Low-speckle laser projection using farfield nonmodal laser emission of a semiconductor laser

G. Craggs,[1] F. Riechert,[2] Y. Meuret,[1] H. Thienpont,[1] U. Lemmer,[2] and G. Verschaffelt[1]

[1] Department of Applied Physics and Photonics, Vrije Universiteit Brussels, Belgium
[2] Light Technology Institute, Universität Karlsruhe, Germany

We investigate how the farfield of a broad-area vertical-cavity surface-emitting laser (BA-VCSEL) in its nonmodal emission regime can be used for low-speckle laser projection. A microlens beam homogenizer is used to exploit the low spatial coherence of the VCSEL's farfield in the nonmodal emission regime. Using farfield instead of nearfield illumination of the homogenizer has some important advantages for a practical projection system: the field emitted by the VCSEL can be directly projected onto the homogenizer without the need for additional lenses or accurate alignment. Speckle contrast values as low as 2.5% are measured and are in good agreement with modeled contrast values.

The use of lasers in projection applications has long been envisaged because it can lead to projectors with high color saturation, highly efficient optical engines and long lifetime of the light source. A major drawback however when using lasers in projection applications is the appearance of a quasi random interference pattern in projected images, referred to as the speckle pattern. Speckle is usually quantified via its contrast C. A fully coherent laser source normally produces speckle of contrast C = 1 which results in serious image degradation [4]. A speckle contrast of about 0.04 has to be achieved in order to make speckle non-disturbing for a human observer. Such low speckle contrasts are hard to obtain with laser sources, because they are typically highly coherent. Different possible methods for speckle reduction in laser projection applications are therefore of current research interest. In [2] we investigated speckle reduction in laser projection based on the low-coherence nonmodal emission regime of a broad area vertical-cavity surface-emitting laser (BA-VCSEL). We measured speckle contrast values as low as 3.5% by projecting the VCSEL's nearfield onto a microlens beam homogenizer. In this contribution we demonstrate that it is also possible to illuminate the homogenizer with the VCSEL's farfield [1]. Thus a number of disadvantages compared to illumination with the imaged nearfield are avoided [2], and at the same time low speckle contrast values can still be achieved. The modeling of the spatial coherence and intensity distribution of the farfield beam also differs from the nearfield case. We properly adapt the modeling of the speckle contrast reduction from [2] and compare the measured and modeled speckle contrast values.

The experimental setup is shown in Fig. 1. It is similar to the one used in [2], however we now directly illuminate the beam homogenizer with the VCSEL's farfield. We measure the speckle for a varying distance between the VCSEL and the homogenizer. In cw (modal) operation, we investigate the speckle at 16 mA (close to lasing threshold) and at 70 mA (close to thermall roll-over). In pulsed (nonmodal) operation of the VCSEL we use a pulse length of 2 μs, two different pulse amplitudes of 157 mA and 240 mA and a duty cycle of 4% in order to avoid any average heating of the VCSEL. The speckle contrast values are measured with a CCD camera that has a spatial resolution on the screen of about 1 mm, which is comparable to the spatial resolution of a human observer at a distance of approximately 3 m. We correct the captured speckle images for CCD-noise and for the contrast that shows up on the paper screen under room light illumination. The distance between VCSEL and homogenizer plays an important role for both the speckle contrast and the illumination uniformity. When we increase this distance, the number of illuminated lenslets in the homogenizer increases and hence an improvement of the illumination uniformity can be expected. The improvement of the speckle contrast is less obvious. We further investigate this effect by plotting the measured speckle contrast versus the distance between VCSEL and homogenizer for the different driving conditions in Fig. 2. It can be seen that the speckle contrast decreases with increasing cw driving current and with increasing current pulse amplitude in pulsed operation. The speckle contrast values in nonmodal operation are lower than the values achieved in cw operation. For all driving conditions, the speckle contrast first decreases with increasing distance between VCSEL and homogenizer, to then saturate for large distances.

