Simulation studies of DFB Laser Longitudinal Structures for Narrow Linewidth Emission

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***Abstract*—Simulation studies targeting high-power narrow-linewidth emission from DFB lasers are presented. The linewidth and output power calculations take into account the mirror losses, including the grating and the facets, as well as spontaneous emission noise, effective refractive index, power and carrier density variations inside the cavity. The longitudinal power and carrier density distributions have been evaluated and their effects on longitudinal spatial hole burning and possible side mode lasing are discussed.**

I. Introduction

High-power narrow-linewidth DFB lasers have many desired properties, including a small footprint and low power consumption, long lifetime, and low device cost, properties that are hard to obtain simultaneously with other commercially available approaches. Since many applications at different wavelengths would benefit from efficient high-power narrow linewidth laser diodes, the optimization of this kind of devices is under intense research.

The theory of semiconductor laser linewidth predicts that the spectral width of a laser line is inversely proportional to the output power [1]. On the other hand experimental observations have shown that there are several detrimental effects (spatial hole burning [2], poor side mode suppression [3], nonlinear gain compression [4]), leading to re-broadening where the emission linewidth increases with increasing output power.

To alleviate the re-broadening effect, the device structure for high-power narrow linewidth lasers requires extensive optimizations in terms of various characteristics. The paper analyzes the effects of some structural device parameters on the carrier and power densities along the DFB laser cavity. The analysis takes into account the end facet reflections, the spontaneous emission noise, the non-linearity of the material gain, and the variations of the effective refractive index.

II. Narrow linewidth dependencies

The lineshape of a single mode laser diode, without the external noise, is expected to be Lorentzian with a linewidth given by the well-known expression derived by Henry [1]

$$\Delta f = \frac{v_g^2 n_{sp}(\alpha_i + \alpha_m)\alpha_m}{8\pi P}(1 + \alpha_H^2), \tag{1}$$

where n_{sp} is the spontaneous emission factor, P is the output power, α_H is the linewidth enhancement factor, and α_i and α_m are the internal loss and mirror loss factors. This expression indicates that the linewidth could be reduced by reducing the mirror losses and by increasing the output power. However, from the DFB laser design point of view, a narrow linewidth and a high output power are contradictory coupled through the product of the grating coupling coefficient (κ) and grating length (L). A large κL implies reduced mirror losses and a narrower linewidth but, at the same time implies reduced output power extraction. Supplementary, the relationship between the linewidth, output power and mirror losses is more complex, largely due to various detrimental linewidth broadening effects [2–4]. We have used numerical time-domain simulations in the design of narrow linewidth DFB lasers to take into account several of these detrimental effects, comprising spatial hole burning, the existence of side modes and gain compression.

In our approach a time-domain traveling wave (TDTW) method [5] connects an optical model, which describes the electromagnetic characteristics of the simulated laser structures, to a carrier rate equation. The carrier rate equation is used to calculate the optical gain and the effective refractive index variations in the longitudinal direction of the cavity.

III. Results

Since using TDTW for the linewidth evaluation is computationally expensive when the linewidth is very narrow, the TDTW simulations were employed on the optimization of the output power, side mode suppression ratio (SMSR), and the uniformity of the longitudinal carrier and photon density distributions. Eq. (1) was used in a first approximation to calculate the linewidth of a DFB laser with no phase shift (PS), and anti-reflection (AR) and high-reflection (HR) coated end facets, under the assumption that the carrier density and the material gain are uniformly distributed. The mirror losses were calculated from:

$$\alpha_m = \frac{\kappa}{2\tanh(\kappa L)} \ln\left(\frac{1}{(1-T_1)(1-T_2)}\right) \tag{2}$$

with $T_1 = 1 - sech^2(\kappa L)(1 - R_1)$ and $T_2 = 1 - sech^2(\kappa L)(1 - R_2)$, where R_1 and R_2 are the phase-matched facet reflectivities. The results, shown in Fig. 1, illustrate that the narrow linewidth and high output power are contradictory coupled through the grating coupling coefficient (κ) and grating length

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(L). The figure shows that, for the 894 nm DFB laser that was analyzed, achieving an emission linewidth smaller than 1.5 MHz and an output power greater than 15 mW is possible only for a limited range of values for κ and L.

