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Effects of Additional Feedback in External Cavity Semiconductor Lasers

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We describe the effects of additional feedback in external cavity semiconductor lasers, which are sensitive to feedback phase. It is shown that additional feedback with favorable phase can serve to enhance mode selectivity. The optimum feedback conditions to maximize the system immunity against unwanted additional feedback with unfavorable phase have also been determined.

1. Introduction

The specrtal purity of semiconductor lasers determines the receiver sensitivity limit in coherent optical communications[1]. Therefore, serious research interest is focused on linewith reduction of semiconductor lasers. Among various methods to reduce the laser linewidth, an external cavity configuration is the most feasible method to reduce the laser linewidth up to several kHz[2].

The behavior of external cavity semiconductor lasers subject to exteranl feedback has been well documented[3], although many aspects of this behavior are not well understood. One particularly interesting question is ; how will external cavity lasers behave when they subject to additional feedback from other external reflectors, such as may occur in optical fiber transmitter or local oscillator modules, coupled-cavity lasers, or OEICs where optical isolation may not be feasible. Here we investigate the effects to assure stable and consistent operation of external cavity lasers under optically harsh environment or to utilize this additional feedback for improvement of the system performances.

2. Theory

An external cavity laser subject to additional feedback can be modeled as a system with two of external feedback mirrors (i.e. a double external cavity laser) as shown in Fig. 1(a), where mirror M_1 and M_2 represent respectively an inherent external cavity and an extra cavity for additional feedback. Here $-r_{ext,k}$ (k=1,2) is the amplitude reflectivity of the k-th external mirror including any external cavity coupling losses (the negative sign arises from the π phase shift upon reflection). It can be represented by a single cavity laser, as shown in Fig. 1(b), by introducing the concept of an effective reflectivity[4] due to the combination of the laser facet and external mirror.

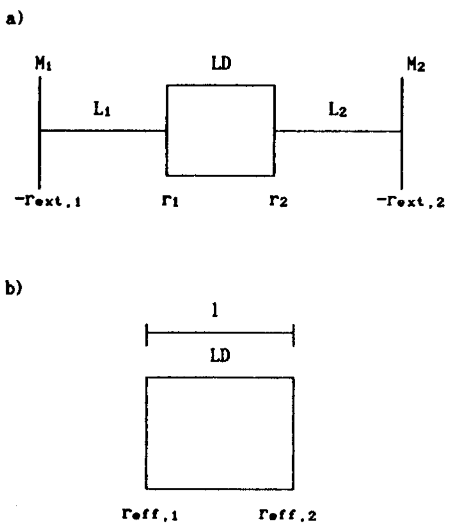

Fig. 1. Schematic representation of (a) an external cavity laser with additional feedback from mirror M_2 and (b) its equivalent. (LD - laser diode, $M_{1,2}$ - externnal mirrors)

Applying similar method in [4], we obtain easily effective reflectivies for both facets of the laser

$$r_{eff}(k) = r_k-(1-r_k^2)r_{ext,k}\sum_{p=1}^{\infty}(r_k r_{ext,k})^{p-1} C_k \exp(ip\omega\tau_{ext,k})\frac{E(t-p\tau_{ext,k})}{E(t)}, \cdots (1)$$

where E(t) is the outgoing complex optical amplitude which is normalized such that $|E(t)|^2$ represents the photon density, $\tau_{ext,k}$ is the external cavity round trip time (= $2L_k/c$), L_k is the external cavity length, c is the light speed in vacuum, C is the coupling efficiency at the laser facet[4], p is the roundtrip index, and ω is the angular frequency. Here the subscript k= 1,2 represents the parameter of the external cavity formed with the k-th facet. Then, we arrive at a modified field equation which is applicable to the double external cavity lasers :

$$\frac{dE(t)}{dt} = [i(\omega - \omega_0) + \frac{\Delta G(1-i\alpha)}{2} + f_e]\, E(t), \cdots (2)$$

where the feedback parameter f_e is given by

$$f_e = \frac{1}{\tau}\ln\left[\frac{|r_{eff}(1)r_{eff}(2)|}{r_1 r_2}\right], \cdots\cdots\cdots\cdots (3)$$

ω_0 is the angular frequency without external feedback, ΔG (= $c\Delta g/\mu$) is the temperal gain change, Δg is the spatial gain change, μ is the refractive index in the active region, and τ is the diode cavity roundtrip time.

