Injection Laser Modulation at 2 Gbit/s by Monolithic Silicon Multiplexer

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Abstract **—Direct laser-diode pulse-code modulation at 2 Gbit/s (NRZ) is performed by a fast Si monolithic integrated bipolar circuit (2.5-μm design rules, p-n-junction isolation, $f_t \approx 7$ GHz at $V_{CE} = 1$ V).**

The current-switch output stage of a 4:1-time-division multiplexer IC feeds a modulation current swing of 8 mA into a CSP injection laser biased above threshold. Measured optical responses of the laser are reported.

I. Introduction

In various laboratories work is being performed on realizing fiber-optic PCM communication systems with bit rates well into the Gbit/s range. Vital electronic circuits for such systems are time-division multiplexers (MUX) for serializing several contributing signals of lower data rate (cf. [1]).

In the past, multi-Gbit/s multiplexers were implemented as hybrid circuits (see, e.g., [2]). With the trend to monolithic solutions even at these high bit rates, GaAs seems to be particularly suited because of its well-known advantages as a material for fast circuits. Indeed, GaAs MUX implementations have been reported which could be operated up to 3 Gbit/s [3], 1.8 Gbit/s [4], and 0.6 Gbit/s [5].

It is the purpose of this paper to show that one must not necessarily turn to GaAs solutions for realizing monolithic injection-laser MUX/driver circuits in the multi-Gbit/s range.

II. Description of the MUX Circuit Driving the Laser

For use in a planned wide-band subscriber network operating at 1.12 Gbit/s [6], an ECL-compatible silicon bipolar 4:1-MUX IC was recently developed and implemented in our Institute at the Ruhr-Universität Bochum for the Heinrich-Hertz-Institut. The circuit is described in detail in [7]; the features of its operation and its design guidelines may be summarized as follows. As shown in Fig. 1, four current switches working on a common load are selected by series-gated select inputs S_0 and S_1. If two pulse trains of period T, shifted in phase by about $T/4$, are applied to S_0 and S_1, the data at the inputs D_1 to D_4 are selected cyclically and appear at the output in time slots of width $T/4$. Without resorting to a very sophisticated technology, the relatively high MUX bit rate was achieved by modifying conventional designs of commercially available multiplexers in some points. This included, as reported in [7], 1) employing differential operation (apart from single-ended operation at the inputs) at reduced single-ended voltage swings, and 2) adding a buffer stage between the serializer and the output emitter-followers. In addition, 3) great emphasis was put on very careful circuit simulation and optimization.

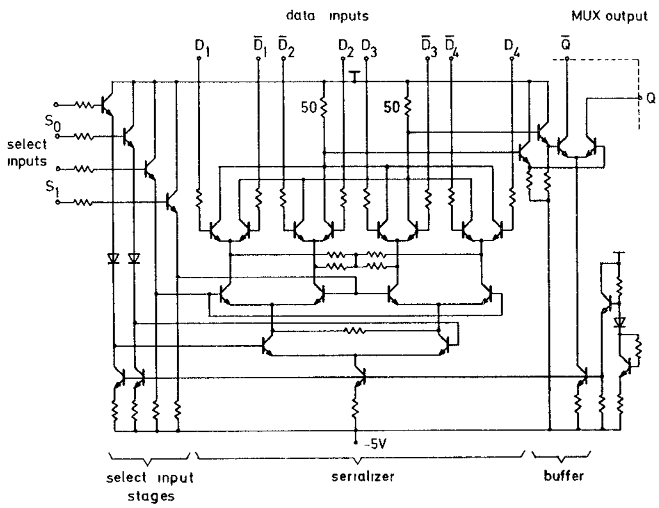

Fig. 1. Circuit diagram of the 4:1 multiplexer IC. In contrast to [7, fig. 1], differential data inputs are applied.

By eliminating output emitter-followers and by letting the current switch of the buffer stage drive the output load directly (Fig. 1), the bit rate could be raised to about 2 Gbit/s [7]. A further increase in bit rate was achieved by employing differential inputs $D1$, $\overline{D1}$ to $D4$, $\overline{D4}$ (as in Fig. 1) instead of single-ended inputs. This option was already prepared in the original MUX layout design [8].

