Speckle Mitigation in Laser-Based Projectors

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Dynamic Optics Applications

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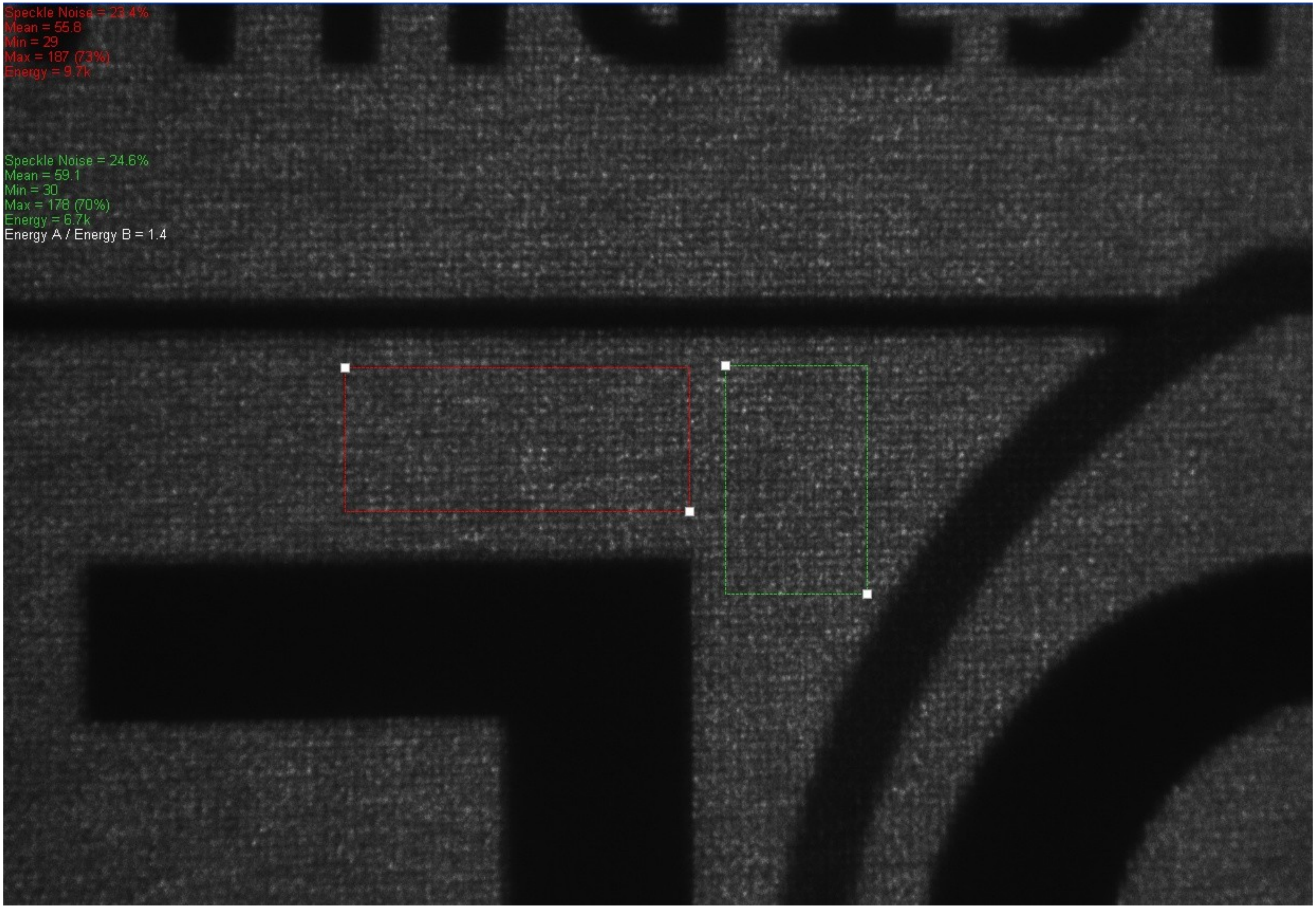
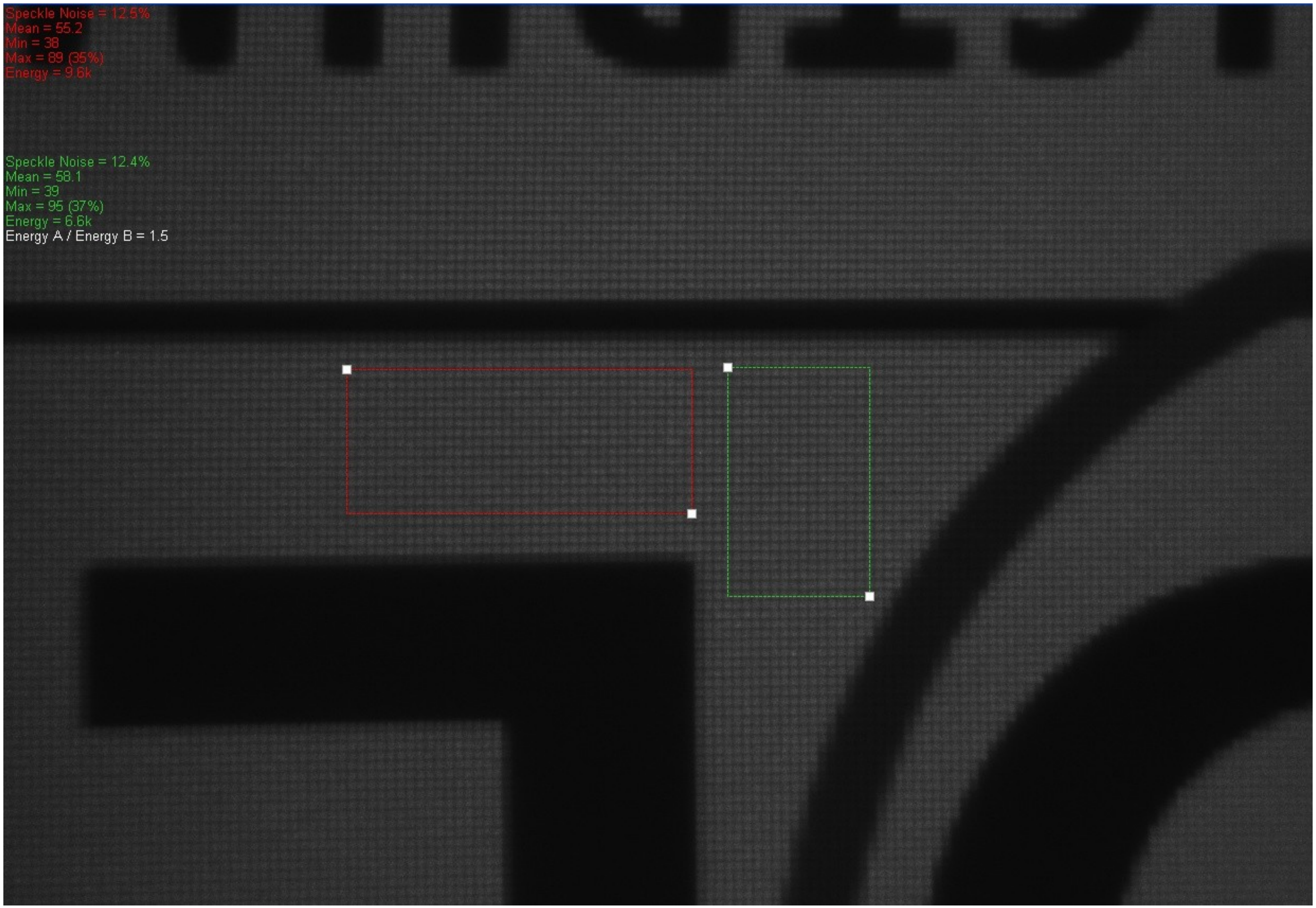
What does speckle look like?



Can speckle be reduced?



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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.

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Laser Primaries and Display Color Spaces

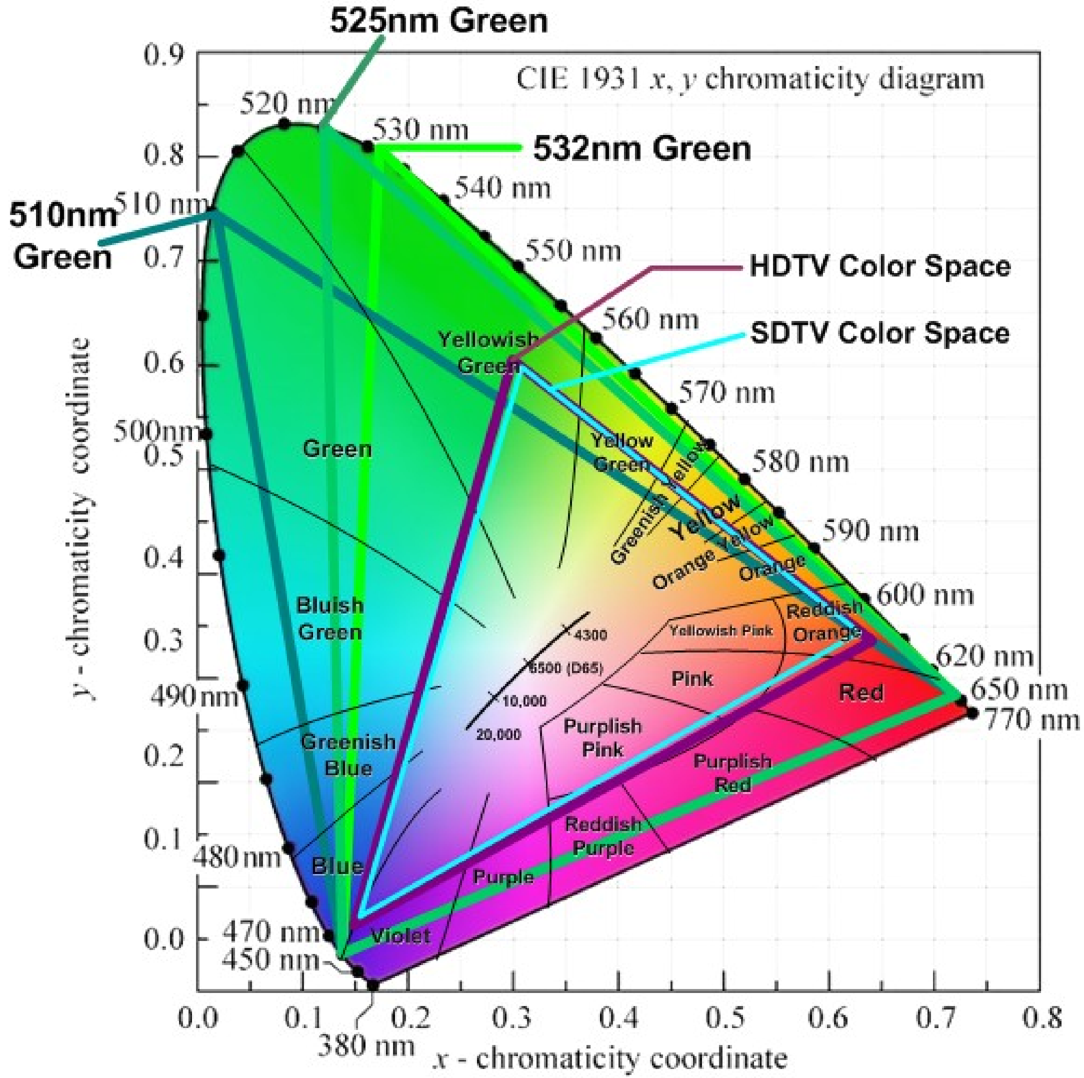

Figure reproduced from Guttag.

