Static and Dynamical Properties of Dispersive Optical Bistability in Semiconductor Lasers

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***Abstract*—Static and dynamic properties of dispersive optical bistability (OB) in semiconductor lasers biased from below to above threshold has been investigated both theoretically and experimentally. The OB result is found to be varied continuously from below to above threshold; Although conventionally the OB switch-off time in dispersive semiconductor laser amplifiers is limited by the effective carrier lifetime, a much faster OB switch-off can be obtained when a laser diode operates well above threshold in the injection-locked condition.**

I. Introduction

OPTICAL BISTABILITY (OB) in semiconductor lasers and resonant-type laser amplifiers has attracted much attentions recently because of its potential application in optical computing and optical switching. The advantages such as inherent optical gain and low optical switching power makes the bistable laser diodes one of the key components in future digital optical communication systems.

When a semiconductor laser, biased just below threshold, operated as an optical amplifier, dispersive OB has been demonstrated [1]–[4]. The externally injected optical signal is amplified in the active cavity of the laser amplifier, the intensity dependent refractive index and the nonlinear gain saturation of the semiconductor laser material makes the resonant frequency of the laser amplifier depending on the input optical signal. When the input optical signal is strong enough, OB phenomena can be observed. On the other hand, OB has also been found recently in optically injection-locked semiconductor lasers [5], [6]. In this later case the laser diode is biased above threshold, the stimulatively emitted optical field of the laser diode is injection-locked by the incoming optical signal. The OB behavior has been observed near the edge of the stable locking range when the power ratio between the injected optical fired and that emitted from the slave laser is sufficiently high. This can be achieved either by sweeping the injected optical power with the fixed frequency detuning near the stable locking band or by sweeping the frequency detuning with a fixed optical power injection.

The OB phenomena have been theoretically explained either in the case when a resonant-type semiconductor amplifier operates below threshold [3], [4] or an injection-locked semiconductor laser works above threshold [5], [6]. Quite different physical images have hitherto been considered for these two cases. Since there is no discontinuity at the threshold of a semiconductor laser, the OB behavior should be continuous from below to above threshold. A unified treatment has been outlined in [7].

From the point of view of OB applications, one of the most important remaining problems with semiconductor laser devices is their limited switching speed. In the conventional dispersive OB applications, a diode laser amplifier is biased just below the lasing threshold, the switch-off time of OB is determined by the spontaneous emission carrier life time [3] and the value is typically 1–2 ns. This limitation has been confirmed both theoretically and experimentally and it limits the application prospective of dispersive OB since a further increase of the system capacity into multi-gigahertz regime seems not possible.

In this paper, we present our experimental measurement on the static and dynamical OB properties of a DFB semiconductor laser. The OB behavior is found to be continuous with the laser diode biased from below to above threshold and more surprisingly the OB switching speed can be increased for more than 10 times respected to the conventional case by biasing the laser diode well above threshold. The switch-off time, in this case, as short as 100 ps has been obtained in a commercially available DFB laser diode. The results have been theoretically analyzed using the rate-equation model and a good agreement between experiment and theory has been obtained. The impact of various laser parameters on the OB performance is investigated and the physical mechanism behind this fast optical switch is also explained.

II. Experiment

The experimental set-up shown in Fig. 1 is described as follows. Three conventional DFB-BH laser diodes with the similar emission wavelength around 1554 nm are used. The first laser (LD1), biased at three times its threshold, is used to generate the signal light and its output is injected into the second laser (LD2) which works as an OB element. The third laser diode (LD3) is used as the master laser to optically injection lock LD1 preventing frequency chirp when LD1 is directly modulated by the injection current. All the lasers used have one facet antireflection coated and the other facet cleaved. Each laser is isolated from external reflection with a double-section Faraday optical isolator providing 70 dB of isolation. A monochromator and a scanning Fabry–Perot interferometer are used for rough and fine measurement of the optical spectrum. Frequency matching and detuning between the lasers is accomplished by adjusting their heat-sink temperature. An electrical signal generator is used to directly

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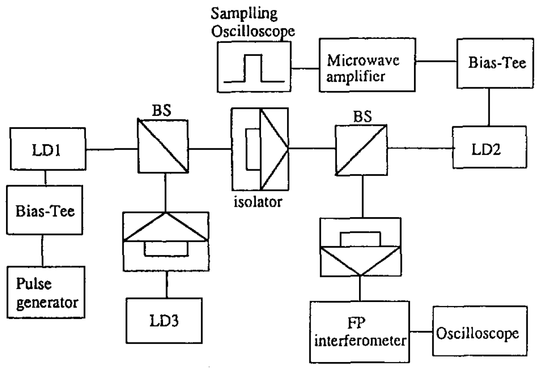


Fig. 1. Experimental set-up.

