Polarization bistability in semiconductor laser: Rate equation analysis

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The bistable switching between the TE and TM modes in semiconductor lasers has been analyzed using the rate equations. The condition of bistability has been determined using linear and nonlinear gain constants. The observed bistable switching behavior can be explained by a numerical simulation.

Recently, polarization bistability has been observed in InGaAsP/InP semiconductor lasers.[1] The bistability is characterized by large hysteresis loops in the polarization-resolved power versus current characteristics of the TE_{00} and TM_{00} modes (electric field parallel and perpendicular to the junction plane, respectively). When the laser is operated within the hysteresis loop, the polarization of the laser output can be switched between the two orthogonal directions by current pulse injection. Possible use of such devices as optical logic gates and memory functions has also been discussed.[2]

Ropars *et al.*[3] previously have studied the polarization bistable switching mechanism in semiconductor lasers based on experimentally determined gain versus current characteristics for the TE and TM modes. Their analysis has shown that the state of operation of the laser is determined by two current-dependent competing terms. One term represents the self-stabilization for the existing lasing mode to resist the onset of a new mode. The other is the gain-recovering term of the nonlasing mode. By comparing the influence of current injection on the junction temperature and on the saturated gains of the two modes, it is concluded that, as the injection current is varied, the changes in the gain-recovering term are dominated by the relative change in the saturated gains of the two modes. In other words, the polarization flip is caused by an electronic process.

In this letter, we analyze the static and transient behavior of polarization bistability in semiconductor lasers using coupled rate equations for the photon and carrier densities. The use of the rate equations enables us to identify the influence of each laser parameter on the device characteristics and to determine the condition for the existence of polarization bistability using these parameters.

The equations we use for the analysis are

$$\dot{P}_E = A_E(N-N_E)(1-\epsilon P_E-\epsilon' P_M)P_E + \beta N/\tau - P_E/\tau_E\,, \quad (1)$$

$$\dot{P}_M = A_M(N-N_M)(1-\epsilon P_M-\epsilon' P_E)P_M + \beta N/\tau - P_M/\tau_M\,, \quad (2)$$

$$\dot{N} = I/eLwd - A_E(N-N_E)(1-\epsilon P_E-\epsilon' P_M)P_E - A_M(N-N_M)(1-\epsilon P_M-\epsilon' P_E)P_M - N/\tau\,. \quad (3)$$

In the above equations, P_E and P_M are the photon densities for the TE and TM modes, respectively, N is the carrier density in the active layer, I is the injection current, d, w, and L are the thickness, width, and length of the active layer, A_E and A_M are the linear gain constants, N_E and N_M are the carrier densities required for transparency in the laser medium for the TE and TM modes, τ_E and τ_M are the photon lifetimes in the laser cavity, β is the fraction of the spontaneous emission coupled into the lasing mode, τ is the carrier lifetime, and ϵ and ϵ' are the contributions to self-saturation and cross saturation from the nonlinear gain.[4–6] The linear gain constants can be deduced from the experimentally measured net gain versus current relations shown in Fig. 1. The gain curves are, in general, nonlinear over a wider current range. Near the threshold, the relation is nearly linear and can be approximated by straight lines whose slopes determine A_E ($=1.45\times10^6\ \mathrm{cm^3/s}$) and A_M ($=1.4\times10^6\ \mathrm{cm^3/s}$) and whose intercepts with the abscissa determine $A_E N_E + 1/\tau_E$ and $A_M N_M + 1/\tau_M$. The photon lifetimes τ_E and τ_M are 2 and 1.55 ps, respectively, for a cavity length of 250 μm, free-carrier absorption coefficient of 15 $\mathrm{cm^{-1}}$ and facet reflectivity of 0.39 for the TE mode and 0.26 for the TM mode. Other relevant parameters are $d=0.2\,\mu$m, $w=2\,\mu$m, $\beta=10^{-4}$, $\tau=3$ ns, $N_E=0.45\times10^{18}\ \mathrm{cm^{-3}}$, and $N_M=0.315\times10^{18}\ \mathrm{cm^{-3}}$. Notice that the mode confinement factors are included in A_E and A_M and that $A_E>A_M$, $N_E>N_M$.

In this two-mode system, the stable lasing mode can be determined, following the method described in Ref. 7, by

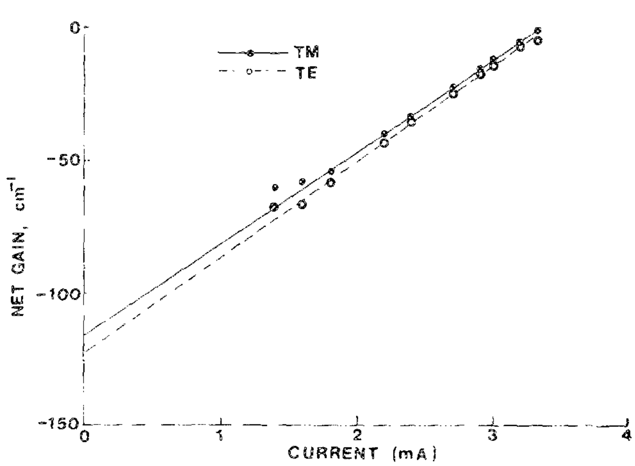

FIG. 1. Net gain vs current curves of a polarization bistable laser.

