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Self-injection-locking linewidth narrowing in a semiconductor laser coupled to an external fiber-optic ring resonator

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ABSTRACT

We develop a theoretical framework for modeling of semiconductor laser coupled to an external fiber-optic ring resonator. The developed approach has shown good qualitative agreement between theoretical predictions and experimental results for particular configuration of a self-injection locked DFB laser delivering narrow-band radiation. The model is capable of describing the main features of the experimentally measured laser outputs such as laser line narrowing, spectral shape of generated radiation, mode-hoping instabilities and makes possible exploring the key physical mechanisms responsible for the laser operation stability.

1. Introduction

Linewidth narrowing and stabilization of semiconductor laser light generation are of topical research interest governed by the great demand of compact cost-effective narrow-band laser sources for a number of potential applications. Among them are high-resolution spectroscopy, phase coherent optical communications, distributed fiber optics sensing, coherent optical spectrum analyzer, and microwave photonics [1–5]. Self-injection locking of a semiconductor laser through an external feedback is one of the most promising mechanisms for the laser line narrowing [6,7]. To provide the effect, a part of the optical radiation emitted by the laser should be returned back into the laser cavity. This relatively simple technique allows to design cost-effective narrow-band laser sources based on standard laser diodes making them an attractive solution in comparison with traditional laser systems based on an active feedback.

Traditionally, self-injection locking laser configuration comprises a narrow bandpass optical filter inside a weak feedback loop. Current progress in this topic is associated with the use of micro-cavity techniques [8]. Employing optical whispering-gallery-mode resonators the linewidth of the semiconductor laser could be decreased down to Hz range in a compact and robust configuration [9]. However, the external cavities used in such systems possessing huge Q-factors ($\sim 10^{11}$) are not flexible for adjustment and require rather complicate coupling of fiber and non-fiber elements. Alternatively, all-fiber cavity solution based on long, but relatively low-Q-factor resonators, in particular fiber ring resonators [10,11] is able to provide comparable semiconductor laser line narrowing employing low-cost fiber configuration built from standard telecom components. In particular, such solutions are of great interest for RF-generation and Brillouin distributed sensing since the same fiber cavity can serve as nonlinear medium to generate Brillouin frequency-shifted light [12–16]. Recently, we have demonstrated significant line-narrowing (more than 1000 times) of a conventional low-cost DFB laser locked to an external fiber optic ring resonator [17]. However, rare mode-hopping events have been found to interrupt the stable laser operation making its practical application questionable [18,19]. Therefore, advancing the understanding of the physical mechanisms responsible for the operation of the laser-feedback cavity system is of great practical importance for further system designs.

Semiconductor lasers with an external feedback are complex dynamical systems demonstrating a wide range of generation regimes varying from a stable light generation, to periodic and quasi-periodic oscillations and to chaotic lasing [20,21]. Although the laser dynamics have already been considered in some system configurations, including the case of a feedback through a narrow-band frequency filter [22,23],

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an appropriate approach for describing semiconductor laser coupled to an external optical fiber ring resonator has not been developed yet. A specific feature of this system is the very narrow linewidth of the generated light that is at least 3 orders of magnitude narrower than the one of the solitary semiconductor laser. Besides, for a typical several-meter long fiber ring cavity several peaks of the fiber resonators transmittance spectrum compete for the laser generation making mode hopping probable. In the present work we develop a theoretical framework for description of a semiconductor laser optically coupled to a ring fiber resonator taking into account multi-peak spectral performance of the external filtering. We report simulation results exploring key features of the laser dynamics important for advanced understanding of the physical mechanisms responsible for laser instabilities and suitable for qualitative explanation of experimental observations.

2. Model

The referenced experimental configuration of a semiconductor laser coupled to a fiber-optic ring resonator is shown in Fig. 1. The laser diode operating at wavelength near 1.55 μm is supplied by a built-in optical isolator attenuating the power of backward radiation by ∼30 dB. Without such an isolation the semiconductor laser is extremely sensitive to parasitic backreflections from fiber splices and connectors and backward Rayleigh scattering that disturb stable laser operation and lead to periodic, quasi-periodic or chaotic light generation [20,21]. The built-in optical isolator eliminates the effects of uncontrollable backreflections and simultaneously reduces the value of a controllable feedback from the external fiber optic ring resonator. In order to implement the injection locking mechanism, the light emitted by the laser passes an optical circulator (OC) and is introduced through a coupler C1 into a ring cavity. The cavity is spliced from couplers C1 (90/10) and C2 (99/1) and comprises totally 4 m length of standard SMF-28 fiber. The coupler C2 is used to redirect a part of the light circulating in the cavity through circulator (OC) back into the DFB laser providing a feedback for self-injection locked laser operation. The typical width of the locked laser spectrum measured by the delayed self-heterodyne method is ∼ 2.4 kHz. Commonly, a stable self-injection locking regime is observed during 1–100 s (depending on environment noise level) and periodically interrupted by mode-hopping events making the laser unstable during typically ∼5 ms.

