Spatio-temporal dynamics of microlasers with chaotic ray dynamics

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Broad-area semiconductor lasers used for high-power applications such as material processing and pump sources feature significant spatio-temporal instabilities [1]. Most attempts to stabilize them aim at reducing the number of transverse lasing modes via injection or feedback but fail at high powers. We demonstrate a different approach for stabilization via complex interference in asymmetric cavities with chaotic ray dynamics. This approach maintains multi-mode operation and is hence compatible with high-power operation [2].

We fabricated edge-emitting GaAs quantum well lasers by photolithography and dry etching. The dynamics of conventional stripe-shaped Fabry-Perot cavities [see Fig. 1(a)] was compared to those of asymmetric cavities featuring chaotic ray dynamics such as the cut-off circle [also called D-cavity, see Fig. 1(c)]. The properties of the passive modes of microcavities with chaotic ray dynamics have been intensively studied in the context of wave-dynamical chaos [3], however, little is known about their lasing dynamics. We measured the spatio-temporal dynamics of the microlasers using a streak camera with picosecond resolution.

The spatio-temporal dynamics of the emission from a Fabry-Perot cavity is shown in Figure 1(b). The emission intensity fluctuates on a sub-nanosecond time scale and is concentrated spatially in several filaments. The spatio-temporal instabilities result from the carrier-density dependence of the refractive index: a strong electric field depletes the carrier density, thus raising the refractive index locally and generating a self-focusing instability. In contrast, the spatio-temporal dynamics of a D-cavity, shown in Fig. 1(d), exhibits much slower and weaker fluctuations with a time scale of 50 ns or longer.

The differences in the dynamics are due to the structure of the lasing mode field distributions. Since the wave fronts in Fabry-Perot cavities travel almost parallel to the cavity axis, the transverse wavelength is of the order of several micron. An intensity variation on this length scale creates a lensing effect and thus a self-focusing instability. In contrast, the modes of a wave-chaotic D-cavity feature a fine-grained and pseudo-random spatial profile due to complex wave interference and have no dominant propagation direction. Thus, no lensing effect can be created, and self-focusing instabilities are prevented, resulting in a stable dynamics.

Furthermore, simulations of one-dimensional semiconductor lasers showed that the chaotic dynamics of a homogeneous cavity can also be stabilized by adding random variations of the refractive index profile to induce complex interference [2]. This demonstrates that the principle of modifying the interaction of lasing modes and active medium by means of a complex cavity environment is of general validity, and we anticipate applications in lasers as well as in other nonlinear wave-dynamical systems.

Fig. 1 Different cavity types and spatio-temporal images of their emission intensity. (a) Sketch of a Fabry-Perot cavity with length L and width w (not to scale) and (b) measured intensity distribution at the output facet of a Fabry-Perot laser with $w = 60 \mu\text{m}$, exhibiting very fast pulsations. (c) Schematic of a D-cavity with radius R and (d) measured intensity distribution at the straight side wall of a D-cavity with $R = 100 \mu\text{m}$ at $0.6 \mu\text{s}$ after the start of the pulse, showing much slower and weaker variations.

References

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