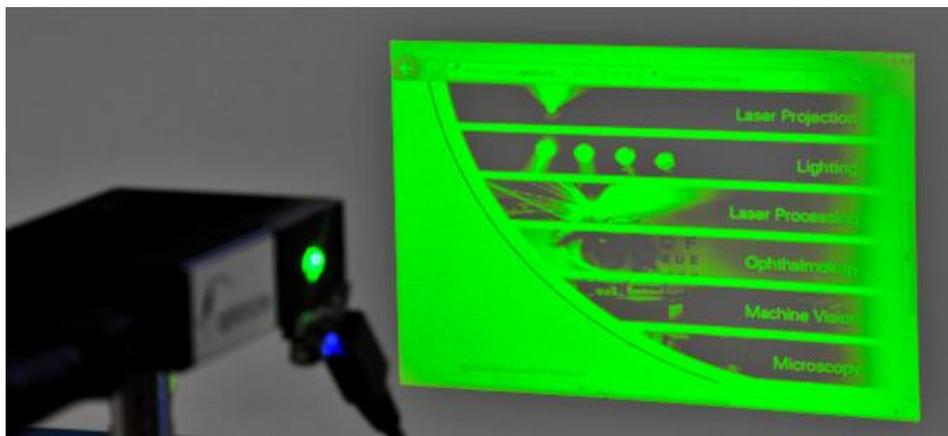


Application Note: LSR-4C for laser speckle reduction



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1. Introduction

Lasers provide numerous advantages over other light sources. For example, the low divergence allows precise control of high optical powers, making lasers attractive for projection systems. Laser projection systems have both a broader colour spectrum and a higher lifetime compared to conventional illumination systems. Another important property is the high degree of spatial and temporal coherence, allowing for tight focusing, collimation over large distances, metrology, and various types of spectroscopy. Although this characteristic is widely utilized in many scientific systems, it leads to a significant drawback – speckles – in applications where a detector is used.

Speckles are local interferences that occur on a surface if the corrugation depth (distance between a peak and a valley in the surface roughness) is on the order of the laser wavelength. Examples of surfaces where speckle patterns are normally observed are walls or cinema screens. Each of the scattered points in a speckle pattern may be described as a secondary coherent light source. Speckles are detected by e.g. a camera or a human eye as a grainy pattern and high-frequency local variations in intensity. An example is shown in Figure 1.

An application that vastly benefits from speckle contrast reduction is laser projection, since speckles strongly degrade the projected image quality. Another application that profits from speckle contrast reduction is metrology, as speckles reduce the resolution of measurement systems. In this application note, the concept of speckles will be further introduced alongside despeckling methods for relevant applications. Different configurations for speckle reduction using Optotune's laser speckle reducer LSR-4C will be characterized and compared, and further configurations suggested.

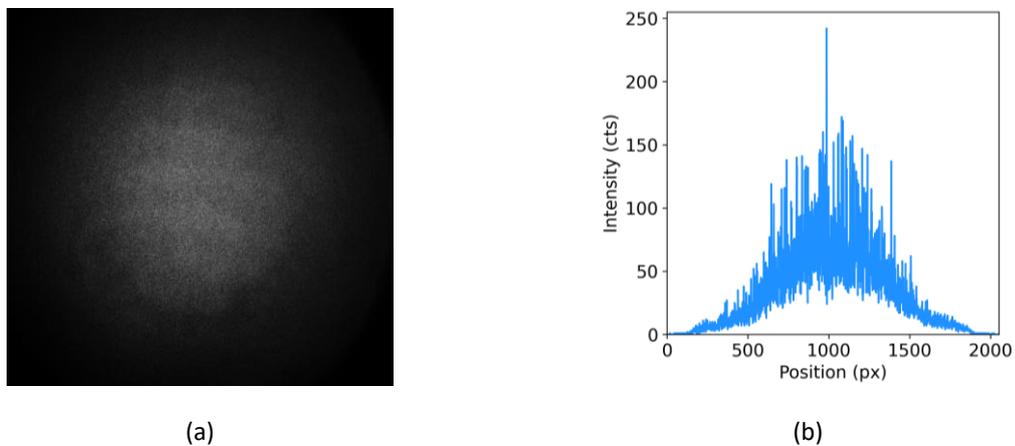


Figure 1: (a) A speckle pattern imaged on a CCD camera. (b) Intensity profile of the speckle pattern, given by a line cut through the image in (a).

2. Properties of a speckle pattern

2.1. Speckle contrast

A speckle pattern is formed when a rough surface is illuminated by coherent light. The specifics of the speckle pattern depend on the properties of the surface, the direction of incidence and observation of the illuminating beam, the temporal and spatial coherence of the illumination, as well as on the polarization and phase distribution of the backscattered wave from the surface.

The speckle contrast S is defined as the standard deviation σ of the intensity within a certain area normalized by its mean value μ :

$$S = \frac{\sigma}{\mu} \quad (1)$$

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

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (I_i - I_{mean})^2} \quad (3)$$

With this definition, the speckle contrast can have a value between zero and one. A speckle contrast of one corresponds to a spot where the intensity variations are on the same order of magnitude as the mean intensity. A speckle contrast of zero, corresponding to a standard deviation in intensity of zero, represents a homogenous spot without speckles.

A typical way to evaluate the speckle contrast is to divide an image into subareas and calculate S for each subarea. The speckle contrast of the full image is then given by the mean of the speckle contrast of the subareas.

2.2. Measurement of speckle contrast

Depending on the detection scheme, either objective or subjective speckles are imaged. A detector positioned directly without an imaging lens in the observation plane will image *objective* speckles, as they are formed in free space. *Subjective* speckles are what is seen through an optical system with a lens (e.g. when imaging the surface of a laser-illuminated screen on a CCD camera) and depend on the parameters of the imaging system.

