Data Transmission at 3 Gb/s over PCB Integrated Polymer Waveguides with GaAs VCSELs

Felix Mederer

GaAs quantum-well based vertical-cavity surface-emitting lasers (VCSEL) at 855 nm emission wavelength are investigated for intraboard polymer waveguide links. We report a 3 Gb/s pseudo random bit sequence (PRBS) non-return-to-zero (NRZ) data transmission over about 5 cm long printed circuit board (PCB) integrated multi-mode polymer waveguide arrays of two different geometries at bit-error rates (BER) of better than 10^{-11}.

1. Introduction

The bottleneck for the next generation of microprocessors with clock rates of more than 1 GHz are the power dissipation and delay time of microchips and multichip modules interconnects [1]. Even with an improved layout the maximum bandwidths and distances of conventional metal based electronic lines are limited and will not satisfy future demands for mid distance (≤ 60 cm) high-throughput (> 1 Gb/s) point-to-point interconnects [2]. Optoelectronic interconnect solutions on the other hand offer the potential for multi-Gb/s transmission over standard distances for high-speed clock and data distribution without increasing power dissipation, delay times [3] and sensitivity for electromagnetic interference (EMI) [4]. Obviously for current supply and low-bandwidth data communication electric metalized circuits are still needed on processor boards. These two demands lead to a hybrid electrical-optical board layout concept with the combined advantages of electrical strip lines and optical waveguides for high-throughput data transmission [5]. VCSELs are highly attractive light sources for low-cost, high-speed data transmission over polymer based optical intraboard waveguides. GaAs or InGaAs based VCSELs with emission at 850 nm or 980 nm wavelengths, threshold currents in the sub-100 μA range [6] and threshold voltages close to the bandgap voltage in combination with extremely high wallplug efficiencies over a large operation range [7] helping to reduce power consumption and dissipated heat in system applications. Nearly temperature independent output characteristics over a -20°C to 100°C temperature range [8], modulation bandwidths of 21.5 GHz [9] and reported single-mode emission of 5.0 mW [10] show the capability for ultra fast, low-cost optical links up to 12.5 Gb/s data rates [11].

In this paper we demonstrate 3 Gb/s data transmission over multi-mode printed circuit board integrated polymer waveguide arrays using a multi-mode GaAs VCSEL source emitting at 855 nm wavelength. Waveguide cores consist of polymer material and are 4.6 cm and 4.3 cm long, with rectangular or trapezoidal cross sectional shapes of about 0.015 mm^2 area.

2. Waveguide Characteristics

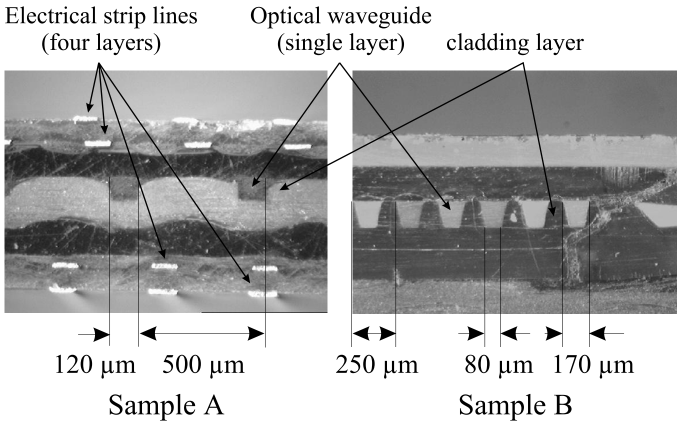

Fig. 1. Cross-sectional view of printed circuit board sample A containing an optical waveguide layer sandwiched between electrical strip layers and sample B with trapezoidal cross sectional waveguide layer.

Fig.1 shows a cross-sectional view of intraboard waveguide array sample A with a single layer of optical waveguides integrated into a four-layer electrical board and sample B with trapezoidal cross sectional shapes. To remain fully compatible with standard electrical PCB manufacturing, the waveguide materials have to withstand long term (>1h) exposure of high temperature (160°C). The waveguides are formed by a two step hot embossing process. In a first step, the waveguide cores are fabricated by using a metal master form, which contains the inverse waveguide structure in form of grooves.

