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Time Domain Traveling Wave Model of Distributed Feedback semiconductor laser with weak optical feedback

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1. Introduction

The Distributed feedback (DFB) semiconductor lasers are widely used in coherent, high speed, long distance optical communications systems due to their attractive properties such as wavelength stability and narrow spectral width [1]. In such systems, external optical feedback happens when a small fraction of the laser output re-enters into the laser cavity from an optical component such as the edge of optical fiber. It is well-established that laser operation could be affected negatively by a small amount of optical feedback [2]. Nevertheless, semiconductor lasers with optical feedback generate a chaotic output which has been used for many important practical applications like secure communication systems and random number generation [3, 4]. Recently, laser designer emphasis on designing semiconductor lasers with high tolerance to optical feedback [5,6].

For numerical simulation, the theoretical framework was provided by the well-known Lang-Kobayashi model [7], this model was derived from the rate equations model and has been used extensively in the last four decades in modeling laser diodes with different types and level of optical feedback. It has been shown that the L-K model is a robust and well researched model and has a very good agreement with the experimental results. In fact, the L-K model was originally developed for the simple Fabry-Pérot Laser diodes and it assumed by many authors to be valid for complicated structure such as DFB laser diodes. However, the L-K model is based on the assumption that the optical fields are uniformly distributed along the laser cavity, therefore it does not take into account the spatial distribution of optical fields and carrier density inside the laser cavity as a result it does not include the spatial-hole burning (SHB), which is now essential in the analysis of DFB semiconductor lasers where these effects are more significant [8]. In addition to that, some important structural parameters of DFB LDs such as diffraction grating and phase-shifts have been ignored in the L-K model [9]. Furthermore, the L-K does not give any information about the spectral characteristics of the laser [10].

In the present paper, we have developed a new approach to investigate the effect of weak external optical feedback on DFB semiconductor lasers by using Time Domain Traveling Wave (TDTW) Model. Although, TDTW model have been already used in modeling Laser diodes with external optical feedback for short external cavities and strong feedback level [11,12]. We focus in this work, on weak feedback regimes. When the DFB laser is subjected to weak optical feedback the lasing state of laser, hence the optical fields inside the laser cavity and boundary conditions change. We express two sets of equations in the time domain for the counter-propagating optical fields deviation by cause of optical feedback. The time delay of reflected light from the external cavity is taken into account in boundary conditions by considering in the equivalent reflectivity of the laser facet submitted to the feedback [13]. Moreover, the multimode operation of the laser, spontaneous emission noise, the spatial distribution and phase of optical fields and structure parameters of the DFB laser are taken into account implicitly in this unified model. The numerical solution of this time domain model is computed directly in the time domain by using the finite difference time domain (FDTD) method.

2. Simulation results and discussion

We have applied the extended TDTWmodel to study an index-coupled quarter phase shifted DFB laser operating at 1550 nm wavelength exposed to different level of weak external optical feedback, the laser parametrs used in numerical simulation are given in [17]. The time step of simulation is 1ps.

The Fig 1.(A) shows the light output power in (mW) versus the injection current in (mA) of solitary laser and for laser exposed to different level of weak optical feedback -80 dB and -45 dB respectively, the calculation of the static characteristics is obtained from the dynamic response by biasing the laser at a

fixed drive current and waits until the laser reaches its steady-state, then calculating the average output power. For solitary laser, the threshold current predicted by the model is approximately: $I_{th} = 18.8\text{mA}$, it can be observed in Fig. 1. (A) that small reduction of the threshold current when the feedback level is -45 dB, where the threshold current become approximately 16.6 mA that represent a 8% reduction of the total threshold current. One the other hand, it can be observed also an increase of the (L-I) curve slope efficiency as the feedback level increases, our result agrees with the theoretical and experimental results in [15, 16].

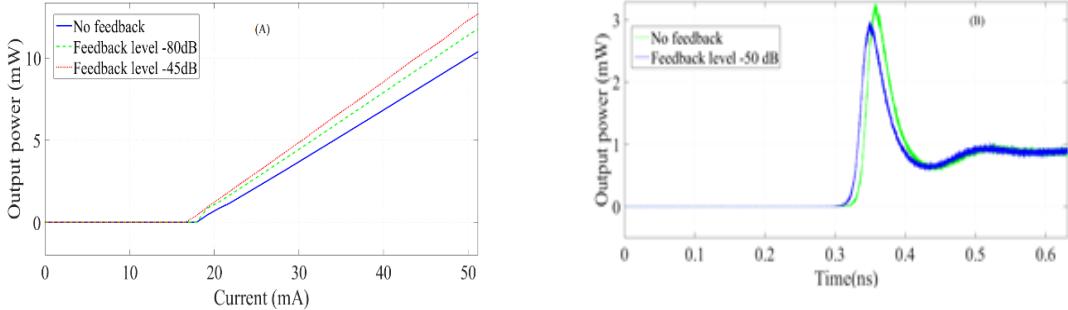


Figure 1 (A) L-I characteristics of (DFB) laser exposed to different amounts of optical feedback, (B) Transient response of (DFB) laser with and without optical feedback.