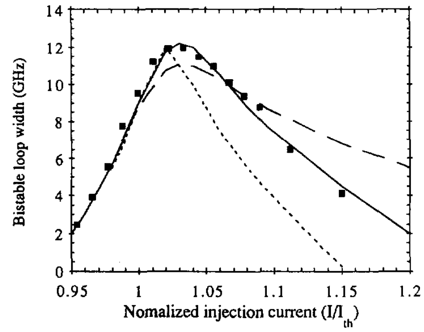


Fig. 2. Measured bistable loop width (rectangles) versus the normalized injection current with the optical injection level at about −23 dBm, together with the calculated results for a purely single mode laser ($\eta = 0$) (short-dashed line), a two-mode laser ($\eta = 1$) (long-dashed line) and a quasi-single-mode laser ($\eta = 0.994$) (solid line). The injected optical power is $P_{in} = -23$ dBm. I_{th} is the free-running laser threshold.

modulate the injection current of LD1 through a bias tee network. Another bias tee is connected to the electrode of LD2 to detect its junction electric voltage variation caused by the injected optical signal. In fact, this junction voltage signal V is inversely proportional to the variation of the carrier density N inside the laser cavity through the depletion of the quasi-Fermi level. The time domain dynamics of optical bistability in LD2 can then be evaluated in this way through a wide-band microwave amplifier and a sampling oscilloscope. This kind of *in situ* measurement on the junction electrical voltage [8], [9] has relatively high sensitivity when the laser diode is biased below threshold. Above threshold, on the other hand, the carrier density and thus the junction electrical voltage is almost clamped at its threshold value in the free-running state. With optical injection locking however, the carrier density changes with the frequency detuning, even if the laser diode is biased well above threshold, this has been verified both experimentally and theoretically [10]–[12]. Quantitative calibration on dV/dN is difficult because it is the derivative at the lasing carrier level, it depends on the band structure, band filling and the package parasitic effects [13].

The injected optical power into the slave laser has been evaluated as follows: first, measure the linewidth enhancement factor α of the slave laser using the injection locking method [12], with this α value known, the injected optical power can then be obtained through the measured injection locking bandwidth when the slave laser is biased above threshold [14].

A. Static Bistable Loopwidth

Generally, the bistable optical output in semiconductor laser devices can be achieved either by sweeping the injected optical power with a fixed frequency detuning or by sweeping the frequency detuning with a fixed optical power injection. In our experiment on the static OB behavior, the frequency OB loop is measured because the lasing frequency of the diode laser LD1 can be swept easily by adjusting either its heat-sink temperature or its injection current. At each bias level of the slave laser LD2 and with a definite optical power objected from LD1, a bistable output from the slave laser can be obtained versus the input signal frequency detuning.

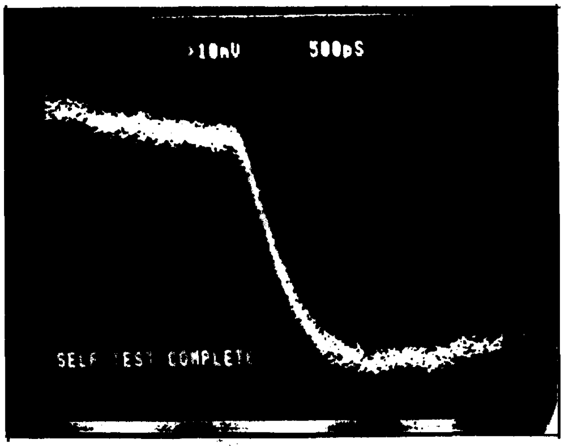
In the case when the slave laser is biased below threshold, it works as a nonlinear resonant-type optical amplifier, OB behavior has already been analyzed extensively. When the slave laser is biased above threshold, on the other hand, optical injection locking can be obtained and bistable output can also be achieved in this case depending on the ratio between the externally injected optical power and the power emitted from the slave laser [6]. In this static measurement, the bistable loop width is an important value representing the OB behavior. However, a continuous loopwidth measurement across the threshold has not as yet been found.

As an example, the rectangles in Fig. 2 report the measured bistable loopwidth versus the relative bias level of the slave laser from below to above threshold while the injected optical power is kept at about −23 dBm. Below threshold, the OB loop increases its width with the increase of the bias level, while at above threshold, the loop width decreases with the bias level. The OB behavior is found to be continuous in the transition region from below to above threshold. The maximum OB loop width is obtained, in our case, at about 1.03 times of the free-running laser threshold and this value is, in general, dependent on the amount of injected optical power [7].

