Modeling the Effect of Slave Laser Gain and Frequency Comb Spacing on the Selective Amplification of Injection Locked Semiconductor Lasers

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***Abstract*— A rate equation model was used to model the optical filtering properties of an injection locked semiconductor laser. The changes in the side mode suppression ratio (SMSR) of an injected optical comb due to the gain of the slave laser, and the frequency spacing of the injected optical comb, were investigated numerically. It was found that the SMSR increases with increasing gain in the slave laser, and also that decreasing the frequency spacing of the comb negatively effects the SMSR of the lowest and highest frequencies in the comb more than the other comb lines.**

I. Introduction

The demand for higher bandwidth has focused recent research on developing more spectrally efficient wavelength division multiplexing (WDM) solutions. Coherent WDM is one such solution [1], which requires the generation, demultiplexing, and modulation of coherent optical combs. Low linewidth coherent optical combs have been demonstrated on monolithically integrated photonic circuits, with comb spacings as low as 4GHz [2]. While arrayed waveguide gratings (AWGs) are used to demultiplex 50GHz WDM channels, AWGs are not viable for coherent combs separated by 10GHz or less. Optical injection locking has previously been investigated as an active frequency filter on photonic integrated circuits, by injection locking a slave laser to one of the lines of the injected optical comb [3].

In this paper, the side mode suppression ratio (SMSR) attainable through injection locking a slave laser to a line of a coherent comb is investigated numerically, based on the models presented in [4], [5]. The effects of the of gain of the slave laser, and the frequency spacing of the optical comb are determined.

II. Theoretical Model

The rate equation model used to simulate the injection of optical combs is based on the model presented in [4]. The complex electric field $\widetilde{E_s}(t)$ of the slave laser is defined as

$$\widetilde{E_s}(t) = E_s(t)e^{i(\omega_0 t+\phi_s(t))} \tag{1}$$

where $E_s(t)$ and $\phi_s(t)$ are the real amplitude and phase of the slave laser, and ω_0 is the angular frequency of the free running slave laser. The field of the master laser $\widetilde{E_M}(t)$ which couples to the slave laser's signal was defined as in [5]

$$\eta f_d \widetilde{E_M}(t) = \sum_j E_j(t)e^{i\omega_j t} \tag{2}$$

TABLE I: Parameters used in the model.

G_N	$7.9\times10^{-13}m^3s^{-1}$	Differential gain
ω_0	$3.798\times10^{14}rads^{-1}$	Slave laser natural frequency
R_p	$1.07\times10^{31}s^{-1}$	Pump rate (at threshold)
N_{th}	$1.7172\times10^{24}m^{-3}$	Threshold carrier density
α_H	5.0	Linewidth enhancement factor
τ_s	$2.0\times10^{-9}s$	Carrier lifetime
τ_p	$2.0\times10^{-12}s$	Photon lifetime
E_{inj}	$3.5\times10^{17}NC^{-1}$	Injected field strength

where η is the coupling efficiency, f_d is the longitudinal mode spacing, and $E_j(t)$ and ω_j are the field amplitude and angular frequency of the j-th comb line. The initial phase of the comb is arbitrary, and was assumed to be zero.

The rate of change of the complex electric field E_S of the slave laser under the injection of the master laser's field E_M is given by [4]:

$$\frac{d}{dt}\widetilde{E_s}(t) = \left(i\omega(N) + \frac{1}{2}\left[G(t) - \frac{1}{\tau_p}\right]\right)\widetilde{E_s}(t) + \eta f_d \widetilde{E_M}(t) \tag{3}$$

Equation (3) can be converted to an amplitude-phase representation as in [4], which gives the rate equations for E_s and ϕ_s

$$\frac{dE_s}{dt} = \frac{G(N)E_s(t)}{2} + \sum_j E_j \cos(\Delta\omega_j t - \phi_s(t)) \tag{4}$$

$$\frac{d\phi_s}{dt} = \frac{\alpha_H G(N)E_s(t)}{2} + \sum_j E_j \sin(\Delta\omega_j t - \phi_s(t)) \tag{5}$$

where the gain $G(N)$ is

$$G(N) = G_N(N - N_{th}) \tag{6}$$

In (4), (5), $\Delta\omega_j$ is the difference in the angular frequency of the free running laser and the j-th comb line, and the amplitude of injected comb lines E_j is assumed not to vary in time. α_H is the linewidth enhancement factor and N is the number of carriers in the slave laser. In (6), G_N is the differential gain of the laser, and N_{th} is the threshold carrier density. The carriers vary as

$$\frac{dN}{dt} = R_p - \frac{N}{\tau_s} - G(N)E_s(t)^2 - \frac{1}{\tau_p}E_s(t)^2 \tag{7}$$

where R_p is the pump rate, and τ_p and τ_s are the photon lifetime and carrier lifetime receptively. The values of the parameters used in the model are presented in table I.