2.3. Reduction of speckle contrast

Speckle contrast reduction is based on the creation and averaging of uncorrelated speckle patterns. Averaging N uncorrelated speckle patterns results in 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. This can be done either by dynamically changing the laser wavelength, angular spectrum, or polarization, by scanning a coherent light spot, or by using a dynamic diffuser. Furthermore, at a fixed laser wavelength and polarization, the speckle contrast can be reduced by increasing the quality of the surface. Optotune's LSR-4C is a laser speckle reducer (LSR) based on the approach with a dynamic diffuser, where speckle patterns are averaged temporally.

Comparing the speckle contrast using an LSR (S_{LSR}) with the speckle contrast of an optical reference system without an LSR (S), the reduction efficiency R is defined as follows:

$$R[dB] = 10 \cdot \log_{10} \left(\frac{S}{S_{LSR}} \right) \quad (4)$$

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

2.4. Key parameters for efficient speckle reduction

The speckle reduction in the case of a moving diffuser depends on several parameters:

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

The higher the motion speed and amplitude of the diffuser, the more patterns are overlapped during the exposure time of the imaging system. This also means that the longer the exposure time, the more speckle patterns are averaged and the lower the speckle contrast. This applies only up to a certain exposure time, after which the reduction rate of speckle contrast with exposure time stays roughly unchanged. For Optotune's LSRs, we recommend exposure times corresponding to at least one full movement cycle of the device. A despeckling effect will nevertheless be seen also for shorter exposure times.

For a moving diffuser, tradeoffs need to be made between the motion speed, amplitude, size and weight of diffuser, and the power consumption of the device. The heavier the diffuser, the higher the power consumption and the lower the resonance frequency of the device.

The smaller the feature size of the diffuser, the larger the diffusion angle. This means that for the same spot size, a diffuser with a smaller grain size will give a larger beam divergence and speckle contrast reduction compared to a diffuser with a large grain size. A few different diffuser grain sizes are illustrated in Figure 2.

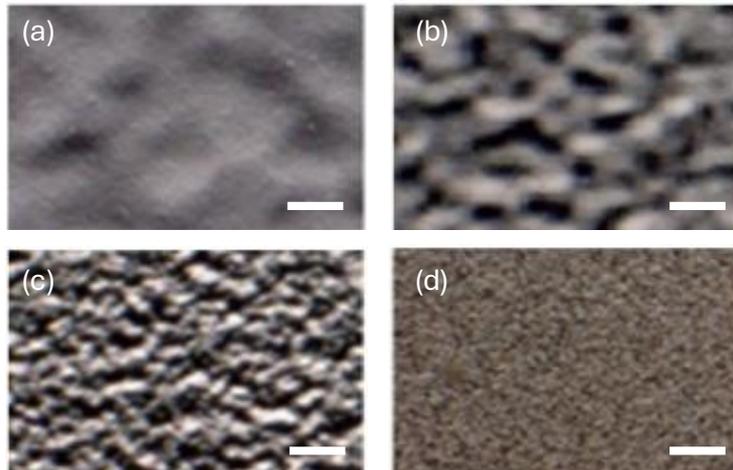


Figure 2: Different diffuser grain structures with an average size (a) 100 μm , (b) 50 μm , (c) 20 μm , and (d) 3 μm .
Scale bar: 100 μm .

3. Optotune LSR-4C

3.1. Working principle

Optotune's laser speckle reducer LSR-4C is shown in Figure 1(a). The speckle reduction principle is illustrated in Figure 3(b). The diffuser mounted in the device is moved at a high frequency, 120 ± 10 Hz, and amplitude, ± 0.4 mm, such that multiple speckle patterns resulting from a transmitted beam are overlaid. A detection system, integrating these patterns over time, sees this as a uniform light distribution. The actuation is done by pulsing current through two coils: the diffuser is mounted on a spring that moves due to the resulting reluctance force. To accommodate for at least a full oscillation cycle of the LSR-4C, a minimum exposure time of 8.3 ms is recommended.

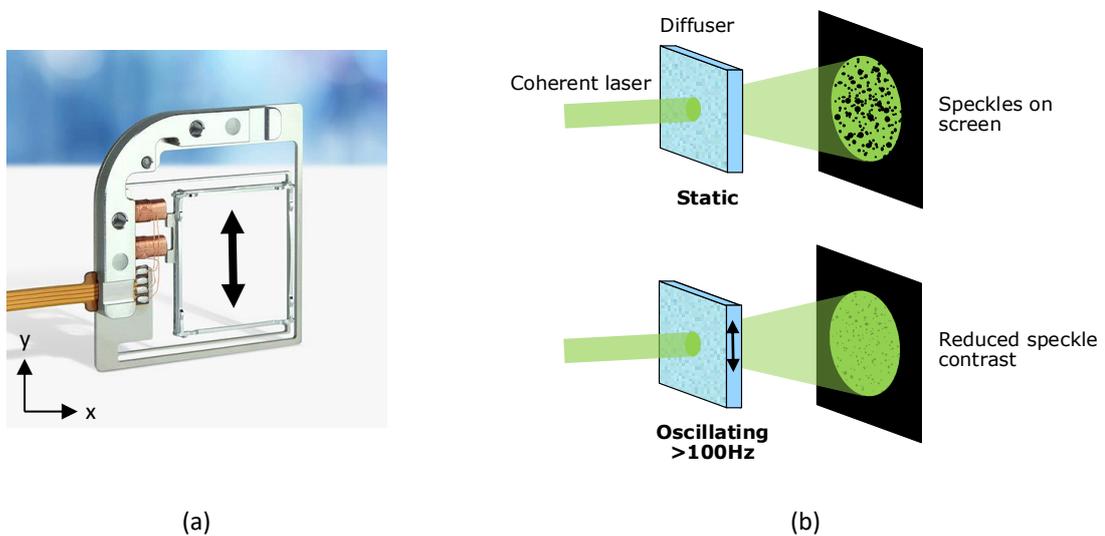


Figure 3: (a) Optotune LSR-4C. The arrow indicates the oscillation direction of the diffuser. (b) Speckle contrast reduction principle: by moving a diffuser, multiple speckle patterns are overlapped and reduce the perceived speckle noise.