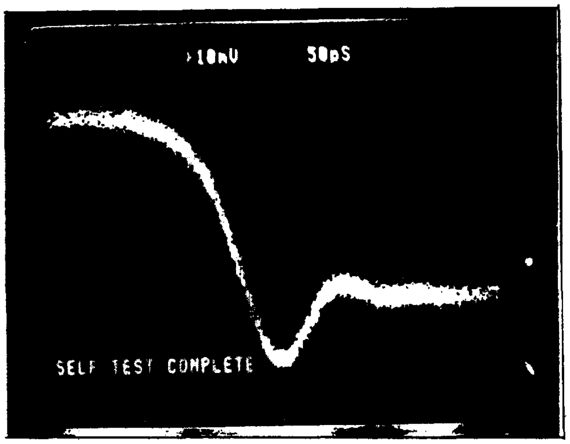
B. Dynamics of OB Switching

In order to investigate the dynamic behavior of OB in laser diodes, we modulate the optical output of LD1 using the direct current modulation with a sinusoidal wave at 300 MHz through a bias tee. LD2 is then optically modulated by the light injected from LD1. When the injected optical power is strong enough, LD2 acts as a thresholding device and the sinusoidal signal is reshaped by the nonlinear response of LD2.

If LD1 is optically injection locked by the master laser LD3, the frequency chirp is suppressed and the optical output from LD1 is mainly intensity modulated. Frequency chirp suppression caused by optical injection locking has been studied extensively [15], [16]. Chirp suppression ratio is, in general, dependent on the ratio between the externally injected optical power and the power emitted from the slave laser [15], [16]. On the other hand, if the master laser LD3 is blocked, LD1 operates freely. In this case the optical output of LD1 is



(a)



(b)

Fig. 3. Measured OB switch-off wave form with LD2 biased at (a) 0.99 and (b) 2.75 times the threshold current. The horizontal scale is 500 ps/div in (a) and 50 ps/div in (b).

mainly frequency modulated because the FM efficiency of this laser is approximately 1 GHz/mA whereas the IM efficiency is about 0.2 mW/mA. When LD1 is biased at three times of the threshold, the output power is 8 mW. With the current modulation of 10 mA*pp* of amplitude, the frequency deviation is approximately 10 GHz and the intensity fluctuation is only about 1.25 dB. Therefore, we can measure both these two kinds of OB with this experimental setup. However, as far as the switching speed is concerned, no difference has been observed between these two cases.

Since the carrier recovery is the main limitation to the OB switch-off time [7], we measured the carrier population variation through the laser junction electric voltage signal. This signal is obtained through the bias-tee connected to LD2 and amplified through a microwave amplifier with 30 dB gain and 12 GHz bandwidth. Since the switch-on time usually depends on the signal optical power, the switch-off time is more important because it depends mainly on the device characteristic [17]. Fig. 3(a) shows the junction electric voltage waveform during OB switch-off when LD2 is biased at 99% of the threshold; the switch-off time is about 1 ns. This value is comparable to the results reported before in resonant-type semiconductor laser amplifiers and obviously, it is determined by the effective carrier life time. If LD2 is biased above threshold, however, it operates in optically injection-locking regime and bistability occurs near the edge of the stable locking band [6]. In this case, the OB switch-off time is found to be much smaller than in the previous case; the waveform during switch-off is shown in Fig. 3(b) when LD2 is biased at 2.75 times the threshold. An OB switch-off time of less than 100 ps is shown in Fig. 3(b). A systematic measurement of the OB switch-off time versus the injection current of LD2 from below to above threshold has been also performed and the result is given in Fig. 4 (open circles); the switch-off time keeps decreasing with increasing bias level. For all the measurements, the wavelengths of the signal laser were chosen at the center of the bistable loop at the steady state.

In order to evaluate the effective carrier life time of LD2, an optical modulation technique is employed. This was performed by the small-signal modulation on LD1 with a microwave network analyzer. LD2 was biased very near the leasing threshold. The modulation frequency swept optical signal injected from LD1 modulates the carrier population of LD2 and the frequency response can be measured through the junction electric voltage signal of LD2 through the bias-tee. In this technique photo detector is not required and the sensitivity is higher then the conventional injection current modulation method, where the spontaneously emitted photons has to be detected by a photodiode. The thermal effect has also been avoided in this optical modulation technique. In the measurement, wavelength matching between LD1 and LD2 is not necessary, in fact we have used the wavelength difference between these two lasers of more 0.5 nm in the experiment to avoid coherence built up. The effective carrier life time can be obtained from this measurement through the relationship $\tau_e = f_{3\,\mathrm{dB}}^{-1}$, where $f_{3\,\mathrm{dB}}$ is the measured 3-dB frequency of the response. Fig. 5 reports a typical result of the measured frequency response (open circles) when LD2 was biased at threshold point. From this measurement, the effective carrier life time of LD2 is found to be approximately 1.4 ns. Obviously, the OB switch-off time reported in Fig. 4 was not limited by the carrier life time when LD2 was biased well above threshold.

