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Stabilized Biasing of Semiconductor Lasers

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In this paper we analyze the design of biasing and control circuits for semiconductor lasers in a generalized context based on an idealized laser characteristic. In particular, we address three major design considerations: whether to bias the laser above or below threshold, how to stabilize the optical output levels independent of variation in the average output power, and to what degree the output levels can be stabilized relative to various circuit and device parameters. Results of our study indicate that to eliminate from the optical output any dependence on either variation in laser device characteristics or the dc average of the input signal, feedback control of both the prebias and modulation current is necessary.

I. INTRODUCTION

Within the past few years digital lightwave communication systems have become a practical reality. Several systems have been demonstrated for both interoffice trunk transmission and the subscriber plant.[1-4] In these applications optical fiber systems have the advantages of inherently large bandwidths and electrical isolation.

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High-bit-rate lightwave systems commonly use semiconductor laser diodes as the optical sources. The diodes are threshold devices whose characteristics depend on both age and operating temperature. As a consequence, large variations in the light output of the lasers will occur unless special measures are taken to properly bias and modulate these devices.

Several circuits for biasing and digitally modulating injection lasers have been reported. To ensure modulation of the laser output at the highest possible rates, these circuits typically dc bias the laser near its threshold. A modulation current is then superimposed on this bias to switch between the high and low light outputs. The circuits described to date commonly used negative feedback control of the bias current to stabilize the laser light output. In some early circuits the feedback stabilizes the average optical output of the laser. For this method to be successful, the digital input codes must exhibit a fixed on-off ratio (constant average value). More recent laser driver circuits employ balancing compensation of the modulation signal and purport to allow arbitrary on-off ratio digital codes.[5–8]

In this paper we consider the design of laser biasing and control circuits in a generalized context. Within this context we address three major design considerations: the choice of biasing the laser above or below threshold, how to stabilize the output independently of the nature of the laser modulation, and to what degree the laser output levels can be readily stabilized relative to various circuit and device parameters. Initially, we consider the stabilization obtainable by means of the approach adopted in a recently described monolithic laser driver, wherein feedback stabilization of the laser bias current is augmented by a simple balancing compensation of the modulation signal.[7] Following this analysis, we examine the benefits of using modulation current compensation.

II. FEEDBACK BIAS STABILIZATION

Figure 1 shows the luminosity versus current characteristic assumed for heterojunction lasers in this analysis. This relation can be characterized by three parameters: the threshold current, I_T, the subthreshold differential slope efficiency, η_1, and the above-threshold slope efficiency, η_2. (The variables used are defined at the back of this paper.) These parameters analytically approximate the characteristic of Fig. 1 by the piecewise linear relationships

$$L = \eta_1 I_L, \qquad I_L \leqslant I_T \tag{1}$$

and

$$L = \eta_1 I_T + \eta_2 (I_L - I_T), \qquad I_L \geqslant I_T, \tag{2}$$

where L is the luminosity (or light output intensity) of the laser.

