Traveling wave model of a twin ridge semiconductor laser

L. J. Orbe-Nava, R.C. Guzman-Martínez, and G. Carpintero-del-Barrio

[1] University Carlos III de Madrid, Dept. of Electronics Technology, Av. De la Universidad 30, 28911 Leganés, Madrid Spain

We have developed a travelling wave model for a twin ridge semiconductor laser. The model includes into the standard propagation model the coupling effects between the two laser cavities through a coupling constant. Our results exhibit the appearance in the optical spectrum of a mode splitting that is proportional to the strength of the coupling constant, observing a lower frequency splitting for lower coupling constant strength, in agreement with previous experimental results. The temporal response shown that the fields within each stripe have an 180º phase shift between them.

1. Introduction

Twin ridge laser arrays are structures where two laser emitters lay in close proximity so that there is interaction among them. The interaction can cause the emitters to operate in a phase-locked state, where transverse modes are established in the device, characterized by fixed phase relations among the electric fields in the different emitters [1]. Such a structure was proposed as a mean to increase the limited amount of optical power delivered by single ridge laser diodes, requiring the structure to operate in the in-phase transverse mode [2]. In a twin stripe array, the theoretically predicted mode structures appear from the splitting of the longitudinal modes of the individual ridges into two lateral modes. One mode is characterized by a 0º phase difference between the electric fields in each ridge while the other, the out-of-phase mode, is characterized by a 180º phase difference [1]. On the other hand, early experiments showed that the device structure favors the out-of-phase operation of the device [3], as well as high frequency spiking phenomena in the transient response [4], and recently, chaotic behaviour [5].

However, an interesting characteristic of the device is that the lateral modes have a frequency spacing determined by the coupling strength between the emitters, which is significantly below the longitudinal mode spacing [1]. The availability of two lateral modes proved to be useful to data transmission beyond the intrinsic relaxation oscillation frequency of semiconductor lasers [5][7]. The experiment has also provided that under different current injection levels into the ridges, different mode structures are obtained. As the current is increases, we achieve a longitudinal mode splitting into in-phase mode at low energy (long wavelength) and out-of-phase mode at high energy (short wavelength). At this point, the modulation at the splitting frequency produces a resonance in the frequency response due to a lateral mode-locking between them [8].

2. Rate Equation model of the twin ridge

Rate equations are usually employed to describe semiconductor lasers. In twin ridge lasers, this approach requires assuming that in the absence of coupling, each laser operates as a solitary laser in a single longitudinal and transverse mode. Then, starting from the standard rate equation model for a solitary laser, new terms are added to account for the coupling between stripes. In the case of evanescent field coupling, the equations that describe the temporal evolution of the carriers and the complex electric field, averaged over each lasing stripe, read as follows [9]:

$$\frac{dE_x}{dt} = \frac{1}{2}(1+i\alpha)\xi(N_x - N_{th})E_x + K E_{3-x}, \tag{1.1}$$

$$\frac{dN_x}{dt} = J_x - \frac{N_x}{\tau_n} - [\Gamma_o + \xi(N_x - N_{th})]|E_x|^2, \tag{1.2}$$

where x = 1,2 is the stripe index. In these equations, N_x and $E_x = a_x \exp[i\phi_x]$ stand for the carrier and complex field in stripe x. The value for each parameter in the equations have been obtained from the static analysis of the device. In the equations, J_x is the injected current term, τ_n is the carrier lifetime (=2.5ns), Γ_o the inverse of the photon lifetime (=7.2E11s^{-1}), ξ the linear gain coefficient (=1.6E4 s^{-1}), N_{th} the threshold carrier level (=7.7E8) and α the linewidth enhancement factor (=5). The constant K comes from the evanescent coupling assumption between the emitters. The field on each stripes receives a contribution from the field on the adjacent stripe. The complex proportionality constant $K = K_r + i K_i$, is the coupling strength. For the analysis of the equations, they are usually expressed in terms of the field amplitudes, a_1 and a_2 for the fields in stripes S_1 and S_2 respectively, phase difference between the two stripes, defined as $\eta = \phi_2 - \phi_1$, and normalized conveniently to produce the following set of equations

$$\frac{dn_x}{d\tau} = j_{x1} - n_{x1} - (n_x - n_{th})a_x \text{, with x=1,2} \tag{2.1}$$

$$\frac{da_1}{d\tau} = T\left[\frac{A}{2}(n_1 - 1)a_1 + k_r a_2 \cos(\eta) - k_i a_2 \sin(\eta)\right] \tag{2.2}$$

$$\frac{da_2}{d\tau} = T\left[\frac{A}{2}(n_2 - 1)a_2 + k_r a_1 \cos(\eta) + k_i a_1 \sin(\eta)\right] \tag{2.3}$$

$$\frac{d\eta}{d\tau} = T\left[\frac{A}{2}\alpha(n_2 - n_1) - k_r\left(\frac{a_1}{a_2} + \frac{a_2}{a_1}\right)\sin(\eta) + k_i\left(\frac{a_1}{a_2} - \frac{a_2}{a_1}\right)\cos(\eta)\right] \tag{2.4}$$

In the normalized system, T is the ratio between the carrier lifetime and the photon lifetime, which for the present values of the device is ~1010, providing that the model is accurate even thought carrier diffusion is not included5. It is worth to note on the normalized system, that there is a symmetry in the equations with respect to the field amplitudes. When the sign of both amplitudes is changed simultaneously, the system remains unchanged.

