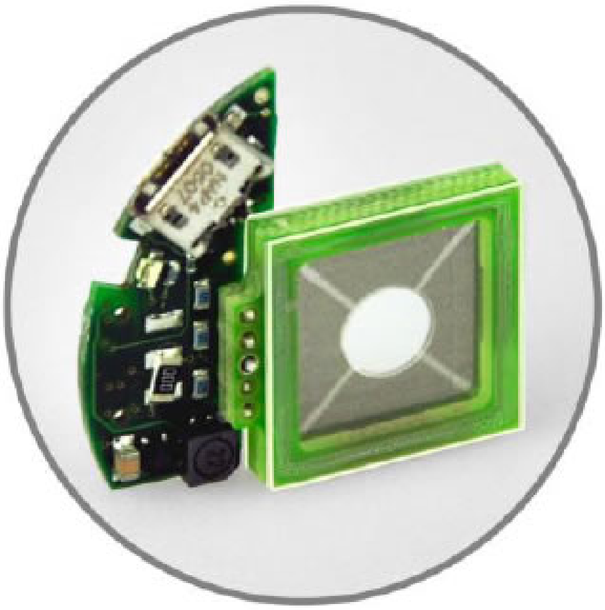
Application Note
Laser speckle reduction with laser speckle reducer STOT-3000 & STOT-OEM



1. Introduction

Lasers provide numerous advantages over other light sources. For example, the low divergence allows precise control of very high optical power, thus making lasers very attractive for projection systems. Laser projection systems have both a broader colour spectrum and a higher lifetime compared to conventional illumination systems. Another very important property of a laser is its high degree of coherence that enables, e.g. efficient interference processes. Although this characteristic is widely used in many scientific systems, its coherence leads to a significant drawback for applications that use a light detector. On rough optical surfaces, e.g. a wall or a cinema screen, local interferences occur which are observed as a grainy pattern of spots by for example a camera or the human eye. This effect causes noise in projected images but also reduces the resolution of measurement systems. Each of these scattered points may be described as a secondary coherent light source. If the corrugation depth is of the order of the laser wavelength, local interferences occur such that a random intensity pattern also known as speckle pattern is observed. Figure 1 shows an image and the corresponding intensity profile of a speckle pattern. One application that vastly benefits from speckle reduction is laser projection since any speckle strongly degrades the projected image quality. The scope of this application note is to introduce the principle of speckles and how to suppress them efficiently using our laser speckle reducer STOT-3000 & STOT-OEM.

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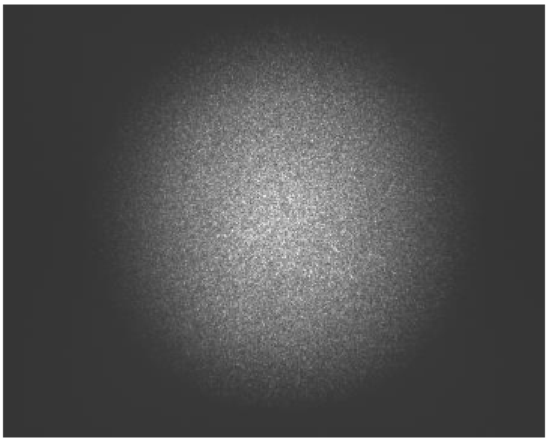
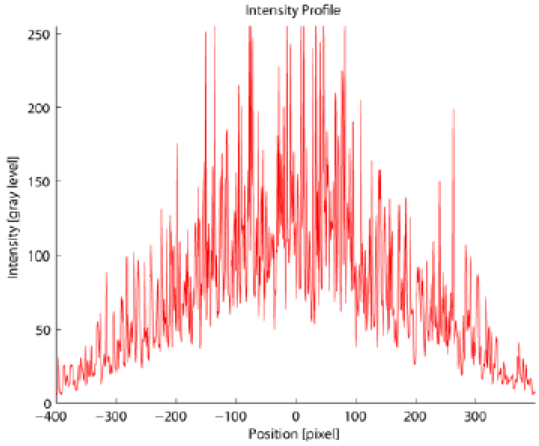


(a)



(b)

Figure 1 (a) Image of a speckle pattern on a CCD camera. (b) Measured intensity profile on a horizontal axis through the spots center. This non-uniform intensity distribution puts significant constraints on light detectors that exhibit local saturation points. Besides, this pattern may disturb the human eye.

2. Properties of a speckle pattern

2.1. Speckle contrast

The speckle contrast S is defined as the standard deviation of the intensity within a certain area normalized by its mean value Imean as shown below

$$S = \frac{1}{I_{mean}} \sqrt{\frac{1}{N} \sum_{i=1}^{N} (I_i - I_{mean})^2} \ , \qquad (1)$$

with

$$I_{mean} = \frac{1}{N} \sum_{i=1}^{N} I_i . \qquad (2)$$

The speckle contrast varies between zero and one, where zero represents a homogenous beam without speckles. Using a laser speckle reducer (LSR) the resulting speckle contrast is reduced.

2.2. Reduction efficiency of the speckle contrast

At a microscopic level, the speckle reduction depends on
- the wavelength and bandwidth of the laser light
- the state of polarization of the laser light

These two parameters are well defined by the laser and contribute, together with the quality of the illuminated surface, to the speckle process. At a fixed wavelength and state of polarization the speckle contrast can be reduced by increasing the quality of the surface. At a macroscopic level, the speckle reduction depends on
- the diffusion angle of the LSR
- the numerical aperture of the detection system

The potential reduction factor by means of angular diversity equals in this case to $\sqrt{\theta / \Omega}$, where θ is the diffusion angle and Ω is the numerical aperture of the detection system. Comparing the speckle contrast using a LSR ($SLSR$) with the speckle contrast of an optical reference system without a LSR (S), the reduction efficiency R is defined as follows

$$R[dB] = 10log_{10}\left(\frac{S}{S_{LSR}}\right). \qquad (3)$$

As an example, a reduction of the speckle contrast from 0.5 to 0.2 provides a reduction efficiency of 4 dB.