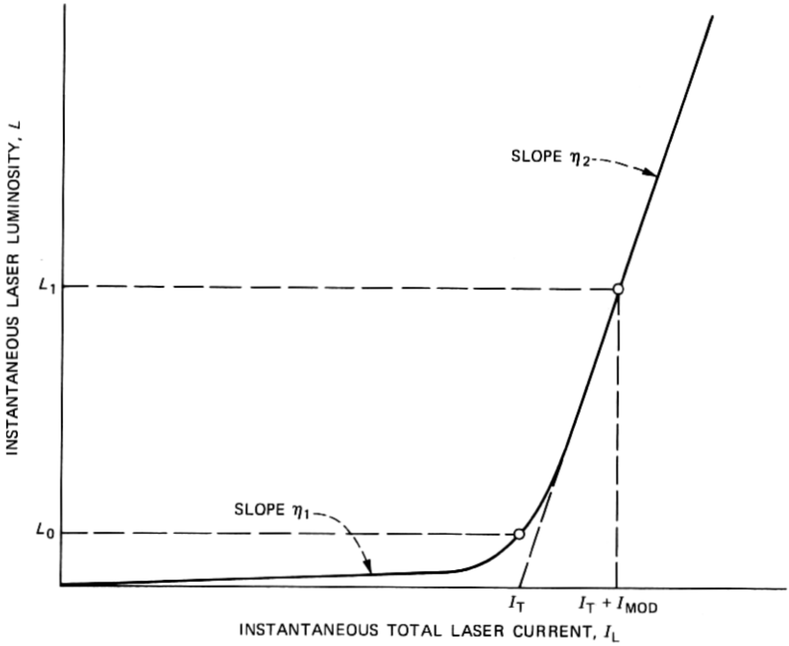

Fig. 1—The luminosity versus current relationship for an injection laser.

Figure 2 is a generalized circuit diagram for a recently reported integrated laser driver employing feedback stabilization.[7] In this circuit the laser is biased near its threshold by a prebias current I_A. Added to this bias is a modulation current, I_M, which switches the laser between its ZERO and ONE light output levels (L_0 and L_1). The prebias current is stabilized by a negative feedback loop comprising the laser, a photodetector, a reference current (I_B), a low-pass filter (C_A), and a current amplifier (A). The photodetector generates a current proportional to the optical output of the laser, typically by monitoring the light emitted from its rear face. The photodetector current (I_D) is compared to the reference current at the summing node, S, and the resulting current difference is then low-pass filtered and amplified to generate the prebias current. Because the modulation current, I_M, will alter the dc component of the laser output, the current I_X is added to node S to cancel this influence, as described below.

It is assumed throughout the analysis that:

1. The differential slope efficiency of the laser is much greater above threshold than below, i.e., $\eta_2 \gg \eta_1$.

2. As a consequence of the filtering provided by C_A, the response time of the feedback loop is long in comparison with the time constants of modulation-related parameters. It is also required, however, that the feedback loop response time be much shorter than the time

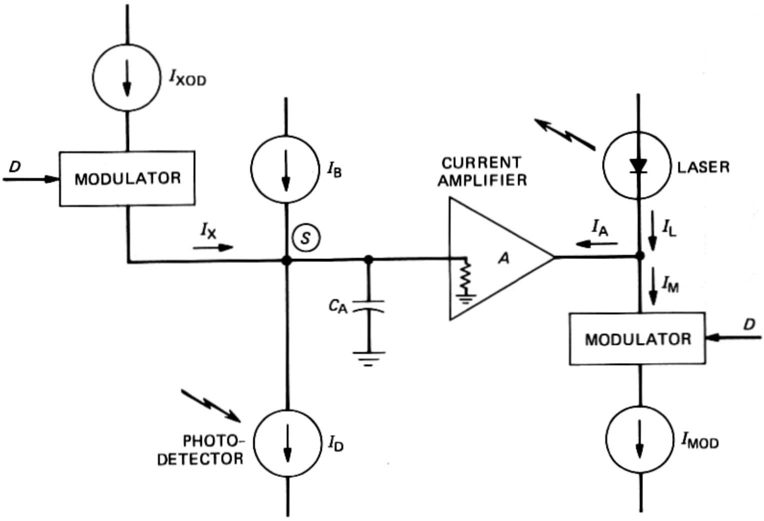

Fig. 2—A laser driver employing feedback stabilization of bias current.

constants of the laser parameter drift that occurs as a consequence of aging or changes in environment.