The LSR-4C is offered as a standard product with a VIS-coated or uncoated fused silica diffuser with a diffusion angle of 8.5° . LSR-4C with uncoated polycarbonate with various diffusion angles is available as a customization. The diffusion angle is defined as the full width half maximum (FWHM) of the diffused light profile (Figure 4).

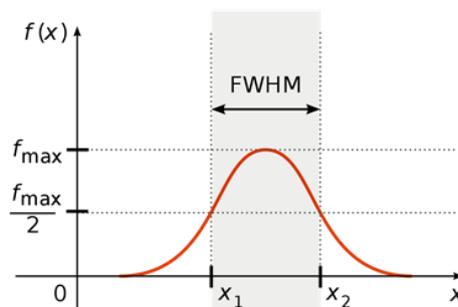


Figure 4: Definition of FWHM diffusion angle given a certain profile with a maximum intensity f_{\max} .

3.2. Combining diffusers

The LSR-4C can be used as a single unit to reduce speckles. This is the default, or -L, configuration. As the diffuser oscillates only in one direction, two LSR-4C units positioned at 90° to each other can be used in series to perform speckle reduction along two perpendicular directions and further reduce the speckle contrast. This is the -LL configuration. In this case, a user has the choice to oscillate either one or both diffusers. Note that for optical systems where the spot of the LSR is imaged onto e.g. a fiber, only a single diffuser should be used.

If two diffusers are combined, the overall total diffusion angle is calculated from the individual diffusion angles θ_1 and θ_2 by

$$\theta_{combined} = \sqrt{\theta_1^2 + \theta_2^2} \quad (5)$$

Table 1 gives an overview of the available standard models with the different diffuser combinations. For more details, please refer to the LSR-4C [datasheet](#).

Standard product	Configuration	Number of diffusers	Diffusion angle	AR coating
LSR-4C-L-18x18-9-T2-VIS	-L	Single diffuser	8.5°	VIS coated
	-LL	Double diffuser	12.0°	VIS coated
LSR-4C-L-18x18-9-T2-NOC	-L	Single diffuser	8.5°	Uncoated
	-LL	Double diffuser	12.0°	Uncoated

Table 1: Standard configurations of the LSR-4C.

4. Measurement of speckle reduction

4.1. Reference setup

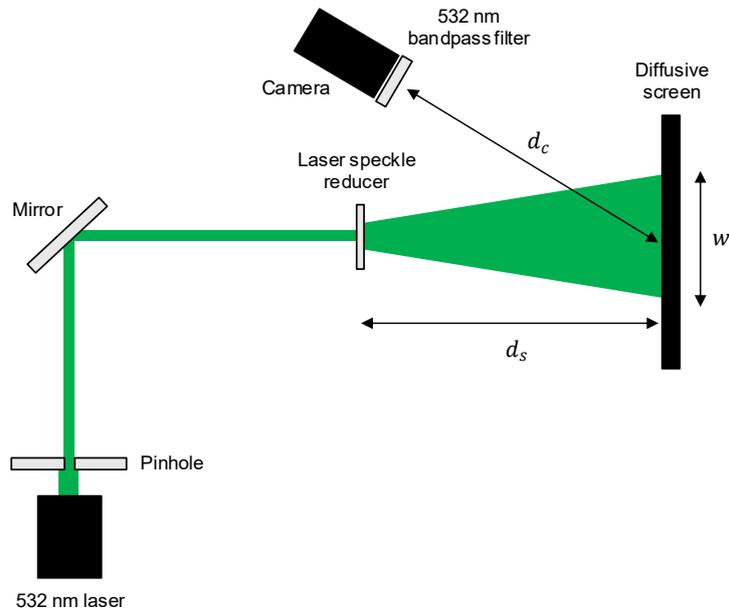


Figure 5: Reference setup for measuring speckle contrast. d_s denotes the distance between the last diffuser and the screen, w the diameter of the laser spot on the screen, and d_c the distance between the screen and camera (measured until the outermost component mounted on the camera).

In this application note, the speckle reduction performance of the LSR-4C in its different configurations will be presented. The experimental setup to measure speckle reduction is shown in Figure 5. The source is a collimated laser-diode-pumped DPSS laser module, outputting a 532 nm, 2.5 mW beam. A pinhole is used to set the beam diameter to 3 mm. The distance d_s between the last diffuser before the screen and the screen is varied between the measurement configurations (8.5 cm for -L, 5 cm for -LL) in order to achieve a $w = 4$ cm diameter laser spot on the screen. A camera (2/3", 5 MP, 3.45 μm pixels, 8 bit) used with an $f = 35$ mm, $f/5.6$ lens is positioned a distance $d_c = 17$ cm from the screen and records images of the laser spot. A 532 nm bandpass filter is used to filter the emission of the laser before the camera.

