Calculation of the spontaneous emission spatial dependency in semiconductor laser using transmission line model

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Abstract

In this paper we calculate the spatial dependency of the spontaneous emission in semiconductor laser cavity using a model based on transmission line laser method (TLLM). Results show that in the simple ridge laser structure, the major part of the spontaneous emission occurs at the middle of the cavity and so uniform spontaneous emission can't be assumed.

Keywords: semiconductor laser, spontaneous emission, spatial dependency, transmission line model.

1. INTRODUCTION

Semiconductor lasers (SL) play an important role in today's optical communication systems. Many different approaches have been reported for modeling the behaviour of these devices [1]-[4]. Transmission Line Model (TLM) is one of these methods which discretize the SL waveguide to the equal sections and generate an equivalent circuit for each section [5]. Therefore using this method we can simulate the dynamic and spatial behavior of SL, carefully. Although TLM method has been used for calculation of the forward and reverse signals propagating through the waveguide, in this work for the first time we present a new numerical approach for calculation of the carrier density in SL instead of the equivalent circuit model [5]. This technique decreases the simulation time. Using the presented method, the transient response of the output power at the facets, the amplified spontaneous emission transient response, and the spatial variation of the carriers in the waveguide are calculated. The results indicate that the carrier density has a peak somewhere in the waveguide. The dependence of this peak on the facet reflectivity and spontaneous emission rate is studied in this work. It's shown that how the facet reflectivity impresses the spontaneous emission and lasing characteristics. In following sections, first we describe the TLLM modeling technique and then the simulation results are presented.

2. MODEL DESCRIPTION

In the Transmission Line Laser Method, the laser cavity length *L* is divided into a number of sections, *s*, each of length *ΔL*. This one-dimensional approach allows multiple longitudinal modes, but only single transverse mode operation is modeled. This is valid for most modern buried-heterostructure lasers which do not suffer from transverse-mode instabilities [6]. Each section includes a propagation delay of *ΔT*. This is related to the laser's cavity length and the group velocity inside the cavity, $c/\overline{n}_e$, by:

$$\Delta T = \Delta L\,\overline{n}_e / c \tag{1}$$

where c is the light speed in the free space and $\overline{n}_e$ is the effective group index.

Each section contains a scattering node, which is represented by a scattering matrix. In one iteration, pulses arriving at all scattering nodes from adjacent nodes (incident pulses) will be used to calculate a set of pulses to be sent down-the-lines to the adjacent nodes for the next iteration (reflected pulses). The process is inherently explicit and highly parallel. In the

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TLLM, the node may be split into a photon model, based on the field equations, and a carrier model, based on the diffusion equation. Each model has its own set of transmission lines, as shown in Fig. 1. The voltages on the field model are labeled V_c. The field model is similar to the waveguide model in [7], but is reduced to one dimension and includes energy sources to represent radiative recombination. Stimulated recombination is represented by frequency selective amplifiers (A) at the nodes. These contain a second-order filter made from transmission-line stubs which act as capacitors or inductors depending on their terminations [8]. Spontaneous recombination is modeled using the filtered noise current sources $(I_s\Delta L/2)$.

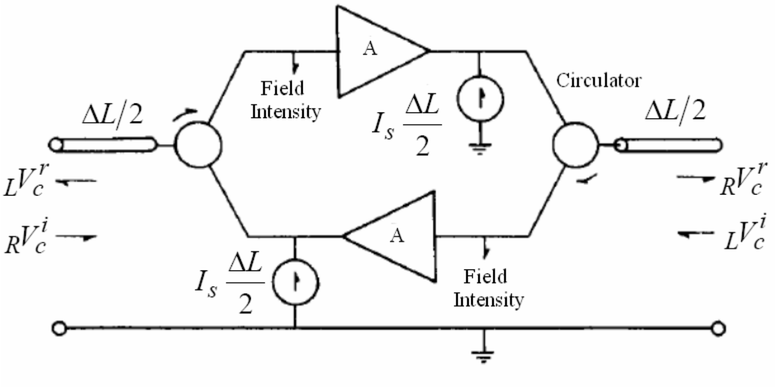


Fig. 1: Transmission-line laser model section with a centrally-placed scattering node connected to adjacent sections with half-time-step long transmission lines.