In the circuit of Fig. 2, the instantaneous laser current, I_L, is given by the sum of the prebias current and the instantaneous modulation current

$$I_L = I_A + I_M, \tag{3}$$

where

$$I_M = DI_{MOD} \tag{4}$$

and D is the binary data signal driving the modulator ($D = 0$ or 1). In Fig. 2, the capacitor, C_A, serves to average the summation of currents feeding the input to amplifier A. Thus,

$$I_A = A_I(I_B + \bar{I}_X - \bar{I}_D) \tag{5}$$

where A_I is the amplifier current gain, and $\bar{I}_X$ and $\bar{I}_D$ are the dc components (averages) of the balance and detector currents, respectively.

The output of the photodetector in Fig. 2 is assumed to be related to the laser light output by a proportionality factor, f. Thus, the average detector output current is given in terms of the average laser luminosity by

$$\bar{I}_D = f\bar{L}. \tag{6}$$

The laser light levels L_0 and L_1 are defined such that $L_0 \triangleq L$ when $D = 0$ and $L_1 \triangleq L$ when $D = 1$. It therefore follows that

$$\bar{L} = \bar{D}(L_1 - L_0) + L_0 \tag{7}$$

and then from (6) and (7) that

$$\bar{I}_D = f[\bar{D}(L_1 - L_0) + L_0]\,. \tag{8}$$

Implicit in this equation is the assumption that time delays in the responses of the laser and photodetector are negligible.

Inserting (8) into (5) and observing that $\bar{I}_X = \bar{D}I_{XOD}$ leads to the relationship

$$I_A = A_I\{I_B + \bar{D}I_{XOD} - f[\bar{D}(L_1 - L_0) + L_0]\}\,. \tag{9}$$

This result, together with the relationship between the laser luminosity (L) and current (I_L), as represented by (1) and (2), will next be used to determine the laser light output levels, L_0 and L_1. However, to proceed with this analysis we must first determine whether the laser is prebiased above threshold or below. This distinction, which seems minor at first glance, has important implications for the ultimate stability of the optical output. We first consider the above-threshold case.

2.1 Above-threshold prebiasing ($I_{L0} \geqslant I_T$)

From eq. (3) and the definition of L_0 and L_1 it follows that

$$I_{L0} = I_A \tag{10a}$$

and

$$I_{L1} = I_A + I_{MOD}. \tag{10b}$$

For the case where the laser is biased above threshold ($I_{L0} \geqslant I_T$), it thus follows from (2) that

$$L_0 = \eta_2(I_A - I_T) + \eta_1 I_T \tag{11a}$$

and

$$L_1 = \eta_2(I_A + I_{MOD} - I_T) + \eta_1 I_T\,. \tag{11b}$$

Substitution of (11) into (9) leads to the result

$$I_A = A_I\{I_B + \bar{D}I_{XOD} - f[\eta_2\bar{D}I_{MOD} + \eta_2(I_A - I_T) + \eta_1 I_T]\}\,. \tag{12}$$

This expression can be solved for I_A to obtain

$$I_A = \frac{A_I[I_B + (k_2 - k_1)I_T] + A_I\bar{D}(I_{XOD} - k_2 I_{MOD})}{1 + A_I k_2}\,, \tag{13}$$

where the laser-photodetector current efficiencies k_1 and k_2 are defined as $k_1 \triangleq f\eta_1$ and $k_2 \triangleq f\eta_2$.

Equations (11) and (13) can be now used to determine the light output levels for the laser:

$$L_0 = \frac{\eta_2 A_I I_B + (\eta_1 - \eta_2) I_T}{1 + A_I k_2} + \frac{A_I \bar{D} \eta_2 (I_{XOD} - k_2 I_{MOD})}{1 + A_I k_2} \tag{14a}$$

and

$$L_1 = L_0 + \eta_2 I_{MOD}\,. \tag{14b}$$

The quantity $A_I k_2$ represents the loop gain of the bias feedback loop. In a proper design the loop gain is necessarily very large ($A_I k_2 \gg 1$). Under this condition, together with the assumption that $\eta_2 \gg \eta_1$, we can simplify the expressions for the laser light output to