The following configurations are tested

- No LSR: no laser speckle reducer in the laser beam path. In order to obtain a similar spot size as with a diffuser, an $f = -50$ mm lens is used to expand the output of the laser.
- LSR-4C-L: a single diffuser. Measured both when the LSR-4C is turned off (static diffuser) and when it is turned on (dynamic diffuser). When turned on, the diffuser is oscillating along the y axis, perpendicular to the optical table on which the components are mounted.
- LSR-4C-LL: two diffusers in series. Measured with both diffusers static, both diffusers oscillating (one in x and one in y), and a hybrid configuration where the beam first passes through one oscillating (in x) diffuser and subsequently goes through one static diffuser.

Further details on the different measurement configurations can be found in Table 2.

	No LSR	LSR-4C-L		LSR-4C-LL		
Configuration	No LSR	Off	On	Off	Hybrid	On
Diffuser type	-	Fused silica, Gaussian profile				
Number of diffusers	0	1		2		
Diffuser movement	-	Static	Dynamic	Static	Static/Dynamic	Dynamic
Oscillation direction	-	-	y	-	x	x and y
Frequency	-	-	120 Hz	-	120 Hz	120 Hz
Diffuser displacement	-	-	~0.8 mm peak-to-peak	-	~0.8 mm peak-to-peak	~0.8 mm peak-to-peak

Table 2: LSR-4C configurations compared in this study.

4.2. Measurement procedure and data analysis

Using the experimental setup shown in Figure 5, each configuration described in Table 2 was measured. For each configuration, three frames per exposure time were acquired for exposure times between 0.2 ms and 20 ms.

Each of the frames was analyzed in the following way:

1. Fit a 2D Gaussian to the summed intensity in x and in y
2. Divide the frame into 7x7 pixel areas (“windows”)
3. For each window j , calculate the standard deviation σ_j and mean μ_j of the intensity
4. Disregard windows in which the mean intensity is below a given threshold, $\mu_j < 0.15 A$, where A is the peak intensity of the 2D Gaussian fit
5. Calculate the speckle contrast S_j of each window given σ_j and μ_j
6. Calculate the speckle contrast S of the complete frame as the mean of all S_j

Subsequently, the speckle contrast for each exposure time was evaluated from the mean of all frames taken with the same exposure time. Only data with sufficient signal-to-noise ratio, acceptable fits, and without saturation on the camera was included in the analysis presented in the following section.

For each measurement configuration, the speckle contrast S as a function of exposure time T_{exp} was fitted according to

$$S(T_{exp}) = a + bT_{exp}^{-0.5} \quad (6)$$

Here, a and b are fitting constants.

4.3. Results

Frames for each measured configuration for an exposure time of $T_{exp} = 10$ ms are shown in Figure 6. The corresponding speckle profiles, given by summing the intensity of vertical cuts through the frames, are shown in Figure 7. Please note that the Gaussian fits are used only for thresholding purposes and not for the speckle contrast calculation.

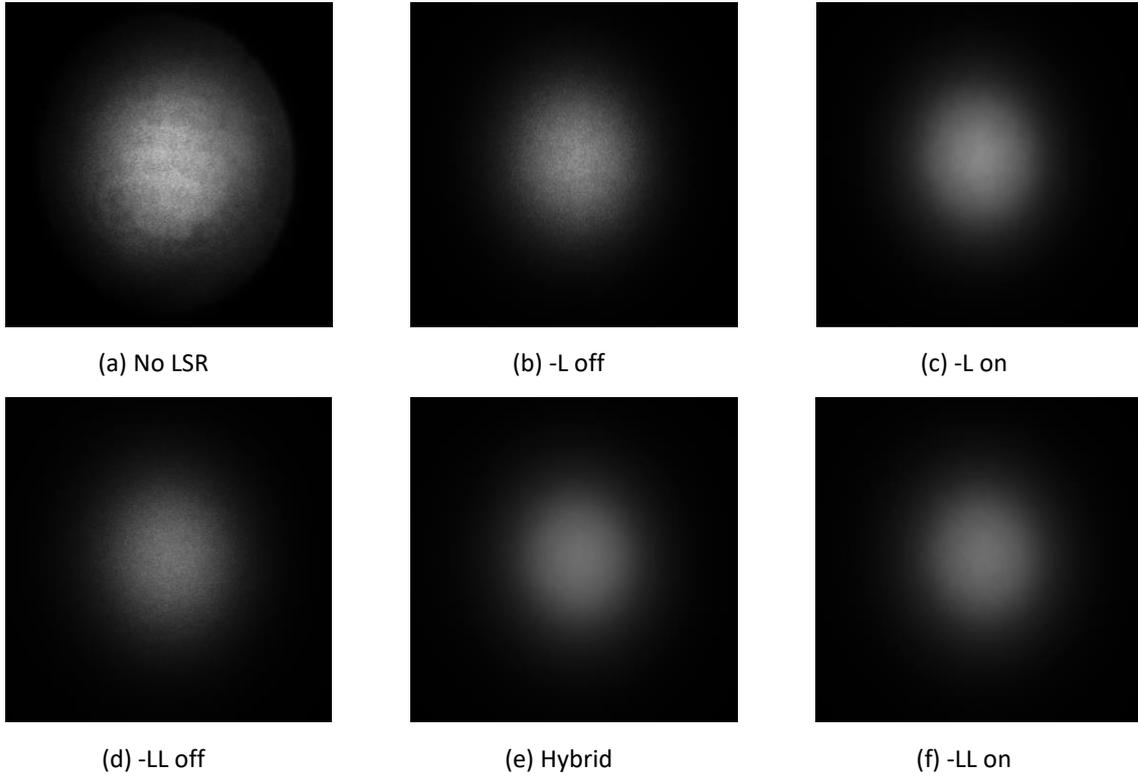


Figure 6: Laser spots for $T_{exp} = 10$ ms.

