STF Series Fiber De-speckler

Our proprietary De-Speckler technology averages the modal noise within an optical fiber. This reduction in speckle is an ideal choice for fiber assemblies used in the Life Sciences, Digital Laser Projection, Interferometry, Laser Beam Homogenization, Lithography, and Metrology. For many fiber coupled applications, modal noise interferes with optimal performance. We have developed a small, simple and integrated de-speckling system which maximizes performance and reliability in illumination, with no optical loss.

Features and Benefits

Speckle is a random granular pattern commonly observed in the output beam of a laser. It is characterized by many dark and light spots of different intensities visible in a given cross section of the laser beam. This effect occurs as a result of interference between various propagation modes of the light.

The reduction of speckle is important for applications where a homogeneous laser output of uniform intensity is ideal, such as laser-scanning microscopy, flow cytometry, and DNA sequencing. By using the De-Speckler to average the modal noise and greatly reduce speckle, maximized performance can be achieved. Other benefits resulting from speckle reduction can include faster integration times, improved signal-to-noise ratios, and higher throughput.

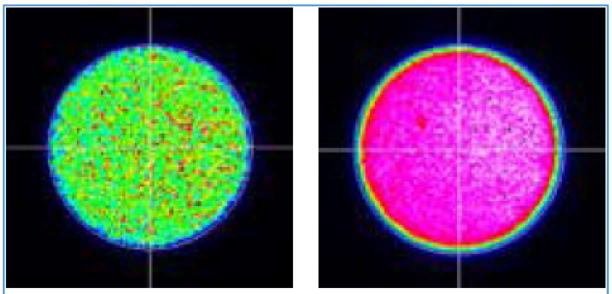
Our speckle reduction solution has a small form factor and is in-line with a customizable fiber assembly. The fiber size, core shape, jacketing, connectors, and length can all be customized to perfectly suit your application. Please view the product specifications for more information.

This product is popularly paired with our square core fiber and RARe Motheye anti-reflection technology.

Applications

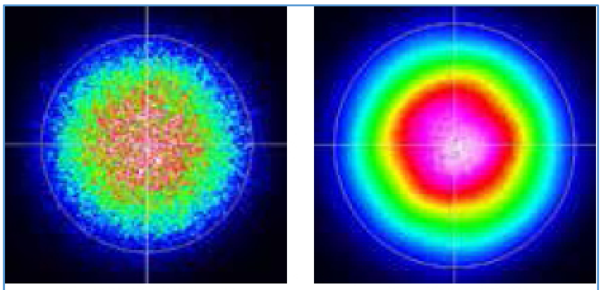
- Life sciences: bioanalytical instrumentation, flow cytometry, gene sequencing, microscopy, spectroscopy
- Digital laser projection
- Interferometry
- Laser beam homogenizers
- Lithography
- Metrology

Sintec Optronics



Near Field Without De-Speckler | Near Field With De-Speckler

400µm Round Core Fiber - Wavelength 445nm



Far Field Without De-Speckler | Far Field With De-Speckler

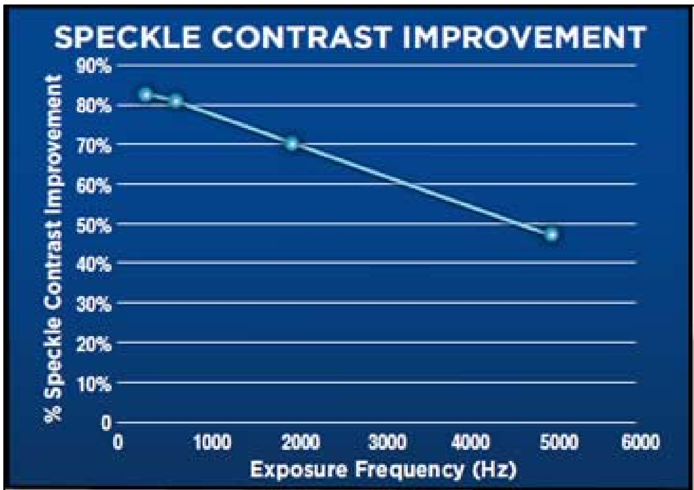
400µm Round Core Fiber - Wavelength 445nm

Specifications

- Power supply: +5 Volts
- Power consumption: < 1 Watt
- Wavelength range: 400nm – 1550nm
- Fiber core size: 100µm – 400µm
- De-speckling rate: up to 5000 Hz

Customization Options

- **Fiber types**: all Silica optical fiber; plastic clad fiber; round or square core fiber; RARe Motheye available.
- **Jacket types**: acrylate, nylon, polyimide, Tefzel
- **Assembly types**: single fiber assemblies
- **Connector types**: 905 SMA; 906 SMA; FC/PC; FC/UPC; FC/APC; ST/PC; ST/UPC; ST/APC; cleaved ends; polished ends; round 2.5mm ferrule; custom connectors



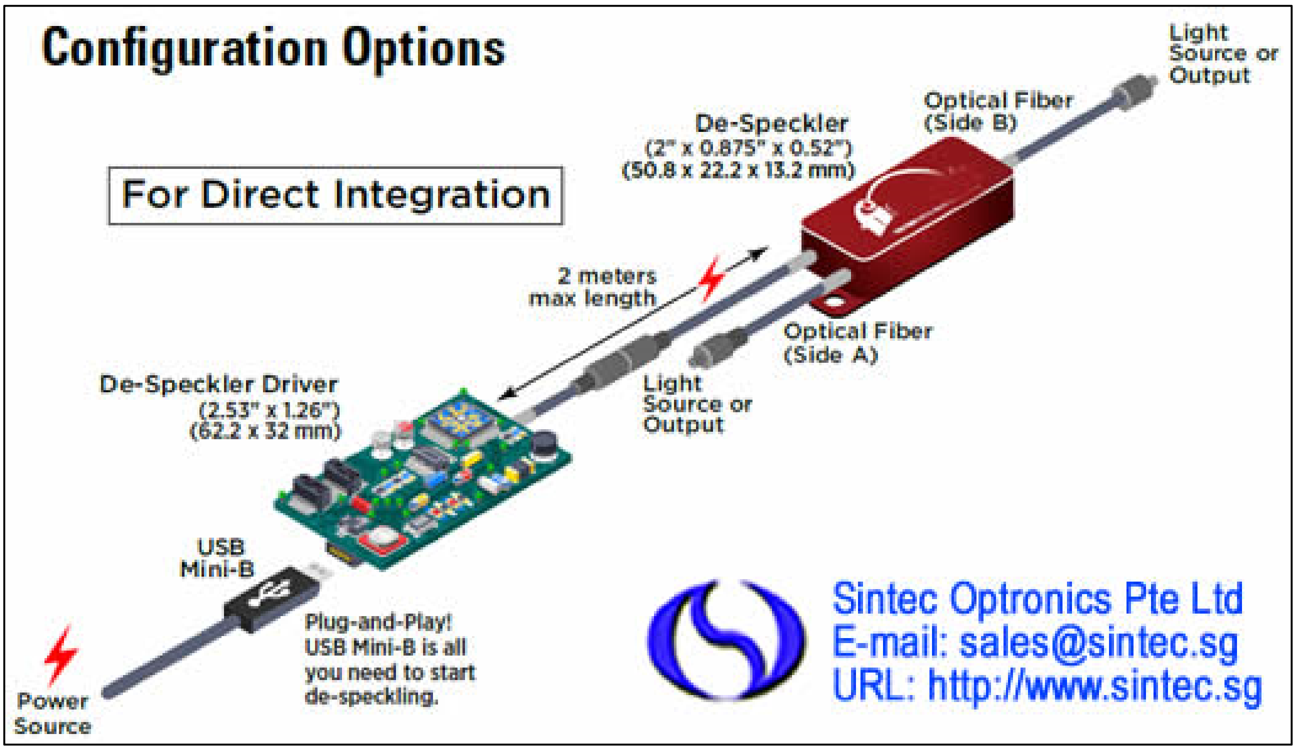
Percent Speckle Contrast Improvement vs. Exposure Frequency
Obtained using 200µm round-core fiber.