In order to explain the laser operation we consider a system consisting of a semiconductor laser and a fiber ring resonator connected though the feedback loop. Further analysis is valid for both Fabry–Perot (FB) and distributed feedback (DFB) semiconductor lasers, as long as the power coupling coefficient in DFB cavity periodic structure could be substituted by an output mirror reflectivity of an equivalent Fabry–Perot laser cavity. For example, a coupling coefficient of the DFB laser of $\sigma L = 2.2$ corresponds to a reflection coefficient of the external mirror of the FP laser of $R = 0.32$ [21]. The whole light frequency range under consideration is limited by ∼100 MHz that covers several modes of the ring resonator of several meters long. The typical light round trip time in a semiconductor FP cavity is a few ps. For the DFB laser with the same length of the cavity this value is lower, but of the same order of magnitude. The solitary semiconductor laser operation is assumed to be single-frequency, which is a natural property of the DFB laser diode. The free spectral range (FSR) of the semiconductor laser is in GHz range, so only one, the most successful longitudinal mode possessing the highest gain and the lowest generation threshold is under consideration. Effects associated with light polarization are not taken into account, i.e. laser light is considered to be linearly polarized and all fiber components (fiber lengths, couplers, a circulator) are assumed to be polarization maintaining [24].

According to [25] the number of photons S, the phase of optical field φ, and the number of carriers n in the semiconductor laser cavity could be described by Lang–Kobayashi type laser rate equations:

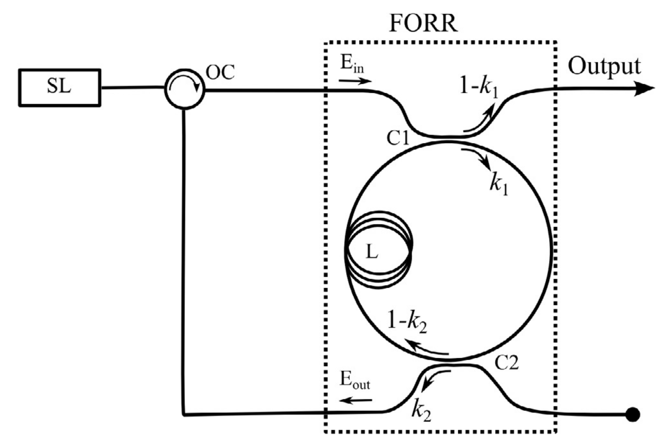

Fig. 1. Experimental setup of the semiconductor laser coupled to a fiber-optic ring resonator (FORR); OC—optical circulator, C1, C2—optical couplers.

$$\begin{aligned}
\frac{dS}{dt} &= \left(G\left(n-n_0\right)-\frac{1}{\tau_p}\right)S+Q+2k_c\sqrt{f_{ext}}\sqrt{S(t)\,S\left(t-\tau_0\right)} \\
&\quad\cdot\cos\left(\omega_0\tau_0+\varphi(t)-\varphi\left(t-\tau_0\right)\right)+F_s(t) \\
\frac{d\varphi}{dt} &= \frac{1}{2}\alpha G\left(n-n_{th}\right)-k_c\sqrt{f_{ext}}\sqrt{\frac{S\left(t-\tau_0\right)}{S(t)}} \\
&\quad\cdot\sin\left(\omega_0\tau_0+\varphi(t)-\varphi\left(t-\tau_0\right)\right)+F_\varphi(t) \\
\frac{dn}{dt} &= \frac{I-I_{th}}{e}-\frac{n}{\tau_s}-G\left(n-n_0\right)S+F_n(t).
\end{aligned} \tag{1}$$

Here τ_0 is the round-trip delay time of the external cavity, k_c is the parameter determined by the reflection coefficient of the semiconductor laser cavity R and the cavity round-trip time $\tau_L = 2n_pL_D/c$:

$$k_c = \frac{1}{\tau_L}\frac{1-R}{\sqrt{R}} \tag{2}$$

f_{ext} is the power fraction of light returned to the cavity, ω_0 is the central frequency of a solitary semiconductor laser at the generation threshold, α is the semiconductor linewidth enhancement factor, $I - I_{th}$ is the difference between the laser pump current and its threshold value, e is the elementary charge, τ_s is the carrier lifetime, τ_p is the photon lifetime. The gain is presented in a linear approximation for the number of non-equilibrium carriers n, i.e. $g = G\left(n-n_0\right)$, where G is the differential gain, n_0 is the number of non-equilibrium carriers corresponding to zero amplification, and n_{th} is the number of non-equilibrium carriers at the generation threshold. The term $Q = \beta/\tau_p$ describes spontaneous emission, where β is the inversion coefficient, F_i are the terms describing the Langevin noise source of a Gaussian statistics simulated through a random number generator [26]. The parameters used for the numerical simulations describe a typical semiconductor lasers and are listed in Table 1.

The values of S_{th} and n_{th} corresponding to the generation threshold of a solitary semiconductor laser could be found analytically from (1) considering its steady-state solution. Numerical simulations of (1) have been performed employing 4-order Runge–Kutta algorithm and resulted in time series of the number of photons $S(t)$, carriers $n(t)$, and the phase of optical field $\varphi(t)$. Then these data have been used for reconstruction of the laser spectrum determined as a Fourier transforms of the complex field amplitude $E(t) = \sqrt{S(t)}\exp(i\varphi(t))$.

For the laser operating with a feedback the threshold gain and the generation frequency are determined from (1) by the power fraction returned to the resonator f_{ext} and by the feedback phase

$$\begin{aligned}
\Delta g &= -2k_c\sqrt{f_{ext}}\cos\left(\omega\tau_0\right), \\
\left(\omega-\omega_0\right)\tau_0 &= -C\sin\left(\omega\tau_0+\arctan\alpha\right),
\end{aligned} \tag{3}$$