10 Gbit/s Bidirectional Data Transmission with Monolithic VCSEL–PIN Transceiver Chips

Alexander Kern and Dietmar Wahl

We report the monolithic integration, fabrication, and electro-optical properties of AlGaAs–GaAs-based transceiver (TRx) chips for 850 nm wavelength optical links with data rates of multiple Gbit/s. Avoiding the use of external fiber coupling optics and using a single butt-coupled multimode fiber (MMF) with 50 or 62.5 μm core diameter, low-cost bidirectional communication in half- and even full-duplex mode is demonstrated. Based on a vertical-cavity surface-emitting laser (VCSEL) and a monolithically integrated p-doped–intrinsic–n-doped (PIN) photodiode (PD), such TRx chips are capable of high-speed bidirectional data transmission with MMFs over distances of a few hundred meters. Standard MMF networks can thus be upgraded using monolithic VCSEL–PIN transceiver chips which can handle data rates of up to 10 Gbit/s.

1. Introduction

The demand for increasingly compact and low-priced high-speed optical links in local-area networks, the industrial and home environments but also in mobile systems requires novel approaches. One of them is bidirectional interconnection over a single multimode fiber with a vertical-cavity surface-emitting laser (VCSEL) acting as an efficient light source and a resonant-cavity-enhanced photodetector [1]. Half-duplex operation at 1.25 Gbit/s data rate over a 50 μm core diameter MMF with 500 m length was achieved with such a dual-purpose transceiver. Full-duplex operation is inherently not possible. Additionally, the resonant detection requires temperature control at both fiber ends, increasing the cost of such a link. Only non-resonant devices with separate epitaxial layers for photodiode and VCSEL can operate in full-duplex mode and without temperature control.

In previous work [2] we have demonstrated full-duplex data transmission at 1 Gbit/s over a 500 m long 50 μm core diameter MMF using monolithically integrated transceiver chips containing VCSELs and size-mismatched 110 μm diameter metal–semiconductor–metal detectors. In order to reduce the inevitable optical crosstalk in such full-duplex links on one hand and to increase the responsivity of rather small photodetector areas on the other hand, PIN PDs are used in miniaturized VCSEL-based 850 nm wavelength range transceivers [3]. In Fig. 1, the top view of such a TRx chip can be seen in which the VCSEL is positioned off-center with respect to the photodetector in order to maximize the effective photodetecting area of the transceiver. The monolithic integration of both components as well as a design enabling data transmission via a single, two-side butt-coupled standard MMF — avoiding the use of external optics as shown in Fig. 4 (top) — saves space, weight, and module cost.

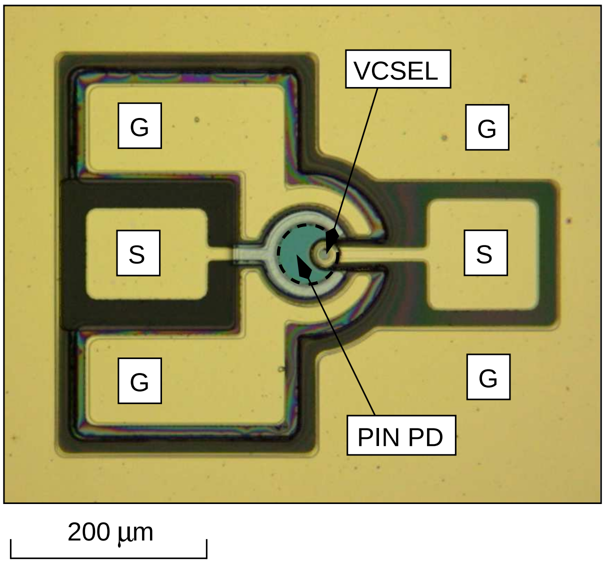

Fig. 1: Photograph of a transceiver chip consisting of a VCSEL and a PIN photodiode, each with indicated ground–signal–ground (GSG) microwave probe contacts. The dashed circle indicates the alignment of a MMF with 50 µm core diameter (from [4]).

