Optical transmitter with 1060 nm VCSEL for low power interconnect

Jean Benoit Héroux[1], Keishi Takaki[2], Clint Schow[3], Alexander V. Rylyakov[3], Richard John[3], Shigeru Nakagawa[1]

1. IBM Research - Tokyo, 1623-14 Shimotsuruma, Yamato, Kanagawa 242-8502, Japan
2. Photonic Devices Research Center, Furukawa Electric co., ltd., 6, Yawata-kaigandori, Ichihara, Chiba, 290-8555, Japan
3. IBM Research - T. J. Watson Center, 1101 Kitchawan Road, Yorktown Heights, NY 10598, USA
heroux@jp.ibm.com

Abstract: An optical transmitter composed of a 90-nm CMOS driver and a high efficiency 1060nm VCSEL is characterized. The 10Gb Ethernet eye mask specification is met with a +33% margin with 1.7 mW/Gbps power consumption.

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1. Introduction

As the complexity of high performance computers increases, there is a greater demand for short range, low power data links operating at a high bit rate within a system. Optical interconnect using VCSEL and photodiode arrays with a high channel density near the processors offers a solution to respond to this need. Recently, the use of strained InGaAs/GaAs quantum wells has led to the realization of VCSELs with a high differential gain and low threshold current, which is advantageous for low power optical interconnect. In parallel to this development, compact new CMOS circuits are being designed to operate laser and detector chip arrays at a high bit rate with low power.

Previously, we reported on a 10 Gbps optical interconnect transmitter using a high efficiency VCSEL operating at 980 nm with a record low 1.5 mW/Gbps power consumption [1]. In this work, we present recent progress on a single channel optical transmitter with a 1060 nm VCSEL [2] operating at 10 and 12.5 Gbps. The VCSEL used was developped by Furukawa Electric co. and has a double intra-cavity structure with a top DBR minimizing the cross-over region between the optical and electrical paths [3]. The laser driver was designed and fabricated at IBM using 90-nm CMOS technology [4].

2. Link components and measurements

The VCSEL has a 0.3 mA threshold current with a differential resistance decreasing from 112 Ω at 1.8 mA to 107 Ω at 2.5 mA. The slope efficiency is above 0.4 mW/mA for a bias below 3.5 mA, and the total output power at 2.5 mA is 946 µW. Fig. 1 shows the frequency response of the VCSEL measured with a GS coplanar probe and a network analyzer (Agilent N5230). A 3 dB frequency f_{3dB} of 12.8 GHz is measured at 2.5 mA, with a slope of 9.9 GHz/√mA at low bias. The device has a relatively high damping at low frequency, which is advantageous to avoid signal distortion and obtain a clear eye pattern in a digital optical link.

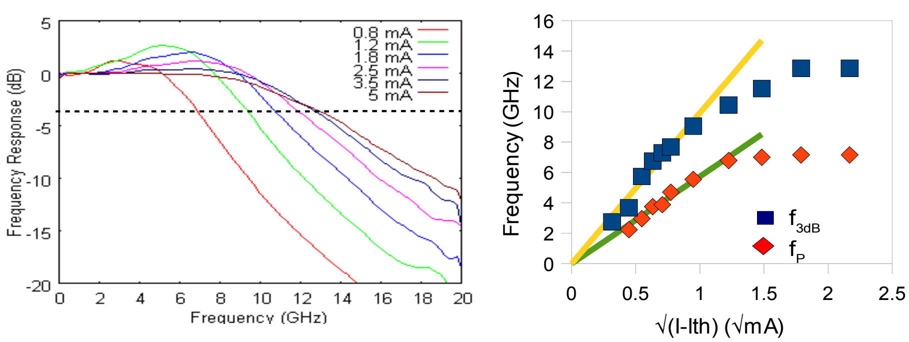

Fig. 1. Small signal frequency response of the VCSEL device.

The laser driver connected to the VCSEL has a 0.056 mm^2 area and three stages with adjustable biases as shown in Fig. 2. A 2^7-1 PRBS signal pattern with a differential 350 mVp-p amplitude was sent to this driver using a GSGSG co-planar microwave probe to simulate a data stream from a 90-nm CMOS chip. High speed characterization of the system was performed with a digital communication analyzer (Agilent 86100C) equipped with an optical receiver module (86105D) and a lens-terminated 50-µm diameter multimode optical fiber. The coupling efficiency from the VCSEL to the analyzer was measured and found to be 2 dB.

