Dynamical switching characteristics of a bistable injection laser

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The switching characteristics of a bistable injection laser with very large hysteresis is examined. Switch-on delays are shown to exhibit a "critical" part and a "noncritical" part, both of which can be reduced by increasing the overdrive current. It is possible to obtain fairly fast switching time (< 20 ns) with a strong overdrive. Nominal delays of 100–200 ns result under moderate overdrives. These long time scales are due to long carrier lifetimes in the carrier-depleted absorption section, a property intrinsic to these bistable injection lasers.

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A bistable injection laser can play a significant role in the fast advancing field of optoelectronic signal processing as an optical counterpart to bistable elements in electronic devices such as schmidt trigger and multivibrators. It was more than a decade ago that Lasher[1] proposed a bistable semiconductor injection laser, based on inhomogeneous current injection resulting from a segmented-contact structure. However, actual devices fabricated to date exhibited little or no hysteresis and, moreover, were beset by the associated pulsations in the optical output.[2–6] Recently we demonstrated,[7] using an advanced laser structure (the buried heterostructure), a practical bistable laser with a sizable hysteresis and *no* pulsations. It was shown that both the size of the hysteresis and the dynamic stability are intimately related to the resistance between the segmented contacts and to the impedance of the current source driving the absorber section. Increasing the value of both of these resistances can result in a near ideal situation where a large hysteresis is manifested with no pulsations. It was also shown that, under certain bias conditions, a negative resistance, reminiscent of a tunnel diode, is obtained at the input to the absorber section that is optoelectronic in origin. This suggests the use of the device in active circuits as an optically controlled negative resistance element.

The basic laser structure and its light-current characteristics are shown in Fig. 1. This laser was described in Ref. 7. In this letter, we describe switching characteristics of the bistable injection laser. In particular, we investigate the technologically important problem of delays during switch-on—the so-called critical slowing down, in the jargon of phase-transition phenomena. When a device is driven from one stable state to the other, a delay occurs before the device actually switches, a delay that is very long compared with any physical lifetimes associated with the system, such as electron-hole recombination or RC time constant. The switching itself is relatively fast. The delay decreases with increasing overdrive.

Figure 2 shows a typical switching of the bistable laser. The laser is operated at a constant I_2, and biased at a certain value of $I_1 (= I_b)$ in the middle of the hysteresis loop, as shown in Fig. 1. A small positive current pulse superimposed on I_1 switches the laser to the "high" (lasing) state while a subsequent negative pulse causes switching back to the "low" state. A closer examination at the switch-on reveals a delay that is dependent on the amount of overdrive (the amount by which the pulse amplitude exceeds $I_c - I_b$ in Fig. 1). The following are the major features of the switching characteristics:

(i) The switching delay (alternatively called slowing down) can be roughly distinguished into a "critical" regime and a "noncritical" regime. The critical regime is observed only at very small overdrives and is characterized by a dramatic increase in the switching delay up to several tens of the intrinsic lifetime of the system. The behavior of the laser in this regime is that of conventional "critical slowing down" and will be discussed below. At higher drive currents, the switching delay is relatively noncritical and is the time required for the carrier density in the absorber section to rise to the level where lasing can occur. This time lapse is on the order of a few carrier lifetimes. A similar delay occurs during switch-on of common injection lasers.[8] These critical and noncritical delays are also revealed in voltage measurements on the absorber section as will be discussed below.

(ii) The carrier lifetime in the gain section is that of a forward-biased diode which is of the order of a few nanoseconds, while that in the absorber section is in the tens of nanoseconds due to the very low carrier densities when the device is in the low state. The determining time constant in the switching is, unfortunately, the long one. Experimentally, the switching delay ranges from about a hundred nanoseconds with fair overdrives, to several microseconds at very small overdrives. Figure 3 shows multiple traces of the switching behavior for several drive currents (labelled i_1). The lowest trace of i_1 is very close to the threshold for switching and the corresponding critical slowing down in the light

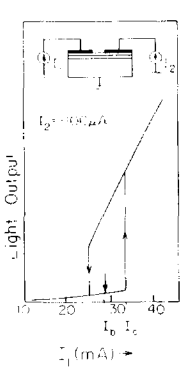

FIG. 1. Measured hysteresis of the light vs current characteristic of a bistable injection laser. I_b is the dc bias point in the switching experiments and I_c is where the transition occurs.