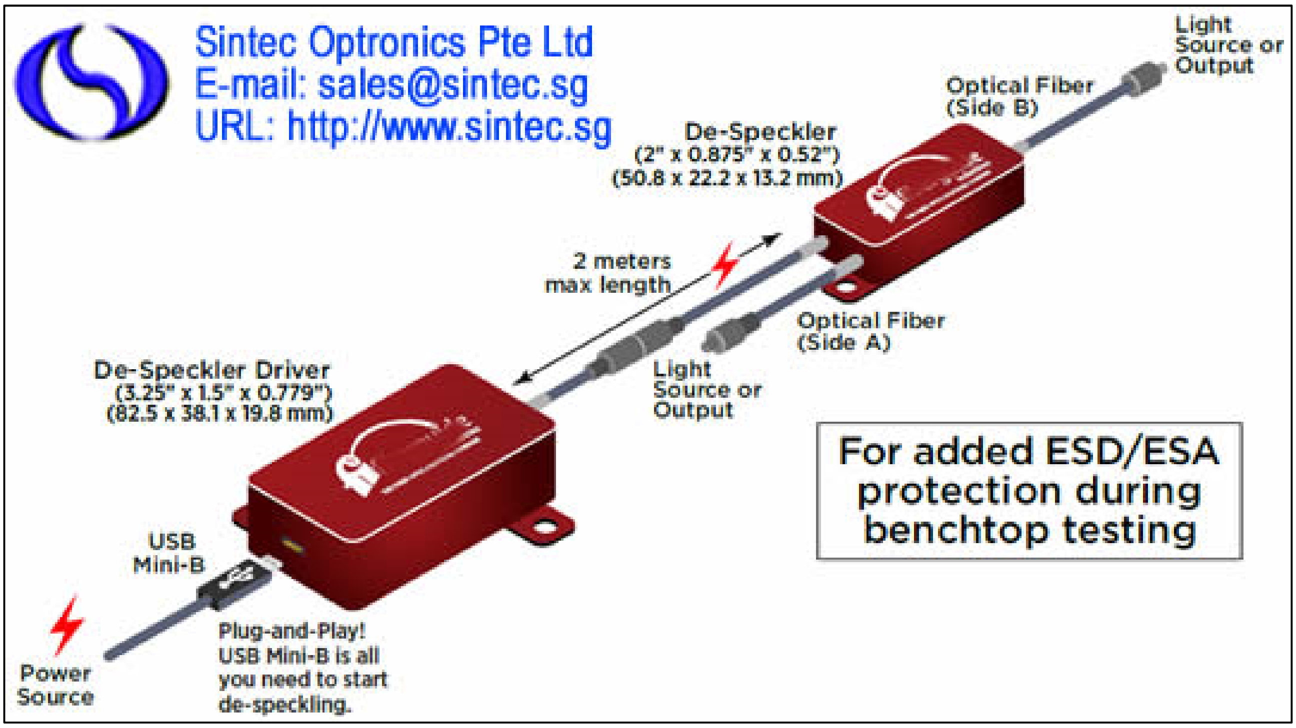
$$C = \frac{\sigma}{\langle I \rangle}$$

C: Speckle Contrast, reported as a ratio

σ: The standard deviation of the intensity over the radial distance

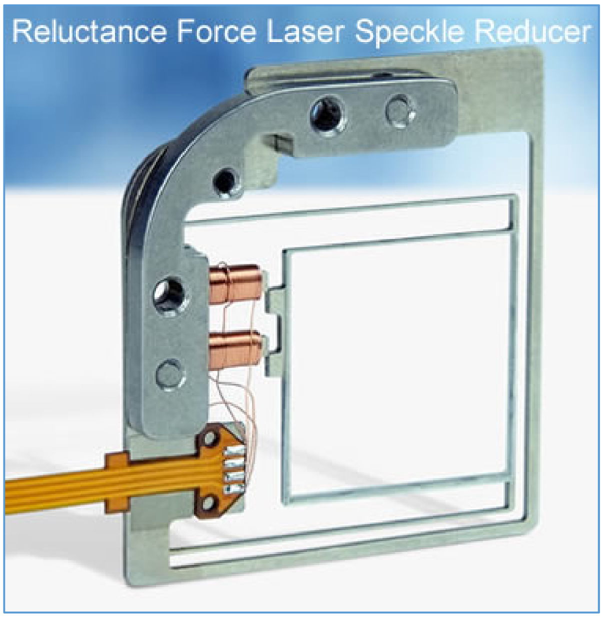
I: Average intensity of the radial distance

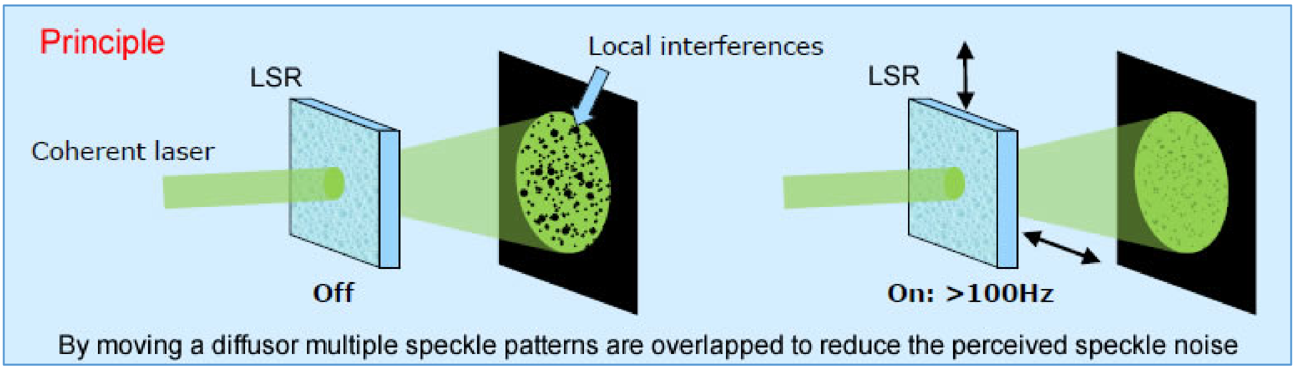

Configuration Options
For Direct Integration
Light Source or Output
Optical Fiber (Side B)
De-Speckler
(2" x 0.875" x 0.52")
(50.8 x 22.2 x 13.2 mm)
2 meters max length
Optical Fiber (Side A)
Light Source or Output
De-Speckler Driver
(2.53" x 1.26")
(62.2 x 32 mm)
USB Mini-B
Plug-and-Play! USB Mini-B is all you need to start de-speckling.
Power Source
Sintec Optronics Pte Ltd
E-mail: sales@sintec.sg
URL: http://www.sintec.sg


Sintec Optronics Pte Ltd
E-mail: sales@sintec.sg
URL: http://www.sintec.sg
Light Source or Output
Optical Fiber (Side B)
De-Speckler
(2" x 0.875" x 0.52")
(50.8 x 22.2 x 13.2 mm)
2 meters max length
Optical Fiber (Side A)
Light Source or Output
De-Speckler Driver
(3.25" x 1.5" x 0.779")
(82.5 x 38.1 x 19.8 mm)
For added ESD/ESA protection during benchtop testing
USB Mini-B
Power Source
Plug-and-Play! USB Mini-B is all you need to start de-speckling.