$$L_0 = \frac{1}{f}\left[I_B - \frac{I_T}{A_I}\right] + \frac{\bar{D}}{f}\,(I_{XOD} - k_2 I_{MOD}) \tag{15a}$$

$$L_1 = L_0 + \eta_2 I_{MOD}\,. \tag{15b}$$

The balance current, I_X, is incorporated in the circuit of Fig. 2 for the purpose of eliminating the dependence of the laser light levels on $\bar{D}$, the dc component of the data input signal. This is accomplished to first order by choosing $I_{XOD} = k_2 I_{MOD}$ so as to eliminate the second term in (15a). However, a dependence on $\bar{D}$ will reappear as a consequence of changes in the above-threshold conversion efficiency, k_2, that results from the drift of η_2 with time. In particular, if I_{XOD} is chosen to balance the circuit at some initial time when $\eta_2 = \eta_2^0$,

$$I_{XOD} = f\eta_2^0 I_{MOD}\,, \tag{16}$$

and if $\Delta\eta_2$ is defined to represent the subsequent drift in η_2,

$$\Delta\eta_2 \triangleq \eta_2 - \eta_2^0, \tag{17}$$

then it follows from eqs. (15) through (17) that the laser output levels can be expressed as

$$L_0 = \frac{1}{f}\left[I_B - \frac{I_T}{A_I}\right] - \bar{D} I_{MOD}(\Delta\eta_2) \tag{18a}$$

and

$$L_1 = L_0 + \eta_2 I_{MOD}. \tag{18b}$$

A principal function of the feedback loop in Fig. 2 is to eliminate the dependence of the optical output on the laser threshold current. However, there remain in (18) terms dependent on I_T, and we now consider their relative importance. Assume the laser is biased near threshold so that $I_{L0} \approx I_T$. Then, if the drift in η_2 is small so that $I_{XOD} = f\eta_2^0 I_{MOD} \approx f\eta_2 I_{MOD}$, it follows from (10a) and (13) that

$$I_{L0} \approx \frac{A_I[I_B + (k_2 - k_1) I_T]}{1 + A_I k_2} \approx I_T. \tag{19}$$

Thus,

$$\frac{I_T}{A_I} \approx \frac{I_B}{1 + A_I k_1}. \tag{20}$$

The quantity $A_I k_1$ is the *subthreshold* loop gain of the feedback loop, and if this gain is large ($A_I k_1 \gg 1$), then

$$\frac{I_T}{A_I} \ll I_B. \tag{21}$$

Therefore, the threshold current dependent terms in (18) are negligible. Thus, under the conditions that the feedback loop gain is large both above and below threshold ($A_I k_2 \gg A_I k_1 \gg 1$), the laser light output levels can be expressed simply as

$$L_0 \approx \frac{I_B}{f} - \bar{D} I_{MOD}(\Delta\eta_2) \tag{22a}$$

$$L_1 \approx \frac{I_B}{f} - \bar{D} I_{MOD}(\Delta\eta_2) + \eta_2 I_{MOD}. \tag{22b}$$

We can draw a number of conclusions with regard to above-threshold biasing from the results expressed in (22):

1. The laser light output levels, L_0 and L_1, are to first order independent of the subthreshold slope efficiency, η_1, and the threshold current, I_T.
2. If the above-threshold slope efficiency, η_2, is constant ($\Delta\eta_2 = 0$), the light output levels are independent of the data signal dc component, $\bar{D}$.
3. If η_2 drifts as a function of time or changes in environment, the light levels L_0 and L_1 will exhibit some dependence on $\bar{D}$.
4. In a proper design of the circuit represented by Fig. 2, the feedback loop gain must be large below, as well as above, the laser threshold.