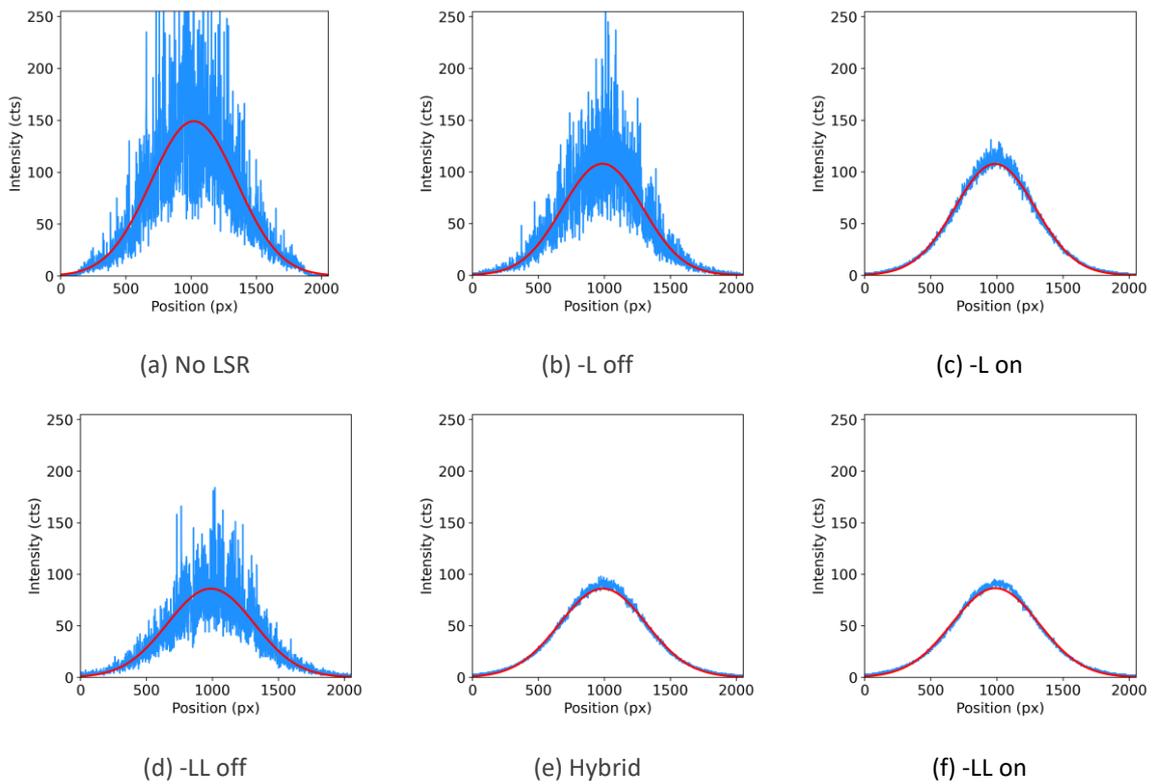


Figure 7: Speckle intensity profiles for $T_{exp} = 10$ ms. Red solid lines represent Gaussian fits.

Compared to the case without any laser speckle reducer, including one or two static diffusers (case (b) and (d), respectively) slightly reduces the perceived speckle contrast and intensity variation. As soon as one or two diffusers are oscillated (cases (c), (e) and (f)), there is a clear reduction in the speckle contrast and intensity variation. What can furthermore be noticed is a slight reduction in intensity in the cases where two diffusers are used instead of one (comparing, e.g., cases (c) and (f)).

The extracted speckle contrast values as well as values for the speckle reduction are presented in Table 3.

Configuration	No LSR	LSR-4C-L		LSR-4C-LL		
	No LSR	Off	On	Off	Hybrid	On
Speckle contrast S for $T_{\text{exp}} = 10 \text{ ms}$	0.3478*	0.3329	0.0547	0.3197	0.0416	0.0333
Speckle reduction S	-	4.3%	84.3%	8.1%	88.0%	90.4%
Reduction efficiency R	-	0.2 dB	8.0 dB	0.4 dB	9.2 dB	10.2 dB

Table 3: Speckle contrast for the different measurement configurations. The speckle reduction S and reduction efficiency R are calculated with respect to the reference measurement of no LSR. *From fit/extrapolated value.

The best speckle reduction is achieved using two dynamic diffusers in the LSR-4C-LL configuration. This fulfills the expectation of two diffusers reducing the speckle contrast more efficiently than one. For an exposure time of $T_{\text{exp}} = 10 \text{ ms}$, the configuration in which the LSR-4C-LL is on provides a reduction in speckle contrast of 90.4% compared to not using any diffuser. In comparison, the configuration where a single diffuser is oscillated using the LSR-4C-L, provides a reduction of 84.3%.

Figure 8 shows the speckle contrast as a function of exposure time for the LSR-4C-L. Fits following Equation (6) are included together with a 95% (2σ) confidence interval. Once the device is turned on, the speckle contrast is reduced by 83.5% compared to when the device is off, for an exposure time of $T_{\text{exp}} = 10 \text{ ms}$.

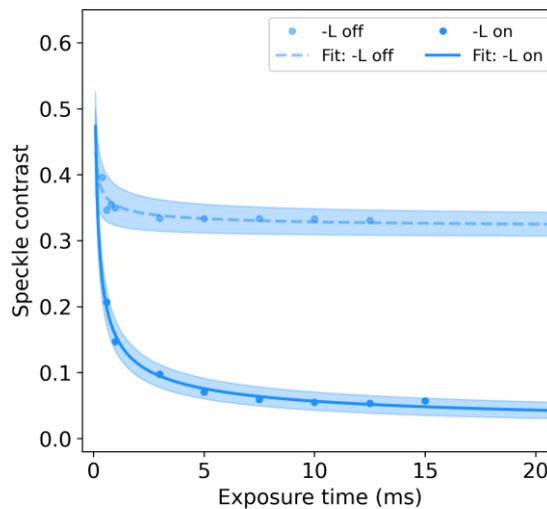


Figure 8: Speckle contrast as a function of exposure time for the LSR-4C-L. Solid lines represent a fit according to Equation (6). Shaded areas correspond to a 95% confidence interval.