3. Working principle of the Laser speckle reducer

3.1. Moving diffuser structure

Our laser speckle reducer is based on a dynamic process. The speckle pattern is moved at a sufficiently high frequency and amplitude such that the detection system integrates the speckle pattern over time as a uniform light distribution.

The LSR consists of a diffuser bonded on a polymer membrane that includes four independent dielectric elastomer actuators (DEAs). Under activation, the surface of the electrodes increases and causes a motion of the rigid diffuser in the membrane plane. The four independent electrodes are used to obtain displacement of the diffuser in both directions of the x- and y-axis, as shown in Figure 2. In case of the STOT-3000, the control signals of the four electrodes (x1, y1, x2 and y2) have the same amplitude and frequency, but with a phase shift of 90° in between. This controlling profile of the electrical signals driving the electrodes generates a circular motion of the diffuser. The moving frequency is optimal when reaching the mechanical resonance frequency of the system und such provides the largest speckle reduction. A dedicated driving electronic that provides the optimal electrical control signal is integrated in the STOT-3000, which is powered through a Micro-USB connector. A 110- 220VAC to 5VDC power supply is included.

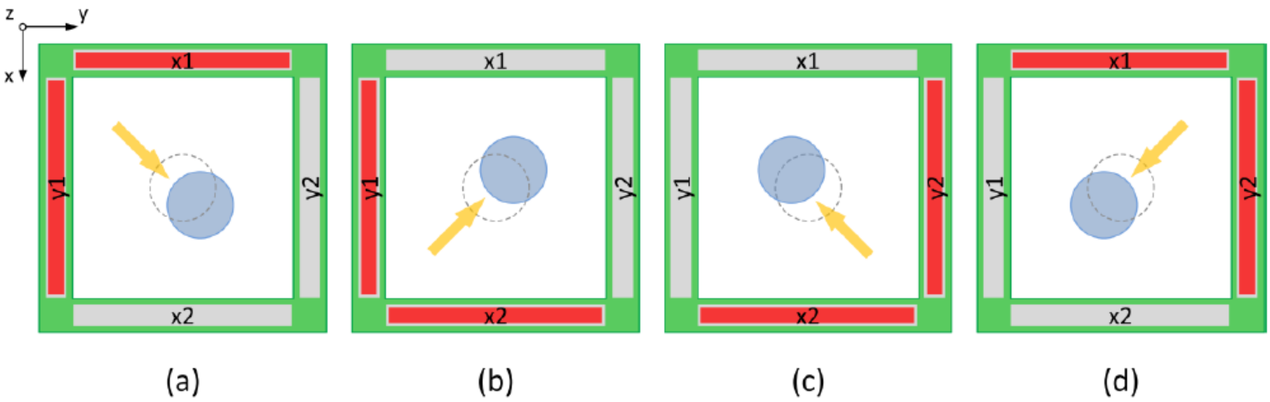


Figure 2: Illustration of four independent DEAs to move the rigid diffuser (blue circle) in the plane of the membrane. The equilibrium (no voltage applied on the electrodes) position of the diffuser is represented by the dashed circle. (a) The x1 and y1 electrodes are activated, the diffuser moves in positive x- and y-direction. In the panels (b), (c) and (d) the analog displacement effect is described as in (a) showing the different states of the diffuser. After reaching state (d), the cycle continues with position (a).

3.2. Combining diffusers

The laser speckle reducers consist of either one or two subsequent diffusers labelled STOT-3000-XS and STOT-3000-XD, respectively. Here, the X in the order number denotes the overall diffusion angle. In case of two diffusers the first diffuser oscillates while the second diffuser is static. This reduces the correlation length of the random patterns that are generated. We recommend the use of two diffusers as the speckle reduction is more effective yet minimizing the increase in beam divergence. If two diffusers are combined, the overall total diffusion angle is calculated by

$$\theta_{combined} = \sqrt{{\theta_1}^2 + {\theta_2}^2}.$$

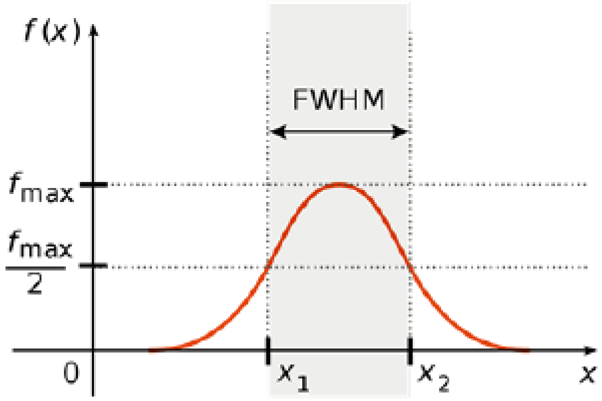
We note that for optical systems where the spot of the LSR is imaged, e.g., onto a fiber (see Figure 15 and Figure (16), no static diffuser is allowed. In that case an LSR with an oscillating diffuser only is recommended. The following table gives an overview on standard models with the different diffuser combinations:

Part number	Total diffusion angle	Diffuser configuration
STOT-3000-6D	6°	4.2° oscillating,4.2° static
STOT-3000-12D	12°	8.5° oscillating,8.5° static
STOT-3000-24D	24°	17° oscillating, 17° static

STOT-3000-17S	17°	17° oscillating, no static

Table 1: Overview on different diffuser combinations for the standard STOT-3000 models.