2.2 Subthreshold prebiasing ($I_{L0} \leqslant I_T$)

When the laser is biased below threshold, it is necessarily the case that $I_{L0} = I_A \leqslant I_T$ and that $I_{L1} = I_A + I_{MOD} > I_T$; it therefore follows from (1), (2), and (10) that

$$L_0 = \eta_1 I_A \tag{23a}$$

and

$$L_1 = \eta_2(I_A + I_{MOD} - I_T) + \eta_1 I_T. \tag{23b}$$

Substitution of (23) into (9) then leads to the expression

$$I_A = A_I(I_B + \bar{D}I_{XOD} - f\{\eta_1 I_A + \bar{D}[\eta_2 I_{MOD} + (\eta_2 - \eta_1)(I_A - I_T)]\}) \tag{24}$$

and this result can be solved for I_A to obtain

$$I_A = \left[\frac{A_I}{1 + A_I k_1 + \bar{D}A_I(k_2 - k_1)}\right] \cdot \{I_B + \bar{D}[I_{XOD} - k_2 I_{MOD} + (k_2 - k_1)I_T]\}, \tag{25}$$

where $k_1 \triangleq f\eta_1$ and $k_2 \triangleq f\eta_2$.

As is the case for above-threshold biasing, the loop gain of the feedback circuit should be large both above and below the laser threshold ($A_I k_2 \gg 1$ and $A_I k_1 \gg 1$). Under these conditions, together with the assumption $\eta_2 \gg \eta_1$, (25) simplifies to

$$I_A \simeq \left(\frac{1}{k_1 + \bar{D}k_2}\right)\{I_B + \bar{D}[I_{XOD} - k_2(I_{MOD} - I_T)]\}. \tag{26}$$

To eliminate the dependence of the optical output levels on $\bar{D}$, I_{XOD} must be chosen so as to remove the dependence of I_A on $\bar{D}$. However, for subthreshold biasing a dependence on $\bar{D}$ will reappear in the event of drift in any of the laser parameters η_2, η_1, or I_T. If η_1^0, η_2^0 and I_T^0 denote the values of η_1, η_2, and I_T at the time when I_{XOD} is initially adjusted to cancel out the $\bar{D}$ dependence of I_A, then from (24) the appropriate value of I_{XOD} is

$$I_{XOD} \simeq k_2^0\left(\frac{I_B}{k_1^0} + I_{MOD} - I_T^0\right), \tag{27}$$

where $k_1^0 = f\eta_1^0$, $k_2^0 = f\eta_2^0$, and we have assumed that $\eta_2^0 \gg \eta_1^0$ and $A_I k_1 \gg 1$. For this choice of I_{XOD} the initial value of I_A is simply

$$I_A^0 \simeq \frac{I_B}{k_1^0}. \tag{28}$$

The expression for I_A at some time following the initialization of I_{XOD} is obtained by substituting (27) into (26), with the result

$$I_A = \left(\frac{1}{k_1 + \bar{D}k_2}\right)\left\{I_B\left(\frac{k_1^0 + \bar{D}k_2^0}{k_1^0}\right) + \bar{D}\,[k_2 I_T - k_2^0 I_T^0 - (k_2 - k_2^0)I_{MOD}]\right\}. \tag{29}$$

It then follows from (23) and (29) that for subthreshold prebiasing, and under the assumption of large feedback loop gain both above and below the laser threshold, the light output levels are given by

$$L_0 = \left(\frac{\eta_1}{\eta_1 + \bar{D}\eta_2}\right)\left\{\frac{I_B}{f}\left(\frac{\eta_1^0 + \bar{D}\eta_2^0}{\eta_1^0}\right)\right.$$

$$\left. + \bar{D}[\eta_2 I_T - \eta_2^0 I_T^0 - (\eta_2 - \eta_2^0) I_{MOD}]\right\} \tag{30a}$$

and

$$L_1 = \left(\frac{\eta_2}{\eta_1 + \bar{D}\eta_2}\right)\left\{\frac{I_B}{f}\left(\frac{\eta_1^0 + \bar{D}\eta_2^0}{\eta_1^0}\right)\right.$$

$$\left. + I_{MOD}(\eta_1 + \bar{D}\eta_2^0) - \eta_1 I_T - \bar{D}\eta_2^0 I_T^0\right\}. \tag{30b}$$

From these complex expressions, as compared to the simple results obtained in (22) for above-threshold biasing, we can draw the following conclusions with respect to subthreshold biasing:

1. The laser light output levels are not stabilized against individual variations in any of the parameters characterizing the laser (η_1, η_2, and I_T).