It should be pointed out, however, that when the laser diode works above threshold, in the "off" state of OB, optical injection locking is no longer kept and the free-running slave mode results. In practical applications, only the optical power in the locked frequency is required and the unwanted free-running slave mode have to be removed, therefore an optical filter is necessary.

III. Theoretical Consideration

In order to simulate the dispersive OB operation in a laser diode, a unified treatment is obviously necessary allowing to consider the laser biased from below to above threshold. Our

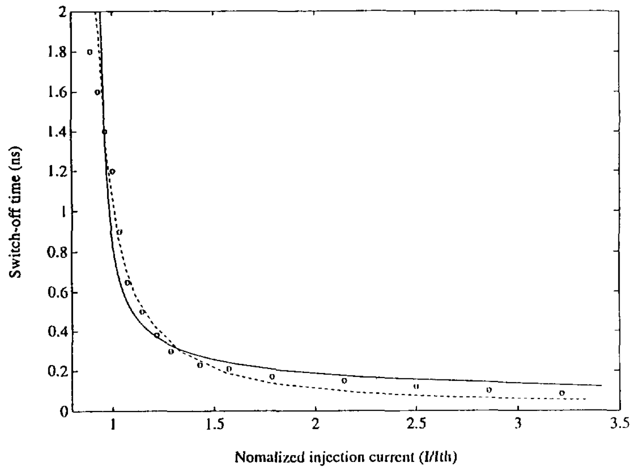


Fig. 4. OB switch-off time versus the normalized injection current for the measured values (open circles) and numerically simulated results (dashed line). The solid line is the inverse of the laser's relaxation oscillation frequency.

theoretical analysis is based on the rate-equation model [16]:

$$\frac{dE}{dt} = \frac{1}{2}[\Gamma G(N,P) - 1/\tau_p]E + i\Delta\Omega E + \frac{1}{\tau_p}E_{\text{ext}} \quad (1)$$

$$\frac{dP_s}{dt} = [\Gamma\eta G(N,P) - 1/\tau_\rho]P_s + R_{\text{sp}} \quad (2)$$

$$\frac{dN}{dt} = I/qv - R(N) - \eta G(N,P)P_s - G(N,P)|E|^2 \quad (3)$$

where $P = P_s + |E|^2$ is the total photon number in the slave laser's active cavity, E is the normalized electric field generated in response to the externally injected optical source E_{ext}, P_s is the photon number generated in response to the spontaneous emission in the non locked mode [16], $\Delta\Omega = \Omega - \omega$ is the relative detuning between the master and the slave lasers' cavity resonance frequency. $G(N,P) = G_N(N - N_0) - G_I P$ is the material gain for the locked mode, being G_N the differential gain and G_I the nonlinear gain. N is the carrier number and N_0 is that at transparency. η represents the gain difference between the locked mode and the unlocked mode, it is usually determined by the shape of the gain profile of the semiconductor material as well as the laser's cavity structure. τ_p is the photon life time, τ_i is the cavity round-trip time, Γ is the confinement factor, I is the electric current, q is the electron charge and v is the active cavity volume. The carrier dependence of the refractive index is represented by the well-known linewidth enhancement factor $\alpha = -2(\delta\omega/\delta N)/G_N$. Unlike the previous analysis that typically assumed a constant carrier life time, carrier dependent recombination is assumed in our treatment, which appears to be important in fitting the theoretical results with the experimental ones. $R(N) = AN + BN^2 + CN^3$ represents the carrier recombination effect with A, B and C nonradiative, radiative and Auger recombination coefficients respectively. The spontaneous emission rate in (2) can therefore be assumed as $R_{\text{sp}} = \beta_{\text{sp}}BN^2$, where β_{sp} is the spontaneous emission coefficient.