The diffuser angle is defined as full width half maximum (FWHM)



4. Measurement of the speckle reduction

4.1. Reference setup

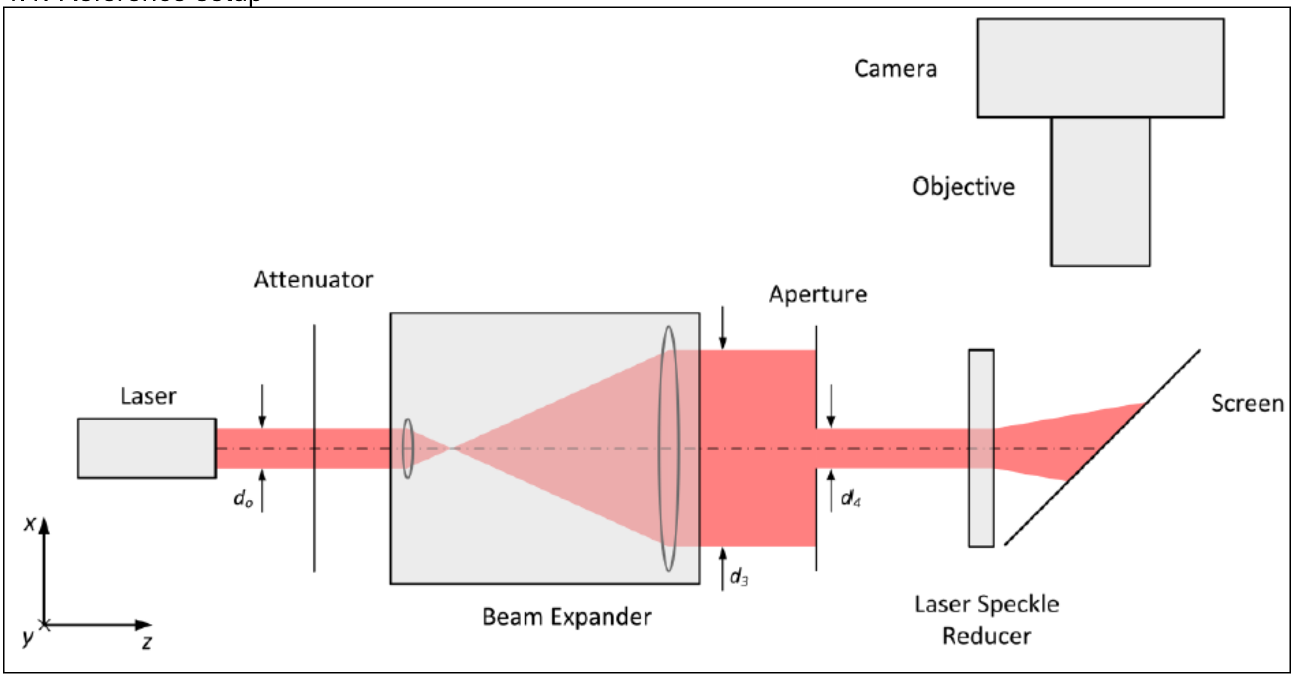


Figure 3: Reference setup for measuring speckle reduction. Laser: He-Ne, P=20mW, λ=632.8nm, linearly polarized. Beam expander: 15x. Objective: Computar, T4Z2813 CS IR. Camera: Mightex Systems, Monochrome 1.3MP CMOS, MCE-B013-US USB2.0.

A scheme of the experimental setup to measure speckle reduction is shown in Figure 3. The laser light is expanded up to a d3 = 5mm beam diameter that is collimated beam by a beam expander. An attenuator at the input of the beam expander controls the laser power. Likewise an aperture d4 can be used at the output of the beam expander to precisely control the illumination beam size of the LSR and minimize stray light on the screen at the very end of the bench. The LSR is positioned in the collimated beam after the aperture and an image of the laser spot on the screen is recorded by the camera. The panels in Figure 4 show typical speckle images that are obtained without any LSR (a), with the LSR in a static mode (b), and with the LSR in a dynamic mode (c). The colored lines show the horizontal plane in where the intensity profiles are measured that are depicted in Figure 5.

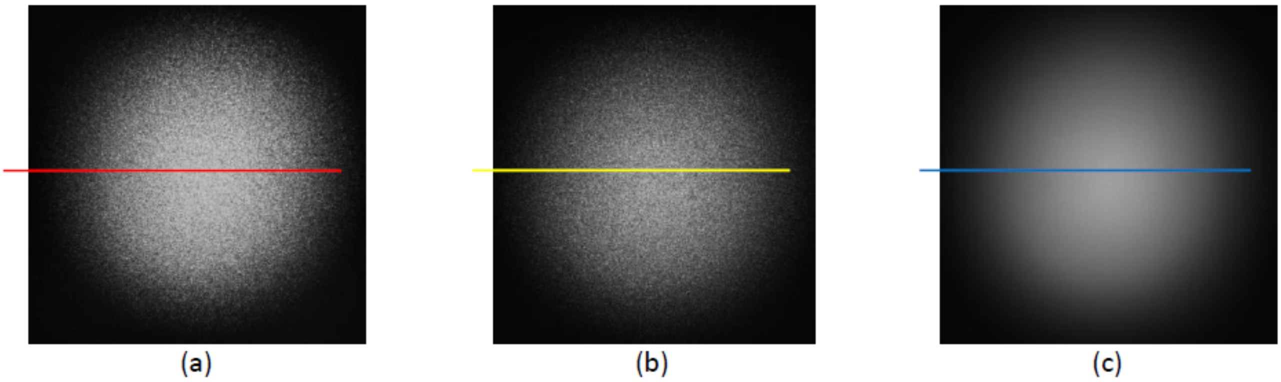


Figure 4: Typical images of the speckle contrast measured on the reference setup (a) without a LSR in the collimated path, (b) with the LSR in a static mode, and (c) with the LSR in a dynamic mode. The colored lines show the cut planes that refer to Figure 5.

