Integrated Laser-Diode Voltage Driver for 20-Gb/s Optical Systems Using 0.3-μm Gate Length Quantum-Well HEMT's

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***Abstract*— An integrated laser-diode voltage driver (LDVD) making use of enhancement/depletion AlGaAs/GaAs quantum-well high electron mobility transistors (QW-HEMT's) with gate lengths of 0.3 μm has been developed. Its large signal bandwidth is 12 GHz. Eye diagrams of the output signal at bit rates up to 8 Gb/s show an opening similar to that of the input signal. Supporting material is given indicating that the LDVD might operate at bit rates up to 20 Gb/s. The maximum output current is over 90 mA; the maximum modulation voltage of 800 mV corresponds to 40-mA modulation current for a laser diode with 20-Ω dynamic resistance. The power consumption is less than 500 mW.**

I. Introduction

The laser-diode driver (LDD) is a key circuit of an optical digital communication system. Due to the following three reasons, its design is very challenging. Firstly, the requirements such as large output current and high speed are contradictory: for a large current in the range of some 10 mA up to more than 100 mA, a large driving signal and large output transistors are necessary. Both are unfavorable for high speed. A suitable circuit structure, some suitable compensation techniques, and a series of optimization steps are necessary.

Secondly, an optimal LDD should offer an output signal having a special waveform instead of a square wave. The reason is that a square-wave driving signal applied to a laser diode (LD) gives rise to two undesired consequences: a) a large overshoot of the optical power accompanied with a serious chirping effect at the rising edge, and b) a longer time for switching off than for switching on. From [1] it is known that the ratio of the peak to on-state photo density is more than 1.7 for an index-guided laser, and the switching-off time $t_{\rm off}$ of the laser is at least 30% greater than the switching-on time $t_{\rm on}$. For another LD with an optical power ratio of $P_{\rm on}/P_{\rm off} = 10$, $t_{\rm off}$ is even 2.5 times as great as $t_{\rm on}$ [2]. To improve the performance of LD's at the rising edge, a driving pulse form with a two-step rising edge was shown to be useful [3], and to reduce the switching-off time, a strong undershoot at the falling edge was proposed [4].

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Thirdly, the connection of the designed LDD and the driven LD becomes a difficult problem when the LD cannot be integrated on the same chip.

In [5] we have reported a 15-Gb/s LDD whose circuit diagram is redrawn in Fig. 1 for convenience in the following discussions. This LDD has two important features.

1) Apart from the high-frequency (HF) voltage compensation in the preamplifier, a complete capacitively coupled current amplifier (C^3A), consisting of $EF_{11}, EF_{12}, EF_{72}, EF_{82}$, C_1, and C_2, was introduced for HF current compensation so that a sharp undershoot could be produced at each transition from ZERO to ONE, and the switching-off delay and the fall time were reduced. However, the rising edge of the output pulse deviated more from the desired shape with the complete C^3A than without it (see Section II).

2) Each of the open-circuited drain pairs, indicated by I_{o1} and I_{o2}, can be considered as a current source modulated by the input data signal. When an LD is on-chip connected to one of the outputs, the low-ohmic LD, normally less than 25 Ω, sets a smaller Miller effect between the gate and the drain of the output transistors, which is beneficial for high-speed application. However, only the cathode of the LD can be connected to one output. Thus, the LDD should be really called an LDCD for both laser-diode current driver and laser-diode cathode driver.

The 15-GHz GaAs/AlGaAs multiquantum-well LD developed at our institute [6] was designed having three mesas in a coplanar ground–signal–ground contact geometry, as shown in Fig. 2. The middle contact served as the anode. With this arrangement the LD can be measured directly by means of standard coplanar microwave probes with ground–signal–ground contacts, but only its anode can be connected to the driver. When the driver is designed using available GaAs as well as Si-bipolar circuit techniques, we find that it becomes a voltage driver. Therefore, the LDCD mentioned above is unusable. That was the main reason why we developed not only LDCD's but also laser-diode voltage driver (LDVD's). In fact, an LDVD has certain advantages over an LDCD in some cases, as given in the following section.

