

Saturable absorption in intracavity loss modulated quantum well lasers

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Voltage, temperature, and intensity dependence of saturable absorption in InGaAs/InP multiple quantum wells are investigated and related to the lasing characteristics of intracavity loss modulated InGaAs/InP quantum well lasers. Bistability in the static laser light output/absorber voltage characteristic arises from the shape of the measured absorption/voltage/intensity surface of the quantum well absorber. This surface is little changed in the temperature range 0–100 °C. A consequence of this fact is that an intracavity absorber modulates laser threshold more efficiently at higher substrate temperatures.

The static and dynamic behavior of a quantum well semiconductor laser can be efficiently controlled using a small saturable intracavity absorber.^{1,2} The highly nonlinear light output characteristics of these voltage-controlled lasers are determined by the dependence of optical absorption (α) on applied modulator voltage (V_S) and on photon flux (I). In this letter we determine the relevant (α, V_S, I) surface for light of wavelength $\lambda = 1.51 \mu\text{m}$. We also relate these measurements to the observed characteristics of intracavity loss modulated InGaAs/InP quantum well lasers.

The absorption modulators investigated were *pin* graded index multiple (10) quantum well InGaAs/InP photodiodes grown at atmospheric pressure on InP substrates by metalorganic vapor phase epitaxy (MOVPE). The well and barrier thicknesses were 8 and 22 nm, respectively. Following crystal growth, diodes were produced by etching a photolithographically defined mesa structure on the sample. Metal contacts, applied to the top of the mesa and the substrate, allow application of an electric field across the wells, while a 20 μm aperture in the top contact allows their illumination. Initially, absorption in these structures was characterized as a function of V_S , λ , and I . A schematic of the experimental arrangement is shown in Fig. 1. The dependence of α on V_S at $\lambda = 1.51 \mu\text{m}$ has two distinct regimes [Fig. 2(a)]. As V_S is increased from -8.0 V, α gradually increases maximizing when $V_S \approx +0.2$ V. The absorption rapidly decreases with further increase of bias to $V_S \approx +0.7$ V. From the wavelength dependence of photocurrent measurements, Fig. 2(b), we attribute the decrease in α with increasing reverse bias (i.e., increasing electric field) to a decrease in electron hole pair oscillator strength.³ We attribute the rapid decrease of α as V_S is increased from $+0.2$ to 0.6 V, to phase space filling (saturation) of the quantum wells.

The intensity dependence of absorption in the quantum wells was measured by illuminating the modulator with a high-power laser diode emitting at $\lambda = 1.51 \mu\text{m}$. Due to the small variation in transmission with V_S (from the short interaction length of light passing through the quantum wells) difference absorption as a function of V_S , was measured for each incident intensity. Subsequently calibration with respect to intensity dependent absorption at $V_S = 0.0$ V yields the surface shown in Fig. 3. The surface shows absorption saturation and, at an applied voltage of

$V_S = 0.0$ V, when fitted to the commonly used phenomenological form $\alpha = \alpha_0 / (1 + I/I_S)$, gave a saturation intensity, I_S , of $\sim 17 \text{ kW cm}^{-2}$.

This absorption surface determines static and dynamic behavior of intracavity loss modulated InGaAs/InP quantum well lasers [shown as the inset of Fig. 4(a)]. The laser structures used have four quantum well active regions, with well and barrier widths of 9 and 22 nm, respectively (see Ref. 4 for fabrication details). For a fixed value of gain section current, I_G , the laser output is controlled by voltage, V_S , applied to the small absorber section. In Fig. 4(a) we show, for two values of substrate temperature ($T = 8^\circ\text{C}$ and $T = 37^\circ\text{C}$), typical light-output of such a Fabry-Pérot laser when $I_G = 37 \text{ mA}$ and V_S is swept over the range $-0.2 \text{ V} \leq V_S \leq +0.4 \text{ V}$. The characteristics display hysteresis, whose origin is apparent from inspection of Fig. 3. As V_S is increased from ~ -0.2 V [A' in Figs. 3 and 4(a)], the change in α with applied voltage is small until, at $V_S = +0.2$ V (A), α decreases rapidly with applied voltage. In the laser, as the operating point moves through A, the device passes through threshold and stimulated emission causes optical intensity to increase, saturating the absorber giving a large and rapid increase in optical output (A-B). Further increase in V_S , gradually increases intensity, moving the laser operating point to B'.