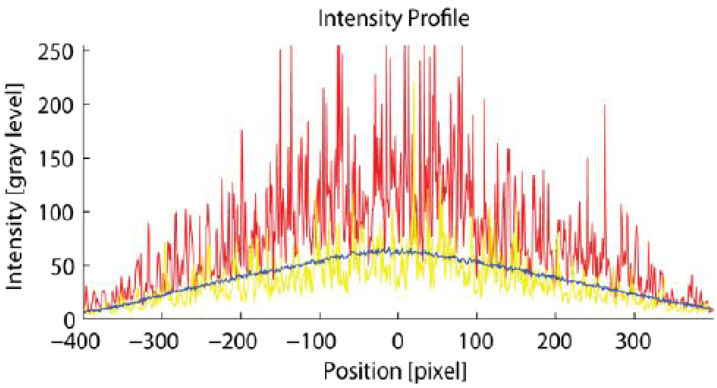
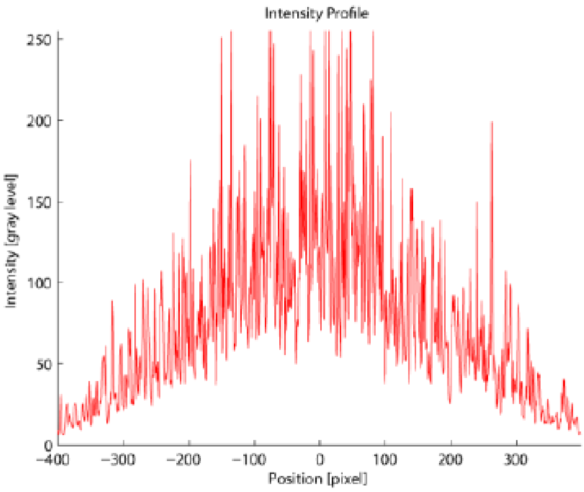


Figure 5: Measurement of the speckle contrast on a horizontal plan as depicted in Figure 4: in red, without any LSR, in yellow with the LSR in a static mode and in blue with the LSR in a dynamic mode.

The same characterization method is applied to all our standard LSR and the results are introduced in the following section.

4.2. Results with standard products of the STOT-3000 Series

- STOT-3005-24D (5mm aperture, 24° diffusion angle, two diffusers with average structure size 3μm)
- Reduction efficiency: R = 15 dB



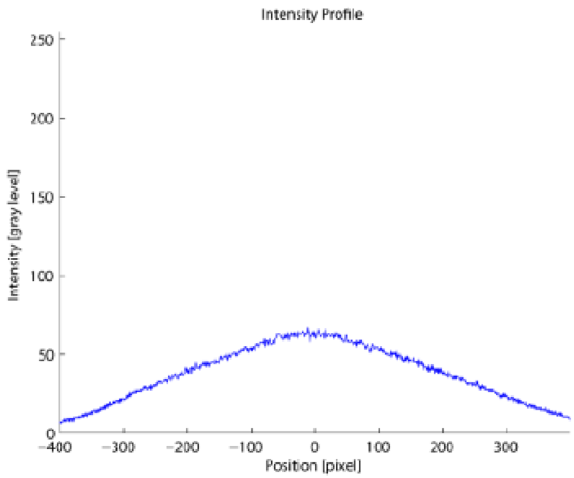


Figure 6: Measurement of the intensity profile: in red without LSR (pure laser) and in blue with the STOT-3005-24D

- STOT-3005-12D (5-mm aperture, 12° diffusion angle, two diffusers with average structure size of 20μm)
- Reduction efficiency: R = 12 dB

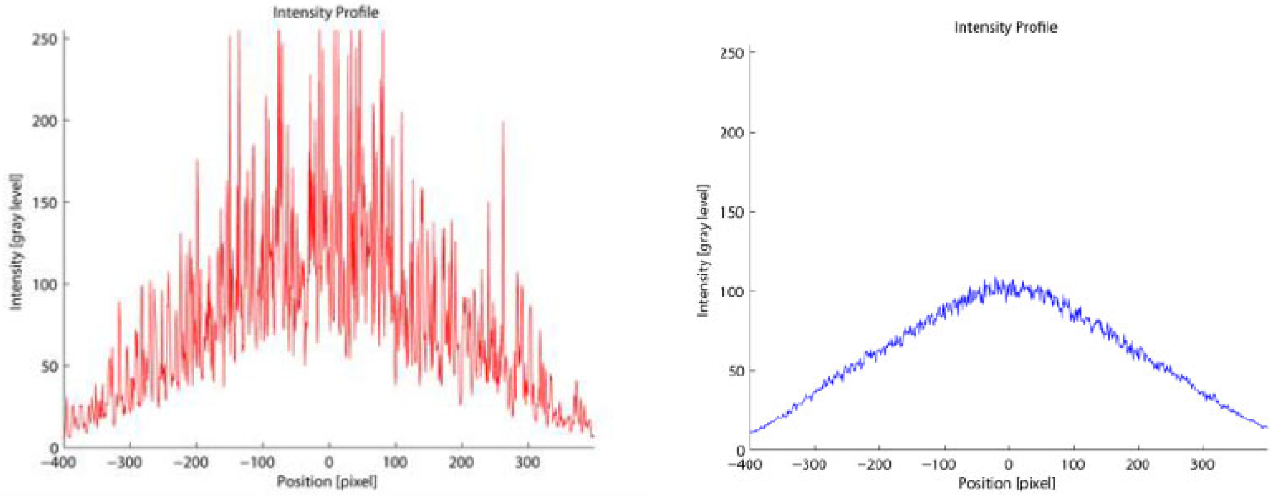


Figure 7: Measurement of the intensity profile: in red without LSR (pure laser) and in blue with the STOT-3005-12D.

