

Multielectrode quantum well laser for digital switching

A. F. J. Levi and R. N. Nottenburg
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

R. A. Nordin
AT&T Bell Laboratories, Naperville, Illinois 60566

T. Tanbun-Ek and R. A. Logan
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 2 November 1989; accepted for publication 18 January 1990)

A multielectrode laser can be used to perform digital logic functions and threshold detection. In addition, the intrinsic gain in these devices allows control of lasing light output without using conventional high-current electrical switches. Device potential is illustrated by demonstrating logical AND operation (demultiplexing) at 1.5 Gbit s⁻¹ with a bit error rate of < 10⁻¹¹ s⁻¹.

Recently it was shown that a small absorber monolithically integrated into a semiconductor laser diode cavity could be used to switch 7 mW of lasing light power with < 30 μW change in electrical power.¹ The use of such low switching power and the associated power gain is attractive for high-speed optoelectronic signal processing.^{2,3} In addition, the nonlinear behavior of such saturable absorbers⁴⁻⁶ can be used to advantage in digital optoelectronic systems where threshold detection of signal levels is important for pulse shaping and error-free data processing.

In this letter we report on the use of two intracavity absorbers to control lasing light output from an InGaAs/InP buried-heterostructure graded-index separate-confinement heterostructure (BH GRINSCH) laser diode with four quantum wells (4 QWs). Essentially error-free (< 10⁻¹¹ errors per second) logical AND operation at a bit rate of 1.5 Gbit s⁻¹ is demonstrated using the device in a demultiplexer application.

InGaAsP crystals are grown on n⁺ (100) oriented InP substrates at a temperature of 625 °C using atmospheric pressure metalorganic vapor phase epitaxy (MOVPE). Ar-sine, phosphine, trimethylgallium, trimethylindium, and a hydrogen carrier gas are used during crystal growth. Small quantities of H₂S and diethylzinc are used to incorporate the n- (S) and p-type (Zn) impurities, respectively. Table I gives the layer structure used. The band-gap wavelength λ_G of the quaternary compounds is indicated in μm and the thickness of the layers is given in nm. After removal from the growth chamber, BH lasers are formed first by stripe mesa etching, then reducing the width of the active region to around 2 μm using a selective etch, and finally regrowing with semi-insulating Fe-InP. Using a geometry similar to that shown in Fig. 1, front-side electrical contact to the n⁺ and p⁺ layers is achieved with standard etching and metallization techniques. The gap between the p⁺ metal stripes is 12 μm and the length of the small absorber sections S₁ and S₂ is 6 μm. The long metal stripes are electrically connected and defined as the gain section. After selectively removing the p⁺-InGaAsP contact layer in the gap region by etching, the isolation resistance between the segments and the gain section is > 1 kΩ. To avoid excess electrical heating, the series

resistance of both the gain section diode and the absorber diode is kept low (see Fig. 2). Laser cavities are formed by cleaving, cavity length is L_C ≈ 500 μm, and lasing wavelength is 1.5 μm.

Figure 3 shows typical light output per facet for various absorber voltages V_{S1} and V_{S2} as a function of gain current I_G. When V_{S1} = V_{S2} = V_G the laser has a threshold current of I_{th} = 25 mA. Reducing both biases V_{S1} and V_{S2} to 0.4 V increases losses in the cavity, there is a Q-switched response, and the threshold current increases to I_{th} = 60 mA. Small variations in V_{S1} and V_{S2} around the threshold value 0.4 V causes switching in laser light output. The AND function shown in Table II may be achieved by applying a constant gain current I_G = 60 mA and voltages to S₁ and S₂ such that if either bias is much less than 0.4 V there is no lasing (logical 0), and if both biases are more than 0.4 V the device lases

TABLE I. Typical layer structure used in fabrication of InGaAs/InP laser diodes with 4 QWs.