2. The light output levels will exhibit a dependence on the data signal average, $\bar{D}$, if changes occur in any one of the laser parameters.

III. MODULATION CURRENT COMPENSATION

As we demonstrated in Section 2.1, if the laser is prebiased above its threshold current, the circuit of Fig. 2 effectively stabilizes the optical output against variations in both the laser's subthreshold slope efficiency, η_1, and its threshold current, I_T. However, the light output levels remain sensitive to the above-threshold slope efficiency, η_2, and, as a consequence, to the average value of the input data, $\bar{D}$. One means of eliminating this remaining sensitivity is to compensate for changes in η_2 through control of the modulation source current, I_{MOD}. This approach has, in fact, already been proposed in specific designs.[6,8]

As in Section 2.1 we assume that the laser is prebiased above threshold ($I_{L0} \geqslant I_T$) so as to eliminate sensitivity of the optical output to η_1 and I_T. It is then apparent from (15) that the sensitivity of the light output levels to η_2 and $\bar{D}$ can be eliminated if the source current I_{MOD} can be continuously adjusted so as to hold the product $\eta_2 I_{MOD}$ constant. This can be accomplished by deriving a signal proportional to the difference between the ZERO and ONE light levels, and then using negative feedback to control I_{MOD} in a manner that stabilizes this difference. After a signal is obtained proportional to the difference $L_1 - L_0$, I_{MOD} is generated as

$$I_{MOD} = I_{REF} - \gamma(L_1 - L_0), \tag{31}$$

where γ is a constant characterizing the feedback loop controlling I_{MOD}, and I_{REF} is a modulation reference, or "baseline", current.

From (11) it follows that for above-threshold biasing

$$L_1 - L_0 = \eta_2 I_{MOD}. \tag{32}$$

Upon substituting this expression into (31) and then solving for I_{MOD}, we obtain

$$I_{MOD} = \frac{I_{REF}}{1 + \gamma\eta_2} \simeq \frac{I_{REF}}{\gamma\eta_2} \quad \text{for} \quad \gamma\eta_2 \gg 1. \tag{33}$$

In this equation the term $\gamma\eta_2$ represents the loop gain of the negative feedback loop controlling I_{MOD} and should necessarily be much greater than unity.

If we substitute (33) in (14) we obtain the following expressions for the laser light output levels:

$$L_0 = \frac{\eta_2 A_I I_B + (\eta_1 - \eta_2) I_T}{1 + A_I k_2} + \left(\frac{A_I \bar{D} \eta_2}{1 + A_I k_2}\right)\left(I_{XOD} - \frac{k_2 I_{REF}}{\gamma\eta_2}\right) \tag{34a}$$

and

$$L_1 = L_0 + \frac{I_{REF}}{\gamma}. \tag{34b}$$

If, as in Section 2.1, we assume that $\eta_2 \gg \eta_1$, $A_I k_2 \gg 1$ and $A_I k_1 \gg 1$, then, recognizing that $k_2 = f\eta_2$, it follows from (34) that

$$L_0 \approx \frac{I_B}{f} + \frac{\bar{D}}{f}\left(I_{XOD} - \frac{f I_{REF}}{\gamma}\right) \tag{35a}$$

and

$$L_1 = L_0 + \frac{I_{REF}}{\gamma}. \tag{35b}$$

It is apparent from (35) that the sensitivity of L_0 and L_1 to η_2 has been successfully eliminated. As in Section 2.1 the remaining dependence on $\bar{D}$ can be removed by the appropriate choice of I_{XOD}, namely,