Setting $E(t) = E_0(t)\exp(-i\phi t)$ and seperating the real and imaginary parts of Eq.(2), we have rate equations for the double external cavity lasers.

At steady state, we get gain change and frequency shift from the rate equations

$$\Delta G = -\frac{\ln|r_{eff,s}(1)\ r_{eff,s}(2)|}{r_1 r_2} \cdots\cdots\cdots\cdots (4)$$

and

$$\Delta\omega = \frac{\alpha\Delta G}{2} - \frac{1}{\tau}\mathrm{Arg}[r_{eff}(1)\ r_{eff}(2)], \cdots\cdots (5)$$

where ln(x) represents the natural logarithm of x, Arg(z) represents the argument of the complex number z, and the subscript s denotes the steady state value

It remains to solve Eqs. (4) and (5) to obtain external cavity resonance modes and their gains, and hence we predict the possible oscillation mode and the selectivity of the mode.

3. Numerical Results and Discussions

3.1 In-phase feedback

Fig. 2(a) and (b) show the external cavity mode structures obtained by solving Eqs. (4) and (5); (a) without additional feedback and (b) with small amount of in-phase additional feedback. In our calculations, we have used r_1 = 0.565, r_2 = 0.1, C_1= C_2 = 0.82, α = 4, $r_{ext,1}$ = 0.7, $\tau_{ext,1}$ = 0.5 nsec, $\tau_{ext,2}$ = 0.05 nsec, and $\omega\tau_{ext,1} = 10\omega\tau_{ext,2} + \pi$ (in-phase feedback). The threshold gain difference between the target mode and neighborhood side modes was increased from 0.02 cm^{-1} to 0.43 cm^{-1}. This result shows that additional feedback can induce the suppression of the adjacent side-modes, resulting in stable single mode operation which is very important for practical applications.

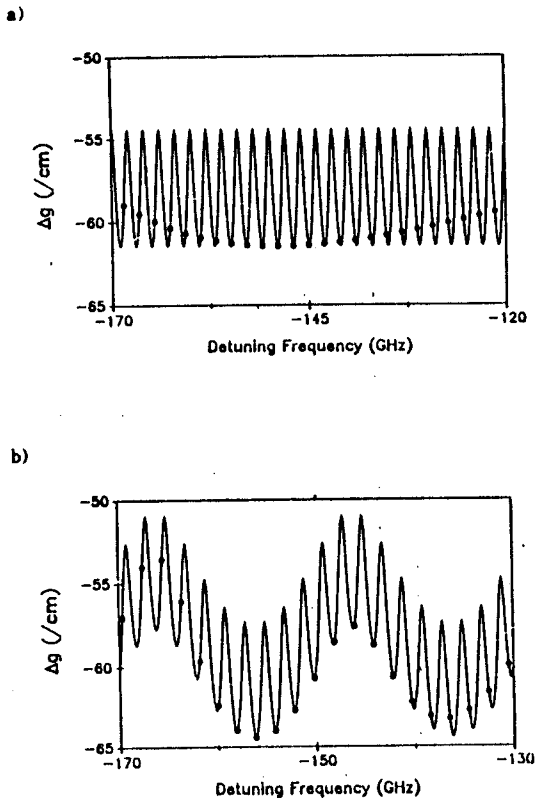

Fig. 2. External cavity resonance modes (•) and their gains near the loss (or $\Delta g = \mu \Delta G/c$) minimum ; (a) $r_{ext,2}$ = 0.(single external cavity laser), (b) $r_{ext,2}$ = 0.1

Experimental results also show that compound cavity mode spacing is increased to the least common multiple of those of both independent single external cavity systems in case that feedback strength from both external cavities are almost same[5]. This indicates that the adjacent side-modes are greatly suppressed to keep stable single mode oscillation. However, to achieve this improved performance careful adjustment of the feedback phase is required.