II. Circuit Principle

The circuit diagram of our LDVD shown in Fig. 3 was developed on the basis of the LDCD in Fig. 1. It consists

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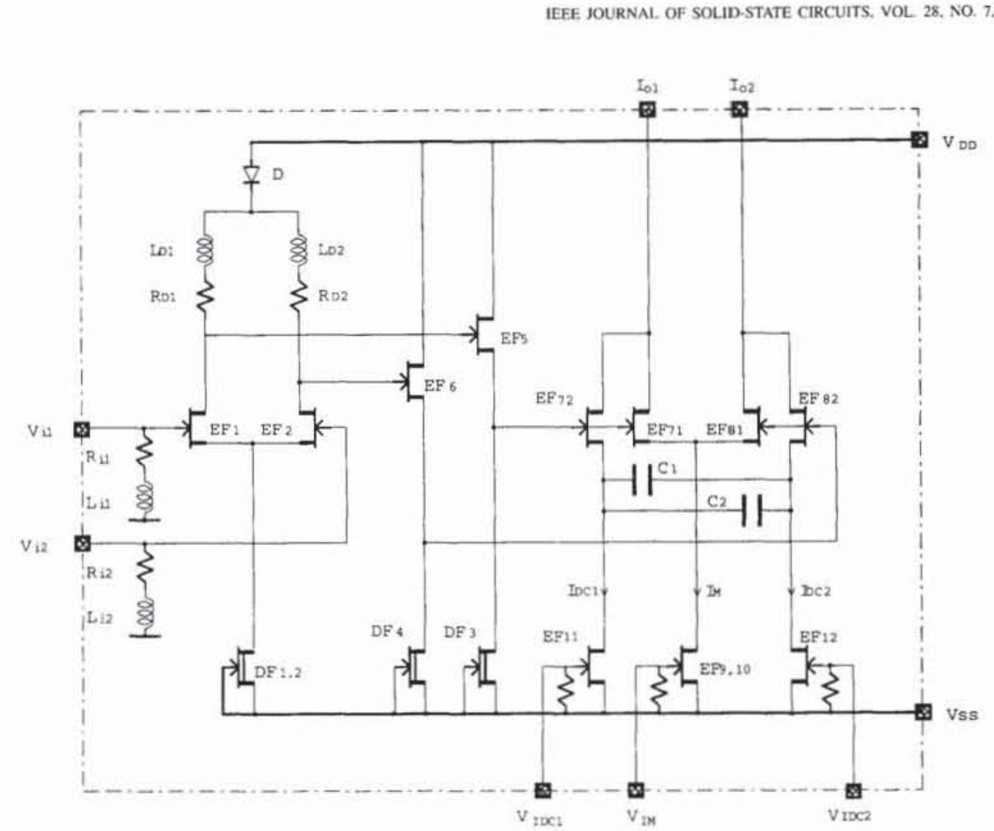

Fig. 1. Circuit diagram of the laser-diode driver in [5].

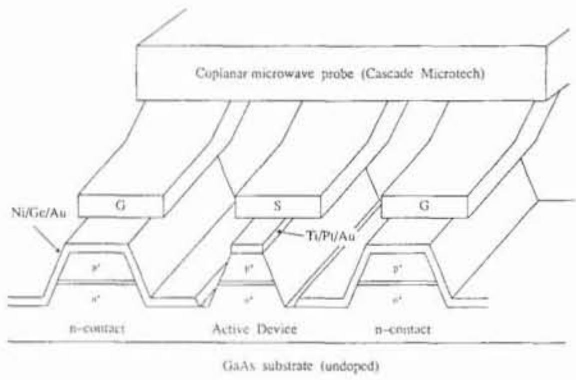

Fig. 2. Geometric arrangement of the high-speed GaAs/AlGaAs multi-quantum-well LD developed at our institute.

of three stages: the preamplifier, the main amplifier, and the voltage output.