2. Transceiver Layer Design and Fabrication

For the full-monolithic chip design, the layers for the VCSEL are grown using molecular beam epitaxy on a GaAs substrate, followed by the layers for the PIN photodiode. Epitaxially separated by a 150 nm thick etch stop layer, as can be seen in Fig. 2, both, the detector layers as well as the etch stop layer can be selectively removed from the VCSEL by a combination of two reactive-ion etching (RIE) and two wet-etching processes [6–8]. The intrinsic $Al_{0.9}Ga_{0.1}As$ between both devices also partially acts as an insulator for capacitive decoupling. Apart from the etching of the VCSEL mesa, which separates both devices spatially, another dry-etching process is required due to the vertical displacement of the PIN PD contacts. With an appropriate $SF_6/SiCl_4$ gas ratio for the RIE process, high etching selectivity between GaAs and $Al_{0.3}Ga_{0.7}As$ can be achieved [6,7]. Thus the n- and p-doped PD contact layers not only act as spectral window layers for the wavelengths of interest at around 850 nm, but likewise as an etch stop layer. Minimizing the bandgap discontinuities between the absorption and contact layers by linearly graded $Al_xGa_{1-x}As$ ($x = 0 \rightarrow 0.3$), an easier escape of the photocarriers from the undoped GaAs is ensured. Both devices are protected from oxidation of the subjacent aluminum-containing layers by n- or p-doped GaAs cap layers.

Current confinement of the VCSEL is achieved by selective oxidation of the p-doped AlAs, positioned in a node of the standing-wave pattern just above the inner cavity. Owing to the stacked layer structure of the transceiver chip, the incident light passes the PD twice after being reflected by the subjacent VCSEL layers. With an Al_2O_3 quarter-wave antireflection (AR) layer sputtered on the PIN PD, the responsivity of a transceiver PD with 3 µm thick GaAs absorption layer reaches 0.61 A/W, corresponding to a quantum efficiency of nearly 88 % [9]. The AR coating reduces the reflectivity of the semiconductor

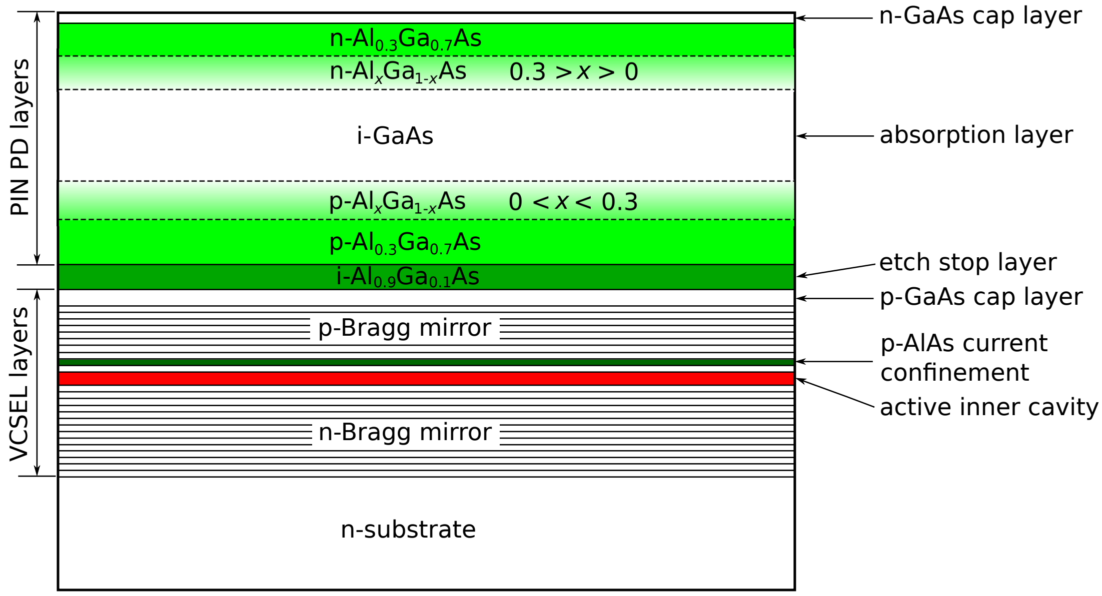

Fig. 2: Schematic layer structure design of the monolithically integrated transceiver chip (from [5]).

