Invited Paper

Reducing laser speckle with electroactive polymers actuators

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ABSTRACT

Laser light sources have inherent advantages in terms of brightness and low beam divergence. However, the coherence of lasers causes speckle to form on the target. In this paper, we show how electroactive polymers can provide a compact and energy-efficient solution to reduce laser speckles. The design parameters are discussed. The speckle reducers are characterized both mechanically and optically. Finally, a case-study is presented, illustrating the implementation of the speckle reducer into a compact laser projector system.

Keywords: Laser speckle reduction, electro-active polymers, laser projectors

1. INTRODUCTION

1.1 Lasers as light sources

Lasers are bright and unidirectional, two properties that are sought after in many optical systems. When compared to conventional illuminations systems, laser have both a broader colour spectrum and a higher lifetime. Lasers also inherently come with a high degree of coherence, a property that is widely used in many scientific systems such as interferometers. In applications where lasers are purely used as a light source, however, optical coherence leads to a significant drawback in the form of speckles. On microscopically rough optical surfaces such as a wall or a cinema screen, local interferences occur which are observed as a grainy pattern of spots. This effect causes noise in projected images and reduces the resolution of measurement systems (1).

1.2 Methods to reduce speckles

Several approaches can be used to tackle the problem of speckles. Moving diffusers destroy the temporal and spatial coherence of the laser and average out the speckle pattern and are an efficient way to reduce speckle in an optical projection system. However, for common rotating systems the required mechanics behind this principle limit miniaturization and are susceptible to faults due to continuous friction. Alternatively, laser light can be passed through a vibrating glass fiber or a bundle of fibers of different lengths to destroy the coherence of the laser, although the practical implementation of these solutions in small projectors is challenging. A mechanically stable and compact solution can be realized using broadband lasers, i.e. lasers with lower coherence. However, this comes at the cost of lower specific brightness, one of the primary arguments to use lasers in the first place.

1.3 Electro-active polymers

Optotune has developed a laser speckle reducer by combining the efficient speckle reduction method moving diffuser with Electro-active polymers (EAP) as actuators technology to enable minimal mechanical friction and wear.

Electro-active polymers consist in an electrically isolating (dielectric) elastomer where each side has been coated with a conductive sheet (2). By applying voltage across the sheets, electrostatic forces compress the elastomer which in turn expands laterally. Due to the large elongations attainable with elastomers, the lateral expansion can be quite big given the actuator size.

For the speckle problem, the large travel range obtainable from an EAP actuator is key, as it allows a compact yet effective means to reduce speckles. Another advantage of using electro-active polymers is energy efficiency. Due to its electrostatic nature, only small amounts of power are required to drive the actuator. Ohmic losses occur only during charge and discharge of the capacitors, and a minor amount of leakage currents happens through the polymer itself. Compared to rotating actuators, the EAPs are near frictionless, guaranteeing high energy efficiency and long lifetime.

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The biggest advantage of all may be integration: the electro-active polymer is not only the actuator, but functions also as the support structure for the optical diffuser and the compliant element of the resonant mass-spring-damper system. By fulfilling three roles with one element, the complexity and size of the whole system is elegantly minimized.

2. DESIGN

The principle of operation of the EAP-based speckle reducer is conceptually described in Figure 1. A circular diffuser is suspended to a transparent membrane. The membrane is coated with four conductive areas surrounding the diffuser and a ground electrode on the backside. The actuators are activated in a round-robin fashion, generating a circular motion of the diffuser in the center of the membrane. By driving the actuators at the natural mechanical resonant frequency of the system, the amplitude of motion of the diffuser can be maximized, which in turn maximizes the speckle reduction.