- STOT-3005-1D (5-mm aperture, 1° diffusion angle, two diffusers with average structure size of 100μm)
- Reduction efficiency: R = 6 dB

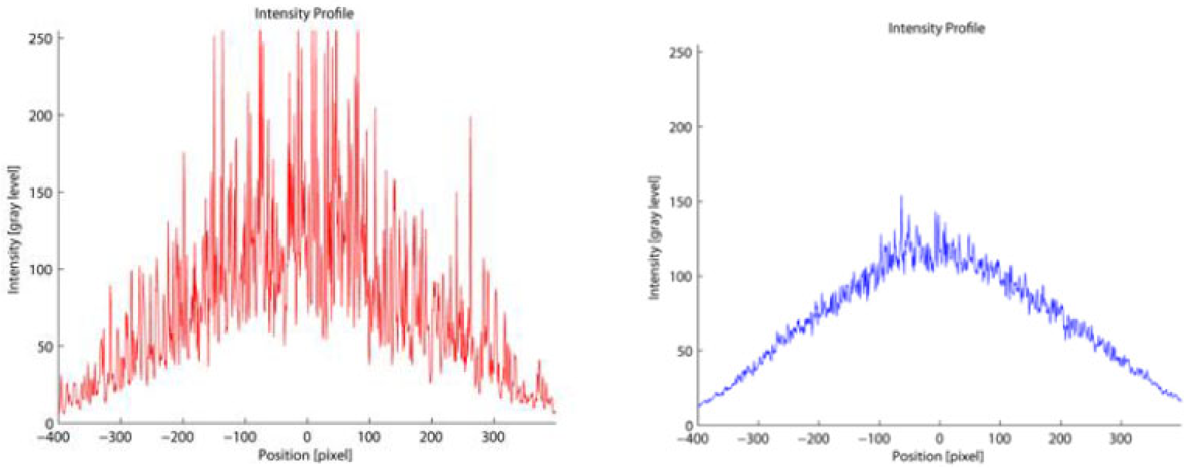


Figure 8: Measurement of the intensity profile: in red without LSR (pure laser) and in blue with the STOT-3005-1D

5. Key parameters for efficient speckle reduction

5.1. Overview

The resulting speckle reduction depends on a number of parameters including

- Motion speed of the diffuser
- Diffuser structure
- Exposure time of the observer/camera
- Optical system layout (beam diameter, position of LSR, additional optics)

5.2. High motion speed

The diffuser moves along a circle (or ellipse) due to the activation cycles of the electrodes, see Figure 2. The main parameters that define the actuation are

- The motion amplitude (path perimeter L = 2π · r)

- The mechanical driving frequency f

These two parameters are shown in Figure 9 and define the motion speed of the diffuser v = L·f.
Example of STOT-3005: r = 200 m, f = 300 Hz v = 377 mm/s.

The higher the motion speed of the diffuser, the more patterns are overlapped during the exposure time of the observer, e.g. a camera. The motion speed can be optimized for custom designs, but there are trade-offs to be made between motion amplitude, frequency, size of the LSR, material parameters, weight of the diffuser and maximum voltage. As an example, the LSR size can be increased which gives a larger displacement amplitude. However, as a consequence the diffuser weight increases, reducing the desired resonance frequency.

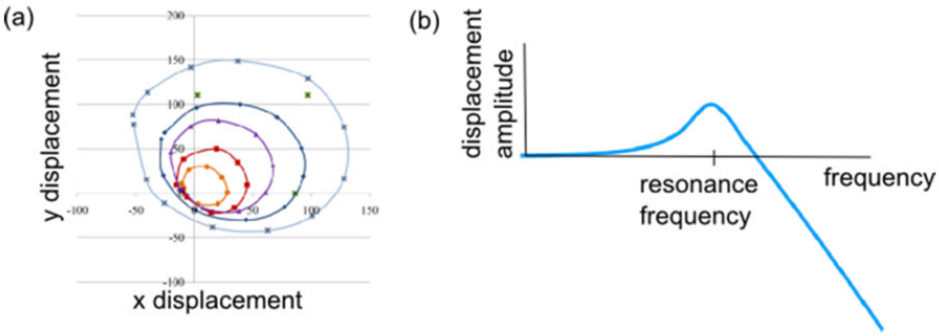


Figure 9: (a) Measurements of the displacement amplitude for different motion amplitudes and a fixed frequency. (b) Illustration of displacement amplitude as a function of mechanical driving frequency.

5.3. Diffuser structures

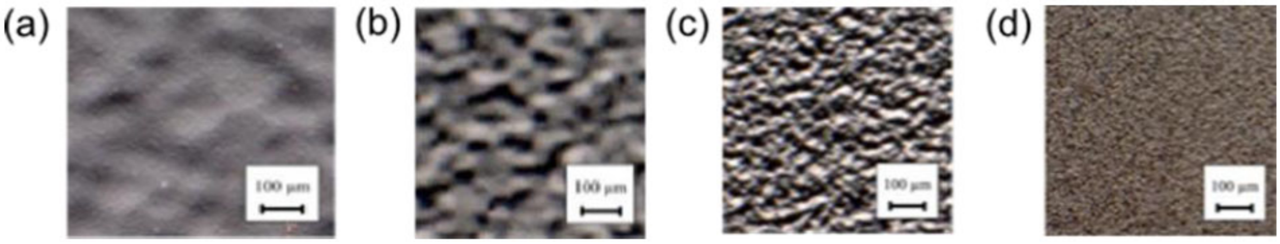


Figure 10: Different diffuser grain structures with an average size (a) 100µm, (b) 50µm, (c) 20µm, and (d) 3µm. The scale bar has a size of 100µm.