surface from initially 30 % down to 1.3 % over a spectral width of nearly 50 nm [3].

3. Experimental Results

3.1 Small-signal operation characteristics

For high-speed measurements, both, VCSEL and PIN PD can be on-wafer tested by two coplanar microwave probes, as seen from the GSG configurations in Fig. 1. A typical small-signal frequency response of an integrated VCSEL with about 8 µm oxide aperture and 25 µm mesa diameter is shown in the left graph of Fig. 3. A maximum 3-dB bandwidth of 11.5 GHz is observed for an operating current of 10 mA, giving a suitable flat frequency characteristic for large-signal experiments. Unintentional cavity detuning has led to optical emission at around 810 nm, a rather high threshold current of 2.3 mA, and a relatively low maximum output power of 2.8 mW and gives much room for further optimization.

The bandwidth of the adjacent 3 µm thick and 60 µm diameter photodetector can be sufficiently improved by increasing its reverse bias voltage to −8 V, as shown in the right graph of Fig. 3. Whereas the frequency response of the VCSEL typically decays strongly for frequencies beyond the resonance peak, the rather slow small-signal decay of the 1st order low-pass of the PIN PD gives a 3-dB frequency in the range of 4.5 to 6 GHz. Nevertheless, the resistor–capacitor (RC) low-pass and drift time bandwidths are expected to be at 14 and 15 GHz, respectively for $R = 50\,\Omega$ and if bondpad capacitances are neglected. The much smaller experimental values as well as the corrugations of the frequency responses can probably be attributed to the non-negligible parasitic coupling with the highly doped VCSEL layers.

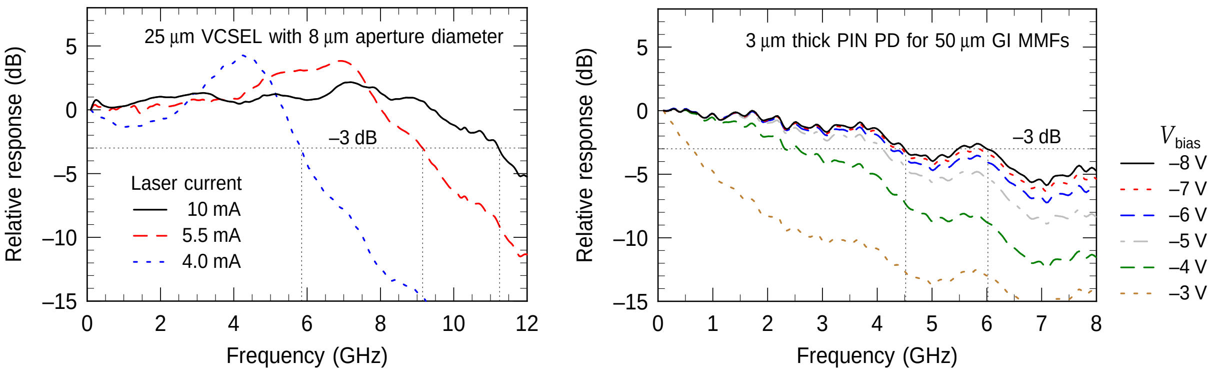

Fig. 3: Small-signal frequency responses (from [5]) of a TRx VCSEL (left) and an integrated PIN PD (right).

