研 究 速 報

Effect of Nonradiative Recombination on Threshold Current in Microcavity Lasers

微小共振器における非発光再結合のしきい値電流への影響

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1. INTRODUCTION

The control of spontaneous emission can play an important role in determining the threshold characteristics of microcavity lasers.[1–3] Devices with a spontaneous emission factor β approaching 1 are predicted to show novel features such as thresholdless lasing[1,2] and squeezing below threshold and lasing without inversion,[4] where β is the fraction of the spontaneous emission that is coupled into the lasing mode. For a given volume the spontaneous emission coupling can be substantially altered by the cavity configuration.[5–9] Some semiconductor laser structures that have achieved high values of the spontaneous emission coupling factor β are vertical cavity surface emitting lasers with small lateral dimensions[10] or curved surfaces,[11] and whispering gallery structures.[12]

This letter explores the limitations due to nonradiative recombination in microcavity lasers. An expression for threshold current in microcavities is developed based on the intercept definition used for macroscopic lasers. This threshold is consistent with the macroscopic threshold definition for small β, and is approximately a factor of two higher than the threshold definition of one photon in the lasing mode. This threshold corresponds to the current used to invert the gain medium at high output power.

2. Threshold Current

Nonradiative recombination has been previously shown to limit microcavity effects on the threshold current when the nonradiative lifetime τ_{nr} is shorter than the radiative lifetime τ_r ($\tau_{nr}/\tau_r<1$) or extremely long.[3] Here we consider the case where the nonradiative lifetime is longer than the radiative lifetime ($\tau_{nr}/\tau_r>1$). In this region, as $\beta\rightarrow 1$ the threshold current is affected by the nonradiative lifetime, even when nonradiative recombination lifetime is very long. An effective value of β is defined that includes nonradiative recombination and is the value that is extracted when fitting β to experimental data. An expression is given for the maximum level of nonradiative recombination in order to observe microcavity effects for a given value of β.

Semiconductor lasers can be described by the coupled rate equations:[4]

$$\frac{dN}{dt} = \frac{I}{qV} - \left(\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}\right) N - \frac{g}{V} p \tag{1}$$

$$\frac{dp}{dt} = \left(g - \frac{1}{\tau_p}\right) p + \frac{\beta VN}{\tau_r} \tag{2}$$

where N is the carrier density, p is the photon number, g is the gain, I is the injected current, and V is the active volume. The carrier lifetimer τ_r is the lifetime inside the microcavity, which can be either increased[8] or decreased[7] from the bulk value depending on the cavity structure, but here is treated as a constant. A rate equation analysis assumes that gain dipole dephasing is fast compared to the photon lifetime and spontaneous emission lifetime.[2]

In order to examine the threshold characteristics of microcavities, it is necessary to define threshold current. Using $g = g'(N-N_o)$ where g' is the differential gain and N_o is the transparency carrier density, and the Einstein relation between the A and B coefficients gives:[4]

$$g' = \frac{\beta V}{\tau_r} \tag{3}$$

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The steady-state current dependence on photon number is:[3)]

$$I = \frac{p}{p+1}\left(I_{tr} + \frac{q}{\beta\tau_p}\right)\left(1 + \beta p + \frac{\tau_r}{\tau_{nr}}\right) - \beta I_{tr} p \quad (4)$$

where I_{tr} is the current at which the medium becomes transparent, although lasing can occur below transparency due to photon recycling.[4)]

$$I_{tr} \equiv \frac{qN_0 V}{\tau_r} \quad (5)$$

The current I_{1p} to give one photon in the lasing mode is

$$I_{1p} = \frac{1}{2}\left(I_{tr} + \frac{q}{\beta\tau_p}\right)\left(1 - \beta + \frac{\tau_r}{\tau_{nr}}\right) + \frac{q}{\tau_p} \quad (6)$$

I_{1p} has been shown to be a useful threshold definition for predicting the onset of spectral coherence.[3)] However, for small β it is approximately a factor of two lower than the conventional threshold current.

Most applications require much more than one photon in the lasing mode. Therefore it is also important to examine the current-power characteristics at higher power. The inversion current I_{inv} required to provide gain to compensate for cavity loss in macroscopic (low β) devices is

$$I_{inv} \equiv \frac{q(N_\infty - N_0)V}{\tau_r} = \frac{q}{\beta\tau_p} \quad (7)$$

where N_∞ is the carrier density in the limit of high output power.

$$N_\infty \equiv N_0 + \frac{\tau_r}{\beta V \tau_p} \quad (8)$$

The dependence of current on threshold number can be rewritten

$$I = I_{th}\frac{p}{p+1} + \frac{q}{\tau_p}p \xrightarrow[p>>1]{} I_{th} + \frac{q}{\tau_p}p \quad (9)$$

where I_{th} represents the intercept of the linear portion of the curve extrapolated back to $p = 0$. With more than a few photons in the lasing mode, the current is a linear function of p.

$$I_{th} \equiv (I_{tr} + I_{inv})\left(1 - \beta + \frac{\tau_r}{\tau_{nr}}\right) \quad (10)$$

This intercept current is equivalent to the threshold current in macroscopic models, but here the dependence on β is explicitly included to account for microcavity effects. The intercept current is the amount of current used to maintain the carrier population when operating at high output power.