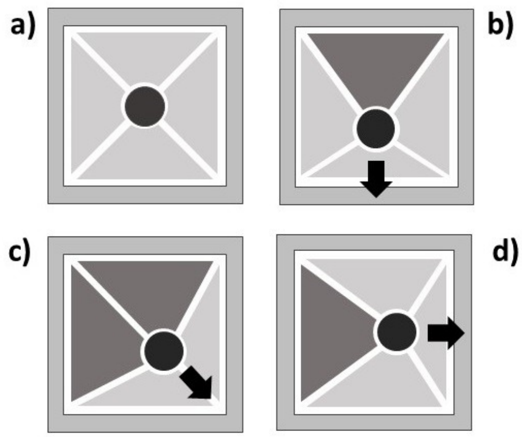


Figure 1. Laser speckle reduction concept. A diffuser (black) is suspended on an elastomer membrane (white). The membrane is coated on both sides with conductive layers that form four electrodes (light gray). By applying voltage to individual electrodes (dark gray), the diffuser is moved away from the electrode due to the lateral expansion of the compressed elastomer. A) Position at rest. B) Vertical diffuser motion. C) Diagonal motion. D) Horizontal motion.

An embodiment of the design is depicted in Figure 2. The system is powered by a 5V input voltage from a micro-USB cable. The printed circuit board (PCB) contains the control electronics that delivers the signals to the four independent electrodes.

2.1 Maximizing speckle reduction efficiency

Essentially, the efficiency of the speckle reduction is maximized when the incoming beam travels over many diffuser structures during the integration period. Four main parameters contribute to an efficient speckle reducer:

1. The motion speed of the diffuser
2. The diffuser's structure
3. The exposure time of the observer/camera
4. The optical system layout (beam diameter, position of the LSR, f-number, additional optics)

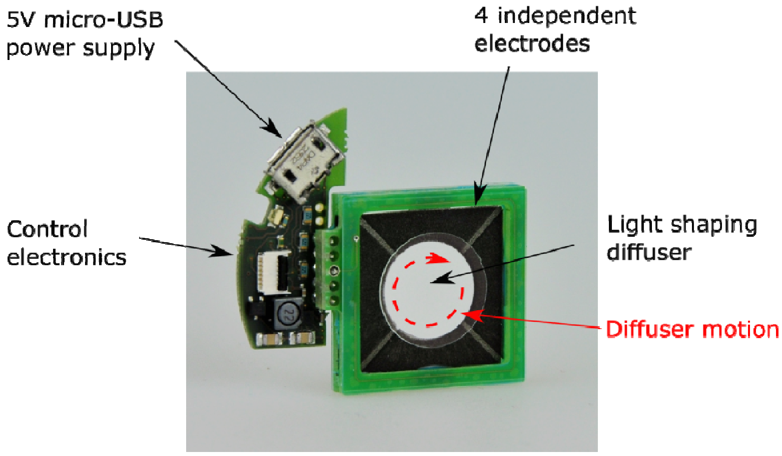


Figure 2. Laser speckle reducer LSR-3010. The clear aperture is Ø10mm. The four electrodes surround the clear aperture. The membrane is held by the green PCB frame. Control electronics transform the incoming 5V into higher voltage, dynamic signals delivered to each electrode independently.

2.2 High motion speed

Motion speed of the diffuser is obtained by increasing either the frequency or the amplitude of the diffuser's path. The frequency can be increased by using a higher membrane stiffness, or a lower mass. The motion amplitude is typically dictated by the actuator's voltage. Actuation at mechanical resonance frequency increases the amplitude drastically. There are many tradeoffs to be made between motion amplitude, frequency, size of the LSR, material parameters, weight of the diffuser and maximum voltage. For instance, a larger actuator increases the force and amplitude, but also increases the chance of a defect in the membrane, leading to an electrical breakthrough. The optimal design is therefore highly dependent on the exact application.

2.3 Diffuser structure

The speckle reduction efficiency is proportional to the number of uncorrelated structures passing through a point during the exposure period. Therefore, by reducing the size of the patterns, this number can be increased. Note that a smaller structure size will result in a larger diffusion angle which in turn leads to a larger beam divergence. We discuss options to reduce beam divergence in the final section of this paper.

2.4 Exposure time

Maximizing the exposure time leaves more time for the diffuser to move. Note however that after one full turn of the diffuser, the speckle reduction doesn't improve much, because it is essentially the same patterns that are being traversed a second time.

2.5 Optical system layout

The way the speckle reducer is integrated into the optical system layout has a large influence on its performance (3).

