Spatial coherence properties of a broad-area Vertical-cavity Surface-Emitting Laser in the incoherent emission regime

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We present measurements of the spatial coherence area of a Broad-Area Vertical-Cavity Surface-Emitting Laser (BA-VCSEL) when it is driven into a regime of spatially incoherent, non-modal emission. This emission regime can be reached by driving the BA-VCSEL with microsecond pulses. This incoherent emission can be understood as emission in multiple, independent, spatially separated coherence islands. Such a high-power, spatially incoherent emission regime is quite uncommon for semiconductor lasers but can be useful in e.g. illumination and projection systems, as the low degree of spatial coherence may help to reduce speckle.

Introduction

In [3] it was shown that a strong reduction of spatial coherence occurs when driving BA-VCSELs with μs-pulses. This special emission property coincides with an apparent breakdown of the globally defined transverse modal profile which typically characterises the BA-VCSEL. This incoherent or non-modal emission can be understood as emission in multiple, independent, spatially separated coherence islands. In [4] it is shown that there is a dynamic transition during the first few hundreds of nanoseconds of the pulse from modal to incoherent emission. The transition takes place on the thermal time-scale of the VCSEL. During this transition the far-field intensity profile evolves from a modal, structured pattern into a Gaussian shaped profile.
This high-power, spatially incoherent emission regime is quite uncommon for semiconductor lasers but can be useful in e.g. illumination and projection applications as the low degree of spatial coherence may help to reduce speckle. In this contribution we present measurements of the spatial coherence area for different positions in the VCSEL aperture using a reversing wavefront interferometer. Furthermore we will discuss in how far the measured coherence radius is limited by the quasi-mode size of a planar cavity.

Setup

The laser we use in our measurements is an oxide confined BA-VCSEL, very similar to the device used in [3]. We also use the same pulse conditions as described in [3] to induce non-modal, spatially incoherent emission. In order to measure the spatial coherence properties of the VCSEL we use a wavefront reversing Michelson interferometer [5, 6].

In each arm of the interferometer, a right-angle prism is used to reflect the beam. In one arm, the beam is flipped horizontally while being reflected by the prism, whereas in the other arm the beam is flipped vertically. Therefore, the two beams interfering at the CCD are effectively spatially rotated 180 degrees with respect to each other. In our setup we thus measure the correlation between radially symmetric points. The setup is discussed in full detail in [1].
Employing this setup, the complex degree of coherence μ can be deduced by recording four images. First, we record the interference pattern I_t^0 when both arms of the interferometer have equal lengths. Next we measure the interference pattern $I_t^{\lambda/4}$ when one of the arms is shifted by a quarter wavelength. We subsequently record the intensity distribution I_0^H when one arm is blocked and I_0^V when the other arm is blocked. Finally, the magnitude of the complex degree of coherence can be calculated as described in [6].
In the following paragraph we will discuss the results obtained from the calculation of the magnitude of the complex degree of coherence. A detailed analysis can be found in [1].

Degree of coherence

Where the beams orginating from both interferometer arms overlap, $|\mu|$ is only large close to the correlation measurement's center. This is in stark contrast to what we obtain in case of modal emission: each of the transverse modes is fully coherent over itself, which results in interference fringes and a non-zero value for $|\mu|$ all over the VCSEL aperture. In CW operation the VCSEL emits a multitude of transverse modes which partly overlap with each other. As a result, $|\mu|$ is non zero at most positions across the area of the VCSEL's emission, exhibiting a complex pattern of mutually coherent spots.
We characterize the extent of $|\mu|$ using the coherence radius ξ at which $|\mu|$ has decreased by $1/e^2$ compared to its value at the correlation measurement's center. To estimate the value of ξ and at the same time investigate the shape of $|\mu|$, we fit a transverse cut of $|\mu|$ through the correlation measurement's center to a Gaussian function. This allows us to determine the coherence radius ξ, yielding a value of 1.91 µm. The coherence radius is thus clearly much smaller than the VCSEL's aperture radius of 25 µm.
We repeat the measurement of $|\mu|$ for different positions of the correlation measurement's center within the VCSEL aperture. The values of the coherence radius ξ that we are thus able to extract show that the coherence radius ξ is not constant across the entire VCSEL aperture, but that it decreases towards the rim of the device. The intensity and area weighted average of the coherence area yields a value $\xi_{average}$ of 1.4 µm. The coherence radius remains in between 1 µm and 2 µm for all positions. If we compare this to the near-field intensity distribution we can see that the intensity does not change drastically over distances of the dimension of the coherence radius. Therefore, we can indeed consider the source to be quasi-homogeneous with a Gaussian shaped coherence function.