studying the phase curves in the P_E-P_M space. For a given initial intensity pair (P_E,P_M), the evolution in time is determined by the position in relation to the zero-slope lines of $dP_E/dt = 0$ and $dP_M/dt = 0$. These two lines are labeled as L_E and L_M, respectively. The bistable operation (with two steady states) is possible if L_E and L_M cross each other in such a way that the intercept of L_E with the P_E axis is larger than that of L_M and the intercept of L_M with the P_M axis is larger than that of L_E. By neglecting the nonlinear gain, the condition for bistability operation can be obtained from Eqs. (1)–(3):

$$(1 + A_E\tau_E\Delta N)(1 - A_M\tau_M\Delta N) \geqslant 1\,, \tag{4}$$

where $\Delta N = N_E - N_M$. In an ideal laser without the nonlinear gain, the mode of operation has two stable states if Eq. (4) is satisfied. However, the modes cannot be switched from one to the other by injection of current pulses because the carrier density above the threshold is effectively clamped and the gain of the nonlasing mode can never reach the threshold value by increasing the current. A realistic modeling of the mode switching behavior needs to take into account that the carrier density continues to increase with increasing current, at a slower rate, above the threshold. The nonidealness of the gain has been treated as a heuristic correction factor to the gain constants.[4,6] To achieve bistable operation, the constraint for ϵ and ϵ' can be derived following the same steps leading to Eq. (4):

$$\epsilon' \geqslant \epsilon\,. \tag{5}$$

The origin of the nonlinear gain is the spectral hole burning effect[5] and the spatial hole burning effect.[6] The relative contribution from these two effects to the nonlinear gain may depend on the device geometry, waveguide dimension, and material type and, so far, has not been fully characterized. Also unknown are the strength of the cross coupling between two orthogonally polarized fundamental modes and the ratio of the self-saturation and cross-saturation constants. We assume that the correction to the gain constants is on the order of a few percent at 3 mW output power[4,6] under the constraint of Eq. (5).

An example of the mode competition diagram is shown

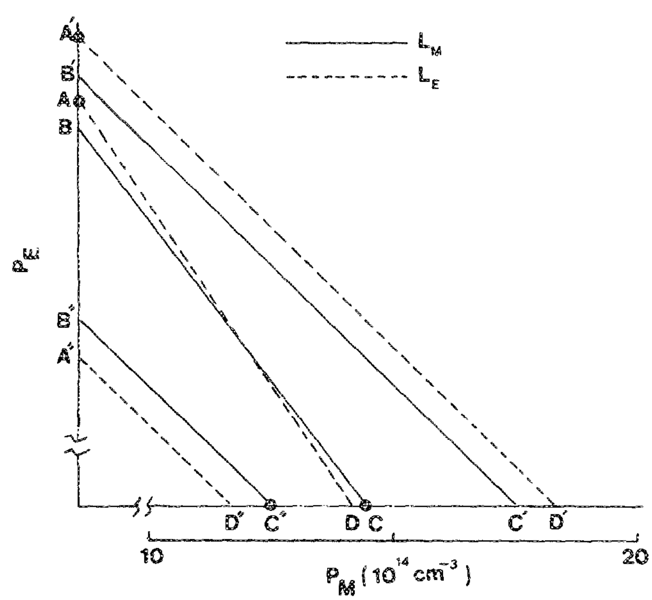

FIG. 2. Diagram showing the intercepts of the zero-slope lines L_E and L_M with the P_E and P_M axes. The intercepts are calculated using the parameters described in the text. The straight lines are drawn between the calculated intercepts.