$$I_{XOD} = \frac{f I_{REF}}{\gamma}. \tag{36}$$

The expressions for the ZERO and ONE light output levels then reduce to the very simple form

$$L_0 = \frac{I_B}{f} \tag{37a}$$

and

$$L_1 = \frac{I_B}{f} + \frac{I_{REF}}{\gamma}. \tag{37b}$$

Clearly these levels are now, to first order, independent of the laser parameters η_1, η_2, and I_T and the dc component of the data signal, $\bar{D}$.

Compensation of the modulation source current as described below can be implemented as illustrated in Fig. 3. Following the approach of Gruber, et al.,[6] the circuit of Fig. 2 is modified by the inclusion of high-speed buffers (B1 and B2), positive (B3) and negative (B4) peak detectors, and a summing amplifier (B5). The current I_{MOD} is developed at the output of the summing amplifier and is proportional to $L_1 - L_0$. The secondary negative feedback loop controlling I_{MOD} will act to hold $L_1 - L_0$ constant.

The modulation current feedback loop will have a characteristic response time. Consistent with our assumption that I_{MOD} is a parameter that changes slowly with respect to the response of the prebias

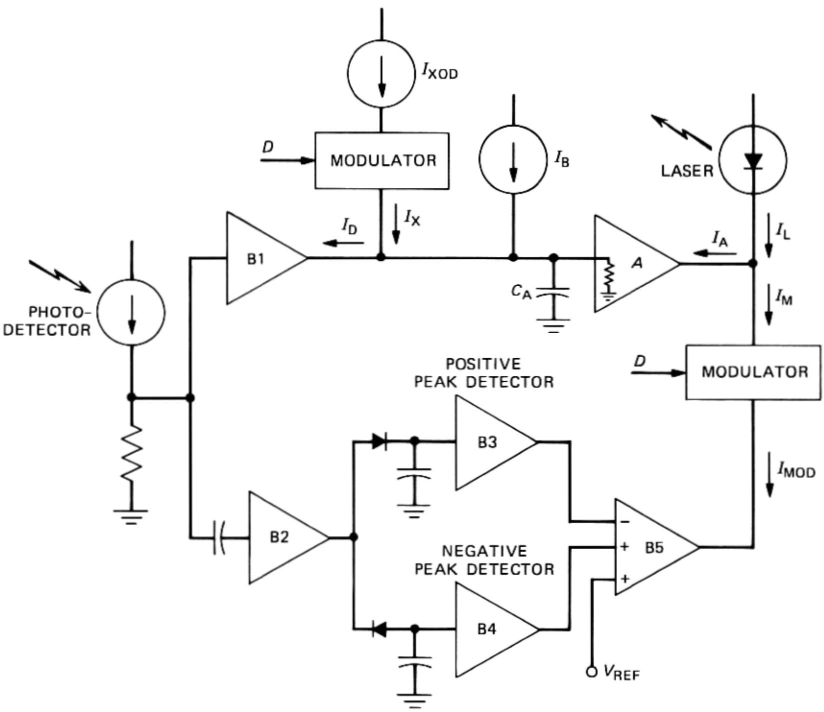

Fig. 3—An improved laser driver incorporating feedback control of both bias and modulation currents. Light output levels are set independently of laser parameters.

current feedback loop, the secondary feedback loop should respond slowly in comparison with the feedback controlling I_A.

IV. CONCLUSION

This paper has presented an analysis of a generalized method of negative feedback stabilized biasing and modulation of semiconductor lasers. Our objective was to evaluate the effectiveness of the stabilization and determine the critical feedback loop parameters. The analysis considered not only the direct influence of variations in η_1, η_2, and I_T, but also the effect of changes in the average modulation signal and the issue of biasing the laser above or below threshold.

