MODELLING OF SEMICONDUCTOR LASERS

I. HABERMAJER

Department of Electron Devices,
Technical University, H-1521 Budapest

Summary

The rate equations for excess stored charge and for the photon number in semiconductor lasers can be represented by a nonlinear equivalent circuit. This circuit is built up with conventional circuit components, thus it is easy to analyse with nonlinear circuit analysis programs. The usefulness of the model is proved by simulation examples.

Introduction

Device models can be classified as structural and functional models. Structural models are based on the mathematical description of dominant and secondary physical phenomena which are important in the device operation, taking into account the structural and material parameters of the device. These models are not directly applicable for circuit and system design because they need high computing power and detailed information on the structure of devices.

The functional models used in circuit and system design have to meet the following, sometimes contradictory, requirements:

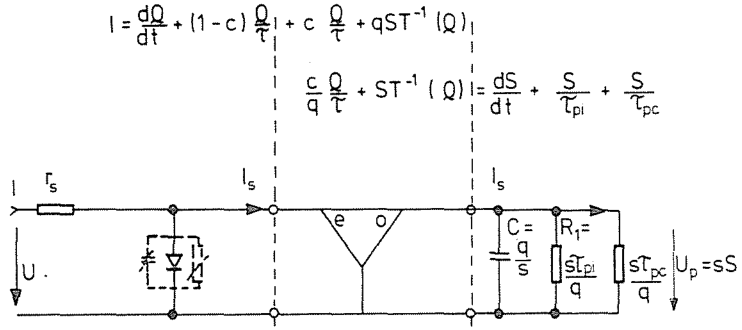
- model the basic phenomena with appropriate accuracy,
- use few intermediate variables,
- parameters of the model should be easily identifiable with measurements.

Highly increases the versatility of the model if it is easily expandable for modelling secondary and composite effects and can be represented by equivalent circuits consisting of conventional circuit components.

The presented functional model for semiconductor lasers satisfies all the above-mentioned requirements.

Description of the model

The most widely used mathematical model for laser diodes are the coupled rate equations for excess minority carrier concentration in the active layer of diode, and for the photon number S in the optical cavity [1]. Using the stored charge Q instead of the carrier concentration, the rate equations can be transformed into the form of Eq. (1). Here I is the input current, τ is the life time of the minority carriers without lasing, c is the ratio of the spontaneous emission into the cavity modes to the total recombination rate, T^{-1} is the rate of the stimulated emission, and τ_{pc}, τ_{pi} represent the coupling and internal losses of the optical cavity, respectively.



(1)

Fig. 1. The connection between the rate equation and the equivalent circuit

Representing the photon number by $U_p = sS$ optical voltage, (where s is an arbitrary scaling factor) and using the well-known $Q(U) = Q_0[\exp((U - Ir_s)/mU_T) - 1]$ relation between the stored charge and the applied voltage the rate equations can be transformed into the circuit equations of the laser diode (Fig. 1).

The voltage dependence of the stimulated emission rate can be written as [2].

$$T^{-1}(U) = T_0^{-1}\left[\frac{1}{1 + b\exp(E/q - U)/mU_T} - \frac{1}{1+b}\right] \tag{2}$$

Where E is the energy of the emitted light, parameters m and b are functions of the material and doping of the active layer, T_0 is the function of the material and construction of the laser, U_T is the thermal voltage. It is easy to show that the circuit shown in Fig. 2 is equivalent to the electrooptical coupling two-port if

$$q_0 = q[s(1+b)]^{-1} \cdot T_0^{-1};\ I_1 = I_0[\exp(U_1/mU_T) - 1]$$
$$I_2 = bI_0[\exp(U_2/mU_T) - 1];\ I_0 \le I_{sp0};$$
$$I_{sp} = cI = I_{sp0}[\exp(U/mU_T) - 1].$$

Using the thermal equivalent circuit of the device and temperature dependent models for diodes, most of the static and dynamic thermal properties of the laser can be simulated.

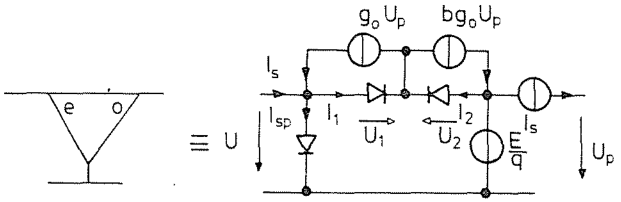


Fig. 2. The equivalent circuit of the electrooptical coupling two-port

Applications

The examples for simulation shown in this section prove the usefulness and easy applicability of the model. Fig. 3 shows the simulated and measured bit pattern sensitivity of a semiconductor laser as a function of bias current. The computed waveform of the output power is very similar to the measured [1] one.

