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Optical Switching of Semiconductor Laser Amplifiers

W. F. Sharfin* and M. Dagenais**

GTE Laboratories, Incorporated, 40 Sylvan Road, Waltham, MA 02254, USA

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Abstract. The underlying physics of optical switching in bistable diode-laser amplifiers is reviewed. The importance of minimizing the switching energy of optical bistable devices is emphasized. It is shown that conventional diode-laser amplifiers are switched with only thousands of photons in less than a nanosecond. Recent developments in single quantum-well lasers allow switching with total energy (including electronic) less than a picojoule.

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The purpose of the present paper is to review the underlying physics of optical switching in diode-laser amplifiers. The motivation for using active devices, rather than the more familiar passive bistable devices is discussed. Minimization of the switching energy and total power dissipation is emphasized. Simple arguments which provide physical insight are favored over a more formal treatment, while references are provided for the latter. Means for improving present device performance are also proposed.

Although bistable diode lasers and amplifiers have only emerged as an active subject of research since about 1981, many review articles have already been written. Adams [1] has reviewed the physics and applications of bistable amplifiers. Kawaguchi, who has studied both bistable lasers with saturable absorbing regions and optically-switched bistable amplifiers, has provided a detailed review [2] of research in both types of devices. Sharfin and Dagenais [3] have discussed bistable amplifiers in the context of optical signal processing. Recently an entire journal issue [4] was devoted to bistable diode lasers and amplifiers.

1. Low Energy Optical Switching

The realization of optical switching requires that some optical property (e.g., absorption or refractive index) of the switching medium be altered by the presence of an optical field. Whether the transmission of the device is altered directly by absorption saturation or by a refractive index change, as in an interferometric device, the transmission ratio between the high (on) and low (off) states of the switch in a typical practical device will be a function of the optical path length of the device. For example, in an optically gated Mach-Zehnder interferometer an optically induced phase shift $\Delta\phi$ is accumulated over a distance L in one arm relative to the other as a result of an intensity-dependent refractive index change $\Delta n(I)$ in the transmission medium

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta n(I)L. \qquad (1)$$

A similar process occurs in a bistable Fabry-Perot etalon in which the transmission T is given by

$$T = \frac{I_{\text{out}}}{I_{\text{in}}} = \frac{T_{\text{res}}}{1+(2/\pi)^2F^2\sin^2\phi}, \qquad (2)$$

where ϕ is the single-pass phase shift in a cavity of length L such that $\phi=\phi_0+\Delta\phi$. F is the finesse of the cavity, and I_{out} and I_{in} are the output and input intensities, respectively. T_{res} is the resonant transmission, which for an amplifier is greater than unity. If the input signal is frequency-detuned from the Fabry-Perot resonance, an increase in the input intensity will either raise or lower the transmission by shifting the position of the resonance according to the sign and magnitude of $\Delta n(I)$. If the transmission increases, then

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* Presently at MIT Lincoln Laboratory, Post Office Box 73, Lexington, MA 02173, USA

** Presently at Department of Electrical Engineering, University of Maryland, College Park, MD 20742, USA

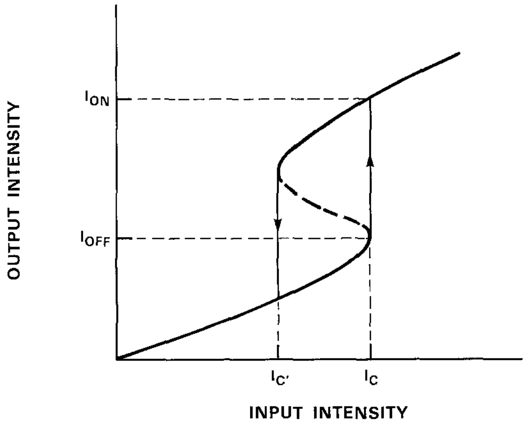

Fig. 1. Transmission curve for a model optical bistable device. The dashed curve is dynamically unstable over the bistable region $I_{c'} - I_c$ so that the transmission of a real device (Fig. 2) switches from one branch to another at input intensities I_c (on) and $I_{c'}$ (off)

