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Thermal Problems of the CW Injection Laser

Abstract: We describe the theoretical dependence of emitted light power on current in a continuously operating p-n junction laser, based on an injection laser model previously developed by the author. The analysis relates power output to threshold current, electrical resistance, thermal resistance, and external quantum efficiency of the laser, all quantities that can be independently measured or calculated for particular structures. The equations presented thus constitute a simple analytical model for both thermal design and diagnosis of operation of cw injection lasers.

Introduction

The purpose of this paper is to describe a calculation of the steady state light power output of a continuously operating p-n junction, or injection, laser. The calculation is based on the simplified model of the injection laser that was used previously in analyses of related problems [1–3]. The model has also been used to discuss bistability in injection laser operation[4] and the criterion developed in Ref. 1 for continuous operation has been extended to include an additional form of the dependence of threshold current on temperature[5]. More sophisticated calculations of cw threshold currents have also been carried out with the aid of an electronic computer[6].

These earlier works have addressed the question, Under what conditions will an injection laser operate continuously? That is, they have emphasized the criteria for continuous operation and bistability. Regarding the injection laser as a useful device, however, one also wishes to know how much light power can be obtained from it. Our model is used here to derive analytical results relating to this latter question.

The model may be described as follows:

1. Recombination of electrons and holes releases energy in a planar region, the p-n junction, at a rate iV, where i is the current through the junction and V is the voltage drop in the junction, taken to be the voltage equivalent of the energy gap of the semiconductor. Much of the energy released becomes heat and flows through a thermal resistance P to a heat sink at the ambient temperature, chosen as the zero of temperature, causing the temperature of the junction to exceed the temperature of the heat sink.

2. Power may also be dissipated in electrical resistance in series with the p-n junction at a rate i^2R, where R is the series resistance. This heat flows through a thermal resistance to a heat sink and such flow leads to a term proportional to the square of the current in the functional dependence of junction temperature on current. The magnitude of the temperature increase at the junction depends on the geometrical relationships among junction, series resistance, and heat sink.

The effect is considered here in the framework of a result of Holm[7], which states that the temperature increase at the junction is that which would be produced by the flow of the Joule heat in the series resistance through half of the thermal resistance. Holm's result is applicable when the flow of heat and the flow of current away from the junction are geometrically identical. Thus the increase of temperature at the junction caused by the production of heat in the series electrical resistance is $\frac{1}{2}i^2\mathrm{P}R$. If the thermal and the electrical resistance problems are geometrically similar, then $\mathrm{P}\kappa = R\sigma$, where κ is the thermal conductivity of the medium in which the junction is embedded and σ is its electrical conductivity[1,3].

In other cases the conditions for the applicability of Holm's result are not satisfied and the value of R in the expression for junction temperature may not be the same as the actual electrical resistance of the laser[8]. For example, if most of the electrical resistance is on one side of the junction and the heat sink is on the other side, all of the Joule heat must flow from the junction to the heat sink and the value of R to be used in the formulas presented is twice the electrical resistance.

3. The threshold current i_t is an increasing function of temperature; its value at the ambient temperature is i_0.

4. Above the threshold current, a fraction η of the recombination energy in excess of that required to achieve threshold escapes from the laser as photons of energy qV. The spontaneous light emitting efficiency of injection lasers is small and the loss of energy from the laser by spontaneous emission is neglected. Thus the remaining recombination energy E_r is converted to heat;

$$E_r = V[i_t + (1-\eta)\ (i-i_t)]. \tag{1}$$

The principal temperature dependence of this energy is in the temperature dependence of i_t. The weak temperature dependences of V and η are not taken into account.

We introduce the following approximations into the thermal model of the junction laser:

1. The dependence of threshold current on temperature is assigned the form[9]

$$i_t = i_0 \exp\ (T/T_1), \tag{2}$$

where T_1 is a parameter with the dimension of temperature. This form has been found to represent experimental data about as well as other forms used, e.g.,

$$i_t = i'[1 + (T/T')^{3\pm1}], \tag{3}$$

which could also be easily programmed for computation or data fitting. Equation (2) is preferred, however, to provide continuity and internal consistency with the previous two papers[1,3] in this series.

