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A1 (Plenary)

ADVANCES IN OPTICAL INTERCONNECT TECHNOLOGY

K.J. Ebeling, F. Mederer, R. King, M. Kicherer, G. Steinle, and R. Michalzik
University of Ulm, Department of Optoelectronics,
Albert-Einstein-Allee 45, D-89069 Ulm, Germany,
Phone: ++49-731-50-26051, Fax: ++49-731-50-26049
E-Mail: karl.ebeling@e-technik.uni-ulm.de

Abstract

VCSEL based optical interconnects for datacom applications are reviewed. In some detail, we discuss 4 × 10 Gbit/s coarse WDM transmission, wide temperature −20 to +100 °C operation, novel GaInNAs VCSEL sources for 1.3 μm wavelength emission, 8 Gbit/s polymer image fiber and 10 Gbit/s printed circuit board integrated optical waveguide transmission as well as two-dimensional VCSEL array modules flip-chip bonded to CMOS drivers.

Introduction

Ever increasing clock rates in computers, presently just passing 1 GHz, and ever growing traffic in the internet with data rates above 1 Terabit per second observed in single-fiber backbone strands indicate the stringent speed requirements imposed on current and future data distribution and data processing systems. It is generally agreed upon that such high data rates can be transmitted most favorably by using optical techniques. Moreover, vertical-cavity surface-emitting laser diodes (VCSELs) [1],[2] are considered almost ideal transmitters for short distance optical interconnects such as local area computer network, rack-to-rack or board-to-board interconnects, or eventually maybe even inter-chip data links. Reasons are manifold, but low driving current and voltage, compatibility with CMOS electronics, high speed operation and high beam quality for efficient fiber coupling, simple formation of two-dimensional arrays for massively parallel links, or low cost mass fabrication with ready on-wafer testing are obvious advantages of VCSEL sources compared to conventional edge emitting laser diodes. It is the purpose of the present contribution to review some recent progress of VCSEL based optical interconnects.

VCSEL Sources for Coarse WDM and Wide Temperature Operation

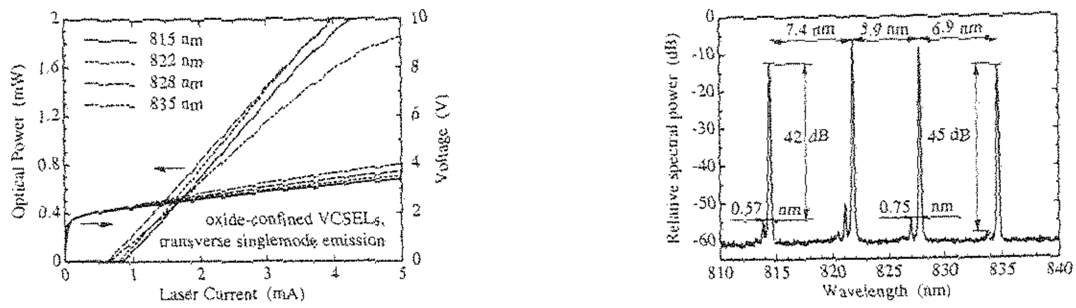


Figure 1: Transverse singlemode, selectively oxidized VCSEL operation characteristics for all four channels of a 40 Gbit/s CWDM system experiment (left) and combined spectrum of the CWDM VCSEL source with all devices driven at 3 mA current (right). Channel wavelength separations, transverse mode spacings and corresponding side-mode suppression ratios are indicated in the figure.