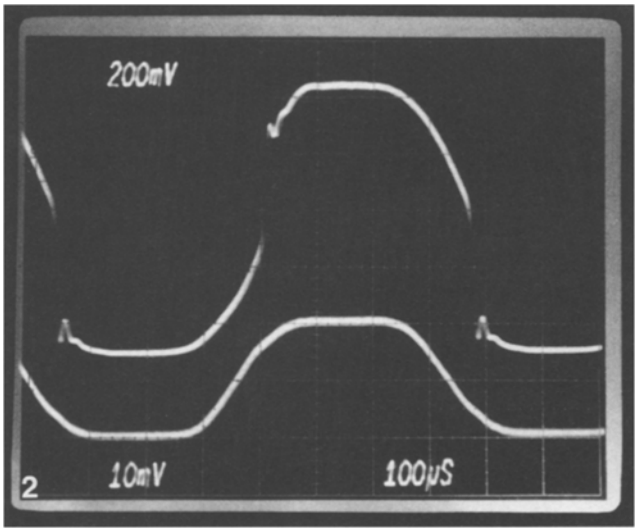

Fig. 2. Oscilloscope trace showing the input (lower trace) and output (upper trace) of a real bistable amplifier

positive feedback occurs, progressively coupling more light into the cavity as the resonant frequency approaches the source frequency. When the device switches on the cavity resonance overshoots the source frequency. Additional increase in the input intensity shifts the resonance away from the source frequency, thereby stabilizing the output intensity through negative feedback. Energy stored in the cavity causes hysteresis. The resultant transmission curve is shown in Fig. 1 for a specific initial detuning. The device is called bistable because two stable output states are associated with one input. Figure 2 shows the optical input and switched output pulse of an actual device.

If optical bistable devices are to enjoy wide-spread applicability, switching energies must be reduced. The importance of low switching energy derives from the thermal limitations on speed and packing density faced by all switching technologies [5]. Two types of problems – steady-state and transient heating – may be identified as undesirable consequences of high power dissipation. The first is associated with high average power consumption and occurs if each switch requires large cw optical bias or dc electronic bias power. The amount of heat that can safely be generated by closely-packed devices is dependent on how efficiently it can be removed to avoid dangerously high temperatures. The heat extraction rate is proportional to the surface area in contact with a heat sink. Secondly, the material properties which are altered in switching are invariably functions of temperature as well as light intensity. Transient temperature fluctuations associated with high (optical) switching energy will cause noise and crosstalk between neighboring switches. Thermal limitations to packing density indirectly affect the processing speed of switching networks through limitations on the signal transit time between devices. For many purposes it is desirable that optical switches be at least as fast as electronic devices. Even where special-purpose optical parallel processors are used in larger optical electronic networks, fast switches will probably be needed for serial interfaces. In highly interconnected networks, gain will also be essential to allow fan-out from one to many devices, and the switching energy per unit gain must be minimized [5].

Switching energy can be lowered by increasing cavity finesse, thereby decreasing the minimum phase shift (π/F) required for switching. The transmitted beam is folded back on itself many times, making the effective path length much larger than the cavity length L. If the source is initially detuned from the cavity resonance by the minimum amount necessary for switching ($\Delta\phi_m \simeq \pi/F$) the ON/OFF transmission ratio of the device is about five. From examination of (1) with the minimum detuning condition, it appears that increasing F and L enables switching with smaller Δn. The switching power would thus be reduced if the focusing geometry remained unchanged. However, to maintain finesse F in a plane-parallel mirror, unguided Fabry-Perot cavity the conditior $F \times L \simeq z_0$ must be satisfied to avoid diffraction losses. z_0 is the Rayleigh length of the input laser beam, which for a Gaussian beam with waist size w_0 (spot radius) and wavelength λ is given by $z_0 = \pi w_0^2/\lambda$. It is assumed that the etalon is placed so that the beam is focused just behind the front mirror (Fig. 3) and that outside the cavity the refractive index is unity. When w_0 is fixed, F and L cannot both be increased. If the cavity medium also has an unsaturable loss mechanism, increasing the cavity length will increase the insertion loss of the device.