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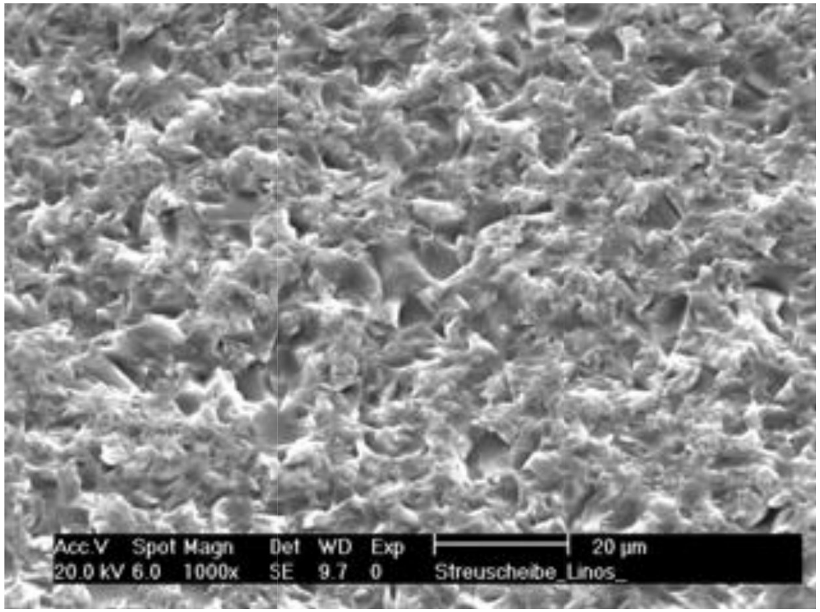
Most effective single approach: Moving Diffuser



- 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

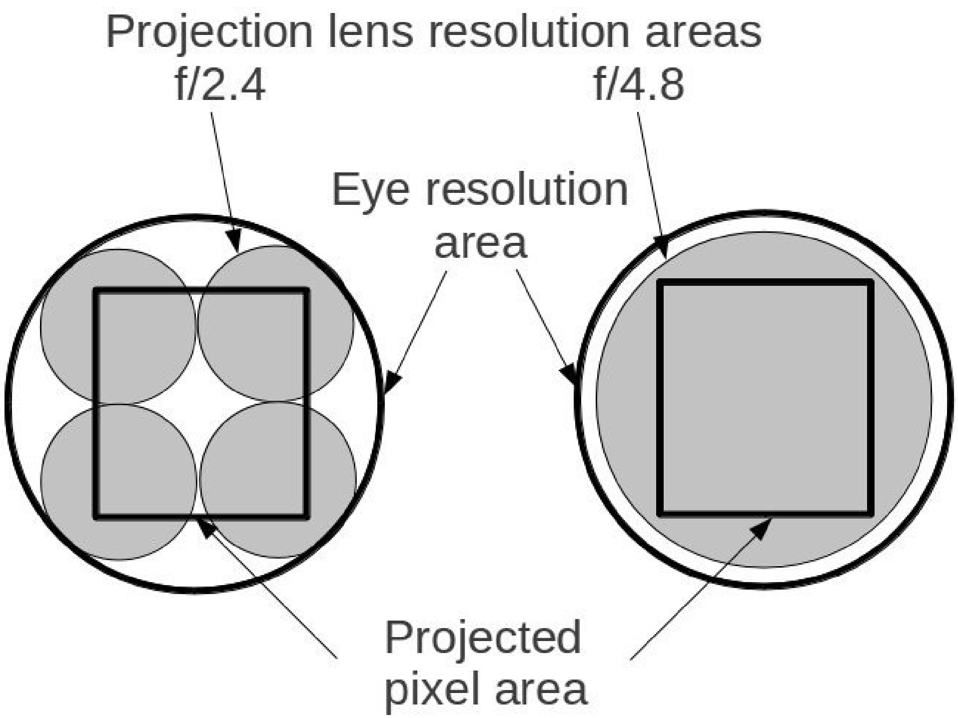


Figure inspired by Goodman.

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

Multiple different approaches used to overcome this limit.

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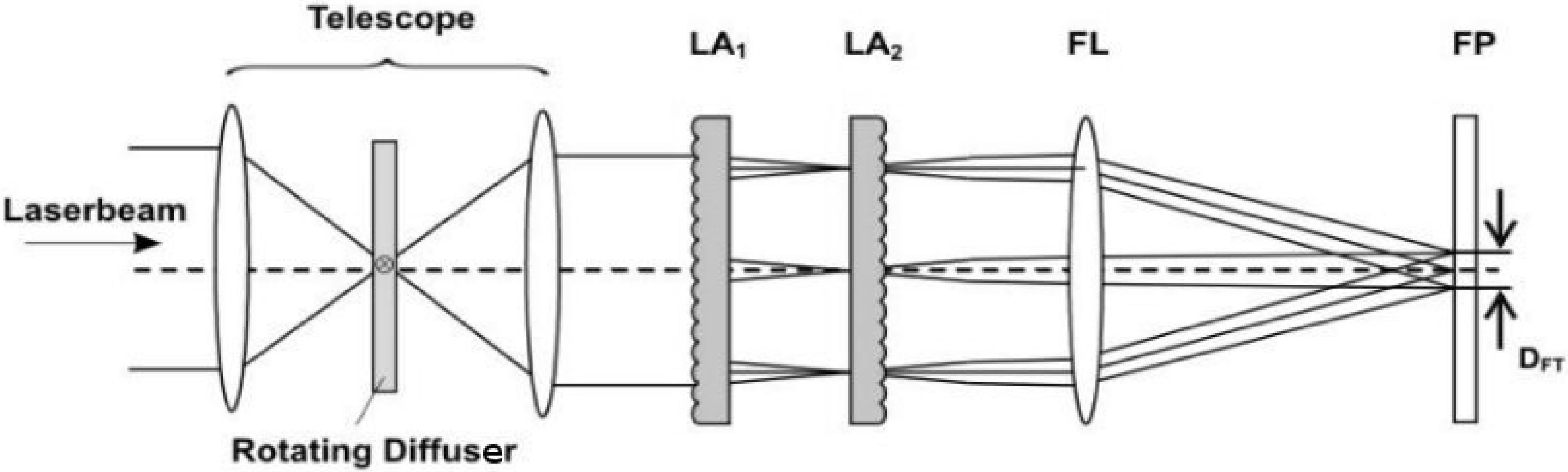
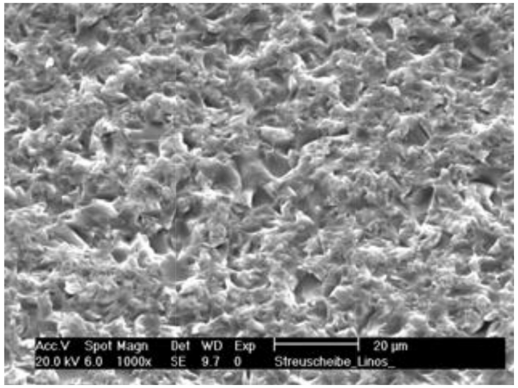
Example illumination optical system



Figures reproduced from Voelkel and Edmunds Optics.

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



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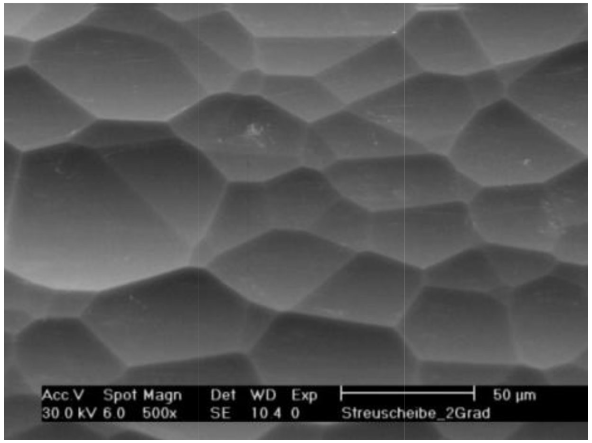
Diffuser types for speckle reduction

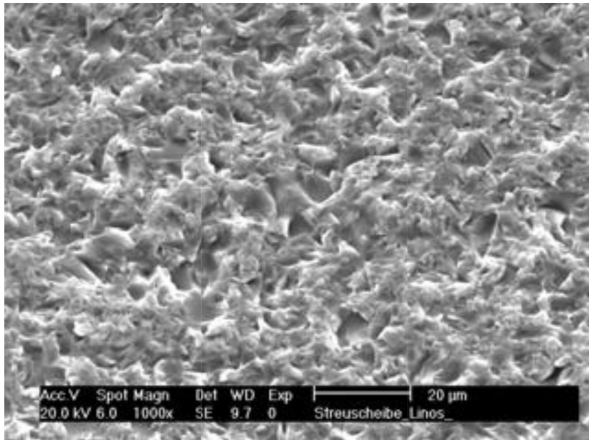
Optimal characteristics:

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

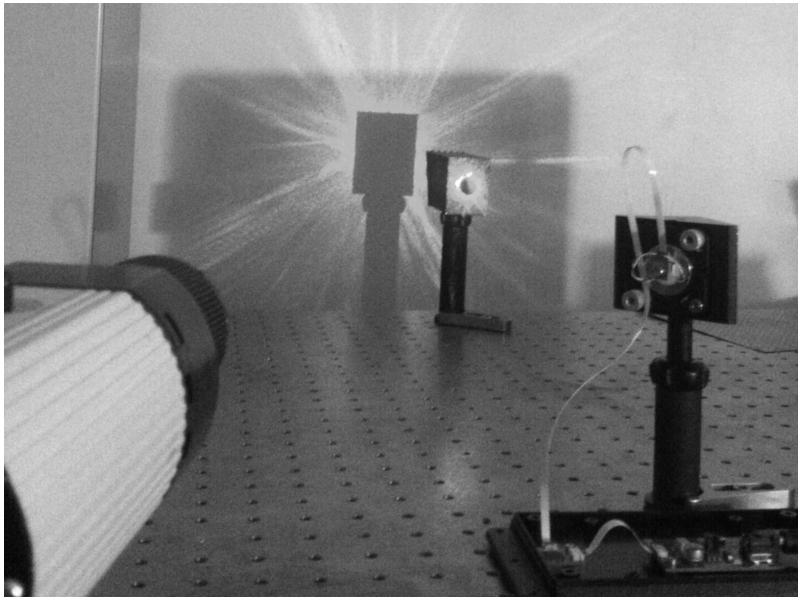
Randomized microlens arrays probably best conventional solution:

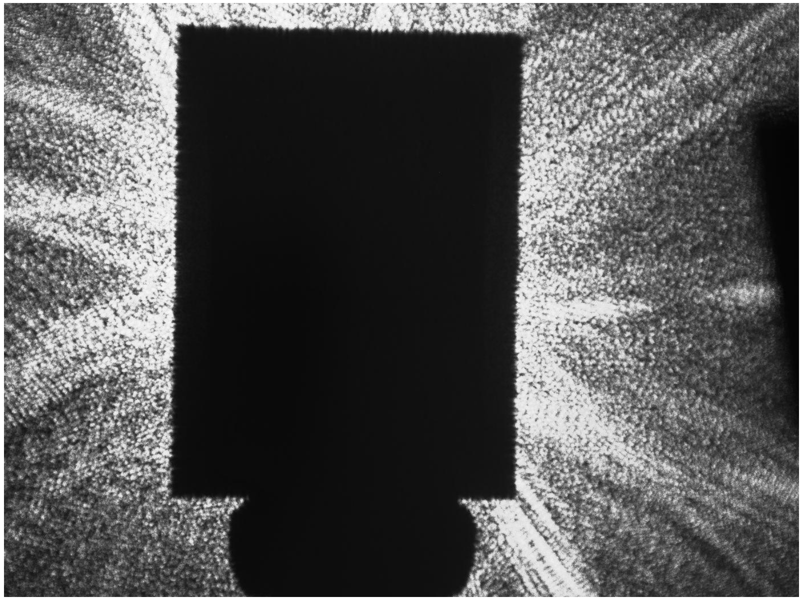
Figures reproduced from Voelkel.





Randomized microlens array problems





- Higher angle scattering losses.
- Sub-optimal anti-reflection coating.
- Correlation lengths >> 100 um.

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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.

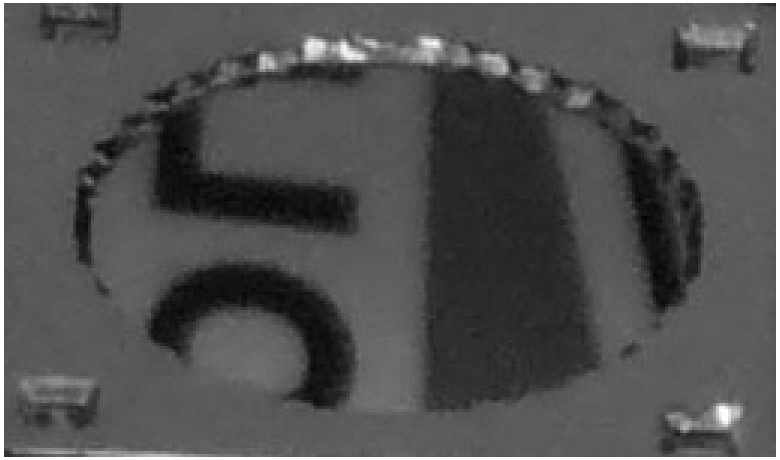
- ***Size***
  - for picoprojectors: 4.5 mm target height.
  - for LCD backlights: also needs to be small.

- ***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.

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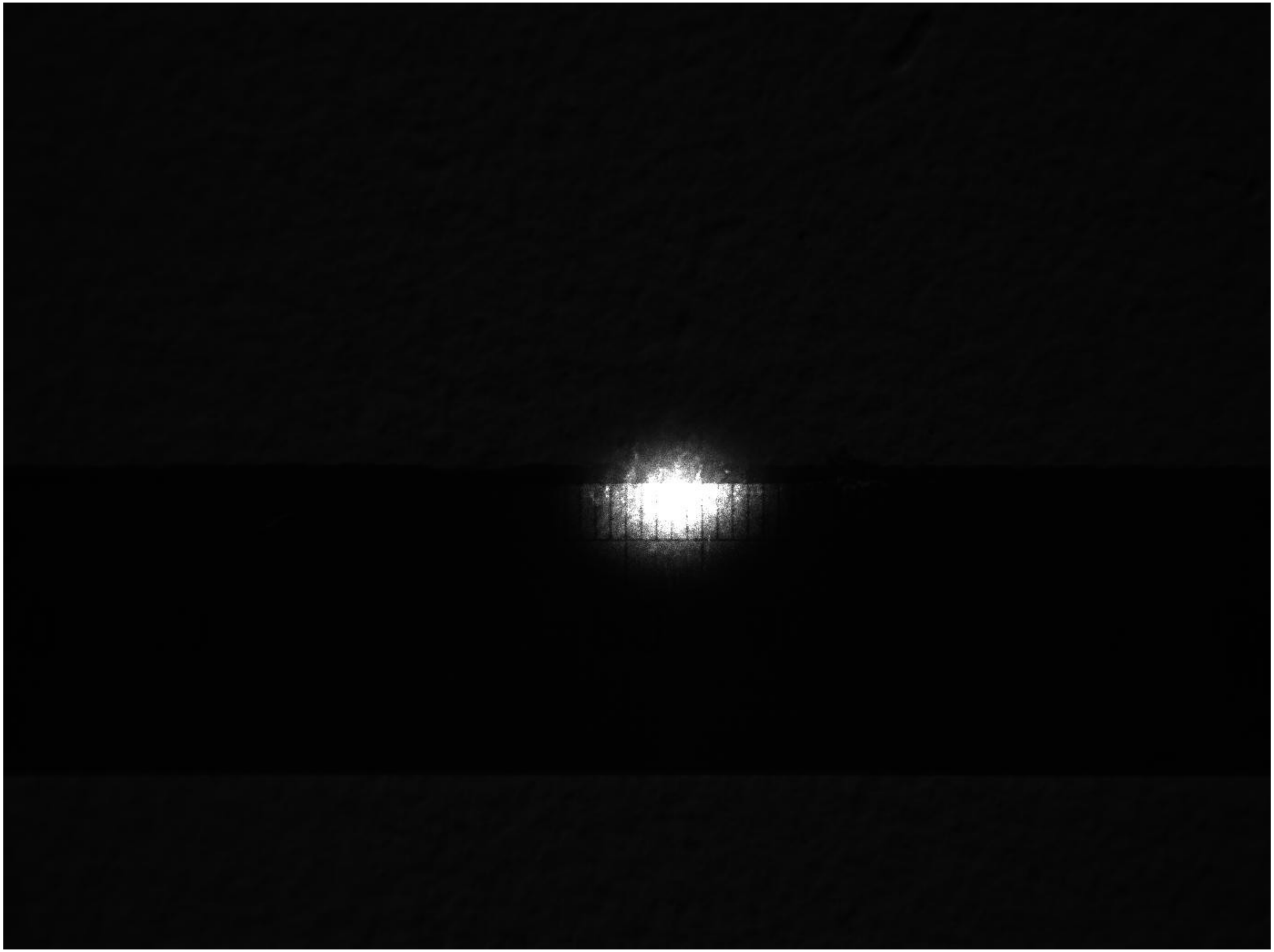
Randomized divergence: 0.5 deg. max.