3. CHARACTERIZATION

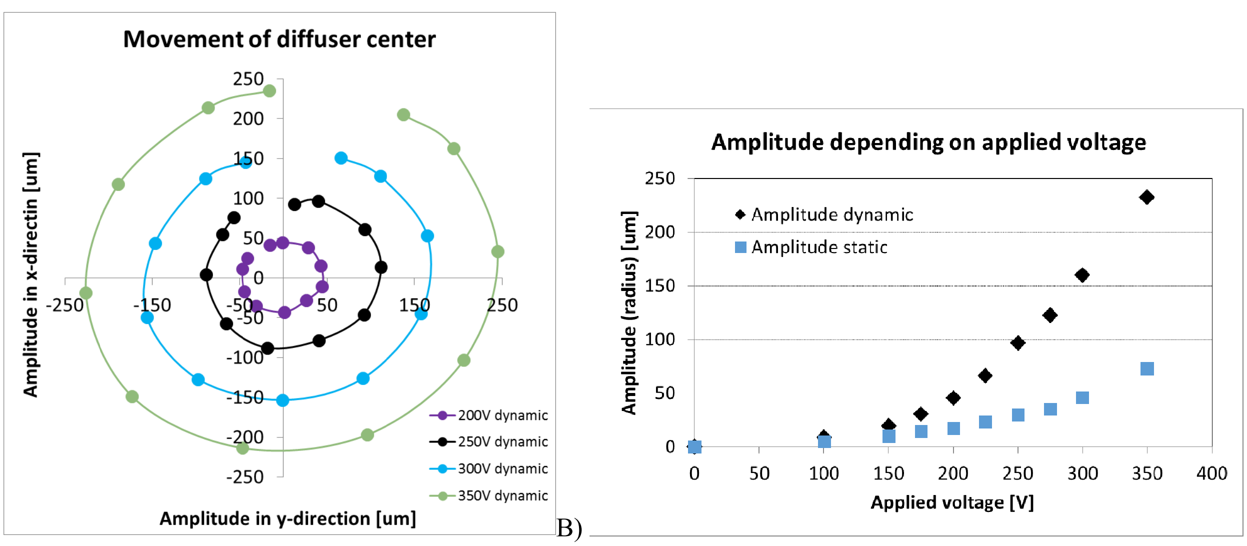
Key mechanical, electrical and optical specifications for two of the most common sizes of the speckle reducers produced by Optotune are given in Table 1. Apart from the aperture size, the main difference lies in the resonant frequencies, which are higher for the smaller speckle reducer, and the oscillation amplitudes, which are larger for the larger speckle reducer. More detailed information can be found in (4).

	LSR-5-17	LSR-10-22	
Mechanical specifications			
Clear aperture	5	10	mm
External dimensions (WxHxD)	17x17x3.8	22x22x3.8	mm
Weight (LSR only / including electronics)	1.44/2.50	2.18/3.24	g
Electrical specifications			
Power supply (micro-USB interface)	5	5	VDC
Power consumption (with std. electronics)	310	310	mW
Electrode capacitance	75	120	pF
Optical specifications			
Diffusion angle (FWHM)	6°/12°/17°/24°	6°/12°/17°/24°	
Damage threshold	>300	>300	W/cm^2
Oscillation frequency	~300	~180	Hz
Oscillation amplitude (peak to peak)	~300	~400	µm
Thermal specifications			
Storage temperature	[-40,+85]	[-40,+85]	°C
Operating temperature	[-30,+85]	[-30,+85]	°C

Table 1. Key specifications of the two most common sizes of EAP based speckle reducers (clear aperture: Ø5mm and Ø10mm)

Figure 3A shows the diffuser path, for different applied voltages. The motion range can achieve about 500µm peak to peak for a voltage of 350V across the membrane. In Figure 3B, the achievable motion of the diffuser is compared in static (non-resonant) and dynamic (resonant) modes. Thanks to the resonant actuation, the radius of motion is increased by a factor 2X to 3.5X, markedly increasing the speckle reduction efficiency. At higher voltages, electrical breakthrough across the membrane may occur.

A)



B)

Figure 3: A): Diffuser path vs actuator voltage for a LSR-10-22 speckle reducer. B) Comparison of achievable motion amplitude in resonant (dynamic) and non-resonant (static) actuation modes.