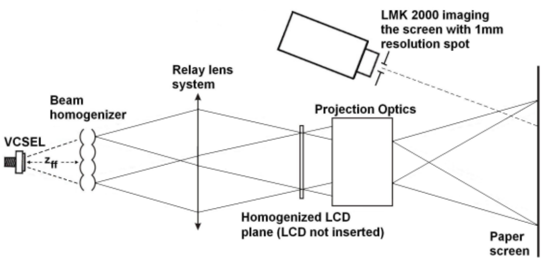

Figure 1: Schematic of the illumination setup

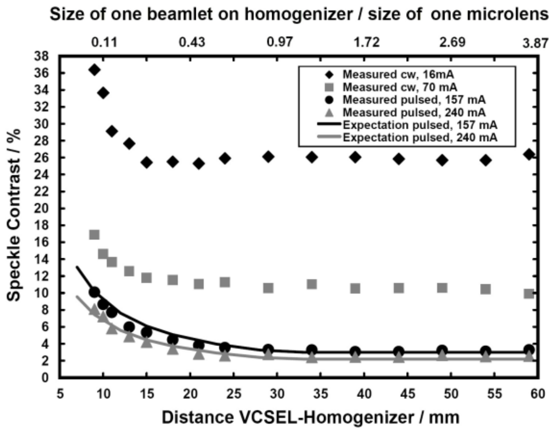

Figure 2: Measurement and modeling results

In our setup, three speckle contrast reducing effects play a major role and will be considered in the following model. As a first effect depolarization of the light backscattered from the paper screen results in a speckle contrast reduction in all setups, independent from the specific driving and illumination conditions. The second effect is the thermal chirp of the VCSEL's emission wavelength in pulsed operation. This chirp - and hence the related speckle reduction - increases with the amount of heat dissipated in the cavity. The resulting speckle contrast reduction is thus larger for larger pulse amplitudes and pulse lengths. We determined the contrast reduction factors resulting from the wavelength chirp in [2] to be 0.68 for the 157 mA pulses and 0.50 for the 240 mA pulses. In third instance, the reduced spatial coherence has to be taken into account. The spatial coherence cannot easily be modeled for cw operation because the VCSEL emits a large number of transverse modes and it is difficult to accurately measure the intensity distribution of these modes. The number of lasing transverse modes increases (up until the thermal roll-over at 70 mA) with increasing driving current. Wolf has shown that the spatial coherence decreases with an increased number of transverse modes contributing to the emission. Therefore, we expect the speckle contrast to decrease with increasing driving current, which is clearly visible in Fig. 2. In order to model the speckle contrast reduction due to reduced spatial coherence in nonmodal operation we need to take into account the characteristics of the VCSEL's farfield. The nonmodal VCSEL has a Gaussian farfield intensity distribution and its half-width farfield divergence angle is 11° [3]. The half- width farfield coherence angle is 0.6° as has been determined from the nearfield intensity distribution [3]. Therefore the farfield beam can be modeled as consisting of approximately 340 beamlets that are all mutually incoherent. Each beamlet produces a speckle pattern and these patterns add on intensity basis because of the incoherence of the beamlets. If a large number of quasi-random interference patterns are superimposed, the result is a more homogeneous intensity distribution with lower contrast. However, in order to achieve speckle contrast reduction, the speckle patterns from different beamlets have to show different intensity distributions, i.e. they have to be at least partly decorrelated. In our case the intensity of the individual beamlets depends on their radial position in the beam, which can easily be determined from the Gaussian shape of the farfield intensity distribution. If different beamlets pass through different microlenses of the homogenizer, the speckle patterns of these beamlets are superimposed on the screen under slightly different angles and are therefore at least partly decorrelated. This angular difference is inversely proportional to the magnification of the projection lens in Fig. 1. In our setup, the magnification is such that the angle between beamlets originating from adjacent microlenses is 0.16°. For a purely surface scattering screen, the necessary angular difference for full decorrelation can easily be calculated from the numerical aperture of the imaging system (0.6×10^{-3} in our setup). This results in a minimally required angular difference of 0.069° in our setup [2]. We measured this minimally required angle for full decorrelation and found that it is only 0.017° for the used paper screen. The angle is smaller than expected for pure surface scattering because the used screen is a volume scatterer. In that case, photons do a random walk inside the screen material prior to being re-emitted towards the imaging system. This random walk leads to a much faster decorrelation of the speckle patterns when changing the illumination angle and hence the minimally required angle for full decorrelation decreases and is much smaller than the angular difference provided in our setup.

If a beamlet is larger than one microlens, this beamlet will still generate only one speckle pattern. Furthermore, if multiple beamlets pass through a single lens, their speckle patterns are non- overlapping on the screen and will not contribute to speckle contrast reduction. The speckle contrast reduction is therefore determined by the amount of lenses in the homogenizer that are illuminated by different beamlets. Thus the size of the beamlets, i.e. their coherence radius, at the position of the homogenizer is critical in determining the resulting speckle contrast. Using this size, the Gaussian intensity profile in the farfield and taking into account the intensity variation of the beamlets, we are able to calculate the expected speckle contrast resulting from the reduced spatial coherence. In order to determine the overall speckle contrast reduction, the three individual contrast reduction factors need to be multiplied. The total calculated speckle contrast is plotted in Fig. 2 for the two investigated pulse amplitudes. The calculated speckle contrasts correspond well with the measured values, and our modeling allows us to explain the experimentally observed trends. The size of a single rectangular microlens of the beam homogenizer is approximately 570 µm x 570 µm. For a small distance between VCSEL and homogenizer, the size of a beamlet on the homogenizer is smaller than the size of a single microlens and thus several beamlets fall into each microlens. If the distance is increased, the coherence radius increases such that more lenses in the homogenizer are illuminated by uncorrelated coherence islands and the resulting speckle contrast decreases. The size of one beamlet divided by the size of one microlens of the beam homogenizer is given in Fig. 2 on the secondary x-axis. When the size of the beamlets becomes larger than the size of the microlenses, no further speckle reduction can be achieved. The maximum speckle contrast reduction is then determined by the number of beamlets and not by the number of illuminated lenses. Therefore, the speckle contrast remains constant for distances larger than 30.5 mm.

In conclusion, we demonstrated and modeled low-speckle laser projection with a broad area VCSEL in the nonmodal emission regime by directly projecting its farfield onto a microlens beam homogenizer. We achieved speckle contrast values as low as 2.5% without using any moving or rotating components to eliminate the coherence of the laser. We profit from the specific nonmodal emission regime [1,5] and use the beam homogenizer to decorrelate the speckle patterns created by the VCSEL's beamlets. By properly tuning the distance between VCSEL and homogenizer, we can choose the size of the beamlets on the homogenizer. Each beamlet has to be larger than one microlens of the homogenizer in order to exploit the full potential of the VCSEL's low spatial coherence. We obtain good agreement between the model and the measured speckle contrast values. However, the used VCSEL emits at a wavelength of 840 nm. An important future task is therefore to investigate whether visible lasers can be driven into the nonmodal emission regime too.

References

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