Traveling wave modelling and mode analysis of semiconductor ring lasers

M. Radziunas
Weierstrass Institute, Mohrenstrasse 39, D-10117 Berlin, Germany

Semiconductor ring lasers (SRLs) are interesting devices for their applications in photonic integrated circuits. For simulating and analysing the SRL one frequently uses a two-mode ODE model consisting of a pair of complex equations for the counter-propagating longitudinal modes and a rate equation for the carrier density [1]. This model, however, cannot recover different multi-mode effects of SRLs such as mode locking or transitions between multiple longitudinal modes. Moreover, it is based on mean-field approximations and does not allow considering spatially inhomogeneous laser parameters and dynamical variables.

In the present work we overcome all these restrictions by applying the traveling wave (TW) model, which is a PDE model having a single spatial dimension corresponding to the longitudinal direction along the ring cavity [2,3]. This model considers clockwise (CW) and counter-clockwise (CCW) propagating slowly varying optical fields $E^{\pm}$ governed by the TW equations $E'=H(\partial_z,\beta^{\pm}(z,n))E$ [4]. The fields are mutually coupled through linear backscattering terms, through nonlinear cross- and self- saturation which imply an asymmetry $\Delta_\beta=\beta^+-\beta^-$ of propagation factors for CW and CCW fields, and are both coupled to the spatially parameterized carrier rate equation. This approach allows simulating ring structures consisting from differently driven sections, considering longitudinal distributions of the carriers and of the optical fields, which can be also expressed as a superposition of the multiple longitudinal optical modes. Moreover, this modeling can take into account optical injections, localized reflections and, therefore, delayed feedback of the optical fields.

Comparing to the ODE model, the TW modeling approach is computationally more demanding and is much more difficult to analyse. In this work we exploit a concept of instantaneous optical modes [5] defined by the spectral problem $i\Omega(\beta)\theta(\beta,z)=H(\partial_z,\beta^{\pm}(z,n))\theta(\beta,z)$ at each instant time moment t, i.e., at each instant distribution of $\beta^{\pm}(z,n(t))$. Namely, we compute modes $(\Omega_k,\theta_k(z))$ of SRL at different operation regimes, discuss splitting of complex frequencies Ω induced by non-vanishing field backscattering and asymmetry of propagation factors, and demonstrate usefulness of these modes when interpreting origin and stability of operation regimes of SRLs.

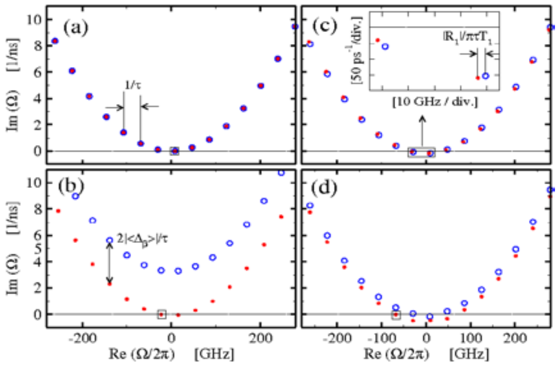

Fig. 1 Main eigenvalues of spectral problem with (a): distributed and localized coupling κ=R=0 and field propagation factor asymmetry $\Delta_\beta=0$; (b): κ=R=0 and $\Delta_\beta\neq0$; (c): $\kappa=\Delta_\beta=0$ and R≠0; (d): R=0, $\Delta_\beta\neq0$; and κ≠0. Small boxes indicate dominating modes in corresponding dynamical regimes.

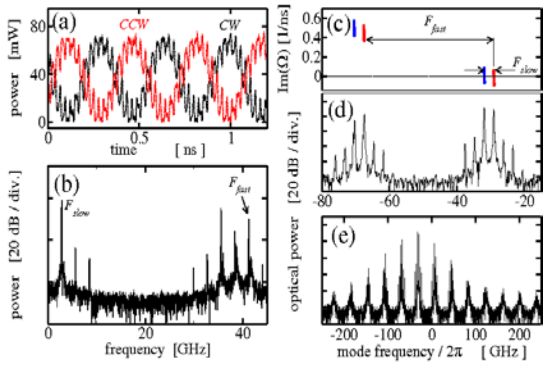

Fig. 2 A dynamic regime induced by beating of different modes. (a): intensities of the emitted CCW and CW fields. (b): radiofrequency spectra of the CW field. (c): four main eigenvalues at several time instants. (d, e): optical spectra of the CW field. Parameters are as in Fig. 1(c), only $\Delta_\beta\neq0$.

We have found that complex frequencies Ω in SRLs appear in pairs (see red and blue bullets in Fig.1), whereas field backscattering and propagation factor asymmetry imply different type of mode splitting (Fig.1b,c,d). Real and positive (negative) imaginary parts of complex frequency Ω indicate relative optical frequency and losses (gain) of corresponding mode. Thus, the modes fully determining stationary (continuous wave) states have Ω with a vanishing imaginary part (modes within small boxes in Fig. 1a,b,d). During dynamical non-stationary regimes main mode frequencies Ω deviate nearby real axis (Fig. 1c and Fig. 2c) and allow recognizing characteristic oscillation frequencies of corresponding state (Fig. 2a,b,d,e).

References

[1] M. Sorel et al., "Operating regimes of GaAs-AlGaAs semiconductor ring lasers: experiment and model", IEEE JQE **39**, 1187 (2003)
[2] M. Radziunas, "Traveling wave modeling of semiconductor ring lasers", SPIE Proc.Ser. **6997**, 69971B (2008)
[3] J. Javaloyes, S. Balle, "Emission directionality of semiconductor ring lasers: a traveling-wave description", IEEE JQE **45**, 431(2009)
[4] U. Bandelow et al., "Impact of gain dispersion on the spatio-temporal dynamics of multisection lasers", IEEE JQE **37**, 183 (2001)
[5] M. Radziunas, H.-J. Wünsche, Chapter 5 in *Optoelectronic Devices: advanced simulation and analysis*, J. Piprek ed. (Springer, 2005)

978-1-4799-0594-2/13/$31.00 ©2013 IEEE