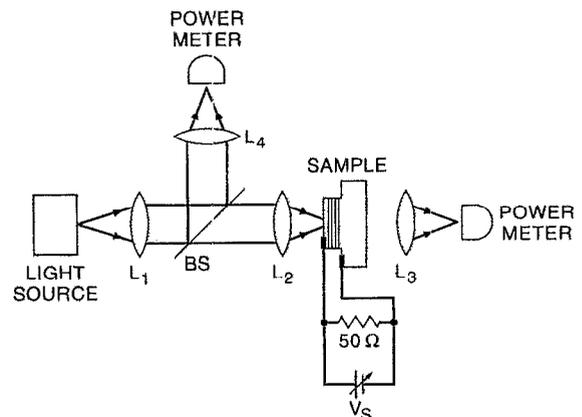


FIG. 1. Experimental arrangement: (L_1 – L_4) microscope objectives, and (BS) beam splitter. The light sources used were a high-power laser diode for intensity-dependent absorption measurements and a lamp and monochromator for wavelength-dependent photocurrent measurements.

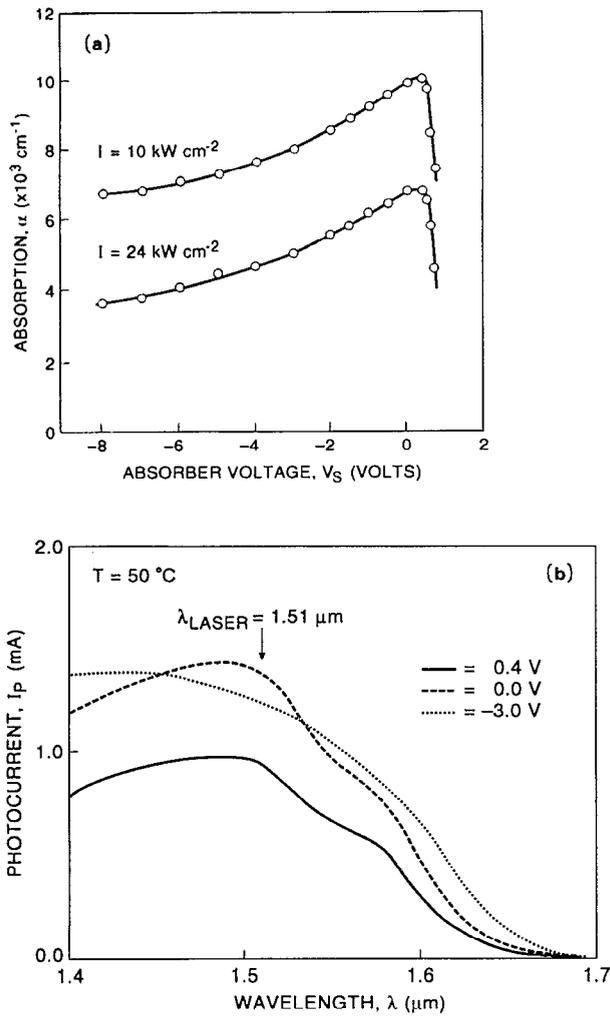


FIG. 2. (a) Measured voltage dependence of modulator absorption at two incident intensities for $\lambda = 1.51 \mu\text{m}$ and $T = 50^\circ\text{C}$. (b) Photocurrent, I_p , under low intensity illumination, plotted against wavelength, λ , for three applied modulator voltages, $V_S = 0.4 \text{ V}$, $V_S = 0.0 \text{ V}$, and $V_S = -3.0 \text{ V}$.

If V_S is now decreased, the light level reduces with increasing reverse bias (due to increasingly efficient photon extraction by the absorber) until at C the laser passes below threshold and abruptly switches off (C-D). The laser approaches its final (initial) state (point A') of the V_S cycle by taking a low intensity α - V_S trajectory. This motion on

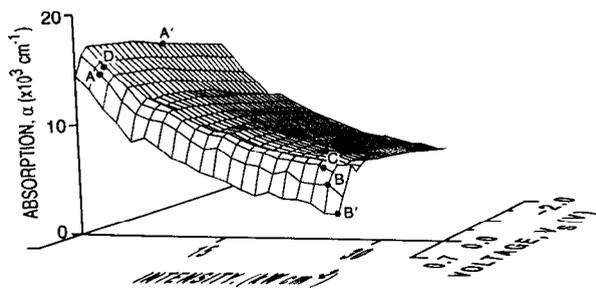


FIG. 3. Measured (α, V_S, I) surface for an InGaAs/InP ten quantum well *pin* photodiode at temperature $T = 50^\circ\text{C}$. V_S is incremented by 0.1 V , I_S by 1.45 kW cm^{-2} . Indicated on the surface are critical points A, B, C, D which explain the bistability of Fig. 4(a).