3.1 Speckle reduction efficiency

The achievable speckle reduction efficiency is highly dependent on the integration of the speckle reducer in the optical system. Many factors play a role: the incoming light, the chosen diffuser, the optical system setup surrounding the speckle reducer, and the way the light is recorded. It is therefore difficult to compare the efficiency of speckle reducers unless they are measured on the same system. We have developed a standardized test setup to make quantitative measurements of speckle reduction efficiency. The details of the setup can be found in (5).

Figure *4* shows measurement results on the standardized test setup. A speckle reduction

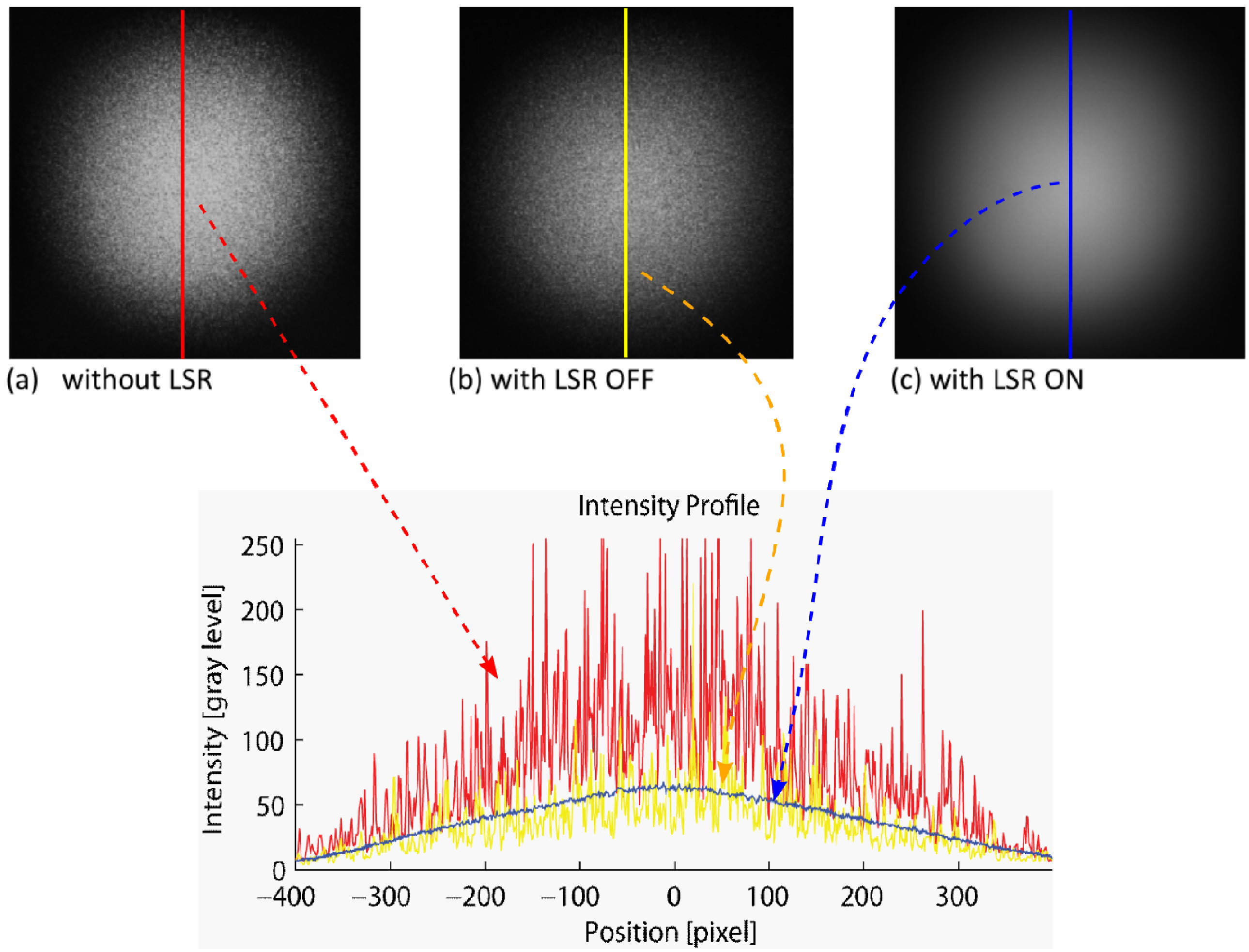


Figure 4 Measurement of speckle reduction efficiency on our standardized test setup. A) speckle pattern with no laser speckle reducer B) speckle pattern with LSR off (the static diffuser already reduces speckles) C) speckle pattern with LSR on. Graph below: Profiles for each of the three images are analyzed and compared quantitatively.