To solve the rate equations (1)–(3), small signal analysis was usually employed around the condition $\Gamma G(N_{\text{th}}) = 1/\tau_p$ [5], [6], where $\Gamma G(N_{\text{th}})$ represents the modal gain at threshold. In this way, a discontinuity would happen at the threshold point, therefore, unified analysis of OB in semiconductor lasers from below to above threshold could not be obtained. In our analysis, we directly solved the rate equations (1)–(3) numerically in the time domain using the fourth-order Runge–Kutta method. In order to make the result stable enough in the static properties' analysis, the calculated data in the time domain were averaged within 10 ns after 30 ns from turn-on. With a definite input optical power and sweeping the input signal frequency detuning up and down, optical bistability can be obtained for the output optical power. As expected, the OB effect depends closely on the bias level of the laser. Optical bistable output can be obtained both in the case when the laser diode is biased below threshold and when it is biased above threshold. Typical results of the calculation are reported in Fig. 6(a) and 6(b) for these two cases with several different values of the injected optical power. The calculated bistable loop width versus the normalized injection current of the slave laser, from below to above threshold, are reported in Fig. 2 for three different side mode conditions. The injected optical power in obtaining Fig. 2 is $P_{\text{in}} = -23$ dBm where $P_{\text{in}} = |E_{\text{ext}}|^2 h\nu$, with $h\nu$ the photon energy. It is interesting to notice from this figure that the bistable loop width is sensitive to the presence of the side mode when the laser diode is biased above threshold. With lower side-mode suppression ratio, or say η approaches to unity, the bistable loop width decrease with the increase of the injection current is slow in the above threshold regime. This means that OB can be more easily obtained in the multi-longitudinal mode laser diodes which work above threshold. On the other hand, when a laser diode with high side-mode suppression is used, for example a $\lambda/4$ shifted DFB laser, the OB loop width decreases rapidly with the injection current. The physical meaning behind this phenomena is not yet clear. In order to fit our measured data, we suppose that the gain difference between the locked main mode and the unlocked side mode is 0.6%. The calculated results agree qualitatively with

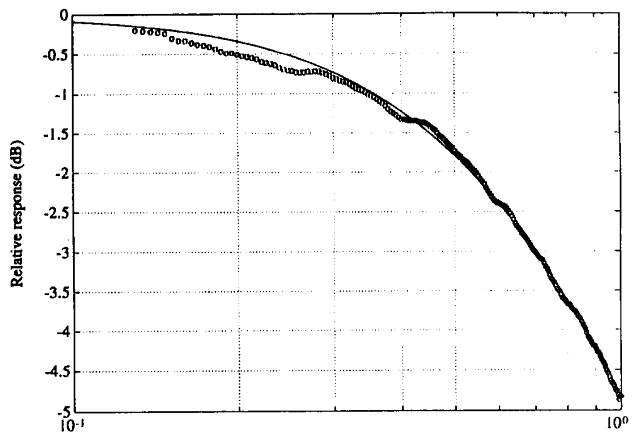


Fig. 5. Measured small-signal optical modulation response of LD2, which was biased at threshold (open points). The solid line is obtained by fitting with $[1/(1 + \tau_e\omega)]^2$ with $\tau_e = 1.4$ ns.

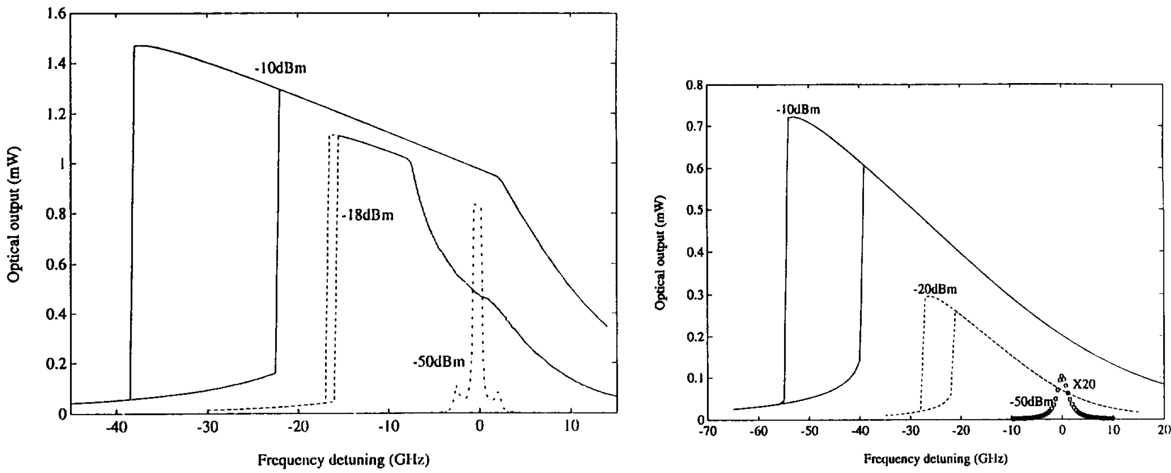


Fig. 6. Typical results of the calculated optical bistable output versus frequency detuning with the laser diode biased (a) above threshold at $1.22I_{\rm th}$ and (b) below threshold at $0.976I_{\rm th}$. Parameters written on the figure indicates the externally injected optical power.

the experiment. It is also evident from Fig. 2 that the maximum values of OB are obtained when the slave laser is polarized at a little bit above its free-running threshold. Another point worth to be noted is that the peak output power is relatively insensitive to the input optical power when the laser diode is biased above threshold, this can be intuitively observed from Fig. 6 and it is reported systematically in Fig. 7. In digital optical systems, it may be useful to be used as a power limiter.