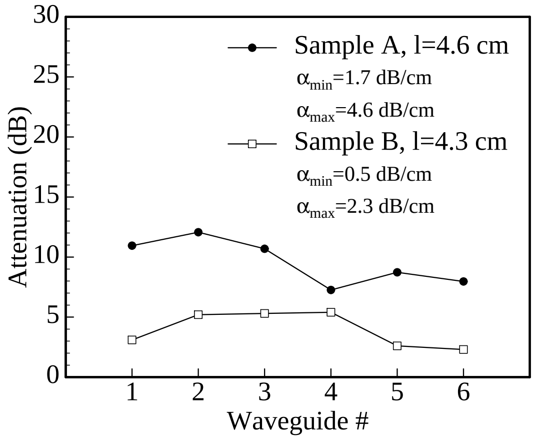

Fig. 2. Attenuation characteristics of several PCB integrated optical waveguides of sample A and B at $\lambda = 835\,\text{nm}$ wavelength.

The waveguide fabrication itself is performed by pressing a high refractive index, temperature stable and highly transparent polycarbonate foil under heat and force into these grooves. In the following second step, a low refractive index substrate foil is laminated on the waveguides. After this step the waveguide-substrate combination is removed from the metal master form and coated with an optical cladding. Waveguides in sample A are arranged at 500 μm pitch and have rectangular shapes of about $120\times130\,\mu m^2$ area. Sample B contains waveguides of trapezoidal shape arranged at 250 μm pitch.

Fig.2 shows the attenuation loss of six individual waveguides of sample A and B measured with a multi-mode VCSEL source. At a wavelength of 855 nm minimum waveguide attenuations of sample A and B are 1.7 dB/cm and 0.5 dB/cm, respectively. As a future alternative, using waveguides made of new COC polymer material with an attenuation minimum of 0.15 dB/cm at 850 nm wavelength [12], short distance (<100 cm) optical data transmission will be no longer attenuation limited.

3. VCSEL Characteristics

Top-emitting selectively oxidized GaAs based 855 nm emission wavelength VCSELs are fabricated using solid source molecular beam epitaxy. The bottom $Al_{0.9}Ga_{0.1}As$/ $Al_{0.1}Ga_{0.9}As$ distributed Bragg reflector (DBR) consists of 37 n-type Silicon doped layer pairs. The active region contains three 8 nm thick GaAs quantum-wells embedded in $Al_{0.2}Ga_{0.8}As$ spacer layers to provide efficient carrier confinement. The top DBR consists of 19 Carbon doped $Al_{0.9}Ga_{0.1}As$-$Al_{0.1}Ga_{0.9}As$ layer pairs. For current confinement a selectively oxidized 30 nm thick AlAs layer is inserted in the top mirror. Planarizing polyimide passivation is used to reduce bondpad capacitance. The laser is wire-bonded from a Ti/Au bondpad to an SMA socket to keep feeding lines as short as possible.

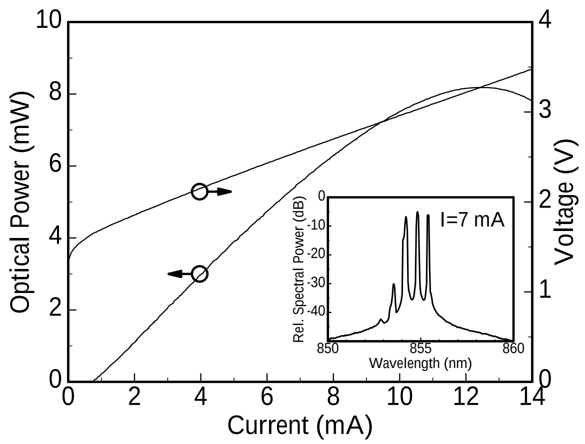

Fig. 3. Output characteristics for a laterally oxidized GaAs VCSEL of 8 μm active diameter.

Output characteristics of the VCSEL with an active diameter of 8 μm are given in Fig.3. Threshold current is as low as 0.8 mA and the maximum output power is 8.2 mW at a current of 12 mA. The CW emission spectrum for 7 mA driving current is given in the inset of Fig.3. The multi-mode emission is centered at 855 nm wavelength.