The preamplifier consists of enhancement HEMT's (E-HEMT's) EF_1 and EF_2, depletion HEMT (D-HEMT) DF_1, load resistors R_{D1} and R_{D2}, and inductances L_{D1} and L_{D2}. This is a differential amplifier with an HF voltage compensation similar to the input stage of the LDCD in Fig. 1. The diode D takes care of level shifting. A pair of source followers consisting of EF_3, EF_4 and DF_3, DF_4 is used as a buffer between the pre- and the main amplifier.

In the main amplifier the E-HEMT EF_5 together with EF_6 and EF_7 constitutes a conventional current amplifier and, in addition, together with EF_8 and EF_{10} and the capacitor C_c constitutes a C^3A. The introduction of this C^3A is to produce a peaked current pulse caused by the loading process of C_c in addition through the load resistor R_{D3}, so that a desired voltage undershoot is formed, and the switching-off time of the driven LD can be reduced. In comparison to the circuit of Fig. 1, it can be seen that half of the C^3A circuit is merged here into the conventional current amplifier. With this modification the undesired enhanced overshoot caused by the complete C^3A in Fig. 1 is removed (see the simulated waveforms in Fig. 4). In addition, fewer devices and less supply current are needed.

The voltage signal over R_{D3} is then transmitted to the gate of the output E-HEMT EF_{11} through the source follower composed of DF_5 and DF_6. A D-HEMT was used for DF_5, because it has a near-zero gate-to-source dc voltage drop. An E-HEMT was used for the output transistor because E-HEMT's have a higher transit frequency (see Table I).

When the driven LD is directly linked to the source of EF_{11} and a sufficient direct current flows through it, the voltage signal over the resistor R_{d3} will be effectively coupled to the source of EF_{11}, i.e., to the anode of the LD. The current I_H at the drain of EF_9 controls the high level of the output voltage. The low level as well as the modulation amplitude is then determined by I_M at the drain of EF_7. Both I_H and I_M can be controlled manually or by other signals, such as the signal from the monitor diode of the LD.