Coarse wavelength division multiplexing (CWDM) with several nm channel spacing is an attractive option for increasing the data throughput in often low-bandwith limited multi-mode fiber (MMF) links. Recently, we have reported 10 Gbit/s data transmission over record distances of 1.6 km [3] or even 2.8 km of a new high-bandwidth 50 μm core diameter MMF with an improved parabolic graded-index profile. Here we

butt Coupling Sys/o
VCSEL - Fiber > 90%

Four singlemode VCSEL outputs at 815, 822, 828, and 835 nm wavelength as shown in Fig. 1 are combined to form the CWDM signal. Each VCSEL is driven by 10 Gbit/s data streams using SMA-connectorized packages containing coplanar strip lines wire-bonded to the ground-signal-ground contacts of the individual lasers. For the transmission experiment, all VCSELs are biased at 3 mA using bias tees and driven by mutually decorrelated 10 Gbit/s pseudorandom bit sequences (PRBS) with $2^7 - 1$ word length. Fig. 2 illustrates measured bit error rates (BERs) for all channels as a function of average received power both with and without inserting the 310 m long MMF cable. In all cases, error rates down to 10^{-12} are achieved without indications of a BER floor. Power penalties vary between 1 and 3 dB, partly due to the relatively low adjacent channel suppression of just 15 dB.

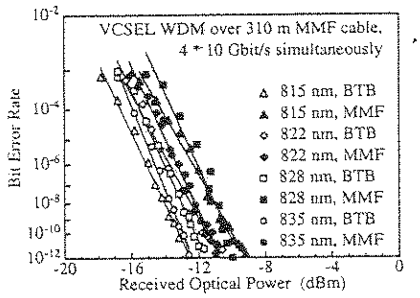


Figure 2: BERs for all four channels versus optical power at the receiver for individual 10 Gbit/s back-to-back (BTB) operation and transmission over 310 m of 50 μm core diameter MMF cable.

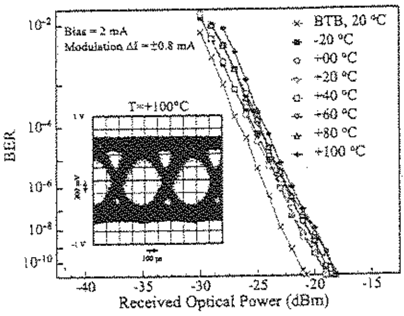
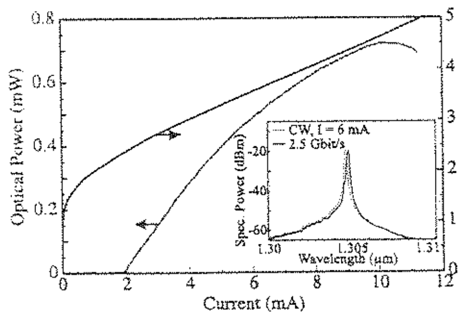


Figure 3: Temperature dependent BER characteristics at 2.5 Gbit/s for 250 m MMF transmission and eye diagram at 100 °C for a BER of 10^{-11} in the inset.

In order to demonstrate the potential of the system for wide temperature operation we show in Fig. 3 BER performance of an individual singlemode VCSEL at various temperatures, operating the laser at fixed bias and modulation currents. It is seen that 2.5 Gbit/s error-free data transmission is easily achieved over a temperature range of –20 to +100 °C.

GaInNAs VCSELs for Data Transmission at 1.3 μm Wavelength



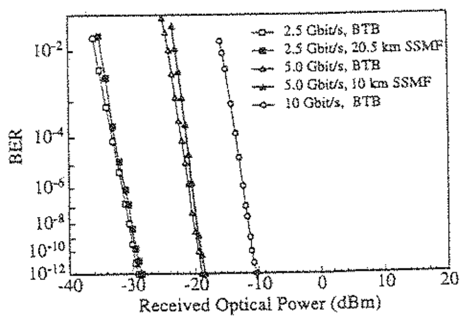


Figure 4: Output characteristics of a 4×6 μm^2 active area singlemode selectively oxidized GaInNAs VCSEL and emission spectrum at 6 mA in the inset (left). BER characteristics for $2^7 - 1$ word length PRBS 2.5 Gbit/s data rate transmission over 20.5 km SSMF and for BTB testing, 5 Gbit/s BTB and over 10 km SSMF and 10 Gbit/s BTB (right).

