Accurate Dynamic Model of DFB lasers

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Abstract—**Efficient and reliable models for semiconductor distributed feedback (DFB) lasers design and optimization are highly desirable. An innovative dynamic model for accurate simulations of DFB lasers is proposed in this paper. The developed algorithm is based on a system of coupled partial differential equations which is solved by the finite element method (FEM). No approximation is assumed and obtained results are affected only by the numerical error of the FEM solver. The code has been validated on the large-signal response of a typical DFB device.**

Keywords-laser; semiconductor laser; DFB laser; finite element method

I. INTRODUCTION

DFB semiconductor lasers, whose main feature is the high spectral purity, have been widely investigated both theoretically and experimentally in the last three decades [1]. As well known, a surface corrugation grating is embedded within the DFB structure in close proximity to the active region usually formed by a multi quantum well (MQW). DFB lasers typically emit an optical signal having a very narrow linewidth and their operating wavelength exhibits a low sensitivity to shifts in drive current or temperature. These features make the DFB laser the most suited optical source in optical communications, microwave photonics and photonic sensing. As an example, a fully integrated InP-based photonic integrated circuit for angular velocity sensing including also a DFB laser has been recently modelled, designed and optimized [2].

Optical propagation in a periodic corrugated waveguide having a complex refractive index and carrier transport in a directly biased p-i-n diode are the two interacting physical phenomena governing the DFB laser operation.

In a DFB lasing structure, slow varying complex envelops of forward- and backward-travelling waves depend on time and propagation direction. Also carrier density depends on these two variables. Models based on rate equations neglect the space dependence of wave amplitude and carrier density whereas transfer matrix-based models do not take into account the time dependence of optical wave amplitude and carrier density [3]. Space/time-dependent model, based on the solution of a system of partial differential equations (PDEs), is a very powerful tool for DFB laser simulation. It is very general and allows also the calculation of dynamic characteristics. Large-signal response can be estimated, too. Several approaches [4-5] have been proposed to achieve the solution of the PDE system implementing this model but they introduce approximations which, in some cases, can introduce not negligible errors.

In this paper we propose an innovative method to implement the space/time-dependent model. No approximation is assumed to develop the model and the PDE system is solved by FEM. Transient response of the DFB laser is estimated in two very important case, i.e. sine-wave and square-wave modulating signal.

II. MODEL DESCRIPTION

Under slow varying envelope hypothesis, wave propagation in the DFB cavity can be accurately modelled by the following coupled PDEs [5]:

$$\frac{\partial F(z,t)}{\partial t} = -v_g \frac{\partial F(z,t)}{\partial z} + \\ +v_g \left\{ \frac{\Gamma A_0 \left[N(z,t) - N_0 \right]}{2\left[1 + \varepsilon \left(\left| F(z,t) \right|^2 + \left| R(z,t) \right|^2 \right) \right]} (1 + i\alpha_m) - \frac{\alpha_{loss}}{2} \right\} F(z,t) + \\ +i\kappa R(z,t) \tag{1}$$

$$\frac{\partial R(z,t)}{\partial t} = v_g \frac{\partial R(z,t)}{\partial z} + \\ +v_g \left\{ \frac{\Gamma A_0 \left[N(z,t) - N_0 \right]}{2\left[1 + \varepsilon \left(\left| F(z,t) \right|^2 + \left| R(z,t) \right|^2 \right) \right]} (1 + i\alpha_m) - \frac{\alpha_{loss}}{2} \right\} R(z,t) \\ +i\kappa F(z,t)$$

where z is the propagation direction, t the is time, $F(z,t)$ and $R(z,t)$ are slow varying complex envelops of forward- and backward-travelling waves, respectively, v_g is the group velocity of the counter propagating waves, $N(z,t)$ is the carrier density, A_0 is the differential gain, Γ is the confinement factor, N_0 is the transparency carrier density, ε is the gain suppression coefficient, α_{loss} is the cavity loss, κ is the coupling coefficient between the two travelling waves, and α_m is the linewidth enhancement factor. The two unknown functions $F(z,t)$ and $R(z,t)$ assume complex values and so the PDE system in Eq. (1) has been solved by deriving a new system of four coupled PDEs in which real and complex parts of $F(z,t)$ and $R(z,t)$ are unknown functions.