3.2 Digital data transmission

According to the results in Fig. 3, the lower small-signal bandwidths of the PIN PDs compared to those of the VCSELs are expected to limit the maximum achievable data rate of the transceivers. For evaluation purposes, two different transceiver chips with 2 and 3 μm thick PIN PDs were used in the experiments. The thinner PD with an increased capacitance has a smaller 3-dB bandwidth of approximately 4.2 GHz. For digital data transmission experiments, a 500 m long 50 μm core diameter OM3-type graded-index (GI) MMF with a bandwidth–distance product ($B \times L$) of ~ 2 GHz × km was butt-coupled (about 30 μm distance) to each chip, as depicted in Fig. 4 (top).

First, data transmission in half-duplex mode was performed in order to avoid the influence of optical and electrical crosstalk in the system. The optical eye diagram in Fig. 4 (bottom left) shows error-free operation with the 2 μm thick PIN PD at 7 Gbit/s, thus fully utilizing the $B \times L$ of the MMF. Here, the maximum data rate is additionally limited by the rising and falling edges caused by RC parasitics. For the opposite channel with a 3 μm thick PIN PD in Fig. 4 (bottom center), an error-free eye with slightly smaller peak-to-peak modulation voltage due to the smaller on–off ratio of the VCSEL on TRx chip 2 can be seen. The RC limit for the 3 μm thick PD is less pronounced. The signals detected by the PDs on the transmitter side correspond to optical crosstalk, which mainly originates from the reflections on each fiber end and the opposite TRx chip. Its contribution is sufficiently smaller than the trace widths of the operating channel, which are predominantly due to the non-ideal frequency responses as well as thermal and amplifier noise. Thus, quasi error-free full-duplex data transmission could be achieved at 6 Gbit/s, shown in Fig. 4 (bottom right). The trade-off of 1 Gbit/s compared to the half-duplex mode operation is attributed to the higher noise level arising from the optical crosstalk. Compared to previous results [2], the full-duplex data rate has been increased by a factor of six and is to our knowledge the highest reported so far.

Additional data transmission experiments were performed in back-to-back (BTB) mode in order to avoid mode dispersion and optical crosstalk effects of the glass fiber and thus to obtain the maximum achievable data rate of the transceivers. The laser beam is focused via free-space optics on the transceiver PIN PD, as shown in Fig. 5 (top). Here, 3 μm