The intercept threshold current is composed of three terms. The term I_{tr} represents the current needed to bleach the medium, which depends on material parameters and scales linearly with the active gain volume. The term I_{inv} is the additional current needed to provide inversion for lasing, which depends on the cavity and scales linearly with β. The term $(1 - \beta + \tau_r/\tau_{nr})$ is an additional microcavity current reduction factor that is important when β is large, and has been related to photon recycling.[4)]

One difference between the two threshold definitions is that as $\beta \to 1$ the intercept threshold $I_{th} \to 0$, leading to thresholdless lasing when defined in terms of output power.[1,2)] The current I_{1p} for one photon in the lasing mode is one half the intercept current plus the current needed to resupply carriers lost due to photon emission. Even for $\beta = 1$, a finite current $I_{1p} = q/\tau_p$ is still needed to maintain one photon in the lasing mode and thus maintain spectral coherence for lasing.[3)]

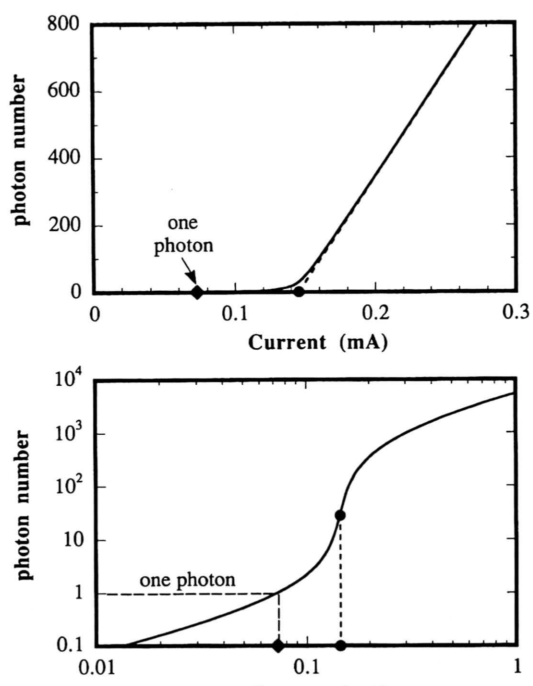

Fig. 1 Calculated photon number and predicted current thresholds for $\beta = 0.1$, $N_0 = 10^{18}\mathrm{cm}^{-3}$, $\tau_r = 1\mathrm{ns}$, $\tau_p = 1\mathrm{ps}$, and $V = 10^{-12}\mathrm{cm}^3$. ◆ = I_{1p}, ● = I_{th}.

Fig. 1 compares the two threshold current definitions on a plot of the photon number with a linear and logarithmic scale assuming negligible nonradiative recombination for $V = 10^{-12}\mathrm{cm}^3$. The one-photon threshold predicts the location of the initial exponential increase in photons, while the linear intercept threshold predicts the onset of high power output. The intercept current I_{th} is an accurate measure of the threshold current based on output power. Fig. 2 compares the threshold current definitions for $V = 10^{-14}\ \mathrm{cm}^3$. Here, the lasing transition has an indistinct threshold, with the output power increasing gradually between I_{1p} and I_{th}. However, the output at high power still fits the intercept threshold definition I_{th}. In both cases, I_{1p} is near the beginning of the transition to higher output efficiency, while I_{th} is in the middle of this transition.

3. Nonradiative Recombination

Nonradiative recombination due to surface recombination can play an important role in microcavities. For high values of β, nonradiative recombination has been shown to limit the minimum threshold current when $\tau_{nr}/\tau_r > 1$.[3] Eqn. 10 can be rewritten in the form of an ideal microcavity without nonradiative recombination by using an effective value of β that includes the effect of nonradiative recombination:

$$I_{th} = (I_{tr} + \frac{q}{\beta_{meas}\tau_p})(1 - \beta_{meas}) \tag{11}$$

This effective value β_{meas} can be found by comparing eqn. 10 and eqn. 11. This effective parameter includes both cavity quantum electrodynamics (QED) effects and material characteristics. For the material dominated threshold regime $I_{tr} >> I_{inv}$,

$$\beta_{meas} \approx \beta - \frac{\tau_r}{\tau_{nr}} \tag{12}$$

For the cavity dominated threshold regime $I_{tr} << I_{inv}$,

$$\beta_{meas} \approx \frac{\beta}{1 + \tau_r/\tau_{nr}} \approx \beta\,(1 - \frac{\tau_r}{\tau_{nr}}) \tag{13}$$

where the last approximation is valid if $\tau_r/\tau_{nr} << 1$. In both cases the nonradiative lifetime can be seen to limit β_{meas} to less than 1. If all of the injected carriers go into the lasing mode and thresholdless lasing can be achieved.[2,3] In both cases the maximum effective spontaneous emission factor β_{max} that can be achieved by cavity QED is

$$\beta_{max} \approx 1 - \frac{\tau_r}{\tau_{nr}} \tag{14}$$

A set of p-I curves is plotted in Fig. 3 using various values of β_{meas} under the conditions of (a) an ideal material with $\tau_{nr} = \infty$ and $\beta_{meas} = \beta$ and (b) an ideal cavity with $\beta = 1$ and $\beta_{meas} = 1 - \tau_r/\tau_{nr}$. The method used to determine β in