Carrier density space and time dynamics has been modelled by the following rate equation [5]:

$$\begin{aligned}&\frac{\partial N(z,t)}{\partial t}=\frac{I(t)}{qV}-\frac{N(z,t)}{\tau}-\\&-BN^2(z,t)-CN^3(z,t)-\\&-v_g\frac{A_0\left[N(z,t)-N_0\right]}{1+\varepsilon\left(\left|F(z,t)\right|^2+\left|R(z,t)\right|^2\right)}\left(\left|F(z,t)\right|^2+\left|R(z,t)\right|^2\right)\end{aligned} \tag{2}$$

where *I*(*t*) is the time-varying drive current, *q* is the electron charge, *V* is the volume of the active region, τ is the linear recombination lifetime, *B* is the coefficient taking into account radiative bimolecular recombination, and *C* is the Auger recombination coefficient.

III. NUMERICAL RESULTS

The home-made code implementing the space/time dependent model is validated on a typical DFB structure with negligible reflectivity at the two end facets. Parameters of the test device are listed in Table 1.

Large-signal dynamic response of the DFB test structure is estimated for two possible modulating current signals:

a. sine-wave having frequency = 0.5 GHz, peak-to-peak amplitude = 20 mA, mean value = 25 mA;

b. square-wave frequency = 0.5 GHz, duty cycle 50 %, current levels = 35 mA / 8.5 mA.

Large-signal responses of the DFB laser are shown in Fig. 1. They are in good argeement with the results expected on the basis of the esperimental literature on directly modulated DFB lasers (see, for example, [6]).

In case of sine-wave modulation, after about 3 ns, the laser output follows very well the modulating current. When the laser is modulated by a square-wave signal, the dynamic response includes the typical relaxation oscillations in correspondence of the laser turn-on. As expected on the basis of the literature on the DFB lasers large-signal response [7], by our model we have observed that the laser output does not follows the modulating signal when its frequency is larger than 5 GHz. This device behavior, which is physically due to the semiconductor laser turn-on delay that is proportional to the carrier lifetime (about 1-2 ns), is well predicted by the proposed simulation technique.

TABLE I. PARAMETERS OF THE DFB TEST STRUCTURE

Parameter	Value
Laser length	0.3 mm
v_g	0.83×10^8 m/s
κ	5 mm^{-1}
Γ	0.3
A_0	2.5×10^{-16} cm^2
N_0	10^{18} cm^{-3}
α_{loss}	50 cm^{-1}
ε	0
α_m	4
V	90 μm^{-3}
B	0
C	0

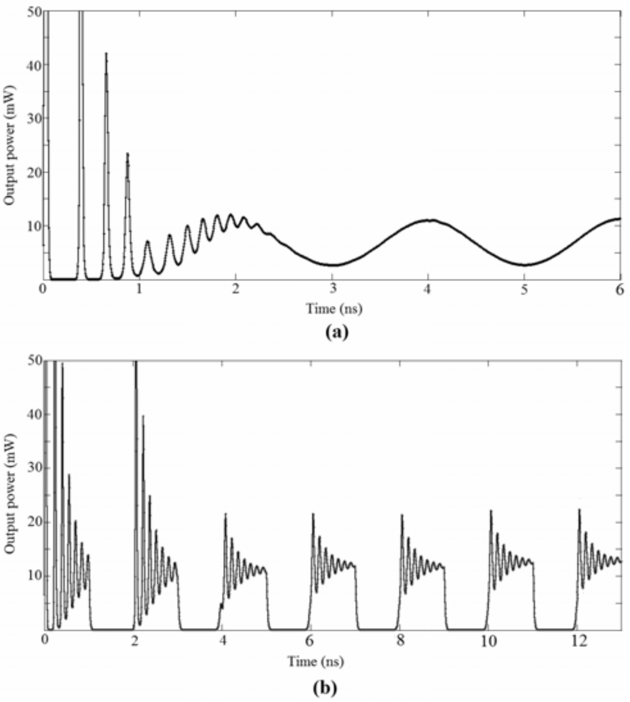

Fig. 1. Large-signal dynamic response of the DFB test structure under (a) sine-wave and, (b) square-wave modulation.

IV. CONCLUSIONS

Potential of a new dynamic modelling approach for DFB laser is described in this paper. The proposed algorithm, based on a PDE system solved by FEM, is an effective tool for accurate computation of large-signal dynamic response. The integration of the developed model with the MQW structures gain model based on the 8 x 8 k•p method [8] could further improve the code predictive capability.

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