The constraints imposed by diffraction and absorption losses are removed by using a guided-wave optical

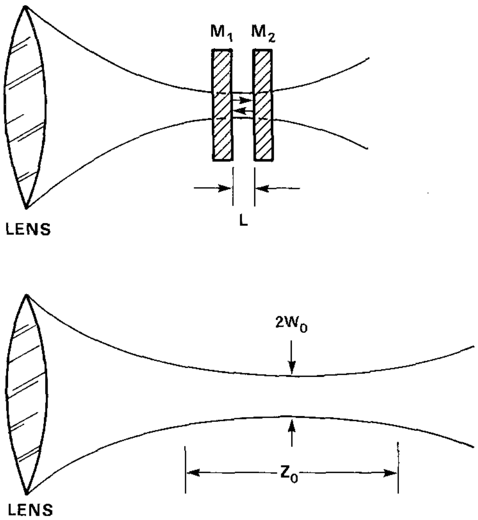

Fig. 3. Illustration of the focusing geometry used for obtaining maximum finesse in a plane-parallel mirror etalon, and showing the beam waist w_0 and Rayleigh length z_0 in the lower figure. A bistable device is made with a transparent nonlinear material between mirrors M_1 and M_2

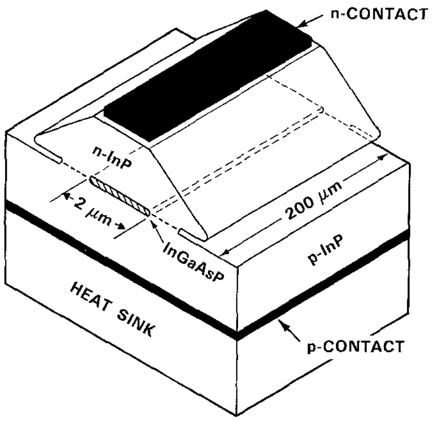

Fig. 4. Schematic illustration of a buried heterostructure diode laser. The active region (waveguide) is shown in cross-section (shaded area). The end face of the waveguide has about 30% reflectivity

amplifier. The finesse of a resonant cavity amplifier is given by

$$F=\frac{\pi(R\exp[(\Gamma g_m-\alpha)L])^{1/2}}{1-R\exp[(\Gamma g_m-\alpha)L]}\,, \tag{3}$$

where Γ is the optical confinement factor. It is the fraction of the waveguide mode volume that is confined to the active region. g_m is the gain and α is the loss per unit length of the active region. Equation (3) neglects noise, thus giving the unrealistic result that the finesse becomes infinite at threshold (when the denominator vanishes). A real diode laser amplifier with a small-signal optical gain of about 20 dB has a finesse about 30 [6]. $F<10$ is typical for an absorptive semiconductor device with a cavity length less than 10 µm [7]. Conventional semiconductor injection lasers (Fig. 4) are operated as bistable optical switches when dc biased at 95–97% of their threshold injection current. The cavity of one of these lasers consists of a waveguide active region a few microns wide, 0.2 µm thick, and about 200 µm long. The mirrors formed at each end of the cavity by cleaving the semiconductor crystal have a Fresnel reflectivity of 0.3. When operated as a high gain (10–20 dB) switch [6], such a device is turned on with an input signal of only thousands of photons (femtojoules) [8]. A typical diode laser amplifier with a 20 mA threshold current and 0.5 ns switching time requires a total switching energy of

$$2\,\mathrm{V}\times 2\times 10^{-2}\,\mathrm{A}\times 0.5\times 10^{-9}\,\mathrm{s}=2\times 10^{-11}\,\mathrm{J}\,.$$

