Large-signal picosecond response of InGaAs/InP quantum well lasers with an intracavity loss modulator

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(Received 21 December 1989; accepted for publication 13 February 1990)

Single and multiple quantum well laser diodes operating at 1.5 μm are fabricated incorporating an intracavity electroabsorptive loss modulator. Absorption in the diode laser cavity is modulated by a femtosecond dye laser used to generate picosecond electrical transients. Two types of electrical excitation are provided to the modulator: a pulse, using an integrated PIN photodiode and a step, using an integrated photoconductive switch. The full width at half maximum (FWHM) for 100% laser modulation is 53 ps. Direct excitation of the loss segment resulted in pulse widths of 38 ps FWHM and 100% modulation.

We investigated the high-speed response of InGaAs/InP single and multiple quantum well laser diodes operating at a wavelength $\lambda = 1.5\,\mu$m which incorporate a small intracavity modulator section similar to that shown schematically in Fig. 1(a). This structure has the advantage that small changes in electrical power (30 μW) result in large changes in optical output power (7 mW).[1] It does not suffer from the problems associated with an external cavity and can be driven directly by low-power digital signals—both desirable characteristics for future optoelectronic devices.[2,3]

The operation of the device shown in Fig. 1(a) may be understood by considering how it differs from a conventional Q-switched laser, which relies on gain depletion. As shown in Fig. 1(b), for conventional Q switching, a step function loss is introduced, and the width of the resulting optical pulse is determined by the time required to deplete the gain. For the modified Q switch used here pulse width is determined by the duration of the electrical signal applied to the loss modulator since gain in this case remains essentially constant compared to the duration of the signal applied to the loss modulator (the effect of gain depletion is to decrease pulse width).

In this experiment a colliding-pulse mode-locked (CPM) laser produces optical pulses with a full width half maximum (FWHM) of less than 100 fs. These pulses generate picosecond electrical transients in two different configurations: a PIN photodiode monolithically integrated with a buried-heterostructure graded index separate confinement heterostructure quantum well (BH GRINSCH QW) laser, and a photoconductive switch also integrated into the BH GRINSCH QW laser chip.

InGaAsP crystals were grown on either n-type or semi-insulating Fe-doped <100> oriented InP substrates using atmospheric pressure metalorganic vapor phase epitaxy (MOVPE). The important steps in the growth sequence are the same as those described in Ref. 1. Optical confinement in the laser is provided by wide-band-gap InP cladding layers. The GRINSCH structure is placed either side of the QWs and is made up of four 22-nm-thick step-like undoped quaternary layers lattice matched to InP and with decreasing band gap of 1.0, 1.1, 1.2, and 1.25 μm. A single QW (SQW) consists of a 14-nm-thick ternary layer and MQW samples consist of 9-nm-thick ternary layers cladded by 25-nm-thick InGaAsP layers with a band gap of 1.25 μm. The BH lasers are made by stripe mesa etching using a selective etch to reduce the active region width to about 2 μm, and then regrowing Fe:InP using MOVPE as described in Ref. 4.

Using a geometry shown schematically in Fig. 1(a), photolithographically defined electrical contacts to the p^+ contact layer are then made. The gap between the metal stripes is 6 μm, the length of the small modulation segment is 2 μm $< L_A < 20$ μm, and the isolation resistance between