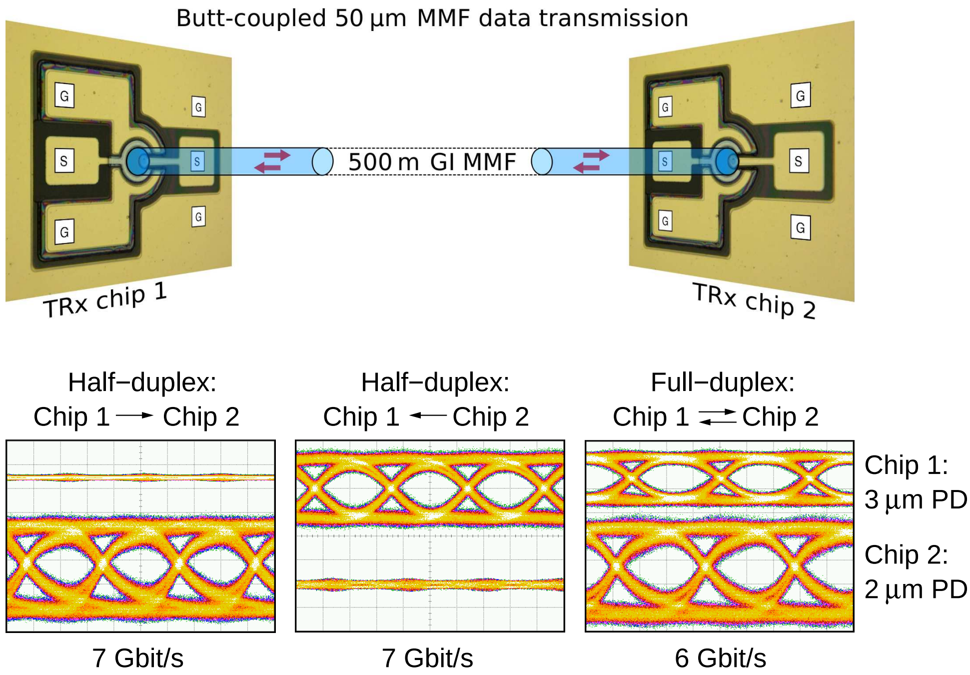

Fig. 4: Optical eye diagrams (from [10]) for error-free half-duplex $2^{15}-1$ word length non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS) data transmission at 7 Gbit/s (bottom left and center), as well as 6 Gbit/s error-free full-duplex operation (bottom right), all over 500 m graded-index (GI) MMF, as indicated in the schematic setup (top).

thick PIN PDs were used in both TRx chips. As can be seen in Fig. 5 (bottom center), quasi error-free data transmission in half-duplex mode was possible at 10 Gbit/s for one channel. Owing to lower optical crosstalk contributions in BTB mode as observed in the eye diagrams for half-duplex transmission (bottom left and center), error-free full-duplex operation could be achieved at 7 Gbit/s for both channels (bottom right). Keeping the data rate for the transmission direction between chip 1 and chip 2 fixed at 7 Gbit/s, we could even demonstrate full-duplex error-free operation at 10 Gbit/s for the channel chip 2 $\rightarrow$ chip 1. In such free-space communication, there is no limit of the maximum data rate by the $B \times L$ of the fiber, as was the case in the previous subsection. Thus, a 10 Gbit/s optical link employing a 500 m long OM4-type fiber with $B \times L \geq 4.7\,\text{GHz} \times \text{km}$ is feasible.

In Fig. 6, bit error ratios (BERs) are shown for different data rates in both, half- and full-duplex mode. For simplicity, only one transmission direction (here from chip 2 to 1) is presented. On average, there is 0.5 dB power penalty for full-duplex compared to half-duplex transmission at the same data rate. At a relatively high optical power of approximately –1.5 dBm, even 10 Gbit/s could be transmitted quasi error-free in full-duplex mode.