2. Physics of Optically Switched Diode Laser Amplifiers

2.1. *Mechanism of Refractive-Index Change*

An experimental setup for observation of optical switching is shown in Fig. 5. The first demonstration of bistable operation of a GaAs/GaAlAs laser amplifier was reported by Nakai et al. [9] in 1983. Ito and colleagues identified the switching mechanism as associated with the carrier-dependent refractive index but no detailed measurements of the switching power or speed were reported. Otsuka and Kobayashi [10] observed switching at constant optical input power as a function of the detuning of the source from the amplifier resonance. Kawaguchi [11] reported optical switching of a laser with a bistable output power/input current relationship. This early work (especially that of Ito and Otsuka) on optically switched laser amplifiers was influenced by work on the effects of the carrier-

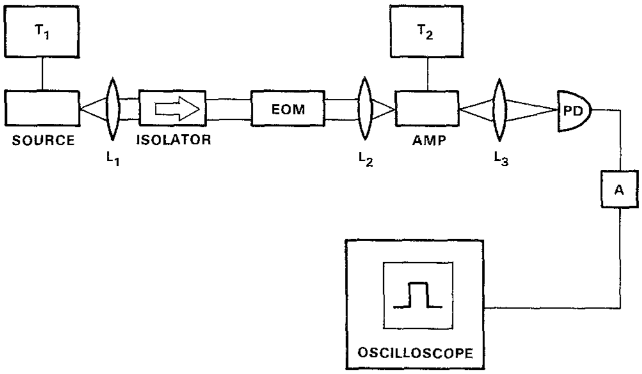

Fig. 5. Schematic diagram of laboratory experiment for observing optical switching in a diode laser amplifier (AMP). The source is a single-mode diode laser. T_1 and T_2 are temperature controllers, EOM is an electro-optic modulator, L_1, L_2, and L_3 are lenses, PD is a photodiode, and A is an electronic amplifier

dependent refractive index on the asymmetry in the locking frequency band associated with injection locking diode lasers [12,13]. The dependence of the refractive index of the diode's active region on its carrier density, results in an intensity-dependent refractive-index change $\Delta n(I)$ usually associated with optical bistability. The connection between the carrier and intensity dependence of n was discussed in detail by Adams and will be briefly summarized here later. The primary physical mechanism for the intensity dependence of the refractive index in diode laser amplifiers is the Burstein-Moss shift of the absorption/gain spectrum. As revealed in absorption measurements, this effect is often called band filling. When carriers are produced by absorption of light in a semiconductor in thermal equilibrium low energy states in the conduction band are populated, leaving only higher-energy states vacant for subsequent excitation. The absorption spectrum shifts to shorter wavelengths. A corresponding change in the dispersion curve of the refractive index occurs which may be calculated from the Kramers-Kronig transform. For small changes in carrier density ΔN at a specific wavelength, the resultant change in refractive index Δn may be computed from the first derivative dn/dN. At energies approaching the band edge where lasing occurs and at carrier densities near the lasing threshold ($\sim 10^{18}$ cm^{-3}) this derivative is negative and of order 10^{-20} cm^3 for GaAs and InGaAsP lasers. In the literature on diode lasers, the linewidth enhancement factor b is more commonly quoted than the change of refractive index with carrier density. The relationship between the two numbers is indicated by the following equation

$$b=\frac{-4\pi}{\lambda}\frac{dn}{dN}\bigg/\frac{dg_m}{dN}=\frac{\mathrm{Re}\{\Delta n\}}{\mathrm{Im}\{\Delta n\}}, \tag{4}$$

where g_m is the gain per unit length of the active region, and $\mathrm{Re}\{\Delta n\}$ and $\mathrm{Im}\{\Delta n\}$ are the real and imaginary changes in the index of refraction. dg_m/dN is often called the differential gain. At threshold carrier density and at the lasing wavelength b is about 3–6 in GaAs and InGaAsP lasers. It tends to be higher in the latter material and is also weakly dependent on the laser structure. The linewidth-enhancement factor appears in the first steady-state theoretical description of optical bistability in diode-laser amplifiers by Otsuka and Iwamura [14]. When a near-resonant, single-frequency optical-input signal is injected into a Fabry-Perot amplifier it causes stimulated carrier recombination, lowering the carrier density and thereby increasing the refractive index of the active region. The single pass phase ϕ of the amplifier may be written

