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THEORY OF SEMICONDUCTOR LASER FEEDBACK INSTABILITY

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A semiconductor laser coupled to an external cavity is investigated using a composite-cavity mode approach. Strong frequency hopping for small cavity length changes is obtained, indicating instability of the laser operation against cavity lengths fluctuations.

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We have theoretically investigated a semiconductor laser which is coupled to an external cavity through one of its mirrors, as sketched in Fig. 1. In our model the end mirrors are assumed to be perfectly reflecting whereas the coupling mirror has a finite transmission. The losses are assumed to be distributed over the entire cavity. The equation for the electro-magnetic field inside the cavity is obtained from Maxwell's equations in which the polarization contribution is calculated microscopically in the quasi-equilibrium free-particle approximation for the excited electrons and holes.[1] From the expression for the polarization we extract gain and refractive index changes as functions of carrier density. The total density of the electron-hole pairs obeys a rate equation, in which the relaxation is described by a simple exponential process and constant pumping is assumed.

Expanding the field equation in the supermodes of the combined cavity,[2] we numerically integrate the resulting eigenmode equations. For the case of low feedback we find that the system assumes a unique steady state where only one mode oscillates. We investigate threshold carrier density and mode frequency for varying feedbacks from the external cavity by changing the length of the external cavity by a small fraction of a wavelength. Our calculations show that the modal gain functions are very sensitive to minor changes. Consequently, as function of the feedback-cavity length the lasing mode frequency changes in a stepwise manner, as shown in Fig. 2 for varying external cavity lengths for three different amounts of feedback (Fig. 2*a* - 2*c*).

Our analysis shows that the stepwise switching of the laser frequency can be traced back to the modal gain function plotted in Fig. 3. The crosses and circles represent the composite cavity modes before and after a small change in feedback-cavity length. We see that the modal gain is large for a subset of approximatively evenly spaced modes, which approximatively correspond to modes of the laser cavity. The change of lasing mode corresponds to a jump between these modes. In between these modes lie several supermodes which approximately correspond to the external cavity modes. The modal gain for these modes is low and they never lase. However, when the length of the external cavity is changed all modes move in frequency and their gain changes according to the modal gain curve (see circles and crosses in Fig. 3). At some point the gain of the current laser mode is less than that of one of the neighboring modes, and these modes exchange their role and the neighboring mode becomes the new lasing mode. An example of such a mode switching is shown in the inset to Fig. 3. For changing cavity length such jumps to neighboring modes may take place several times before the original mode lases again. Numerical investigations of the coupled supermode equations for larger amounts of feedback are in progress to investigate additional dynamical instabilities. Already our present results for relatively small feedback show that the frequency jump corresponding to changes of oscillating mode can be quite large, several meV, and we speculate that this frequency hopping can be a partial cause for some forms of coherence collapse obtained in semiconductor lasers with external feedback.

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REFERENCES

1. see, e.g., H. Haug and S.W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors*, World Scientific Publ., Singapore (1990)

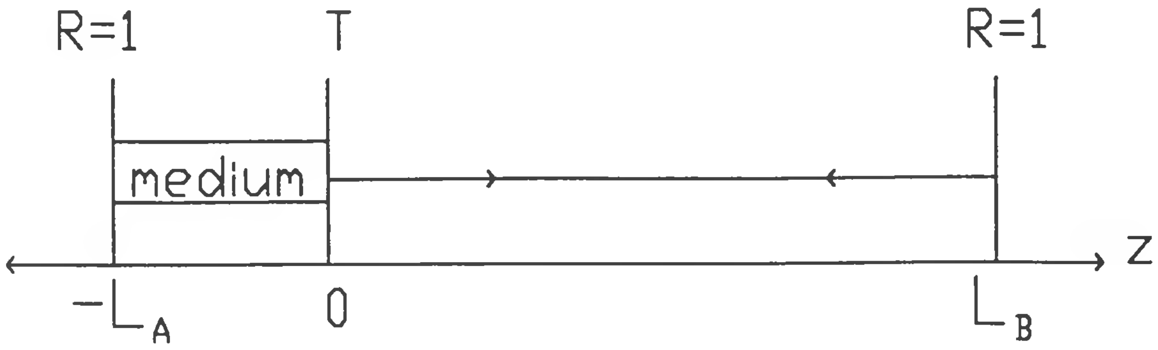
2. W.W. Chow, IEEE J. Quantum Electron. QE-22, 1174 (1986).