Figure 9 shows the speckle contrast as a function of exposure time for the LSR-4C-LL. Fits following Equation (6) are included together with a 95% (2σ) confidence interval. Once the device is turned on, the speckle contrast is reduced by 89.5% compared to when the device is off, for an exposure time of $T_{\text{exp}} = 10$ ms.

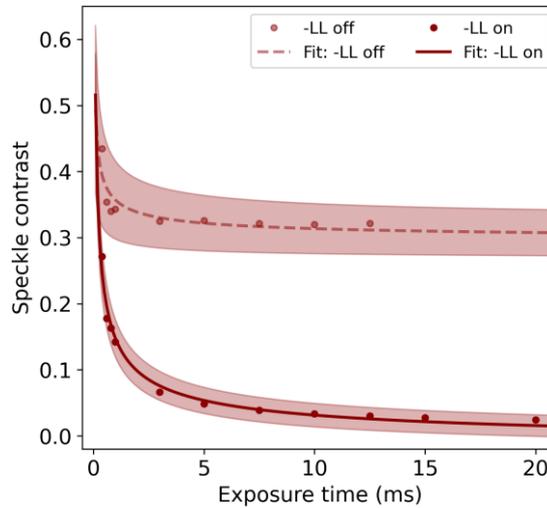


Figure 9: Speckle contrast as a function of exposure time for the LSR-4C-LL. Solid lines represent a fit according to Equation (6). Shaded areas correspond to a 95% confidence interval.

Figure 10 shows the trends of speckle contrast with exposure time for all measured configurations. The best speckle reduction for exposure times above 3 ms is when the LSR-4C-LL is used in a dynamic configuration, closely followed by the hybrid configuration with one oscillating and one static diffuser. Note that the exact speckle contrast values obtained in a different optical system layout might differ from the values obtained in this study.

A settling behavior is seen for exposure times above 8-10 ms, in agreement with the expectation of optimal despeckling for exposure times above 8.3 ms (a full oscillation cycle of the LSR-4C). This highlights that a sufficiently large number of different speckle patterns is generated within one oscillation period of the device.

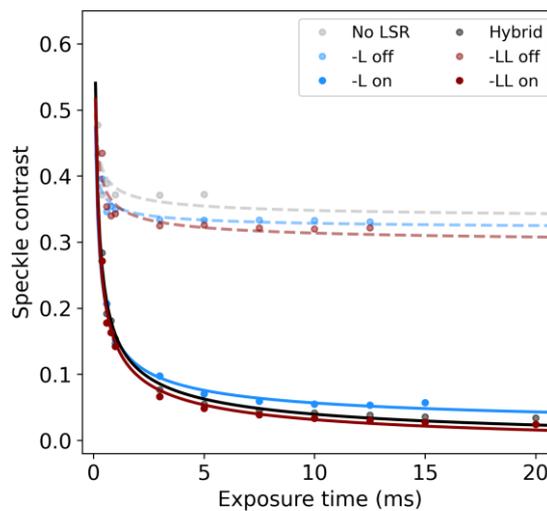


Figure 10: Speckle contrast as a function of exposure time for all measured configurations. Solid lines represent a fit according to Equation (6).

For exposure times below $T_{\text{exp}} = 3$ ms, there are only slight variations among the dynamic configurations and among the static configurations. Nevertheless, even for such short exposure times, there is a clear reduction in the speckle contrast when using one or two dynamic diffusers compared to one or two static diffusers. This means that even for exposure times that do not allow the LSR-4C to complete a full oscillation cycle, a certain amount of despeckling can be expected once the diffuser is oscillated. Still, for optimal despeckling, we recommend using the LSR-4C with exposure times above 8.3 ms. A reduced despeckling performance and larger frame-to-frame variations in speckle contrast can be expected for shorter exposure times.

In this study, the size of the spot on the screen in front of the diffusers was kept the same between the measured configurations. This allows for comparing data from the camera sensor at similar intensity values, differing only by the slightly lower transmission of two diffusers instead of one. For a fair comparison between the different configurations, this is crucial, as the signal-to-noise ratio of the camera sensor changes depending on the signal intensity. The signal-to-noise ratio will be different when the intensity is close to the noise floor compared to when the intensity is close to saturating the sensor. This can partly be mitigated by using a camera with a higher bit depth, to increase the intensity range between the noise floor and saturation.

4.4. Conclusions

For optimal speckle reduction, the LSR-4C-LL should be used in a dynamic configuration where two diffusers placed in series are oscillating along perpendicular directions. This reduces the speckle contrast by 90.4% compared to not using a diffuser, for an exposure time of $T_{\text{exp}} = 10$ ms. The recommendation applies in cases where the light does not need to be coupled back into a fiber, and when there is space available (the -LL configuration has a slightly larger device footprint and $\sim 1.4x$ larger diffusion angle than the -L configuration).

Compared to not using a diffuser at all, even a single oscillating diffuser in the LSR-4C-L configuration provides a large improvement in the speckle contrast. In applications where the LSR-4C-LL cannot be used, this is an excellent alternative. LSR-4C-L, when turned on, reduces the speckle contrast by 84.3% compared to not using a diffuser, for $T_{\text{exp}} = 10$ ms.