For the more simple bias schemes reported to date, we showed that the laser light levels are susceptible to variation in any of the laser parameters when the laser is dc biased below threshold. When the laser is biased above threshold, only changes in η_2 affect the light output.

We also analyzed a method of stabilizing the difference $L_1 - L_0$ and thereby fixing laser light output independent of variations in any laser or modulation parameters. To maintain this independence the laser must, of course, be prebiased to remain above threshold under all expected conditions. Moreover, the optical output will still be sensitive to changes in the photodetector light-to-current conversion factor, f.

LIST OF VARIABLES

Device parameters

η_1 laser subthreshold differential slope efficiency
η_2 laser above-threshold differential slope efficiency
I_T laser threshold current
f photodetector light-to-current conversion factor
k_1 laser-photodetector subthreshold conversion efficiency $\triangleq f\eta_1$
k_2 laser-photodetector above-threshold conversion efficiency $\triangleq f\eta_2$

Modulation-related (rapidly changing) parameters

D digital signal data (ONE or ZERO)
I_L instantaneous total laser current
I_M instantaneous modulation current: 0 or I_{MOD}
I_X instantaneous balance current: 0 or I_{XOD}
I_D instantaneous photodetector output current
L instantaneous laser luminosity

Nominally DC (slowly changing) parameters

$\bar{D}$ average (dc) value of digital signal data
I_{L0} logic ZERO laser current

I_{L1} logic ONE laser current
I_{MOD} modulation source current
I_{XOD} balance source current
L_0 logic ZERO laser luminosity
L_1 logic ONE laser luminosity
I_B bias current
I_A amplifier output current $\triangleq$ laser prebias current $= I_{L0}$
A_I amplifier current gain
I_{REF} modulation reference current
γ conversion efficiency of feedback loop controlling the modulation source current, I_{MOD}

Notation: For an arbitrary variable X, the bar notation $\bar{X}$ signifies the average or dc value of X.

REFERENCES

1. "Atlanta Fiber System Experiment," Special Issue, B.S.T.J., *57*, No. 6 (July–August 1978), pp. 1717–888.
2. M. I. Swartz, "Design and Performance of the FT3 Lightguide Transmission Medium," IEEE Int. Conf. Commun. Conf. Record, *1* (1981), pp. 6.1.1–8.
3. H. Buenning, H. W. Kreutzer, and F. Schmidt, "Subscriber Stations in Service Integrated Optical Broad Band Communications Systems," IEEE Trans. Commun., *COM-30*, No. 9 (September 1982), pp. 2163–71.
4. K. Asatani, R. Watanabe, K. Nosu, T. Matsumoto, and F. Nihei, "A Field Trial of Fiber Optic Subscriber Loop Systems Utilizing Wavelength Division Multiplexers," IEEE Trans. Commun., *COM-30*, No. 9 (September 1982), pp. 2172–84.
5. P. W. Shumate, Jr., F. S. Chen, and P. W. Dorman, "GaAlAs Laser Transmitter for Lightwave Transmission Systems," B.S.T.J., *57*, No. 6 (July–August 1978), pp. 1823–36.
6. J. Gruber, P. Marten, R. Petschacher, and P. Russer, "Electronic Circuits for High Bit Rate Digital Fiber Optic Communication Systems," IEEE Trans. Commun., *COM-26*, No. 7 (July 1978), pp. 1088–98.
7. R. G. Swartz, B. A. Wooley, A. M. Voshchenkov, V. D. Archer, and G. M. Chin, "An Integrated Circuit for Multiplexing and Driving Injection Lasers," IEEE J. Sol. State Circuits, *SC-17*, No. 4 (August 1982), pp. 753–60.
8. F. S. Chen, "Simultaneous Feedback Control of Bias and Modulation Currents for Injection Lasers," Electron. Letts., *16*, No. 1 (January 3, 1980), pp. 7–8.

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