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MICROWAVE CIRCUIT MODELS OF SEMICONDUCTOR INJECTION LASERS

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Small-signal two-port circuit models of packaged broad-stripe and buried-heterojunction AlGaAs laser diodes are presented. The models show good agreement with measured reflection coefficient and modulation frequency response data.

Introduction

The semiconductor injection laser is well established as an important light source for fibre-optical and integrated-optical systems.[1] Recently, it has also found application in optically controlled microwave circuits such as switches [2] and injection-locked oscillators.[3]

In the analysis and design of optical and microwave circuits using directly modulated laser diodes, it is often necessary to determine the dynamic response of the laser for a given electrical input signal. Traditionally, the modulation response of the laser has been determined using a direct solution of the rate equations.[1] This method of analysis has several disadvantages: it requires specialized software, it is not suited to the inclusion of package parasitics, and device-circuit interactions are not easily taken into account. An alternative approach is to use a circuit analysis based on a circuit model of the device. However, to date very little has been published on circuit models for laser diodes.

This paper presents examples of laser diode small-signal circuit models that can be easily incorporated in conventional microwave circuit analysis programs. Element values are given for commercial diodes from two different laser manufacturers. The models include the effects of package parasitics, space-charge capacitance, heterojunction I-V characteristics, and electro-optical dynamics in the active layer. Thus the major factors which contribute to the small-signal dynamic response of the laser are taken into account. In all previous reports of laser diode circuit models [4,5,6] at least one of these effects has been neglected.

Models

The laser diode circuit models presented here are based on a small-signal model of the intrinsic device chip. This chip model was obtained by linearizing a large-signal laser diode model described by Tucker.[7] In carrying out the linearization, closed-form solutions were obtained for the element values of the chip model in terms of basic laser parameters such as the active layer volume, the electron and photon lifetimes, the spontaneous emission coefficient, and the slope of the optical gain versus drive current characteristics.[7] The basic chip model is similar to the small-signal model described by Katz et al.[4] for a laser with no saturable absorption.

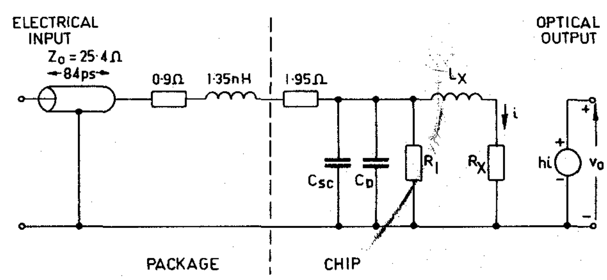
The complete laser diode model was constructed by adding to the basic chip model a space-charge capacitance, a substrate resistance and capacitance (where appropriate), and package parasitics. The complete model is a two-port circuit, with one port representing the electrical input terminals of the device, and the other representing the light output. The voltage at this output port is an analog of the light output intensity of the laser,[7] and becomes the output variable in frequency response calculations.

Using this basic topology, models have been developed for a broad-stripe laser (Laser Diode Labs. LCW-10) and a buried-heterostructure (BH) laser (Hitachi HLP-3400). Both lasers are AlGaAs devices, with emission at a wavelength of approximately 0.83 μm. Element values for the models were obtained as follows:

(a) The lasers were mounted in 50-Ω microstrip test fixtures and were temperature-stabilized to within ±0.2 C at room temperature. Broadband measurements were made of the electrical reflection coefficient at the device terminals using a semi-automatic network analyzer. The modulation frequency response was measured with the lasers mounted in the same test fixtures, and driven from a 50-Ω source. The light output was detected with a high-speed photodetector (Opto-Electronics PD10-01), coupled to the laser with a lens. The frequency response of the photodetector was determined in a separate experiment and this information was used to improve the accuracy of the measured modulation response data.

(b) Element values for the package model, the substrate resistance and capacitance, and the (zero-bias) space-charge capacitance were all determined by computer optimization, using measured reflection coefficient data for a number of dc bias conditions above and below threshold. The space-charge capacitance under forward-bias was estimated from the zero-bias value.

(c) The basic laser parameters (electron lifetime etc.) were initially estimated using published data [1] and then adjusted slightly to improve the match between the measured and calculated frequency response for each diode. These parameters are all independent of the dc bias conditions above threshold, and enable the circuit elements of the intrinsic chip model to be determined as a function of bias current.



I_b(mA)	C_{sc}(pF)	C_D(nF)	R_1(Ω)	L_x(pH)	R_x(mΩ)
117	138	6.46	0.550	6.89	20.8
121	138	6.46	0.507	3.91	6.71
125	138	6.46	0.470	2.72	3.25

Fig. 1. Circuit model of the LCW-10. Element values of the chip model are given for three values of the bias current I_b. The light output intensity is represented by v_o, which is in turn determined by a current-controlled voltage source. The scaling factor h can be selected to give convenient numerical values for v_o.