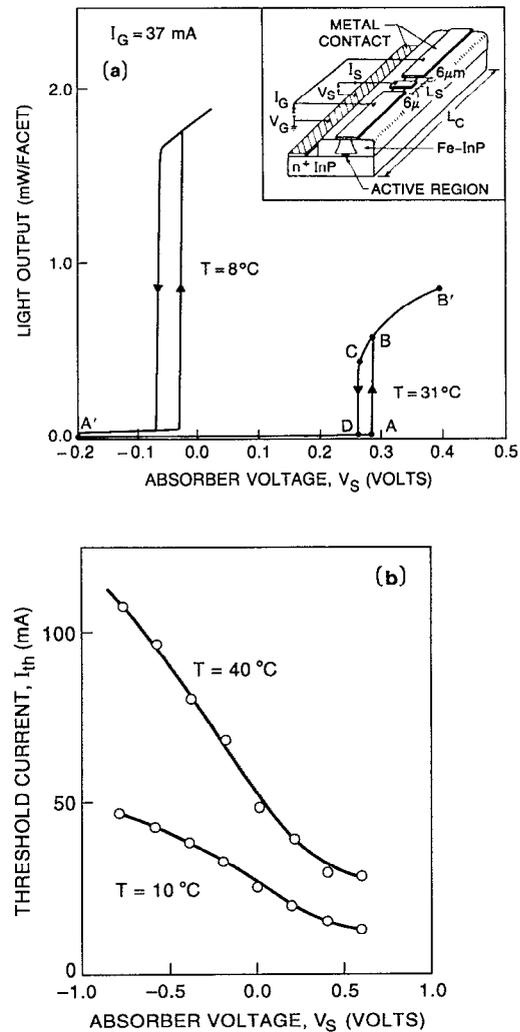


FIG. 4. (a) Measured static light intensity output plotted against absorber voltage V_S at a constant gain section current, $I_G = 37 \text{ mA}$, for an InGaAs/InP MQW intracavity loss modulated laser diode for two values of the substrate temperature, $T = 8^\circ\text{C}$ and $T = 31^\circ\text{C}$. The characteristics display hysteresis due to saturation of the intracavity loss. (b) Pulsed laser threshold current, I_{th} , plotted against absorber voltage V_S for two substrate temperatures, $T = 10^\circ\text{C}$ and $T = 40^\circ\text{C}$.

the (α, V_S, I) surface gives rise to the bistable loop ABCD exhibited in the static light-output versus V_S curve of Fig. 4(a). In passing, we note that these results distinguish the physical origin of hysteresis in our lasers from that of previous work in which bistability resulted from parasitics in laser drive circuitry.⁵

There is some interest in device applications of voltage-controlled lasers and so it is important to understand what role saturable absorption plays in the temperature dependence of the laser operating characteristics. With this in mind, we investigated the temperature dependence of saturable absorption in quantum well structures. Our measurements indicate that, in the range $0^\circ\text{C} < T < 100^\circ\text{C}$, any effect of changes in temperature on the value of saturation intensity are less than our approximately 10% measurement uncertainty. This is confirmed by measurements we have made of the temperature dependence of threshold current of intracavity loss modulated lasers. The variation

in threshold current, $I_{\text{th}}(T)$, with temperature, T , of a semiconductor laser is commonly expressed as $I_{\text{th}}(T) = I_0 \exp(T/T_0)$, where I_0 is a constant.^{6,7} T_0 is a characteristic (phenomenological) temperature whose value is a measure of the temperature sensitivity of threshold current. Although the physics determining T_0 is unclear,⁷ typically, for InGaAs/InP quantum well lasers with uncoated facets, $T_0 \approx 50$ K. From pulsed light/current characteristics taken at different substrate temperatures we have measured T_0 for a number of absorber voltages (V_S) including $V_S = V_G$, i.e., forward bias. The characteristic temperature of our intracavity loss modulated devices ($T_0 \approx 40\text{--}45$ K) is insensitive to V_S although in the vicinity of $V_S = 0.0$ V the measured value of T_0 varies about 10% with V_S . This variation may result from changes in laser threshold carrier number due to modulation of absorption in the loss section by change in V_S .² In Fig. 4(b) we plot pulsed laser threshold against V_S for two values of substrate temperature. As may be seen, modulation of laser threshold by V_S is *more efficient* at elevated substrate temperatures. This significant fact is a consequence of T_0 being mainly related to the laser gain section and essentially independent of the absorber.

In conclusion, we have investigated the voltage, temperature, and intensity dependence of absorption in multi-

ple quantum wells and have related these results to the observed lasing characteristics of intracavity loss modulated quantum well lasers. We have shown that bistability, observed at fixed gain section currents, in the static light output versus V_S characteristic may be explained using an appropriate (α, V_S, I) surface for the quantum well absorber. The temperature insensitivity of this surface relative to the laser gain section results in more efficient voltage-controlled modulation of lasing threshold with increasing substrate temperature.

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