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APPLICATION OF STABLE OPERATING CRITERION TO GRATING TUNED STRONG EXTERNAL FEEDBACK SEMICONDUCTOR LASERS

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ABSTRACT

Stability analysis is done by applying criterion $d\omega_0(\omega)/d\omega>0$ for grating tuned strong external feedback semiconductor lasers. The resulting stable and unstable operating ranges agree well with experiment results.

INTRODUCTION

Much attention has been paid to external feedback semiconductor lasers since 1980 (Lang *et al*, 1980), and recently to grating tuned strong external feedback semiconductor lasers because of their applications as narrow linewidth, frequency tunable emission sources in coherent optical communication systems (Yamamoto *et al*, 1981; Wyatt *et al*, 1985; Glas *et al*, 1982; Zorabedian *et al*, 1987; Sun *et al*, 1990). Strong external feedback is defined as the case when the reflectivity of the external feedback reflector is larger than the reflectivity of laser diode's internal facet which is close to the external reflector. For strong external feedback semiconductor lasers, experimental results on bistable tunings of both emission power versus operating electrical current and emission power versus operating laser light frequency had been reported (Glas *et al*, 1982; Zorabedian *et al*, 1987). Steady state solutions show that there are three-value tuning curves of threshold gain (or emission power) versus operating electrical current, and of threshold gain versus operating laser light frequency (Glas *et al*, 1982; Zorabedian *et al*, 1987). However, steady state solutions can not explain why the middle value tuning curves are unstable as shown by experimental results. There is a general stable operating criterion $d\omega_0(\omega)/d\omega>0$ for external cavity semiconductor lasers (Tromborg *et al*, 1987), where ω_0 is the resonant frequency of the semiconductor laser without external feedback and ω is the operating frequency of the semiconductor laser with external feedback. Glas *et al* (1982) applied this criterion to the first case of threshold gain versus operating current tuning curves. They found that the middle value tuning curve was really unstable. As far as we know there is still no one who applies this criterion to the second case of threshold gain versus operating frequency tuning curves in order to determine if the middle value tuning curve is stable. In this paper we present our application of this general stable operating criterion to the second case of threshold gain versus operating frequency tuning curves.

THEORY

Figure 1 shows schematically a typical setup of an grating external feedback semiconductor laser. A Littrow grating is used as the external optical feedback reflector. The semiconductor laser and the grating compose a compound cavity laser. For simplicity the grating is assumed to be a frequency filter reflector with an amplitude reflectivity r_3 for frequencies within the filter range and a zero reflectivity for frequencies outside the filter range (Zorabedian *et al*, 1987). The filter range can be tuned by tuning the reflecting angle of the grating. The semiconductor laser has its internal facet antireflection coated with an amplitude

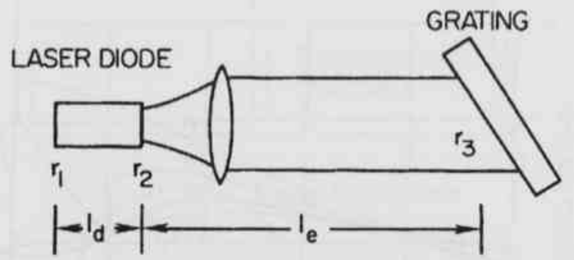

Figure 1. Grating tuned external feedback semiconductor laser scheme.

reflectivity of $r_2 < r_3$. The effective reflectivity of the external cavity composed of r_2 and r_3 is (Zorabedian *et al*, 1987)

$$r_e(\omega) = [r_2 + r_3\exp(-i\omega t_e)]/[1+ r_2 r_3 \exp(-i\omega t_e)]$$
$$= |r_e(\omega)| \exp[-i \arg(r_e)] \qquad (1)$$

where ω is the operating frequency of the semiconductor laser with external feedback (or the operating frequency of the compound cavity laser), $t_e = 2l_e/c$ is the light round trip time in the external cavity, l_e is the length of the external cavity and c is the light velocity in a vacuum.

The steady state solution can be obtained from the compound cavity laser field equations (Zorabedian *et al*, 1987)

$$g = -(1/\ell_d) \ln(r_1 |r_e|) \qquad (2)$$

$$\omega - \omega_0 = -(1/t_d) \arg(r_e) \qquad (3)$$

where g is the threshold gain, ℓ_d is the semiconductor laser cavity length, r_1 is the amplitude reflectivity of another facet of semiconductor laser, $\omega_d = p\pi c/n\, \ell_d$ is the resonant frequency of the semiconductor laser with external feedback, n is the refractive index of the semiconductor laser active medium with external feedback, $t_d = 2n\, \ell_d/c$ is the light round trip time in semiconductor laser with external feedback and integer p is the mode number. The refractive index of laser diode without external feedback n_0 is related to n by (Zorabedian *et al*, 1987)

$$n - n_0 = (\alpha c/2\omega)(g - g_0) \qquad (4)$$

where α is the linewidth enhancement factor (Henry, 1982) and $g_0 = -\ln(r_1 r_2)/\ell_d$ is the threshold gain of the semiconductor laser without external feedback. We now have three equations (2), (3) and (4) and three unknown parameters ω, g and n. Combining eq(3) and (4) to eliminate n we obtain

