Integrated Optoelectronic Chips for Bidirectional Optical Interconnection at Gbit/s Data Rates

Martin Stach and Alexander Kern

We report on the fabrication and properties of 850 nm wavelength AlGaAs–GaAs-based transceiver chips, in which vertical-cavity surface-emitting lasers (VCSELs) and metal–semiconductor–metal (MSM) photodiodes are monolithically integrated. Various types of devices allow half- and full-duplex bidirectional optical interconnection at up to 2.5 Gbit/s data rate using butt-coupled glass or polymer-clad optical fibers with diameters in the 100 to 200 μm range.

1. Introduction

Bidirectional transmission is a largely neglected technique in optical interconnection despite obvious advantages like lower volume and weight and potentially lower system cost. We have conceived and fabricated monolithic transceiver (Tx/Rx) chips that specifically target optical links with Gbit/s data rates. The chips are designed for 850 nm wavelength operation and consist of a vertical-cavity surface-emitting laser diode (VCSEL) and a metal–semiconductor–metal photodiode (MSM PD). For lowest assembly and packaging cost, they should be butt-coupled to the transmission fiber without any external optics. First generation devices had a light-sensitive diameter of slightly more than 200 μm, thus fitting to step-index polymer-clad silica (PCS) fibers which are attractive for automotive network incorporation. Data rates of 1 Gbit/s could be transmitted over a distance of 5 m with very large eye opening [1]. The versatility of the PCS fiber is much enhanced with a so-called semi-graded-index profile. Over the 200 μm diameter doped glass core, the refractive index is graded but has an additional step between the core and the surrounding polymer cladding. The fiber is a product of OFS (URL http://www.ofsoptics.com/), has a numerical aperture of 0.38 and an attenuation coefficient of less than 6 dB/km at 850 nm wavelength. Its bandwidth–distance product is larger than 40 GHz $\times$ m and is thus more than an order of magnitude higher than that of the step-index PCS fiber. In [2], bidirectional optical data transmission over such a 50 m-long fiber is reported at 1 Gbit/s data rate. The semi-GI PCS fiber has thus the potential to serve as a future-proof waveguiding medium in automotive optical networks, where multiple Gbit/s data streams are expected to be generated by, e.g., high-resolution real-time video equipment used for extensive road surveillance.

A further increase of data throughput is obtained with smaller core diameter graded-index glass fibers. In [1] we have reported half-duplex bidirectional interconnect experiments

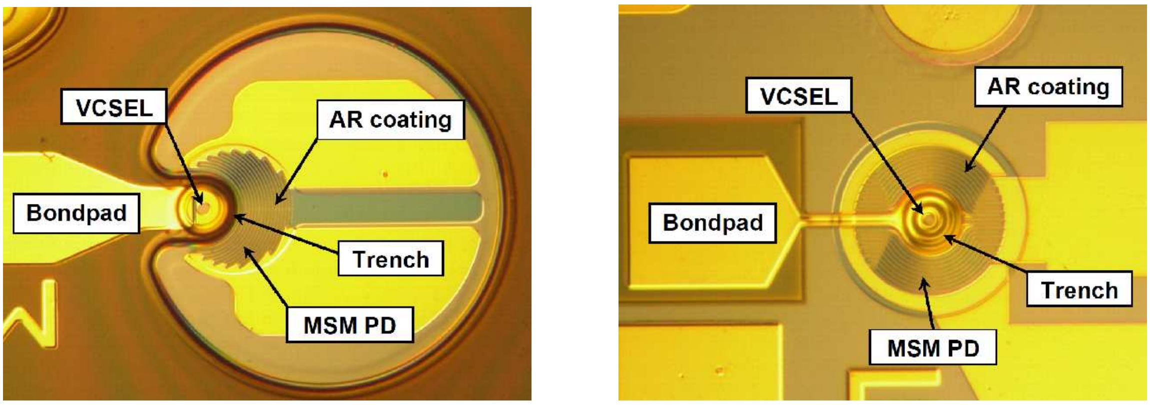

Fig. 1: Previous transceiver chip design (left) and modified version containing a centered VCSEL (right), both with 110 µm MSM photodiode diameter (from [5]).

with 110 µm diameter transceiver chips. Clearly open 1 Gbit/s eye diagrams are obtained for transmission over a 100 µm core diameter graded-index silica fiber with 100 m length. As with the PCS fiber, butt-coupling is applied at both ends of the link. The data throughput is in accordance with the fiber's bandwidth–distance product of about 100 GHz × m. The much increased fiber bandwidth allows extended reach applications, e.g., in home, industrial, or in-building networks as well as within computer clusters or central offices.