2. Other laser parameters, specifically, the thermal resistance, the electrical resistance, the quantum efficiency, and the voltage are taken to be temperature independent.

Thus the temperature of the laser in the steady state is

$$T = \mathrm{P}[i_tV + (1-\eta)\ (i-i_t)V + \tfrac{1}{2}i^2R] \tag{4}$$

and the light output of the laser is

$$W = \eta[i-i_t(T)]V, \tag{5}$$

where the dependence of i_t on T has been explicitly indicated.

The number of independent variables that characterize the injection laser can be reduced by scaling, i.e., by normalizing current variables to the threshold current at ambient temperature, i_0, temperatures to T_1, and other variables to appropriate combinations of i_0, V, and T_1. This normalization is shown in Table 1 and the remaining

Table 1 Reduction of variables to dimensionless parameters.

Quantity	*Reduced variable*
i	$i^* = i/i_0$
R	$B = R\mathrm{P}i_0^2/T_1$
T	$T^* = T/T_1$
W	$w = W/i_0V$
P	$\mathrm{P}^* = \mathrm{P}i_0V/T_1$

problem is characterized by the thermal resistance, the electrical resistance, and the external quantum efficiency. The equations corresponding to Eqs. (2), (4), and (5) are

$$i_t^* = \exp T^*, \tag{6}$$

$$T^* = \mathrm{P}^*[i^*(1-\eta) + \eta i_t^*] + \tfrac{1}{2}Bi^{*2}, \text{ and} \tag{7}$$

$$w = \eta(i^*-i_t^*) \tag{8}$$

Special cases

The laser will not operate continuously if the parameters P* and B are too large. The criterion for continuous operation when $B = 0$ is $\mathrm{P}^* < 1/e$, and if $B > 0$, P* must be even smaller[1]. If the conditions for continuous operation are satisfied, the course of events as the current is increased is shown in Fig. 1. The applied current begins to exceed the threshold current, which is increasing because of the heating in the junction region, at current i_a. Above i_a the current rises faster than i_t and the light output, which is proportional to the difference between the current and the threshold current, increases from zero as shown in the figure. The threshold current, however, rises at an increasing rate as the current is increased and eventually begins to increase more rapidly than the current itself. Thus the light output passes through a maximum at current i_m and thereafter decreases. At another point, when the current is i_b, the threshold current again becomes equal to the applied current and stimulated emission ceases.

The currents i_a and i_b are defined by the condition that the power outputs be zero:

$$0 = i_a^* - \exp\ [\mathrm{P}^*i_a^* + \tfrac{1}{2}Bi_a^{*2}]$$

and

$$0 = i_b^* - \exp\ [\mathrm{P}^*i_b^* + \tfrac{1}{2}Bi_b^{*2}]. \tag{9}$$

Since the heating due to electrical resistance is proportional to the square of the current, this power loss is more important at higher currents and causes the power output to decrease rapidly after the maximum is passed. In many lasers $Bi_a^{*2} \ll \mathrm{P}^*i_a^*$ and P* can be determined as

$$\mathrm{P}^* = \ln i_a^*/i_a^*. \tag{10}$$

Then B can be determined from i_b^*, at which current the series resistance term is likely to be important:

$$B = 2(\ln i_b^*/i_b^* - \ln i_a^*/i_a^*)/i_b^*. \quad (11)$$

When the light output is zero, i.e., when the applied current has the value i_a or i_b, no energy is lost as light. Therefore the turn-on and turn-off currents, i_a and i_b, are the same whether or not the loss of energy as photons is taken into account [as may be verified by inspection of Eqs. (4) and (5)] and are independent of η.