Laser Speckle Reducer

Our laser speckle reducers (LSRs) are nothing other than moving diffusers. But the way they are actuated is absolutely unique. Two innovative technologies are offered, each with its own advantages.

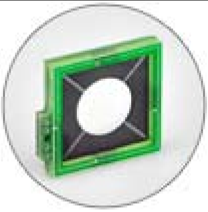




Electro-active Polymer Laser Speckle Reducer
With its launch in 2011, we are the first to commercialize electro-active polymers (EAPs) in the field of optics. The basis of this approach is a thin, elastic membrane that carries a lightweight diffuser in its center and four electrodes surrounding it. Actuated at a 90° phase shift, the electrodes induce a circular oscillation of the diffuser in x- and y-direction. The ultra-compact form factor, minimal weight and the absence of noise and vibrations make this technology particularly attractive for hand-held devices.

Reluctance Force Laser Speckle Reducer
Launched in 2016, the reluctance force LSR is particularly suitable for applications that require large format glass diffusers. The basis of this approach is a single thin steel structure that is brought into resonance by pulsing an actuating coil with current, which generates a strong reluctance force. Thanks to a high q-factor large amplitudes in the range of 800um are achieved at low power consumption even for heavy glass diffusers.

- Compact
- Silent
- Low power
- Low vibration

	Electroactive polymer LSR	Reluctance force LSR
Specifications		
Clear aperture	5 or 10mm	18.5x18.5mm
Diffuser	Polymer	Glass or polycarbonate
Transmission	Up to 93%	Up to 98%
Oscillation type	2D (circular)	1D (linear)
Oscillation amplitude	300-400um	800um
Resonant frequency	300 or 180Hz	~120Hz (depends on diffuser weight)
Weight	3g	11g
Vibrations	None	Low (depends on mechanical mount)
Cover glasses	Required	None
Electronics	5 VDC (EAP is pulsed with 300V)	5 VDC (coils are pulsed with current)

Applications
Our laser speckle reducer is the ideal choice for application in:

- Laser projection displays from cinema to pico
- Head-up displays
- Beam homogenizer
- Metrology
- Microscopy
- Interferometry
- Lithography

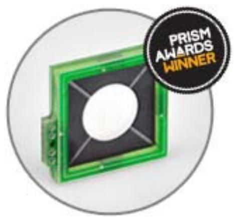
Customization
Our laser speckle reducers can be taylored to your specific demands in terms of size, oscillation frequency or transmission range. Tell us your requirements and we will be happy to assess the feasibility.

1. Electroactive Polymer Laser Speckle Reducer

Within a height of less than 1mm, electroactive polymers are used to bring a polymer diffuser into resonant oscillation with e.g. 400µm travel at several 100 Hz. This electrostatic principle is very power-efficient, completely silent and free of vibrations, an ideal choice for hand-held devices.

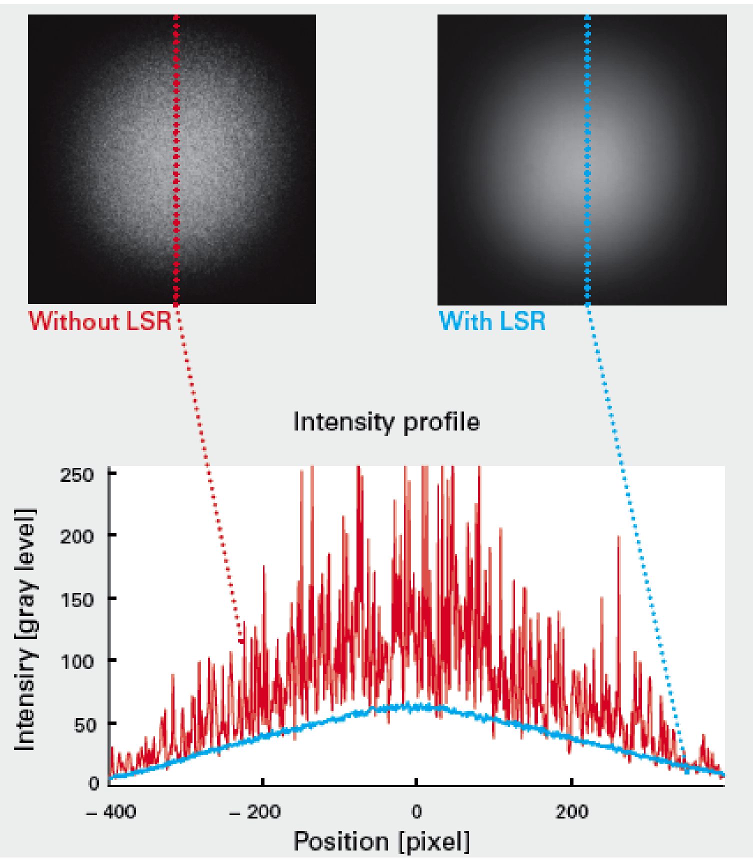
- Ultra compact
- No noise
- No vibration
- Low power

The following table summarizes the main specifications of currently available laser speckle reducers:

Specifications	STOT-LSR-3005	STOT-LSR-3010	STOT-LSR-5-17	STOT-LSR-10-22
				
Product description	Scientific standard	Scientific standard	OEM standard	OEM standard
Size (Ø or L x H)	41mm x 8.8mm	48mm x 8.8mm	17mm x 3.8mm	22mm x 3.8mm
Clear aperture	5mm	10mm	5mm	10mm
Oscillation frequency	300Hz	180Hz	300Hz	180Hz
Oscillation amplitude	300um	400um	300um	400um
Electronics	Integrated, CE certified	Integrated, CE certified	Optional, not certified	Optional, not certified

Results

The following figure shows typical images of the speckle contrast measured on a reference setup with and without LSR. The colored lines show the cut planes that correspond to the intensity plot.



Speckle reduction measured with a CCD camera

Applications

- Laser projection displays from cinema to pico
- Head-up displays
- Beam homogenizer
- Metrology
- Microscopy
- Interferometry
- Lithography

1.1 Transmissive laser speckle reducer STOT-LSR-3005

The STOT-LSR-3005 is designed for practical use on your optics table and integrates certified drive electronics powered through a single micro-USB connector (5VDC). Four standard diffuser configurations are available ranging from 6° (highest optical efficiency) to 24° (best speckle reduction). Most models combine an oscillating diffuser with a static diffuser to reduce the correlation length of the random patterns that are generated. This provides more effective speckle reduction yet minimizing the increase in beam divergence. The 17° model, which consists of a dynamic diffuser only, is particularly suitable when the diffuser needs to be in the image plane as is the case e.g. with holographic LCOS or in fiber coupling setups.

With an oscillation frequency of 300Hz and an amplitude of about 300um, the 5mm aperture model is the preferred choice for applications with high frame rates. VIS and NIR coated cover glasses are provided as a standard. Other coating options as well as diffuser combinations are available upon request.