The Fig. 1.(B) shows the transient response of DFB laser feedback without and with feedback level of -50 dB, in both situations the laser takes less than 0.4 ns to reach the steady state condition. We can notice that there is a slight change in the damping ration and turn-on delay time due to feedback that's as a result of changing the end facet reflectivity at the right end facet. This result is confirmed when calculating the resonance frequency of relaxation.

In order to get the optical spectra, we performed a Fourier transform of the electric field on facet submitted to feedback facet after the laser reach stable output. For the simulation of the spectrum, the laser is biased at 45 mA, and the average output power for solitary laser is approximately 7.3 mW. Fig 2. (A) illustrates the spectrum of a solitary DFB laser, the laser linewidth is about 6 MHz which is calculated by the TDTW model by taking the FWHM at the central lasing wavelength of spectrum

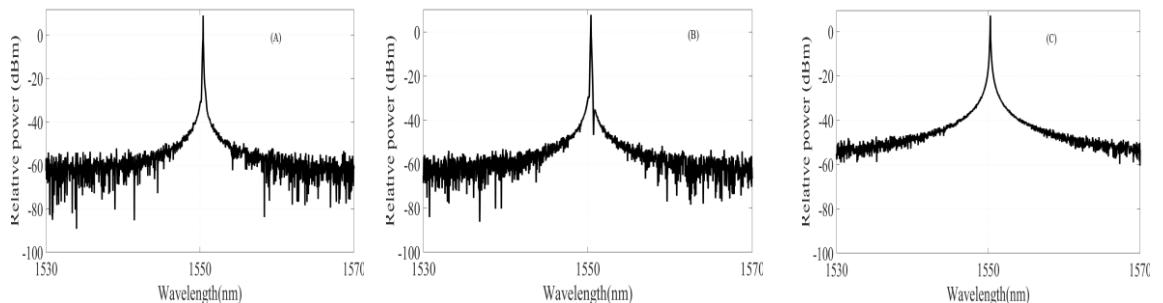


Figure 2 Optical spectrum of a: (A) solitary (DFB) laser, (B) with in phase feedback -80 dB, (C) with out of phase feedback -70 dB

The Fig. 2. (B) shows spectrum of the laser subjected to very weak optical feedback of -80 dB and external cavity length 0.4 cm which correspond to roundtrip delay in the external cavity is 2 ps that match the calculated feedback parameter less than 1 (Regime I)[18], we notice a small reduction of the linewidth from 6 MHz for solitary laser to 4 MHz, as suggested by [14] we conclude that the reflected wave is in phase with the wave inside the laser cavity [14,18,27]. We increase slightly the feedback level to -70 dB, the feedback parameter still less than 1, (Regime I) [18], the Fig. 3. (C) shows that the laser linewidth is broaden to 8 MHz, the feedback light is out of phase with the wave inside the laser cavity [14,18,19].

Let's now consider a feedback level of -65 dB and the external cavity length about 20 cm which correspond to roundtrip time in external cavity 1.32 ns, that match calculated feedback parameter greater than 1, the Fig. 3. (A) shows the calculated spectra, it can be observed in the curve the appearance of the line splitting and mode hopping as result of external cavity modes that lead to poor side-mode suppression ratio (SMSR), that operation corresponds to the transition to out of phase Regime II [18]. We increased the feedback level to -60 dB and change carefully the value of phase of the feedback light, the

spectra of the laser is plotted in Fig. 3. (B), the linewidth of the laser is reduced to 2.7 MHz, that corresponds to in phase Regime II [18, 19]. Let's further increase the feedback level to -45 dB, the Fig. 3. (C) shows the calculated spectra, we notice that the laser linewidth is reduced to 1 MHz, which represent the narrowest measured linewidth, this correspond to transition to Regime III independent on the phase of the reflected light [14,18].

