Digital Communications Above 1 Gb/s Using 890-nm Surface-Emitting Light-Emitting Diodes

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***Abstract*—We report high-speed digital modulation of GaAs–AlGaAs light-emitting diodes. Open eye patterns and bit error rates less than 10^{-9} were obtained for data rates from 750 Mb/s to 1.7 Gb/s. These results are the first report, to our knowledge, of error-free digital modulation experiments for LEDs at bit rates above 1 Gb/s.**

***Index Terms*—Digital communication, error analysis, light-emitting diodes, optical communication, optical interconnections, optical transmitters.**

I. Introduction and Device Specifications

OPTICAL fiber data links rely on both semiconductor light-emitting diodes (LEDs) and lasers [diode, fiber, and vertical cavity surface-emitting (VCSEL) lasers] as sources. Although lasers offer higher performance, the low cost, easy fabrication, simplicity, and high reliability of the LED make it an interesting choice for some short-distance (tens of meters or below), moderate-speed serial and parallel interconnect applications, such as computer peripheral interconnects for local area networks, home networks, and gigabit Ethernet. Commercial LEDs currently support modulation bandwidths up to 800 MHz [1]. We recently reported high-efficiency LEDs with an analog frequency response of 1.7 GHz [2]. Here, we describe the first high-speed digital modulation experiments using these LEDs. Our results demonstrate error-free modulation well above 1 Gb/s, for the first time to our knowledge for LEDs. These results are a step toward demonstrating LED-based data links above 1 Gb/s for local interconnect applications.

In LEDs, high-speed operation is usually achieved with heavily doped material since the radiative minority carrier lifetime decreases as the carrier concentration increases, resulting in an increased bandwidth [3]. Heinen *et al.* and De Lyon *et al.* reported LEDs with cutoff frequencies of ~800 MHz [4] and above 1 GHz [5]. However, the resulting efficiencies of 0.4 μW/mA are insufficient for digital communications. The infrared LEDs we used in our experiments have a GaAs–AlGaAs double heterostructure grown by molecular beam epitaxy (MBE) [2] at reduced growth temperature [2], [6]. The excess arsenic forming at the reduced growth temperature results in nonstiochiometric GaAs epilayers, which make it possible to achieve a beryllium doping of 7×10^{19} cm^{-3} with an external quantum efficiency of 2.5 μW/mA. The power versus current curve is linear for currents up to 100 mA. The device design is simple and no extra effort (such as antireflecting or passivating layers) has been spent on extracting the light. The internal quantum efficiency is measured to be ~10%. The emitting surface diameter is ~60 μm with area around 2830 μm^2. Although the emission area is relatively large (which increases the output power), the speed is still high due to the heavy doping. The measured small signal electrical bandwidth is ~1.7 GHz at the 3-dB point. The light spectrum peaks at ~890 nm with approximately 50-nm bandwidth.

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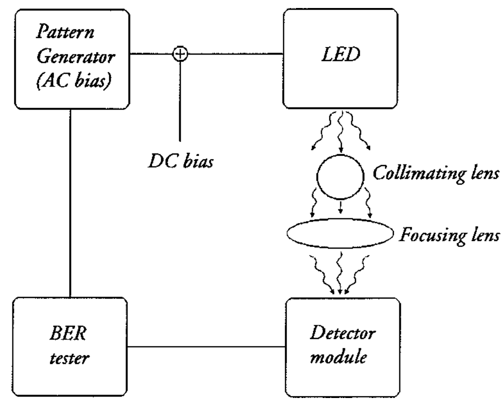

Fig. 1. Experimental setup.

II. Digital Communication Experiments

The experimental setup is shown in Fig. 1. We tested the digital modulation performance of these LEDs in a simple back-to-back configuration, where light from the LED was focused directly onto a photodetector. The LED was driven with signals originating from a pattern generator that is part of a bit error rate (BER) test set, and the error counter part of the set with a fast oscilloscope were used to analyze the BER performance and the received eye diagrams. One difficulty with LEDs is that due to the large divergence of the emitted light (most of the power is in the 120° arc according to Lambert's cosine law), the light is hard to collect. We obtained the best results using a pair of lenses, one acting as a collimator, the second as a focusing element. A ball lens performed best as the collimator due to its low F number. Either an aspheric