The following table summarizes the main specifications of the standard STOT-LSR-3005 series:

Part number	Total diffusion angle	Diffuser configuration	Cover glass coating
STOT-LSR-3005-6D-VIS	6°	4.2° oscillating, 4.2° static	400 - 700nm
STOT-LSR-3005-12D-VIS	12°	8.5° oscillating, 8.5° static	400 - 700nm
STOT-LSR-3005-24D-VIS	24°	17° oscillating, 17° static	400 - 700nm
STOT-LSR-3005-17S-VIS	17°	17° oscillating, no static	400 - 700nm
STOT-LSR-3005-6D-NIR	6°	4.2° oscillating, 4.2° static	700 - 1100nm
STOT-LSR-3005-12D-NIR	12°	8.5° oscillating, 8.5° static	700 - 1100nm

Finding an appropriate system layout is key to effective and efficient speckle reduction. Our application note contains several suggestions, suitable for a variety of applications.

1.2 Transmissive laser speckle reducer STOT-LSR-3010

The STOT-LSR-3010 is designed for practical use on your optics table and integrates certified drive electronics powered through a single micro-USB connector (5VDC). Two standard diffuser configurations are available: 6° for highest optical efficiency and 12° for best speckle reduction. Both models combine an oscillating diffuser with a static diffuser to reduce the correlation length of the random patterns that are generated. This provides more effective speckle reduction yet minimizing the increase in beam divergence.

With an oscillation frequency of 180Hz and an amplitude of about 400um, the 10mm aperture model is the preferred choice for applications with frame rates below 180Hz or for the human eye. For the STOT-LSR-3010 series only VIS coated cover glasses are provided as a standard. Other coating options as well as diffuser combinations are available upon request.

The following table summarizes the main specifications of the standard STOT-LSR-3010 series:

Part number	Total diffusion angle	Diffuser configuration	Cover glass coating
STOT-LSR-3010-6D-VIS	6°	4.2° oscillating, 4.3° static	400 - 700nm
STOT-LSR-3010-12D-VIS	12°	8.5° oscillating, 8.5° static	400 - 700nm

Finding an appropriate system layout is key to effective and efficient speckle reduction. Our application note contains several suggestions, suitable for a variety of applications.

1.3 Transmissive laser speckle reducer STOT-LSR-5-17

The OEM version of our laser speckle reducer comes with a minimal housing and is available with or without drive electronics.

The most important parameter is the choice of diffuser angles. Standard diffuser angles of 1°, 4.3°, 8.5° and 17° are available. The STOT-LSR consists of a dynamic diffuser and optionally a subsequent static diffuser. The latter is recommended when no homogenizing optics follow the STOT-LSR to increase the speckle reduction factor. Finding an appropriate system layout is key to effective and efficient speckle reduction. Our application note contains several suggestions, suitable for a variety of applications.

Our standard diffusers are made of a proprietary polymer, which offers a transmission range of 240 to 2500nm at a typical transmission of 93% and damage threshold of 300W/cm^2. The diffuser itself is not coated, however VIS and NIR coated cover glasses are available as a standard. It is also possible to work with glass diffusers if they are similar in size and weight.

With an oscillation frequency of 300Hz and an amplitude of about 300um, the 5mm aperture model is the preferred choice for applications with high frame rates.

Design possibilities
We has custom designed speckle reducers to suit diverse requirements. On the large side, diffusors of 50x20mm size have been actuated at >60Hz for head-up displays. On the small side, an STOT-LSR as tiny as 9x6x1mm has been prototyped for pico-projectors.

1.4 Transmissive laser speckle reducer STOT-LSR-10-22

The OEM version of our laser speckle reducer comes with a minimal housing and is available with or without drive electronics.

The most important parameter is the choice of diffuser angles. Standard diffuser angles of 1°, 4.3°, 8.5° and 17° are available. The STOT-LSR consists of a dynamic diffuser and optionally a subsequent static diffuser. The latter is recommended when no homogenizing optics follow the STOT-LSR to increase the speckle reduction factor. Finding an appropriate system layout is key to effective and efficient speckle reduction. Our application note contains several suggestions, suitable for a variety of applications.

Our standard diffusers are made of a proprietary polymer, which offers a transmission range of 240 to 2500nm at a typical transmission of 93% and damage threshold of 300W/cm2. The diffuser itself is not coated, however VIS and NIR coated cover glasses are available as a standard. It is also possible to work with glass diffusers if they are similar in size and weight.

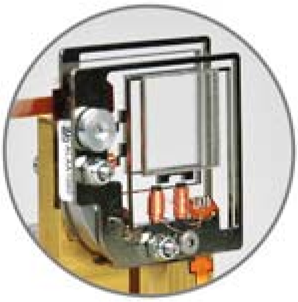
With an oscillation frequency of 180 Hz and an amplitude of about 400um, the 10mm aperture model is the preferred choice for applications with frame rates below 180Hz or for the human eye.

Design possibilities
We have custom designed speckle reducers to suit diverse requirements. On the large side, diffusors of 50x20mm size have been actuated at >60Hz for head-up displays. On the small side, an STOT-LSR as tiny as 9x6x1mm has been prototyped for pico-projectors.

2. Transmissive Laser Speckle Reducer STOT-LSR-4C

Our STOT-LSR-4C speckle reducer has an aperture of 18.5x18.5mm and is especially suitable for applications where high laser powers and large beam diameters are used. The diffusor is mounted in a thin steel frame. As part of a larger metallic structure the frame is set into motion by the reluctance force, generated by the oscillating magnetic field of a driving coil. If required, the STOT-LSR-4C can combine two oscillating diffusors rotated by 90°, realizing optimized despeckling in both directions. The compact driving electronics, assembled on a flexible plastic substrate, stabilizes the resonance frequency in closed-loop mode and includes an error signal.

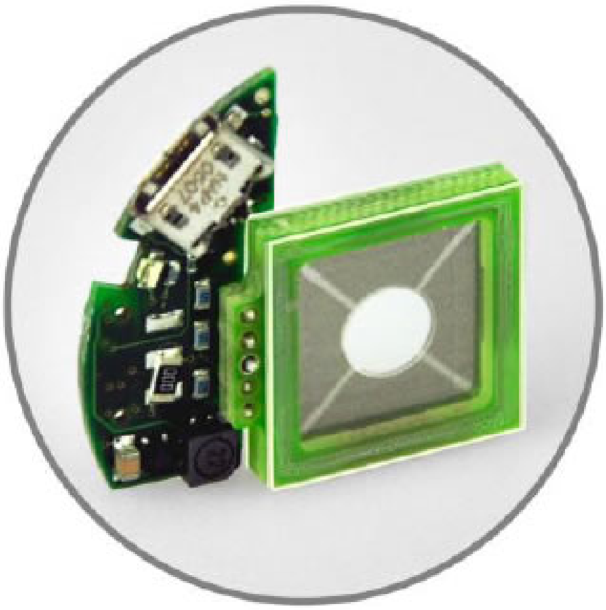
STOT-LSR-4C-L
(single linear oscillation)



STOT-LSR-4C-LL
(double linear oscillation)

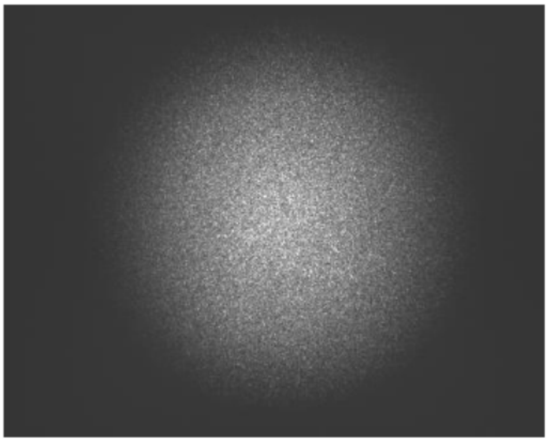
Sintec Optronics

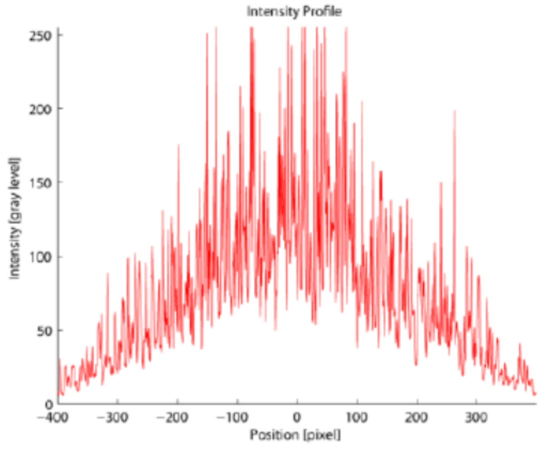
Application Note
Laser speckle reduction with laser speckle reducer STOT-LSR-3000 & STOT-LSR-OEM



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-LSR-3000 & STOT-LSR-OEM.


