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Abstract: We theoretically and experimentally investigate the dynamics of external-cavity mode-locked semiconductor lasers, focusing on stability properties, optimization of pulsewidth and timing jitter. A new numerical approach allows to clearly separate timing and amplitude jitter.

OCIS codes: (140.5960) Semiconductor lasers; (140.4050) Mode-locked lasers; (320.7120) Ultrafast phenomena

Mode-locked semiconductor lasers are compact and efficient short-pulse sources with a number of different applications. However, due to the complex dynamics and dispersion properties of the gain and absorber media incorporated into the laser, the stability as well as the emerging pulse and noise properties are not yet understood in detail. We apply a fully distributed time-domain model [1] to theoretically investigate the dynamical properties of external-cavity mode-locked semiconductor lasers (ECMLL) [2] and compare with experimental results. The device studied is a two-section buried heterostructure with 6 QWs, 50 μm saturable absorber, and 560 μm amplifier (SOA). The position of the diffraction grating in the external cavity is adjusted to achieve 10 GHz repetition rate.

Different operation regimes appear upon variation of the reverse bias and injection current, cf. Fig. 1. The device-parameters have been optimized in order to extend the regime of stable mode-locking (ML). When the unsaturated losses are large and the current is close to threshold, regimes of weakly and fully developed Q-switching ML are obtained. The tendency to Q-switch is reduced when lowering the optical losses, e.g. by using HR mirrors, short absorbers, low internal losses, and lasing near the absorption edge. From these observations, it turns out that operation in the red side of the gain spectrum is convenient in terms of stability of the ECMLL. On the other hand, incomplete ML dominates for low reverse bias and higher currents. In the time domain, the onset of incomplete ML manifests itself in optical pulses containing a non-steady multiple peaked structure. The optimum operation point, providing the shortest optical pulses in Fig. 1, is obtained for large reverse bias and close-to-threshold operation, in good agreement with experimental findings. The changes in pulsewidth arise from pulse shaping by the grating and fast effects explicitly introduced in the absorber and amplifier models. We find a distinctive trade-off between pulsewidth and stability. The pulsewidth can thus be further reduced down to ~1 ps (uncompressed pulse) by increasing the bandwidth of the grating or operating at a shorter wavelength, but at the expense of a reduction of the regime of stable ML.

The measurement of timing jitter using the RF-spectrum relies on integration of the noise skirts around successive harmonic peaks [3]. For lasers operating at high repetition frequencies, however, this method becomes impractical since it requires the measurement of harmonics at very high frequencies. Hence, in most cases only the first harmonic is considered, which may be problematic when components of the timing jitter fall in a frequency range with important amplitude fluctuations. We have developed an alternative numerical method based on detecting in real-time the mean pulse position and energy. This approach allows to unambiguously distinguish timing fluctuations from amplitude noise, and establishes a connection between our fully-distributed model and the master equation theory [4].

In Fig. 2(a), we show the phase noise spectra obtained from the two methods. The higher levels of phase noise in the RF-spectrum arise from amplitude fluctuations. We observe that these differences are relevant beyond ~10 MHz. In panel 2(b) we compare the predicted timing jitter integrating the phase noise from 1 MHz up to the Nyquist frequency. The curves agree only at low frequencies. For integration beyond 10 MHz, the jitter obtained from the first harmonic peak in the RF-spectrum increases as a result of amplitude fluctuations, leading to an overestimate of the real timing jitter. The suitable integration limit depends on the particular device and the operation conditions, because of the damping and position of the relaxation oscillations with respect the harmonic peak.

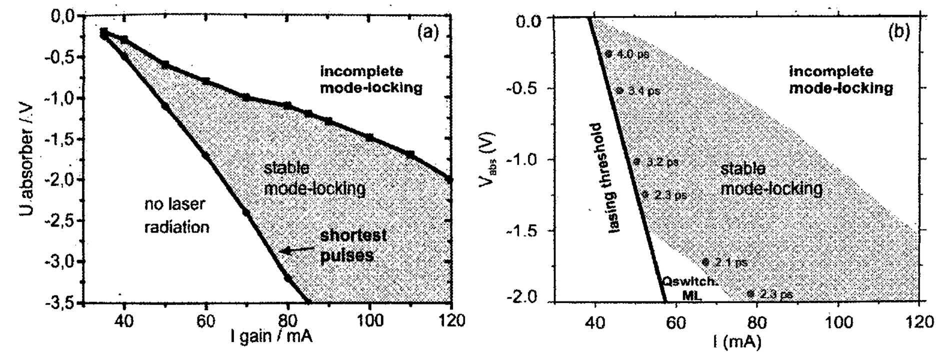

Fig. 1. Experimental (a) and simulated (b) operation regimes of a 10 GHz ECMLL composed by 50 μm absorber, 560 μm SOA and 20 μm transition region. The numbers annotated in (b) correspond to the uncompressed pulsewidths.

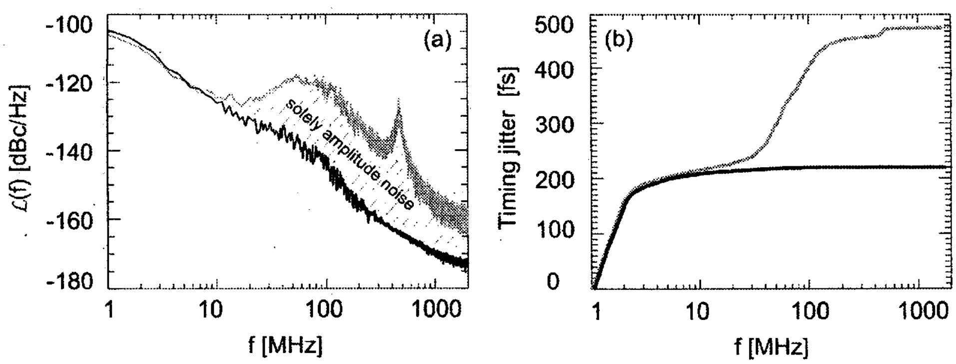

Fig. 2. Passive 4 GHz ECMLL operating 1.5 times threshold. (a) Constructed phase noise and (b) integrated timing jitter. Black lines are obtained from direct pulse detection whereas grey lines are calculated from the RF-spectrum.

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