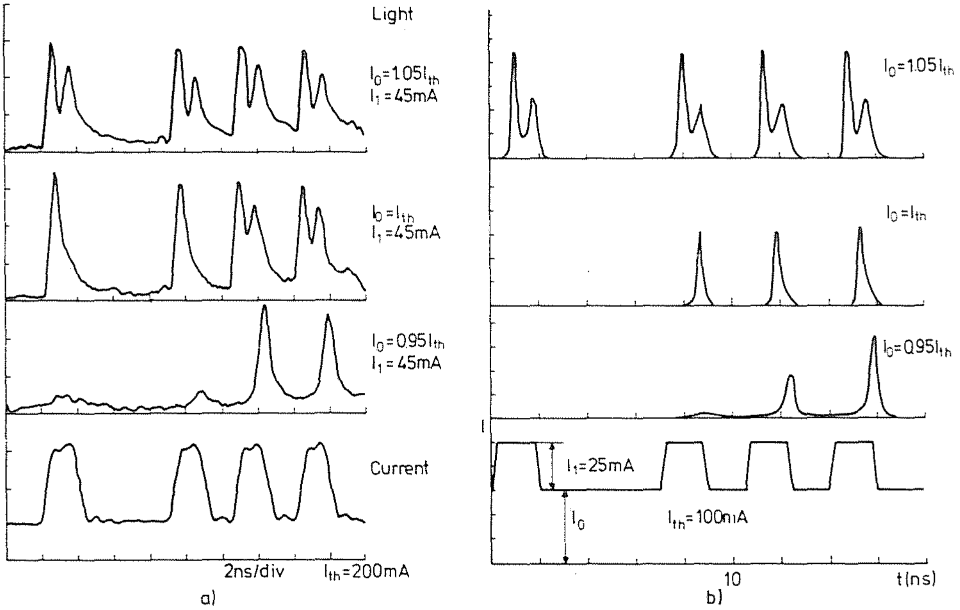


Fig. 3. Direct modulation of a semiconductor laser at 280 Mbit/s and different bias currents. The measured (a) (Fig. 7.5 in Ref [1]) and the simulated (b) bit pattern sensitivity

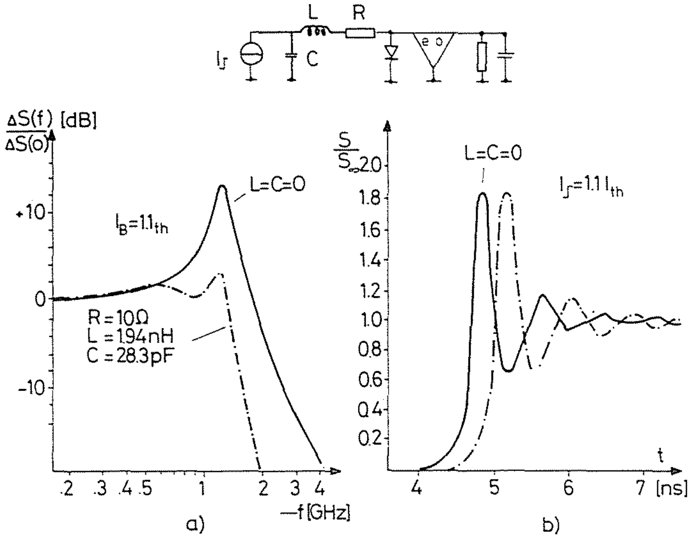


Fig. 4. The effect of compensating *L*, *C* components. The small signal transfer characteristics (a) and the step response (b)

In Fig. 4 is shown the effect of parasitic or compensating series inductance *L* and the parallel capacitance *C*. It is interesting that while the small signal A. C. transfer characteristic can be effectively smoothed by properly choosen *LC* components, the large signal step response, apart from a delay, remains nearly unchanged.

The next figures show simulated characteristic features of some composite structures.

The damping effect of optical bias, accomplished by another laser, was analitically and experimentally examined by Arnold et al. [3]. The simulated transient response of the same structure is shown in Fig. 5. The simulated step responses are strong damped and very close to the measured ones.

Figure 6 shows the simulated effect of the short distance optical reflexion. The round trip delay was about half of the periodicity of original relaxing oscillation. It can be seen that by a controlled amount of reflexion the relaxing oscillation of the step response can be greatly supressed.

Both in electrooptical information storing and regeneration the triggerable or bistabil laser structures may play an important part. In this structures the injected current is inhomogeneous, and the underexcited segment acts as a saturable absorber [4]. It is worth remarking that the same holds true due to some mistakes of construction or of the technology, as well. These structures show a back bending, unstable transfer characteristics [5]. In