Optotune recommends that the LSR-4C is used for exposure times above 8.3 ms. Nevertheless, a certain level of speckle reduction will be seen even for shorter exposure times as long as the diffuser is oscillated.

5. How to integrate the LSR-4C in a laser system

5.1. General advice for efficient speckle reduction

For efficient laser speckle reduction, we generally advise to

- position the LSR perpendicular to the optical axis
- illuminate the LSR by a collimated beam

Figure 11 illustrates the simplest experimental layout including an LSR. The larger the cross-section of the beam, the more of the diffuser structure will be sampled by the beam and the better the despeckling, as more speckle patterns will be overlaid.

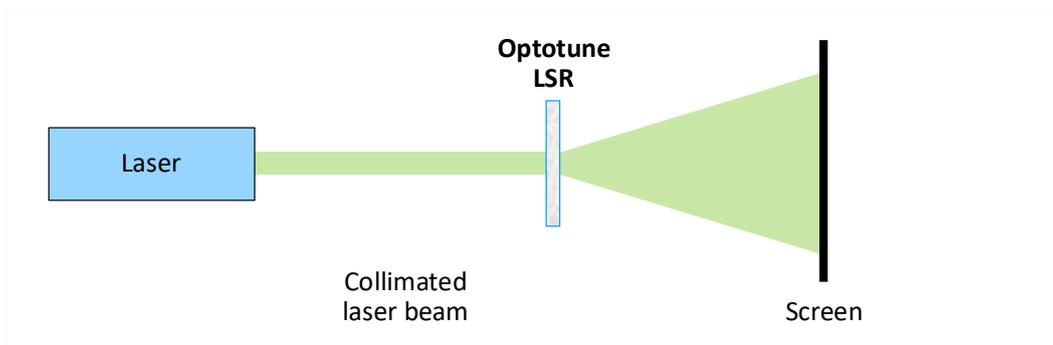


Figure 11: Positioning of the LSR in a laser system.

In this configuration, the LSR diverges the collimated beam with an angle corresponding to its diffusion angle. If the incoming light is not collimated, the outgoing light angle is calculated following

$$\theta_{exit} = \sqrt{\theta_{incident}^2 + \theta_{diffuser}^2} \quad (7)$$

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 can be positioned downstream from the LSR at a distance matching the focal length of the lens. The diameter of the lens should be equal or larger than the diverging beam diameter. This setup is illustrated in Figure 12. Note that this is not a true collimation, as the diverging beam contains many different diffusion angles owing to random scattering.

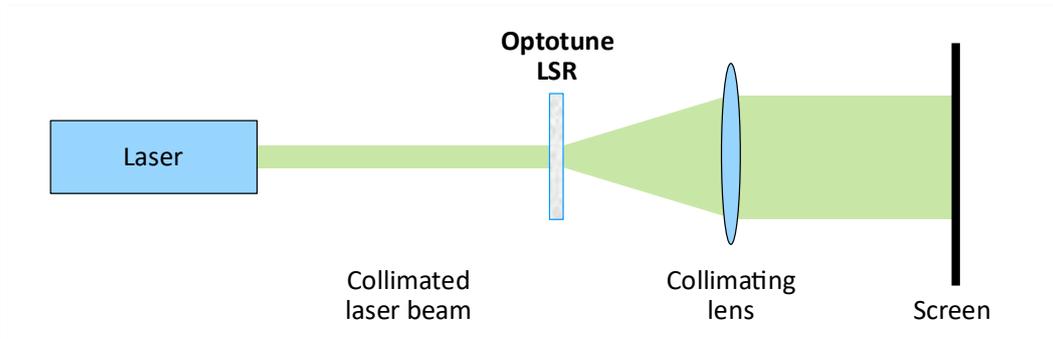


Figure 12: The LSR combined with a collimation lens, used to reduce the beam divergence.

5.2. 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, and 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 microlens array (MLA) might be needed, see Figure 13. A second advantage of an MLA is 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 the necessary averaging of speckle patterns can occur (e.g. a 100 μm spot size for a 20° diffuser with a $\sim 3 \mu\text{m}$ structure size). Note that in this case, no static diffuser is allowed.

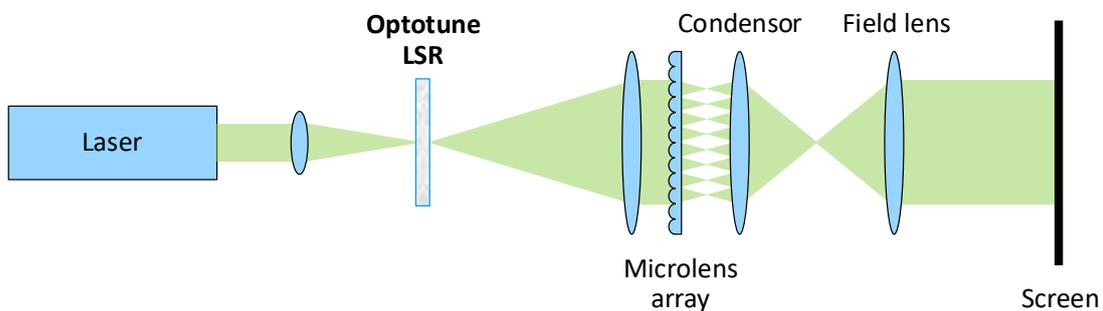


Figure 13: Optical layout with the LSR in the focal point of the laser, followed by a homogenizer.

5.3. 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 14 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.

