Evolution of multi-mode operation in vertical-external-cavity surface-emitting lasers

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Abstract: The longitudinal multi-mode emission in a vertical-external-cavity surface-emitting laser is investigated using both single shot streak camera measurements and interferometric measurement techniques. For this, the laser is operated in the single- and two-color emission regime using both an etalon and a free-running configuration without etalon, respectively. The laser emission is analyzed with respect to pump power and output coupling losses for a long and for a short resonator. We observe a steep increase of emission bandwidth close to the laser threshold and monitor the transition between longitudinal single- and multi-mode operation. Additionally, the results indicate that a stable two-color operation is related to a sufficiently high number of oscillating longitudinal modes within each color.

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1. Introduction

In recent years, vertical-external-cavity surface-emitting lasers (VECSELs) have attracted much scientific interest [1–3]. Beside their compactness and their ability for high power operation, these lasers also provide an excellent output beam quality [1,4,5]. Moreover, a large range of emission wavelengths starting from the visible to the mid infrared can be realized using appropriate semiconductor materials for the active region [2,3]. These features make VECSELs interesting for a variety of research fields like mode-locking [6–10], single-frequency emission [11–13] and power scaling [14,15]. Due to potentially high intra-cavity powers, a VECSEL is furthermore ideally suited for intra-cavity frequency conversion processes [16–18].

Many applications, particularly in the field of spectroscopy, require single-frequency emission, which – in most cases – is obtained by using a birefringent filter placed inside the resonator. Nevertheless, at some point, a transition to multi-mode operation (longitudinal as well as transverse) is observed with increasing pump power [13]. Without any intra-cavity filter, a VECSEL tends to operate in a longitudinal multi-mode regime, at least if the resonator is sufficiently long. Even with the use of an additional filter such as an etalon, the laser emission still is longitudinally multi-mode in most cases. Moreover, it has been shown that by inserting an etalon inside the cavity or by utilizing an external diffraction grating [19] the VECSEL can be forced into two-color emission. This configuration can be utilized for the generation of continuous wave terahertz (THz) radiation making use of intra-cavity difference frequency generation (DFG) inside a lithium niobate crystal [20]. In this case, the emission is condensed into two spectral lines (i.e. two colors) which are typically separated by a few nanometers with at least one longitudinal mode within each color. Especially for the generation of terahertz waves, the number of longitudinal modes involved matters as their
beat signal is directly transformed into the THz spectrum. Moreover, a stable two-color emission is absolutely crucial in order to achieve high conversion efficiencies.

In this context, a first study on the temporal emission dynamics of a two-color VECSEL was performed using a streak camera to characterize the laser emission [21]. Therein, a strong dependence of the two-color emission stability on the applied pump power was observed. Nevertheless, the underlying mechanism for the observed behavior deserves further investigation. Thus, a thorough experimental study focusing on the dynamics and the evolution of multi-mode operation in a VECSEL is of great importance. This will provide a deeper understanding of the phenomenon and helps to derive boundary conditions for efficient difference frequency generation via two-color lasing inside a VECSEL cavity.

Here, we present detailed investigations on the VECSEL longitudinal multi-mode emission performing both streak camera measurements and interferometric measurement techniques. The laser emission is analyzed in dependence on the pump power employing two different cavity designs as well as various output couplers. Close to the laser threshold, we observe a steep increase of emission bandwidth whereas only minor bandwidth-changes are noted at higher powers. Furthermore, we find that output-coupling losses mainly affect the laser emission when no intra-cavity filter is in use. Additionally, we observe that in our setup a stable two-color lasing, in which the two colors share the same gain region on the chip, is related to a sufficiently high number of longitudinal modes participating in the laser emission. This finding is underlined by numerical simulations of random mode intensity fluctuations.

2. Setups and measurement techniques

2.1 Chip and resonator design

For our studies we employ a VECSEL chip based on a (GaIn)As quantum-well stack as active medium and AlAs/AlGaAs quarter-wave layers serving as highly reflecting Bragg mirror. On top of the active region, a λ/2 GaInP cap layer is deposited providing a resonant design for an emission wavelength of approximately 1010 nm. The characterization procedure involves two experimental setups which are schematically shown in Fig. 1. In all cases, the VECSEL chip is mounted to a water-cooled copper heatsink with a temperature set to 18 °C. The chip is pumped by a fiber-coupled diode laser emitting at 808 nm.