$$\phi=\phi_0+\frac{b}{2}g_0L\frac{I_{\mathrm{out}}}{I^s_{\mathrm{out}}}(1+I_{\mathrm{out}}/I^s_{\mathrm{out}})^{-1}. \tag{5}$$

g_0 is the unsaturated gain coefficient and I^s_{out} is the output intensity of the amplifier at saturation. Equation (2) is then rewritten

$$\frac{I_{\mathrm{out}}}{I_{\mathrm{in}}}=\frac{G_s(1-R)^2}{(1-RG_s)^2+4RG_s\sin^2\phi}, \tag{6}$$

where $G_s=\exp[(\Gamma g_m-\alpha)L]$ and $g_m=g_0/(1+I_{\mathrm{out}}/I^s_{\mathrm{out}})$ and g_0 is the small-signal gain coefficient.

Adams et al. [15] have compared active and passive bistability in semiconductors. Their analysis indicates that it is more correct to replace the ratio $(I_{\mathrm{out}}/I^s_{\mathrm{out}})$ in the previous expressions with I_{av}/I_s, where I_{av} is the spatially averaged intracavity intensity and I_s is a saturation intensity given by

$$I_s=\frac{h\nu}{\Gamma(dg_m/dN)\tau_s}, \tag{7}$$

where $h\nu$ is the band-gap energy and τ_s is the spontaneous carrier lifetime. The decay rate is assumed to be a linear function of carrier density. Equation (5) may be rewritten in the simpler form

$$\phi=\phi_0+\frac{2\pi}{\lambda}\frac{dn}{dN}\Delta NL, \tag{8}$$

where ϕ_0 is again the phase in the absence of an optical input signal and ΔN is the change in carrier concentration due to the presence of the optical signal.

2.2. *Switching Dynamics*

Detailed studies of optical switching of InGaAsP/InP laser amplifiers were performed by American and British groups following the initial Japanese work. Sharfin and Dagenais [6], and Adams et al. [16] showed that only a few microwatts of optical power – a factor of 10^3 less than in absorptive devices – is required to switch diode laser amplifiers. There is an additional factor of ten improvement in switching time over passive devices because the carrier lifetime is shorter ($\sim$2 ns) at the higher carrier densities that exist in amplifiers. The switching dynamics was first modeled by Adams [17] and later, somewhat differently, by Sharfin and Dagenais [18]. Sharfin and Dagenais reported subnanosecond switching times [8] and the British Telecom group measured [19] the maximum modulation frequency of these nonlinear amplifiers.

Adam's analysis of the switching dynamics employs an adiabatic approximation in which it is assumed that the cavity field adjusts instantaneously to changes in the carrier density. The field in the cavity is described by the steady-state equations of the type (2) and (6) because the cavity round trip time τ_p (picoseconds) is very short compared to the carrier lifetime (nanosec-