VCSELs with 1.3 μm wavelength emission are well suited for standard singlemode fiber data transmission thus extending typical datacom applications into the local area network (LAN) arena. Fig. 4 shows output characteristics of a singlemode intracavity contacted GaInNAs VCSEL emitting at 1304 nm wavelength and BER characteristics for data transmission [5]. Although the maximum output power is limited to 700 μW and the electrical layout is not yet optimized for high speed operation we achieve error-free transmission at 2.5 Gbit/s and 5 Gbit/s over 20.5 km and 10 km of standard singlemode fiber and still 10 Gbit/s transmission over short distance.

High-Speed Data Transmission over Multi-Mode Polymer Optical Waveguide

Image polymer optical fiber (POF) as well as printed circuit board (PCB) integrated polymer waveguides are considered convenient low-cost media for short distance data links. We have explored speed limits of both kinds of systems.

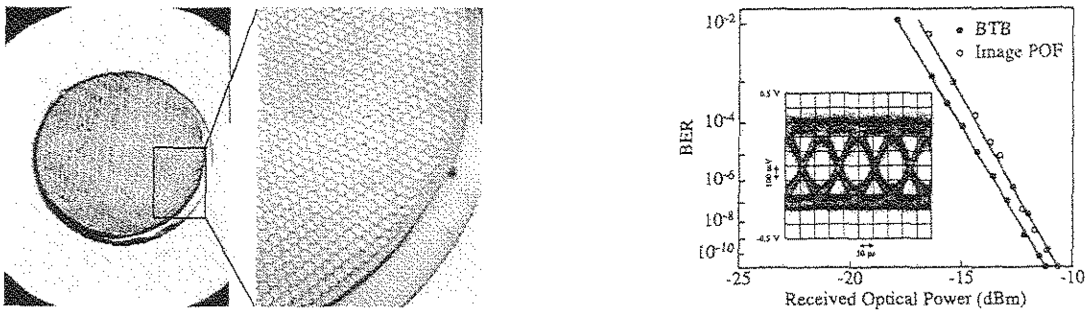


Figure 5: Cross-sectional view of 1 mm diameter image POF consisting of some hundreds of 10 μm step-index POFs (left). Eye diagram for a BER of 10^{-11} and BER characteristics at 8 Gbit/s and $2^7 - 1$ PRBS word length for 52 cm long, 1 mm diameter image-POF transmission (right).

Fig. 5 shows a cross-sectional view of an image POF and BER characteristics for 8 Gbit/s transmission over 52 cm length of image POF. The image fiber consists of some hundreds of 10 μm diameter step-index POFs. Due to the smaller number of guided modes the bandwidth-length product is considerably larger than in standard 120 μm step-index POFs. In addition, optical coupling of the 10 μm diameter fiber elements to small area high-speed photodetectors is much easier than in conventional POF and excess noise due to mode selective losses can be avoided. Measured attenuation of the 52 cm long image POF under investigation is 5 dB at 980 nm wavelength. Measured bandwidth-length product is 3 GHz·m which is to be compared to 2 GHz·m typical for 120 μm diameter step-index POF. BER studies in Fig. 5 indicate that 8 Gbit/s error-free transmission can be achieved over 52 cm image POF.

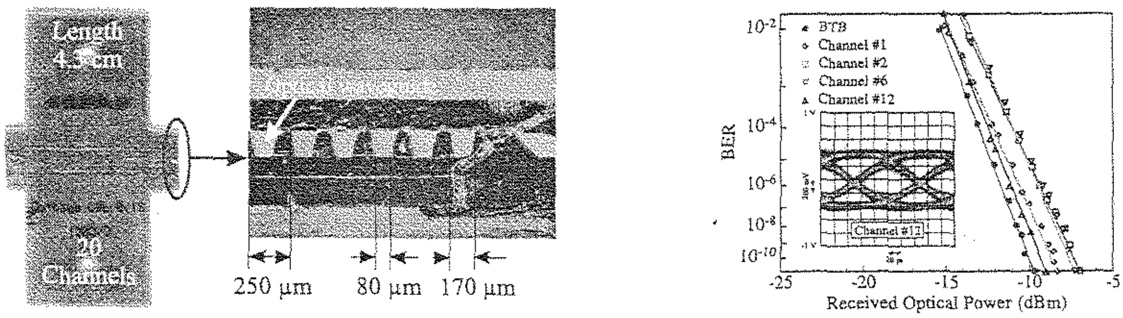


Figure 6: Top and cross-sectional view of PCB integrated polymer optical waveguides (left) and BER performance of various channels for 10 Gbit/s data transmission over the 4.3 cm long waveguides of trapezoidal cross-sectional shape (right).