The first setup employs a V-shaped cavity with a total length of 51 cm, using a highly reflective (HR) plane end mirror as well as a spherical output coupler with a radius of curvature (ROC) of 250 mm, respectively. The second cavity has a linear geometry using the same spherical mirror while the total cavity length corresponds to 1.5 cm. In each case, a Fabry-Pérot etalon made of silica with a thickness of 100 µm is inserted into the cavity in order to enforce single- and two-color emission, respectively. In the case of two-color emission, the etalon is slightly rotated so that two laser lines build up with nearly the same lasing intensity for each. The two lines are separated by 3.4 nm corresponding to approximately 1 THz. In addition, both setups are operated in the free-running configuration, i.e. without any intra-cavity filter. Thereby significant differences to the etalon-driven regime are revealed. For all cavity configurations we establish an optimum matching between the pump beam and the transverse profile of the laser mode on the VECSEL chip which ensures laser operation in a TEM₀₀ mode. Monitoring of the transverse mode profile is performed via a CCD camera.
For the characterization of the laser emission we apply two different techniques allowing for the investigation of either the emission bandwidth or the temporal dynamics of the two-color emission.

### 2.2 Interferometer setup

The first measurement technique employs a conventional optical Michelson interferometer using two silver mirrors, a 50:50 beam splitter and a silicon photodiode as detector. The movable mirror is mounted on a translation stage which provides a total travelling path of 5 cm. This corresponds to a maximum time delay of around 333 ps. In order to damp the signal below the saturation limit of the photodiode, a combination of a grey wedge and a neutral density filter is used. Figure 2(a) shows an exemplary interferogram recorded for the cavity with a length of 51 cm for the case of two-color operation. A clear envelope is observed indicating that the spectrum consists of multiple longitudinal modes within each color. A magnification of the central region (red dashed box) shows the beating between the two lasing intensities with a period of 1 ps (or 300 µm in spatial coordinates). This matches the difference frequency of approximately 1 THz. Further magnification resolves the single fringes connected to the fundamental lasing wavelength of 1010 nm (lower inset of Fig. 2(a)). From a theoretical point of view, an interference pattern as shown in Fig. 2 displays the 1st order autocorrelation of the underlying electric field. This autocorrelation provides access to the intensity spectrum via transformation into the frequency domain. For our purpose it is fully sufficient to determine the envelope function of the interference pattern as this directly relates to the envelope function in the frequency range. We define the emission bandwidth as the full-width-at-half-maximum (FWHM) of the envelope function in the frequency range. The minimum detectable bandwidth is limited by the total delay provided by the translation stage which in our case results in 3 GHz (corresponding to 0.01 nm). The measurement procedure using the Michelson interferometer is as follows: for each setting of the pump power the etalon is rotated so that it provides single-color emission and, in a second measurement series, two-color emission, respectively. Interferograms are measured for both cases as well as for the free-running configuration without etalon. Subsequent determination of the envelope function directly delivers the lasing bandwidth. For data analysis we additionally calculate the normalized bandwidth $\frac{\Delta \nu}{\Delta \nu_{\text{cav}}}$ which is the ratio of the measured bandwidth $\Delta \nu$ to the free spectral range $\Delta \nu_{\text{cav}}$ of the cavity. This number is a measure for the number of longitudinal modes participating in the laser emission.

### 2.3 Streak camera setup

The second characterization method allows for the acquisition of spectrally and temporally resolved real-time images of the two-color emission by the use of a monochromator that is coupled to a streak camera. This technique, which was introduced in [21], is utilized here to investigate and compare the two-color emission stability for two different resonator designs in...
combination with measurements of the emission bandwidth. Details on the overall measurement procedure can be found in [21]. Figure 2(b) shows an exemplary streak camera image in which two laser lines can clearly be identified. For the data analysis we calculate the relative intensity difference $\Delta I_{12} = (I_1 - I_2) / (I_1 + I_2)$, where $I_1$ and $I_2$ represent the intensities of the first and second color, respectively. Results are presented in terms of the $2\sigma$-value which represents twice the standard deviation of the $\Delta I_{12}$-distribution and thus is a measure for the strength of the relative intensity fluctuations.

$$\Delta I_{12} = \frac{I_1 - I_2}{I_1 + I_2}$$

![Exemplary interference pattern for the case of two-color operation employing the long cavity with a length of 51 cm.](image)

![Exemplary streak camera image using a time window of 10 µs.](image)

3. Experimental results

This section describes the experimental results for the long cavity with a length of 51 cm and, in a following subsection, for the short cavity with a length of 1.5 cm.

