Photon Recycling for Threshold Reduction in Semiconductor Lasers*

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Abstract

Photon recycling, or the re-absorption of spontaneously emitted photons by an active gain medium can, in principle, reduce a laser's threshold to zero even when the number of cavity modes is large. We calculate the magnitude of this effect for the current VCSELD device structures and discuss appropriate conditions for effective recycling.

Introduction

Dramatic progress in semiconductor laser materials and structures has led to room-temperature lasing threshold currents in the range of 1mA [1]. Even these currents, however, are impractically high when arrays of thousands of sources are contemplated, as for optical interconnection applications. One of the factors determining the lasing threshold is the spontaneous recombination of carriers. Spontaneous recombination of carriers decreases the required population inversion without contributing to the lasing mode of the cavity. Therefore, if most of the spontaneously emitted photons can be re-absorbed by the active medium, a dramatic decrease in the pumping current density needed to reach threshold can be achieved. This "photon recycling" can be done by the deposition of highly reflective layers on all but the output facet of the laser structure. This effectively returns the spontaneously

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emitted photons to the active medium where they may be re-absorbed and ultima! tely exit the laser medium in the

desired mode [2].

We have calculated the magnitude of the reduction of the lasing threshold brought about by the photon recycling effect for the case of a vertical cavity surface emitting laser diode (VCSELD). The device model we used in our calculation is the current vertical-to-surface transmission electrophotonic (VSTEP) device [3].

Calculations

Due to intraband relaxation [4], the step-like nature of the gain and emission spectra of the Quantum Well (QW) laser are rounded off. As a result, the spectra at lasing threshold are very similar to those of the conventional heterostructure laser [5][6]. We therefore approximate the theoretical gain and emission spectra of the QW medium with that of the conventional lasers and apply a scaling factor to the gain spectrum to take into account the difference in the QW gain. To find the threshold of the laser, we equate the laser gain with the total loss of the mirrors and medium:

$$\Gamma_r \cdot 2d \cdot \gamma(E_l, \Delta n_0) = -\log(R_{up} R_{dn}) + 2\alpha_l D \tag{1}$$

where Γ_r is the relative confinement factor due to the positioning of the active medium with respect to the maximum of the electric field in the cavity [7], d is the length of the gain medium, $\gamma(E_l, \Delta n_0)$ is the gain coefficient of the medium with lasing photon energy E_l and threshold inversion carrier density Δn_0 [8], R_{up} and R_{dn} are the reflectivities of the upper and lower distributed Bragg reflectors (DBR) respectively at lasing threshold, α_l is the free carrier absorption coefficient and D is the vertical dimension of the VCSELD.

The threshold equation (1) enables us to find Δn_0 and the quasi-Fermi levels for the electrons and holes of the gain medium. From these parameters, the fraction of the spontaneously emitted photons with energy E which is re-absorbed in the active medium can then be obtained as [9]:

$$\theta(E) = \frac{-\gamma(E, \Delta n_0) d}{-\gamma(E, \Delta n_0) d + \alpha_l D + T_s D(1/W + 1/L)/2 + (T_{up}(E) + T_{dn}(E))/4}$$

where:

W	:	width of the device
L	:	length of the device
T_s	:	transmissivity of the side wall of the VCSELD
$T_{up}(E)$	:	transmissivity of the upper DBR with photon energy E, averaged over all the solid angles
$T_{dn}(E)$	:	transmissivity of the lower DBR with photon energy E, averaged over all the solid angles

$$\begin{aligned}
T_{(\cdot)}(E) &\equiv 1-(\int_0^{\phi_c} R_{(\cdot)}(E,\vartheta)\sin\vartheta d\vartheta + \cos\phi_c) \\
R_{(\cdot)}(E,\vartheta) &: \text{reflectivity of the DBR with photon energy } E \text{ and incident angle } \vartheta, \\
& \quad \text{where } (\cdot) \text{ refers to either upper or lower DBR.} \\
\phi_c &: \text{critical angle between the medium and DBR}
\end{aligned}$$

The percentage of threshold reduction due to photon recycling is given by $\eta\theta_{av}$, where η is the quantum efficiency for the radiative recombination of the electrons and holes and θ_{av} is the overall fraction of the spontaneously emitted photon which is re-absorbed into the medium, given by:

$$\theta_{av} = \frac{\int \theta(E) R_{sp}(E) dE}{\int R_{sp}(E) dE} \tag{2}$$

where $R_{sp}(E)$ is the rate of spontaneous emission of the medium with photon energy E [8].

