Spatio-temporal dynamics of semiconductor microlasers with chaotic ray dynamics

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Broad-area semiconductor lasers (BALs) are highly nonlinear systems. Effects such as spatial hole burning, carrier-induced index changes and carrier diffusion with different spatial and temporal scales result in a very complex dynamics. BALs can thus exhibit spatio-temporal instabilities like filamentation and pulsations on a sub-nanosecond time scale [1]. These instabilities are detrimental for applications in material processing, imaging and laser surgery. Methods such as injection or delayed feedback have been used to stabilize the dynamics with, however, only limited success.

Complexity can, however, also arise from the cavity geometry. While conventional semiconductor lasers use Fabry-Perot (FP) cavities, microlasers with asymmetric cavities that can exhibit chaotic ray dynamics have been studied in the context of wave-dynamical chaos [2]. A wealth of different geometries like stadia, deformed circles or polygons have been investigated to understand how the classical ray dynamics manifests in the passive cavity mode properties, e.g., the spectra or near- and far-field distributions [2]. However, very little is known about the dynamics of asymmetric microcavity lasers. We investigate semiconductor microlasers which have the form of a circle from which a section is cut off $R/2$ away from the center, so-called D-cavities, as an example with completely chaotic ray dynamics.

We experimentally studied the spatio-temporal dynamics of conventional FP broad-area lasers as well as of D-cavity lasers [3]. The edge-emitting GaAs quantum well microlasers are pumped electrically with microsecond pulses. The FP-cavities exhibit severe spatio-temporal instabilities as expected. In contrast, the emission of the D-shaped microlasers is inherently stable without filaments or fast pulsations. It is surprising to see that adding more complexity to the system by using a geometry with chaotic ray dynamics leads to a stabilization of the dynamics. While both FP-cavity and D-cavity lasers feature the same nonlinearities due to the active medium, their consequences for the spatio-temporal dynamics strongly depend on the structure of the field distributions of the lasing modes.

In a FP cavity, the optical field propagates along the cavity axis and features a transverse wavelength of several micron. Intensity variations on this length scale create a lensing effect and result in a self-focusing instability due to carrier-induced index changes. The field distributions of the D-cavity, in contrast, consist of a superposition of plane waves in all possible directions and feature the same wavelength-scale structure size in all directions due to the chaotic ray dynamics. Hence, no lensing effect can appear and the formation of filaments is suppressed due to complex wave interference.

Furthermore, stabilization of chaotic dynamics was observed in simulations of one-dimensional semiconductor lasers with random variations of the refractive index profile [3] compared to the case of a homogeneous cavity. This demonstrates the general usefulness of complex wave interference induced by the cavity environment for suppressing spatio-temporal instabilities, and we believe that this principle will also find applications in other fields such as nonlinear optics or turbulent fluid dynamics.

Références

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