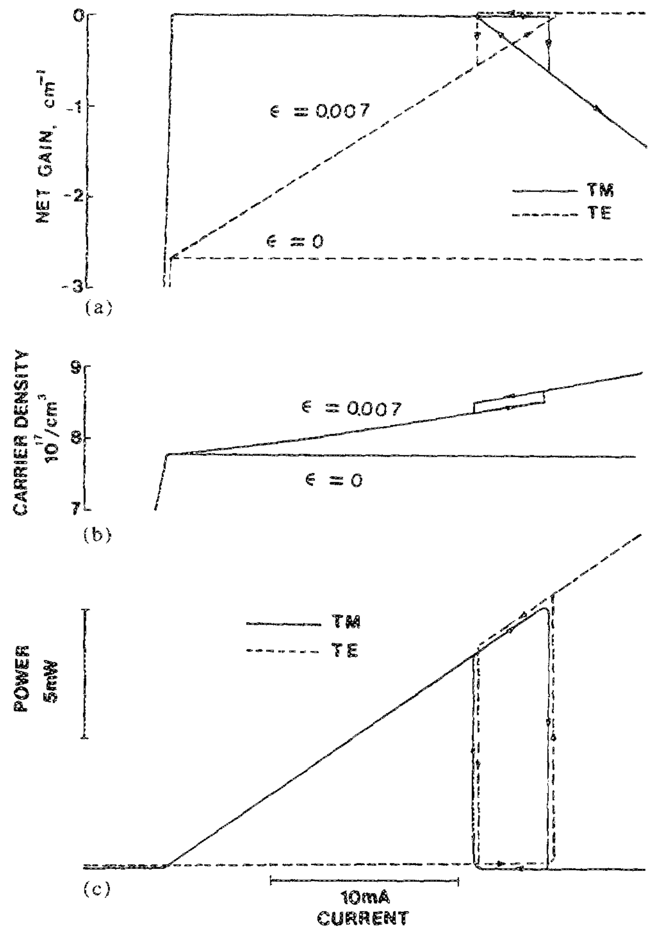

FIG. 3. Calculated (a) net gains, (b) carrier density, and (c) power vs current characteristics. The origins of the curves for the TE mode have been shifted for clarity.

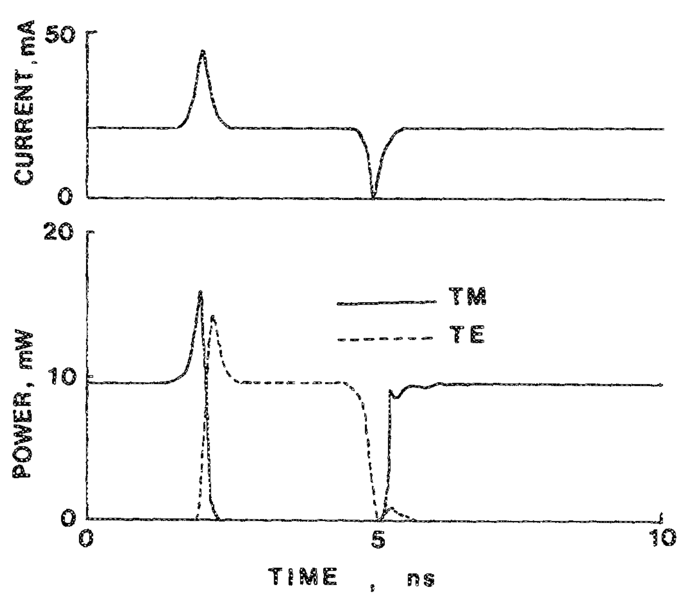

FIG. 4. Calculated mode switching behavior between the TE and TM modes triggered by current pulses.

in Fig. 2 where we illustrate the intercepts A, B, C, D calculated for three representative cases of mode stability condition at $I = 19$, 24, and 26 mA, corresponding to TM-stable, bistable, and TE-stable operations, respectively. The stable states for each bias current are marked by circles. In this example, we assume $\epsilon' = \epsilon = 0.007$. As the state of operation is changed by varying the carrier density, points A and D move at a faster rate compared to points B and C. This relative movement makes it possible to change the stability condition by current injection. In the bistable regime, mode switching from TM to TE can be achieved following the path $ABCD \rightarrow A'B'C'D' \rightarrow ABCD$. Likewise the switching from TE to TM follows the path $ABCD \rightarrow A''B''C''D'' \rightarrow ABCD$. The calculated net gains, carrier density, and power versus current characteristics are shown in Fig. 3. The net gains of the TE and TM modes are defined as $A_E(N - N_E) - 1/\tau_E$ and $A_M(N - N_M) - 1/\tau_M$, respectively. For comparison, the calculated curves for $\epsilon = 0$ are also included. Notice that for $\epsilon = 0$ the net gains of both the lasing mode and the nonlasing mode are clamped at their respective values at the threshold current. The mode of operation cannot be switched by current. For nonzero ϵ the net gain of the lasing mode is clamped while the net gain of the nonlasing mode varies with current. The polarization flip takes place at the crossing of the gain curves. Further calculation indicates that, as long as Eq. (7) is satisfied, the existence of bistability is not sensitive to the magnitude of ϵ from 0.002 to 0.02. The hysteresis loop shrinks with decreasing ϵ. The mode inhibition becomes ineffective if $\epsilon < 0.99$. At this point, the laser operates in two modes simultaneously and the hysteresis disappears.

The transient mode switching characteristics can also be modeled using Eqs. (1)–(3) by direct integration. Figure 4 shows the bistable switching of the lasing mode triggered by 0.25-ns-wide, hyperbolic-secant-shaped current pulses. The switching time delay depends on the amount of current overdrive. For smaller triggering current, the switching delay increases and can be as long as several microseconds as the switching overdrive approaches zero. This is typical of the critical slowing down phenomenon in bistable systems.

In conclusion, we have analyzed the polarization bistability in semiconductor lasers using the rate equations. The condition for bistability has been expressed analytically using lasers parameters. The nonlinear gain is found to play an important role in the mode switching mechanism. Using experimentally measured gain constants and with proper assumption for the magnitude of the nonlinear gain, the polarization bistable switching behavior can be explained.

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