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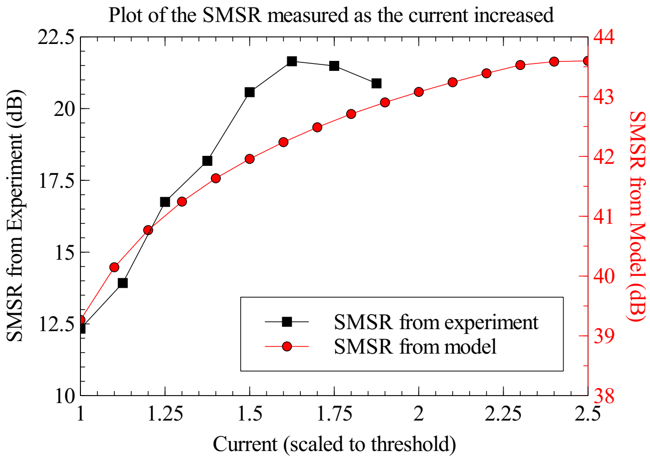

Fig. 1: Experimental (black) and theoretical (red) results showing the change in SMSR as laser current increases.

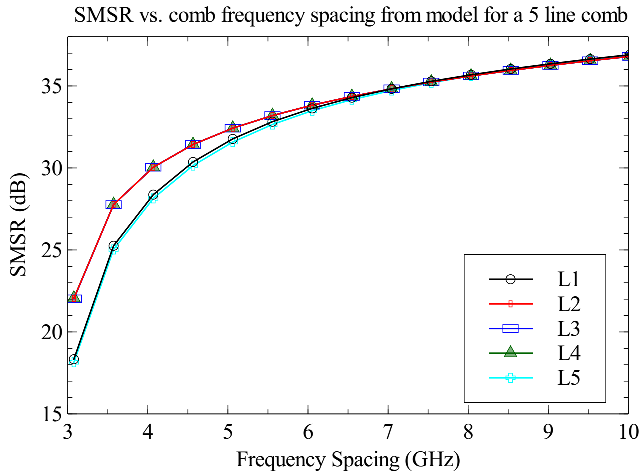

Fig. 2: The SMSR measured when injection locking to each line of a 5 line comb, as the comb spacing decreases (labeled from the lowest to the highest frequency line, L1 toL5).

III. Results and Discussion

The rate equations (4), (5) and (7) were solved numerically using a fourth order Runge-Kutta method, with a time step of 1.2ps. Spectral information was obtained by taking a fast Fourier transform of the output of the slave laser.

Initially, the change in SMSR due to the gain of the laser was investigated. In Fig. 1, theoretical and experimental results show how the SMSR of an optical comb changes as the current of the slave laser increases. The slave laser was injection locked to the lowest frequency line of a 3 line 12.5GHz comb in both cases. The experimental setup used was as in [3]. The slave laser under injection was a 7 slotted Fabry-Perot laser [6], which was operating in a single moded regime. The experimental results in Fig. 1 show that as the current increased in the slave laser, the SMSR increased until 1.62 times threshold, at which it began to decrease. This decrease in SMSR is due to the increase of gain seen by the other frequencies in the comb. The SMSR predicted by the rate equation model increased monotonically, as the model is single moded, and the other comb lines experience much less gain than the lasing mode as the pump rate increases. The single moded assumption of the model is also the reason that the calculated SMSRs are significantly larger (>20dB) than the experimental results.

The SMSR attainable through injection locking to each line of a 5 line optical comb was then investigated numerically, as the frequency spacing of the comb decreased. Shown in Fig. 2, the slave laser's frequency was varied to lock to each line individually, as the frequency spacing was swept from 12.5GHz to 3GHz. The laser was pumped at 1.2 times threshold. At 12.5GHz, the SMSR attainable when locking each line was effectively the same. As the frequency separation decreased, the model shows that the filtering properties of the injection locked slave laser became significantly worse, particularly when locking to the lowest and highest frequency lines. The main cause of the decrease in the SMSR is due to the increase in gain the neighboring comb lines experience as they move closer to the locked mode. When locked to the lowest and highest frequency lines of the comb, there is an asymmetric distribution of light from the comb on either side of the locked frequency. As the frequency spacing decreases, this asymmetry more negatively effects the SMSR obtained for the highest and lowest comb lines, as seen in Fig. 2.

IV. Conclusions

The effect of the slave laser's gain on the SMSR attainable from an injected optical comb has been investigated. The rate equation model used showed the SMSR increase beyond 2.5 times the threshold current. The experimental data presented shows the SMSR roll off after 1.62 times threshold current, due to the increase in gain experienced by the unlocked comb lines. The change in the SMSR as the comb frequency spacing decreased was also noted, and it was shown that the SMSR decreases as the spacing decrease. The SMSR decreases more rapidly with this change when locking the slave laser to the highest and lowest frequencies in the optical comb.

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