Small-Signal Modulation Bandwidth of Purcell-Enhanced Nanocavity Light Emitters

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Abstract We present a new analysis of the modulation bandwidth of nanocavity light emitters. The modulation bandwidth is enhanced by the Purcell effect, but only if the device is operated below threshold. The maximum Purcell-enhanced 3-dB bandwidth scales inversely with the modal volume.

Introduction

Semiconductor nanocavities are of interest for their potential as threshold-less lasers and high-speed modulated sources. It has been postulated that the Purcell effect can enhance the modulation speed of nanocavity light emitters (NCLEs) [1, 2]. Here, we derive a new analytical expression for the maximum obtainable 3-dB bandwidth of a NCLE, and show that the bandwidth scales inversely with the modal volume. To maximize the bandwidth, the Purcell factor is optimized and this, in turn, determines the optimum cavity Q.

Theory

To accurately represent a NCLE, the classic laser rate equations are modified to include the Purcell factor, F [3]:

$$\frac{dN}{dt} = J - GS - (F-1)R_{sp}^{'} - \frac{N}{\tau_N} \quad \text{and} \quad \frac{dS}{dt} = \left[\Gamma G - \frac{1}{\tau_p}\right]S + \Gamma F R_{sp}^{'} \qquad (1,2)$$

where N is the carrier density, S is the photon density, J is the carrier injection rate, G is the optical gain, τ_N is the carrier lifetime, Γ is the confinement factor, and τ_P is the photon lifetime. As shown in (1,2), the spontaneous emission rate into the lasing mode, $R_{sp}^{'}$, is enhanced by the Purcell factor, F [4, 5]. The Purcell factor is given by $F = 2p\Gamma_r Q/\pi^2 V_n$, where p is the polarization anisotropy factor, Γ_r is the relative confinement factor, and Q is the cavity quality factor. The normalized modal volume is $V_n = V_p/(\lambda/2n)^3$, where V_p is the modal volume, λ is the lasing wavelength, and n is the effective index of the cavity mode. As shown below, the normalized modal volume is a key parameter that strongly influences the modulation bandwidth.

Using linear models of the gain and spontaneous emission, and solving the steady-state solution for (2), we obtain a relationship between the steady-state carrier and photon densities, N_0 and S_0 respectively:

$$N_0 \approx N_{th0}\, S_0 V_p \Big/ \left(S_0 V_p + \kappa F\right), \qquad (3)$$

where S_0V_p is the cavity photon number, $\kappa \approx 1/4$ is a fitting parameter used in our linearized gain model, and the classical threshold carrier density N_{th0} is given by $N_{th0} = N_{tr}(1+1/\Gamma g_1 N_{tr}\tau_p)$, where g_1 is the differential gain. A possible definition of lasing threshold is when the stimulated emission just exceeds the spontaneous emission: $\Gamma G S_0 = \Gamma F R_{sp}^{'}$. Using a linear gain model, the threshold condition is

$$N_{th} = \left(N_{tr} + N_{th0}\right)/2 \quad \text{and} \quad S_{th}V_p = \kappa F\left(N_{th0} + N_{tr}\right)/\left(N_{th0} - N_{tr}\right). \qquad (4,5)$$

When $\kappa F >> S_0V_p$, the Purcell-enhanced spontaneous emission dominates over the stimulated emission. By (5), this can only occur below threshold. In this regime, the resonance frequency ω_R is dominated by the spontaneous emission dynamics, rather than the classical stimulated emission dynamics, yielding

$$\omega_R^2 = \gamma_p \gamma_{sp} \qquad (6)$$

where $\gamma_p = 1/\tau_p$ is the photon decay rate and $\gamma_{sp} = 1/\tau_{sp}$ is the enhanced spontaneous emission rate. The damping factor γ can be approximated as

$$\gamma \approx \gamma_p + \gamma_{sp}\,. \qquad (7)$$

The spontaneous emission rate is

$$1\big/\tau_{sp} = \gamma_{sp} = F\big/\tau_{sp0}\,, \qquad (8)$$

where τ_{sp0} is the bulk spontaneous emission factor. The maximum 3-dB bandwidth can be approximated as

$$\omega_{3\text{dB,max}} \approx \frac{\gamma_p \gamma_{sp}}{\gamma_p + \gamma_{sp}} = \frac{1}{\tau_p + \tau_{sp}}\,. \qquad (9)$$

Intuitively, the bandwidth is limited by both the rate of creation of the spontaneous emission photons (γ_{sp}) and by the rate of photons exiting the cavity (γ_p), whichever is the slower of the two. Fig. 1 shows a plot of the maximum bandwidth as a function of the two independent parameters, Q and V_n. We can achieve bandwidths above 100 GHz for $V_n = 0.1$, and > 300 GHz for $V_n = 0.01$. These are higher than what is possible for a laser biased above threshold.

Conclusions

The Purcell effect enhances the bandwidth when the spontaneous emission exceeds the stimulated emission. Therefore, bandwidth enhancement occurs only in the sub-threshold regime, where there is no lasing. Maximum bandwidth is achieved by minimizing the modal volume and by optimizing the cavity Q. The optimum Purcell factor is ~ 900. We predict maximum bandwidths of >100 GHz and >300 GHz at normalized modal volumes of 0.1 and 0.01, respectively. The maximum bandwidth is limited by the material gain, the transparency carrier density and the modal volume. While NCLEs may have high bandwidth, they may not benefit from reduced noise, linewidth, and other properties usually found in lasers. Nevertheless, NCLEs may be attractive for applications where coherence requirements are relaxed.

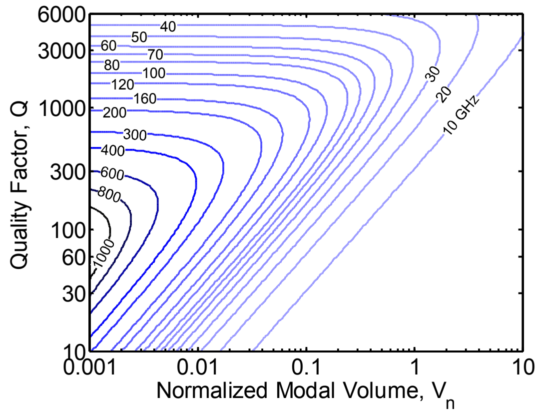

Fig. 1. Contour plot of $f_{3dB,\max}$ (in GHz) on the Q-V_n plane.

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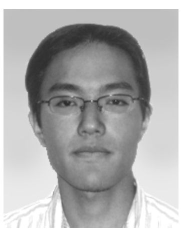

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