A photograph of the optoelectronic chips that were used so far is shown in Fig. 1 (left). It is seen that the laser is offset with respect to the PD center. The VCSEL position is a compromise between high fiber coupling efficiency and high quantum efficiency. For full illumination of the fiber cross-section, the area occupied by the VCSEL effectively reduces the responsivity of the PD. In a new design [3], the size of the VCSEL mesa is much reduced, such that the laser can be centered with respect to the photodiode without excessive consumption of light-sensitive area. Such a device is depicted in Fig. 1 (right). Higher coupling tolerances to the optical fiber are the main advantage of this approach. With an offset VCSEL, the coupling tolerances are asymmetric for displacements along the direction defined by the centers of laser and photodiode. This issue is investigated in detail in [4] and [1] for the 200 µm step-index PCS fiber and the 100 µm graded-index multimode fiber, respectively.

Optimized MSM photodiodes with highest bandwidths are grown on semi-insulating substrates in order to avoid capacitive coupling between the electrodes and doped semiconductor regions. Because of the presence of the electrically driven VCSEL, this approach cannot be easily followed in the integrated transceiver chips. As a consequence, the bandwidths of the photodiodes do not exceed 1.5 GHz even for small diameters of 110 µm. Since the intrinsic photodiode layers are rather thin, there is a large capacitive coupling between the PD metallization and the highly conductive VCSEL layers. Increasing the thickness of the absorption layer reduces the bandwidth due to longer transit times of photo-generated carriers. In this article, we present a new approach which increases the bandwidths of the MSM PDs by about 80 % through the incorporation of a 1 µm-thick undoped $Al_{0.3}Ga_{0.7}As$ layer between both devices (Fig. 2). The improvements are demonstrated by error-free full-duplex 2.5 Gbit/s bidirectional data transmission over a

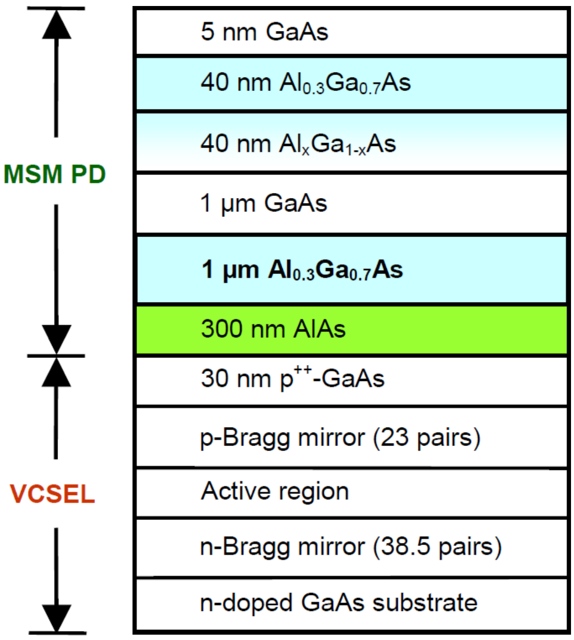

Fig. 2: Layer structure of monolithically integrated transceiver chips with enhanced bandwidth (from [5]).

50 m-long graded-index multimode fiber (MMF) with 100 µm core diameter, fully utilizing its specified bandwidth–distance product.

2. Transceiver Chip Fabrication

The monolithic transceiver chips contain all layers necessary for signal generation and reception. The MSM PD has a 1 µm-thick GaAs absorption layer and is grown on top of the VCSEL layers (Fig. 2). The lithographic process is similar to the one formerly described in [4], but an important difference arises due to the implementation of the additional 1 µm-thick $Al_{0.3}Ga_{0.7}As$ layer. To access the highly p-doped cap layer of the centered VCSEL (Fig. 1) homogeneously, a dry-etch process is applied followed by wet etching with a suitable citric acid solution. This step quickly and selectively removes residual $Al_{0.3}Ga_{0.7}As$ and stops reliably at the 300 nm-thick AlAs layer which is subsequently removed by hydrofluoric acid.