Complete curves of light output as a function of current are readily constructed by varying the parameter T^* in the equations

$$i^* = \{[P^*(1-\eta)/B]^2 + 2(T^*-\eta P^* \exp T^*)/B\}^{1/2} - P^*(1-\eta)/B \quad (12)$$

$$w = \eta(i^* - \exp T^*). \quad (13)$$

It is straightforward to solve for the current at maximal light output if the resistive heating is neglected. The result is

$$i_m^* = [\ln(1/P^*) - \eta]/(1-\eta)P^*, \text{ and} \quad (14)$$

$$i_m^* - i_t^* = [\ln(1/P^*) - 1]/(1-\eta)P^*. \quad (15)$$

The course of events when loss of energy as light is taken into account is shown in Fig. 2, which is analogous to Fig. 1. Below the threshold current value the two curves are the same. Above the threshold value, however, the laser heats less rapidly than in the approximation of Fig. 1 and the threshold current is less for any given applied current. Because the heating is less the threshold current rises more slowly than in Fig. 1 and the point at which the maximum is attained is shifted to larger currents. The value of the maximum is significantly increased.

If the loss of energy as light is large enough, stimulated emission may persist to currents even larger than i_b; that is, there is a region of thermal bistability in the laser operation[4]. However, this bistability is found at quite large currents and a small amount of Joule heating, which has been neglected in Fig. 2, can destroy it. In fact, a much more pronounced bistability can be produced by trapping centers and this has been observed[4,10]. Quantitatively, the condition on the external quantum efficiency and the thermal resistance for bistability to exist is

$$\eta > 1/P^* i_b^*. \quad (16)$$

A final point to be noted in connection with the discussion of efficiency is that the so-called "differential quantum efficiency," which is obtained by differentiating the light output with respect to the current at threshold, i.e.,

$$\eta_D = dW/d(iV)|_{i=i_a}, \quad (17)$$

is less than the "external quantum efficiency" η. This is because as the current is increased above the threshold value, the temperature of the laser increases and the threshold current also increases. It is found by differentiating Eqs. (4) and (5) or (6) and (7) that