$$g = (1/\alpha \ell_d)[(\omega_0-\omega)t_0 - \arg(r_e)] - (1/\ell_d)\ \ln(r_1 r_2) \qquad (5)$$

where $t_e = 2n_0 \ell_d/c$ is the light round trip time of the semiconductor laser without external feedback $\omega_0 = p\pi c/n_0 \ell_d$ is the resonant frequency of the semiconductor laser without external feedback. Combining eq(2) and (5) to solve for g and ω we obtain the threshold gain - operating frequency tuning curves shown in Fig. 2 for various values of r_2 and fixed values of $r_1 = 0.5$, $r_3 = 0.5$, $\alpha = -7$, $\ell_d = 0.3$mm, $n_0 = 3$, $\ell_e = 90$mm and for a frequency range between $\omega t_0/2\pi = p$ and $\omega t_0/2\pi = p + 1$. There are 100 solutions when the grating filter is tuned over this frequency range since $\ell_e = 100 n_0 \ell_d$. In Fig. 2 four curves associated with four different values of r_2 are displayed. Curve A shows that for a large r_2 value there appear three-value tuning curves within a certain frequency range (for a larger r_3 or/and a smaller α there is a larger critical value of r_2 which is about 0.1 in our case). Experimental results showed (Zorabedian *et al*, 1987) that the operating points along tuning curve A between marks u are unstable and the other operating points along the two tuning curves between marks s and u are stable, these two tuning curves compose bistable tuning (Zorabedian *et al*, 1987). But the steady state solution can not explain this phenomenon.

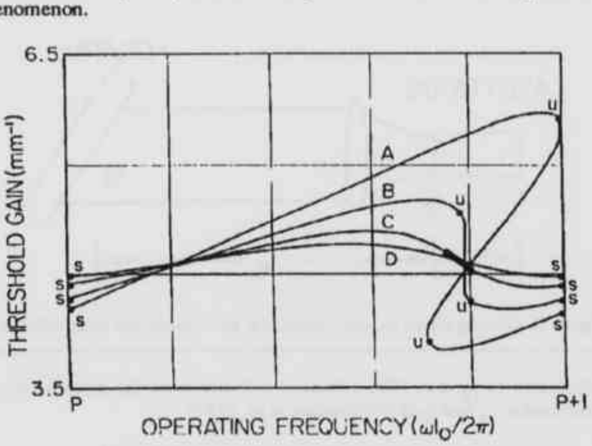

Figure 2. Threshold gain - operating frequency tuning curves with $\alpha = -7$, $r_1 = 0.5$, $r_3 = 0.5$, $r_2 =$; A: 0.2, B: 0.1, C: 0.05, D: 0.03. Operating points between marks u are unstable, between marks u and s are stable.

In the following we carry out a stability analysis by applying the general stable operating criterion

$$d\omega_0(\omega)/d\omega > 0 \qquad (6)$$

to the steady state solutions to see what happens. Combining eq(2) and (5) to eliminate g we have

$$\omega_0(\omega) = [-\alpha \ln(|r_e|/r_2) + \arg(r_e) + \omega t_0]/t_0 \qquad (7)$$

which is just what we want for stability analysis. Inserting eq(7) into (6) results in, for curve A, the stable operating points between marks u and s, and the unstable operating points between marks u and u as shown in Fig. 2. This result agrees well with the experimental result (Zorabedian *et al.*, 1987). Applying the criterion to curve B, we find that the stable and unstable operating points are also between marks u, s and marks u, u respectively. All the operating points on curves C and D are stable. We know that there exist experimental results showing that for a very small value of r_2 the tuning curve (something like curve D) is completely stable. However, as far as we know, there is no corresponding experimental results for a large value of r_2 since an accurate measurement of the value of r_2 is not easy. Therefore we do not know at this stage how well the experimental and our theoretical results for tuning curves B and C agree. We note that the criterion $d\omega_0(\omega)/d\omega > 0$ is necessary but not sufficient for stable operation (Tromborg *et al*,1987). That is, there may be other types of instability or chaotic behavior for operating points which satisfy the stable operating criterion. We also note that the advantage of this stability analysis is that it is simple. However, the physical mechanism of stable, unstable and bistable tuning is not very clear.

DISCUSSION

We have carried out (Sun *et al*, 1992) a direct stability analysis from eq(2) and (5) by introducing a small fluctuation in refractive index $\Delta n^{(1)}$ and studying the resulting time evolution. We find that the first small fluctuation in refractive index $\Delta n^{(1)}$ will cause the second fluctuation $\Delta n^{(2)}$ which will cause the third one $\Delta n^{(3)}$ and so on. If for one operating point the condition $|\Delta n^{(i)}| > |\Delta n^{(i+1)}|$, where i is any integer, is always true (or always false), the fluctuation will be damped (or amplified) and this operating point is stable (or unstable). Using this stable operating criterion to judge all the operating points of curves A, B and D result in the same stable and instable operating ranges, but for curve C it results in a small instable range shown by thick line. Until now one could not explain the different results for curve C. However the direct stability analysis presented there provides a straightforward insight into, and a clear explanation for, stable, unstable and bistable operating of grating tuned strong external feedback semiconductor lasers.

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