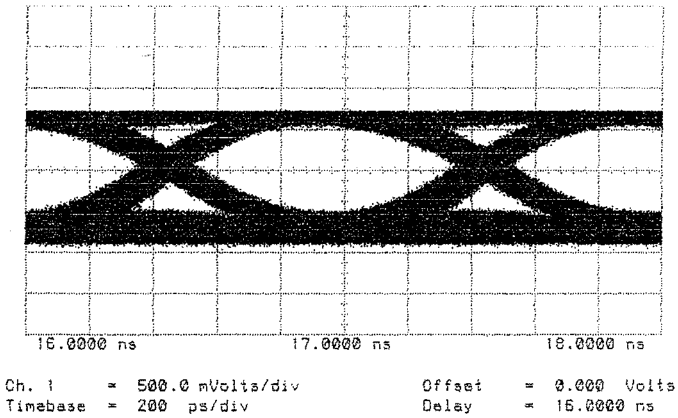

Fig. 2. Eye diagram for $2^{31} - 1$ PRBS at 1 Gb/s.

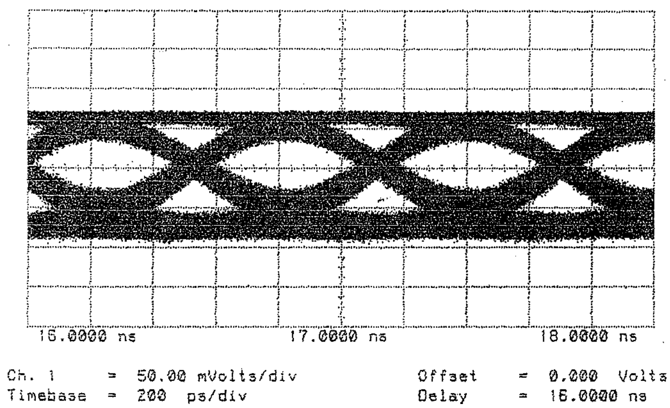

Fig. 3. Eye diagram for $2^{31} - 1$ PRBS at 1.7 Gb/s.

condenser lens or a biconvex lens was used as the focusing element with comparable results. The LED was modulated with a current of 0–90 mA (maximum optical output of 225 μW) using length $2^{31} - 1$ pseudorandom bit sequences (PRBS). The detector package (Hamamatsu C5658) consisted of a silicon avalanche photodiode (APD) integrated with a low-noise amplifier. The detector has a 3-dB cutoff frequency of 1 GHz, an effective diameter of 0.5 mm, a temperature-stabilized avalanche gain of 100 and a total responsivity of 1.75×10^5 V/W at 890 nm. We were able to achieve $\sim$3.4% coupling efficiency from the LED to the detector. This gave a maximum received power of $\sim$7.5 μW, resulting in a zero-to-peak signal of 1.4 V at 750 MHz.

The eye patterns for modulation at 1 Gb/s and 1.7 Gb/s are shown in Figs. 2 and 3. In both cases the eyes are wide open, although a significant decrease in the distance between the rails is observed in the 1.7-Gb/s trace. We attribute this primarily to the 1-GHz photodetector bandwidth, which is less than the measured LED bandwidth. BER curves for 750 Mb/s, 1 Gb/s, 1.5 Gb/s, and 1.7 Gb/s are displayed in Fig. 4. In all cases, we were able to measure BERs below 10^{-10} and observe a linear BER versus power plot with no sign of an error rate floor. Compared to the trace at 750 Mb/s, the power penalties at 1, 1.5, and 1.7 Gb/s are approximately 1, 5, and 7 dB at 10^{-9} BER. The increasing power penalties above 1 Gb/s are expected due to the bandwidth limitation of the detector as well as (at the higher modulation rates) the LED. Additionally, a comparison of the 1-Gb/s BER performance for four individual LEDs is presented in Fig. 5. As can be seen, reasonably similar BER results are obtained for the devices with received power variations of $\sim$2 dB. The variations occur because the individual devices belong to several different growths and process runs with slight differences in doping levels and layer thickness. The required powers for 10^{-9} error rate performance range from approximately -29.5 dbm to -31.5 dbm, which is 8–10 dB below the maximum power we could couple onto the photodetector at 1 Gb/s.