3.1 Long cavity with $L = 51$ cm

Figure 3 depicts laser power curves and corresponding results from bandwidth measurements for the first setup. The subfigures show corresponding data for three configurations of interest, i.e. single-color emission (a1 and a2), two-color emission (b1 and b2), and the free-running configuration (c1 and c2), respectively. The laser power curves are shown in the upper row whereas the corresponding power dependent bandwidth diagrams are depicted in the lower row. Since the normalized bandwidth is a measure for the number of longitudinal modes, this magnitude is scaled for each graph on the right vertical axis. The effective pump power is renormalized in order to account for reflection losses of approximately 34% occurring at the air/chip interface. For all investigated configurations, a steep increase of emission bandwidth close to the laser threshold is noted with only minor changes at higher pump powers. For single-color emission, the measured bandwidth lies between 5 GHz and 40 GHz (corresponding to 17 and 136 longitudinal modes, respectively). For pump powers higher than a specific value – that is for instance 14 W for the HR configuration – the laser tends to run on two-colors, so no more data points have been acquired. Even in the case of the two-color configuration, the measured bandwidth per color ranges from 5 GHz to 30 GHz corresponding to 17 and 102 longitudinal modes per color, respectively. This result clearly shows that the etalon rather provides a selection of two distinct “longitudinal mode packages” but not two single longitudinal modes. Above a certain power value, three- or even four-color
operation is observed for which reason no further data points are acquired. Owing to pump dependent broadening of the gain, a transition to many-color operation sets in particularly early for the configuration employing an HR mirror. Here, the onset of three-color operation coincides with the last three data points causing a slight bandwidth reduction. Without an etalon, the emission bandwidth increases significantly with values of several hundreds of GHz corresponding to hundreds or even thousands of longitudinal modes, see Fig. 3(c2). Also with this configuration, a significant increase of the bandwidth for small pump power is observed. At higher pump power, the emission is found to become more and more chaotic. Especially for the HR configuration, providing highest intra-cavity powers, the bandwidth fluctuates for higher pump power values.

Our results clearly demonstrate that even with the use of an etalon the laser is still running on many longitudinal modes. Moreover, the results show how the emission bandwidth evolves shortly after the onset of lasing. An increase of the output coupling losses mainly affects the laser in the free-running configuration leading to a significant decrease of emission bandwidth. This finding agrees with theoretical predictions in which the emission bandwidth scales with the inverse of the cavity loss rate [16,22]. This circumstance is intuitively clear as for higher losses less modes reach the lasing threshold for a fixed pump power level. For the configurations using the etalon as frequency filter, however, output coupling losses do not show a pronounced influence.

Fig. 3. Interferometric measurements for the cavity with a length of 51 cm using three different output couplers. The upper row shows the laser curves whereas the lower row depicts the corresponding emission bandwidth (left vertical axis) as well as the normalized bandwidth (right vertical axis).

In a subsequent measurement series, the two-color emission dynamics are investigated using the combination of a monochromator and a streak camera. For each recorded image (1000 images in total) we use a time window of 10 µs. Furthermore we integrate the data
within time steps of 1 µs in order to lower the influence of the detector noise. A time resolution of 1 µs lies below the photon lifetime in the cavity which is calculated to be 20 µs. The respective data is depicted in Fig. 4. Here, only the two-color configuration using the HR end mirror is studied. We plot the laser curve in Fig. 4(a) indicating high intra-cavity powers up to 1.75 kW shortly before the beginning of thermal roll-over. Figure 4(b) displays the 2σ-value for the $\Delta I_{12}$ distribution. Near the lasing threshold, the 2σ-value exhibits values as big as 90% indicating major relative intensity fluctuations. In this region, the two lasing intensities almost never are emitted simultaneously due to a strong anti-phase behavior. With increasing pump power the conditions change rapidly. The relative intensity fluctuations decrease to a value of approximately 18% where they stay fixed for further increasing pump power. This region is marked as stable as indicated by the green highlighted background.

Fig. 4. Two-color emission dynamics for the cavity with a length of 51 cm using the HR plane end mirror. (a) shows the intra-cavity power as function of the effective pump power. (b) depicts the 2σ-interval, i.e. the width of the $\Delta I_{12}$-distribution as function of the effective pump power. The region in which a stable two-color emission is observed is highlighted in green.