3. Static and Dynamic Characteristics

Figure 3 shows the photocurrents of MSM PDs with 110 µm diameter, 1 µm finger width, and 2 µm finger spacing as a function of the optical power for a number of bias voltages. The slope of the curves is constant for voltages exceeding 2 V. The corresponding responsivity amounts to 0.38 A/W and is independent of the light intensity. Both light reflection at the VCSEL layers and an antireflection (AR) coating contribute to the high responsivity.

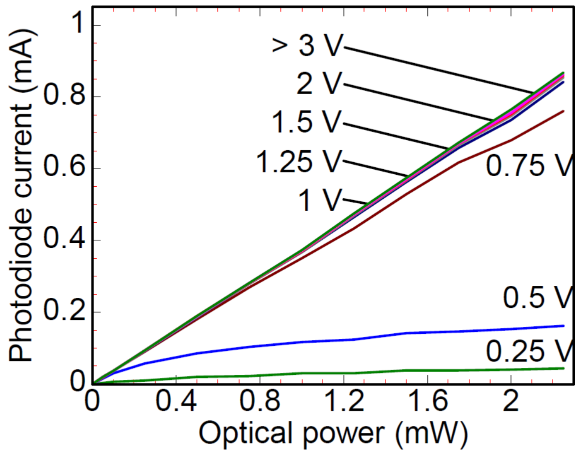

Fig. 3: Photocurrent of a transceiver MSM photodiode with 110 µm diameter as a function of incident optical power for various bias voltages (from [5]).

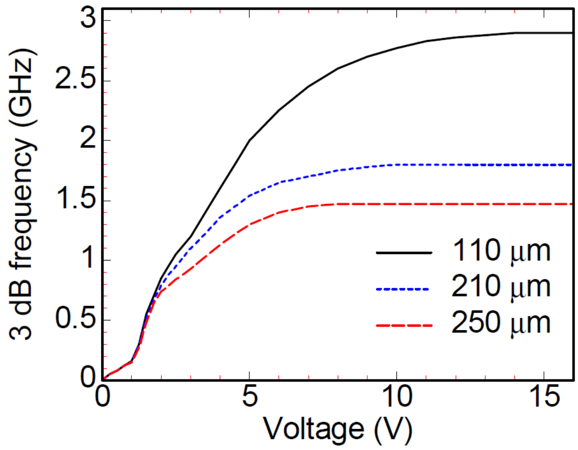

Fig. 4: Bandwidths of transceiver MSM PDs with different diameters on the new layer structure according to Fig. 2 (from [5]).

Typical bandwidths of transceiver MSM PDs with the improved layer structure and the same electrode configuration are depicted in Fig. 4. For photodiodes with 110 µm diameter of the light-sensitive area, the bandwidths saturate at 2.9 GHz. Larger diodes with 210 and 250 µm diameter have 3-dB bandwidths of 1.8 and 1.5 GHz, respectively. The increase of the corner frequency is about 80 % compared to Tx/Rx MSM PDs based on the previous layer structure.

The transceiver chips incorporate standard multimode 850 nm top-emitting oxide-confined VCSELs with 10 µm active diameter. Transverse multimode operation is preferred to single-mode emission due to more favorable modal noise properties in combination with a multimode fiber. As seen in Fig. 5, the lasers have minimum threshold currents of 1.4 mA at room temperature and still deliver optical output powers exceeding 3 mW at 100 °C. Typical small-signal 3 dB-frequencies are around 7 GHz (Fig. 6). Thus, the 110 µm diameter transceiver PDs still limit the maximum data rate despite of their enhanced bandwidths.