Broad-Stripe Laser

Fig. 1 shows the circuit model of the LCW-10. The package of this laser was modeled with a length of transmission line (characteristic impedance and one-way propagation time shown), a small loss resistance, and a bondwire inductance. Elements of the intrinsic chip model are given for three values of dc bias current I_b (117, 121, and 125 mA). The threshold current of the device was 112 mA. The forward-bias space-charge capacitance C_{sc} was estimated to be 138 pF. It is felt that this is more realistic than the very large values for C_{sc} used by Dumant et al.[5]

Fig. 2 shows the measured and calculated reflection coefficient for the LCW-10, forward-biased at a current of I_b = 121 mA. The measured and calculated modulation frequency response is given in Fig. 3 at three bias currents for frequencies up to 2 GHz. Beyond 2 GHz, the measured data became unreliable due to noise in the photodetector system. The frequency response shows the well-known effects of electro-optical resonance.[1] Agreement between the experimental and theoretical data is good.

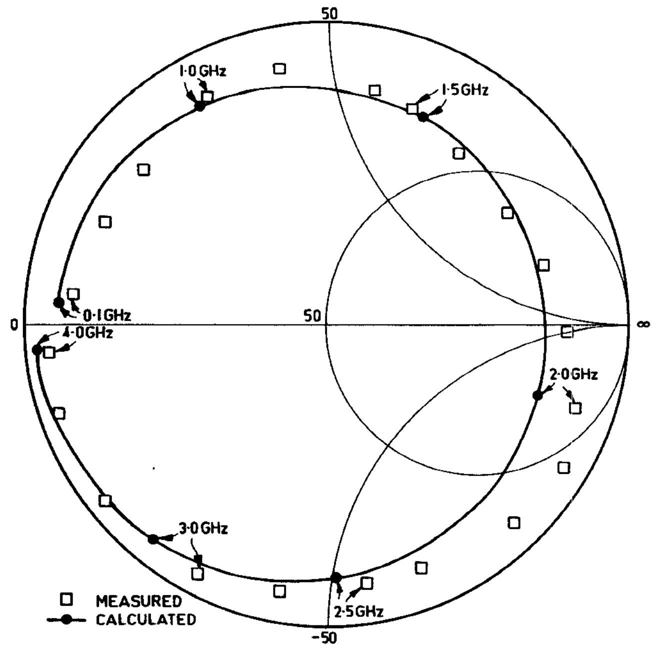


Fig. 2. Measured and calculated reflection coefficient of the LCW-10, biased above threshold.

Buried-Heterostructure Laser

The circuit model of the HLP-3400 is shown in Fig. 4, with element values of the intrinsic model given for two values of bias current above threshold. The threshold current of the device was 13 mA. The package model of the HLP-3400 is relatively simple. However, the substrate capacitance and resistance (14.1 pF and 13.1 Ω respectively) are quite large. The reflection coefficient and modulation frequency response of the HLP-3400 are shown in Figs. 5 and 6 respectively. Agreement between the measured and calculated data is generally good.

As expected,[1] the resonance peak in the frequency response is much smaller for the BH laser than the broad-stripe laser. This is due to increased damping resulting from a larger value of the spontaneous emission coefficient in the BH structure.[1] An additional difference between the two responses is the

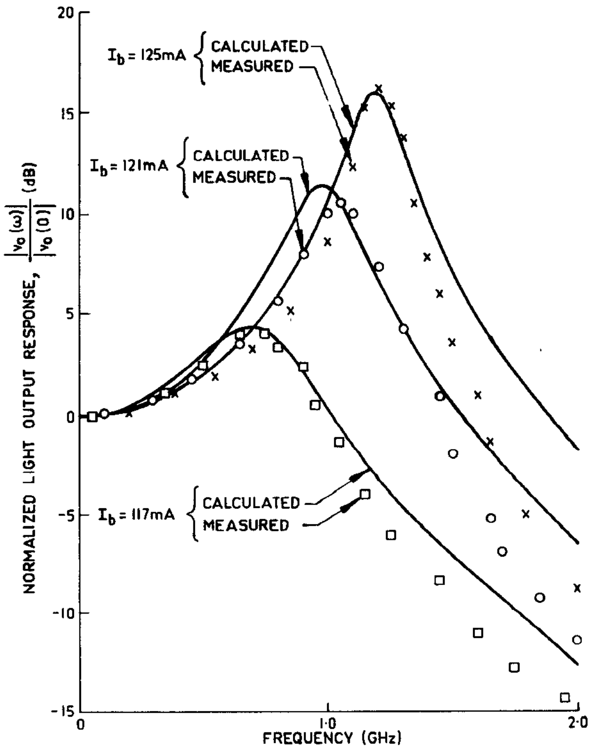
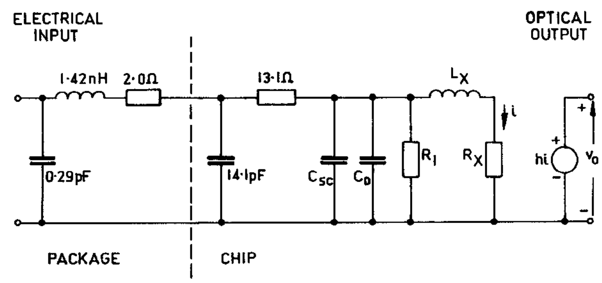


Fig. 3. Measured and calculated small-signal frequency response of the LCW-10 for an RF source with a 50-Ω internal resistance. The response is given for three values of dc bias current.