3.2 Short cavity with $L = 1.5$ cm

In this section, we analyze multimode features of a short linear cavity in a similar manner as for the long V-cavity. A cavity with a length of 1.5 cm increases the free spectral range to a value of 10 GHz. Thus, less modes will experience sufficient gain to overcome the losses. For the short cavity only one high reflectivity mirror with a ROC of 250 mm is used. Figure 5 depicts the interferometric results for the single-, two-color and the free-running configuration, respectively. The data is evaluated only for the region in which the laser emits a TEM_{00}-mode. Due to the oblique incidence of the pump beam (incidence angle approximately 60°) a TEM_{00}-mode cannot be maintained for all settings of the pump power. The results are shown in Fig. 5 where the quantities are plotted in the same manner as for Fig. 3. In the case of one-color emission, the bandwidth diagram consists of two operation regimes, as shown in Fig. 5(a2): the first regime corresponds to a very low bandwidth in the range of 3 GHz. Furthermore, the normalized bandwidth is smaller than one which indicates single frequency operation. At a pump power of 6 W, the bandwidth experiences a sudden transition to 17 GHz corresponding to at least two oscillating longitudinal modes. Forcing the laser into two-color operation is more difficult than before, as the two-color emission is unstable over the entire range of applied pump powers (see Fig. 6). Therefore, at low pump power it is not possible to measure a meaningful interference pattern as the relative fluctuations lead to extreme perturbations preventing the formation of a clear envelope. Even at higher pump powers, the unstable emission introduces high uncertainties resulting in increased error bars, see Fig. 5(b). As can be seen, the bandwidth per color is slightly increasing from 3 GHz to around 20 GHz. In this region, the emission is governed by up to two longitudinal modes per color. In contrast, the bandwidth increases up to 400 GHz in the
free-running configuration corresponding to approximately 40 longitudinal modes. For pump powers higher than 15 W the laser is not working in TEM$_{00}$ operation.

![Fig. 5. Interferometric measurements for the cavity with a length of 1.5 cm.](image)

(a1) one color emission  
(b1) two color emission  
(c1) free-running

In the grey highlighted regions the laser operates in a higher order transverse mode.

Figure 6 shows the two-color stability analysis for the cavity with a length of 1.5 cm. Here, a time window of 5 µs for each streak camera image is used (1000 images in total). For the analysis, we also time integrate the data leading to a time resolution of 0.5 µs. This value lies below the photon lifetime in the cavity which is calculated to be 0.85 µs. At first glance, the observed behavior seems to be similar to the results obtained for the long cavity. Nevertheless, major differences exist: Firstly, the relative intensity fluctuations, especially at low pump powers, are significantly higher than for the long cavity. Here, the 2σ-value starts at 180% whereas for the long cavity a maximum value of 90% was observed. Secondly, with increasing pump power the relative intensity fluctuations reduce and the 2σ-value lies between 25% and 40% for pump powers between 2 and 30 W. We relate the fluctuating behavior magnified in the inset of Fig. 6(b) to a varying amount of longitudinal modes which is a consequence of strong gain competition. This leads to a random spread of the 2σ-values in a fairly wide range from which on the average an unstable emission can be deduced. For the last setting of the pump power we observe highly unstable five-color emission indicated by additional points in the figure. Altogether, the result indicates an unstable two-color operation as on the average the relative intensity fluctuations are still well pronounced over the whole range of applied pump powers. In contrast to Fig. 4 we therefore do not draw a highlighted green region. For pump powers higher than 15 W, the laser operates in a higher transverse mode profile.
Fig. 6. Two-color emission dynamics for the cavity with a length of 1.5 cm. (a) shows the intra-cavity power as a function of the effective pump power. The highlighted grey region corresponds to a higher transverse mode operation. At high pump power the beginning of thermal roll-over is noted. (b) depicts the $2\sigma$-interval in dependence of the effective pump power. The inset in (b) shows a magnification of the encased area.

4. Discussion

From the measurements presented in Figs. 3 and 4 we can derive several conclusions. Firstly, the laser is working in a longitudinal multi-mode regime, even if the etalon is acting as frequency filter. The emission bandwidth increases rapidly after the onset of lasing and saturates at higher pump powers. This finding is related to an increase of gain with increasing pump power allowing more and more modes to reach the lasing threshold. The observed saturation is a consequence of mode filtering introduced by the finite effective gain bandwidth. Indeed, the observed behavior agrees well with theoretical findings on solid-state lasers reaching back to 1963 [23]. Although the conditions in a VECSEL exhibit major differences to typical solid-state lasers, the evolution of multi-mode emission turns out to be quite similar.

In the case of the HR mirror setup, which is the favored configuration for intra-cavity frequency mixing, the rapid increase of emission bandwidth occurs at relatively low pump powers between 5 W and 10 W, for both one- and two-color emission, respectively. This power range directly corresponds to the instability region where the $2\sigma$-value exhibits significant changes, see Fig. 4(b) for comparison. For pump powers higher than 10 W, a stable emission regime is reached. From this study it is apparent, that the stability of the two-color emission is strongly related to the number of longitudinal modes.

