Speckle Reduction II:
Laser Projection Without Speckle Noise? Experimental Investigation

Florian Dötzer*, Klaus Mantel**, Gerd Häusler*

**Institute of Optics, Information and Photonics, Friedrich-Alexander-Universität Erlangen-Nürnberg*
***Max Planck Institute for the Science of Light, Erlangen*

mailto: gerd.haeusler@fau.de

Theoretical considerations [1] show that instantaneous reduction of speckle noise is possible, even with laser illumination. Here we report about the experimental implementation. Incoherent beamlets are created from a single laser beam by exploiting its finite coherence length. We further discuss the information theoretical and technical costs.

1 Introduction

As pointed out in [1], the finite *temporal* coherence of lasers enables illumination with low *spatial* coherence, allowing the reduction of coherent noise. We investigate this speckle reduction method for the example of "scanning laser projection" [2]. Two possible implementations [3] are shown in Fig. 1.

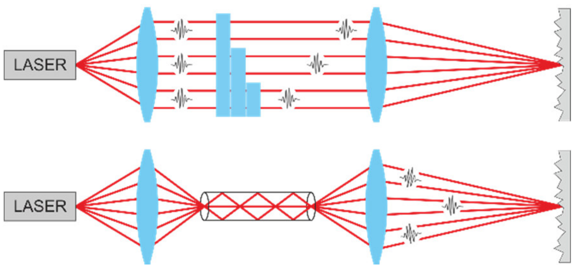

Fig. 1 *OPD via delay plates or a multimode fibre*

The basic idea is to fill the illumination pupil with mutually incoherent sources by introducing optical path differences (OPD) larger than the coherence length of the laser. The first implementation introduces the OPDs via a stack of glass plates with 3x3 sub-apertures. The second approach exploits the intermodal dispersion of a multimode fibre. Figure 2 displays two magnified images of a 62.5µm fibre core, illuminated by a laser with a long or short coherence length, respectively. If the coherence length is longer than the OPD between the modes, they superimpose coherently and form a speckle pattern. For a sufficiently short coherence length, there is incoherent superposition, resulting in a more homogeneous intensity distribution.

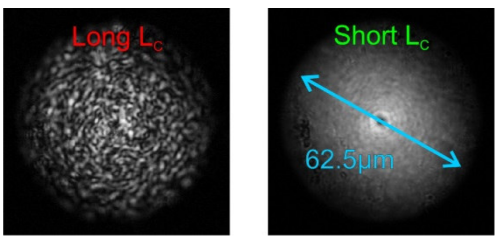

Fig. 2 *Intensity pattern at the output surface of a fibre*

For the speckle reduction experiments described in chapter 2 we use a different fibre with 10µm core diameter, an aperture of NA=0.1 and a length of 5m. This fibre then supports 7 modes (i.e. sub-apertures) and generates a total OPD of about 10mm.

How many sub-apertures (or modes) should be implemented for a given illumination- and observation aperture? This is a crucial question, because significant noise reduction demands for many sub-apertures. Where is the limit?

As illustrated in Fig. 3, each sub-aperture generates its own, separate diffraction pattern. More (smaller) sub-apertures within a given total aperture lead to a wider diffraction pattern at the screen. For sub-apertures smaller than the observation aperture, the corresponding loss of lateral resolution becomes disturbing for the observer.

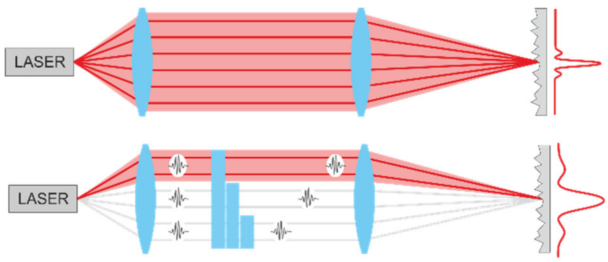

Fig. 3 *Diffraction patterns of total aperture & sub-aperture*

Moreover, coherence theory tells us that we cannot achieve a signal-to-noise ratio better than $SNR_{max} \sim \sin u_{ill} / \sin u_{obs}$ [4]. SNR_{max} is already reached when the sub-apertures are equal to the observation aperture. Smaller sub-apertures do not further improve the SNR, but only reduce the lateral resolution.