(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-LSR-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-LSR-3000, which is powered through a Micro-USB connector. A 110- 220VAC to 5VDC power supply is included.

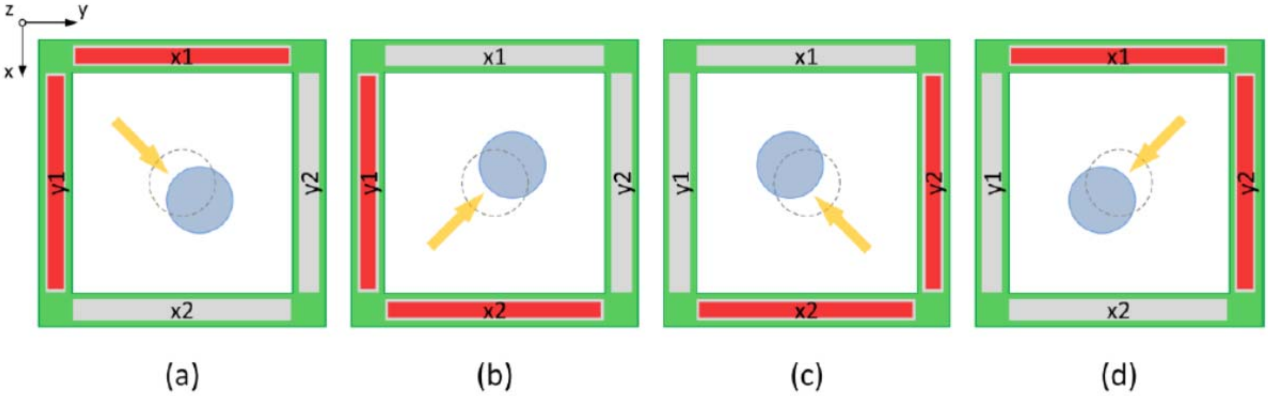


Figure 2: Illustration of four independent DEAs to move the rigid diffuser (blue circle) in the plane of the membrane. The equilibrium (no voltage applied on the electrodes) position of the diffuser is represented by the dashed circle. (a) The x1 and y1 electrodes are activated, the diffuser moves in 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-LSR-3000-XS and STOT-LSR-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

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

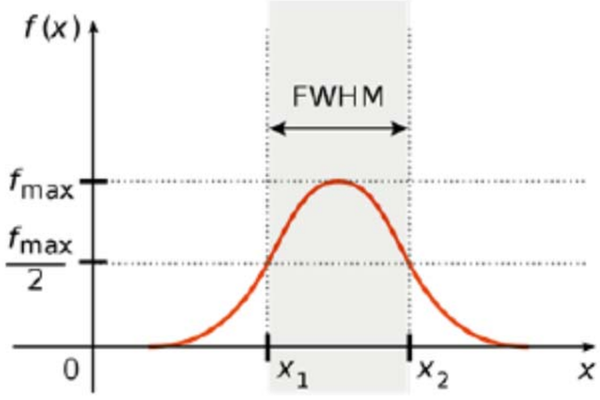
We note that for optical systems where the spot of the LSR is imaged, e.g., onto a fiber (see Figure 15 and Figure (16), no static diffuser is allowed. In that case an LSR with an oscillating diffuser only is recommended. The following table gives an overview on standard models with the different diffuser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

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

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

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

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



4. Measurement of the speckle reduction

4.1. Reference setup

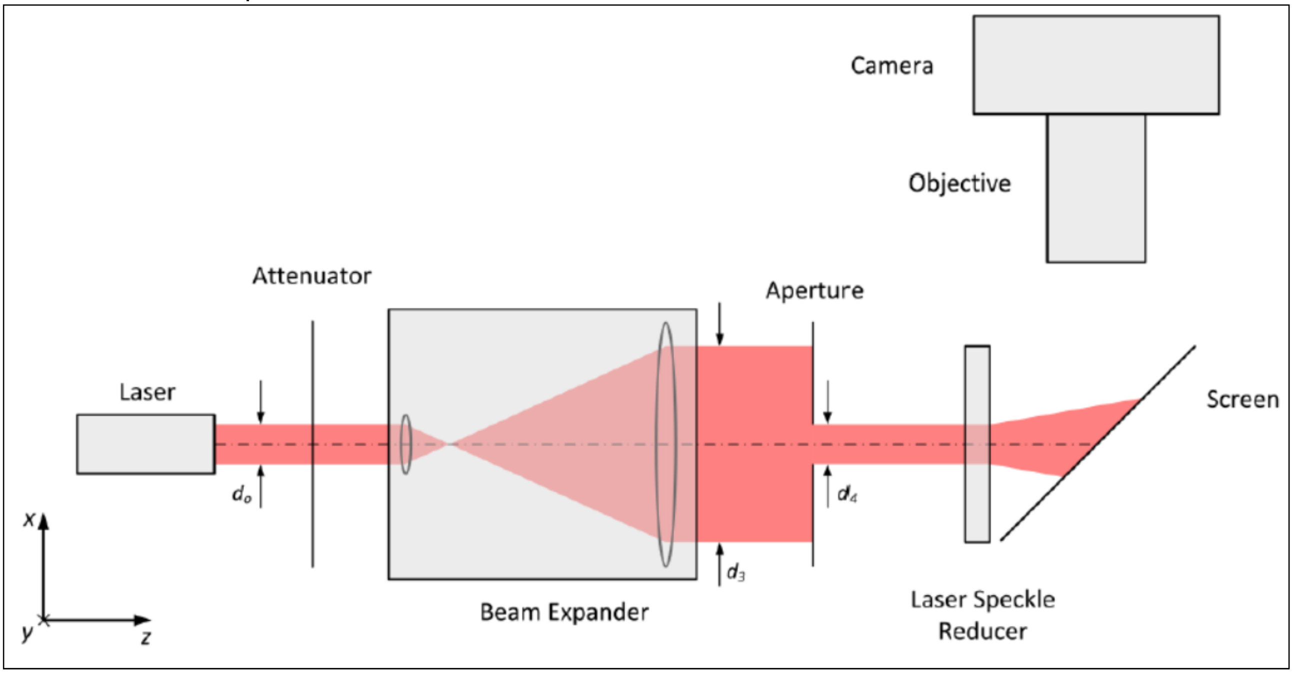


Figure 3: Reference setup for measuring speckle reduction. Laser: He-Ne, P=20mW, λ=632.8nm, linearly polarized. Beam expander: 15x. Objective: Computar, T4Z2813 CS IR. Camera: Mightex Systems, Monochrome 1.3MP CMOS, MCE-B013-US USB2.0.