Fig. 2(a) and (b) shows measured output eye diagrams for static data input patterns at 2.24 Gbit/s.[1] The value of 2.24 Gbit/s is expected to be the next higher stage in the planned European PCM hierarchy and is the intended bit rate for the trunk lines in the above-mentioned integrated services network [6]. Fig. 2(a) is the eye diagram of the *differential* MUX output signal, whereas Fig. 2(b) shows the corresponding eye diagram representation of the

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[1] Static data inputs and pseudorandom data inputs lead to very similar eye diagrams of the output signals, as found by measurements at 2 Gbit/s.

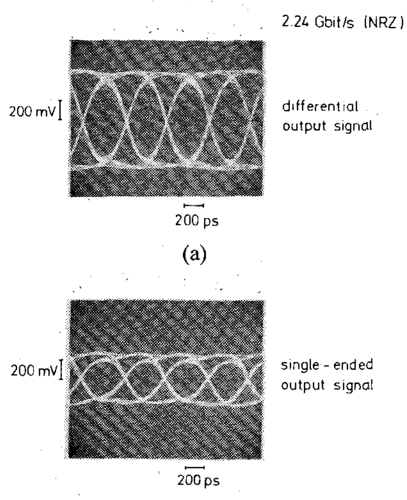

Fig. 2. Eye patterns of MUX output signals if the MUX drives a 50-Ω load at 2.24 Gbit/s. (a) Differential output signal. (b) Single-ended output signal.

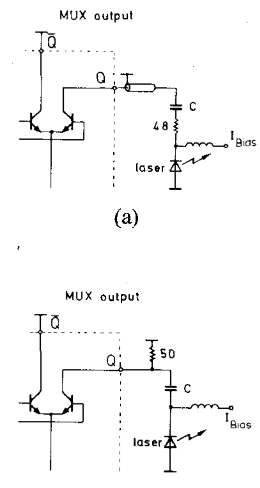

Fig. 3. Two different methods of driving the laser by the MUX IC. (a) The laser is connected to the MUX output via a transmission line. (b) The laser cathode is connected directly to the MUX output.

single-ended signal of one output. The current-switch output is terminated by the 50-Ω input impedance of the sampling oscilloscope. It is evident that even at this high bit rate the eye opening is sufficient for a reliable operation. The major differences between Fig. 2(a) and (b) is 1) half the voltage swing and 2) a creeping at the end of the transients in Fig. 2(b). This creeping of the single-ended output signal is due to the switching-off behavior of the current-switch transistors.

At bit rates beyond 2.24 Gbit/s, a gradual closure of the output eye pattern is expected. So, this value is considered as the limit for a reliable operation of the present MUX IC at high bit rates.

The MUX/driver IC was implemented in a bipolar technology using double implantation, 2.5-μm emitter stripe widths, p-n-junction isolation, and two-layer metallization. The transistor transit frequency was measured to be about 7 GHz at $V_{CE} = 1$ V, which corresponds to a 20-ps transit time. The chip power consumption is 220 mW. The MUX is mounted in a leadless chip carrier; the chip carrier is soldered onto a microwave substrate.

III. Injection Laser Modulation

The current-switch version of the 4:1 MUX IC after Fig. 1 was used for modulating both a channeled substrate planar (CSP) laser (Hitachi HLP 1400, $I_{th} \simeq 58$ mA, $\lambda = 0.83$ μm) and a transverse junction stripe (TJS) laser (Mitsubishi ML-2205F, $I_{th} \simeq 17$ mA, $\lambda = 0.83$ μm; with fiber pigtail) at 2 and 2.24 Gbit/s (NRZ). The present paper is focused on recent results obtained with the CSP laser; the same type of laser (HLP 1400) was also used for investigations at the Heinrich-Hertz-Institut on fiber-optic systems at 2.24 Gbit/s [9]. Modulation experiments at 2.24 Gbit/s using the TJS-laser are reported in [10].

As indicated in Fig. 3(a) and (b), the laser diode is driven by the output current-switch of the MUX IC; no external driver is required. A high-speed silicon avalanche photo-diode (APD, BPW 28) was employed as receiver. The APD was located close to the laser output (about 2 mm) in the experimental setup.

Different methods of driving the laser by the MUX IC were investigated.

