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Chaotic dynamics of a broad-area VCSEL

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Abstract: We investigate the polarization, spatial, spectral and dynamic properties of a broad-area VCSEL in continuous-wave operation. The transverse and polarization mode competition results in a complex bifurcation scenario leading to chaotic dynamics. © 2022 The Author(s)

1. Introduction

Semiconductor lasers can exhibit complex and chaotic ultrafast dynamics which are of interest for chaos-based applications including cryptography, sensing, and computation [1]. Instabilities and chaos in semiconductor lasers can be induced by, e.g., delayed feedback and optical injection, but chaotic dynamics in solitary operation due to multimode interaction is very rare. Unlike edge-emitting lasers, VCSELs exhibit two polarization states coupled to the spin-dynamics of the carrier system [2], and hence free-running VCSELs can exhibit polarization chaos [3].

The interaction of several transverse modes in broad-area VCSELs (BA-VCSEL) has the potential for even more complex dynamics, however, so far there have been no experimental investigations of their dynamics and bifurcation scenarios in continuous-wave operation. Our comprehensive study of the polarization, spatial, spectral and dynamical properties of a commercial BA-VCSEL with 15 μm aperture diameter unveils complex dynamics due to competition between modes with different spatial structure and polarization state. We find a series of polarization switching points and bifurcations, and furthermore we observe for the first time ultrafast chaotic dynamics for a free-running BA-VCSEL.

2. Polarization and laser spectrum

The measurements of the polarization state of the BA-VCSEL using a rotating polarizer [Fig. 1(a)] show two main polarization axes, $\alpha_u = 74^\circ$ and $\alpha_v = 164^\circ$. The polarization is, however, not fully linear ($P/\langle P \rangle_\alpha < 2$) for any pump current. The degree of linearity indicated by the contrast between maximal and minimal power varies with the pump current and we observe several polarization switching points (PSPs) at which the dominant axis changes.

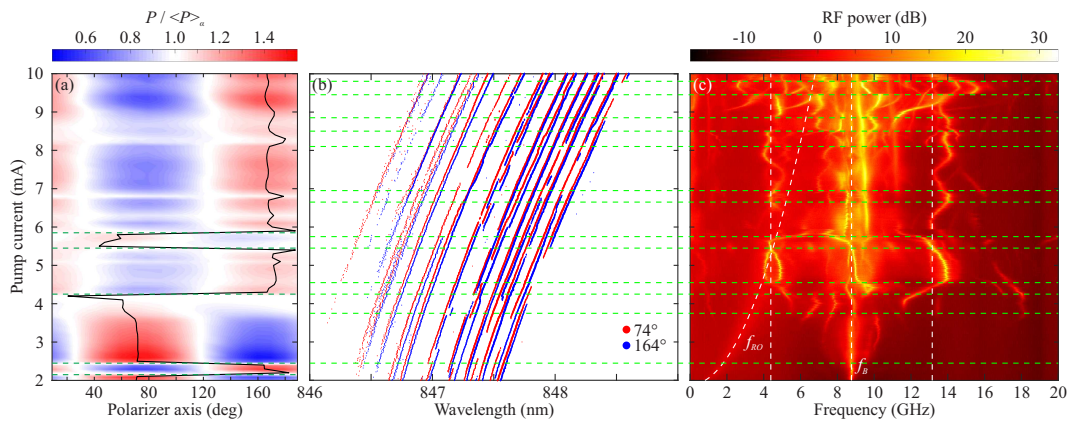


Fig. 1. (a) Relative transmission P through a polarizer as function of its angle α and the pump current. The black line indicates the major polarization axis and the green dashed lines the PSPs. (b) Optical spectra for the two polarization axes $\alpha_u = 74^\circ$ (red) and $\alpha_v = 164^\circ$ (blue). The dot sizes are proportional to the peak amplitudes in dBm. (c) RF-spectra (PSD) and bifurcations. The vertical dashed white lines indicate f_B , $f_B/2$ and $3f_B/2$, and the curved white dashed line the relaxation oscillation frequency f_{RO} . The dashed green lines in (b) and (c) highlight bifurcations.