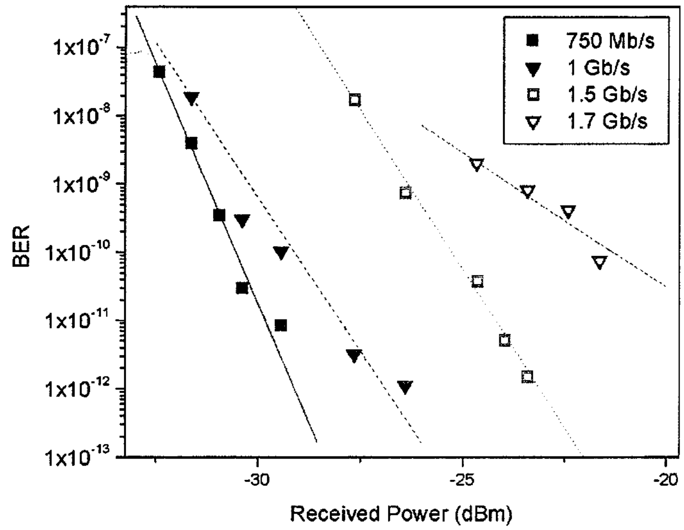

Fig. 4. BER performance at various data rates.

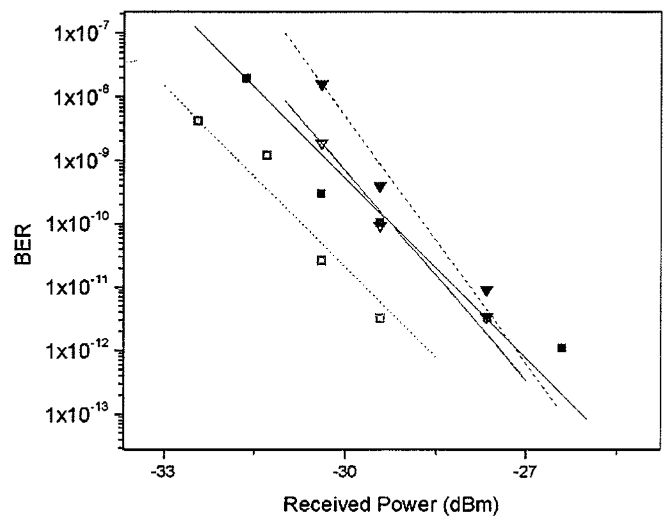

Fig. 5. Comparison of 1-Gb/s BER performance for four individual devices.

III. Discussion

Due to the push for low cost in local interconnect applications, a simpler receiver such as a p-i-n structure would be preferred. Unfortunately, the power that could be coupled onto the detector in our experiments was insufficient for good error rate performance with a simple p-i-n. The electrical signal-to-noise ratio (SNR) for a thermal noise limited p-i-n detector is given by the well known formula [7]

$$\mathrm{SNR} = \frac{I_p^2}{\left(\frac{4kTBF_n}{R_L}\right)}$$

where

- I_p photocurrent;
- B receiver bandwidth;
- R_L load resistor;
- F_n noise figure of the electronic amplifier following the detector.

To relate the SNR to the BER, Gaussian statistics are assumed for the additive noise, and the following formula is obtained [7]:

$$\mathrm{BER} = \frac{1}{2}\, erfc\left(\frac{\sqrt{\mathrm{SNR}}}{2\sqrt{2}}\right).$$

The SNR required for a BER of 10^{-9} is calculated as ~144. If we assume a 50-Ω load resistor, a 1-GHz bandwidth, and $F_n = 3$ dB, we find that a photocurrent of ~9.8 μA is required for a BER of 10^{-9}. For a detector responsivity of 0.35 A/W, this corresponds to 26.2-μW received power, which is significantly greater than the power we could couple at this bandwidth (~7.1 μW). The choice of the APD–low-noise amplifier receiver in the current experiments provides a very high sensitivity [7] enabling us to investigate the LED large signal modulation characteristics above 1 Gb/s.

There are several possibilities that might allow improvements in the future. The LEDs themselves can be improved through texturing of the LED surface [8] or fabricating an integrated dome lens structure [9] in order to increase their brightness and coupling efficiency. Furthermore, other choices of receivers are possible. For example, relatively simple p-i-n-FET or MSM-FET detectors [10] can be optimized to allow a larger area (hence, better power collection) at bandwidths comparable to or even higher than the current value of 1 GHz.

IV. Conclusion

We have demonstrated error-free digital modulation of an LED at bit rates above 1 Gb/s. BERs below 10^{-9} were achieved at rates up to 1.7 Gb/s. With further improvements, such sources have potential for applications in short-distance optical interconnects.

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