Miniaturized Monolithically Integrated Transceiver Chips for Bidirectional Data Transmission over Graded-Index Glass Optical Fiber

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We present bidirectional data transmission experiments in half-duplex mode at 1 Gbit/s data rate over 100 m graded-index glass optical fiber with VCSELs and MSM photodiodes as parts of a GaAs-based monolithically integrated transceiver chip.

1. Introduction

As a possible way to satisfy the need for compact and inexpensive solutions for high-speed optical interconnection, we describe a transceiver (Tx/Rx) chip that consists of a vertical-cavity surface-emitting laser (VCSEL) and a metal–semiconductor–metal photodiode (MSM PD). The monolithic integration of both components as well as a design avoiding the use of external optics are expected to simultaneously save space, weight, and module cost. A part of the circular-like detector area is occupied by the integrated VCSEL, thus enabling data transmission between two transceiver chips via a two-side butt-coupled fiber. Owing to an advanced processing technology, miniaturized Tx/Rx chips with 110 µm effective diameter have been fabricated, matching the 100 µm core of a graded-index multimode glass optical fiber (MMF). Compared to Tx/Rx chips with 210 µm diameter for data transmission over a step-index polymer-clad silica (PCS) fiber [1], the new design optimizes the detector area through circular-shaped MSM PD electrodes (Fig. 1). The MMF offers a bandwidth–length product of 100 GHz · m in contrast to the rather poor 3 GHz · m of the PCS fiber. Thus there is the capability to transmit signals at 1 Gbit/s data rate over distances found in high-volume industrial and home network sectors [2]. We first outline the processing of the Tx/Rx chips, followed by investigations on the dark current behavior of the PDs and coupling efficiencies between VCSEL and fiber. Dynamic characterization is performed in terms of bidirectional data transmission in half-duplex mode between two Tx/Rx chips.

2. Transceiver Chip Fabrication

A monolithically integrated transceiver chip must contain all layers necessary for signal generation and reception. The layers for the receiving MSM PD are epitaxially grown (by molecular beam epitaxy) on top of the VCSEL layers. A 200 nm-thick AlAs layer serves as an etch-stop and a barrier for the photo-generated carriers. The generation of the electron–hole pairs takes place in an undoped 1 µm-thick GaAs layer suitable for light detection at 850 nm wavelength. This layer is separated from a dark current-reducing 40 nm $Al_{0.3}Ga_{0.7}As$ Schottky barrier by a 40 nm $Al_xGa_{1-x}As$ layer (linearly graded from $x = 0$ to 0.3) to minimize the energy band discontinuity which could hinder the transport of the light-induced carriers. The top GaAs layer serves as a protection layer to prevent $Al_{0.3}Ga_{0.7}As$ oxidation.

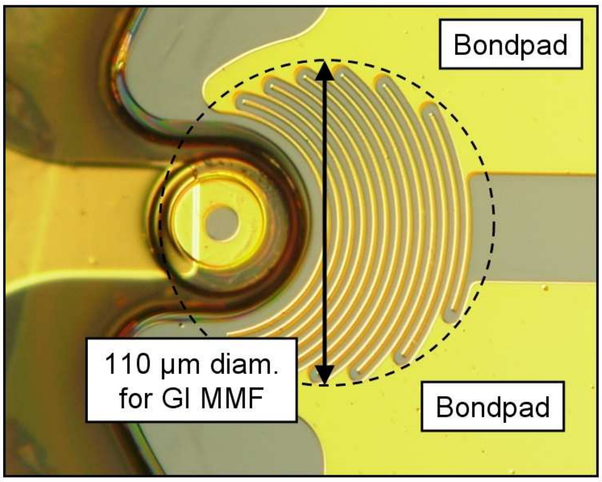

Fig. 1: Transceiver chip with 110 µm effective diameter, matching the 100 µm core diameter of the MMF indicated by the dashed circle. The 1.5 µm-wide PD fingers are separated by 2.5 µm interdigital spacings.

To access the highly p-doped cap layer of the VCSEL, the detector layers surrounding the resist-protected photodiode area are selectively removed by citric acid solutions. The process is terminated at the AlAs etch-stop layer which is subsequently removed by hydrofluoric acid. A dry-etch process is applied to define the VCSEL mesa, during which the photodiode is protected by photoresist. Subsequently, photolithographic steps are performed to put bondpads on the surface, thus allowing wire bonding for dynamic characterization. The 110 µm PD diameter is adapted to the 100 µm core diameter of the MMF that shall be centered in front of the transceiver chip (Fig. 1). The PD-to-VCSEL offset is a trade-off between coupling efficiency and remaining detector area.

3. Dark Currents of the MSM PDs

For dark current characterization, full-area circular MSM PDs with three different diameters are compared with each other, where all PDs have a finger width-to-spacing ratio of 1.5-to-2.5 µm. As expected, the dark current is lowest for the smallest PD and amounts to 0.5 nA at 5 V, as shown in Fig. 2. A further decrease of the dark current is expected if an antireflection (AR) coating is applied. The AR coating will passivate the surface and will also enhance the responsivity which currently amounts to about 0.35 A/W.

