduction Evaluation

- Appropriate projection lens must be used.
- Contrast ratio of about 3% is considered minimum perceptable.
- Side-by-side subjective comparisons very useful.
“Wide-field” Performance Evaluation

Highly defocused camera lens blurs screen surface texture \textit{and} projection lens-limited speckle.

Only “wide-field” speckle remains. [Note: pattern moves with different velocity]

In our experience, if “wide-field” speckle eliminated then speckle contrast is minimized.
Performance in DLP® projector

- Achieves speckle contrast ratio imposed by projection lens.
- Better *optical efficiency* than moving diffusers.
Performance with optical fiber
Other interesting characteristics

- Achromatic when coated appropriately. Only one mirror required for R, G, and B.
- Preserves angles between multiple laser sources.
- Efficient coupling into waveguides/optical fiber, e.g. 100 um core diameter.
- Sizes from 100 mm to 3.0 mm diameter.
- Max. optical power tested is 100 W but much higher possible.
- Works well to dynamically distribute visible Blue laser onto Yellow phosphor to give reduced speckle “white” without damage to phosphor.
Interesting characteristics, continued.

- Can be very fast! >> 1 MHz possible.
Availability

- Evaluation systems with reconfigurable control electronics and PC-hosted reconfiguration software available now.
- Price of miniaturized version is now appropriate for companion picoprojector now in volumes of 1,000/month.
- Our Asia-based manufacturer ready to scale up production to >10,000/month.
Conclusions

• Projection lens limits speckle reduction: use fastest f/# possible, even at the cost of focus-free operation! [Note: Lens focusing time is short compared to viewing time---Improved image quality is worth the effort.]

• Multiple speckle reduction approaches may be necessary to achieve the required image quality.

• Will broader linewidth laser diodes need active speckle reduction? Yes!

• Dyoptyka's deformable mirror is superior to a moving diffuser with regard to: optical efficiency, power consumption, size, reliability, and cost.
Thank You!

Questions?

Also please do contact me later in person or by email ...