Quasi-mode size

Based on the previous sections we are able to conclude that our pulsed BA-VCSEL is indeed a partially-coherent quasi-homogeneous source with a Gaussian shaped coherence function. In [4] it is proposed that the loss of modal emission is due to the fast thermal chirp of the VCSEL's cavity during the pulse, which - in combination with a spatially distributed thermal lens - prevents the build-up of cavity modes. However, this does not

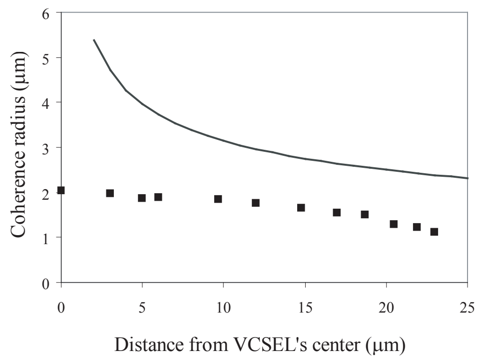

Figure 1: Coherence radius ξ as a function of the position within the VCSEL aperture (squares) and comparison with the quasi-mode size (full line).

explain why we obtain a coherence radius of approximately 1.4 µm or, equivalently, a far-field divergence angle of 11 degrees.
In order to understand by which mechanisms the coherence area is being limited we have considered the approach taken by [7–9]. This approach defines the mode size in a planar cavity, taking into account diffraction in the cold cavity. Starting from a planar cavity implies neglecting the boundary conditions imposed by the oxide aperture at the outer rim of the device. This seems to be a good approximation since the coherence radius ξ is much smaller than the device's aperture radius *R*. The assumption of a cold cavity neglects the influence of spatial carrier distribution. In addition, dynamical effects are neglected, as a full dynamical study requires microscopic modeling of the semiconductor medium and a spatially resolved treatment of the cavity. This is beyond the scope of this manuscript. Nevertheless, the consideration presented here and fully explained in [1] provides an upper limit for the expected coherence radii and allows to evaluate the importance of the considered mechanism. We start from the mode size in a planar cavity [9]. For our experimental driving conditions the VCSEL exhibits a considerable gradient in refractive index because of inhomogeneous current injection and Joule heating [10]. This spatially distributed thermal gradient induces an emission wavelength shift, which we need to take into account once it becomes comparable to the linewidth attributed to the modes as described in [7].
The mode size is plotted in Fig. 1, together with the measured coherence radius for different radial positions. We obtain an upper limit for the coherence radii of the order of 4 µm. This is already one order of magnitude smaller than the laser aperture, indicating that the spatial coherence properties have significantly changed compared to modal emission. We note that the measured coherence radii are still about a factor of 2 smaller than this upper limit. This indicates that additional mechanisms, including the afore mentioned spatial carrier distribution and dynamical effects, further contribute to the decrease of the mode size. Nevertheless, our simplified considerations illustrate the limits of the mode-size imposed by diffraction in a cavity with a strong refractive index profile. According to our estimates the coherence radius increases strongly towards the center of the VCSEL's aperture. This is in contrast to our experimental findings where the coherence radius is homogeneous across the device aperture, with only a slight decay towards the rim. The origin of this is still unclear, however we emphasize that the behavior of the VCSEL's

central part has a small effect on the overall characteristics of the device: it will only contribute to the total emission for a small amount as both the emitted power density and the emission area are smallest in this region.

Conclusion

We have used a 180 degrees reversing wavefront Michelson interferometer to measure the complex degree of coherence of a BA-VCSEL with an aperture diameter of 50 μm. The BA-VCSEL was driven into a spatially incoherent emission regime that can be obtained by strongly pulsing these devices. Our measurements show that in this regime the VCSEL can be considered a quasi-homogeneous source with a Gaussian shaped coherence function. The extracted coherence radius varies slightly within the VCSEL's aperture, but always remains small compared to the aperture size. The Gaussian shape of the coherence function manifests itself in a Gaussian intensity distribution in the far-field. The average coherence area of 1.4 μm corresponds well with the measured far-field divergence angle of 11 degrees [3]. Our approach can also be used to measure the spatial coherence properties of other sources and might e.g. be useful to measure the build-up of spatial coherence in coherent VCSEL arrays [11].
The coherence area or mode size is limited because of the thermal gradient within the VCSEL aperture. The thermal gradient results in a radial wavelength shift that prevents the modes to grow beyond a few microns. The derived mode size is only weakly dependent on the pulse parameters and the VCSEL's structure. The proposed model can not fully explain the particular size of the measured coherence area, but rather it provides an upper limit for the coherence area. In practice, the measured coherence area is even smaller and much more uniform across the VCSEL aperture than expected from the model, which is promising for applications that make use of the VCSEL's quasi-homogeneous properties. These results are important to better understand the behavior of BA-VCSELs as partially coherent light sources. Such high-power primary sources of spatially incoherent radiation can be useful as the low degree of spatial coherence may help to reduce speckle. The small size of the coherence radius is beneficial for speckle reduction, as each spatially uncorrelated region can in principle lead to the formation of an independent speckle pattern.

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