In the *first* method, as shown in Fig. 3(a), the Q output of the output current-switch is loaded by a 50-Ω transmission line (coaxial line) which terminates in a series-connection consisting of a chip-resistance of 48 Ω and the low laser impedance. In this way a 50-Ω termination is approximated.

In the *second* method (Fig. 3(b)), the laser cathode is connected directly to the chip carrier output pin by a chip capacitance. The cooling stem of the laser mount is screwed to the ground plate of the microwave substrate. A resistance of 50 Ω provides a dc path from the collector of the transistor to ground.[2] In this way, access from the current-switch output of the MUX IC to the laser chip is made as close as possible and long transmission lines with potential reflections due to imperfect line terminations are avoided. Note that the current-switch output is working on a low-impedance load in Fig. 3(b).

In both methods the laser diode is coupled capacitively to the MUX output.

Fig. 4(a) and (b) shows detected laser responses of the CSP-laser to a pseudorandom current pulse sequence at 2 Gbit/s, whereas Fig. 4(c) presents a section of the single-ended current pulse bit stream and the corresponding eye diagram representation.[3] Note that the current-switch output, in Fig. 4(c), is again terminated by the 50-Ω input impedance of the sampling oscilloscope.

In the modulation experiment of Fig. 4(a), the laser is connected to the driving circuit via a 50-Ω transmission line, according to Fig. 3(a), whereas in the experiment of

[2] DC coupling of the laser diode to the MUX output cannot be applied if the MUX IC and the laser are connected to a common ground, as in Fig. 3(a) and (b); dc coupling would lead to transitor saturation.

[3] The value of 2 Gbit/s results from the fact that the available pseudorandom pulse generator could be operated up to a maximum bit rate of 2 Gbit/s.

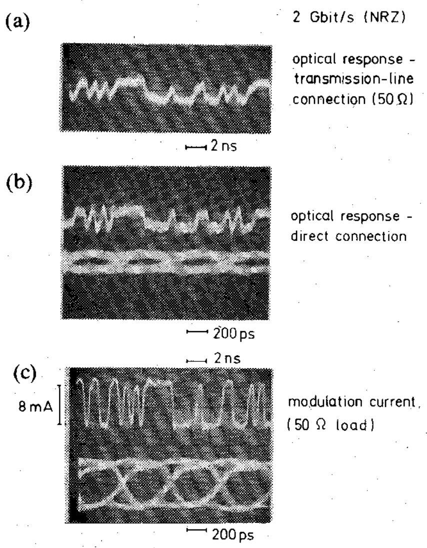

Fig. 4. Detected CSP-laser responses and modulation current. (a) Laser response at 2 Gbit/s: transmission-line connection as in Fig. 3(a). (b) Laser response to the same current pulse sequence and eye pattern representation: direct connection as in Fig. 3(b). (c) Modulation current bit stream (50-Ω termination of the MUX output) and corresponding eye pattern representation.

Fig. 4(b) the laser is directly coupled to the MUX output, as in Fig. 3(b). The results of Fig. 4(a) and (b) come close to what was expected. The shape of the optical pulses reflect the difference between the current pulse shapes. A low-impedance load (Figs. 3(b) and 4(b)) leads to steeper current pulse edges and, hence, to steeper optical pulse responses than a 50-Ω termination (Figs. 3(a) and 4(a)). Current pulse rise and fall times are about 160 ps and 220 ps (20–80-percent values), respectively, as found by circuit simulations; experimental verification, however, is not possible, since the current through the diode cannot be monitored in the circuit of Fig. 3(b).

The relatively low vertical eye opening of the optical response displayed in Fig. 4(b) is a consequence of the weak photodiode signal (no post-amplification) in conjunction with noise. The broad trace on the screen stems from the oscilloscope noise (unfiltered oscilloscope operation).

A comparison of the modulation current bit pattern (Fig. 4(c)) with the optical laser-diode response and the corresponding eye pattern representation show that the diode responds correctly to the modulation signal. The dc bias of 68 mA (i.e., 10 mA above threshold) in conjunction with the modulation current of 8-mA peak-to-peak brings the laser "off"-state current 4 mA above the threshold value. This operation well above threshold prevents relaxation oscillation in the optical response, as found experimentally. The modulation current swing of 8 mA, which is considered to be relatively low for the laser employed, is a result of the specifications of the MUX IC. The modulation current swing may be increased by suitably adapting the design of the output current-switch of the IC to a higher output current.

