Multi-Channel Optical Interconnection Modules up to 2.5Gb/s/ch

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Abstract
With the rapid growth of the telecom and datacom market, the information throughput in switching and routing systems such as digital cross-connects or IP routers is increasing immensely. This causes the systems to continually move to higher data rates and also to become more decentralized. The result is a huge demand for high-speed interconnects within those systems. We have developed a 4-channel Transceiver link with a data rate of 2.5Gb/s/ch and are able to provide an ideal solution to overcome this data bottleneck. The Transceiver modules incorporate a 1310nm Fabry-Perot laser diode array and a maximum link length of 2km is specified using single-mode fiber. Providing a hermetic seal on the package guarantees highest reliability. The package is also designed for solder reflow used in standard assembly lines. Our Transceiver modules are now ready to be produced in large volume quantities.

1. Introduction
Fiber optic communication has been established for more than a decade already, in particular for long-haul applications. With the rapid increase of data transmission, mainly caused by the Internet, the demand for bandwidth has surpassed the capacity of copper cable also for of short-reach applications, like the ones in central offices of switching and routing systems. As the link length for these kinds of applications is only a few hundred meters up to a few kilometers, however, multi-channel optical links seem to offer a more cost effective solution than serial optical links. One of the reasons for that is the cost of the electronic integrated circuits (ICs), which becomes very large at high transmission frequencies. Also, module packaging and system board design are far more complex at higher frequencies. Various projects on multi-channel optical interconnects have been reported. [1] – [8] Fiber ribbon cables have become popular in the last few years not only with regard to multi-channel optical interconnects, but also in metro applications as fiber ribbons use up less space than individual fiber cables.

With regard to the choice of laser technology employed in our multi-channel interconnection modules, we are aware of continuous development efforts on 850nm vertical-cavity surface-emitting lasers (VCSELs) and their potential for low fabrication and packaging costs. In our applications, 1310nm Fabry-Perot (FP) edge-emitting lasers (EELs) have proven more beneficial for the following reasons: 1.) Both single mode (SM) and multi mode (MM) operation is possible, 2.) The low fiber dispersion enables optimization of the distance bandwidth product, 3.) The low optical loss in the fiber results in low link budget requirement, 4.) Laser eye safety standards for class 1 (FDA and IEC) can be easily met 5.) The laser diodes (LDs) have been proven to be reliable and have a high manufacturing yield, as this technology has been used in telecom applications for many years.

The fiber demand for multi-channel optical interconnects has predominantly been MM at data rates of 1.25Gb/s/ch, but at 2.5Gb/s/ch SM fiber is requested more often. The reason for this tendency can be explained twofold: 1.) Data rates in switching systems are increasing, which decreases maximum link length and 2.) The size of switching systems is growing larger and larger, which increases the demand for larger link lengths.

In this paper we report a 4-channel Transceiver link, which provides an ideal solution to this rapidly increasing demand for bandwidth. The packaging technology and the optical interface are being described. Then, performance and specifications are being presented and finally considerations about manufacturing and reliability considerations are being discussed.

2. 4-channel Transceiver link concept

Figure 1: 4-channel Transceiver modules with fiber ribbon cable

The Transceiver link is bi-directional and has a total data throughput of 10Gb/s for each direction. 10Gb/s is a standard interconnect requirement in switching systems today as this corresponds to the optical carrier level OC-192 that is mainly used in long-haul communication.
Figure 1 shows a photograph of a 4-channel Transceiver module with a fiber ribbon cable using the MPO/MTP® connector [MTP® is a registered trade mark of US Conec]. The concept of the Transceiver link is shown in figure 2.

A Transceiver link consists of a set of two identical Transceiver modules and a custom fiber ribbon cable assembly. There are two aspects of customization for the cable assembly: First, the optical interface of the Transceiver module matches the 12-fiber MTP® connector, but only the outer 8 fibers are active; the middle 4 fibers are inactive. In order to link the Transceiver modules with an 8-fiber ribbon cable, two jumper cables are needed. The jumper cables serve the purpose to reduce the fiber count from 12 to 8. It consists of a regular 8-fiber ribbon cable with regular 8-fiber MTP® termination on one side and on the other side a custom termination with a 12-fiber MTP® connector but leaving the middle 4 fiber spaces vacant. One might oppose that the custom termination causes fiber damage because the fiber in the ribbon has to be bent. There is no reason for that concern, however, as the MTP® connector housing is large enough to keep the bend radii small enough and no bare fibers have to be bent. Instead of using an 8-fiber cable and two jumper cables, a 12-fiber cable only can be used with the disadvantage that 4 of 12 fibers in the cables will not be used.