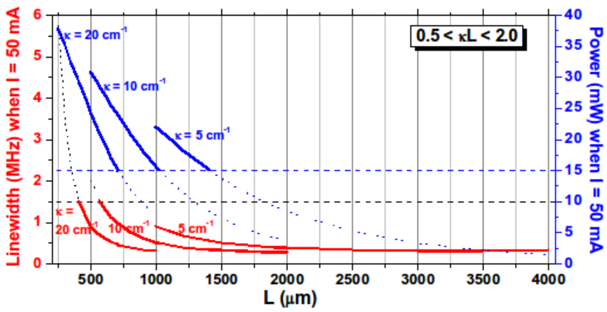

Fig. 1. Linewidth and output power variation with grating length at different κ for a 894 nm DFB laser operated at 50 mA bias current

Since the non-uniformity of carrier and photon density longitudinal distributions is adversely affecting the linewidth, the TDTW model was used to investigate the effects of structural changes on these longitudinal distributions. The power distribution along DFB lasers with no PS and AR/HR-coated end facets, and with one $\lambda/4$ and two $\lambda/8$ phase shifts and AR/AR-coated end facets are shown in Fig. 2. In the simulation the bias current varies between the different lasers such that the output power is 10 mW in all of the cases.

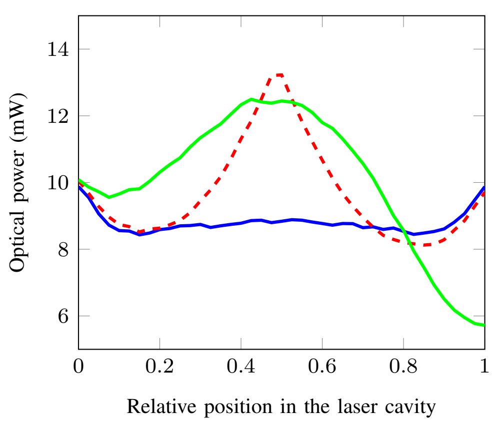

Fig. 2. Longitudinal power distributions for DFB lasers with no PS and AR/HR (3%/90%) coated end facets (green), one $\lambda/4$ PS and AR/AR (3%/3%) coated end facets (dashed red) and two $\lambda/8$ PSs and AR/AR coated end facets (blue). The κL-product is 1.25 in all of the cases.

The distributions shown Fig. 2 show that the structure with two $\lambda/8$ phase shifts and AR/AR-coated end facets has the most uniform longitudinal power distribution, which is also associated with a relatively flat carrier density distribution. A supplementary comparison between the other DFB laser structures is provided in Fig. 3, where the SMSR values and output powers for the DFB laser with no PS and for the one with $\lambda/4$ phase shift DFB laser are shown.

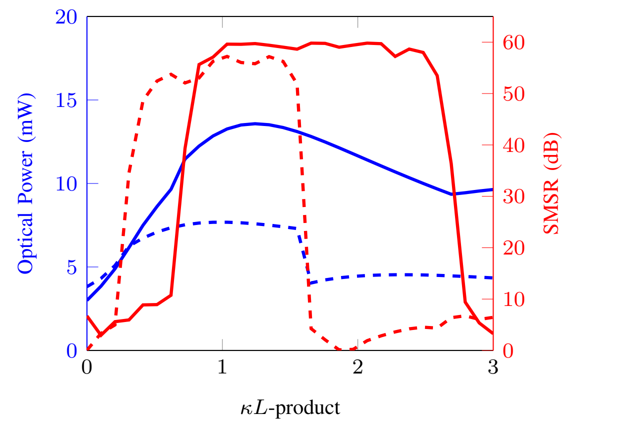

Fig. 3. Simulated SMSR values (red) and output powers (blue) as a function of κL-product for a DFB laser with 0 PS and AR/HR (3%/90%) coated end facets (dashed), and for a $\lambda/4$ shifted DFB laser with 3% end facet reflectivities (solid).

IV. Conclusion

A contradictory coupling between linewidth reduction and output power maximization through the grating coupling coefficient κ and grating length limits the possibility to achieve high-power emission with narrow linewidth from DFB lasers. Calculations show that structural variations in the cavity, like using a distributed phase-shift, can improve the uniformity of photon and carrier density longitudinal distributions, thus reducing the spatial hole burning and the possibility of side mode lasing at higher injection levels. An analysis based on more detailed calculation results indicates that W-level output power with sub-MHz linewidth could be obtained with a monolithic master-oscillator power-amplifier (MOPA) structure, having a narrow linewidth DFB master oscillator section and an integrated flared semiconductor optical amplifier.

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