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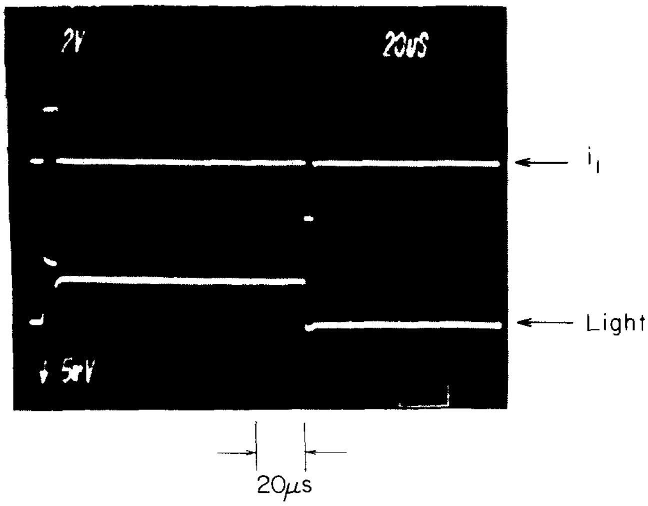

FIG. 2. Switching of a bistable injection laser. Upper trace: switching current (i_1) applied to the gain section, with dc bias at the middle of the hysteresis loop; lower trace: light output. Hor.: 20 μs/div.

ouput is evident. In our experiment, where the bias current (I_b) is 3.5 mA below the switching value, the delay can be reduced drastically to below 20 ns when the switching current pulse is increased to about 9 mA.

(iii) To observe the inherent switching behavior, the external parasitic capacitances at the absorbing section must be reduced to a minimum. In our experiments, the diode was isolated from the capacitances at the current source (and cables) by placing a 250-kΩ resistor as close to the diode as possible. In this way the capacitance was reduced to a measured 6.5 pF (intrinsic capacitance of the diode plus parasitic) in the low state and 20 pF in the high state, while the measured series resistance across the absorber section was, respectively, 50 and 1 kΩ. These numbers lead to RC time constants of $\approx$300 ns in the low state and $\approx$20 ns in the high state, consistent with, respectively, the delay and switch-on times of Fig. 3.

Considerable insight can be gained into the switching dynamics by probing the voltages across the gain and absorber sections, thus in effect probing the carrier densities. These voltages are related to the Fermi levels in the sections and thus to the carrier densities. Probing the voltage across the gain section, however, does not reveal much because any

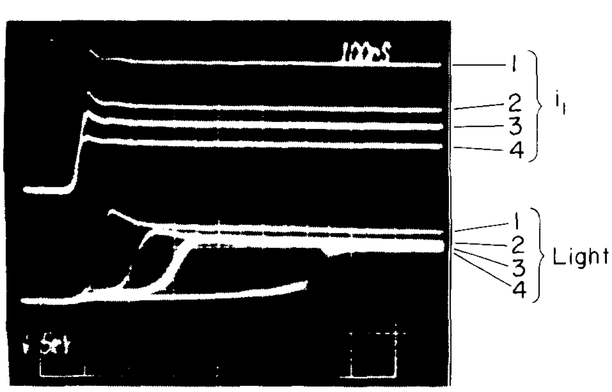

FIG. 3. Slow down during switch-on. Light output for four different amplitudes of switching current i_1. Hor.: 100 ns/div.

change in the carrier density is masked by the voltage produced by the series resistance. Probing the voltage across the absorbing section (V_2), gives very interesting results, as shown in Fig. 4. The upper traces show the change in V_2 after a switch-on current is applied to the *gain* section, for five different values of current amplitudes (the device is initially in the low state). It can be seen that the voltage initially rises slowly, with a time constant of 500–700 ns, signifying that the carrier density is building up in response to the absorption of increased spontaneous emission from the gain section. Lasing occurs when V_2 reaches a certain level (0.8 V) in this case), the device switches to the high state and V_2 jumps to 1.4 V, which corresponds to the carrier density at transparency—the absorber is bleached in the lasing state. It clearly shows that, as the switching current is reduced to near the threshold value (as in traces numbered 5 in Fig. 4) V_2 actually "creeps" toward the level required for switching, i.e., critical slowing down. Notice, however, that the overall response time in Fig. 4 is longer than that in Fig. 3, due to the excess capacitance introduced by the very probe that detects the signal.

Such delays or slowing down observed above are in fact commonplace in almost every bistable system including electronic schmidt triggers and pure optical systems.[9] Theories predicting the occurrence of optical slowing down[10] are probably special cases of a universal process that can be visualized from the following heuristic argument. The steady-state solutions to most bistable systems take the form of an S curve as shown in Fig. 5, whence it can be shown that the middle of the S curve (dotted) is unstable. A small signal dynamic analysis along the dotted curve must exhibit at least one pole in the right-half complex frequency plane. In the remainder of the S curve the poles must fall in the left-half complex plane. In going through the transition point (A) a pole must be passing from the left to the right half-plane and therefore must fall on the origin at point A, provided that the system is oscillation-free. A pole at the origin means an infinite response time to a perturbation, and produces what is

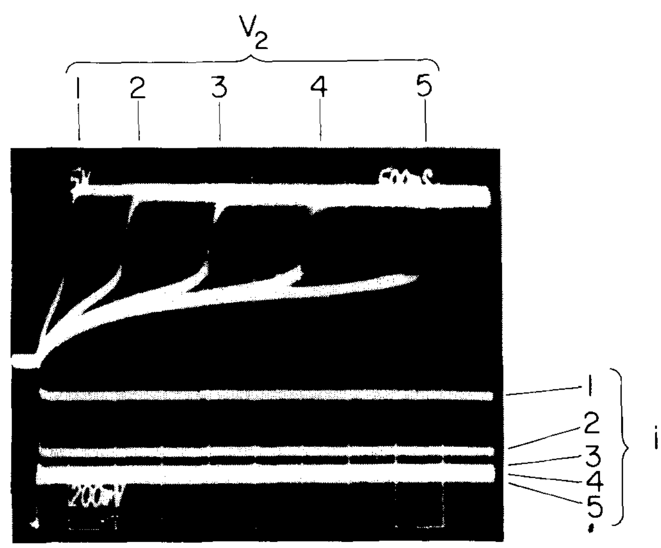

FIG. 4. Voltage change on the absorber section (V_2), during switch-on, for five different values of input current (i_1) amplitudes. The five different traces of V_2 are marked at their points of switch-on. Hor.: 500 ns/div.