2 Experiments

We use a setup that mimics typical scanning laser projection. As sketched in Fig. 4, a 2D galvo-scanner projects a homogeneously illuminated "image" onto the screen and a camera mimics the observer.

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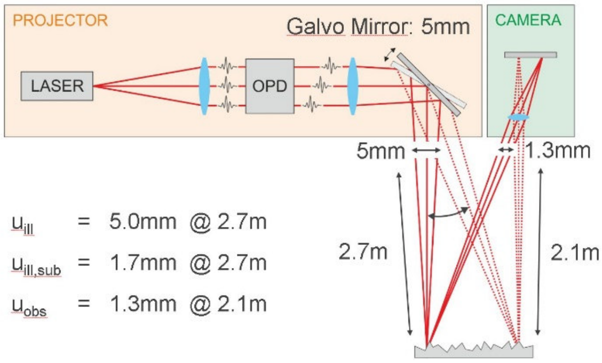

***Fig. 4** Setup, mimicking realistic laser projection*

As explained above, the sub-apertures were optimally chosen to match the observer aperture. To avoid gaps between the lines which could be misinterpreted as speckle contrast, the lines are projected densely, i.e. with a line spacing much smaller than the laser spot size. As the lines are projected time-sequentially, this already causes some incoherent averaging, even for a single sub-aperture. Simulations predict a speckle contrast of 50% in this case, which is accounted for in the evaluation of the measurements. Figure 5 displays the results of the speckle reduction experiments.

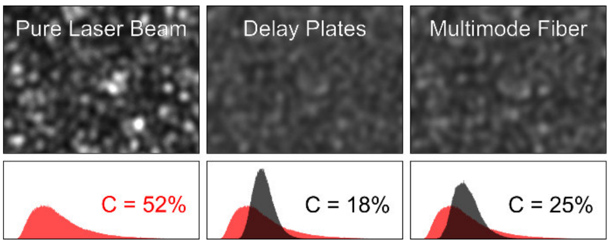

***Fig. 5** Speckle Pattern, intensity histogram and contrast*

Compared to the fully coherent laser illumination, we could reduce the speckle contrast by a factor of two (multimode fibre) and by a factor of three (delay plates).

The measured speckle contrast for the pure laser beam is in good agreement with the simulation. The speckle contrast obtained via the nine delay plates matches the expected value of $17\% = 52\%/\sqrt{9}$. The multimode fibre shows slightly higher contrast than expected for seven modes ($20\% = 52\%/\sqrt{7}$). A possible reason is that neither the laser power nor the path differences are distributed evenly among the fibre modes.

The experiments demonstrate that instantaneous speckle reduction is indeed possible with the proposed methods.

It should further be noted that only simple technology is required. There are no mechanically moving parts and only a single laser source is necessary.

3 Information- and Technological Limits

As discussed in [1], noise reduction is not for free. We have to introduce a large illumination etendue. In information-theoretical terms this means an excess channel capacity, which the observer cannot fully exploit. In fact, we trade in lateral resolution for a better signal-to-noise ratio. If we can accept this, it might be a good deal.

However, if we aim for “pico projectors” [2], the demanded large illumination aperture is a dealbreaker: The laser projector with noise reduction as described in [1] is designed for a pixel size of 1mm, an image size of $1x1m^2$ and 64 sub-apertures. The aperture of the human eye can be estimated to 3mm. To accommodate the 64 sub-apertures, an illumination aperture of 24mm is necessary. However, the effective illumination aperture is given by the diameter of the scanning mirror. Available scanning mirrors which achieve the necessary line frequency of 100 kHz have an aperture of at most 1mm [5]. Such a scanning mirror cannot provide the required large etendue, so one must sacrifice either SNR or image size and resolution. And, obviously, “a lens-less” projector without depth of field problems is no longer possible with a large illumination aperture.

4 Summary

It is experimentally demonstrated that instantaneous speckle reduction for scanning laser projectors is possible. The technology is simple and low cost, although the required large illumination etendue may cause some technological effort.

It should be emphasized that the basic idea, to reduce the spatial coherence by filling the illumination aperture with mutually incoherent laser beamlets, can be applied to non-scanning systems as well.

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