The speckle reduction efficiency R (see Equation (3)) is proportional to the number of structures passing through a point during exposure time. Adding N uncorrelated speckle patterns results into a reduction of the speckle contrast by a factor $1/\sqrt{N}$. Thus, the goal is to create as many uncorrelated speckle patterns as possible. Apart from moving the diffuser at highest motion speed, this can be influenced by optimizing the structure of the diffuser. As shown in Figure 6 - Figure 8, the reduction efficiency is better using smaller structures which are exemplary presented in Figure 10. Note that a smaller structure size is results into a larger diffusion angle which in turn leads to a larger beam divergence.

5.4. Exposure time

The best performance of our speckle reducer can be achieved by recording as many different speckle pattern per camera frame as possible, i.e. maximizing the exposure time of the camera. The STOT-3005 has an oscillation period of 300Hz corresponding to one round trip of the diffuser within 3.3 ms. As it can be seen in Figure 11, a very good speckle reduction is already be achieved with an exposure time of 3.3ms. For larger exposure times the reduction of the speckle contrast is not significant improved as the number of independent speckle pattern does not increase. This highlights that already within one oscillation period a sufficiently large number of different speckle pattern is generated.

Ideally, the frequency of the LSR is at least as high as the frame rate of the camera. In the case of the human eye, which has an exposure time of about 17ms (60Hz), this is easy to achieve. An industrial camera, however, might run at higher rates. We want to emphasize that down to an exposure time 1ms the STOT-3000 series can show a speckle contrast of less than 3%, see Figure 11. As outlined in the previous section, this exact value of the speckle contrast depends on the motion amplitude and the structure size of the diffuser. If the exposure time of a camera is less than 1ms, the speckle reduction process will be less efficient.

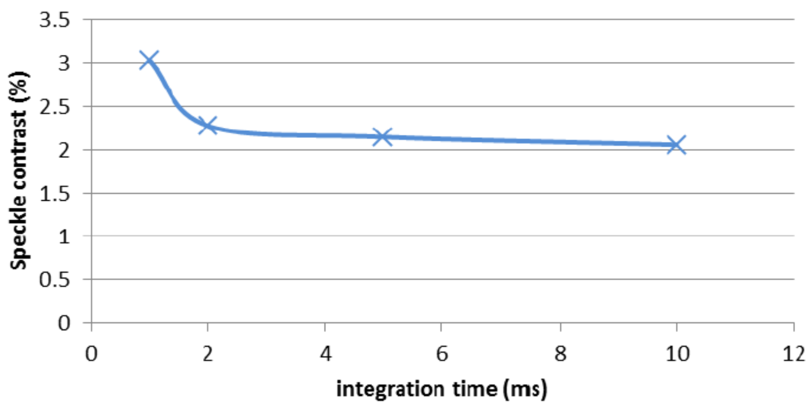


Figure 11: Speckle contrast obtained with the STOT-3005-24D for different integration times ranging from 1ms to 10ms

6. How to optimise the integration of the LSR in a laser system

For efficient laser speckle reduction, we generally advise to

- position the LSR perpendicular to the optical axis
- illuminate the LSR by a collimated beam
- match the collimated laser beam size that enters the LSR with its clear aperture (⩽ 5mm diameter)

Figure 12 illustrates the most straight-forward use of the LSR. The laser beam is collimated and its cross-section matches the clear aperture of the LSR. The zoom-in Figure 12 shows the correct positioning of the LSR along the light path.

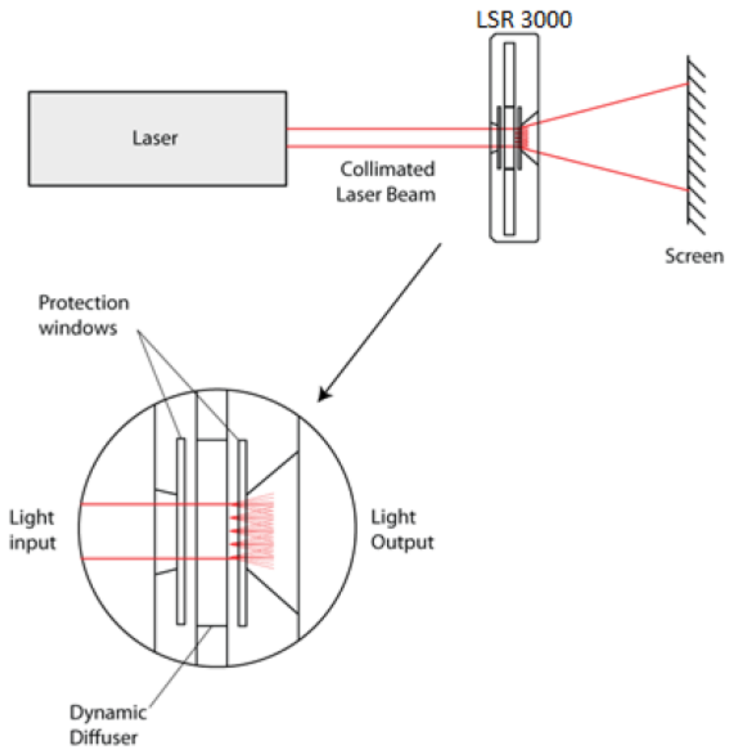


Figure 12: Straight-forward use and positioning of the LSR in a laser system.