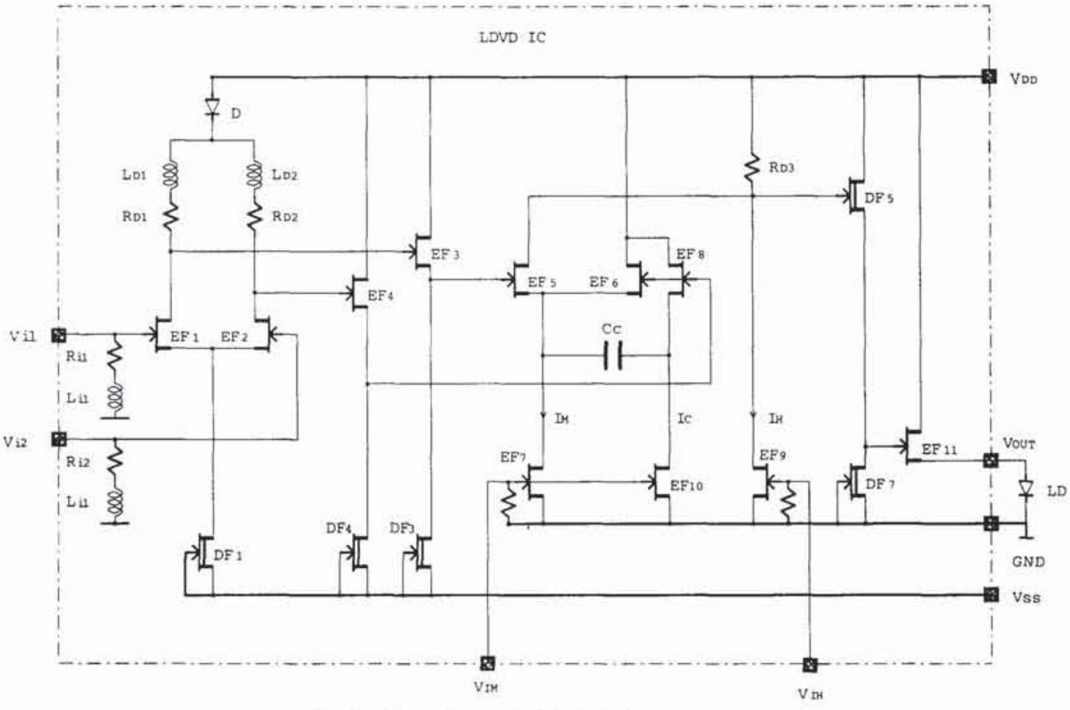

Fig. 3. Circuit diagram of the laser-diode voltage driver.

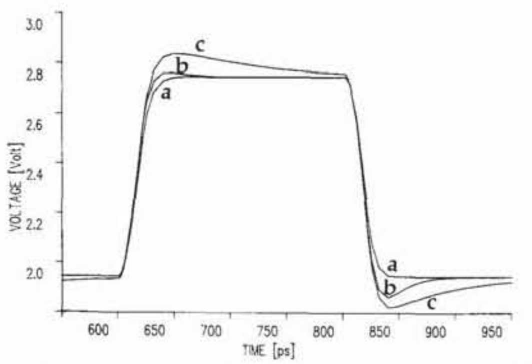

Fig. 4. Simulated output pulseforms of the main amplifier of the LDVD: *a*) without C^3A, *b*) with the merged C^3A, and *c*) with a complete C^3A.

TABLE I
TRANSISTOR PARAMETERS
Gate Length = 0.3 μm

	E	D
V_{th}	0.05 V	-0.7 V
I_{dsat}	200 mA/mm	180 mA/mm
	(V_{gs} = 0.8 V)	(V_{gs} = 0 V)
G_m	500 mS/mm	400 mS/mm
R_s	0.6 Ωmm	0.6 Ωmm
f_t	50 GHz	45 GHz

In comparison to the LDCD in Fig. 1, the LDVD shows further advantages. First, a very large dimension can be used for EF_{11} because EF_{11} alone is required for the output, and the Miller effect need not be taken into consideration. In our design the gate width of EF_{11} is 0.5 mm. For a saturated length specific drain current of 200 mA/mm, the maximum output current can approach 100 mA. The output HEMT's in Fig. 1 must exist in pairs. To produce I_M, I_{DC1}, and I_{DC2}, EF_9–EF_{12} are also needed. Each HEMT must have a dimension that is comparable to that of the HEMT connected with it. For the same output current and, for example, an $I_{DC1}/I_{DC2}/I_M$ ratio of 10/40/60, a minimum total gate width of about 1.4 mm (2 × 0.05, 2 × 0.2, and 3 × 0.3 mm for I_{DC1}, I_{DC2}, and I_M branch, respectively) is necessary for the LDCD. For such large gate widths, a greater chip area is necessary. Certainly other HEMT's in the LDVD also require space, but these HEMT's can be much smaller than those in LDCD because the currents flowing through these can have much smaller values. Assuming the dynamic impedance of the LD is 20 Ω and R_{D3} is 100 Ω, the current in the preamplifier of the LDVD is only one fifth as much as that in the LDCD. The chip area of an LDVD, therefore, can be much smaller than that of an LDCD for the same large output current. In fact we have designed another LDVD with an on-chip LD having a chip area of only 0.3 × 1.0 mm^2.