Band gap λ _G (μm)	Material	Thickness (nm)	Impurity concentration (cm ⁻³)
1.0	InGaAsP	150	p = 1 × 10 ¹⁹
	InP	1000	p = 5 × 10 ¹⁷
1.0	InGaAsP	22	i
1.1	InGaAsP	22	i
1.2	InGaAsP	22	i
1.25	InGaAsP	22	i
	InGaAs	9	i
1.25	InGaAsP	25	i
	InGaAs	9	i
1.25	InGaAsP	25	i
	InGaAs	9	i
1.25	InGaAsP	25	i
	InGaAs	9	i
1.25	InGaAsP	22	i
1.2	InGaAsP	22	i
1.1	InGaAsP	22	i
1.0	InGaAsP	22	i
	InP	1000	n = 5 × 10 ¹⁷
	InP	substrate	n ⁺

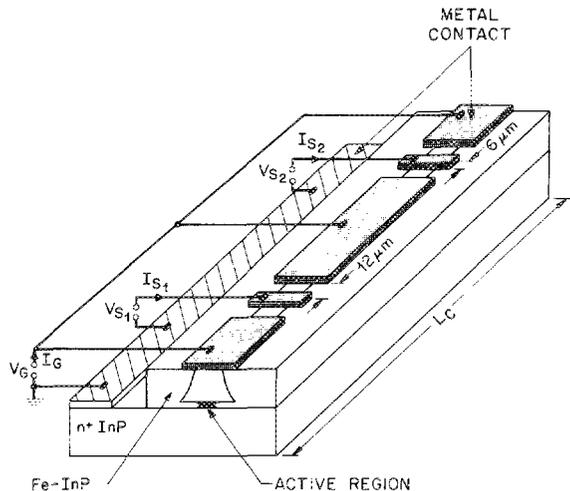


FIG. 1. Schematic sketch of a BH GRINSCH 4QW laser diode with a cavity length L_c and two absorbers S_1 and S_2 . The current into the long gain section is I_G , the absorber voltages and currents are V_{S_i} (V_{S_1} , V_{S_2}) and I_{S_i} (I_{S_1} , I_{S_2}), respectively.

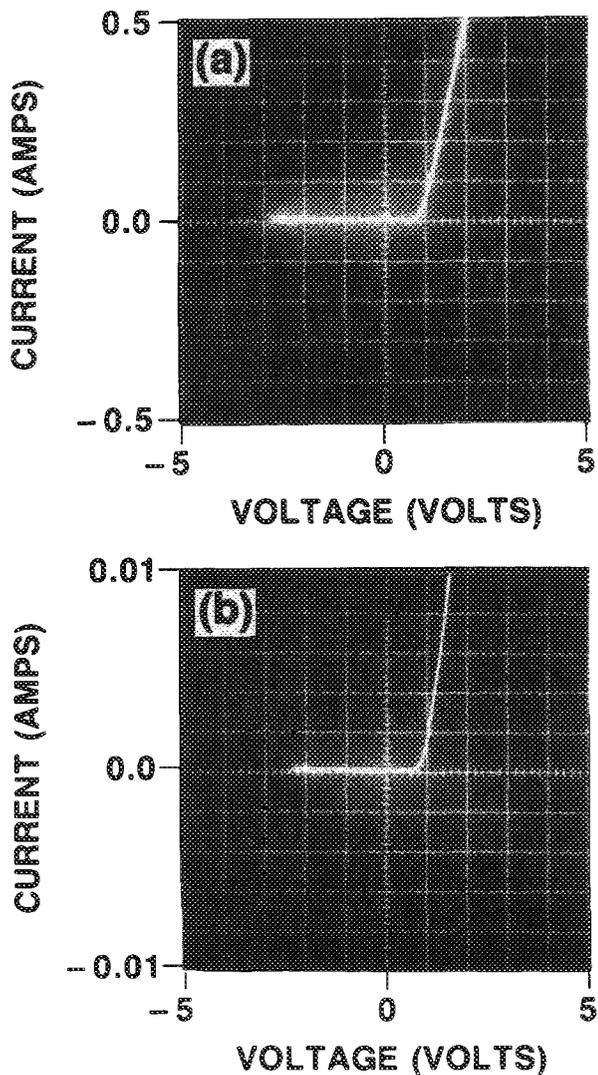


FIG. 2. Room-temperature current-voltage characteristic of the gain section diode showing a series resistance of (a) $R = 2 \Omega$ and (b) an absorber section with $R = 6 \Omega$.