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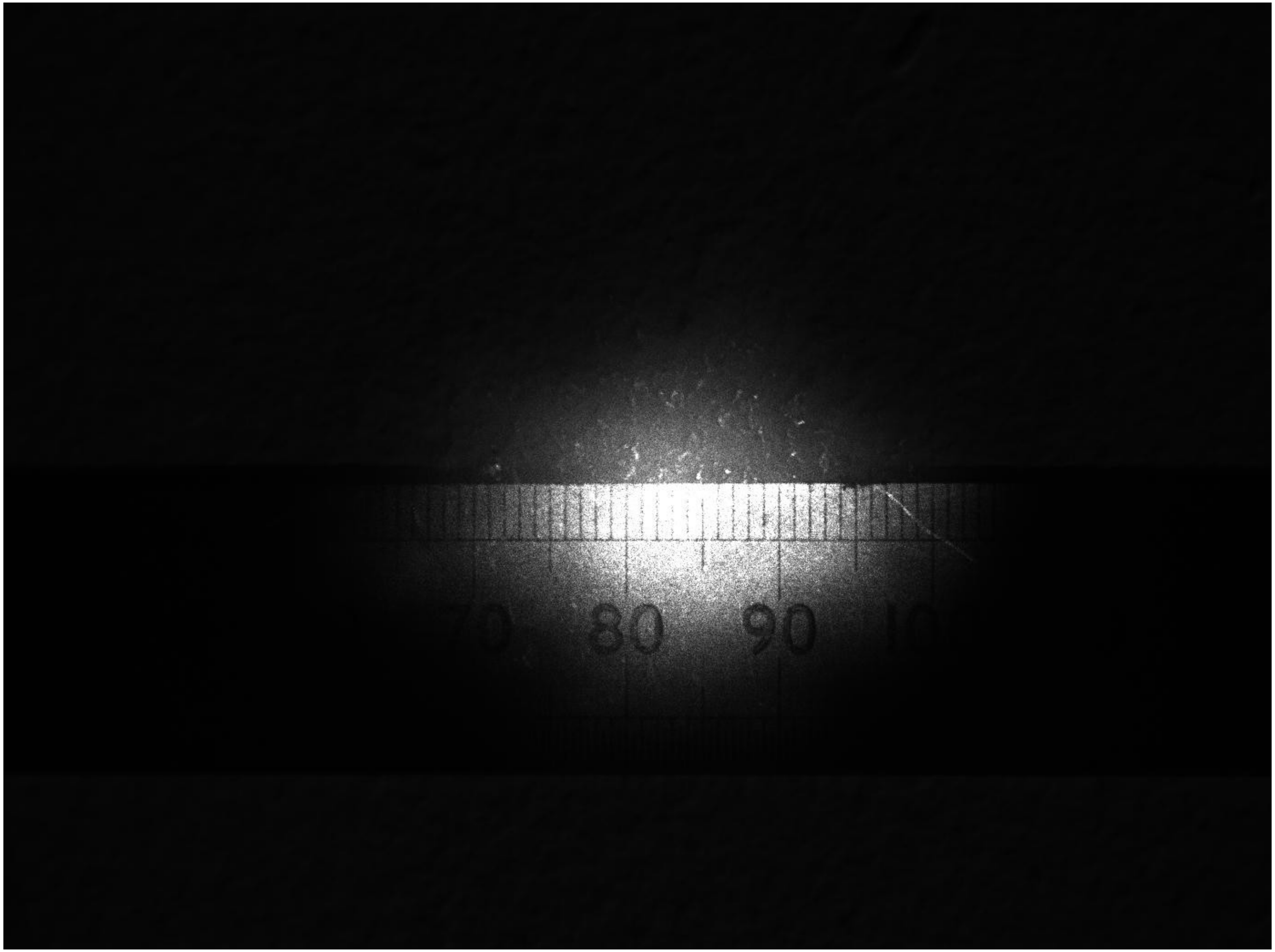
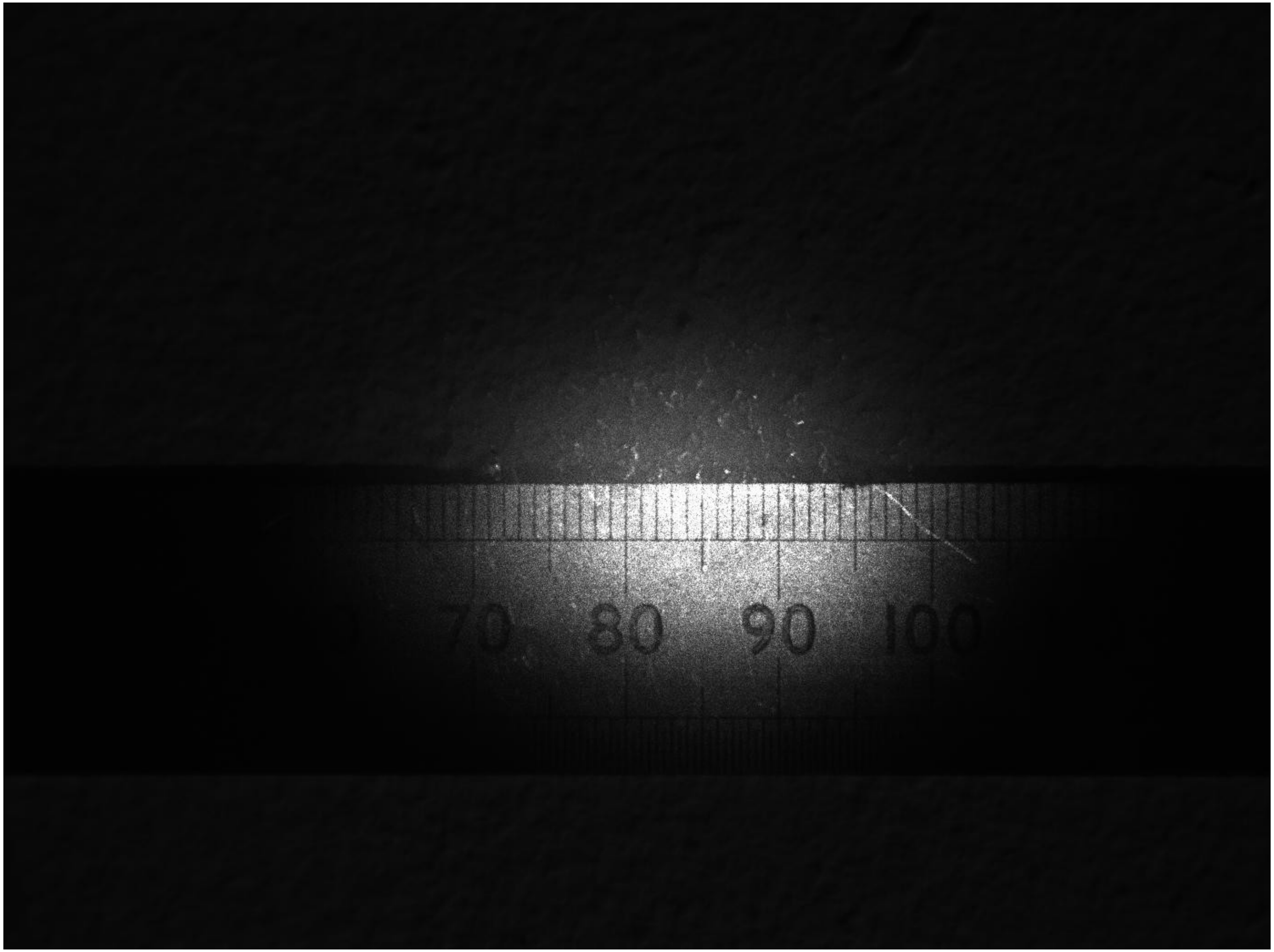
Randomized divergence: 1.5 deg. max.



Randomized divergence: 2.0 deg. max.



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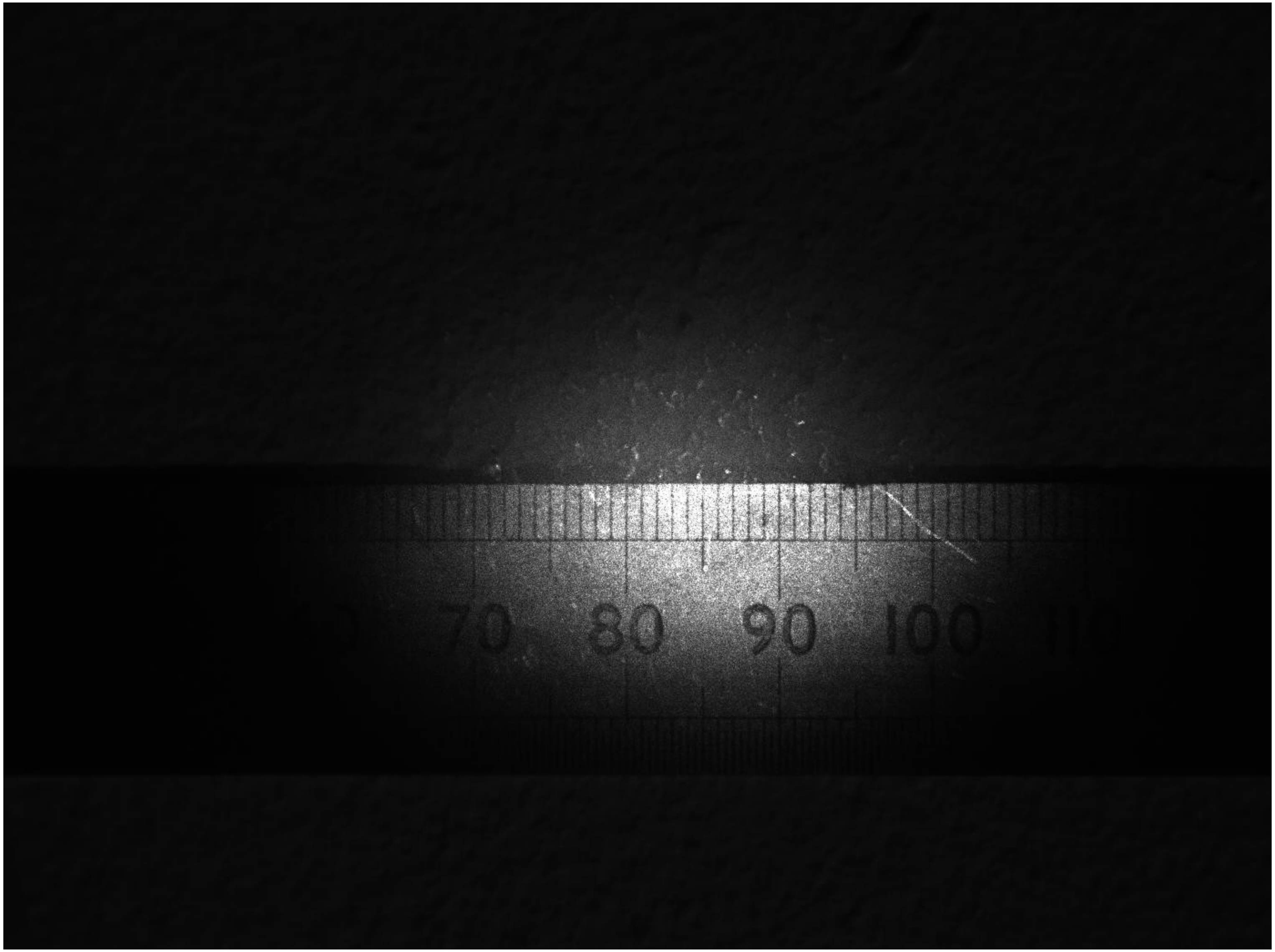
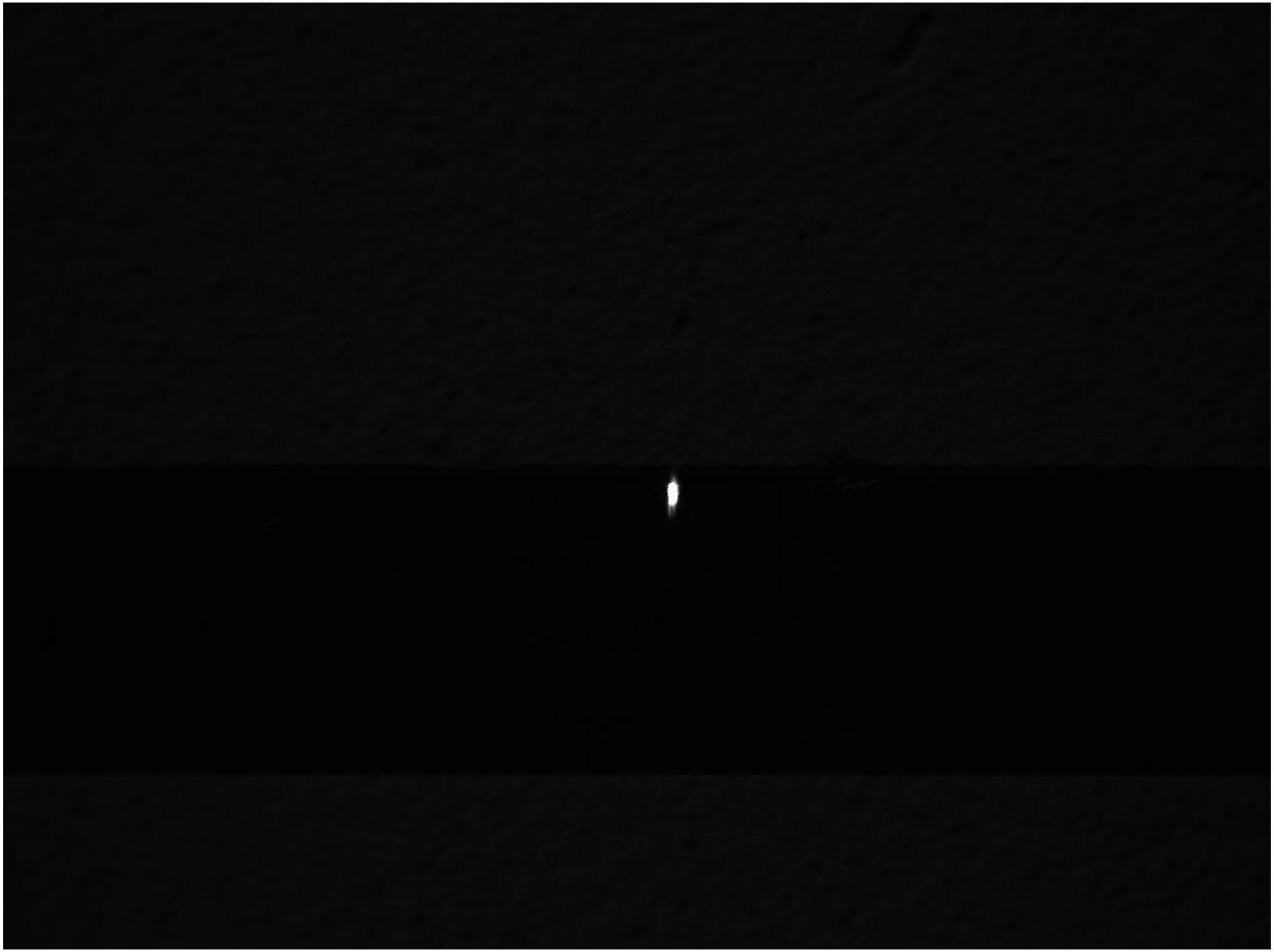
Randomized divergence: 2.5 deg. max.