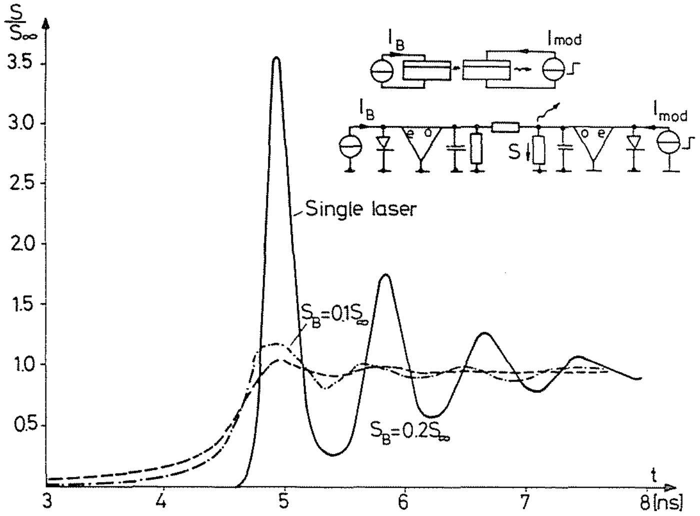


Fig. 5. Damping effect of the optical bias accomplished by another laser

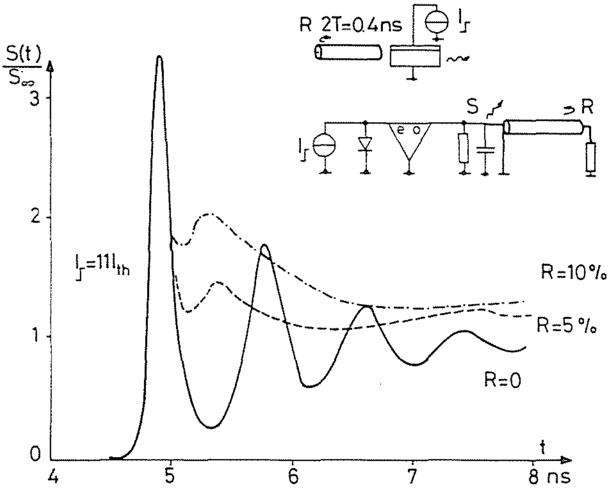


Fig. 6. Simulated effect of short distance optical reflexions

the unstable part of the characteristics occurs a sustaining optical pulsation and in the measured transfer characteristics a kink appears. The computation of the unstable characteristics can easily be carried out by adding to the equivalent circuit a virtual negative feedback. The analysed structure and the calculated transfer characteristics are shown in Fig. 7.

All simulation examples discussed above were carried out by TRANZ-TRAN nonlinear circuit analysis program system [6].

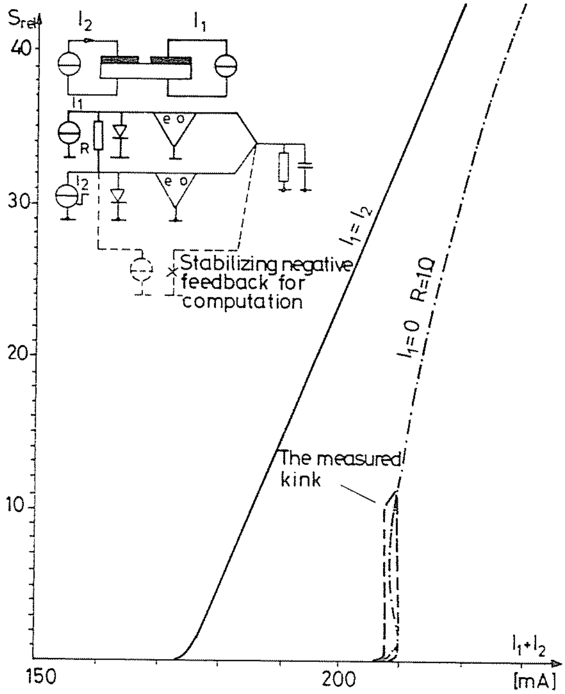


Fig. 7. Computed transfer characteristics of an unstable laser structure

Conclusions

The discussed equivalent circuit representation of semiconductor laser describes the basic properties of the device with satisfactory accuracy. It makes easy to simulate the effects originating both from the electrical and from the optical environment of the laser.

References

1. Semiconductor Devices for Optical Communication (Edited by H. Kressel Springer-Verlag Berlin, Heidelberg, New York, 1980).
2. HABERMAJER, I.: Nonlinear circuit model for semiconductor lasers. Optical and Quantum Electronics *13*, 461 (1981).
3. ARNOLD, G.—PETERMANN, K.—RUSSER, P.—BERLEC, F. J.: Modulation behaviour of double heterostructure injection lasers with coherent light injection. AEÜ Electronics and communication *32*, 129 (1978).
4. BASOV, N. G.: 0—1-Dynamics of injection lasers IEEE J. Quantum Electronics *QE-4*, 855 (1968).
5. HARDER, CH.—LAU, K. Y.—YARIV, A.: Bistability and pulsations in cw semiconductor lasers with a controlled amount of saturable absorption Appl. Phys. Letters *35*, 382 (1981).
6. TARNAY, K.—SZÉKELY, V.: The TRANZ-TRAN nonlinear circuit analysis program. Híradástechnika *24*, 257 (1973). (in Hungarian)

Dr. István HABERMAJER 1521 Budapest