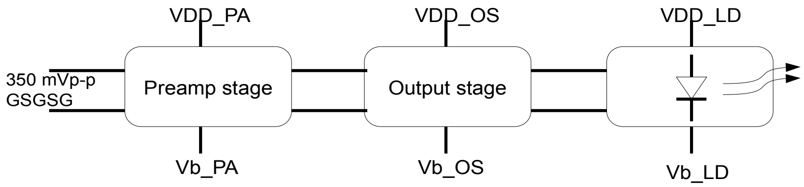

Fig. 2: Three-stage driver schematic description.

3. Results and link optimization stragegy

Fig. 3 (a) shows the back-to-back eye pattern obtained at 10 Gbps with a -4 dBm optical modulation amplitude (OMA). The eye diagram satisfies the 10 Gigabit Ethernet mask specification with a +33% margin with no failed samples over 1000 waveforms, which represents an improvement over our previous results [3]. Bathtub curves are shown in fig. 2 (b) and (c). The eye opening extrapolated to a 10^{-12} bit error ratio is 0.49 UI, and the total jitter is 46 ps. The measured average zero and one optical levels are 265 and 517 µW respectively, corresponding to a 2.9 dB extinction ratio and DC current levels of 1.3 and 2.17 mA.

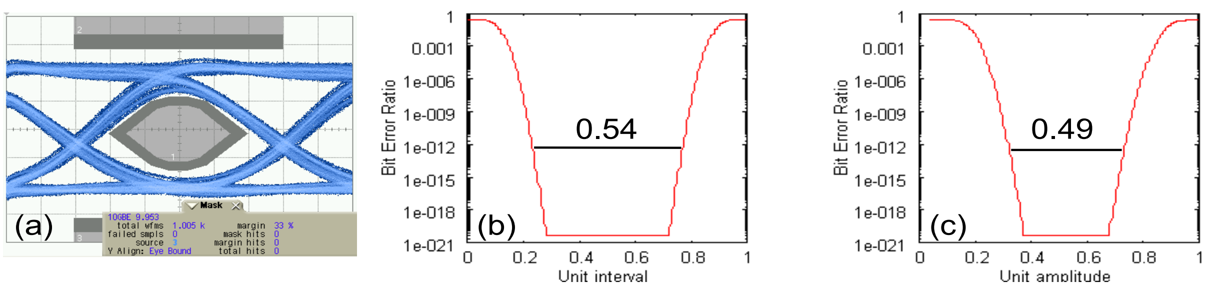

Fig. 2: Eye pattern and bathtub curves obtained at 10 Gbps.

We also tested the transmitter at 12.5 Gbps. In this case, a clear eye opening as shown in Fig. 3 was obtained with an OMA of -1 dBm at the emitter. The eye opening and total jitter are 0.50 UI and 33.1 ps respectively, and the average zero and one optical levels are 939 and 1440 µW corresponding to 3.8 and 6.67 mA DC current levels. intersymbol interference is visible in the eye pattern.

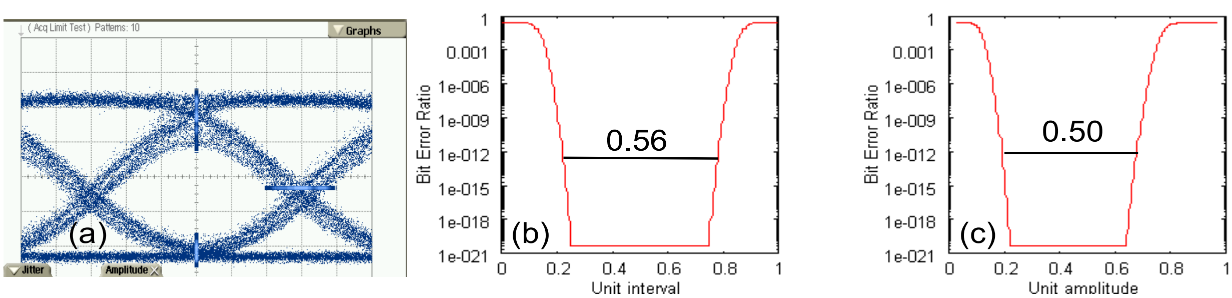

Fig.3: Eye pattern and bathtub curves obtained at 12.5 Gbps.