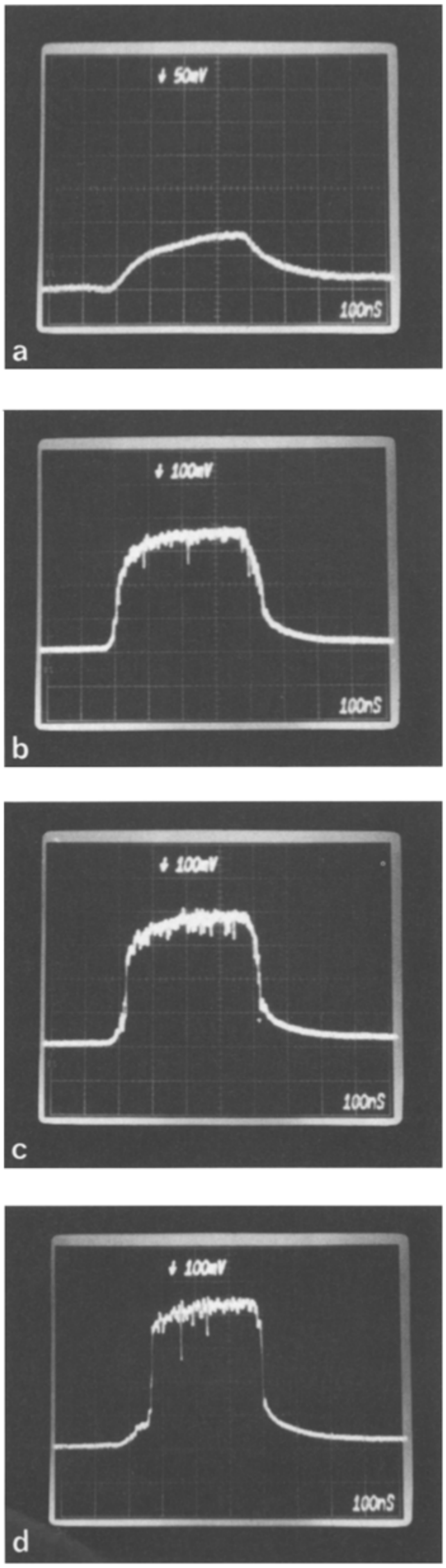

Fig. 6. (a) Optical input pulse to bistable laser amplifier. (b–d) Optical output pulses showing fast switching at various initial detunings ranging from about two Fabry-Perot linewidths ($-2\pi/F$) in (a) to about four linewidths in (d)

onds). This is generally a good approximation which becomes worse only very near threshold where the finesse may become large enough so that the condition $F\tau_p \ll \tau_s$ is no longer satisfied (i.e., the cavity lifetime approaches the carrier lifetime). Adams then shows that the time dependence of the phase ϕ is found from the expression

$$\frac{d\phi}{dt}=\tau_s^{-1}\left[(\phi_0-\phi)\left(1+\frac{I_{av}}{I_s}\right)+g_0L\frac{b}{2}\frac{I_{av}}{I_s}\right]. \qquad (9)$$

It is easily seen that if the bistable amplifier is operated as an optical gate [20] and the switching beam is instantaneously turned off so that I_{av}/I_s becomes small, the dynamics of the phase recovery are governed by the carrier lifetime τ_s. The recycling time of the switch is thus limited by τ_s. Equivalently, it can be said that the maximum modulation frequency at which the device can be repetitively switched is that at which the rise and fall time of the modulating signal is equal to the carrier lifetime. It should be noted that the switch-off time (decay of the cavity transmission) is more often quoted for bistable devices, rather than the modulation rate. The cavity transmission T is related to ϕ through (6). As the cavity finesse is increased (i.e., increase in the injection current) the magnitude of $dT/d\phi$ increases at frequencies near resonance. This causes a slight decrease of the switch-off time with increasing injection current within the regime of validity of the adiabatic approximation. Under these conditions the switch-off time actually decreases as the cavity lifetime increases [18]. Figure 6 shows the input and switched output pulses from a bistable laser amplifier biased at about 97% of lasing threshold current. The output in (*d*) switches off in less than a nanosecond, as determined from other measurements with better temporal resolution [21].

Switch-on time is limited by the cavity lifetime at high pulse energies where critical slowing down [22] does not occur. If a short optical triggering pulse is applied to the amplifier with a pulse energy well above the switching energy and a duration longer than the cavity lifetime, but shorter than the carrier lifetime, the switch-on time will be comparable to the pulse duration. The refractive-index change produced (change in carrier density) will follow the integral of the pulse. It is thus more meaningful in comparing the speed of different bistable devices to quote the device recycling rate or switch-off time, rather than the switch-on time.