Using the geometry given in [3] and assuming a laser diode gold-plated on the sides, we have $T_s \sim 0.03$. We assume the lasing wavelength $\lambda_l = 1\mu$m, $d = 500$Å, $D = 0.85\mu$m, $W = L = 10\mu$m, $\alpha_l = 5\text{cm}^{-1}$, $R_{up} \approx 1$, $R_{dn} \approx 0.995$ [10] and $\Gamma_r = 1.8$. As the upper DBR is plated gold in our model, the angular reflectivity of it will be very uniform and so $T_{up}(E) \approx 0$. The reflectivity of the lower DBR depends very strongly on the incident angle of the photon with energy E. By modelling the reflectivity of the lower DBR [11], we observe that about half of the incident photons are reflected within the pass window ϑ between 0 and ϕ_c, more or less independent of the photon energy E. Taking refractive indexes $n_{\text{GaAs}} = 3.5$, $n_{\text{AlAs}} = 3.0$, we have $\phi_c = 67^o$ and $T_{dn}(E)$ is ≈ 0.3.

Results

Figure 1 shows the plot of the absorptivity of the medium, $-\gamma(E, \Delta n_0)$, and the rate of spontaneous emission, $R_{sp}(E)$, against photon energy E at the threshold condition. With the parameters assumed, $\theta_{av} \approx 22\%$. For a carefully processed device, non-radiative recombination of the carriers may not be significant. With $\eta \approx 0.9$, a threshold reduction of $\sim$20% can therefore be achieved.

As the lower DBR has a relatively large area compared with the areas of the side walls of the device and the reflectivity of it is very angularly selective, most of the spontaneously emitted photons are lost through the lower DBR. If we could make an angle-insensitive mirror instead of the usual DBR, the photon recycling effect will be even more significant. With this type of mirror, $T_{dn} = 1 - R_{dn} \approx 0.005$, a threshold reduction up to $\sim$60% is possible. Most of the spontaneously emitted photons are therefore effectively re-absorbed in this case. Even with perfect angle-insensitive reflectors, there are still loss of photons due to the transmittivity of the side walls and free carrier absorption of the medium.

In summary, we have calculated that with photon recycling, current density for lasing threshold can be reduced by $\sim$20%, using the model of the current VCSELD devices. With an improvement in the design of the mirrors, even higher threshold reduction through photon recycling can be achieved.

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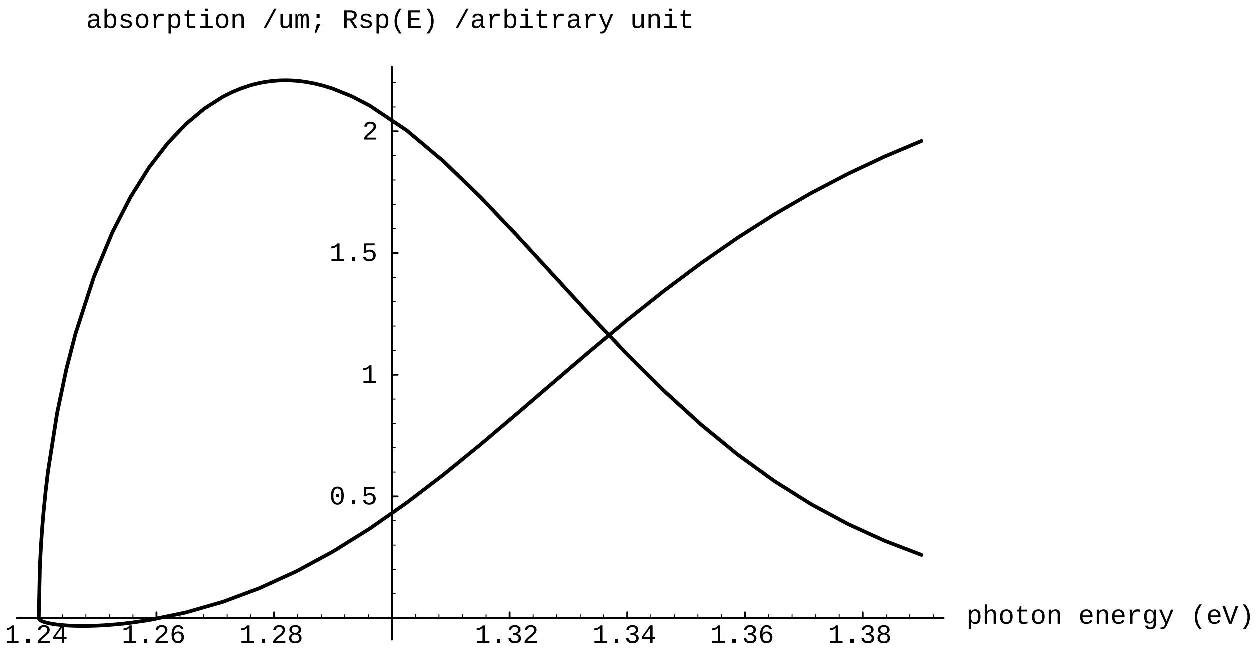

Figure 1: Absorptivity, $-\gamma(E, \Delta n_0)$, in $\mu\mathrm{m}^{-1} = 10^4\mathrm{cm}^{-1}$, and spontaneous emission spectrum, $R_{sp}(E)$, of the InGaAs QW laser at threshold versus photon energy E in eV.