We now comment on the use of a long operation wavelength and our optimization strategy to decrease the power consumption of an optical link. The input and output voltage pulse amplitudes are fixed and determined by the CMOS chip technology. Between these two end points, there is some flexibility to select components and adjust parameters to obtain the best performance. For a typical optical link, a -4 dBm OMA at the VCSEL output is used and a total loss of 7 dB is allowed in the optical path. An OMA above -11 dBm reaches the receiver, with an eye width above 0.4 UI.

The use of a VCSEL with compressively strained quantum wells in the active region is advantageous to decrease the link power as the transparency current decreases and the differential gain increases [5]. A higher modulation current efficiency, and thus high modulation bandwidth with low bias current, can thus be obtained. An additional advantage of the structure that we used with an InGaAs/GaAs active region is a high reliability, as demonstrated experimentally in [3]. GaAs is also transparent at 1060 nm, so that a top or bottom emitting design can be used in a system [6].

An important adjustable paramater is the VCSEL DC bias current, which is lowered as much as possible while maintaining a clear eye pattern. The laser driver has six adjustable biases determining the gain at the three stages and the VCSEL modulation condition. With careful tuning, a low consumption power and clear eye pattern can be obtained. Table 1 shows bias settings that were used at 10 and 12.5 Gbps. The power per Gbps for the eyes shown in Figs. 2 and 3 are 1.78 and 3.1 mW/Gbps respectively. At 10 Gbps, the power consumption is slightly higher than our previous result [2] and the extinction ratio is slightly below our target of 4 to 6 dB due to the fact that the zero level had to be kept relatively high to avoid mask hits at the lower edge. However, the results that we obtain are better than for a link where a state-of-the-art commercial 850 nm VCSEL was used, i.e., larger eye opening and lower power consumption.

Table 1: Three-stage preamp settings at 10 and 12.5 Gbps. Settings at the Vb levels are not shown and have a current in the µA range.

Gbps	Output OMA (dBm)	Total Power (mW)	VDD-PA	IPA	VDD-OS	IOS	VDD-LD	ILD	Mask margin (%)	Eye opening (mUA)	Jitter (ps)
10	-1	23.9	0.87	17	0.72	4	2.09	3	39	631	31.4
10	-4	17.6	0.79	16	0.55	2	1.9	2	33	492	45.9
12.5	-1	38.5	1.09	23	0.64	3	2.3	5	0	500	33.1

An advantage of using 1060 nm over an 850 nm wavelength is that if low cost, legacy OM2 fibers with an index profile optimized for a peak bandwidth near 1.1 µm are used (as opposed to higher cost OM3 fibers), the penalty is less. As a result, good performance can be obtained with negligible signal degradation for an OM2 fiber as long as 100 m or more, which is suitable for rack to rack communication.

For the receiver system, InGaAs lattice-matched to an InP substrate is used as an active region at 1060 nm, whereas a GaAs intrinsic region is a better choice at 850 nm. The absorption coefficient is a factor over 2.5 higher in the former case, and the structure of the detector must be modified accordingly to obtain a high bandwidth. InP is transparent at the longer wavelength, so that back illumination is possible and overall system design flexibility is enhanced.

We are planing next to integrate a receiver to the present system to obtain data with a complete long wavelength optical link. With further optimization of the transmitter and other components, we expect low power operation at data rates of 15 Gbps and above with a total power consumption below 5 mW/Gbps, and bit error ratio well below 10^{-12}. Clear eye patterns with large opening were recently obtained from measurements performed with the VCSEL devices directly modulated with a large-form, commercial pulse pattern generator at 20 Gbps [7].

4. Summary

In summary, a high efficiency optical transmitter including a 1060nm VCSEL and a 90-nm CMOS driver was built and characterized. The 10Gb Ethernet eye mask specification is met with a 33% margin with 1.7 mW/Gbps power consumption. A clear eye pattern with -1 dBm OMA and a 3.1 mW/Gbps power consumption was obtained at 12.5 Gbps.

5. References

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