4. CASE STUDY: IMPLEMENTATION IN A LASER PROJECTOR

4.1 Integration of diffuser-based speckle reducers

Whenever a diffuser is introduced in an optical system, the outgoing beam will diverge. To avoid beam divergence, an additionally lens can be introduced into the system (see Figure 5).

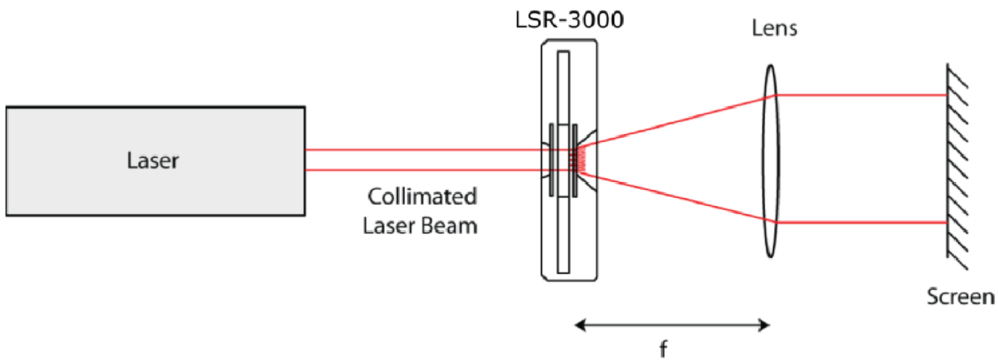


Figure 5 Simplified pseudo-collimation of output beam.

It must be noted that such a setup does not yield a truly collimated output beam. Each individual diffuser structure scatters light and is therefore a new point source for the outgoing light. A truly collimated output can be achieved in several ways. It is outside of the scope of this paper to cover all of these options, so the interested reader is directed to (5)& (6) for a detailed review. However, we will focus on one case-study where collimated output is desired, namely the usage of the speckle reducer in a laser projector system.

4.2 Laser projector case study

In this case study, a commonly faced problem is described. An integrator wants to build a laser based projector system to take advantage of the high luminosity of the laser. However, the speckles are ruining the output image. To achieve a highly collimated and homogenous beam, an elegant solution can be found in the combination of an axicon, a speckle reducer and a beam homogenizer. The setup is described in Figure 6.

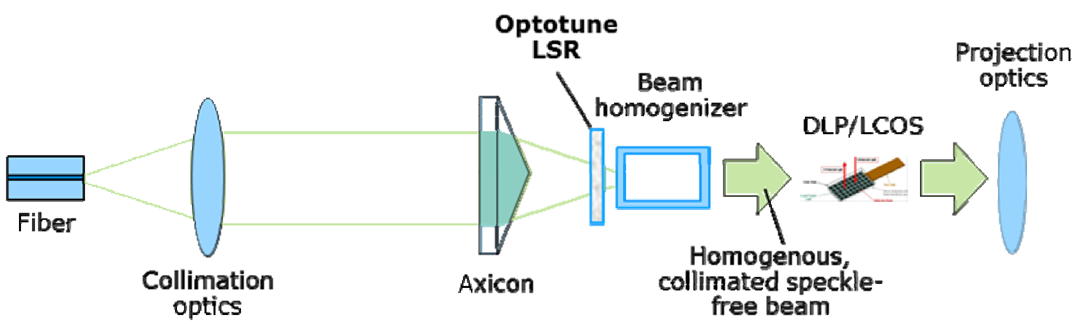


Figure 6: LSR is positioned between a focusing axicon lens and the homogenizer to illuminate the DLP/LCOS with speckle-free light.

The axicon is a special lens that provides a uniform angle distribution output beam from the typical Gaussian distribution. The LSR reduces coherence, and the beam homogenizer outputs a uniform light field energy distribution to the DLP /LCOS systems that form the image.