I_b(mA)	C_{sc}(pF)	C_D(pF)	R_1(Ω)	L_X(pH)	R_X(mΩ)
20	100	310	1.08	5.76	29.5
30	100	310	0.519	2.36	5.01

Fig. 4. Circuit model of the HLP-3400. Element values of the chip model are given for two values of the bias current I_b.

roll-off in the frequency response of the BH laser at frequencies *below* the resonance peak. Both of these characteristics are predicted by the models. The roll-off in the frequency response is of significance since it affects the ultimate bandwidth of the device. A study of the model in Fig. 4 has shown that the roll-off is caused mainly by the substrate capacitance and resistance mentioned above. For improved device bandwidth, these elements would need to be reduced in value.

Conclusion

Accurate circuit models have been presented for two commercial packaged semiconductor laser diodes. Element values for the models were obtained using measured reflection and transmission frequency response

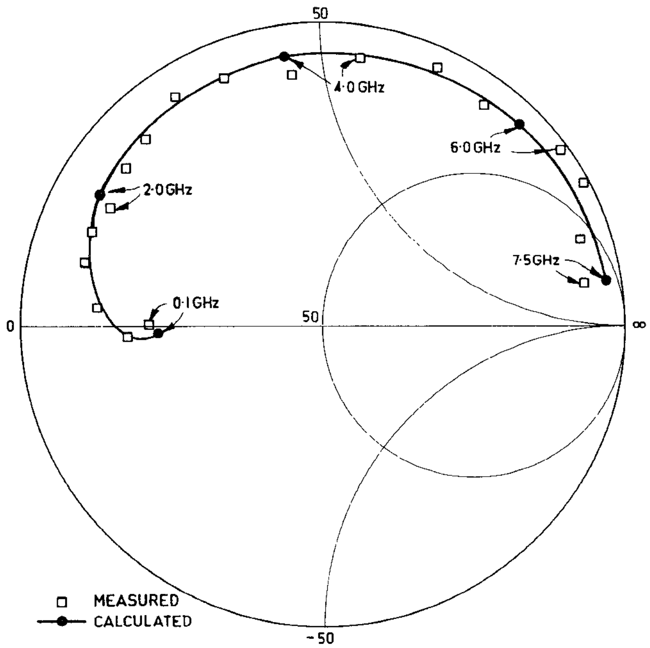


Fig. 5. Measured and calculated reflection coefficient of the HLP-3400, biased above threshold.

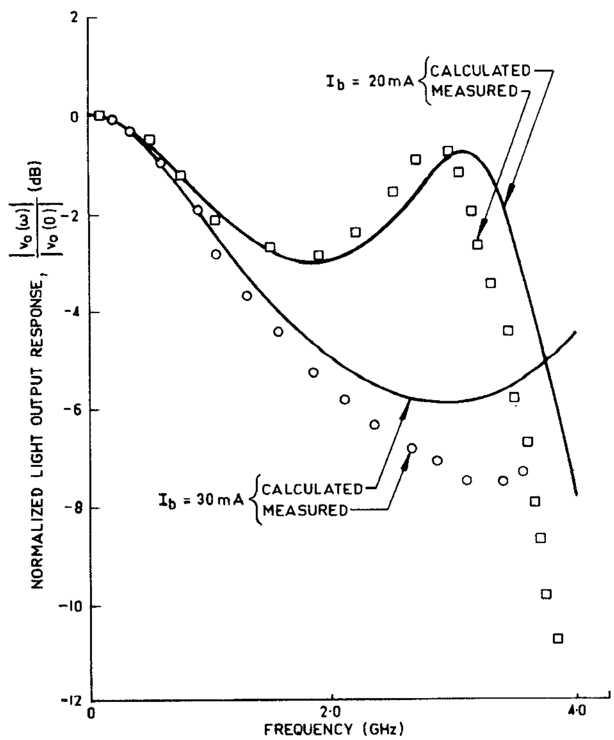


Fig. 6. Measured and calculated small-signal frequency response of the HLP-3400 for an RF source with a 50-Ω internal resistance. The response is given for two values of dc bias current.

data. The models show good agreement with measurements over a wide range of frequencies and dc bias levels. They can be easily incorporated in standard microwave circuit analysis programs, and should find application in the analysis and design of optical and microwave circuits.

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