The second aspect of cable customization is the cable termination of the main ribbon cable, which has to be opposite than for a standard cable (figure 3). In order to connect two identical Transceiver modules, a straight ribbon cable is needed that guarantees the transmit side to be connected to the receive side. A standard ribbon cable, on the other hand, flips the fibers in order to maintain same channel numbering on transmitter and receiver side.

The fabrication of a straight cable does not cost more than the fabrication of a standard cable as the same parts can be used. The only difference is the orientation of the key of the MTP® connector housing when mounting it onto the MT ferrule (see figure 4). In the case of a standard ribbon cable the key is up on one side and down on the other side, for the straight cable the key orientation is the same on both ends.

3. Packaging

The Transceiver module has a hermetically sealed ceramic package. All the components inside the package are either soldered or assembled with epoxy that doesn’t out-gas. The optical head, as it can be seen in figure 5, is machined to be able to slide into a hole in the back of the package and the touching surfaces are metalized for soldering. In front of the optical head there is a custom receptacle housing designed to match the standard MTP® connector. The optical head consists of an all-solder fiber array assembly and a set of laser diode (LD) and photo-diode (PD) sub-assemblies, which are joined to the fiber array by laser welding. The lid is seam welded after the package has been filled with Nitrogen. Providing a hermetic seal guarantees most protection for all the inside components and therefore highest reliability for the module.

The package is also designed for automated assembly onto printed circuit boards. Two conditions have to be met for automated assembly: automated pick and place and solder reflow capability. Our modules can meet the weight
requirement of standard pick and place machines and the top of the package is flat enough for the modules to be picked up by a standard vacuum tool. The modules are able to withstand the high temperature spikes when going through a solder reflow process. All the materials within the package meet high temperature requirements and are thermally matched with each other. The module is guaranteed to handle 3 temperature cycles at 260ºC of 30 seconds each. The package contains all the electrical components, such as laser driver and receiver IC as well as off-chip components for filtering. The heat dissipation of the package happens through the bottom and no additional heat sink or cooling fins are required.

4. Optical head

The basic structure of the optical head is a straight fiber array that allows the optical signal to propagate through the wall of the hermetically sealed package. The LD and PD sub-assemblies are mounted directly to the fiber array structure. The optical head therefore contains all the optical alignment and can be assembled as a stand-alone unit. Figure 6 shows a picture of the Transceiver optical head.

![Fiber Array](image)

**Figure 6:** Transceiver optical head with LD and PD sub-assemblies

**Fiber array**

The fiber array comprises a metal substrate and two ceramic substrates of which one of them incorporates 12 high precision v-grooves (figure 7). The four middle fiber places are left vacant leaving enough space between LD and PD sub-assemblies for convenient alignment and mounting. This assembly is all soldered.

We developed the composition of the ceramic substrates to have a thermal expansion coefficient that matches the one of the metal substrate. This was a crucial step for the robustness of the optical alignment when exposed to high temperatures.

Employing our mature v-groove technology we are able to position the fibers with less than 1µm accuracy, which is necessary for SM fibers. Figure 8 shows the results of a typical fiber core position measurement. The average offset (20 samples) of the ideal core position has been displayed for each channel. According to fiber coupling loss measurements, a lateral fiber-to-fiber offset of 1µm results in a coupling loss of about 0.2dB.

There exist two additional large grooves in the ceramic substrates that are designed for the guide-pin holes of the MTP® connector. As the SM MTP® connector is angle polished, the corresponding face of the fiber array is also angle polished matching its orientation.

**Figure 7:** Conceptual drawing of optical head fiber array

**Figure 8:** SM fiber core deviation in v-grooves

**LD and PD sub-assemblies**

The LD sub-assembly comprises an array of four 1310nm InGaAsP/InP MQW laser diodes, a ceramic sub-mount and a metal substrate on the bottom. The LD array is mounted on top of the ceramic sub-mount (see figure 6). As the LDs are edge-emitting lasers (EEL) they can couple the light straight into fibers. The gap between LD and fiber is 25µm and no lens array is being used.

