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Enhancement of Locking Bandwidth in DFB Lasers by Side-Mode Injection-Locking

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Semiconductor lasers with a larger modulation bandwidth are promising in the high-speed digital and analog fiber-optic communications. One effort to achieve the large modulation bandwidth and a small chirp is using external optical injection locking technique, in which the light from one laser (Master Laser, ML) is injected into another laser (Slave Laser, SL). The modulation bandwidth of a strongly injection-locked semiconductor laser can be significantly improved [1]. But, it requires the careful control of the ML light injection power and the frequency offset between two lasers because of the narrow stable-locking range. We have been looking into a method to achieve the broad stable-locking range, and recently found the side-mode injection locking of DFB lasers quite useful [2].

In this paper, we analyze the stable-locking range of a side-mode injection-locked DFB laser. The analysis is based on the modified rate-equations with one side-mode taken into account, and shows that the side-mode injection locking can provide the broader stable-locking range than the fundamental injection-locking does.

When one side-mode of a DFB laser is taken into account, the DFB laser under external light injection can be described as follows.

$$\frac{dS_1}{dt}=\left[\Gamma g_1(N,S)-\frac{1}{\tau_p}\right]S_1+R_{SP}+C_1\left\{2K_C\sqrt{S_{inj}S_1}\cos\theta_1\right\}$$

$$\frac{d\Phi_1}{dt}=\frac{1}{2}\alpha\left[\Gamma g_1(N,S)-\frac{}{\tau_p}\right]+C_1\left\{-(\omega_{inj}-\omega_1)+K_C\sqrt{\frac{S_{inj}}{S}}\sin\theta_1\right\}$$

$$\frac{dS_j}{dt}=\left[\Gamma g_j(N,S)-\frac{}{\tau_p}\right]S_j+R_{SP}+C_j\left\{2K_C\sqrt{S_{inj}S_j}\cos\theta_j\right\}$$

$$\frac{d\Phi_j}{dt}=\frac{1}{2}\alpha\left[\Gamma g_j(N,S)-\frac{1}{\tau_p}\right]+C_j\left\{-(\omega_{inj}-\omega_j)+K_C\sqrt{\frac{S_{inj}}{S_j}}\sin\theta_j\right\}$$

$$\frac{dN}{dt}=\frac{I}{qV_a}-\frac{N}{\tau_N}-\sum_{i=1\ and\ j}g_iS_i$$

$g_1(N,S)=g_0(N-n_t)(1-\varepsilon S)$, and $g_j(N,S)=g_r g_1(N,S)$.

S_1 and S_j are the photon densities of the fundamental mode and side-mode in the DFB laser, respectively, and Φ_1 and Φ_j the corresponding optical phases. S is the total photon density in the laser cavity. S_{inj} and ω_{inj} are the incident ML photon density and angular optical frequency. θ_{1y} and θ_j are the phase detuning for the fundmental injection locking and side-mode injection locking cases. g_r is the gain suppression factor, whose value is chosen for the side-mode to be suppressed by 30 dB. The coupling rate (K_C) is defined as $\upsilon_g/2L$. The value of 141.7 GHz is used for K_C in our analysis, which corresponds to the SL cavity length (L) of 300 μm. Other parameters have the usual meanings, whose values are obtained from [3].

Fig. 1 shows the stable-locking ranges for the fundamental injection locking and side-mode injection locking cases. The conditions for the stable-locking range can be determined by the s-domain stability analysis of the linearized rate-equations above. It is assumed that the SL is biased at $2\times I_{th}$ and the side-mode suppression ratio is 30 dB in the free-running (no optical injection) state. Fig. 1 shows three noticeable points. The first one is that the side-mode injection contributes little to the broad stable-locking range in the lower boundary. The second one is, however, the significant contribution of the side-mode optical injection to the broadening of the stable-locking range in the upper boundary. For R of -12.4 dB, the stable-locking range of the side-mode injection is of around 28.1 GHz, which is over twice as broad as that of the fundamental injection, 13.8 GHz. R is defined as the power ratio between the incident ML photon density and the free-running SL photon density. The last one is that there exists a minimum R in making the stable-locking occur and its locking range broaden in the side-mode of the DFB laser. In our analysis, the required R should be more than –30 dB.

Fig. 2 shows the resonance frequency enhancement of the DFB laser by the fundamental optical injection for R = -11.2 dB in Fig. 1. From Fig. 2, the resonance frequency can be improved just by the proper control of the frequency offset between ML and SL, but will decrease as the frequency offset is detuned toward the lower boundary of the stable-locking range. This is well related with the damping factor of the laser [1].

Fig. 3 shows the resonance frequency enhancement and mode suppression ratio by the side-mode optical injection for the same R in Fig. 2. The resonance frequency is also improved with increasing the frequency offset toward the upper boundary. Near the upper boundary of the stable-locking range, however, there are the dips in the modulation spectra and the amplitude at the resonance frequency becomes smaller than that the DC amplitude. This comes from the fact that the modulation spectrum is made up of two resonances [1]. Fig. 3 also shows the fundamental mode suppression when the side-mode is injection-locked. The mode-suppression ratio changes with the frequency offset detuning. From Fig. 3, one can see that the resonance frequency enhancement occurs when the fundamental mode is suppressed by more than around 30 dB.

In conclusion, we have analyzed the side-mode injection-locked DFB lasers based on the modified rate-equations in which the side-mode of the DFB laser is taken account. And, it is found that the stable-locking range can broadened by the side-mode optical injection rather than the fundamental optical injection.

References

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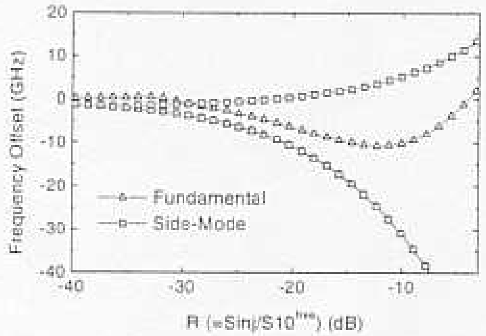

Fig.1 Stable-locking range for the fundamental and side-mode optical injection. The symbols in the lower boundary are overlapped each other.

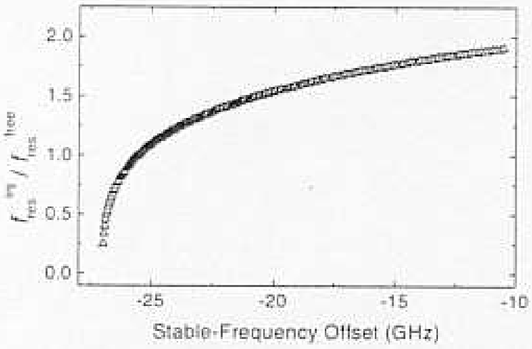

Fig.2 Enhanced resonance frequency by the fundamental optical injection for R = -11.2 dB.

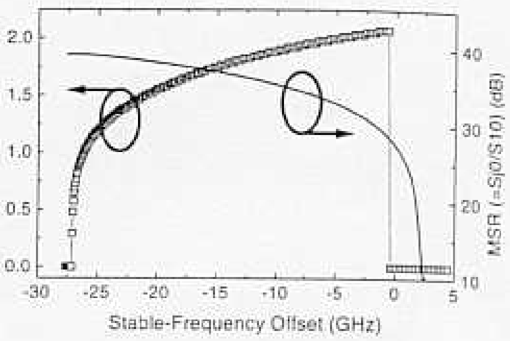

Fig. 3 Resonance frequency Enhancement and mode suppression ratio by the side-mode optical injection for R = -11.2 dB.