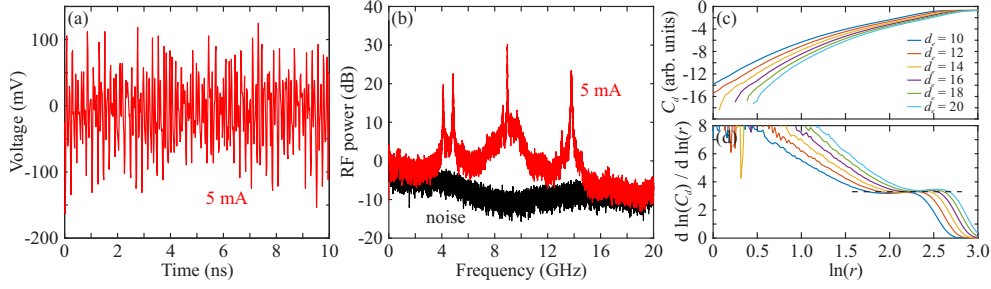


Fig. 2. (a) Time trace of laser power fluctuations for 5 mA and (b) its PSD. (c) Correlation integrals of the time trace for embedding dimensions $d_e = 10$ –20. (d) The slopes of the correlation integrals in (c) exhibit a plateau around a correlation dimension of $d_c \simeq 3.3$ (dashed black line).

The lasing spectra in Fig. 1(b) show multimode lasing with several transverse modes in both polarization states with a birefringence splitting of $f_B \approx 9$ GHz. With increasing pump current, new lasing modes turn on while existing modes change their amplitude or even turn off, evidencing a complex mode competition via spatial hole burning and polarization effects. The complicated evolution of the polarization state including PSPs in Fig. 1(a) is hence due to a gradual redistribution of power between several transverse modes with linear polarization, a mechanism not found for single-mode VCSELs.

3. Laser dynamics

Figure 1(c) presents the power spectral density (PSD) of the time traces measured with a fast photodetector and oscilloscope (bandwidth 22 GHz). Just above threshold ($I_{th} = 1.9$ mA) we observe oscillations at the birefringence frequency f_B and weak relaxation oscillations. The complexity of the RF-spectra increases with the pump current as additional frequency components appear in a cascade of bifurcations, in particular around $f_B/2$ and $3f_B/2$, which indicates period doubling. Many bifurcations coincide with major changes in the lasing spectrum, i.e., modes turning on or off. We thus conclude that nonlinear dynamics and bifurcations are driven by a combination of mode competition and polarization effects.

The time trace measured for 5 mA is shown in Fig. 2(a). It exhibits fast oscillations with approximately 9 GHz and irregular variations of the envelope. Its PSD in Fig. 2(b) features major peaks near $f_B \approx 9$ GHz, $f_B/2$ and $3f_B/2$. Interestingly, the relaxation oscillation frequency f_{RO} approaches $f_B/2$ in this current region [see Fig. 1(c)]. Statistical tests like surrogate data analysis and titration of chaos indicate that the time trace in Fig. 2(a) exhibits chaotic dynamics, and we use the Grassberger-Procaccia algorithm [4] to estimate the fractal dimension of the strange attractor. The correlation integrals C_d calculated from the time trace embedded with delay $\tau_e = 200$ ps and embedding dimensions as high as $d_e = 20$ are shown as function of the integration radius r in Fig. 2(c). The slopes of the C_d curves in Fig. 2(d) show a clear plateau region, indicating a correlation dimension of $d_c \simeq 3.3$.

4. Conclusions

We present the first systematic study of the dynamics of a BA-VCSEL [5] and find a complex nonlinear dynamics driven by mode competition via spatial hole burning, where the dominant frequency scale is given by the birefringence splitting f_B . Thus, the nonlinear dynamics appears to originate from a combination of transverse mode competition and polarization effects, a situation unique for BA-VCSELs. We observe a complex series of bifurcations that leads to chaotic dynamics with fractal dimension $d_c \simeq 3.3$. Our investigation thus presents the first experimental observation of chaotic dynamics in a free-running BA-VCSEL.

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