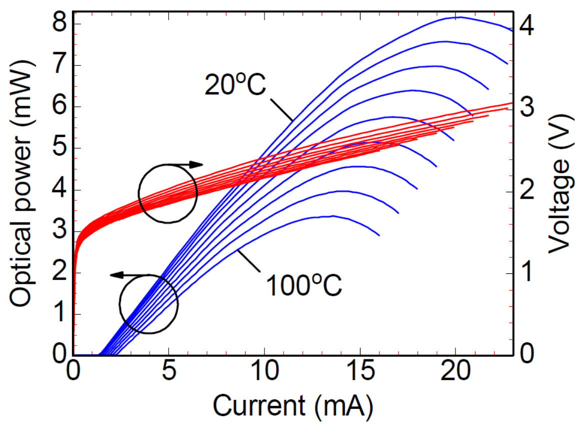

Fig. 5: Temperature-dependent operation characteristics of a transverse multimode transceiver VCSEL in steps of 10 °C (from [5]).

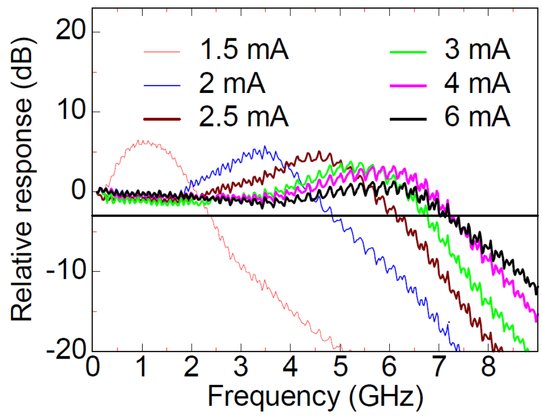

Fig. 6: Small-signal response curves of a transceiver VCSEL for various bias currents above threshold.

4. Digital Data Transmission

We first consider data transmission in the so-called back-to-back (BTB) mode, i.e., without the optical fiber. This is useful to determine the maximum system data rate without the influence of fiber dispersion. The transmission is established between a reference VCSEL and a circular PD (where no space is cut out for the VCSEL) on a transceiver-type layer structure according to Fig. 2 using two lenses for collimation and focusing. We employ a photodiode with 210 µm diameter, which has 1 µm finger width and 2 µm spacing. Its responsivity is 0.4 A/W and its 3-dB bandwidth amounts to 1.8 GHz. An amplifier with 10 GHz bandwidth and 50 Ω input impedance is used, and the signal is low-pass filtered, matched to the chosen data rate. Quasi error-free (10^{-11} bit error rate) 2.5 Gbit/s transmission of a non-return-to-zero coded pseudorandom bit sequence with 2^7–1 word length is achieved at –14.6 dBm received optical power (Fig. 7). The eye diagram is wide open even at 4 Gbit/s. For the transmission of still higher data rates using direct detection without signal processing, smaller photodiodes with lower capacitance and higher bandwidth must be used. This is illustrated with the good eye openings in

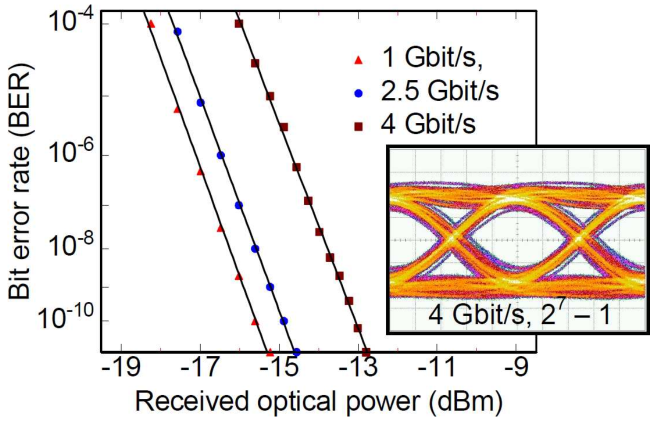

Fig. 7: Bit error rate curves for back-to-back (BTB) data transmission between VCSEL and transceiver photodiode with 210 µm diameter for various data rates as well as 4 Gbit/s eye diagram (from [5]).