Randomized divergence: none.



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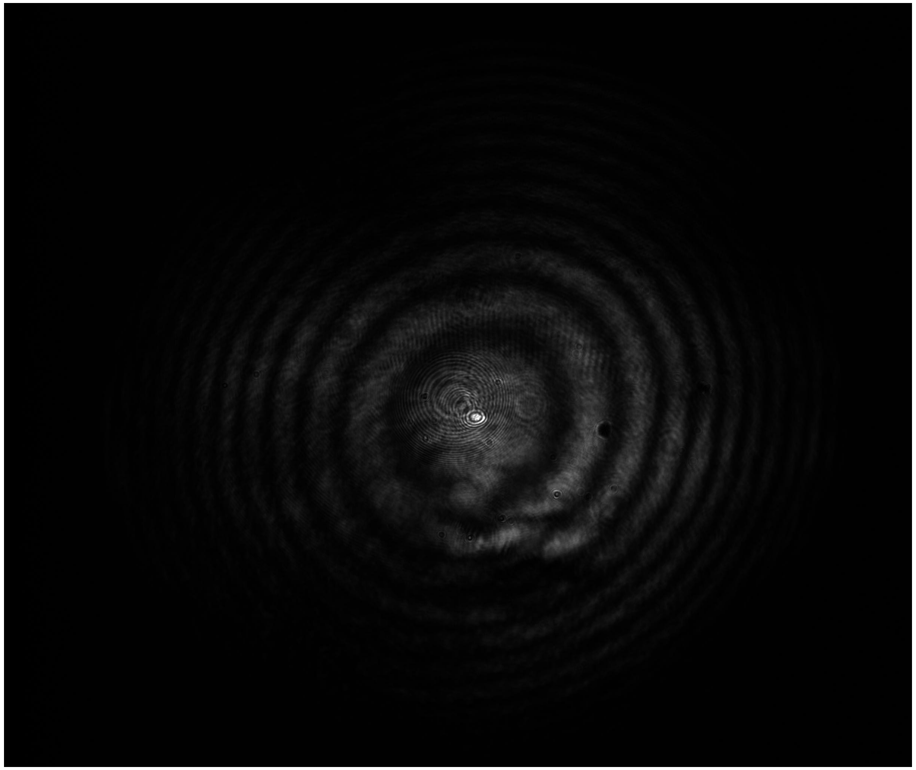
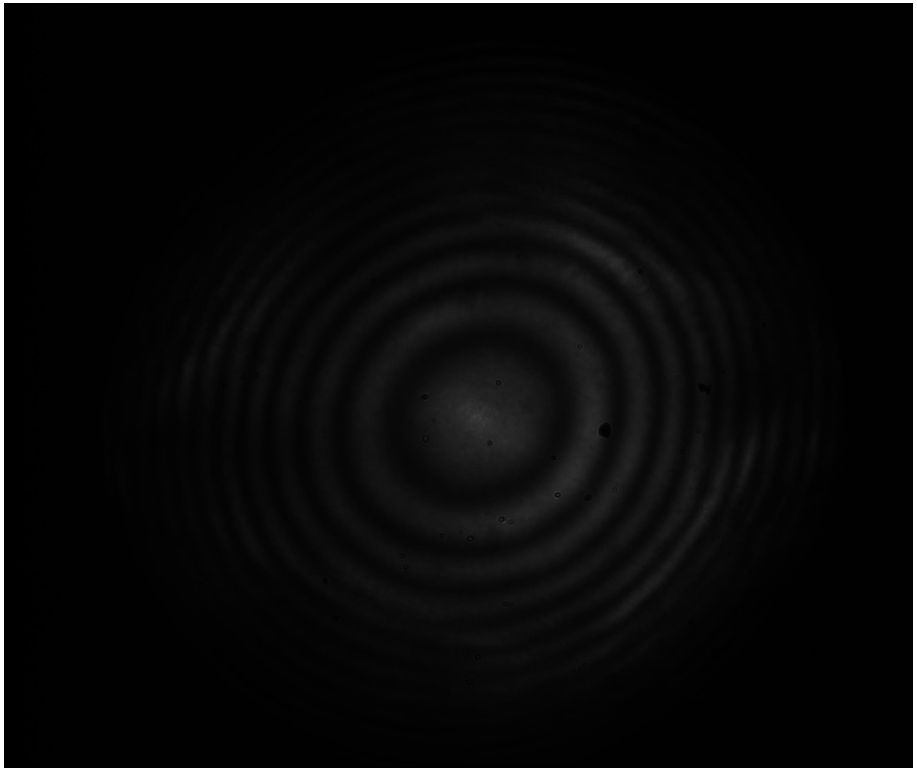
Randomized divergence: non-diffusing.





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

Beam ***directionality*** and ***coherence*** preserved!

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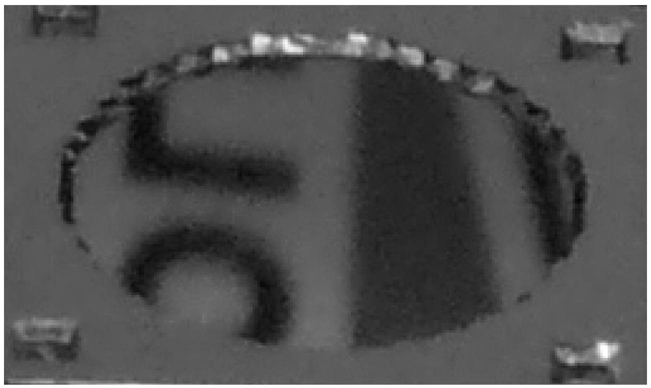
Use with large aperture periodic microlens array to create diverse optical paths



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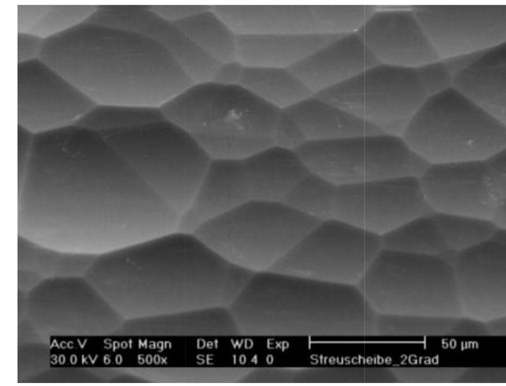
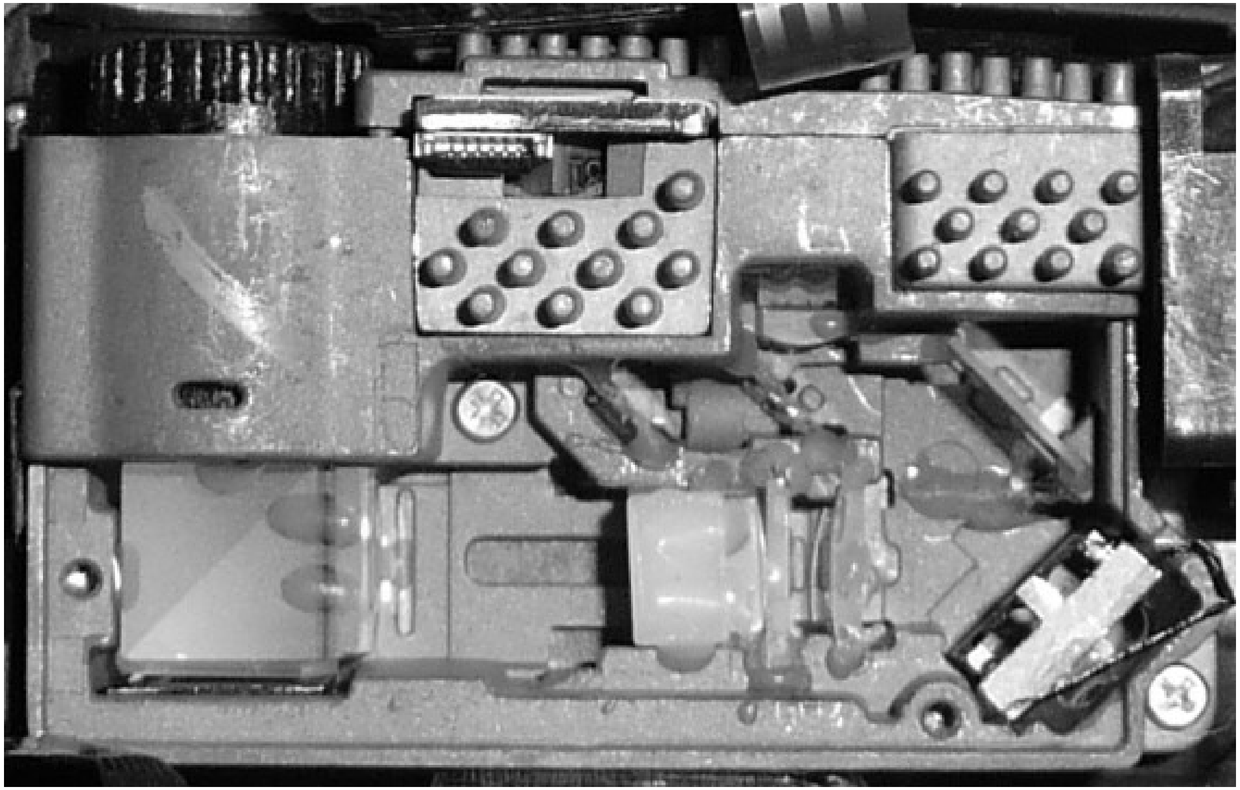