This claim is directly supported by a comparative investigation of the short cavity with a length of 1.5 cm. In this case, the number of longitudinal modes is significantly reduced. At the same time, a stable two-color emission is not observed. These findings indicate that the stability of the two-color operation is related to the amount of oscillating longitudinal modes within each color. In our setup, a stable two-color emission regime can be maintained as soon as we have tens of modes oscillating in the laser cavity. As soon as the mode number decreases significantly, a breakdown of the two-color emission stability is observed. These circumstances impose restrictions on the cavity design and the suitable power ranges in which efficient difference frequency generation inside a VECSEL cavity is possible. Moreover, as the beat signal of the two fundamental wavelength packages is transformed to the DFG spectrum, the generation of a low linewidth DFG signal is inherently not possible.

5. Simulation of mode statistics

In this section, a numerical simulation of the mode emission statistics is presented in order to underline the experimental findings on the two color emission stability.
The dependence of a stable two-color lasing on a sufficient number of longitudinal modes can be explained by assuming that all mode intensities are randomly fluctuating over time. This assumption seems reasonable if gain competition is considered. In addition, since the cavity is not actively stabilized, mode intensity fluctuations as well as mode hopping are very likely to occur. Each of the two lasing intensities seen by the streak camera represents the average over all longitudinal modes constituting the corresponding mode package. In the case of many participating modes per color, the fluctuations should cancel out on the average leading to more or less the same lasing intensity for both colors. As soon as the number of modes becomes small, the fluctuations govern the overall emission dynamics leading to an unstable two color emission.

In order to prove this assumption, we perform a numerical simulation taking into account random mode intensity fluctuations. For each color, a time trace of data points is created in which each point represents the average over \( n \) longitudinal mode intensities. These intensities can exhibit random values between 0 and 1 using an equal distribution. To account for cross-saturation effects, the modes evolve in a way that the average intensities for both colors exhibit anti-phase dynamics. In total, \( 10^4 \) data points are generated for each color. This procedure is repeated for different values of \( n \) running from \( n = 1 \) to \( n = 100 \). Figure 7 illustrates the corresponding 2\( \sigma \)-value as function of the mode number \( n \). For low mode numbers, the relative deviations exceed 100\% but rapidly decrease as more and more modes participate in the laser emission. Subfigures (1), (2) and (3) in Fig. 7 show exemplary \( \Delta I_{1,2} \)-distributions for one, ten and one hundred modes per color, respectively. From these figures the increase of emission stability is identified by the formation of a pronounced peak whose width decreases with an increasing amount of longitudinal modes.

![Fig. 7](image.png)

**Fig. 7.** Numerical simulations of the random mode intensity fluctuations. The figure shows the strength of relative intensity fluctuations (expressed in terms of the 2\( \sigma \)-value) in dependence of the number of oscillating longitudinal modes. The small subfigures show exemplary \( \Delta I_{1,2} \)-distributions for one mode per color (1), ten modes per color (2) and one hundred modes per color (3), respectively.

### 6. Conclusion

In summary, we experimentally investigate the dynamics and evolution of the longitudinal single- and multi-mode emission in a VECSEL using both streak camera measurements and interferometric measurement techniques.
Two cavities with lengths of 51 cm and 1.5 cm are employed delivering free spectral ranges of 0.3 GHz and 10 GHz, respectively. In each case, the laser is operated in single- and two-color emission using a Fabry-Pérot etalon as frequency filter. Furthermore, a free-running configuration without etalon is realized. In all cases, we measure a steep increase of emission bandwidth close to lasing threshold where only minor variances are noted at higher pump powers. In the case of the free-running configuration a significant decrease of emission bandwidth with increasing output coupling losses is observed. Employing the short cavity with a length of 1.5 cm allows for single frequency emission within a certain power range. The transition to longitudinal multi-mode emission for higher pump powers is directly monitored. It is worth to note that the evolution of multi-mode emission in a VECSEL shows some interesting similarities with conventional solid-state lasers. Although VECSELs exhibit major differences, the results indicate the presence of inhomogeneous effects in the gain medium which facilitate the build-up of many longitudinal modes.

By combination of both the bandwidth and the streak camera measurements we observe that a stable two-color emission – in which both mode packages share the same gain region on the chip– is related to a sufficiently high number of oscillating longitudinal modes within each color. These modes exhibit random intensity fluctuations which cancel out on the average if many of them participate in the laser emission. This finding is in agreement with additionally performed numerical simulations which focused on the evolution of the two-color emission process from a statistical point of view. The presented results impose restrictions on the cavity design and suitable power ranges in which efficient difference frequency generation inside a VECSEL cavity is possible.

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