In this configuration the LSR diverges the collimated beam with an angle that matches its diffusion angle (e.g. 20° FWHM value for the STOT-3005-20). If the incoming light is not collimated, the outgoing light angle is calculated as follows

$$\theta_{exit} = \sqrt{\theta_{incident}{}^2 + \theta_{diffuser}{}^2}$$

The diffuser is regarded as an infinite number of point sources, each with the NA of the diffusion angle. In order to compensate for the beam divergence, a collimation lens might be positioned downstream the LSR at a distance that matches its focal length. The diameter of the lens should be equal or larger than the diverging beam diameter. This setup is illustrated in Figure 13. Note that this is not a true collimation because the diverging beam, due to random scattering, contains many different diffusion angles.

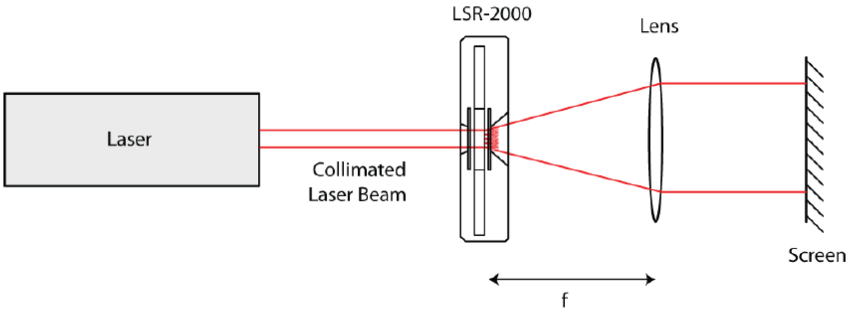


Figure 13: The LSR combined with a collimation lens that is used to reduce the beam divergence.

6.1. LSR in focal plane + homogenizer

If a highly collimated beam is required, an alternative use of the LSR is to position it in (or close to) the focal point of the laser. The diffusion angle after the LSR will be acting as a small point source, the beam can be well collimated again. To homogenize the collimated beam, i.e. to obtain a flat intensity distribution, a homogenizer such as a micro-lens array, might be needed, see Figure 14. A second advantage of a micro-lens array would be the suppression of any structure on the illuminated screen that might originate from the diffuser structure. The result is a speckle-free, collimated and homogeneous beam. For this setup, it is advised to use a large diffusion angle with structures that are a magnitude smaller than the spot size, so that enough averaging of the speckle pattern can occur (e.g. 20° diffuser with ~3um structure size for a 100um spot size). Note that in this case no static diffuser is allowed.

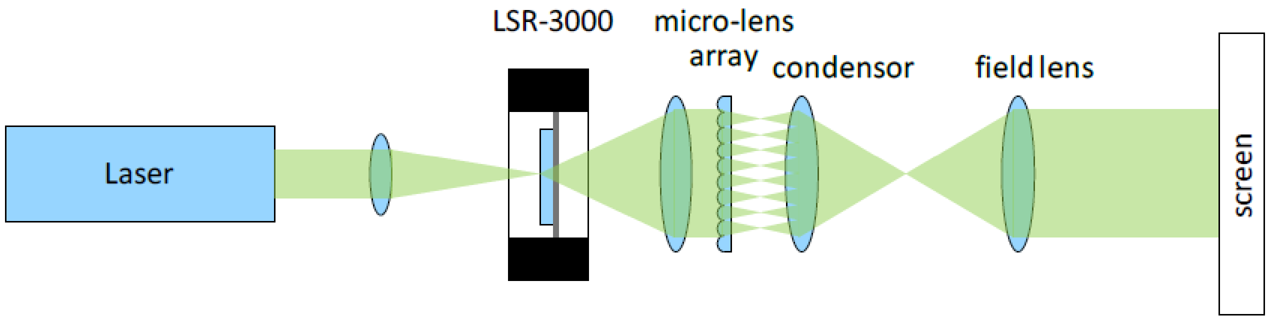


Figure 14: Optical system layout with the LSR in the focal point of the laser, followed by a homogenizer

6.2. LSR in focal plane + multimode fiber

Similar to the example above, a fiber can be used instead of a homogenizer. A lens setup as depicted in Figure 15 is the best option to couple into the fiber. For good efficiency, the spot size on the diffuser should not be larger than the core diameter of the fiber. Note that in this case no static diffuser is allowed.

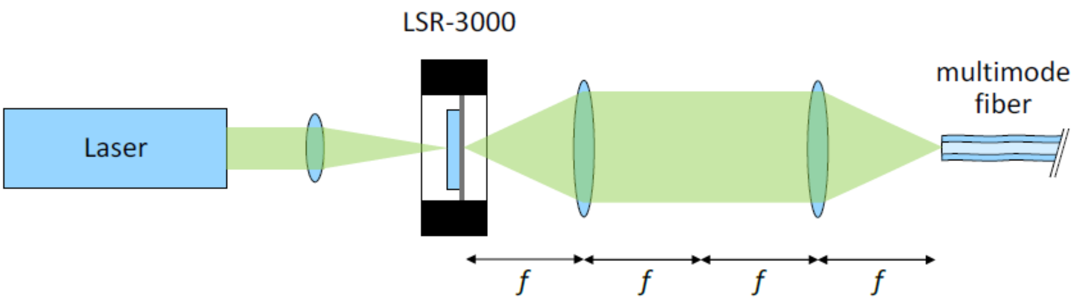


Figure 15: Optical layout for a fiber coupling solution with the LSR.