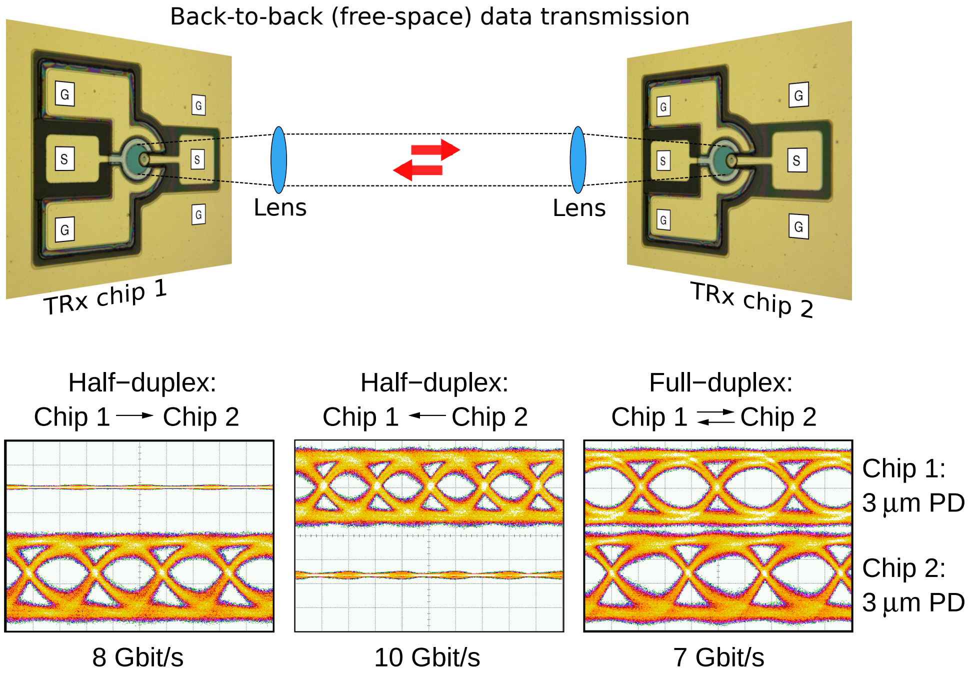

Fig. 5: Optical eye diagrams (bottom) for back-to-back (top) error-free half-duplex $2^{15} - 1$ word length NRZ PRBS data transmission at 8 Gbit/s (left) and 10 Gbit/s (center), as well as 7 Gbit/s error-free full-duplex operation (right).

4. Conclusion

In summary, we have presented the current achievements on the fabrication and properties of monolithically integrated 850 nm wavelength transceiver chips for bidirectional data transmission over a single butt-coupled multimode fiber. The VCSEL–PIN transceiver chips were miniaturized in order to match with standard MMFs of 50 and 62.5 µm core diameters. The main challenge in chip processing was the sophisticated combination of selective dry- and wet-etching techniques for various mesa formations. PIN PDs with maximum bandwidths of 4.5 to 6 GHz and VCSELs with 11.5 GHz can handle data rates of up to 10 Gbit/s in BTB half- and full-duplex data transmission. Over a 500 m long butt-coupled OM3 MMF, data rates of 7 Gbit/s in half-duplex and 6 Gbit/s in full-duplex mode could be demonstrated — mainly limited by the relatively low bandwidth–distance product of the fiber. With optimized epitaxial TRx chip design and the use of an OM4-type MMF, even further improvements in bidirectional single-fiber data transmission reaching 10 Gbit/s are realistic.

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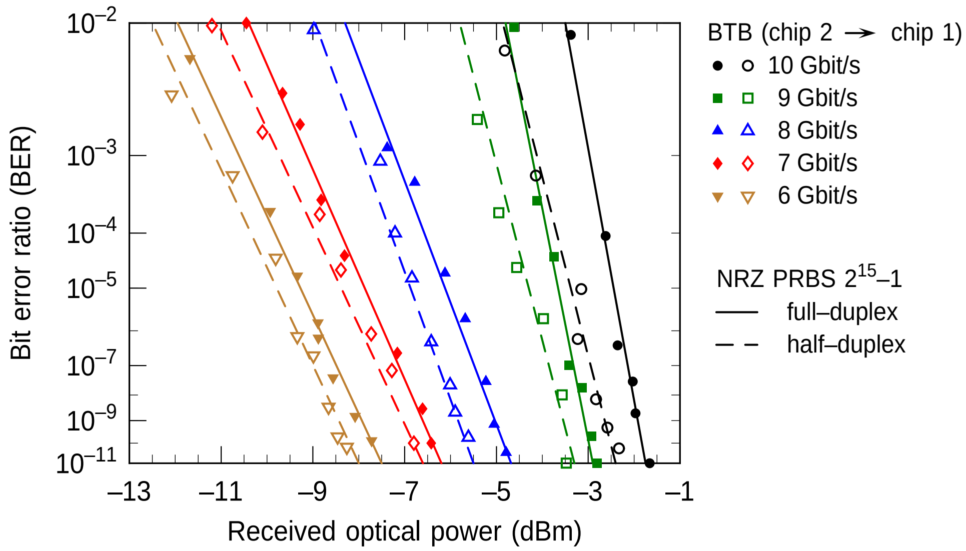

Fig. 6: BER characteristics for back-to-back half- and full-duplex $2^{15} - 1$ word length NRZ PRBS data transmission.

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