IV. Conclusions

Direct laser-diode pulse-code modulation at 2 Gbit/s is performed by a fast monolithic integrated bipolar circuit. The laser diode employed is a CSP-laser with a threshold current of 58 mA. The modulation current swing is 8 mA. The effect of bias current and modulation current swing on the laser spectrum has not been considered.

Two different driving methods are employed. First, the laser is series-connected to a resistance terminating a transmission line (50-Ω characteristic impedance); the MUX output, therefore, feeds a 50-Ω load. Second, the laser is connected directly to the MUX output as a low-impedance load. The second version proves to be more favorable. 1) Long transmission lines with potential reflections are avoided and 2) a low-impedance load leads to steeper pulse edges and, hence, to an increase of the potential bit rate.

Fig. 2(a) eventually suggests to drive the laser in a differential mode due to an improved vertical eye opening. Therefore, "hybrid integration" of the MUX/driver IC and the laser on a single-chip carrier in conjunction with the differential mode operation may be a favorable solution. This proposal, however, would require sufficient heat sinking of the laser.

A change to oxide-wall isolation, which is undertaken presently, should further increase the achievable bit rate of the MUX/driver IC. If, in addition, the structural dimensions of the IC are reduced in accordance to bipolar scaling rules [11], bit rates of silicon MUX's (and of comparable circuits) up to 4 Gbit/s do not seem out of reach.

At our Institute, 4:1 MUX performance was quite recently extended to 3 Gbit/s operation (2-stage structure) [12]; there has been no laser modulation experiment so far.

References

[1] B. G. Bosch, "Gigabit electronics—A review," *Proc. IEEE*, vol. 67, pp. 340–379, 1979.

[2] U. Barabas, U. Langmann, and B. G. Bosch, "Diode multiplexer in the multi-Gbit/s range," *Electron. Lett.*, vol. 14, pp. 62–64, 1978.

[3] G. D. McCormack, A. G. Rode, and E. W. Strid, "A GaAs MSI 8-bit multiplexer and demultiplexer," in *Tech. Dig. GaAs IC Symp.*, 1982, pp. 25–28.

[4] J. K. Carney, M. J. Helix, and R. M. Kolbas, "Gigabit optoelectronic transmitters," in *Tech. Dig. GaAs IC Symp.*, 1982, pp. 48–51.

[5] A. D. Welbourn, G. L. Blan, and A. W. Livingstone, "A high speed GaAs 8-bit multiplexer using capacitor-coupled logic," *IEEE J. Solid-State Circuits*, vol. SC-18, pp. 359–364, 1983.

[6] C. Baack, G. Elze, and G. Heydt, "A fiber-optic broadband integrated services network for the subscriber area," in *Proc. Europ. Conf. Optical Commun.*, 1983, pp. 339–342.

[7] H.-M. Rein, D. Daniel, R. H. Derksen, U. Langmann, and B. G. Bosch, "A time division multiplexer IC for bit rates up to about 2 Gbit/s," *IEEE J. Solid-State Circuits*, vol. SC-19, pp. 306–310, 1984.

[8] H.-M. Rein, D. Daniel, R. H. Derksen, U. Langmann, and B. G. Bosch, "Design and implementation of a Gbit/s bipolar multiplexer IC," in *9th Eur. Solid-State Circuits Conf.*, 1983, pp. 85–88.

[9] W. Albrecht, C. Baack, G. Elze, B. Enning, G. Heydt, L. Ihlenburg, G. Walf, and G. Wenke, "Optical digital high-speed transmission: General considerations and experimental results," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1535–1547, Oct. 1982.

[10] B. G. Bosch, U. Langmann, and D. Daniel, "2.24 Gbit/s direct modulation of injection laser by monolithic silicon multiplexer," in *Dig. Tech. Papers IEEE MTT-S Int. Microwave Symp.*, 1984, pp. 537–539.

[11] P. M. Solomon and D. D. Tang, "Bipolar circuit scaling," in *Dig. Tech. Papers IEEE Int. Solid-State Circ. Conf.*, 1979, pp. 86–87.

[12] H.-M. Rein and R. H. Derksen, "An integrated time-division multiplexer for bit rates up to 3 Gbit/s," *Electron. Lett.*, vol. 20, pp. 546–548, 1984.