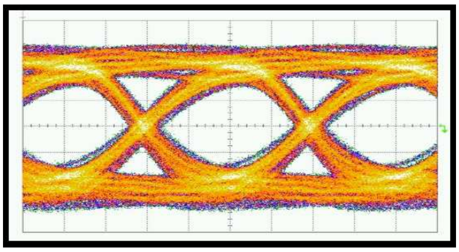
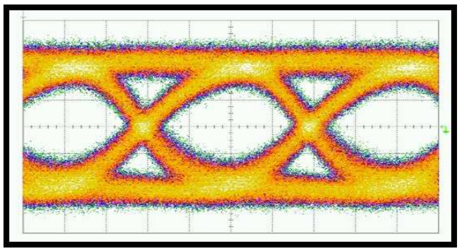

Fig. 8: 5 Gbit/s eye diagrams for BTB transmission between VCSEL and high-bandwidth PD with 110 µm diameter at word lengths of 2^7–1 (left) and 2^{31}–1 (right) (from [5]).

Fig. 8, where 5 Gbit/s data are received by 110 µm MSM PDs with otherwise identical finger structure. In this case, a low-pass filter with 5 GHz corner frequency was used.

For bidirectional data transmission, one butt-coupled transceiver chip is used at each fiber end at a distance of about 50 µm. In addition to the bidirectional nature of the chip, the lack of additional optics would greatly simplify the design of packaged modules. Each Tx/Rx chip consists of a 110 µm MSM PD according to Fig. 4 and an oxide-confined VCSEL similar to the one in Fig. 6. Both chips are nominally identical, however, due to a thickness gradient over the epitaxial wafer, the actual emission wavelengths (and threshold currents) are 852 nm (1.5 mA) and 839 nm (2.0 mA). For data transmission experiments in half-duplex mode, only one VCSEL is modulated, while the other one is biased above threshold. Low-pass filters with 3-dB bandwidths of 2000 and 2400 MHz help to reduce effects of electric on-chip crosstalk. The eye diagrams for transmission of a non-return-to-zero pseudorandom bit sequence with 2^7–1 word length at 2.5 Gbit/s data rate over 50 m MMF with 100 µm core diameter and 100 GHz × m bandwidth–distance product are wide open, indicating error-free transmission (Fig. 9 top left and right). The data transmission remains error-free also in full-duplex mode at the same bit rate using a second (3.0 vs. 12.5 Gbit/s maximum data rate) pattern generator (Fig. 9 bottom). Bias (and modulation) conditions are 9 mA (250 mV_{pp}) and 6 mA (500 mV_{pp}), where the minimum available peak-to-peak voltages have been used. Despite of the low-pass filters and antireflection-coated Tx/Rx PDs, the eye openings are still slightly reduced, caused by both the remaining on-chip electrical crosstalk and the optical crosstalk chiefly arising from reflections at the far-end chip. The eye diagrams of channels 1 and 2 deviate somewhat, mainly due to different modulation and power levels. Error-free operation has also been achieved at 500 Mbit/s transmitted over a 300 m-long fiber. Data rates and fiber lengths are close to the limit imposed by the bandwidth–distance product of the fiber. Operation at the high data rate was only possible with the low-capacitance chips. Full-duplex transmission at 2.5 Gbit/s over several tens of meters is a very attractive option for many interconnect application areas.