By considering the spontaneous power which is injected per mode per section when the cavity is in nonresonant mode, the mean-square value of these sources is shown to be:

$$I_s^2 = 2m^2\beta N(n)hfs\big/(\Delta L\cdot Z_p\tau_s) \tag{2}$$

where I_s is the noise current per unit length, β is the spontaneous emission coupling coefficient, $N(n)$ is the carrier density in section n, h is Plank's constant, Z_p is the transverse-wave impedance of the waveguide, m is unity factor, and τ_s is the carrier lifetime.

Now from this circuit the photon density can be calculated by:

$$S(n) = \frac{\left(\left|{}_LV_c^i\right|^2 + \left|{}_RV_c^i\right|^2\right)\times\overline{n}_e}{Z_p\cdot h\cdot f\cdot c\cdot m^2} \tag{3}$$

The carrier concentration is obtained from the rate equation using the finite difference method:

$$N^{k+1}(n) = N^k(n) + \Delta T\left\{\frac{I(n)}{qV} - \frac{N^k}{\tau_s} - \Gamma\left[a(N^k - N_{tr})\times S(n)\frac{c}{\overline{n}_e}\right]\right\} \tag{4}$$

where $I(n)$ is the total current which is injected into each section of SL, V is the volume of each section, Γ is the confinement factor, a is the gain coefficient, N_{tr} is the transparency carrier density, and $S(n)$ is the photon density which is calculated from the forward and backward fields in each section.

3. RESULTS AND DISCUSSIONS

The laser parameters used in the modeling are given in Table 1. For the transient response, a current equal to 44 mA is applied to SL. In Fig. 2 the transient response of the laser is shown. The relaxation oscillation can be seen in the output power spectrum. The obtained relaxation oscillation time is in good agreement with the previous works [5]. In Fig. 3 the amplified spontaneous emission in the final section is shown which predicate the output power response.

Table 1-Laser parameters

Symbol	Parameter	Value
λ_0	Free-space wavelength	850nm
L	Cavity length	300μm
n_e	Group index	4
R	Facet reflectivity	0.3
$a*\Gamma$	Gain constant * Confinement factor	$1.5*10^{-16}$ cm^2
N	Transparency carrier density	$1.5*10^{18}$ cm^{-3}
D	Active region depth	0.1μm
W	Stripe width	5μm
τ_s	Carrier lifetime	4ns
B	Spontaneous factor	0. 01
α_{sc}	Internal attenuation	20cm^{-1}