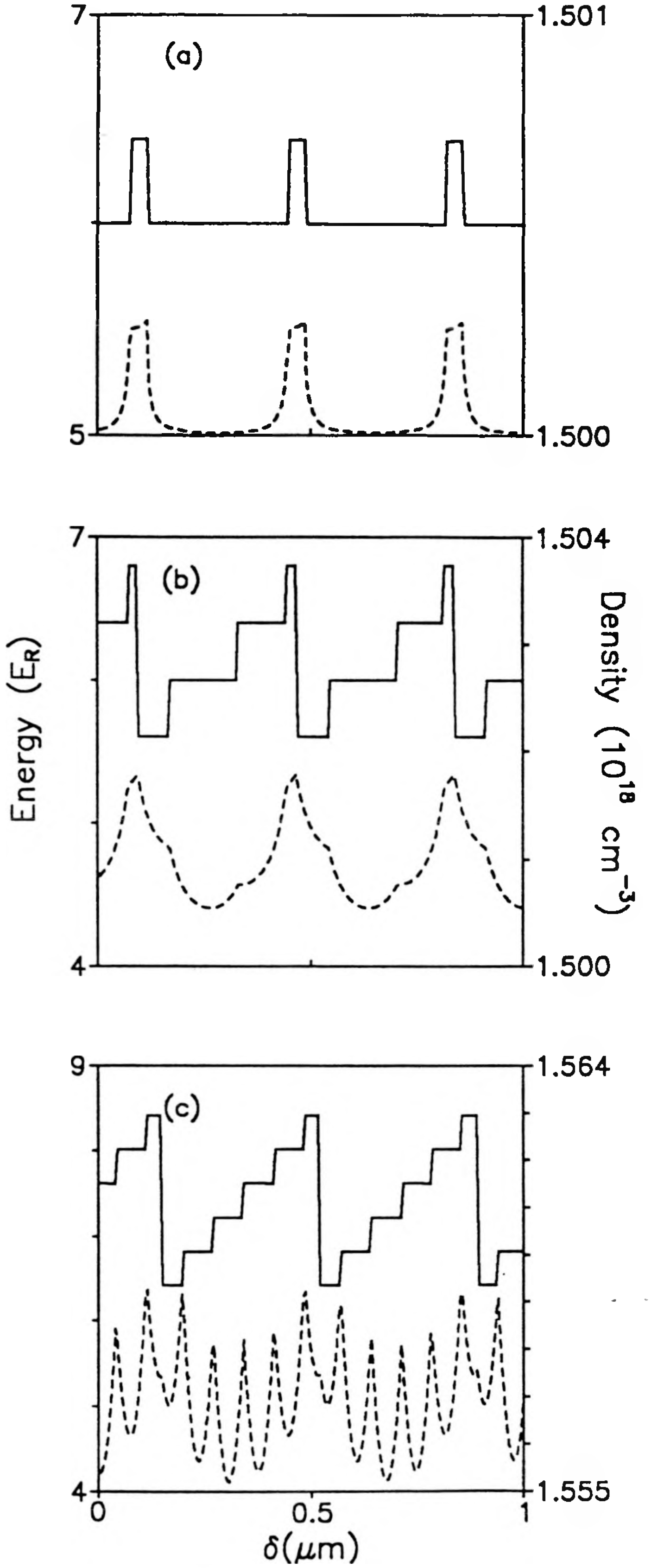
FIGURE CAPTIONS

Fig. 1: Schematic plot of the coupled cavity configuration. T represents the transmission of the coupling (middle) mirror which controls the amount of light fed back into the laser. We assume perfectly reflecting mirrors at $z = -L_A$ and $z = L_B$. The semiconductor medium is placed between $z = -L_A$ and $z = 0$.