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.

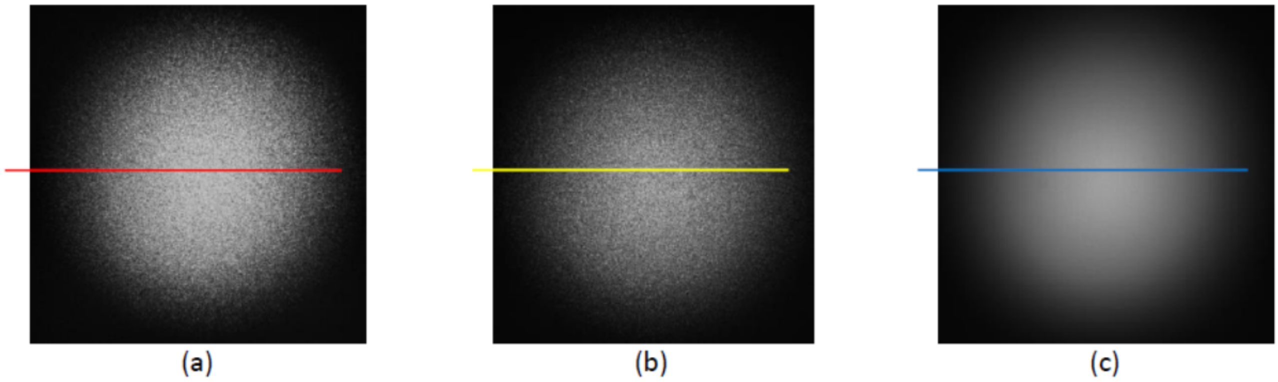


Figure 4: Typical images of the speckle contrast measured on the reference setup (a) without a LSR in the collimated path, (b) with the LSR in a static mode, and (c) with the LSR in a dynamic mode. The colored lines show the cut planes that refer to Figure 5.

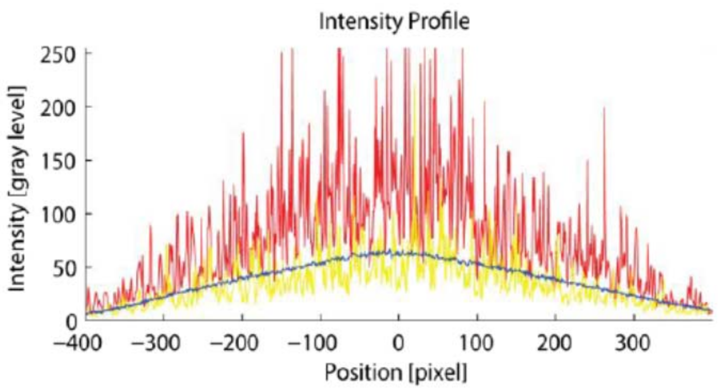


Figure 5: Measurement of the speckle contrast on a horizontal plan as depicted in Figure 4: in red, without any LSR, in yellow with the LSR in a static mode and in blue with the LSR in a dynamic mode.

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-LSR-3000 Series

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

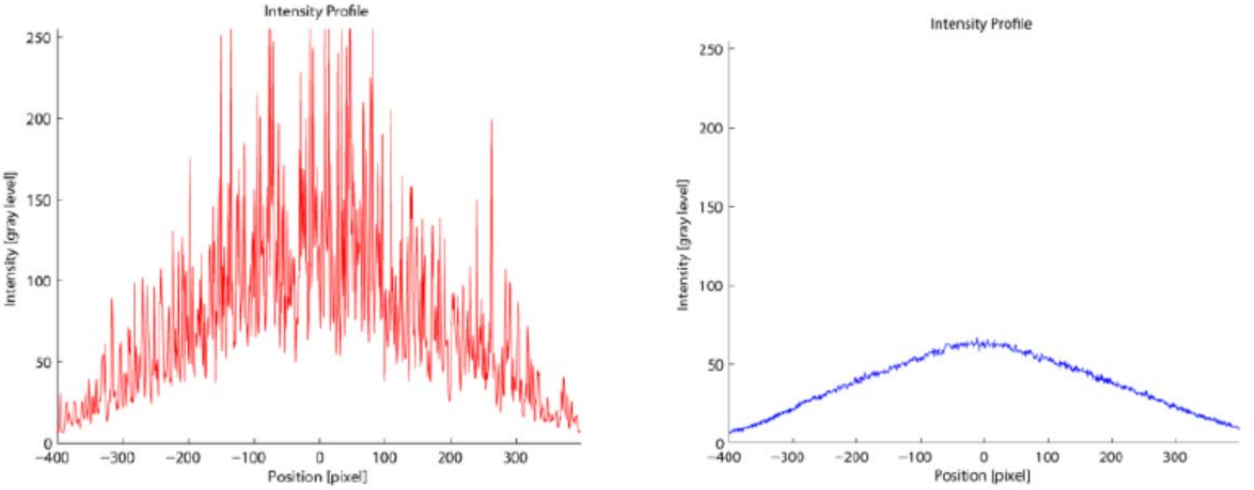


Figure 6: Measurement of the intensity profile: in red without LSR (pure laser) and in blue with the STOT-LSR-3005-24D

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

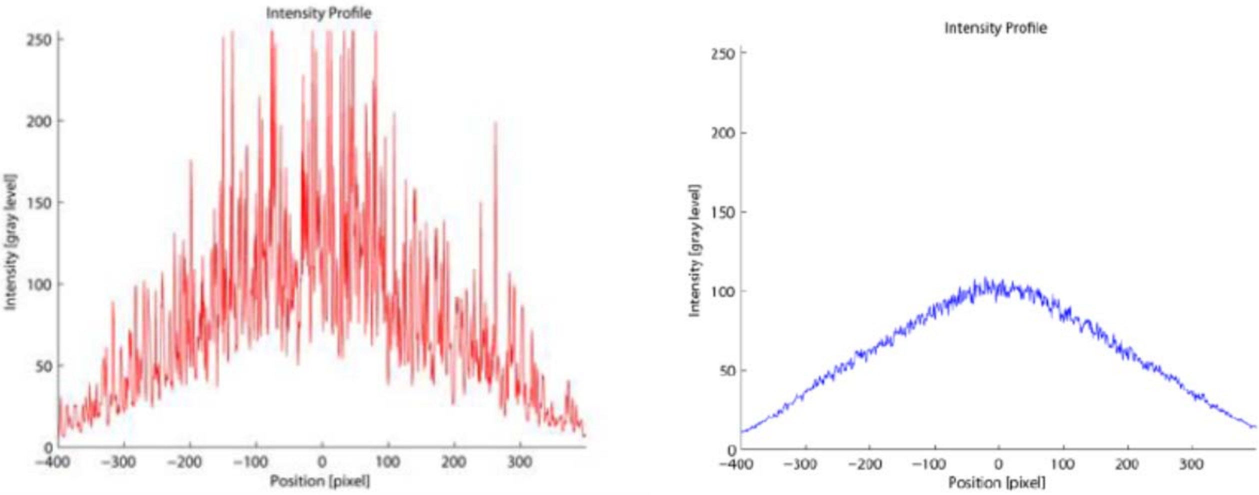


Figure 7: Measurement of the intensity profile: in red without LSR (pure laser) and in blue with the STOT-LSR-3005-12D.