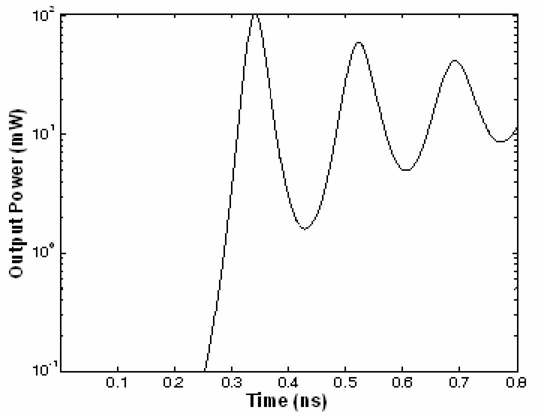


Fig. 2: Output power response at the right facet

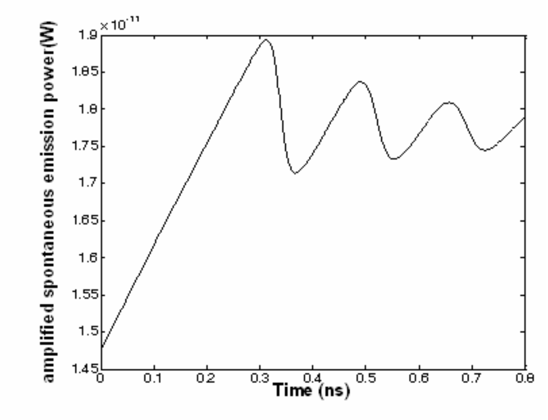
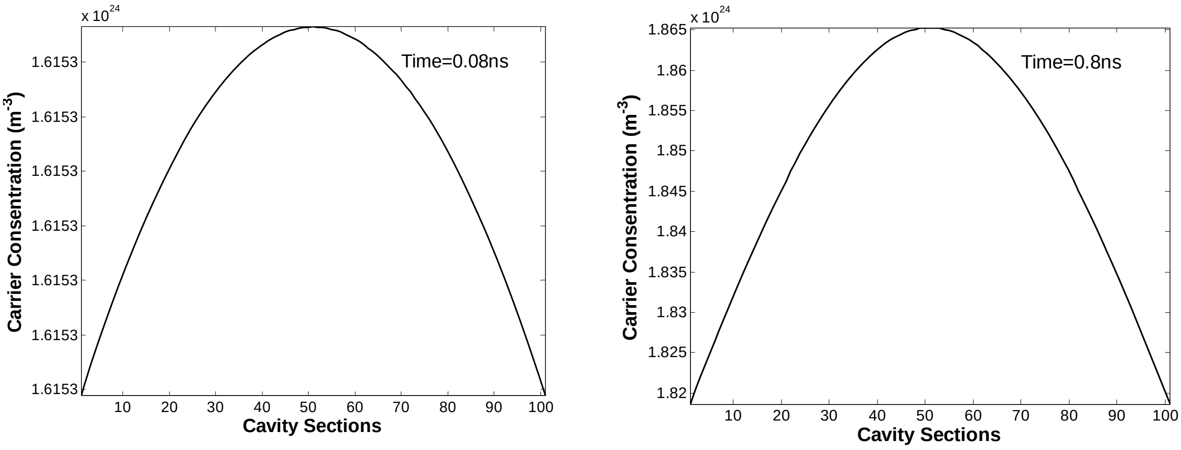


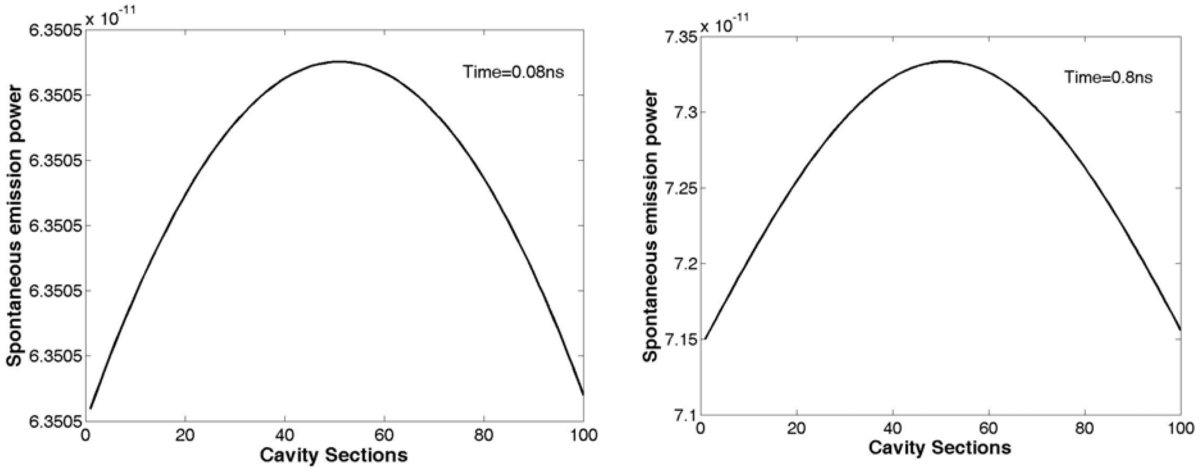
Fig. 3: Amplified spontaneous emission in the final section

In Figs. 4(a) and 4(b) the carrier density spatial dependency are shown at the times 0.08ns and 0.8ns after the current injection, respectively. It is easily concluded from this Figs. that the spontaneous emission affects on the carrier density. It shows that at the middle section, the carrier density reaches to its maximum . Spontaneous emission power shown in Figs. 5(a) and 5(b) which shown the maximum variation in steady state condition.



(a) (b)

Fig 4: Carrier concentration spatial variation in (a) 0.08ns and (b) 0.8ns



(a) (b)

Fig 5: Spontaneous emission spatial variation in (a) 0.08ns and (b) 0.8ns

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