Performs better than moving randomized microlens array:

- No higher-angle scattering losses.
- Better anti-reflection coatings on larger microlenses.
- Only motions required are < 1 um 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

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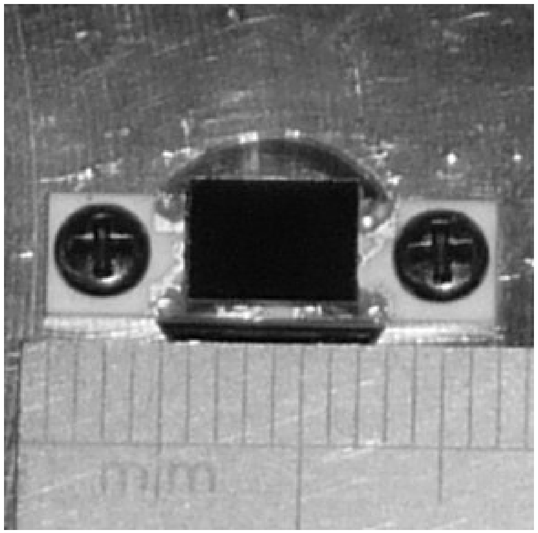
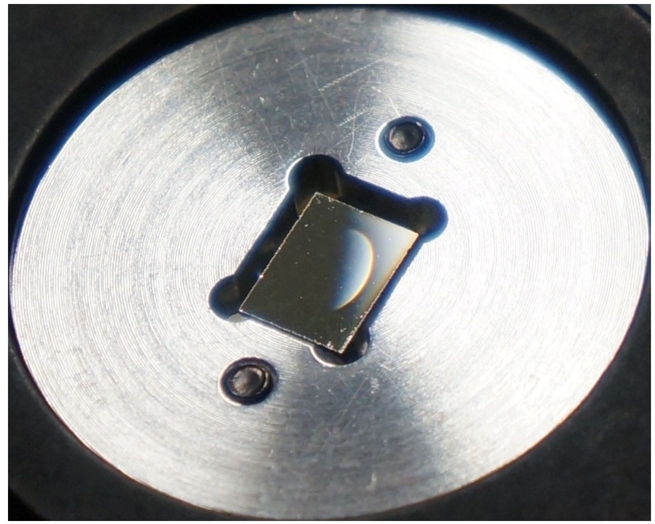
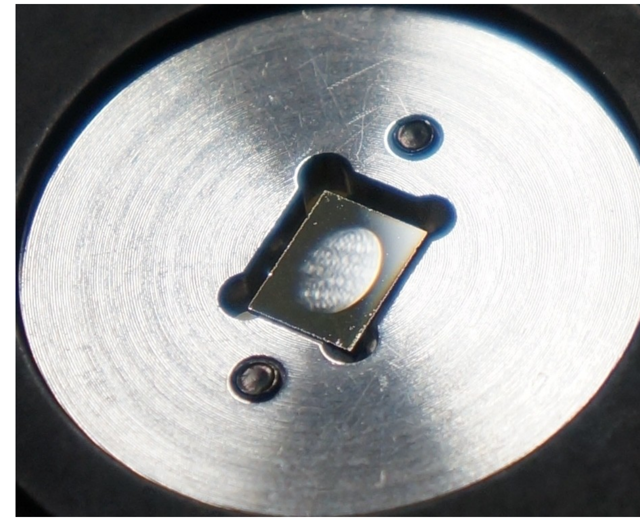
Miniaturized versions available

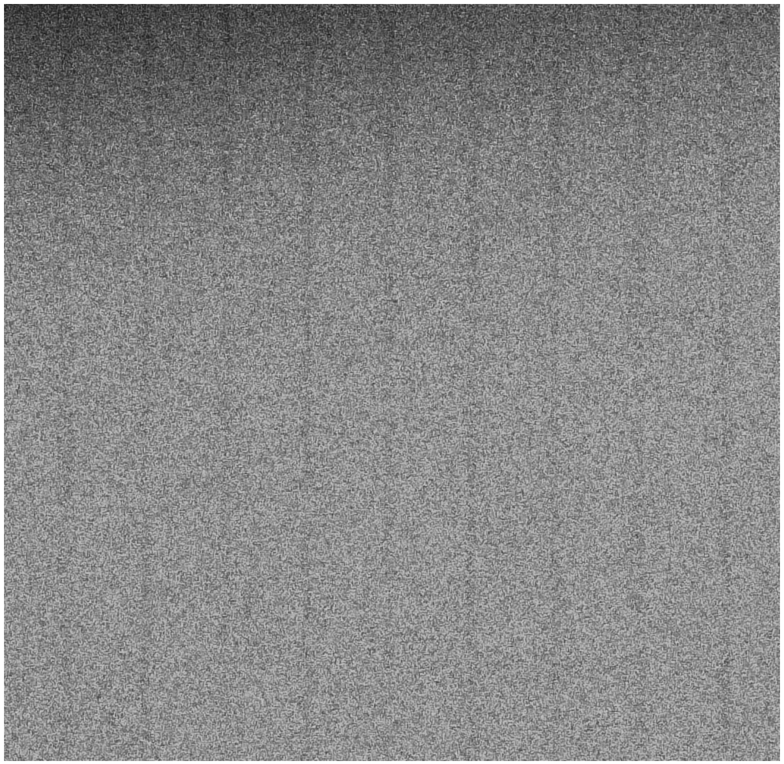


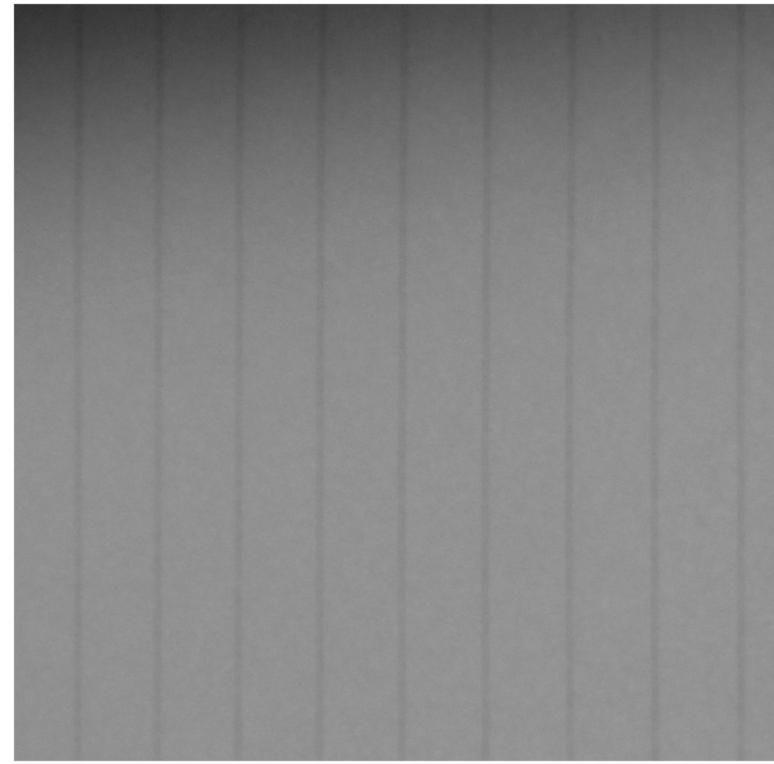




- 4.5 mm high with active area 3.0 mm x 4.5 mm.
- > 99% efficiency dielectric coating for R, G, B.
- < 30 mW power consumption at 5V or 3.3V.
- 10 mm x 10 mm control electronics PCB.

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.

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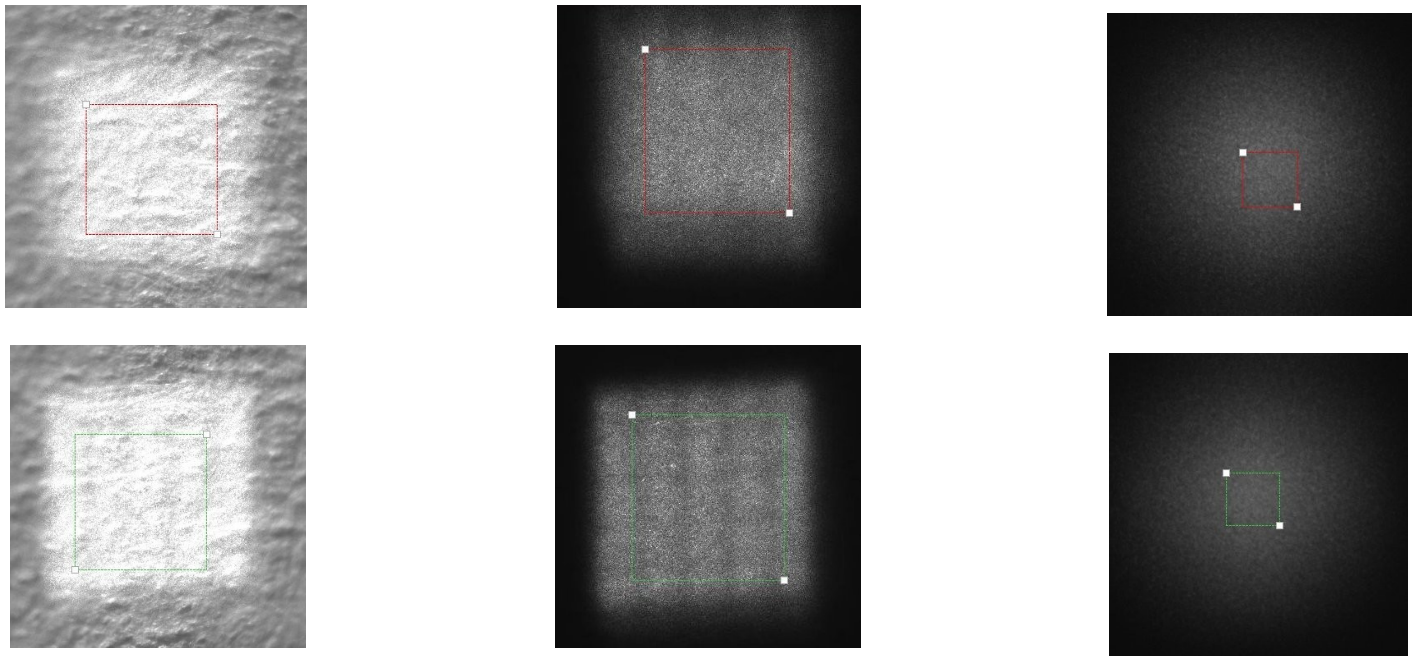
"Wide-field" Performance Evaluation



- Highly defocused camera lens blurs screen surface texture *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.