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

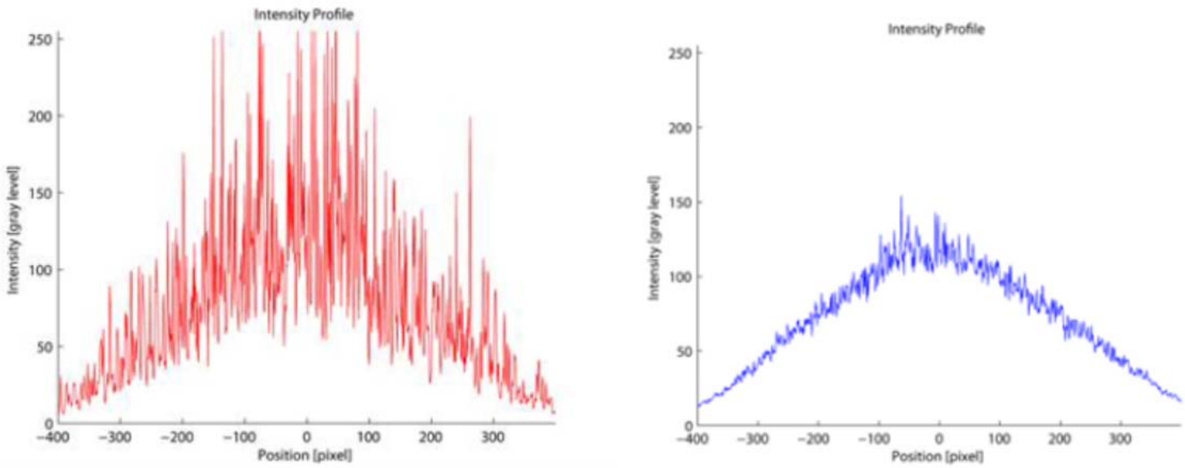


Figure 8: Measurement of the intensity profile: in red without LSR (pure laser) and in blue with the STOT-LSR-3005-1D

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 $L = 2\pi \cdot r$)
- The mechanical driving frequency f

These two parameters are shown in Figure 9 and define the motion speed of the diffuser $v = L \cdot f$.
Example of STOT-LSR-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.

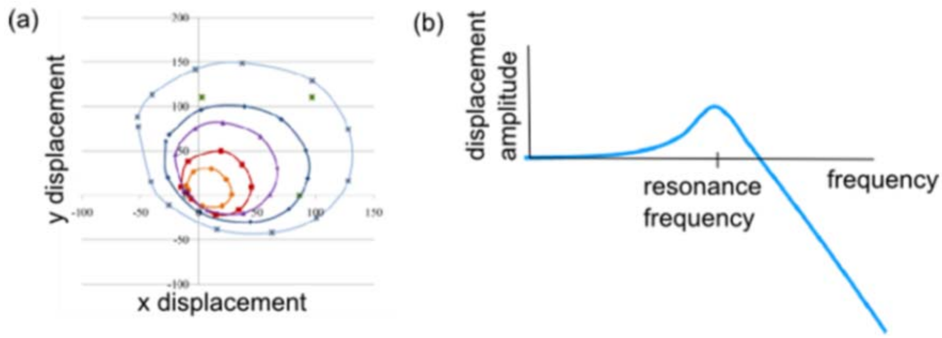


Figure 9: (a) Measurements of the displacement amplitude for different motion amplitudes and a fixed frequency. (b) Illustration of displacement amplitude as a function of mechanical driving frequency.

5.3. Diffuser structures

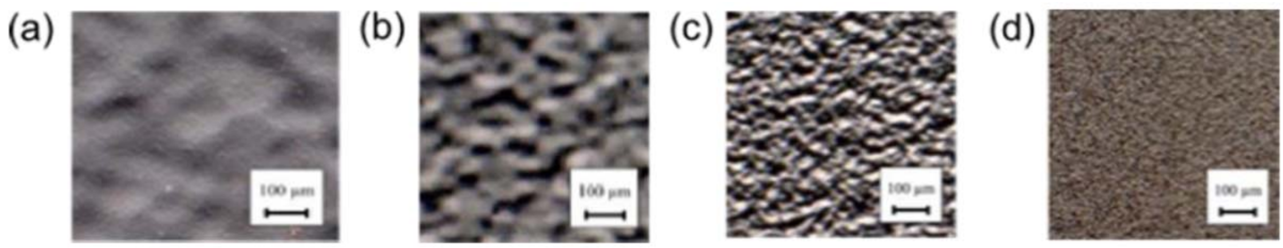


Figure 10: Different diffuser grain structures with an average size (a) 100μm, (b) 50μm, (c) 20μm, and (d) 3μm. The scale bar has a size of 100μm.

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-LSR-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-LSR-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.

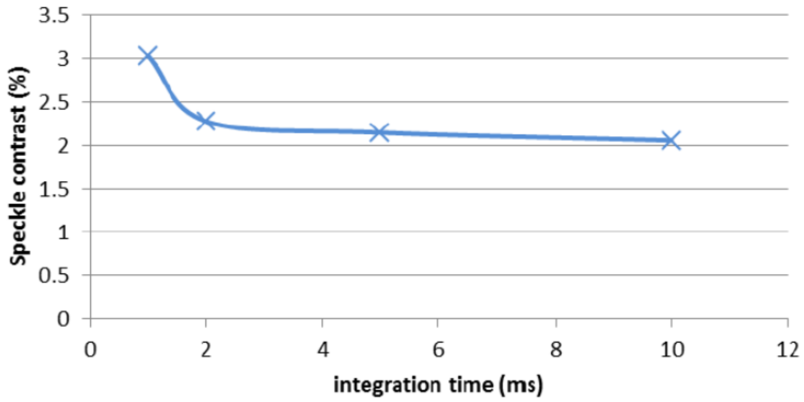


Figure 11: Speckle contrast obtained with the STOT-LSR-3005-24D for different integration times ranging from 1ms to 10ms

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 ($\leqslant$ 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.

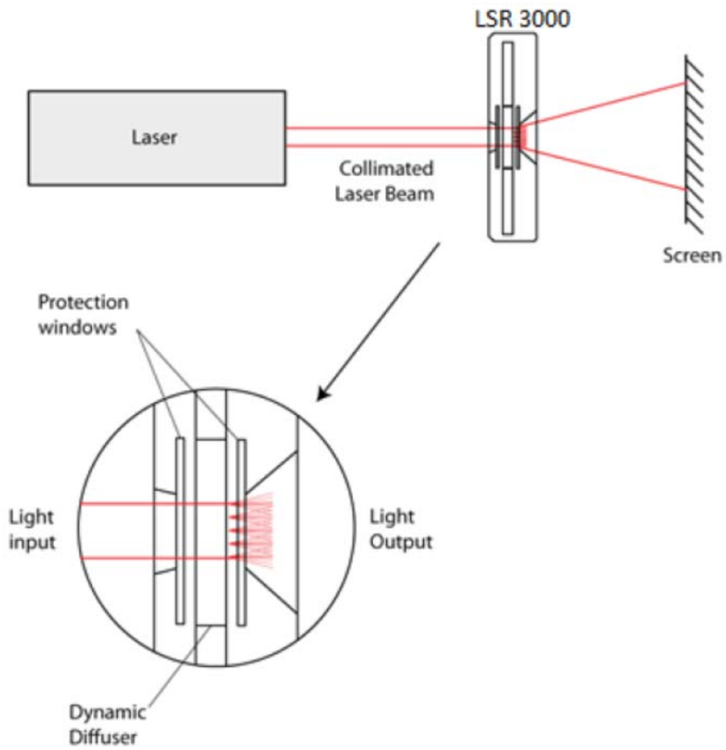


Figure 12: Straight-forward use and positioning of the LSR in a laser system.

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-LSR-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.