3.2 Out-of-phase feedback

It has been shown experimentally that the existence of double loss minima in each diode mode leads to unstable operation[4], such as diode mode splitting, nearly sinnusoidal intensity noise, and chaotic broad -band noise. Numerical results show that additional feedback with out-of-phase also leads double loss minima, resulting in unstable operation similar to that observed in asymmetric external cavity lasers.

In real situations, (unwanted) additional feedback may have arbitrary phase and the effects should be minimized. Here we consider an external cavity configuration with $\omega\tau_{ext,2} = 2\omega\tau_{ext,1}$ (worst case), where any unwanted additional feedback has the greatest chance of producing detrimental effects, i.e. double loss minima. In our simulation, C_1 = C_2 = 0.82 and r_2 = 0.565 have been used.

Fig. 3(a) shows the bifurcation point of the loss as a function of r_1 at $r_{ext,1}$ = 0.7 and 0.9. For a fixed value of $r_{ext,1}$, there exists an optimum value of r_1 which maximizes the system immunity against unwanted external feedback. For example, for strong feedback system with $r_{ext,1} \geq 0.5$, the value is $r_1 \simeq 0.23$. This result is very important, since stable and consistent operation of external cavity lasers under optically harsh environments is required in many applications. Fig. 3 (b) shows the bifurcation point as a function of $r_{ext,1}$ at several values of r_1. The optimum value of $r_{ext,1}$ decreases with increasing r_1. It is very interesting to note that, beyond the optimum point, the system can actually become more susceptible to unwanted external feedback as the coupling strength increases, i.e. as r_1 decreases at a fixed external cavity reflectivity $r_{ext,1}$ (or, as $r_{ext,1}$ increases at a fixed facet reflectivity r_1).

a)

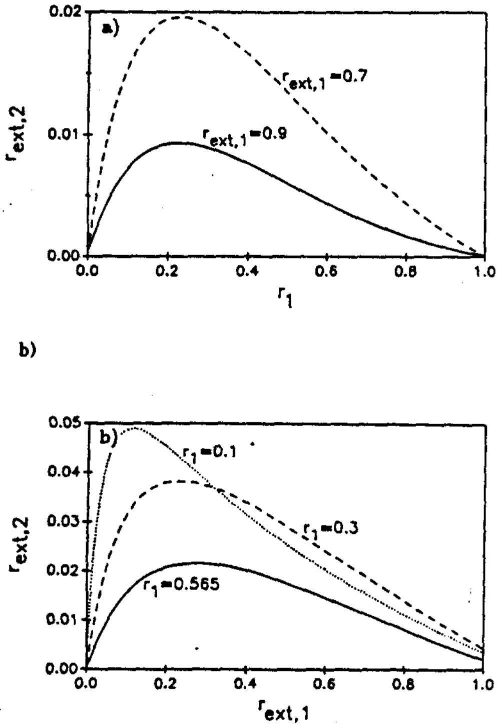

Fig. 3. Bifurcation point of the loss (or Δg) minimum as a function of (a) the value of r_1 for $r_{ext,1}$ = 0.9 (solid line) and 0.7 (dashed line), and (b) the value of $r_{ext,1}$ for r_1 = 0.565 (solid line), 0.3 (dashed line), and 0.1 (dotted line).

4. Conclusions

We have demonstrated that additional feedback can induce stable single loss minimum suppressing side-modes or double loss minima leading to unstable operation, depending on feedback phase of the additional feedback.

The optimum feedback conditions to maximize the system immunity against unwanted additional feedback with arbitrary phases have also been determined.

References

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