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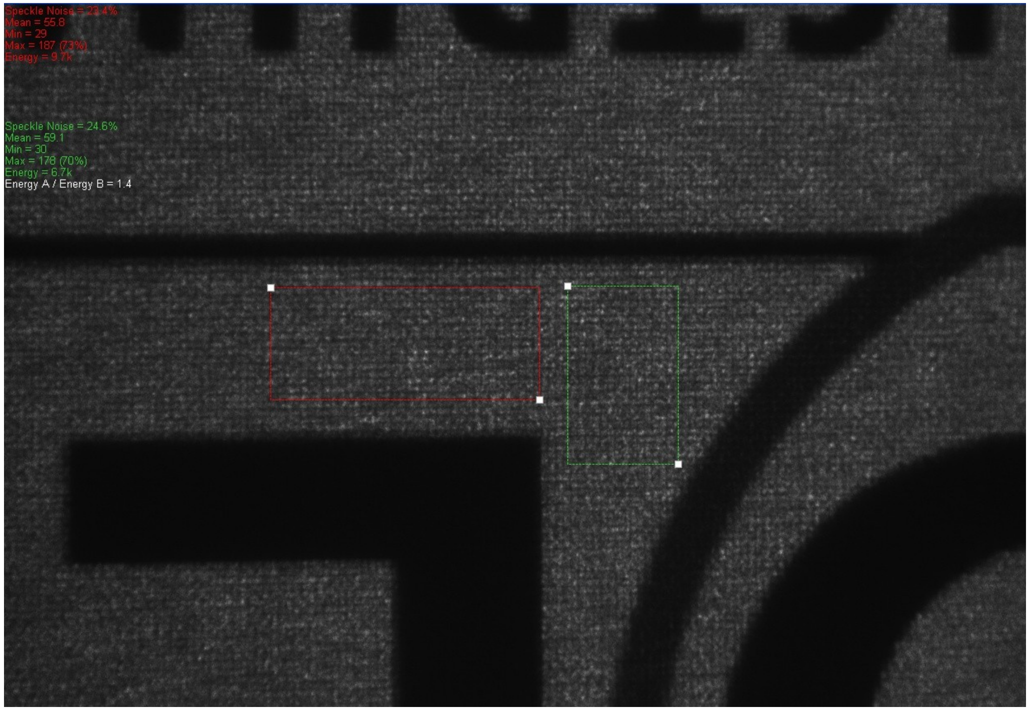
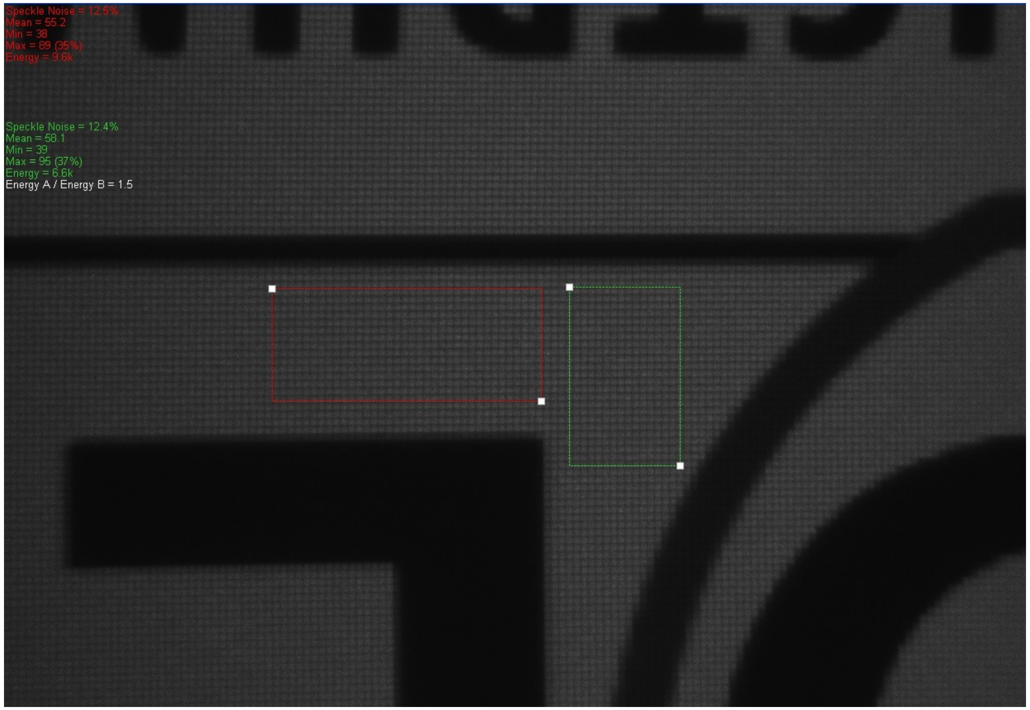
Performance in DLP® projector





- Achieves speckle contrast ratio imposed by projection lens.
- Better *optical efficiency* than moving diffusers.

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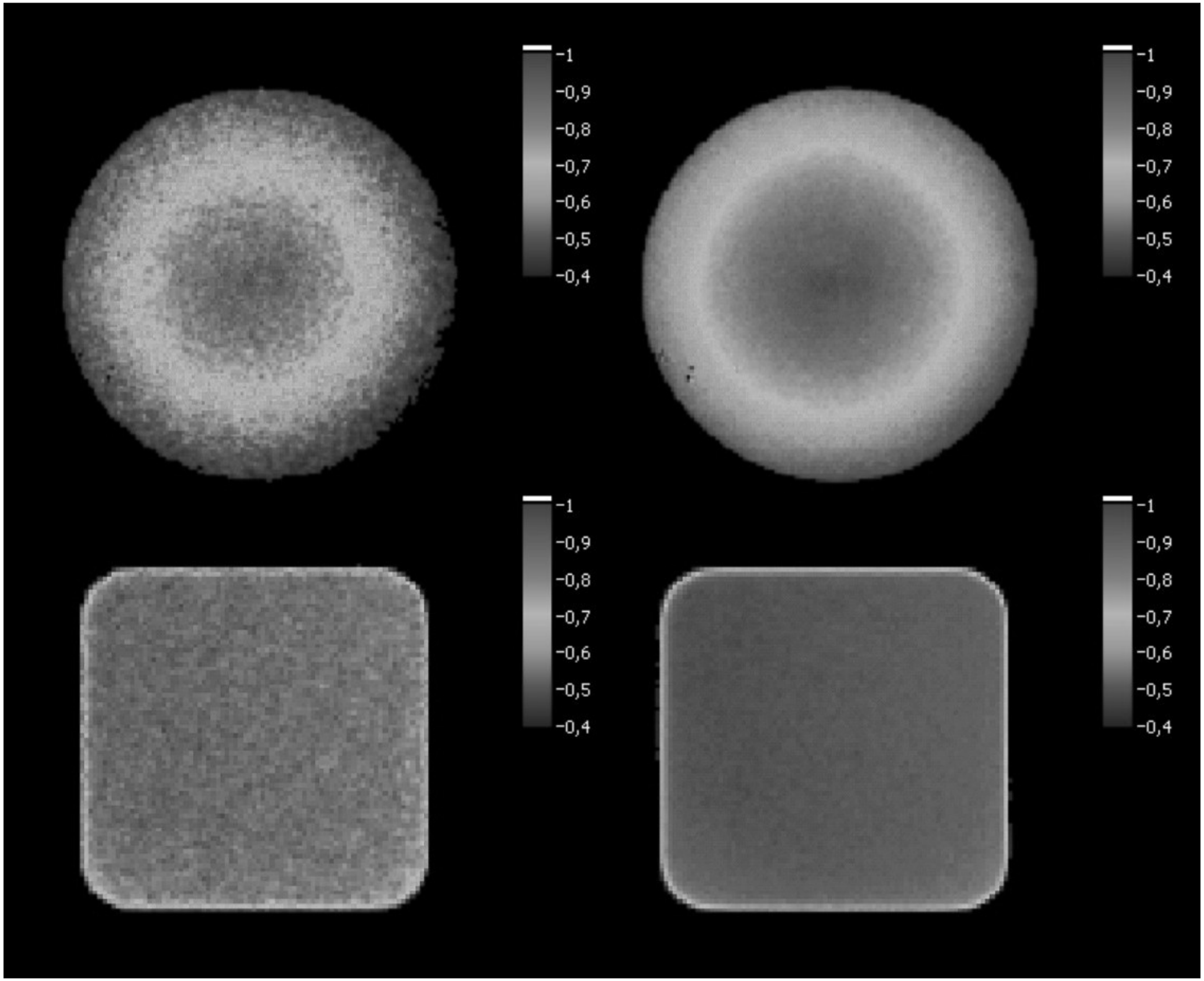
Performance with optical fiber



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.