4. Data Transmission Results

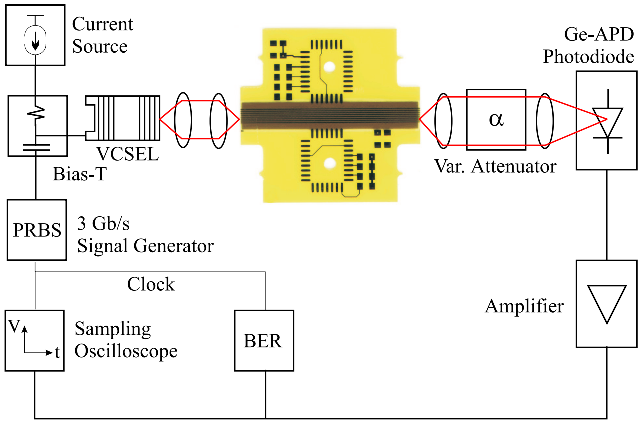

Fig. 4. Setup for data transmission experiments.

The setup for data transmission experiments is indicated in Fig.4. The VCSEL is biased at 7 mA current and modulated with a 1.5 V_{pp} PRBS signal. After transmission through the waveguides the optical signal is passed through a variable attenuator and detected with a 50 μm diameter Germanium avalanche photodiode of 2 GHz bandwidth using demagnifying imaging. The amplified digital signal is monitored with an electrical sampling oscilloscope and analyzed with a BER detector.

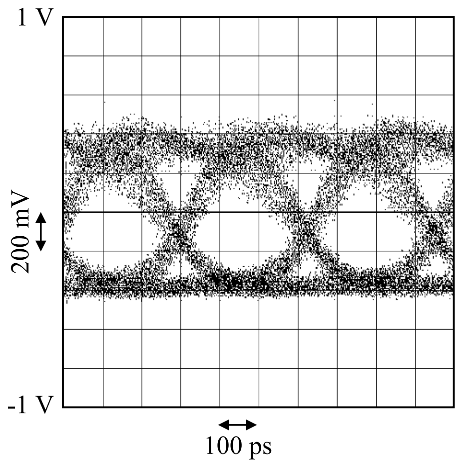

Fig. 5. Eye diagram recorded for 3 Gb/s PRBS of $2^{31} - 1$ word length over sample A.

Fig.5 illustrates the eye diagram for 3 Gb/s PRBS modulation recorded after transmission over a waveguide of sample A. The eye is symmetric and without any significant relaxation oscillations. Similarly, the eye diagrams for the other waveguides on sample A or sample B show no significant differences to Fig.5.

Fig.6 shows the results of the transmission experiments where the BER is plotted versus the received optical power. For 3 Gb/s PRBS NRZ signals of $2^{31} - 1$ word length the

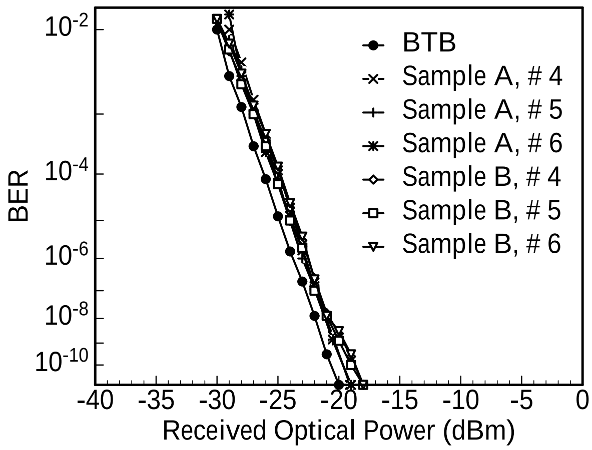

Fig. 6. BER recorded for 3 Gb/s PRBS of $2^{31} - 1$ word length.

received optical power for a BER of 10^{-11} is -20 dBm under back-to-back operation (BTB, filled circles). For sample A a power penalty of 1 dB is found for transmission over waveguides 4,5 and 6 (crosses, pluses and stars). Using sample B, the power penalty for a BER of 10^{-11} is 2 dB for waveguides 4, 5 and 6 (diamonds, rectangles and down-triangles).

5. Conclusion

We have successfully demonstrated VCSEL based error-free 3 Gb/s data transmission over highly multi-mode intraboard polymer optical waveguides. Using optimized fabrication technology still compatible with standard PCB manufacturing we have achieved waveguide losses as low as 0.5 dB/cm at 855 nm wavelength. Even lower losses obtaining quite recently indicate that mode dispersion rather than waveguide attenuation is of primary concern for extremely high bandwidth, e.g. 10 Gb/s, intraboard optical interconnects when transmission distances of several ten cm length are to be considered .

Acknowledgments

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