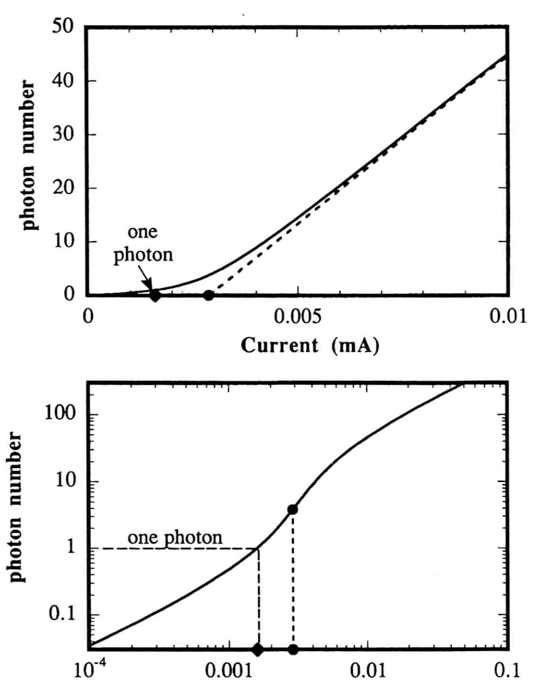

Fig. 2 Calculated photon number and predicted current thresholds for $\beta = 0.1$, $N_0 = 10^{18}\mathrm{cm}^{-3}$, $\tau_r = 1\mathrm{ns}$, $\tau_p = 1\mathrm{ps}$, and $V = 10^{-14}\mathrm{cm}^3$. ◆ = I_{1p}, ● = I_{th}.

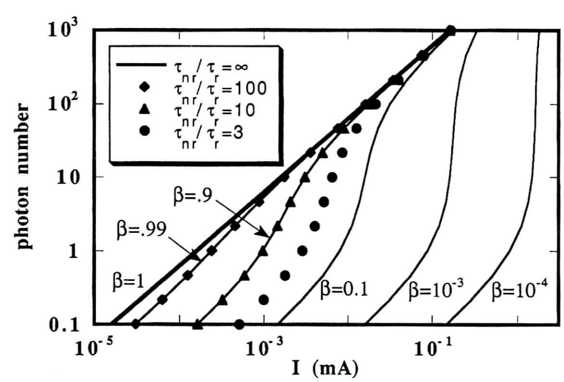

Fig. 3 Calculated photon number vs. injection current for different values of β with $\tau_{nr} = \infty$ (solid lines) and different values of τ_{nr} with $\beta = 1$ (legend). Laser parameters are $N_0 = 10^{18}\mathrm{cm}^3$, $V = 10^{-13}\mathrm{cm}^3$, $\tau_r = 1\mathrm{ns}$, and $\tau_p = 1$ ps.

microcavity structures is to fit the laser parameters to the measurement of p vs. I.[10–12] Above threshold the slope of the p-I curve is independent of β, but the characteristics below threshold depend on β. Figure 3 demonstrates that the p-I measurement produces a value β_{meas} that includes nonradiative recombination rather than directly measuring β, and that microcavity and nonradiative recombination effects are not easily separated in this measurement. Nonradiative recombination can have a strong effect on measured data, particularly near $\beta = 1$. Nonradiative recombination should be considered when comparing measured and calculated β values.

4. Summary

An expression for threshold current in microcavities is developed based on the intercept method analogous to macroscopic lasers. This threshold is about a factor of two higher than the definition of one photon in the lasing mode, and is consistent with the macroscopic threshold definition for small β. The intercept threshold is useful for predicting power extraction and the power lost to inversion of the gain medium at high output power.

The effect of nonradiative recombination on the threshold current is considered for the case where the nonradiative lifetime is longer than the radiative lifetime ($\tau_{nr}/\tau_r>1$). As $\beta \rightarrow 1$ the threshold current depends on the nonradiative lifetime, even when the nonradiative recombination lifetime is very long. In this regime, nonradiative recombination can limit the observation of microcavity effects.

The value of the spontaneous emission factor β can be extracted by fitting to measurement of the light vs. current curve. This measurement includes the non-radiative recombination effect, which will cause a discrepancy between calculated and measured β in microcavities for large values of β.

5. Acknowledgements

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