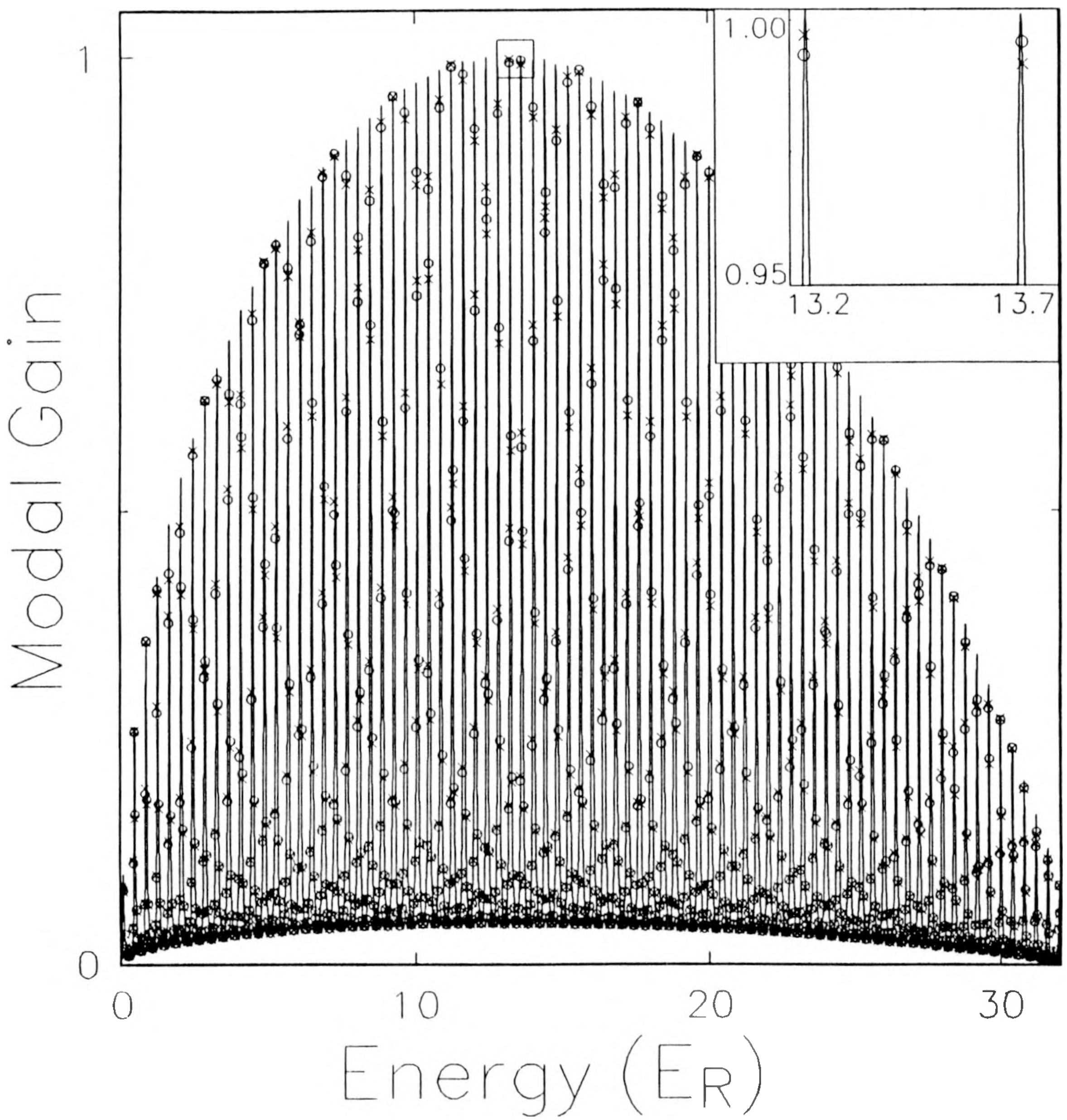
Fig. 2. Energy of the lasing mode (solid line) in units of E_R (= 4.2 meV for GaAs) and threshold carrier density (dashed line) as function of the external cavity length variation δ (μm). The transmission coefficients of the coupling mirror are *a*) $T = 10^{-5}$, *b*) $T = 10^{-3}$, *c*) $T = .1$.

Fig. 3. Modal gain showing allowed modes at two different lengths separated by 0.01 μm. The crosses represent the supermodes at the initial external cavity length and the circles represent the same supermodes after the change in cavity length by 0.01 μm. Inset: Blowup of the peak (boxed) illustrating the mode hopping mechanism.


R=1
T
R=1
medium
Z
−L_A
0
L_B



(a)
(b)
(c)
7
5
7
4
9
4
1.501
1.500
1.504
1.500
1.564
1.555
0
0.5
1
Energy (E_R)
Density (10^18 cm^-3)
δ(μm)



1.00
0.95
13.2
13.7
1
0
0
10
20
30
Modal Gain
Energy (ER)