Bidirectional optical data transmission over a single multimode fiber

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New, low-cost transceiver chips are made by the compact, monolithic integration of a surface-emitting laser and a p-doped intrinsic n-doped photodiode.

The increasing demand for high-speed optical interconnections in mobile systems—found in cars, airplanes, as well as industrial and home networks—requires compact and low-cost transceivers. These are devices in which a transmitter is integrated with a receiver. A well-established transceiver model is the media-oriented systems transport (MOST) network, based on butt-coupled (i.e., no external optics) polymer optical fibers. The fibers are placed directly on top of low-cost transceivers that consist of a hybrid integrated LED as the light source and silicon-based p-doped intrinsic n-doped (PIN) photodiode as the photodetector. MOST devices are ideal for short-reach applications (such as for use in cars) because they are built for large fiber core diameters (up to 1mm), are easily aligned for coupling with light sources and photodiodes, and are inexpensive to manufacture. However, their data rate is limited to ~150Mb/s. Here, we describe our design and fabrication of high data-rate transceivers for longer reach optical link networks of a few hundred meters in length.

The first monolithically integrated transceiver chips for optical links were achieved with gallium arsenide (GaAs). The device comprised vertical cavity surface-emitting lasers (VCSELs) with an intimately integrated photodetector on the same chip. However, these devices used one epitaxial layer structure for the VCSEL and photodetector, necessitating temperature control at each fiber end to tune the very narrow spectral range of the wavelength-resonant photodetector. In contrast, employing separate epitaxial layers for non-resonant detection avoids this costly temperature stabilization. Thus, we sought to combine monolithic integration of a laser source and a non-resonant photodetector capable of half- (i.e., single direction) and full-duplex (i.e., simultaneous transmission in both directions) data transmission. Designed for use with butt-coupled multimode fibers (MMFs), this would enable compact, efficient, and low-cost optical interconnection for networks with Gb/s data rates without the need for temperature control.

We initially developed several monolithically integrated VCSELs and metal-semiconductor-metal (MSM) photodiodes for MMFs with different core diameters, namely 100 and 200μm. For example, with our MSM photodiodes (110μm in diameter)...
we were able to achieve 2.5Gb/s full-duplex operation over a graded-index (GI) MMF (100μm core diameter, 50m in length). This data rate fully exploits the bandwidth-distance product $(B \times L)$ of 100GHzx\(\text{m}\), which defines the maximum possible bandwidth of such glass fibers of a given length. An increase of the data rate by the laser (i.e., >2.5Gb/s) would lead to higher error rates in the transmission.

In order to increase the data rate further, we needed to miniaturize the transceiver chips. This would ensure their compatibility with standard MMFs, with core diameters of 50 or 62.5μm and higher $(B \times L)$ values. MSM photodiodes generally suffer from lower responsivities because their metal contact fingers partially shadow their photosensitive area. In contrast, PIN-type photodiodes are ideal because their photosensitive areas are fully exposed. Figure 1 shows our transceiver chip with PIN photodiode and laterally integrated miniaturized VCSEL, which maximizes the effective photodetecting area.

For the fully monolithic chip, we grew the layers of the VCSEL—followed by the PIN photodiode layers—on a GaAs substrate using molecular beam epitaxy. Our fabrication of the transceiver chips is based on subsequent lithographic structuring with photosensitive resists, followed by etching or material deposition steps. Importantly, at the core of our processing technique is the removal of the photodiode layers from the top of the VCSEL. Since both are epitaxially (in the vertical direction) separated by a 150nm thick etch stop layer (see Figure 2) the detector and etch stop layers are selectively etched by a combination of two reactive-ion etching and two wet-etching processes. The active region of the VCSEL is sandwiched between p- and n-doped Bragg-mirrors, which build the laser cavity. We achieve current confinement in the VCSEL by selective oxidation of the p-doped aluminum arsenide layer, which is accessible from the 2–4μm wide trench that horizontally separates the VCSEL from the PIN photodiode (see Figure 2). Finally, we sputter an alumina quarter-wave antireflection layer on the PIN photodiode in the last lithography step. In doing so, we reduce the reflectivity of the semiconductor surface from 30% to 1.3% over a spectral width of nearly 50nm.

Having fabricated our transceiver chips, we assessed their properties in a number of tests. The VCSEL structure underneath the photodiode leads to reflection of the incident, non-absorbed light. It is directed back through the photodiode absorption region to increase the quantum efficiency and signal power. The responsivity of the transceiver PIN photodiode (with a 3μm thick GaAs absorption layer) thus increases to 0.61A/W at 850nm, which corresponds to a quantum efficiency of nearly 88%. Our transceiver consists of two independently operating devices (i.e., the VCSEL and PIN photodiode), each with their own contacts for on-wafer high-speed measurements. A typical, top-emitting, predominantly multimode VCSEL with an oxide current aperture of around 8μm has a maximum 3dB bandwidth frequency of 11GHz at an operating current of 10mA. However, the 3dB bandwidth of the adjacent PIN photodiode is strongly bias-dependent in the range of 4.5–6GHz at a reverse-bias voltage of –8V. Thus, the maximum data rate in the...
large-signal modulation of our monolithic transceiver is limited by the photodiode.

For digital data transmission experiments, we butt-coupled a 500m long 50μm core diameter GI MMF with a $B \times L$ of $\sim 2$GHz×km (about 30μm distance) to each chip: see Figure 3(A).

To avoid the influence of optical crosstalk from reflections at the fiber end-faces, as well as at the opposite transceiver chip, we performed digital data transmission in half-duplex mode first. We demonstrated error-free operation at 7Gb/s: see Figure 3(B).

The signals detected by the photodiodes on the transmitter side correspond to the optical crosstalk. We found this contribution to be sufficiently smaller than the trace widths of the operating channel. Importantly, the superposition of optical crosstalk with the signal in full-duplex mode operation still enabled quasi error-free data transmission at 6Gb/s. Thus, our transceivers would be ideal for upgrading standard MMF networks with distances of a few hundred meters, typically found in computer clusters and offices.

In summary, we developed monolithically integrated transceiver chips consisting of a VCSEL and PIN photodiode for optical half- and full-duplex mode data transmission over a single, standard MMF. Avoiding the use of external coupling optics, the anti-resonant signal detection—and hence the size- and weight-saving compact design—enables low-cost, short-reach networks at Gb/s data rates. In future work, we will investigate the parasitic effects, as well as a revised epitaxial design, to improve the dynamic properties of our transceiver chips. The potential bandwidth limit of our optical links is expected to be far above the results shown here, at $\sim 10$Gb/s.

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References
1. MOST150—Annual Achievement Report 2011 www.mostcooperation.com