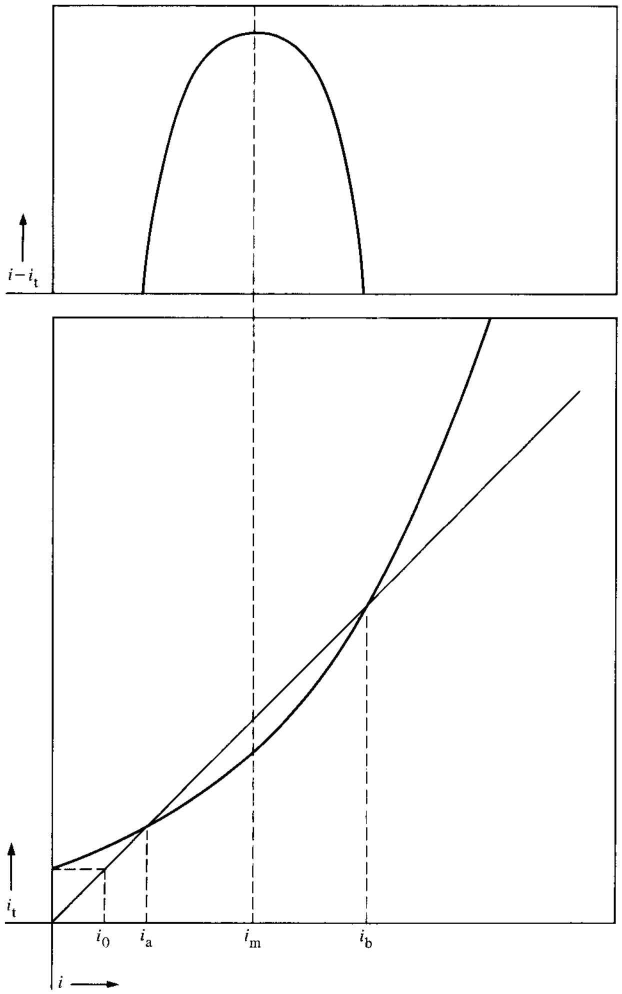


Figure 1 The course of events with increasing current in a continuously operating injection laser. The laser does not turn on at i_0, the threshold current at the ambient temperature, because this current heats the laser above the ambient temperature. The laser turns on at the current i_a when the current itself, as indicated by the dashed line, begins to exceed the threshold current i_t. The power output shown in the upper part of the figure is proportional to $i - i_t$ and passes through a maximum at i_m. Above i_m the threshold current increases with current more rapidly than the current itself and the laser ceases to operate at current i_b, where the threshold current again exceeds the applied current.

$$\eta_D = \eta\,[1 - P^* i_a^*(1 + i_a^* B)]/(1 - P^* i_a^* \eta). \quad (18)$$

If $B = 0$, Eq. (18) has the much simpler form

$$\eta_D = \eta(1 - \ln i_a^*)/(1 - \eta \ln i_a^*). \quad (19)$$

Example

As an example to illustrate the application of this model, consider an injection laser made and described by Marinace[11]. The light output of this laser is shown as a

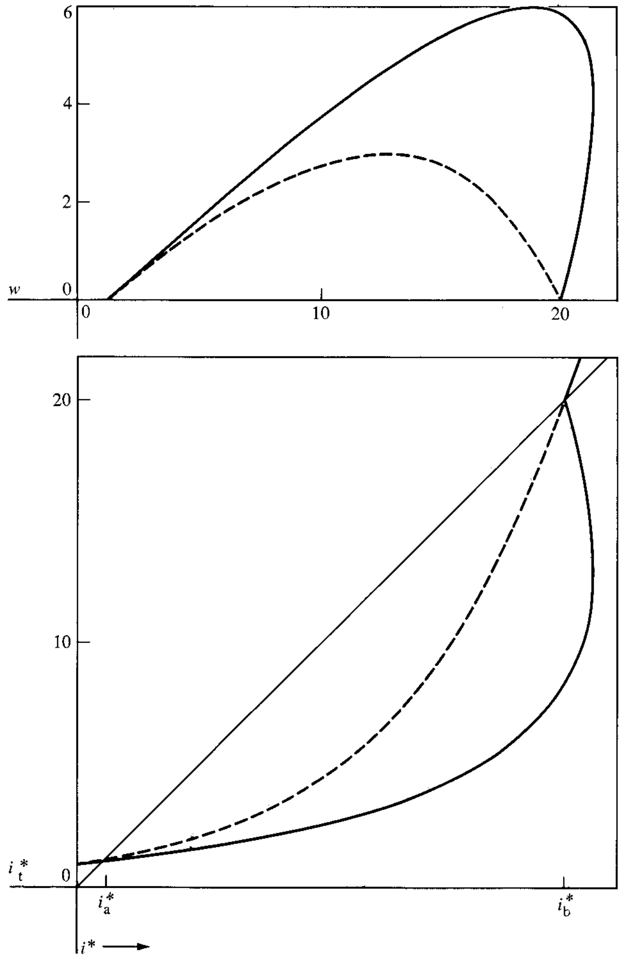
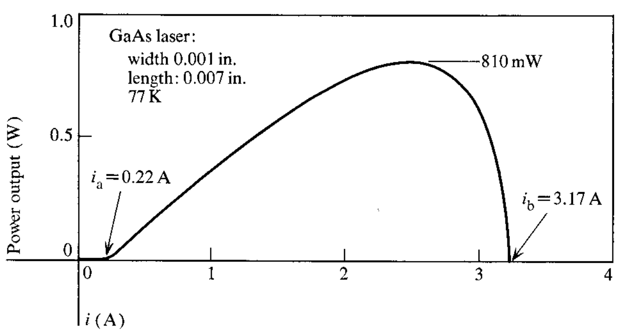


Figure 2 Dimensionless parameters representing current and power output of an injection laser (analogous to Fig. 1) when the loss of energy as light is taken into account in calculating the temperature of the junction. The curves are drawn for the case $P^* = 0.15$, $B = 0$, and $\eta = 0.5$. Note the region of bistability at large current. The dashed lines show for comparison the same quantities when the loss of energy as light is neglected in calculating the temperature.