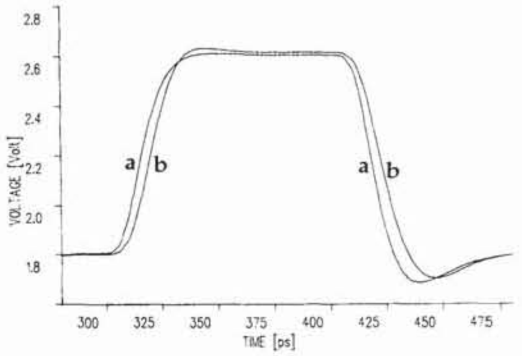

Fig. 5. Output signal of the LDVD *a*) with a 50-Ω resistor and *b*) with the composite load.

Second, the proportions of the direct and modulation current of the LD driven by an LDVD can be adjusted in the whole range of the maximum value (e.g., 100 mA), whereas the direct and modulation current of an LDCD can be adjusted only in the range of the respective maximum values (e.g., the assumed 40 and 60 mA). That means the LDVD can be applied with more flexibility.

Third, the circuit of the LDVD can be used as a driver of optical modulators simply by increasing the amplitude of the output voltage up to the desired value, e.g., 4 V_{p-p}. For this application the LDVD should be better than an LDCD because optical modulators are basically voltage-controlled devices [7].

III. Simulated Results

To gain as much information as possible, the main amplifier of the LDVD was separately simulated with the following three circuit variants:

1. without C^3A,
2. with a complete C^3A as shown in Fig. 1, and
3. with the merged C^3A as shown in Fig. 3.

All simulations are carried out by using the popular program SPICE-2 and an in-house adapted HEMT model. The corresponding pulseforms of the output voltage over R_{D3} are plotted in Fig. 4. The pulseform of the circuit with a merged C^3A is clearly improved, approaching the desired shape. The dynamic characteristic of the complete LDVD was simulated for two different loads:

1. a 50-Ω resistor to match the 50-Ω probe, and
2. a composite load, consisting of a 20-Ω resistor and a 0.53-pF capacitor in parallel, and a 1.4-V voltage source in series, to simulate a quasi-ideal on-chip LD with a limiting frequency of about 15 GHz.

A large-signal bandwidth of about 13 GHz was obtained under both loading conditions. The output pulseforms of the LDVD with a 50-Ω resistor and the composite load are shown in Fig. 5. The rise times of both pulses are approximately 18 ps (10–90%). The fall time is 15 ps for a 50-Ω resistor and 18 ps for the composite load. In addition, the pulse obtained over the composite load has a relative delay of 5 ps. Both the

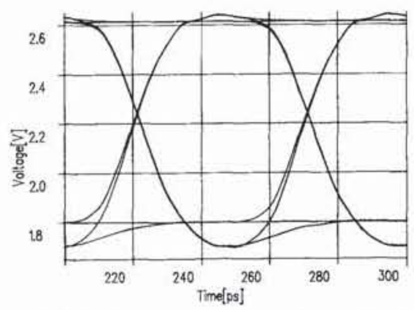

Fig. 6. Eye diagram of the output signal of the LDVD with the composite load at a bit rate of 20 Gb/s.

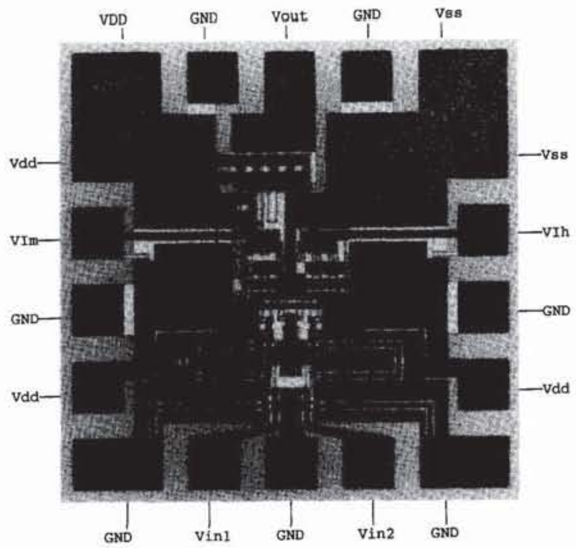

Fig. 7. Photomicrograph of the realized IC of the LDVD.

greater fall time and delay are due to the 0.53-pF capacitor. Simulations also show that the LDVD could function jitter-free at bit rates up to 20 Gb/s. The eye diagram of the output voltage at 20 Gb/s, obtained from the composite load by using a self-developed plotting program, is shown in Fig. 6. The direct and modulation currents were approximately 20 and 40 mA, respectively.