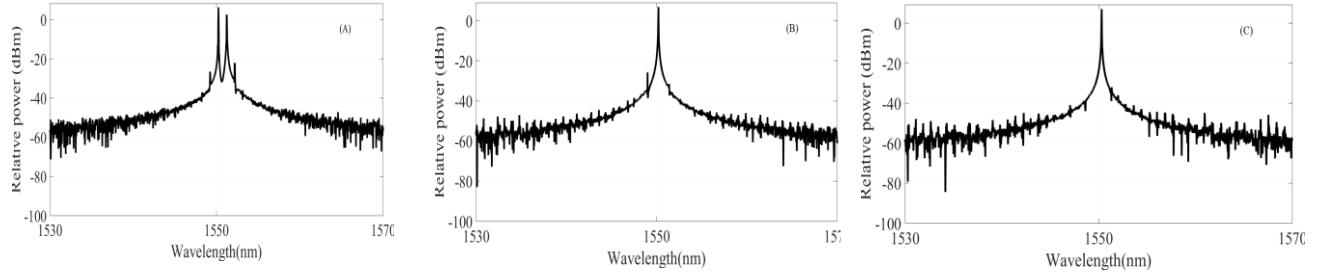


Figure 3 Optical spectrum of a DFB: (A) out of phase feedback -63dB, (B) out of phase feedback -60 dB, (C) feedback - 45dB

Fig. 4. (A) illustrates the average value of the Relative Intensity Noise (RIN) over a frequency range of [0-10GHz] for device biased at different values of injection current for several levels of weak feedback level, the RIN is calculated in the same manner as in rate equations modeling [20]. It can be seen that weak optical feedback has no effect on the average RIN, this result is demonstrated theoretically and experimentally in [6, 21]. We plot in Fig. 4. (B) the resonance frequency of relaxation oscillations as function of feedback level, it is well known that the modulation frequency must be smaller than the relaxation oscillations frequency of the laser [22]. For solitary laser the resonance frequency of the relaxation oscillations calculated by the TDTW model for drive current at: $I = I_{th}$, $I = 1.3I_{th}$, $I = 1.9I_{th}$ is respectively 1.96 GHz, 3.6 GHz and 7.2 GHz, for drive current equal to threshold it can be seen that there is no significant change in frequency of relaxation oscillation, but as the drive current increases to $I = 1.3I_{th}$ and $I = 1.9I_{th}$, we notice that a small change in feedback level causes a significant change in the frequency of relaxation oscillations [23], these results demonstrates that the resonance frequency of relaxation oscillations can be easily altered by the weak feedback in order of 1~2 GHz depending on the output power.

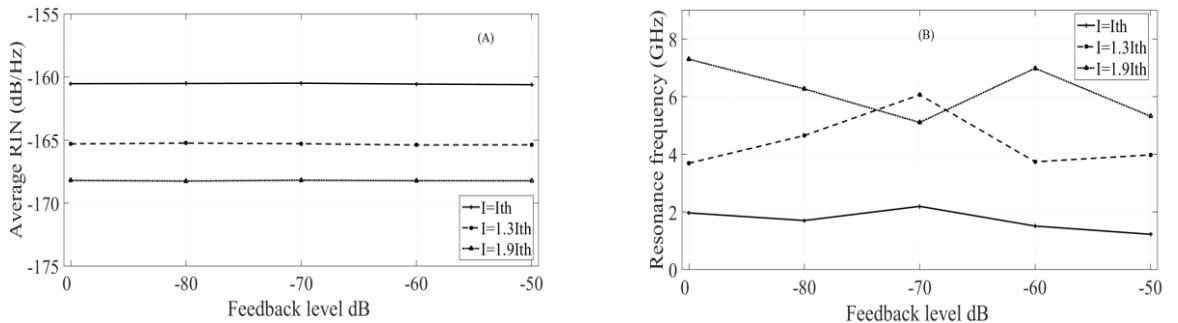


Figure 4 (A) Average RIN over frequency range versus external optical feedback level for different values of bias current.
(B) Relaxation resonance frequency versus external optical feedback level for different values of bias current.

3. Conclusions

A new theoretical model for distributed feedback semiconductor laser with weak optical feedback has been presented. New fields equations deviations in the time domain have been derived for the change of the lasing state of the laser due to optical feedback. The simulation results are obtained and compared for different values of external cavity parameters. To validate the accuracy of our model we have compared our results with other theoretical and experimental results, which they show a good agreement. Our results also show that the proposed model can be used as a straightforward simulation tool in the analysis of static, dynamic and noise characteristics of DFB laser with weak optical feedback.

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