6.3. LSR in focal plane + fiber source and multimode fiber afterwards
The scheme in Figure 14 can be extended with an additional lens setup if the light source is already a fiber. In this case, the fiber end is imaged on the LSR with a first lens system and the spot on the LSR is then imaged on the second fiber with the second lens system, see Figure 16. For good efficiency, the spot size on the diffuser should be approximately the size of the fiber core of the first fiber and should not be larger than the core diameter of the second fiber. Note that in this case no static diffuser is allowed.

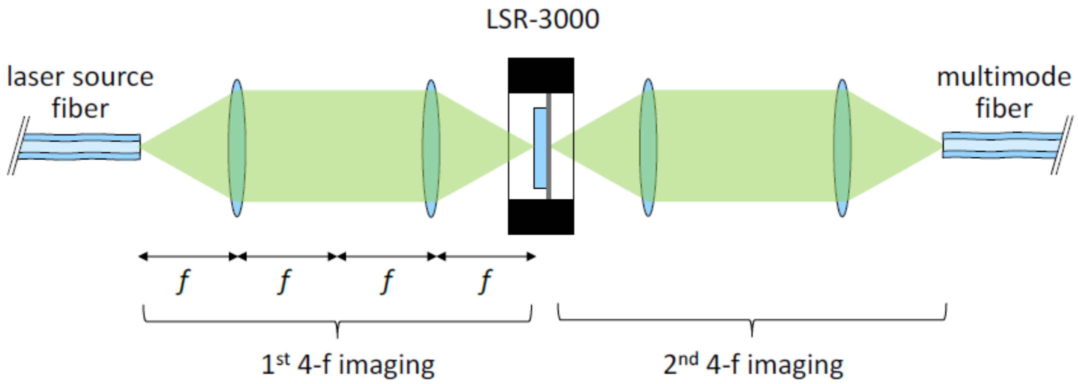


Figure 16: Optical layout for a fiber-to-fiber coupling solution with the LSR.

6.4. LSR for use with DLP/LCOS micro displays

In Figure 17 and Figure 18, two principle setups are shown to integrate the LSR into a projection system based on digital light processing (DLP) displays or liquid crystal on silicon (LCOS) micro displays.

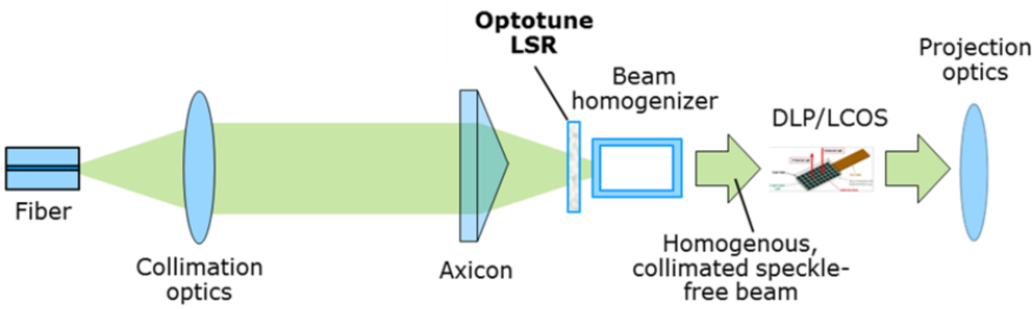


Figure 17: LSR is positioned between a focusing axicon lens and the homogenizer to illuminate the DLP/LCOS with specklefree light.

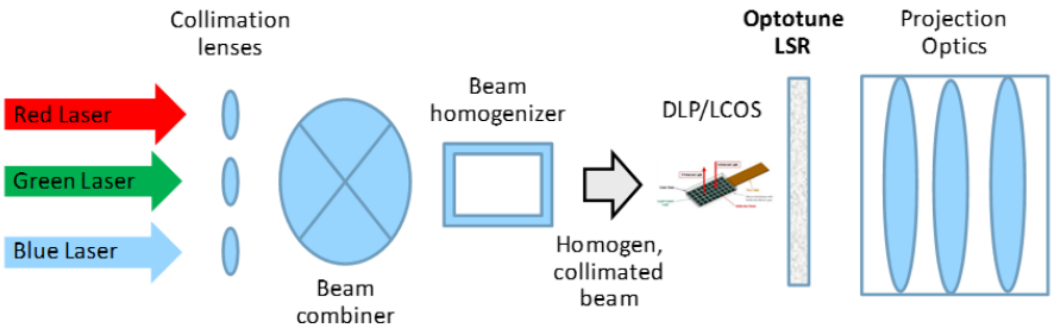


Figure 18: The LSR positioned after the micro display in the image plane of the projection optics. The Image stays in focus thanks to minimal out-of-plain motion of the LSR.

7. Trouble shooting

7.1. The output beam does not exhibit any speckle reduction
- Check that the power supply is turned on (blue light)
- Check that a significant difference is obtained when the LSR is switched on (dynamic mode, Figure 4 (c)) compared to when the LSR is switched off (static mode, Figure 4 (b))

- To check if the diffuser is moving at all, place the diffuser in the focal point of the light source to make an image of the diffuser structure on the screen. Thanks to the magnification, the movement should be visible.

7.2. The output beam does not exhibit a sufficient speckle reduction

- Try to optimize the speckle reduction by increasing the size of the input beam to match the size of the clear aperture of the LSR.
- Try to optimize the position of the LSR perpendicular to the optical axis.
- Try to increase the exposure time of your camera.
- If none of the above solves your problem, this means the chosen LSR does not provide a sufficient speckle reduction ratio R for your application. A LSR with a larger diffusion angle should be used.

Please note that the achieved speckle reduction highly depends on the configuration such as the optical setup, the LSR in use, etc. as discussed above. We have already gained experience in a wide range of applications and our application engineers are happy to help you on finding the optimal setup also for your application.