IV. Fabrication

The photomicrograph of the 1 × 1-mm^2 chip is shown in Fig. 7. The QW-HEMT structure was fabricated by molecular beam epitaxy. Both enhancement- and depletion-mode HEMT's are incorporated on the same chip. The 0.3-μm-long gates were patterned by electron-beam direct writing [8]–[10]. The gate recesses were obtained by reactive ion etching. The typical E- and D-HEMT parameters are listed in Table I. The precision resistors were made using nickel-chromium thin films. For capacitors the MIM structure was chosen. The inductors were realized by short-circuited coplanar waveguides.

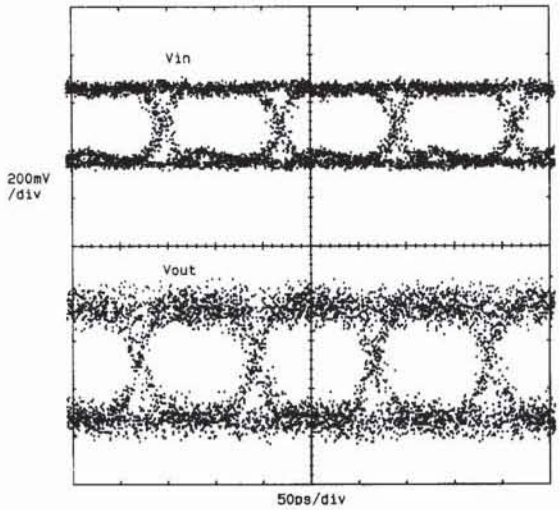

Fig. 8. Eye diagram of the input and output signals of the LDVD IC at 8 Gb/s from a 50-Ω measuring setup.

V. Experimental Results

The chips were measured first on wafer using 50-Ω coplanar test probes. A maximum output current of 90 mA was measured with a power consumption of less than 500 mW. The maximum output voltage amplitude was 800 mV corresponding to a modulation current of more than 40 mA for a LD with a dynamic resistance of less than 20 Ω. Eye diagram measurements could only be made for bit rates up to 8 Gb/s and with single-ended signals due to the available pattern generator. Eye diagrams of the input and output signals of an LDVD chip at 8 Gb/s are shown in Fig. 8. It can be seen that both signals have almost the same degree of opening. Furthermore, the chips were measured using sine-wave signals. A maximum large-signal bandwidth of about 12 GHz was obtained [11].

Considering that a 12-GHz sine-wave signal is equivalent to a 24-Gb/s data signal of repeated "10" codes, and based on the simulation results and that we obtained an open eye diagram at 20 Gb/s from a monolithically integrated 2 : 1 multiplexer and LDCD whose simulated rise and fall times and measured large-signal bandwidth were approximately 40 ps and 10 GHz, respectively [12], we are confident that our LDVD with an on-chip high-speed LD can operate at bit rates up to 20 Gb/s.

VI. Conclusion

We have designed, fabricated, and tested a laser-diode voltage driver IC using AlGaAs/GaAs quantum-well transistors and a capacitively coupled current amplifier. The maximum output current was 90 mA. The maximum large-signal bandwidth was 12 GHz. At bit rates up to 8 Gb/s the eye diagrams of the output signal showed almost the same opening as that of the input signal. The IC has already been used to measure our laser diodes, and will be used in an optical digital transmitter to drive an on-chip high-speed laser diode at bit rates up to 20 Gb/s.

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