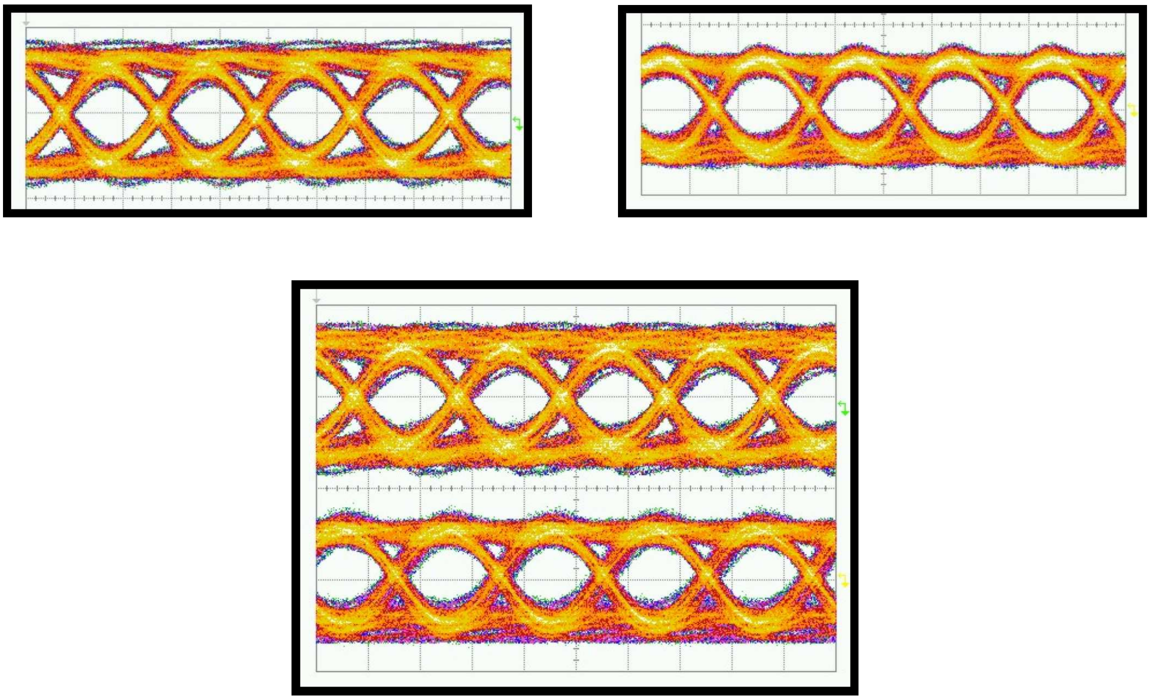

Fig. 9: Eye diagrams for bidirectional data transmission at 2.5 Gbit/s data rate over 50 m of 100 μm core diameter MMF in half-duplex mode for channel 1 (top left) and for channel 2 (top right) and full-duplex mode for channel 1 (bottom up) and channel 2 (bottom down).

5. Conclusion

A new generation of VCSEL–MSM transceiver chips was shown to be well suited for 100 μm core MMF data transmission at 2.5 Gbit/s owing to optimized PDs with bandwidths approximating those of solitary devices. Chips with smaller PDs adapted to standard MMFs are expected to offer even larger bandwidth–distance products of bidirectional optical data links.

References

[1] R. Michalzik, M. Stach, F. Rinaldi, and S. Lorch, "Monolithic integration of VCSELs and MSM photodiodes for bidirectional multimode fiber communications" (invited), in *Vertical-Cavity Surface-Emitting Lasers XI*, K.D. Choquette, J.K. Guenter (Eds.), Proc. SPIE 6484, pp. 648409-1–10, 2007.

[2] M. Stach, F. Rinaldi, J. Scharpf, S. Lorch, and R. Michalzik, "1 Gbit/s bidirectional optical data transmission over 50 m semi-GI PCS fiber with monolithically integrated transceiver chips", in Proc. *EOS Conf. on Trends in Optoelectronics, Sub-conf. on Information and Communication*, pp. 61–62. Munich, Germany, June 2007.

[3] M. Stach, F. Rinaldi, D. Wahl, D. Rimpf, S. Lorch, and R. Michalzik, "1 Gbit/s full-duplex bidirectional optical data transmission over 500 m of 50 μm-core graded-index multimode fiber with novel monolithically integrated transceiver chips, in Proc. *33rd Europ. Conf. on Opt. Commun., ECOC 2007*, vol. 5, pp. 127–128. Berlin, Germany, Sept. 2007.

[4] M. Stach, F. Rinaldi, M. Chandran, S. Lorch, and R. Michalzik, "Bidirectional optical interconnection at Gb/s data rates with monolithically integrated VCSEL-MSM transceiver chips", *IEEE Photon. Technol. Lett.*, vol. 18, pp. 2386–2388, 2006.

[5] M. Stach, F. Rinaldi, D. Wahl, D. Rimpf, S. Lorch, and R. Michalzik, "Monolithically integrated miniaturized transceiver chips for bidirectional graded-index fiber systems" (in German: "Monolithisch integrierte miniaturisierte Transceiver-Chips für bidirektionale Gradientenindexfaser-Systeme"), *14th ITG Symposium on Communication Cable Networks*, Köln, Germany, Dec. 2007. In *ITG-Fachbericht Kommunikationskabelnetze*, vol. 204, pp. 115–119, 2007.