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Modulation performance of semiconductor laser coupled with an ultra-short external cavity

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ABSTRACT

We present modeling on the evaluation of the modulation performance of semiconductor laser coupled with an ultra-short external cavity in terms of the intensity modulation (IM) response, relative intensity noise (RIN), carrier to noise ratio (CNR), and frequency chirp. The modulation is characterized along the period-doubling (PD) route to chaos induced by optical feedback (OFB). We focus on the possibility of increasing the modulation bandwidth by improving the carrier–photon resonance (CPR) frequency or inducing resonant modulation due to photon–photon resonance (PPR). We show that along the route to chaos, OFB could increase the CPR frequency and improve the 3 dB-modulation bandwidth from 19 GHz to 28 GHz. When strong OFB keeps the continuous wave (CW) operation or induces periodic oscillation (PO), PPR becomes significant and reveals resonance modulation over mm-frequency passband exceeding 50 GHz. Both CNR and frequency chirp are also enhanced around the CPR and PPR frequencies. The highest CNR peak is obtained when modulating the CW or PO laser, whereas the maximum peak of chirp corresponds to non-modulated chaotic laser.

1. Introduction

Improving the modulation bandwidth of semiconductor lasers has received much attention for applications in dense-information transmission technologies, such as the broadband radio-over-fiber (RoF) networks. Several schemes have been applied to increase the modulation bandwidth of the semiconductor laser, including multiple quantum-well structures [1], optical injection locking [2,3], and modulation integration [4]. Another efficient technique is the OFB induced by coupling (or integrating) the laser to an ultra-short external cavity. OFB happens to sustain the relaxation oscillation of semiconductor lasers, improve the CPR, and increase the modulation bandwidth [5–7]. In the limit of ultra-short external cavities, OFB has been deployed to induce PPR at frequencies beyond the conventional CPR frequency and enhance the IM response spectrum over a passband around the PPR frequency [8–10]. Tuning the PPR frequency at a desired high frequency requires tailoring the length of the external cavity and optimizing the feedback ratio [9,11,12]. A frequency gap in the IM response and lower than the 3 dB-level is normally seen between the CPR and the induced PPR frequencies, which limits the benefit of the laser modulation to the high-frequency passband of the resonance modulation. The IM response within this frequency gap could be fulfilled and a flat response spectrum is achieved by optimizing the modulation parameters and OFB configuration [9,13]. In this case, the IM response is extended to the PPR frequency and the modulation frequency is boosted to ultra-large frequencies.

The modulation performance of the semiconductor laser is measured not only by the spectral characteristics of the IM response, but also by the associated intensity noise, distortion and frequency chirp of the modulated signal [14,15]. Noise is an intrinsic property of the semiconductor laser induced due to the quantum nature of the processes of drop/add processes of photons and injected carriers in the lasing process [16]. The noise properties of the laser are evaluated by the spectrum of RIN, which is enhanced around the modulation frequency [17,18]. In analog applications, the modulation and noise performance of the laser can be evaluated by the CNR that defines the power carried at the modulation (carrier) frequency relative to noise background [19,20]. Modulation generates also distortion, and even clipping, in the modulated signal [14,18,21,22] due to intrinsic nonlinear effects, such as the relaxation oscillations, spatial hole burning, and gain suppression [23,24]. The signal distortion adds to the laser noise, especially in the frequency regime of the CPR frequency [14,17,18]. In addition, the modulation performance of both high-speed lasers and their application systems is significantly affected by frequency chirp, which accompanies the intensity modulation [15,25]. In applications such as fiber communications, this frequency chirping may interact with chromatic dispersion and induce distortions of the laser signal traveling along the optical fiber

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[26].

On the other hand, OFB is not always advantageous to the operation of semiconductor laser; it may destabilize the laser dynamics and increase both the laser fluctuations and frequency chirp [27–33]. In the limit of short-external cavities, a non-modulated laser follows a PD route to chaos in the regime of weak and intermediate OFB [34,35]. Along this route, the laser exhibits period-1 oscillations, followed by PD oscillations before entering a regime of chaos [35]. In the regime of strong OFB, the laser may keep CW operation, or have PO or chaos [33]. On the other hand, when the laser subjected to OFB is sinusoidally modulated, the waveform of the modulated signal depends on the dynamic state of the non-modulated laser in addition to the modulation conditions [36]. The signal could be of period-1 or PD, clipped, superposed by relaxation spikes or oscillations, or chaotic [36]. Several groups investigated the modulation response of the semiconductor laser under OFB, however their main interest was to tailor the modulation bandwidth [5–13]. Inadequate attention has been given to look into the laser dynamics and the associated noise and correlating them to the modulation response. Such a study could contribute to control the modulation performance and optimized the design of semiconductor coupled with an ultra-short external cavity.