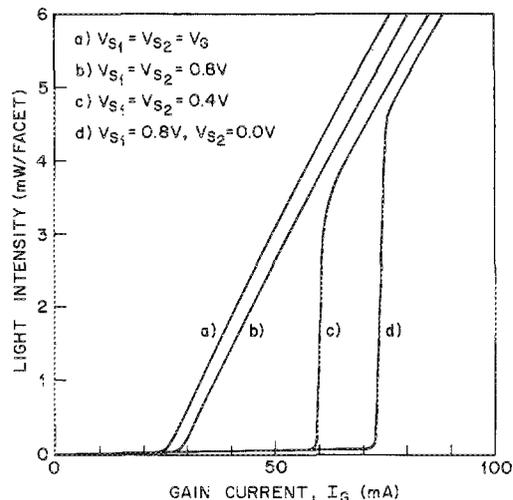


FIG. 3. Light intensity per facet as a function of gain current I_G for various absorber voltages V_S .

(logical 1). Clearly, I_{th} determines lasing light intensity and threshold bias voltage for logic.

A schematic diagram of the experimental arrangement for demultiplexing is shown in Fig. 4. A $1.525 \text{ Gbit s}^{-1}$ non-return to zero data stream is supplied directly from the output of a 24-bit word pattern generator to S_1 . This signal is time division demultiplexed using a one out of four selector signal applied to S_2 . The resulting lasing light passes through an optical fiber to a receiver whose output is monitored on an oscilloscope. Typical results of such an experiment are shown in Fig. 5. In this example a 101010.... data stream is sent to S_1 . It is clear from the data that every fourth bit is correctly demultiplexed and that the output signal is somewhat cleaner than the input signals V_{S_1} and V_{S_2} . Noise on the input signals V_{S_1} and V_{S_2} is due to electrical reflections from sections S_1 and S_2 . The difference between the rise and fall time of the detected signal is due to receiver response. The bit error rate at 1.5 Gbit s^{-1} either with or without demultiplexing 24-bit words was measured to be $< 10^{-11} \text{ s}^{-1}$.

Significantly higher bit rates should be possible by appropriate impedance matching at S_1 and S_2 . Separate experiments on similar inhomogeneously pumped BH GRINSCH QW diodes indicate that high-speed operation can be achieved in these devices (more than 6 GHz bandwidth at 100% modulation).³ Other improvements, such as optical coating of cavity mirrors, are also expected to enhance device performance.

TABLE II. Table illustrating logical AND. For a gain current $I_G = 60 \text{ mA}$, voltages $< 0.4 \text{ V}$ applied to S_1 or S_2 correspond to logical 0 and voltages greater than 0.4 V are logical 1.

S_1	S_2	Output
0	0	0
1	0	0
0	1	0
1	1	1

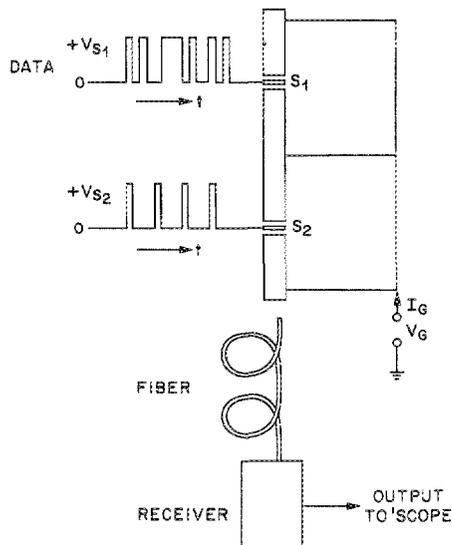


FIG. 4. Schematic diagram of the experimental arrangement for a demultiplexing experiment. The electrical data stream is applied to S_1 , the demultiplexing signal is applied to S_2 , and a constant current I_G flows through the gain section. In logical AND operation lasing occurs when V_{S_1} and $V_{S_2} > 0.4$ V, and $I_G = 60$ mA. An optical fiber passes lasing light to a receiver whose output is displayed on an oscilloscope.