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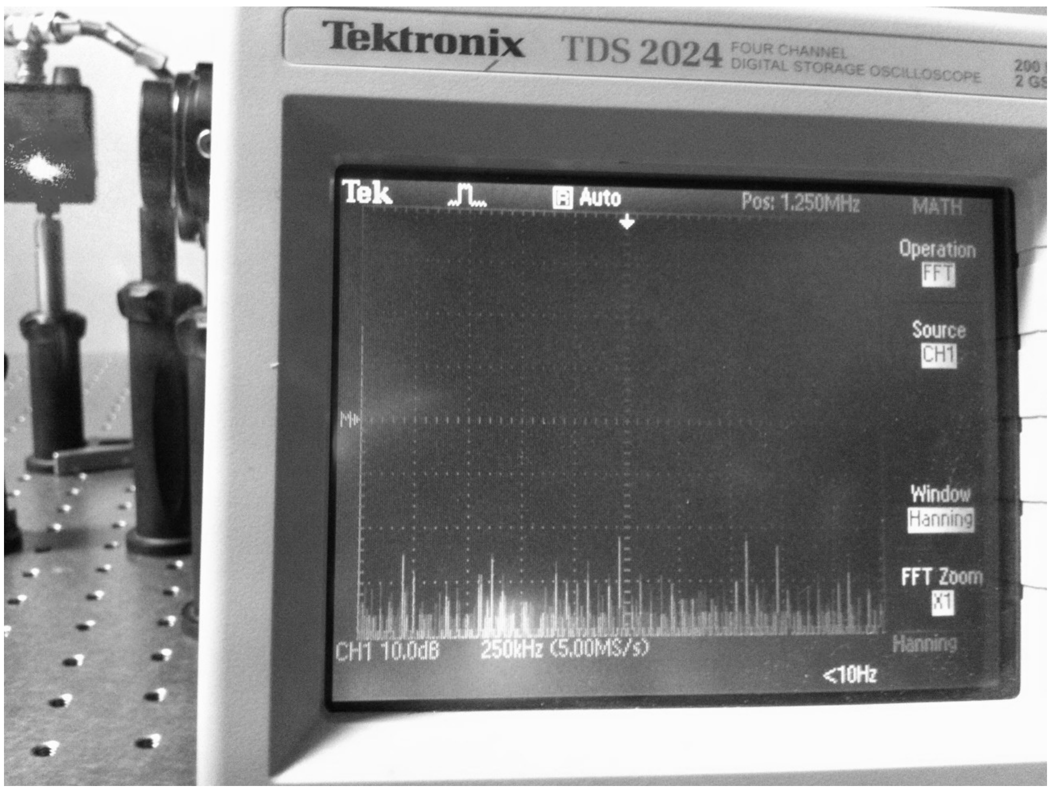
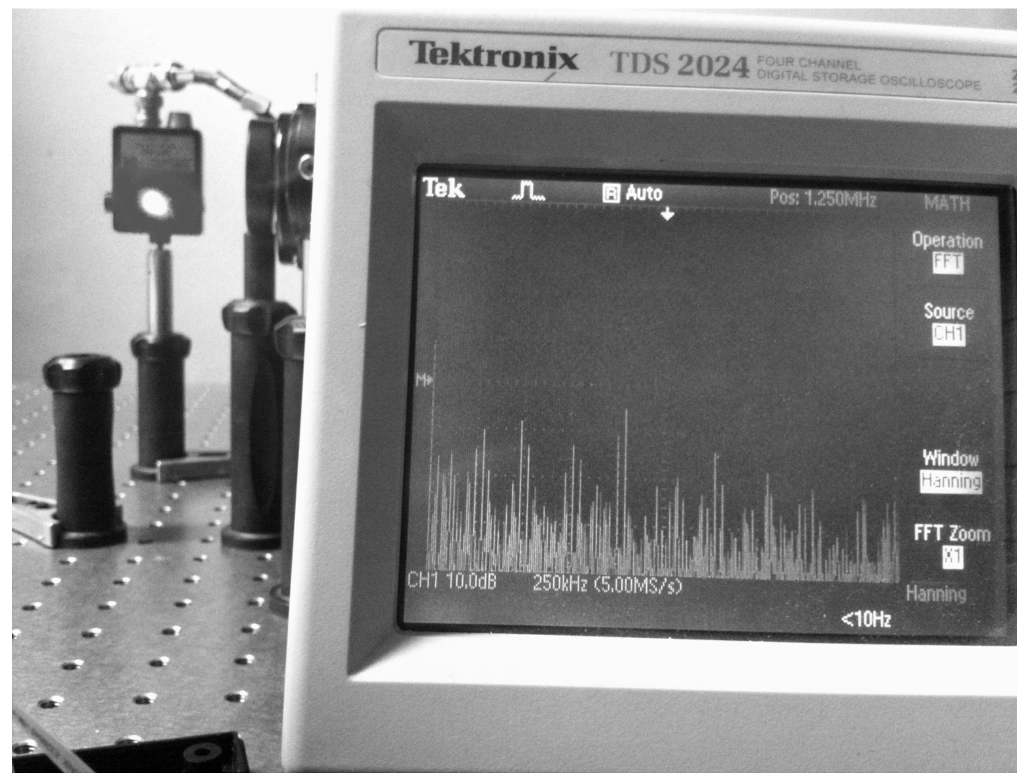
Interesting characteristics, continued.

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





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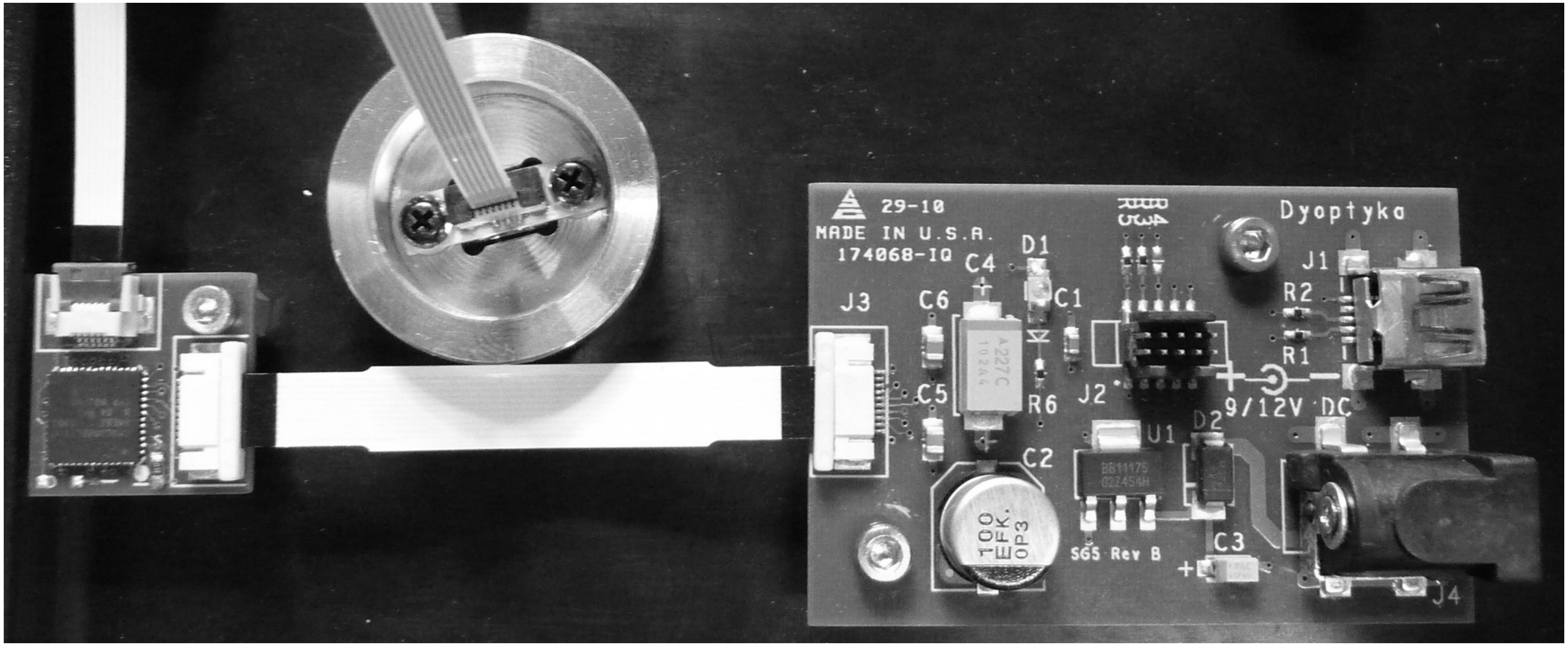
Availability



- 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*.

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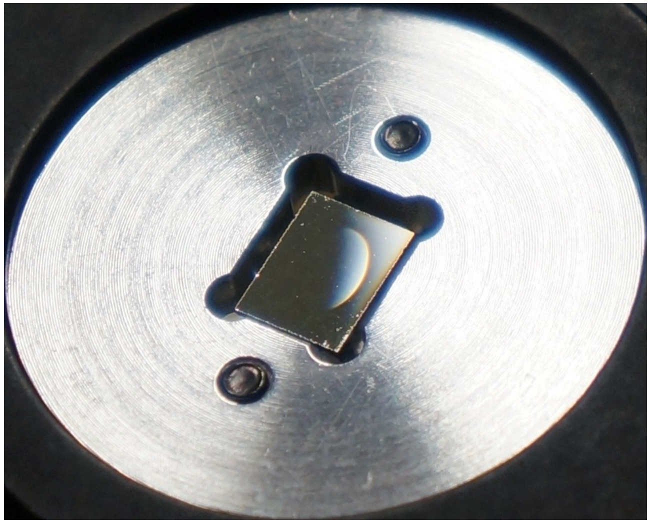
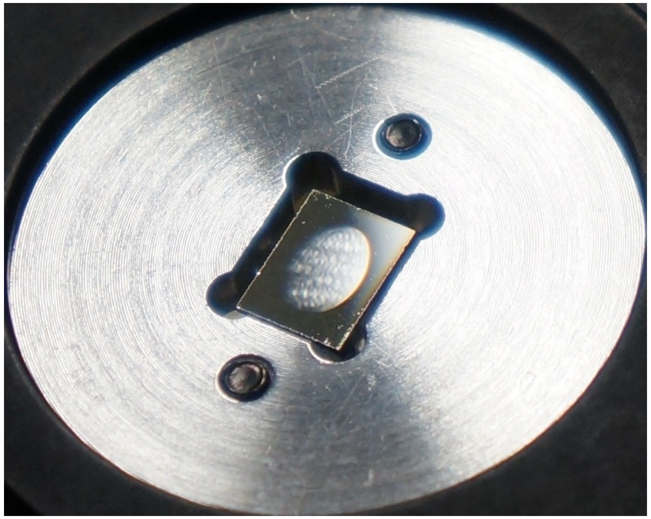
Thank You!



Questions?



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

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