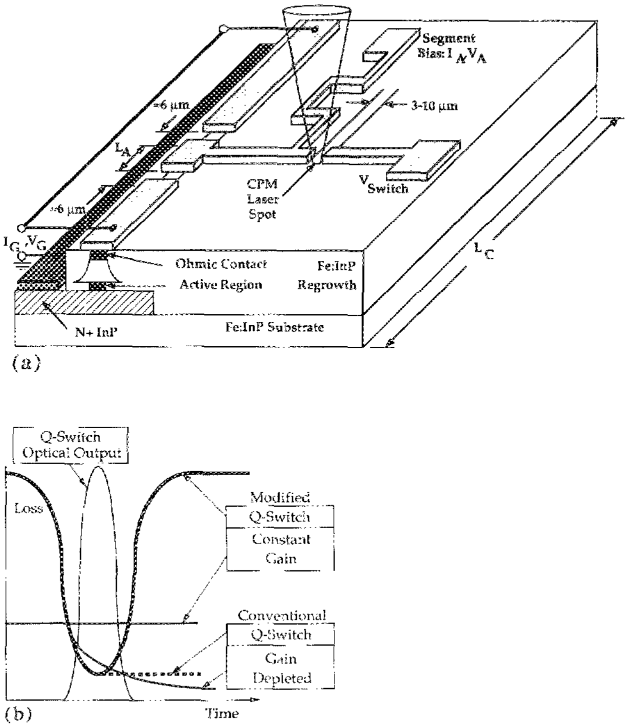

FIG. 1. (a) Schematic view of the laser diode chip for the case of the photoconductive (semi-insulating InP) switch. Metallizations are shaded areas and bold lines indicate electrical connections. The CPM spot was focused onto a 3–10 μm gap using a 10× objective. L_A was typically 6 μm. Voltage bias applied to the absorber is V_A, the bias on the photoconductive switch is $V_{\rm switch}$, and the current in the gain section is I_G. (b) Schematic relationship between gain (constant) and loss (heaviest solid line) for the modified Q switch used in this experiment. A conventional Q switch uses a step change in loss (dashed line) and gain depletion to determine pulse width.

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0003-6951/90/171629-03$02.00

segments is 5–10 kΩ. An inductive meander line is used to provide a dc bias to the high-speed line with minimal signal degradation.[5] The high-speed line is made long enough (100–200 μm) to provide a long reflection-free time window to the loss segment. Mirror facets for the lasers are formed by cleaving and are uncoated. Cavity lengths are in the range $300\,\mu\text{m} < L_C < 600\,\mu\text{m}$ and typical threshold currents with the absorber forward biased are $I_{\text{th}} = 15$–30 mA.

A set of light emission versus gain current curves illustrating the dramatic change in threshold current with absorber bias is shown in Fig. 2. It is also clear from the figure that in the Q-switching regime, a large change in light output intensity can occur for a small change in absorber bias voltage[1] corresponding to saturation of the loss segment.

The same femtosecond CPM laser[6] was used to both generate the electrical transient, and cross correlate the resultant 1.5 μm laser diode pulse. CPM laser pulses are typically 60–80 fs FWHM. Jitter between the two trains of optical pulses is essentially zero.[6] Figure 3 shows the experimental configuration. The second dye laser pulse train is mixed with the 1.5 μm pulse from the laser diode in a nonlinear LiIO_3 mixing crystal cut for normal incidence. To ensure the mixing crystal does not limit the measurement bandwidth its thickness was reduced to 100 μm.

Signal detection is accomplished using a cooled photomultiplier tube and lock-in amplifier.[7] Typical cross correlations are acquired in a single pass of the optical delay rail (signal strengths are so large that averaging is not required). The voltage biases, applied to the photoconductive or PIN switch, are chopped at a lock-in frequency of ≈ 20 kHz. Pulse widths are limited to only a few microseconds due to heating in the uncooled laser diode chip.

By choosing a suitable combination of biases, the laser diode could be made to operate in either the normally-off or normally-on states. The PIN diode is formed by an annealed metal contact (AuBe-Au) to the Fe:InP and n-InP. Thus maximum response is achieved with edge illumination so that the photogenerated carriers are efficiently collected. The electrical transient was launched between the V_{switch} electrode and the n^+ substrate at ground potential. The resultant corss-correlated optical pulse is 53 ps FWHM (uncorrected) and is shown in Fig. 4(a). There was a slight ringing on the tail of some samples which was probably caused by ringing in the electrical signal. Note the asymmetry in the cross correlation due to the asymmetry in the electrical excitation.

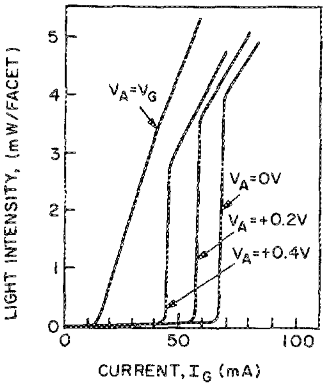

FIG. 2. Typical single facet light emission vs gain current I_G for an InGaAsP BH GRINSCH MQW laser diode for the indicated absorber bias voltages, V_A, cavity length $L_C = 450\,\mu$m, absorber length $L_A = 6\,\mu$m, and lasing wavelength $\lambda = 1.5\,\mu$m.