In this paper, we introduce numerical modeling and comprehensive computer simulations on the modulation performance of semiconductor laser coupled with an ultra-short external cavity. The modulation performance is evaluated in terms of various properties, including the waveform of the laser intensity and frequency shift, and the frequency spectra of the IM response, RIN, CNR, and frequency chirp. These modulation characteristics are investigated and correlated in the possible OFB-induced dynamic states of the non-modulated laser, including CW operation, PO, PD oscillations and chaos. The investigated OFB ranges between weak and very strong and is modeled by a time-delay rate equation approach that considers the multi-reflections occurring in the external cavity. We focus on the conditions that correspond to improving the modulation bandwidth either by increasing the CPR frequency or by inducing PPR modulation and gain insight of the corresponding modulation characteristics. We elucidate the origin of the PPR as a result oscillation of external-cavity modes due to strong OFB. We show that along the PD route to chaos of the laser coupled with 2.5 mm-length external cavity, OFB could increase the CPR frequency and improve the 3 dB-modulation bandwidth from 19 GHz to 28 GHz. When strong OFB keeps CW operation or induces PO, PPR becomes significant and reveals resonance modulation with enhanced response of 3.2 dB around a frequency of 53 GHz. Both CNR and frequency chirp are also enhanced around the CPR and PPR frequencies. The highest CNR peak (84 dBc) is obtained when modulating the CW or PO non-modulated laser, whereas the maximum peak of chirp (21 GHz) corresponds to chaotic non-modulated laser.

In the next section, we introduce the theoretical model of modulation of semiconductor laser under OFB as well as the numerical procedures of calculation. In section 3, we present the results on evaluation of the modulation performance. Finally, this work is concluded in Section 4.

2. Modeling of laser subjected to OFB under modulation

The time-delay treatment of OFB in semiconductor lasers is schematically shown in Fig. 1. The laser cavity of length L_D, and front and back facet reflectivities of R_f and R_b, respectively, is coupled with an ultra-short external cavity of length L_{ex}, refractive index n_{ex}, and end-mirror reflectivity R_{ex}. The output beam is assumed to travel several roundtrips in the external cavity due to multiple reflections between the laser and the external reflector. After every roundtrip, light is injected back into the laser cavity from the front facet with strength $\Gamma=\eta R_f$, where η represents the coupling efficiency into the laser cavity. Therefore at the front facet, and every roundtrip of period $\tau=2n_{ex}L_{ex}/c$, the injected light is regarded as light of time delay τ relative to the light reflected back into the laser cavity. Then the threshold gain and phase conditions of the laser are modified to [37,38]

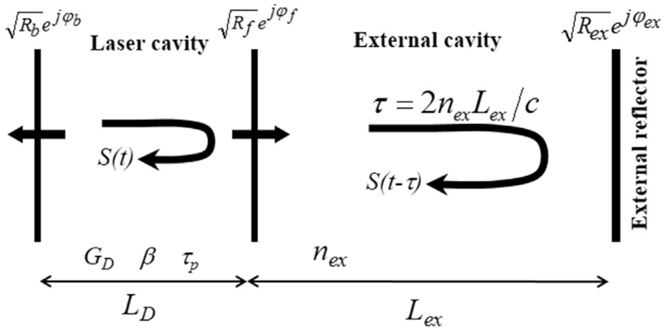

Fig. 1. Scheme of OFB of a semiconductor laser coupled with an external cavity.

$$G_{th}=\frac{1}{\tau_p}-\frac{v_g}{L_D}\ln|U(t-\tau)| \tag{1}$$

$$2\beta L_D+\phi_f+\phi_b+\phi=2s\pi \tag{2}$$

where τ_p is the photon lifetime in the laser cavity, φ_f and φ_b are the optical phases at the front and back facets of the laser, respectively, β is the phase constant in the laser cavity, and s is an integer. $U(t-\tau)$ is a time-delay function that accounts for the OFB due to multiple reflections in the external cavity, and is given by [37]

$$\begin{aligned}U(t-\tau)&=|U(t-\tau)|e^{-j\phi}\\&=1-\frac{1-R_f}{R_f}\sum_{p=1}\sqrt{\eta R_{ex}R_f}^{\,p}e^{-jp\omega\tau}\sqrt{\frac{S(t-p\tau)}{S(t)}}\frac{e^{j\theta(t-p\tau)}}{e^{j\theta(t)}}\end{aligned} \tag{3}$$

where $S(t)$ and $\theta(t)$ are the photon number and optical phase of the oscillating field, respectively, and $S(t-\tau)$ and $\theta(t-\tau)$ are the corresponding time-delay values. P is an index for the roundtrips. The exponent $\omega\tau$, where ω is the angular frequency of the laser emission, represents the OFB phase delay of the oscillating field in one round trip.

By using the lasing conditions (1) and (2), the modulation and noise characteristics of semiconductor lasers under OFB can be described by the following time-delay rate equations of the carrier number $N(t)$, photon number $S(t)$ and optical phase $\theta(t)$

$$\frac{dN}{dt}=\frac{1}{e}I(t)-\frac{N}{\tau_s}-\frac{av_g}{V}\frac{N-N_g}{1+\varepsilon S}S+F_N(t) \tag{4}$$

$$\frac{dS}{dt}=[\xi\frac{av_g}{V}\frac{N-N_g}{1+\varepsilon S}-G_{th}]\,S+\xi\beta_{sp}\frac{N}{\tau_s}+F_S(t) \tag{5}$$

$$\frac{d\theta}{dt}=2\pi\Delta\nu(t)=\frac{1}{2}(\alpha\xi\frac{av_g}{V}(N-N_{th})-\frac{v_g}{L_D}\phi)+F_\theta(t) \tag{6}$$

where $\Delta\nu(t)$ is the shift of the lasing frequency induced by the instantaneous variation of the optical phase due to variations in $S(t)$ and $N(t)$. The maximum variation of this frequency shift defines