Figure 7 shows an embodiment of the concept based on off-the-shelve components. Figure 8 compares the image quality with and without the speckle reducer.

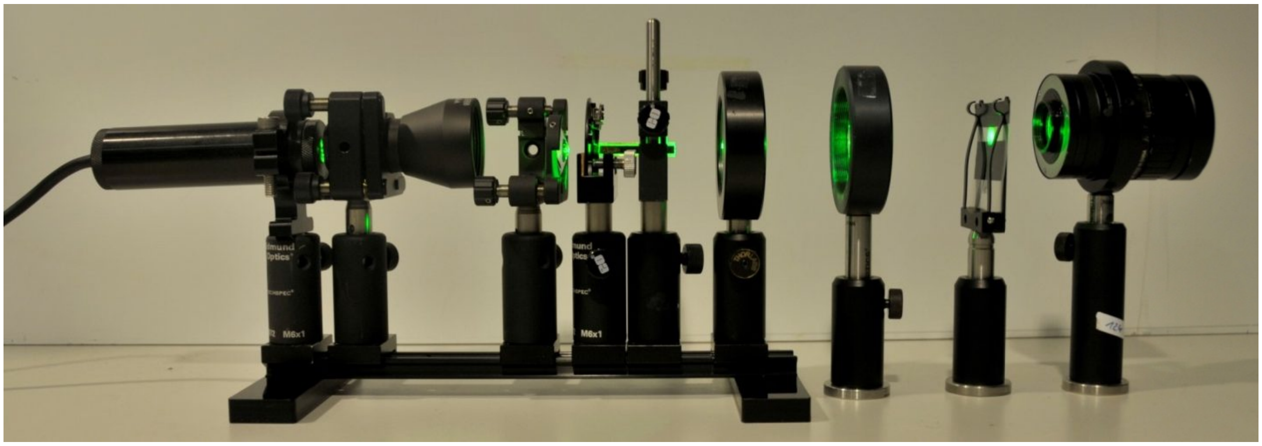


Figure 7 Speckle free laser projector using off-the-shelve components.

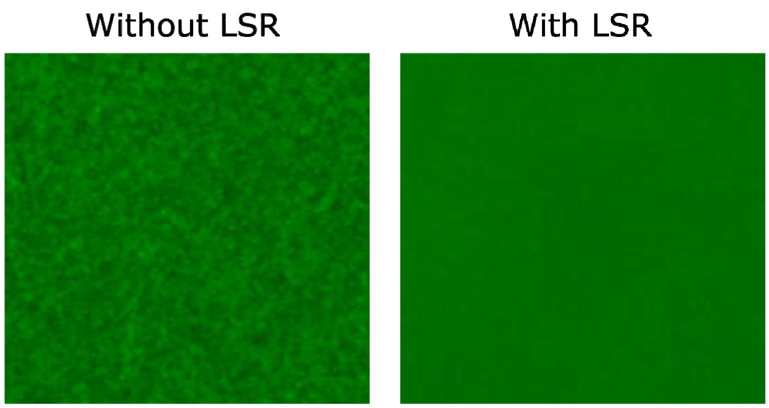


Figure 8 Resulting image, with no speckle reducer and with LSR speckle reducer

5. DISCUSSION & CONCLUSION

5.1 EAPs

Electro active polymer actuators have a set of unique properties that allow tightly integrated designs. In this application, the electro active polymer membrane fulfilled three roles: actuation, mechanical support of the diffuser, and elastic return element for operation at resonance. This has allowed the design to be significantly shrunk down in size compared to other approaches. Of course, whenever a component has multiple roles, it can be challenging to fulfill all requirements concurrently. This has probably hindered more wide spread usage of electroactive polymers in commerciadl applications. We strongly believe, however, that with the right expertise in material science, optical, and mechanical engineering, solutions can be found where the benefits far outweigh any compromises.

5.2 Speckle reducers based on EAPs

As light sources based on lasers become more popular, a solution must be found for the inherent speckles. The Optotune speckle reducer provides a compact and robust solution that can be applied to miniature hand-held projectors all the way up to full-theater projection systems. This paper has explained the design, characterized the performance and presented a case-study of the integration of Optotune's laser speckle reducer technology.

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