Dynamical properties of the OB switching have been investigated in the time domain using the same rate equations. The slave laser's injection current ranges from $I = 20$ mA to $I = 24$ mA while the threshold current is $I_{\rm th} = 21.3$ mA. In order to be comparable with the previous study [17] and practical situations, the Gaussian input optical pulse is chosen in this case with the FWHM (full width at half maximum) of 2 ns and the peak power of 0.8 mW centrated at $t = 15$ ns. The initial frequency detuning of the master from the slave is kept the same. Fig. 8(a) reports the optical output signal. In order to have a clear presentation, the curves are delayed with each other of 1 ns. An overshoot spike is clearly shown in each curve at switch-on. This phenomenon has already been observed when the slave laser operated below threshold [3], [4]. Our calculation demonstrates that this spike exists also in the OB of the injection-locked case. In addition to the previous observation that the switch-off time becomes smaller as the injection current is increased toward the threshold level [17], we found that the switch-off can be even faster when the slave laser is biased above threshold. Fig. 8(b) illustrates the relative variation of the carrier population inside the slave laser's active cavity. It is evident that below threshold, the carrier recovery at switch-off is determined mainly by the effective carrier lifetime. Above threshold however, this carrier recovery can

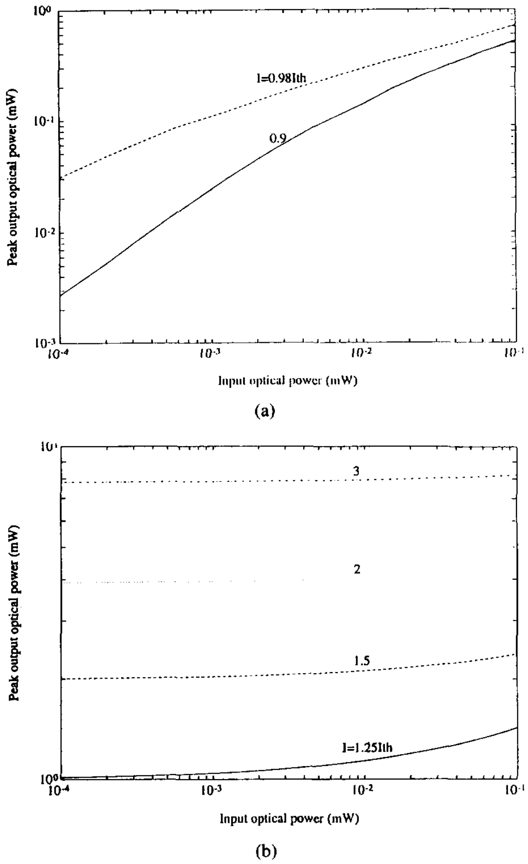


Fig. 7. Calculated peak output optical power versus the input optical power, with LD2 biased (a) below and (b) above threshold. Parameters written on the figure indicated the relative bias level of the laser diode.