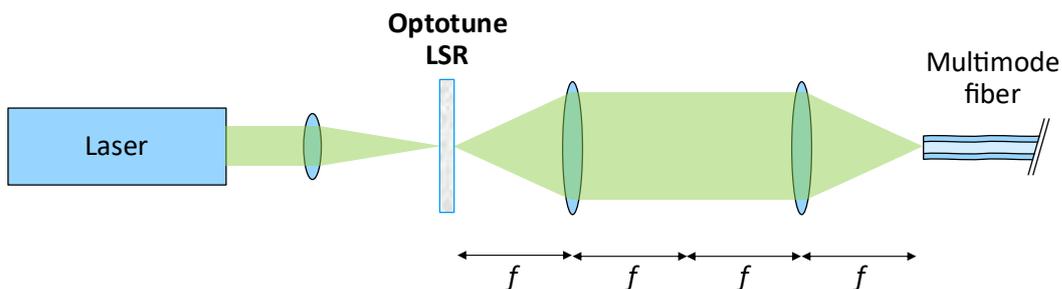


Figure 14: Optical layout for a fiber coupling solution with the LSR.

5.4. LSR in focal plane + fiber source, outcoupling via multimode fiber

The scheme in Figure 13 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 4f lens system and the spot on the LSR is then imaged on the second fiber with a second 4f lens system, see Figure 15. For good efficiency, the spot size on the diffuser should match 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.

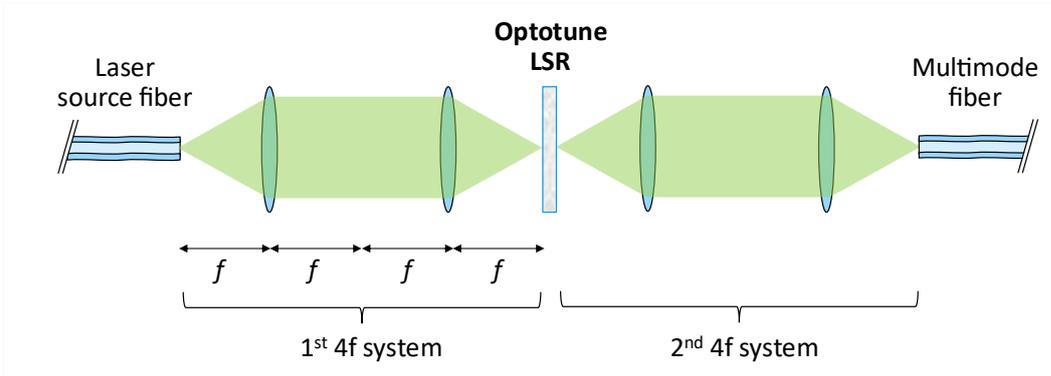


Figure 15: Optical layout for a fiber-to-fiber coupling solution with the LSR.

5.5. LSR for use with DLP/LCOS micro displays

In Figure 16 and Figure 17, two example setups integrating the LSR into a projection system based on digital light processing (DLP) displays or liquid crystal on silicon (LCOS) micro displays are shown. In Figure 16, the LSR is placed before the beam homogenizer such that a homogeneous, collimated and speckle-free beam impinges on the DLP/LCOS. In Figure 17, the LSR is placed after the DLP/LCOS such that a speckle-free beam impinges on the projection optics. The image stays in focus thanks to the minimal out-of-plane motion of the LSR.

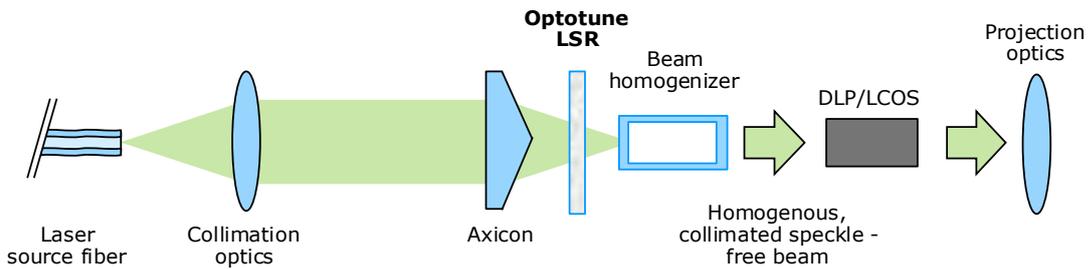


Figure 16: LSR positioned between a focusing axicon lens and the homogenizer to illuminate a DLP/LCOS with speckle-free light.

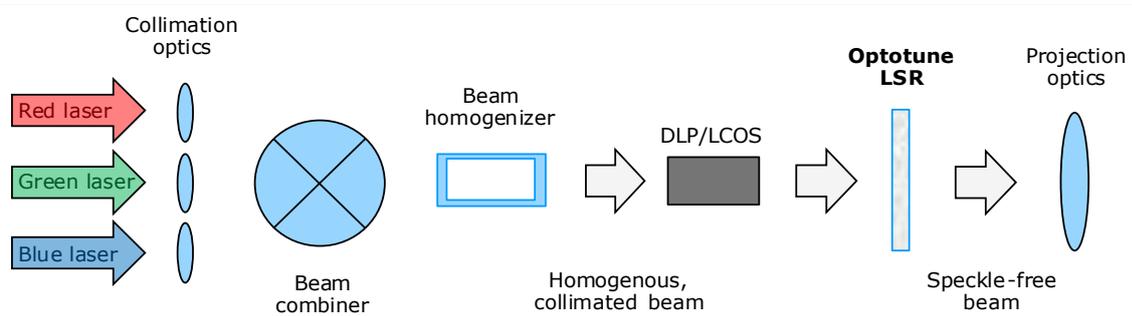


Figure 17: LSR positioned after the micro display in the image plane of projection optics, to illuminate the projection optics with a speckle-free beam.

For further information and support, please do not hesitate to contact us at sales@optotune.com.