In conclusion, the nonlinear light output characteristics of lasers with saturable intracavity absorbers can usefully be used to implement essentially error-free high-speed digital optoelectronic signal processing. An advantage of the intrinsic power gain in these devices is that lasing light output may be controlled using standard silicon electronic circuits. Lasing light output can be switched without the use of high-power current drivers, pulse-shaping circuits, or external threshold detectors. To illustrate device operation we have demonstrated logical AND operation in a BH GRINSCH 4QW laser with two intracavity absorbers. The device performs demultiplexing at a bit rate of 1.5 Gbit s^{-1} with $< 10^{-11}$ errors per second. The implications for short haul transmission and switching schemes are apparent. Finally, it is worth mentioning that some of the advantages of digital

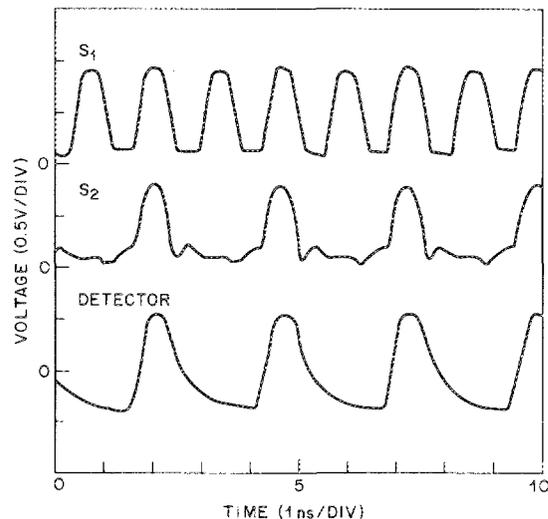


FIG. 5. Oscilloscope trace of data stream V_{S_1} (upper curve), selector signal V_{S_2} (middle curve), and p - i - n receiver output (lower curve). Data taken with $I_G = 60$ mA.

amplitude modulation signal processing in multielectrode lasers can also be applied to the digital wavelength switching recently demonstrated in QW lasers.^{8,9}

¹K. Berthold, A. F. J. Levi, T. Tanbun-Ek, R. A. Logan, and S. N. G. Chu, *Appl. Phys. Lett.* **55**, 1940 (1989).

²D. A. B. Miller, *Opt. Lett.* **14**, 146 (1989).

³D. Dykaar, K. Berthold, A. F. J. Levi, T. Tanbun-Ek, and R. A. Logan (unpublished).

⁴Y. Arakawa, A. Larson, J. Pasiaski, and A. Yariv, *Appl. Phys. Lett.* **48**, 561 (1986).

⁵*Optical Switching in Low-Dimensional Systems*, NATO ASI Series, Vol. B194, edited by H. Haug and L. Banyai (Plenum, New York, 1989).

⁶K. J. Vahala, M. A. Newkirk, and T. R. Chen, *Appl. Phys. Lett.* **54**, 2506 (1989).

⁷T. Tanbun-Ek, R. A. Logan, and J. P. Van der Ziel, *Electron. Lett.* **24**, 1483 (1988).

⁸K. Berthold, A. F. J. Levi, S. J. Pearton, R. J. Malik, W. Y. Jan, and J. E. Cunningham, *Appl. Phys. Lett.* **55**, 1382 (1989).

⁹K. Berthold, A. F. J. Levi, T. Tanbun-Ek, and R. A. Logan, *Appl. Phys. Lett.* **56**, 122 (1990).