The PD sub-assembly is built in the same manner as the LD sub-assembly using an array of four InGaAs PIN photodiode detectors. The PD array is mounted on the lateral
surface of its sub-mount facing the fibers. The distance between fibers and PDs is 50µm.

**Optical alignment**
The LD and PD sub-assemblies are mounted to the fiber array block by an active alignment process. First, the sub-assembly is being moved towards the fiber array until the two metal substrates touch. This stabilizes the gap between the LDs and PDs to the fibers. Then, the sub-assembly is moved in the two lateral alignment directions parallel to the front face of the fiber array and plus one rotational axis. At the same time the coupling efficiency on all the channels is measured until the values are optimized. Finally, the two metal substrates are welded together with a YAG laser. LD array alignment and PD array alignment happen in two separate processes. The complete optical alignment process has been automated and is controlled by computer. One advantage of active alignment, with respect to passive alignment, is that test results are automatically recorded in the process of alignment. This way, parts that don’t meet the specifications can be detected and reworked. Figure 9 shows a picture of the optical alignment setup at our manufacturing facility. The PD or LD sub-assembly is mounted on a stage that can be moved with regard to the fiber array. During the alignment process a MT fiber ribbon is connected to the fiber array.

![Figure 9: Optical alignment setup](image)

**5. Electronic circuit integration**
The most critical aspect when designing multi-channel components is channel-to-channel crosstalk. In order to avoid crosstalk problems, not only the ASIC design has to be considered but also the isolation of the traces within the package and the filtering of the power supplies. We designed our own multi-layer high-frequency ceramic package. The differential signal pairs are guided on microstrips. At critical locations ground planes are included in between channels. Considering the Transceiver module, not only channel-to-channel crosstalk has to be considered but also crosstalk between transmit and receive side. In order to isolate transmit and receive side, the power supplies and also the grounds have been isolated.

With regard to LD driver design, an automatic temperature control (ATC) circuit has been implemented that ensures constant optical output power over a temperature range from 0°C up to 80°C. This is necessary because the optical output power of the LD decreases with increasing temperature while the threshold current increases. In addition to that, the slope efficiency decreases with increasing temperature, which affects the modulation characteristics of the optical signal. The ATC circuit operates on the basis of a signal from the temperature sensor (thermistor) that is placed near the LD array and generates a feedback current to adjust biasing and modulation current of the LDs.

**6. Manufacturing**
The key of moving from the development status to production is automation. The process of automated optical alignment has already been explained in section 4. The design of an optical head unit that contains all the optical alignment was one of the key technologies for production. Furthermore, all the components are mounted into the module packages automatically. Wire bonding is done with an automatic wire-bonding machine. Figure 10 shows a picture of a component mounting equipment. In the foreground there are the trays with the modules in it.

![Figure 10: Component mounting machine](image)

**7. Performance**
Table 1, 2 and 3 summarize all the characterization parameter of the Transceiver link. Every production module that is being sent to a customer has been tested at room temperature and at 70°C ambient for the following parameters: transmit optical power, receive sensitivity and saturation, eye diagram, mask and jitter test of the link. Also, every module is being tested for hermeticity.
Figure 11 and 12 show the eye diagram of a Transceiver link. These measurements have been performed while all channels were running simultaneously, each with a different signal pattern.

### Physical Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>2.5 Gb/s/ch</td>
</tr>
<tr>
<td>Number of Channels</td>
<td>4</td>
</tr>
<tr>
<td>Temperature Range(^1)</td>
<td>0 – 70 °C(^1)</td>
</tr>
<tr>
<td>Module Lifetime</td>
<td>25 years at 70 °C(^1)</td>
</tr>
<tr>
<td>Laser Safety Standard</td>
<td>FDA Class 1, IEC Class 1</td>
</tr>
<tr>
<td>Maximum Reflow Temperature</td>
<td>260 °C(^1,2)</td>
</tr>
</tbody>
</table>