Figure 3 Observed power output as a function of current for the laser described in Ref. 11.



function of current in Fig. 3. The threshold current i_0, measured with short pulses, was found to be 0.185 A. Thus from Fig. 3, $i_a^* = 1.19$, $i_b^* = 17.1$, and $i_m^* = 13.5$; with $V = 1.5$ V, $w_m = 2.92$.

One can determine from Eqs. (6) through (8) that this value of i_a^* corresponds to $P^* = 0.146$ if $B = 0$, which implies that $i_b^* = 20.7$. The difference between 20.7 and the observed value is caused by series electrical resistance, which is more effective at higher current levels and reduces i_b^* without much effect on i_a^*. Using Eqs. (10) and (11) one finds that $B = 0.0023$ would produce the observed value of i_b^*.

The power lost as light at the peak of the curve in Fig. 3 is almost 20 percent of the input power; thus radiation loss cannot be neglected in calculating the power output curve. By analyzing Eqs. (6) and (8), we find that the choice of laser parameters $P^* = 0.145$, $B = 0.0023$, and $\eta = 0.37$ gives good values for the observable quantities, namely, $i_a^* = 1.19$, $i_m^* = 13.5$, $i_b^* = 17.1$, and $w_m = 2.85$. Also, Eq. (13) yields $\eta_D = 0.33$, in good agreement with Fig. 3.

Translating these results into dimensional properties of the laser requires a knowledge of T_1. As in our previous work[1], T_1 is chosen to be 55° C. Then the above value for P^* yields $P = 29$ deg/W, which is a reasonable value. For example, 29 deg/W is the thermal resistance of 0.025 mm (1 mil) of GaAs in series with the junction. The value found above for B implies that $R = 0.13$ ohm, whereas it was estimated from electrical measurements that $R = 0.19$ ohm.

References

1. R. W. Keyes, *IBM J. Res. Develop.* **9**, 303 (1965).
2. W. Engeler and M. Garfinkel, *Solid State Electronics* **8**, 585 (1965).
3. R. W. Keyes, *IBM J. Res. Develop.* **14**, 158 (1970).
4. J. E. Ripper and T. L. Paoli, *Proc. IEEE* **58**, 178 (1970).
5. C. H. Gooch, *IEEE J. Quantum Electronics* **QE-4**, 140 (1968).
6. J. C. Dyment, J. E. Ripper, and T. H. Zachos, *J. Appl. Phys.* **40**, 1802 (1969).
7. R. Holm, *Electric Contacts*, Hugo Gebers Forlag, Stockholm 1946, pp. 23 through 32.
8. J. C. Dyment and L. A. D'Asaro, *Appl. Phys. Letters* **11**, 292 (1967); I. Hayashi, M. B. Panish, P. W. Foy, and S. Sumski, *Appl. Phys. Letters* **17**, 109 (1970).
9. See, for example, Ref. 6 and I. Hayashi, M. B. Panish, and F. K. Reinhart, *J. Appl. Phys.* **42**, 1929 (1971).
10. J. E. Ripper, T. L. Paoli, and J. C. Dyment, *IEEE J. Quantum Electronics* **QE-6**, 300 (1970).
11. J. C. Marinace, *Extended Abstracts of Electronics Division, Electrochemical Society*, **14**, No. 1, pp. 84 through 87 (Spring Meeting of the Electrochemical Society, May 9–13, 1965); also unpublished work.

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