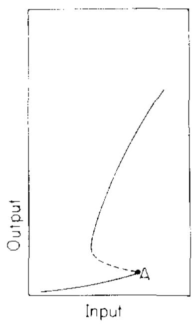

FIG. 5. Typical calculated steady-state solution of a bistable system. Dotted part of curve is unstable.

called critical slowing down. In our special case of a segmented-contact injection laser, a small signal analysis of three rate equations (one for the gain section, one for the absorber, and the third for the photons) reveals the pole behavior described. The details of the analysis will be given separately.

While the switch-on characteristics show various interesting effects, the switch-off is usually fast without any delay. This arises from the fact that the switch-off process involves stimulated recombination of carriers at high densities which is extremely fast.

In conclusion, switch-on delays are shown to exhibit a critical part and noncritical part, both of which can be reduced by increasing the overdrive. It is possible to obtain fairly fast switching time (< 20 ns) with strong overdrives (more than three times the threshold switching current amplitude). Nominal delays of 100–200 ns results under moderate overdrives. These long time constants are associated with the long carrier lifetimes (or equivalently the RC time constant) in the absorber section, a property intrinsic to these bistable lasers.

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[1]G. J. Lasher, Solid State Electron 7, 707 (1964).
[2]T. P. Lee and H. R. Roldan, IEEE J. Quantum Electron. **QE-6**, 339 (1970).
[3]H. Ito, N. Onodera, K. Gen-Ei, and H. Inaba, Electron. Lett. **17**, 16 (1981).
[4]H. Kawaguchi and G. Iwane, Electron. Lett. **17**, 167 (1981).
[5]J. K. Carney and C. G. Fonstad, Appl. Phys. Lett. **38**, 303 (1981).
[6]Ch. Harder, K. Y. Lau, and A. Yariv, presented at the 3rd International Conf. on Integrated Optics and Optical Fiber Tech., paper TuM6, San Francisco April 1981; Appl. Phys. Lett. **39**, 382 (1981).
[7]The laser we used to obtain the very large hysteresis was identical to that in Ref. 6, except that the resistance between the two contacts has been increased to 60 kΩ; Appl. Phys. Lett. **40**, 124 (1982).
[8]H. Kressel and J. K. Butler, *Semiconductor Lasers and Heterojunction LEDs* (Academic, New York, 1977), p. 566.
[9]E. Garmire, J. H. Marburger, S. D. Allen, and H. G. Winful, Appl. Phys. Lett. **34**, 374 (1979).
[10]R. Bonafacio and P. Meystre, Optics Commun. **29**, 131 (1979).

Observations of the morphology of laser-induced damage in copper mirrors

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The results of multiple-pulse damage tests on copper mirrors using 1.7-ns CO_2 lasers are reported. The measured reduction in the brightness reflectivity of the mirrors is shown to be correlated to the dramatic appearance of fine scale microstructure on the mirror surface. Scanning electron micrographs of this surface structure are presented and possible explanations of the effects are discussed.

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The interaction of high-power lasers with material surfaces has received considerable attention over the past several years. This interest has been motivated both by the requirement for accurate damage thresholds for optical components to allow realistic designs of laser systems and the desire to understand the damage mechanism in material surfaces to assess the military potential of laser weapons systems. In both cases experiments have emphasized the laser power (or energy) requirements necessary to cause catastrophic failure of the material surface due to melting,[1–3] fracture, or slip plane distortions.[4,5] More recent work by the authors[6,7] has examined the progressive deterioration of metal surfaces when exposed to successive pulses of 10-μm radiation. In that work it was shown that measurable changes in the optical properties of metal mirrors take place when the surface is irradiated by a sequence of short (2 ns) pulses, each pulse of which is below the damage threshold for the material. In this letter, we report the extension of this previous work and present scanning electron micrographs taken of Cu surfaces exposed to pulses of CO_2 radiation.

Damage threshold measurements were made using a short pulse CO_2 oscillator/amplifier system grating tuned to the 10-P(20) line. A two-stage electrooptical switch provides a reliable 1.7-ns full width at half-maximum (FWHM) Gaussian pulse for the experiment. A schematic of the damage test setup is shown in Fig. 1. The sample under test was placed 10 cm inside the focal point of a 1-m focal length lens where the $1/e^2$ spot radius was 1 mm, as measured with a 32-