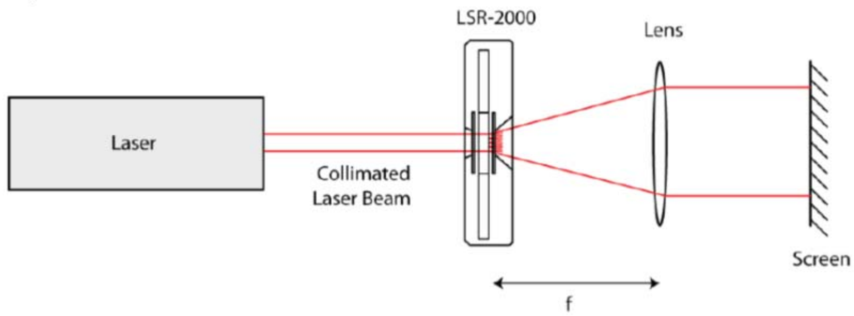


Figure 13: The LSR combined with a collimation lens that is used to reduce the beam divergence.

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.

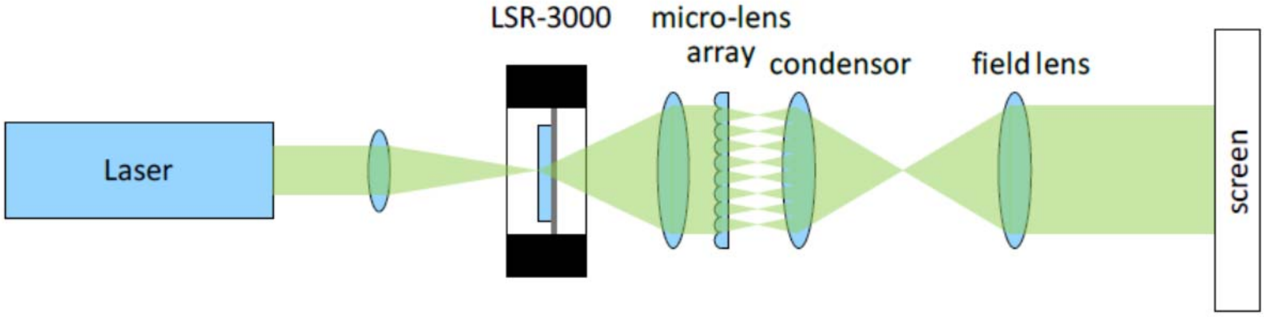


Figure 14: Optical system layout with the LSR in the focal point of the laser, followed by a homogenizer

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.

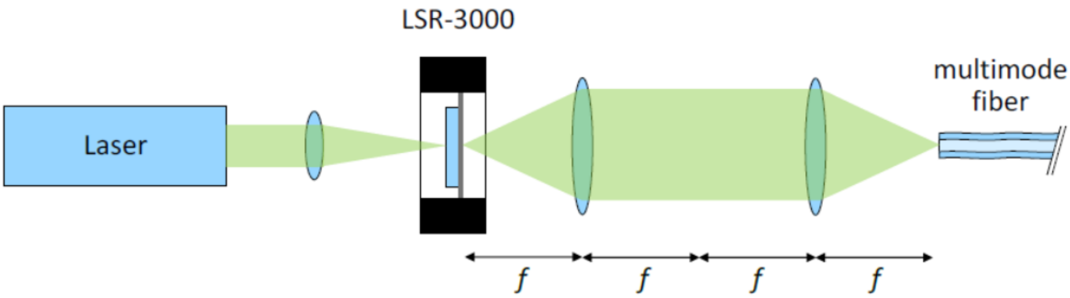


Figure 15: Optical layout for a fiber coupling solution with the LSR.

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.

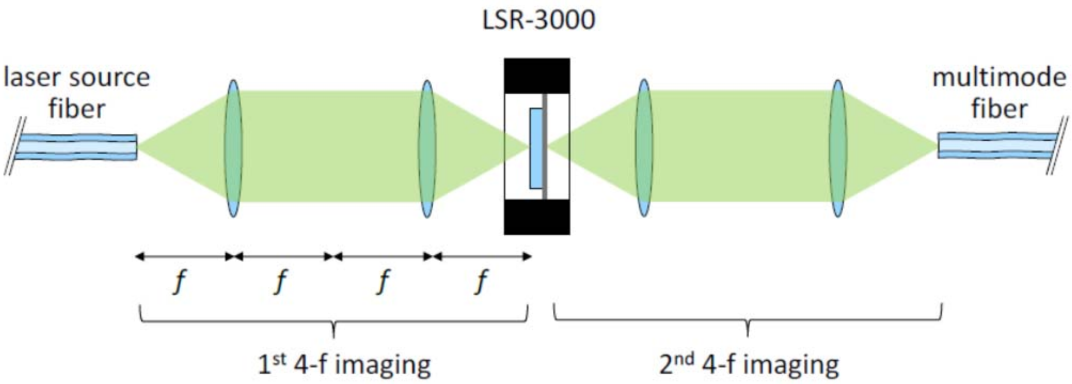


Figure 16: Optical layout for a fiber-to-fiber coupling solution with the LSR.

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.

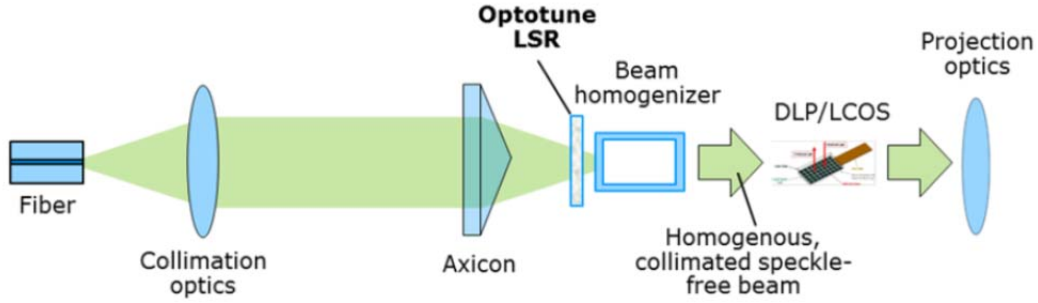


Figure 17: LSR is positioned between a focusing axicon lens and the homogenizer to illuminate the DLP/LCOS with specklefree light.

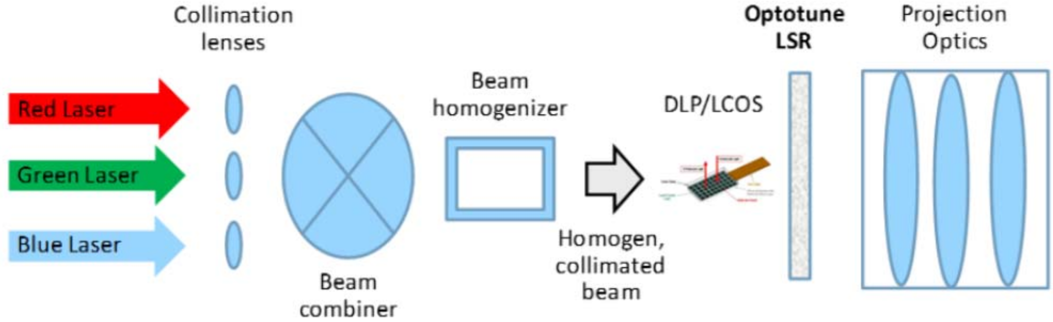


Figure 18: The LSR positioned after the micro display in the image plane of the projection optics. The Image stays in focus thanks to minimal out-of-plain motion of the LSR.

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.