3. Prospects for Lower Energy or Higher Speed

We have seen that the optical switching energy of bistable diode laser amplifiers formed of unmodified laser devices is about 10^4 times smaller than that of typical passive (all-optical) devides. As this energy corresponds to only thousands of photons, it is within approximately an order of magnitude of the photon shot noise limit for useful optical switching. If the optical switching energy were reduced by more than this amount, shot noise would cause intolerable errors in the distinction between on and off signal levels. The total switching energy of the amplifiers that have been studied is about 10^4 times greater than their optical switching energy. Therefore when the consumption of electrical power is considered, conventional active devices have similar total energy requirements to passive devices. However, there are a number of advantages associated with active devices. Their high gain is obtained by electrical pumping, which eliminates the severe difficulties (especially when dealing with a guided-wave device) of employing an additional beam in order to optically bias the device near I_c (Fig. 1) to obtain gain. Even if high gain is not required, thermal transients resulting from the switching beam will then pose a much less severe problem in the active device. It is possible that the optical switching power may be lowered by a small amount by optimization of the mirror reflectivity, but more significant improvements would involve a reduction of the dc bias power, and an improvement in speed (where required). Until recently, optimization of even linear laser amplifiers has received little attention. Interest in coherent communications has revived interest in linear amplifiers. A recent paper [23] on nonresonant linear amplifiers indicated that the optical saturation power could be increased by decreasing the carrier lifetime through a decrease in the active layer thickness. This results in an increase in injected carrier density at the same current density. Until this point we have considered the spontaneous carrier decay rate to be a linear function of carrier density N with proportionality constant τ_s^{-1}. This is a reasonable approximation for describing the switching dynamics of the nonlinear amplifier, because in the usual case of interest the carrier density varies by no more than a few percent during switching. As the carrier density is changed by large amounts the importance of higher order decay terms (i.e., $\propto N^2$, N^3) become more significant. The rate equation for the carrier density N may be written

$$\frac{dN}{dt}=\frac{j}{ed}-R(N)-\frac{\Gamma g_m}{h\nu}I_{av}, \tag{10}$$

where j is the injected current density, e is the charge of an electron, d is the active layer thickness, and the recombination rate $R(N)$ is simply $R(N)=A+BN+CN^2+DN^3$ with $A,B,C,D\geqq 0$. If the concentration dependence of the decay rate is incorporated into the lifetime $\tau_s(N)$ such that $N/\tau_s(N)=R(N)$ then higher injected carrier densities resulting from a decrease in d are easily seen to result in smaller $\tau_s(N)$. Then from (9), the switching speed will increase at the expense of higher I_s. Thus in applications in which switching speed is critical, greater speed can be obtained at the expense of higher switching power.

Perhaps a more intriguing result is the recent demonstration [24] that the threshold bias current of single-quantum-well GaAs/GaAlAs lasers is already a factor of twenty lower than typical levels for lasers made from bulk materials. An ultimate reduction by 10^2 is expected. Bistable amplifiers made from these materials can have total switching energies a hundred times less than present passive devices.

The thickness of the active region in a single-quantum-well (SQW) laser is just the thickness of the well, or about 10 nm. By comparison the thickness of the active region in a typical double heterostructure (DH) laser is about 200 nm. Even though the carrier density required for transparency (gain coefficient equal to zero) is approximately the same, the current density at transparency is much smaller for the SQW laser because of smaller d, see (10). The optical confinement factor Γ is also much smaller in the SQW laser because the waveguide mode volume is much larger than the volume of the thin active region. Thus the losses in the active region are small and the contributions to the threshold current associated with the transparency current and the active region losses are both much smaller than in the double heterostructure laser. Hence the mirror losses dominate in the SQW laser so that the threshold can be lowered substantially by applying high reflectivity coatings to the laser facets. This was the approach used by Derry et al. [24] to achieve the low (< 1 mA) threshold currents in their quantum well lasers.

4. Conclusions

We have shown that active guided-wave Fabry-Perot devices offer several advantages for low-energy optical switching deriving from their high gain (10–100) and high finesse (10–100). Conventional laser devices require only femtojoules of optical switching energy and picojoules of electrical energy. Using recently developed SQW diode lasers the total switching energy can be reduced below a picojoule.

Present devices switch-off in less than a nanosecond and may be recycled in a few nanoseconds. Their speed may be increased by small amounts (e.g., to greater than a GHz modulation rate) by decreasing the carrier recombination time, at the expense of an increase in switching power. The very low switching energy, well-developed technology and compatibility with existing optoelectronic technologies make bistable laser amplifiers promising candidates for use in nonlinear optical processors of the future.

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