A Numerical Study on the impact of Purcell Effect and Spontaneous Emission Factor in Lower-Dimension Semiconductor Nanolasers

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Abstract: This paper presents a numerical approach to estimating the spontaneous emission coupling efficiency in semiconductor lasers with lower-dimension gain mediums. Also, the impact of the Purcell effect F and spontaneous emission factor β on the threshold and the height of the kink in the L-L curves is studied. Our theoretical calculations provide more insights into the laser behavior and help to optimize the laser cavity to achieve a lower threshold and higher coupling efficiency before fabrication.

Keywords: Semiconductor laser, Spontaneous emission, Purcell effect, Threshold, Gain, Laser rate equations.

1. Introduction

Semiconductor lasers are useful due to their small size, strong optical mode confinement, and high efficiency. When the size of the cavity is comparable with the emission wavelength, the Purcell effect becomes more apparent as it can significantly impact the spontaneous emission lifetime and the stimulated emission rate [1]. E. M. Purcell proved that when a system couples to a resonator, spontaneous emission lifetime is decreased by the Purcell factor [2]:

$$F = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3\left(\frac{Q}{V}\right) \qquad (1)$$

In which Q is the quality factor, λ is the wavelength, n is the refractive index, and V is the volume of the cavity. Optimizing the Purcell factor is one of the fundamental techniques for achieving an ideal thresholdless nanocavity laser in which almost all spontaneous emissions couple to the lasing mode [3]. Although such lasers can theoretically exist, observing a thresholdless nanolaser is still experimentally challenging due to the imperfect fabrication processes [4]. Threfore, it is crucial to understand the relation between the Purcell factor and the spontaneous emission coupling efficiency (β) in nanolasers using quantum well, nanowire, and quantum dots as gain medium

2. Results and Discussions

Here, we introduce the carrier (N) and photon (S) density rate equations for single-mode nanocavities in which the Purcell and spontaneous emission factors are studied separately:

$$\frac{dN}{dt} = \frac{\eta P}{hfV} - \frac{(1-\beta_0)N}{t_{sp}} - \frac{F\beta_0 N}{t_{sp}} - \Gamma g S \qquad (2)$$

$$\frac{dS}{dt} = \Gamma\frac{F\beta_0 N}{t_{sp}} + \Gamma g S - \frac{S}{t_p} \qquad (3)$$

η is the pump efficiency, hf is the energy of a photon, V is the effective mode volume, Γ is the confinement factor, g is the gain, t_{sp} is the spontaneous emission lifetime, F is the Purcell factor, and β_0 is the spontaneous emission factor without the Purcell effect. The total spontaneous emission coupling efficiency β in a laser determines the ratio of the spontaneous emissions that couple into the lasing mode and is related to the Purcell factor as:

$$\beta = \frac{F\beta_0}{(1+(F-1)\beta_0)} \qquad (4)$$

β is usually treated as a fitting parameter shaping the height of the kink in the L-L curves. However, for a conventional bulk semiconductor laser, it can be calculated from the ratio between the spontaneous emission rate into the lasing mode to the total spontaneous emission rate as $\beta_{Bulk}\sim\frac{\lambda^4}{4\pi^2 V\Delta\lambda n^3}$ when the emission wavelength equals the gain center [5]. λ is the wavelength, V is the volume of the gain medium, $\Delta\lambda$ is the spontaneous emission linewidth, and n is the refractive index. Using the same approach as [5], we propose to calculate the spontaneous emission factor (β) for quantum well (*2D*), nanowire (*1D*), and quantum dot (*0D*) as follows:

$$\beta_{Quantum-well}\sim\frac{\lambda^3 L_z}{2\pi^2 V\Delta\lambda n^2} \qquad (5)$$

$$\beta_{Quantum-wire}\sim\frac{\lambda^2 L_y L_z}{2\pi n\Delta\lambda V} \qquad (6)$$

$$\beta_{Quantum-dot}\sim\frac{\lambda^2}{\pi c\Delta\lambda} \qquad (7)$$

assuming that in (5) L_z is the confined length of the gain material along z-axis. Similarly, in (6) L_y, and L_z are the confined lengths of the gain medium along the y and z-axis, respectively.

To examine the impact of the Purcell factor on the threshold and the height of the kink, we use the nanowire laser structure in [6]. For ten quantum disks embedded in a 2.2 μm height nanowire, we calculated $F_{max}\sim 26.17$, and $\beta\sim 0.1$. This agrees with the experimental results. Solving (2) and (3) for different Purcell factor values ranging from 1 to 26 shows that smaller nanowires result in higher *F*, which decreases the threshold non-linearly, as shown in Figure 1a. Higher values of *F* lead to shorter spontaneous emission lifetimes. Therefore, there will be more spontaneous emissions inside the cavity to couple into the lasing mode creating less pronounced kinks, as presented in Figure 1b. It is evident from figure 1b that for higher values of *F*, β gets closer to unity representing a thresholdless laser.

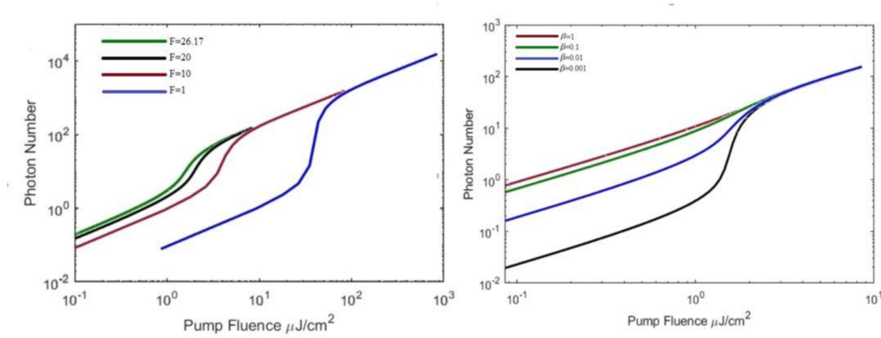

Figure 1. a) Impact of the Purcell factor, b) Impact of spontaneous emission factor

3. Conclusion

This paper first discusses how β can be obtained numerically in lower-dimension semiconductor nanolasers. Then, we show that the Purcell factor can non-linearly decrease the threshold of the laser by shortening the spontaneous emission lifetime. Higher spontaneous coupling efficiency results in a less pronounced kink in the L-L curves.

4. References

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