Fig. 6 shows top and side views of a 20-channel intraboard waveguide array and measured BER behavior for data transmission at 10 Gbit/s over 4.3 cm long waveguides. In order to remain fully compatible with standard electrical PCB manufacturing, the waveguide materials have to withstand long term (> 1 h) exposure to high temperatures (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 the form of grooves. 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. The waveguides have a trapezoidal shape and are arranged at 250 μm pitch. Minimum waveguide attenuation of the first prototypes is about 0.5 dB/cm. Light is launched into the edge of the board and coupled into a 50 μm core diameter MMF pigtail of a 10 Gbit/s-compatible InGaAs pin-photodiode based receiver. BER characteristics measured for various channels show that 10 Gbit/s signals can be easily transmitted in an error-free fashion.

4×8 Two-Dimensional Interconnection Modules

The use of 2-D optical data transport is especially attractive for CMOS chip-to-chip interconnections where due to increased clock speed and integration density electrical data lines approach their physical limit. Fig. 7 shows the photograph of an optoelectronic field programmable gate array chip with interleaved CMOS analog driver and receiver circuitry onto which VCSEL transmitter arrays and InP-based photodiode arrays are flip-chip mounted. The hardware is the result of a major collaborative effort in a EU funded project [6],[7] where IMEC-Ghent University and ETH Zurich were responsible for the CMOS part, Ulm University provided the VCSEL array and transmitter testing, and Marconi Caswell were involved in flip-chip mounting and packaging. The 0.6 μm-CMOS VCSEL transmitter contains 32 parallel channels. Eye diagrams of four arbitrarily chosen VCSEL channels recorded at 1 Gbit/s data rate are depicted in the right hand part of Fig. 7. Power consumption of the transmitter chip is 15.7 mW per channel for 1 Gbit/s modulation rate.

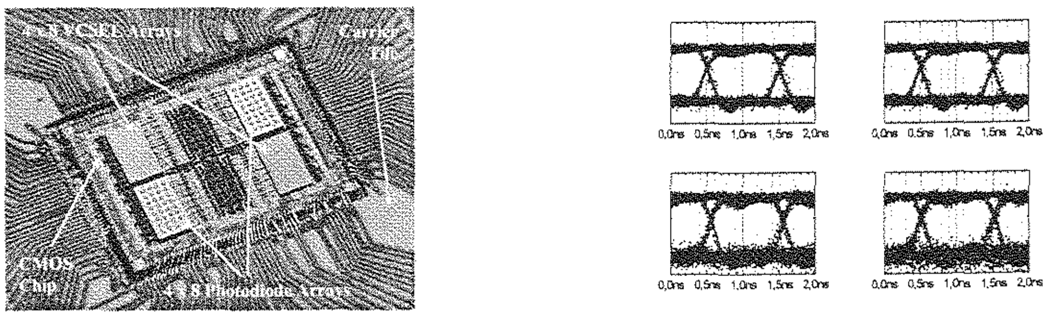


Figure 7: VCSEL and pin-photodetector 4×8 arrays flip-chip mounted on a CMOS chip (left) and eye diagrams of four arbitrarily chosen VCSEL channels driven at 1 Gbit/s data rate (right).

Conclusions

We demonstrated 4 × 10 Gbit/s CWDM optical data links operating at 850 nm wavelength, studied 10 Gbit/s operation of novel 1.3 μm wavelength GaInNAs VCSELs, analyzed polymer image fiber and PCB integrated waveguides for 8 Gbit/s and 10 Gbit/s data transmission, and finally presented 4×8 CMOS integrated VCSEL array modules for low power 1 Gbit/s per channel transmission. The various results demonstrate the attractive potential of VCSEL sources for high throughput optical interconnects.

References

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