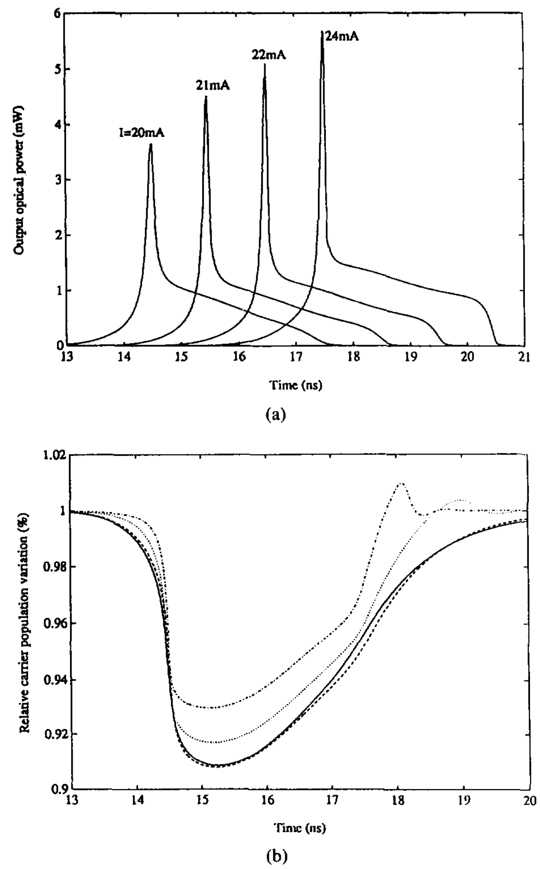


Fig. 8. (a) Calculated optical output pulse from OB element with increasing electric bias current from $I = 20$ to $I = 24$ mA. The threshold current of the slave laser is $I_{\text{th}} = 21.3$ mA. The curve has been delayed for 1 ns for $I = 21$ mA, 2 ns for $I = 22$ mA, and 3 ns for $I = 24$ mA in order to have a better representation. (b) Calculated relative variation of the carrier population when the slave laser was biased at $I = 20$ (solid line), 21 (dashed line), 22 (dotted line), and 24 mA (dash-dotted line).

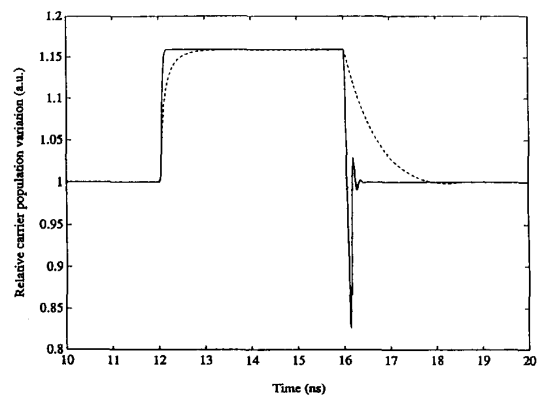


Fig. 9. Absolute values of the calculated relative carrier population variation with the laser diode biased at $I = 0.95I_{\text{th}}$ (dashed line) and $I = 2.7I_{\text{th}}$ (solid line).

be much faster. Since the carrier recovery is slower than the optical switch-off, the time constant which limits the transition speed should be the former.

For a systematic calculation of the switch-off time for different bias level of the laser diode, a square wave is then chosen as the optical input in order that the switch-off time can be extracted easily. The calculated carrier population variation in the time domain is reported in Fig. 9, with the laser biased at $I = 0.95I_{\text{th}}$ (dashed line) and $I = 2.7I_{\text{th}}$ (solid line). To obtain this figure, the input optical signal switches on and off at 12 ns and 16 ns respectively from 0 to 0.316 mW (−5 dBm). The frequency detuning was chosen such that at 0.158 mW constant optical injection, the signal wavelength was at the center of the frequency bistable loop. Obviously, the switch-off is much faster in the later case and ripple at the switch off edge is present, which reflects the effect of relaxation oscillation. Qualitative agreement between these calculated results and the measured results reported in Fig. 3 is obtained. However, the spike at the switch-off is more pronounced in the calculated waveform than the measured one when the laser operated far above threshold. This may be caused by the limited bandwidth (12 GHz) of the microwave amplifier used in the experiment and the parasitic effect in the laser package.

The calculated OB switch-off time versus the normalized injection current is plotted in Fig. 4 as a dashed line, which agrees well with the experiment. Parameters used in the calculation are: $\alpha = 6$, $G_N = 8 \times 10^3$ s^{-1}, $G_I = 6.8 \times 10^5$ s^{-1}, $N_0 = 5 \times 10^7$, $\tau_i = 5.5$ ps, $\tau_p = 1$ ps, $A = 10^8$ s^{-1}, $B = 3$ s^{-1}, $C = 4 \times 10^{-9}$ s^{-1}, $\beta_{sp} = 10^{-5}$, and $v = 5 \times 10^{-11}$ cm^3. These are the typical values for bulk DFB semiconductor lasers. With these values, the spontaneous emission carrier lifetime at threshold is 1.4 ns, which is equivalent to that experimentally measured in LD2.

The physical mechanism behind this fast switching is that during the switch-off transient the stimulated recombination is predominant instead of the spontaneous recombination. The carrier dynamics is now governed no longer by the spontaneous emission effective carrier lifetime, rather, it is determined by the inverse of the relaxation oscillation frequency of the slave laser. Therefore, much faster switch-off can be obtained if the slave laser is biased at relatively high levels. As an approximation, the inverse of the laser's relaxation oscillation frequency versus the normalized injection current is also plotted in Fig. 4 as a solid line. A qualitative agreement is also obtained.