Table 1: Physical Specifications of Transceiver module

\(^1\)Ambient temperature, \(^2\)3 cycles for 30 seconds each

### Optical Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1310 nm</td>
</tr>
<tr>
<td>Transmitter Optical Power</td>
<td>-8 dBm/ch</td>
</tr>
<tr>
<td>Minimum Received Optical Power</td>
<td>-19 dBm</td>
</tr>
<tr>
<td>Maximum Received Optical Power</td>
<td>-6 dBm</td>
</tr>
<tr>
<td>Array Optical Power Variation</td>
<td>3 dB</td>
</tr>
<tr>
<td>Fiber Type</td>
<td>9 µm SM</td>
</tr>
<tr>
<td>Maximum Distance</td>
<td>2000 m</td>
</tr>
</tbody>
</table>

Table 2: Optical Specifications of Transceiver module

### Electrical Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>300 mW/ch</td>
</tr>
<tr>
<td>Jitter (Peak-to-Peak)</td>
<td>100 ps</td>
</tr>
<tr>
<td>Channel-to-Channel Skew</td>
<td>100 ps</td>
</tr>
<tr>
<td>BER (PRBS 2(^{15})-1 NRZ)</td>
<td>(10^{-14})</td>
</tr>
<tr>
<td>Electrical Interface</td>
<td>CML</td>
</tr>
<tr>
<td>Low Cutoff Frequency</td>
<td>160 kHz</td>
</tr>
</tbody>
</table>

Table 3: Electrical Specifications of Transceiver module

8. Quality assurance and reliability

Previous to the development of the 4-channel Transceiver module, 8-channel and 12-channel Transmitter and Receiver modules have been developed for which all the reliability tests have been completed. The reliability test for the Transceiver modules are currently in progress. As the packaging technology has not changed, the same reliability characteristics can be expected for the Transceiver module as for the Transmitter and Receiver modules.

The reliability tests are being done according to the Bellcore Standard GR-468-CORE (see table 4). In the following figures (13 and 14) an example of accelerated aging tests for transmitter and receiver is shown.

The component that is most sensitive to failure is normally the LD. With the choice of EEL, as already discussed in the introduction, we know that this technology has a proven record of reliability. In addition to that, we operate our LDs at about a third of the maximum optical output power. The measured MTTF (mean time to failure) by our LD vendor at 85°C and at maximum laser output power is \(10^5\)h (~11 years). Under our operating conditions we can expect \(3*10^5\)h
We specify a lifetime for our modules of 25 years at 85°C. By optimizing reliability and lifetime of our components we can reduce the overall cost of ownership.

**Reliability Tests Based on Bellcore Standard (GR-468-CORE)**

<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration</td>
<td>20G, 20 ~ 2,000 Hz, 4min/cy, 4cy/axis</td>
<td>Tx: Δ Opt. Power ≤ ±2dB</td>
</tr>
<tr>
<td>Mechanical Shock</td>
<td>5 times / axis, 1,500G, 0.5ms</td>
<td>Rx: Responsivity ≤ -19dBm</td>
</tr>
<tr>
<td>Temperature Cycling</td>
<td>-40°C / +85°C, ≥ 500 cy</td>
<td>Link eye-diagram tested after each test</td>
</tr>
<tr>
<td>Cyclic Moisture</td>
<td>-10°C ~ +65°C, 80 ~100% RH, 24 hrs/cy x 20 cy</td>
<td></td>
</tr>
<tr>
<td>Reflow Test</td>
<td>260°C x 40 sec, 3 cy</td>
<td></td>
</tr>
<tr>
<td>Accelerated Aging</td>
<td>85°C, ≥ 2,000hrs</td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Reliability tests

5000 Hrs, 85 °C, 3.3V Tx

![Graph](image1)

Figure 13: Transmitter accelerated aging tests

5000 Hrs, 85 °C, 5V Rx

![Graph](image2)

Figure 14: Receiver accelerated aging tests

**9. Conclusions**

A 4x2.5Gb/s SM Transceiver module has been developed up to production level. The modules are packaged with a hermetic seal and are able to be mounted onto system boards with automated assembly lines. We have also developed 8x2.5Gb/s Transmitter and Receiver modules (not discussed in this paper) and are planning further optical interconnects at higher data rates.

The data rate per channel in switching systems is foreseen to increase even higher, which will make the use of MM fiber more difficult. Having developed a multi-channel optical interconnection module with SM compatibility, we have laid out a clear upgrade path to higher data rates.

**10. Acknowledgments**

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**11. References**