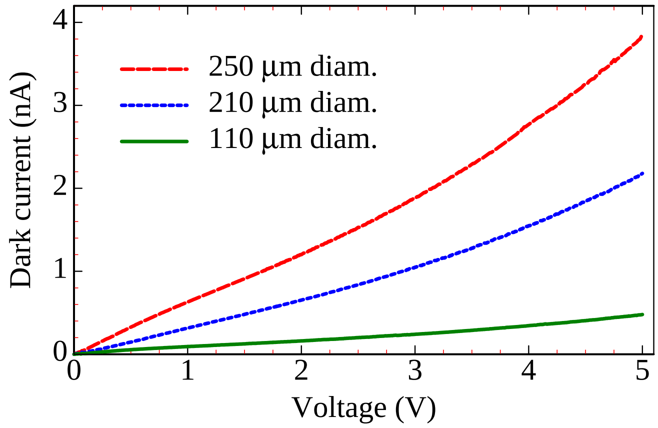

Fig. 2: Voltage-dependent dark currents of Tx/Rx MSM PDs for various PD diameters.

4. Coupling Efficiencies

Two types of chips have been fabricated, namely with 29 and 39 µm radial offset according to Fig. 1. For each chip, this eccentricity between VCSEL and PD results in two different lateral alignment tolerances. From Fig. 3 one obtains the tolerances for a 3 dB decay of coupled power. These are ±38 µm for 29 µm eccentricity and ±31µm for 39 µm offset. A constant 25 µm distance between chip and fiber has been used and the lateral displacement is performed in the direction normal to the PD–VCSEL axis. For displacement parallel to the axis, one finds −20 and +78 µm tolerances for 29 µm radial offset. With this eccentricity, the same maximum coupling efficiency of 89 % as in the case of a centered VCSEL (0 µm offset) is reached. On the other hand, the detector area is somewhat smaller compared to the 39 µm offset case.

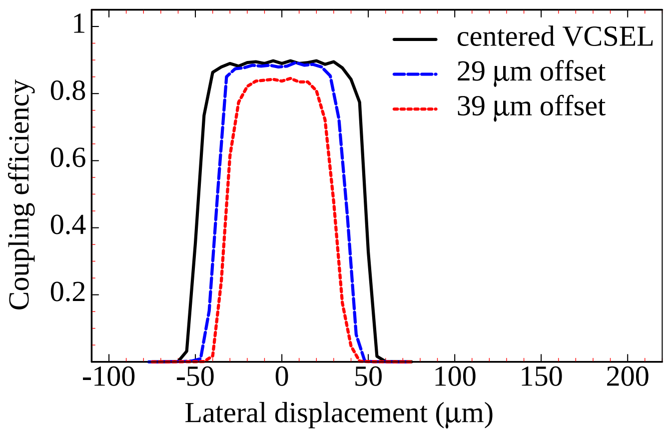

Fig. 3: Coupling efficiencies between VCSEL and fiber for various eccentricities, where a lateral displacement of 0 µm corresponds to a Tx/Rx chip position centered with respect to the fiber axis.

5. Digital Data Transmission

For bidirectional data transmission, one butt-coupled Tx/Rx chip at each fiber end is used, i.e. there are no optics between chip and fiber and the distance is smaller than 25 µm. Each transceiver chip consists of a 110 µm MSM PD and an oxide-confined VCSEL with 7 µm active diameter which has a lasing threshold of 1.6 mA and a 3 dB bandwidth exceeding 5 GHz. For maximized coupling efficiency, the 29 µm offset chip versions are employed. To optimize the photocurrent at both receiving photodiodes, a proper alignment of the Tx/Rx chips is necessary. The data transmission experiments are performed in half-duplex mode, i.e. one VCSEL is modulated while the second laser and the PDs have a constant bias. The eye diagrams for transmission of a non-return-to-zero pseudo-random bit sequence at 1 Gbit/s data rate over 100 m MMF show a clear eye opening both for $2^7 - 1$ and $2^{31} - 1$ word length, indicating error-free transmission (Fig. 4).

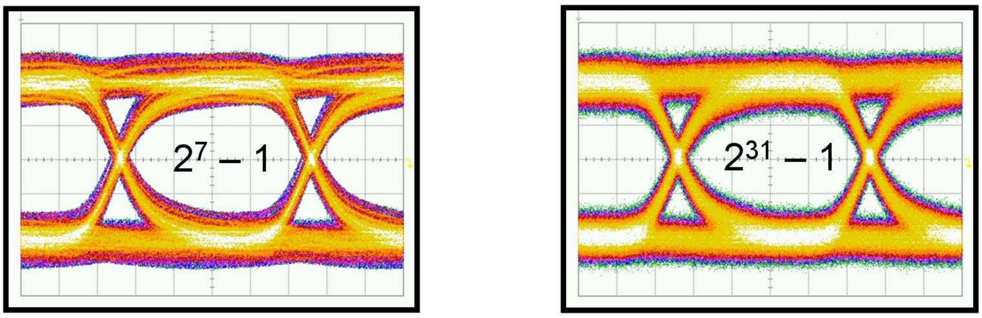

Fig. 4: Eye diagrams for bidirectional data transmission in half-duplex mode at 1 Gbit/s data rate for different word lengths over 100 m of 100 µm core diameter MMF from chip 1 to chip 2 (opposite case similar).

6. Conclusion

With novel miniaturized, monolithically integrated Tx/Rx chips, a 1 Gbit/s data rate, half-duplex mode optical link has been established using a two-side butt-coupled 100 m-long MMF. Such an approach is deemed to be attractive for cost-sensitive industrial and home networks.

References

[1] 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.

[2] M. Stach, F. Rinaldi, A. Gadallah, S. Lorch, I. Kardosh, P. Gerlach, and R. Michalzik, "1 Gbit/s bidirectional data transmission over 100 m graded-index glass optical fiber with monolithically integrated transceiver chips", in Proc. *Europ. Conf. on Opt. Commun., ECOC 2006*, vol. 3, pp. 493–494. Cannes, France, Sept. 2006.