The limitation to the bias level is set by the increase of the optical signal required to be injected into the slave laser to achieve the bistable operation [6]. From the application point of view, since the slave laser operates above threshold, an optical filter is usually required to remove the stimulated emission from the slave laser itself. At switch-off, the frequency difference between the signal and the free-running slave mode can be of the order of tens of gigahertz depending on the ratio between the injected optical power and the power of the slave laser [6]. This free-running slave mode can be filtered out by using, for example, an integrated Mach–Zehnder interferometric optical filter. In order to filter out easily the stimulated emission from the slave laser, one can either increase the signal optical power or decrease the bias level of the slave laser. However, the former is limited by the power of the semiconductor laser sources available and the latter will result in the increase of the transient time. Therefore, a tradeoff between the switching time and the possibility of filtering have to be considered in the practical application.

IV. Conclusion

In conclusion, a unified investigation of dispersive OB in semiconductor laser operating from below to above threshold has been performed systematically. The result can be useful to have a better understanding on the OB performance in semiconductor lasers and to optimize the condition for OB operation. The OB switch-off time is found to decrease continuously with the laser biased from below to above threshold. A fast OB switch-off in less than 100 ps has been observed experimentally when the laser operates far above threshold in the injection-locked regime. To the best of our knowledge, this is the fastest switch-off in dispersive OB of semiconductor lasers ever reported.

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References

[1] K. Otsuka and H. Iwamura, "Analysis of multistable semiconductor light amplifier," *IEEE J. Quantum Electron.*, vol. QE-19, p. 1184, 1983.
[2] K. Otsuka and S. Kobayashi, "Optical bistability and nonlinear resonance in a resonant-type semiconductor laser amplifier," *Electron. Lett.*, vol. 19, p. 262, 1983.
[3] A. J. Adams, H. J. Westlake, M. J. Mahony, and I. D. Henning, "A comparison of active and passive optical bistability in semiconductors," *IEEE J. Quantum Electron.*, vol. QE-21, p. 1498, 1985.
[4] M. J. Adams and R. Wytter, "Optical bistability in distributed feedback semi-conductor laser amplifiers," *Inst. Elect. Eng. Proc*, vol. 132, pt. J, p. 343, 1985.
[5] H. Kawaguchi, K. Inoue, T. Matsuoka, and K. Otsuka, "Bistable output characteristics in semiconductor laser injection locking," *IEEE J. Quantum Electron.*, vol. QE-21, p. 1314, 1985.
[6] R. Hui, A. D'Ottavi, A. Mecozzi, and P. Spano, "Injection locking in distributed-feedback semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 27, p. 1688, 1991.
[7] R. Hui, S. Benedetto, and I. Montrosset, "Optical bistability in diode laser amplifiers and injection-locked laser diodes," *Opt. Lett.*, vol. 18, p. 287, 1993.
[8] P. A. Andrekson, P. Andersson, A. Alping, and S. T. Eng, "In situ characterization of laser diodes from wide-band electrical noise measurement," *J. Lightwave Technol.*, vol. LT-4, p. 804, 1986.
[9] A. Alping, B. Bentland, and S. T. Eng, "100 Mbit/s laser diode terminal with optical gain for fiber-optical local area networks," *Electron. Lett.*, vol. 20, p. 794, 1984.
[10] H. Nakajima and R. Derouiche, "Direct demodulation of 140 Mb/s FSK signals in an injection-locked multiquantun-well DFB laser," *IEEE Photon. Technol. Lett.*, vol. 3, p. 1029, 1991.
[11] R. Hui, S. Benedetto, and I. Montrosset, "Analysis of the direct discrimination of FSK modulated optical signal using injection-locked DFB lasers," *Inst. Elect. Eng. Proc.*, vol. 138, pt. J, p. 276, 1991.
[12] R. Hui, A. Mecozzi, A. D'Ottavi, and P. Spano. "A novel measurement technique of α factor in DFB semiconductor lasers by injection locking," *Electron. Lett.*, vol. 26, p. 997, 1990.
[13] D. Marcus, "Heterodyne detection with an injection laser—Part I: Principle of operation and conversion efficiency," *IEEE J. Quantum Electron.*, vol. 26, p. 85, 1990.
[14] I. Petitbon, P. Gallion, G. Debarge, and C. Chabran, "Locking bandwidth and relaxation oscillation of an injection locked semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-24, p. 148, 1988.
[15] N. A. Olsson, H. Temkin, R. A. Logan, L. F. Johnson, G. J. Dolan, J. P. Van der Ziel, and J. C. Campbell, "Chirp-free transmission over 82.5 km of single mode fibers at 2 Gbit/s with injection locked DFB semiconductor lasers," *IEEE J. Lightwave Technol.*, vol. LT-3, p. 63, 1985.
[16] R. Lang, "Injection locking properties of a semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-18, p. 976, 1982.
[17] W. F. Sharfin and M. Dagenais, "Dynamics of optically switched bistable diode laser amplifiers," *IEEE J. Quantum Electron.*, QE-23, p. 303, 1987.

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