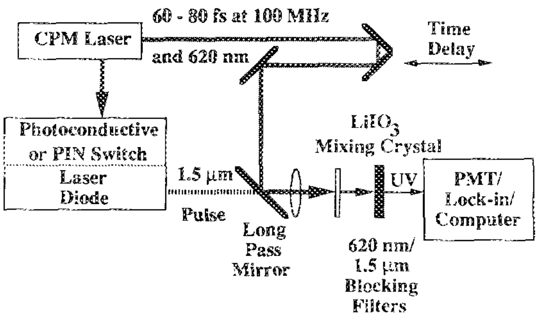

FIG. 3. Experimental configuration showing the CPM laser in standard pump-probe arrangement.

In the case of the photoconductive switch, semi-insulat-

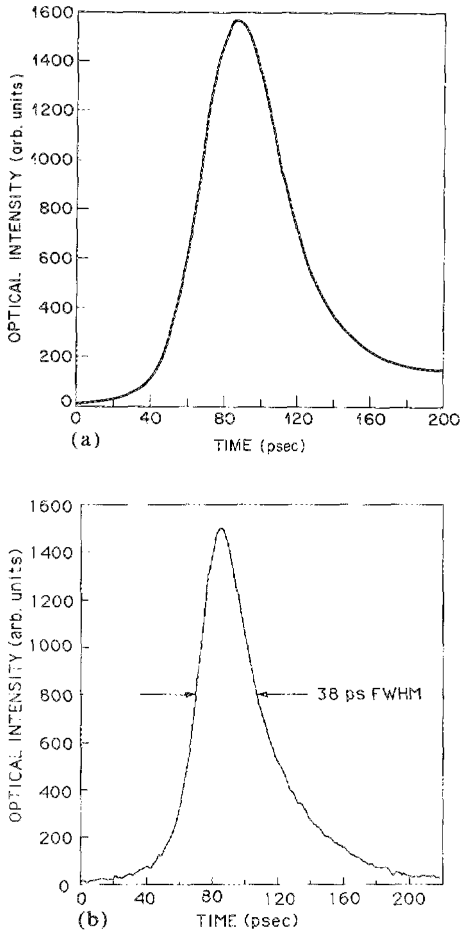

FIG. 4. Optical cross correlation of the $\lambda = 620$ nm femtosecond pulse from the CPM laser and the $\lambda = 1.5\,\mu$m pulse from a BH GRINSCH QW laser diode. (a) Laser diode with an n-type substrate and pulse width of 53 ps FWHM with 100% modulation. Electrical excitation delivered via PIN photodiode as shown in Fig. 1. (b) Laser diode with an n-type substrate and pulse width of 38 ps FWHM and 100% modulation. One corner of the loss segment was shorted directly to the gain segment using the excitation beam.

ing InP was regrown on a semi-insulating substrate. This switch operates in the usual way, by generating carriers at the surface and "shorting" between the two electrodes. By biasing the gain section at $I_G \approx 2I_{\text{th}}$ large signals similar to those generated with PIN switches, with 100% modulation depth and ≈ 50 ps FWHM could be generated.

As an independent measure of laser diode speed (using devices from a different wafer), the CPM laser was used to illuminate the segment directly. In this mode the segment (reverse bias) is shorted directly to the gain electrodes (forward bias). In addition, carriers may be injected directly into the active region which is located 1 μm from the surface. Figure 4(b) shows the measured pulse width of 38 ps FWHM. Here too the optical pulse is asymmetric, and a linear fit to the rise time is $\tau_{10\text{-}90} \approx 20$ ps (corresponding to a large signal bandwidth of 17.5 GHz).

Clearly, the number of photon round trips required to reach lasing threshold is an important parameter in determining laser pulse width. For a cavity length $L_C = 500\,\mu$m the typical round trip time is ≈ 10 ps. Thus a 50 ps FWHM optical pulse for *uncoated* facets corresponds to five round trips. Since the gain per unit length is constant, decreasing the cavity length with uncoated mirror facets should not change the pulse width; i.e., the reduced gain means more round trips are required to achieve the same threshold. This was seen for lasers with $345\,\mu\text{m} < L_C < 600\,\mu$m which all gave about the same pulse width. Therefore, high-reflectivity facet coating could reduce the number of round trips required to achieve lasing for a given cavity length, resulting in a significantly faster response.

In conclusion, we have demonstrated that the light output of InGaAs/InP BH GRINSCH QW laser diodes with an intracavity loss modulator can be operated in a picosecond large signal pulse regime. Using optically generated picosecond electrical transients to excite the intracavity loss modulator, laser diode optical pulses of 53 ps FWHM at 100% modulation were generated. By directly shorting the loss segment to the gain segment, optical pulses of 38 ps FWHM at 100% modulation were generated.

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