3. Travelling Wave model of the twin ridge

Due to the Fabry-Perot resonator structure in the device, without mode selection schemes to facilitate the processing, the optical spectrum shows to be composed of a large number of longitudinal modes. As shown in the Figure 1, the longitudinal modes are coupled, giving each rise to the transverse mode structures. Due to the multimode nature of the device, we need an alternative model to analyze the behavior.

Figure 1.
Far-field mode structure of the twin ridge laser on a monochromator.

The traveling wave scattering matrix model considers the multimode nature of the device by sampling the cavity. An important advantage of this model is that it has been successfully used to analyze DFB structures, which already incorporate coupling effects [10]. We have adapted the coupling between the two propagation directions in the DFB to describe the coupling effect between the two emitters in the twin ridge device. The coupling constant has an important effect on the device characteristics [11].

To verify the performance of the proposed model, we have verified the basic know phenomena occurring in these structures. First of all, the appearance of a coupling length, Lc, defined as the minimum distance to transfer the total optical power from one cavity to the other, which is known to depend on the value of the coupling coefficient, κ, by the relation: $Lc = \pi / 2\kappa$. Figure 2.a represents the time evolution with the model, showing the back and forth transfers of optical power from one waveguide to the other when neither gain nor losses are included in the model. Comparing our numerical results with the analytic expression for the coupling length, shown in Figure 2.b, the relative error does not go beyond 4.5%.

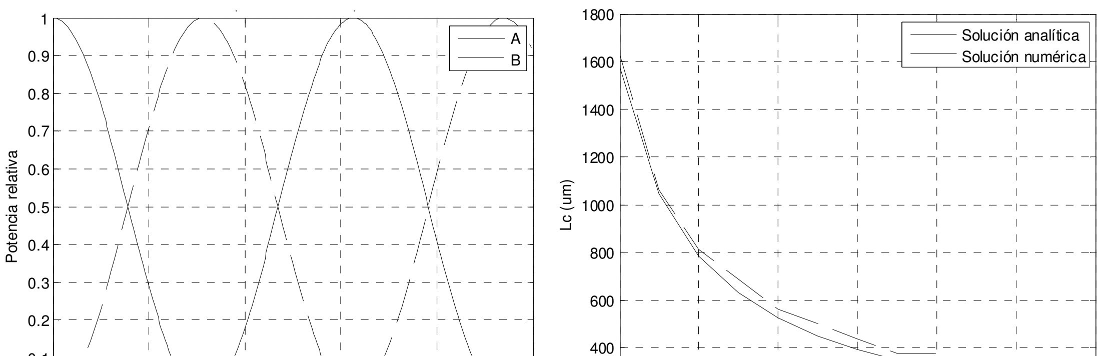

Figure 2.
Coupling distance on a passive scattering matrix laser model: a) Time evolution of the optical power, and b) Dependence between coupling constant and coupling distance, Lc.

Introducing gain and loss into the model to describe two coupled Fabry-Perot structures, and looking for evidence of the effect of the coupling, we have compare the resulting optical spectrum in Figure 3. The optical spectrum shows the appearance of the transverse coupled mode solutions, as each peak in the modeled optical spectrum for the independent structures (with $\kappa = 0$) doubles, showing two peaks when $\kappa = 2000$. Just as the resonance frequency due to the beat among the modes changes with the separation distance between the emitters, we have found that the spacing depends on the value of κ.

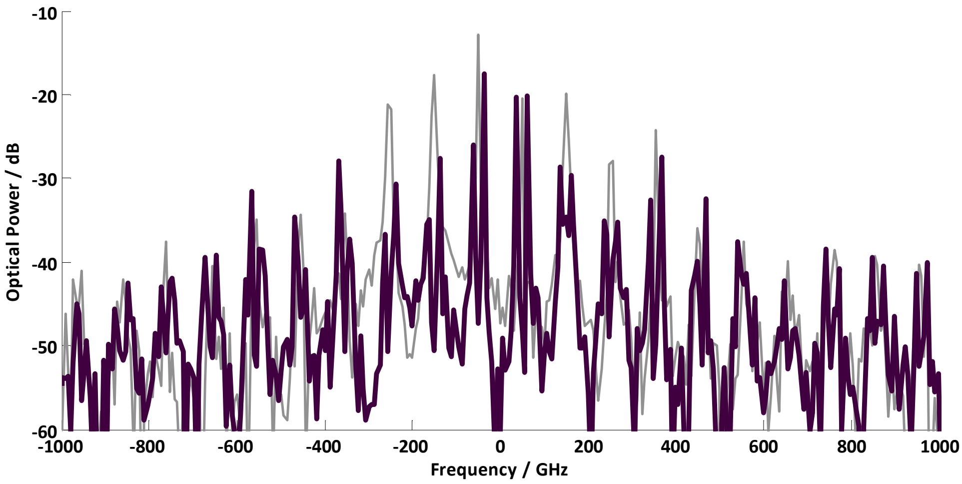

Figure 3.
Optical spectra obtained using the proposed twin ridge scattering matrix model.

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