Versatile transceiver development status

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ABSTRACT: The Versatile Link common project is developing optical link architectures and components to be used for readout and control of future HL-LHC experiments. The on-detector optoelectronic module, the Versatile Transceiver (VTRx), is derived from an industry standard module type and is adapted through minimal customization to the requirements dictated by the HL-LHC-specific front-end environment. We present the methods and results of the functional tests carried out on the transceiver components and summarize the development status of the different VTRx variants. Finally we show the results obtained using the packaged VTRx module.

KEYWORDS: Optical detector readout concepts; Radiation-hard electronics; Front-end electronics for detector readout

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1 Introduction

The deployment of custom-developed, high-speed, radiation tolerant opto-electronic data transmission links in large quantities has been one of the key enabling technologies for the success of the particle physics experiments at the Large Hadron Collider (LHC). Upgraded detectors at the High Luminosity LHC (HL-LHC) will require new optical links that meet even more stringent requirements in terms of performance and radiation hardness. Bi-directional functionality will be required to support detector data readout and transmission of timing and control information on the same optical link. The optical link development effort is being shared between several groups that participate in the Versatile Link project [1, 2]. The proposed link architecture is shown in figure 1.

The Versatile Transceiver (VTRx) is the bi-directional opto-electronic module which will be installed on-detector (at the front-end). It will be deployed in systems based on either single-mode or multi-mode fibre plants, operating at 1310 nm or 850 nm wavelengths. The VTRx module is based on the industry standard Small Form-factor Pluggable (SFP+) transceiver format and has been tailored to the HL-LHC detector environment. The customized module uses fewer components than commercial devices and is packaged using low-mass material. The transmitter path consists of the radiation-tolerant GigaBit Laser Driver (GBLD) [3] and a commercial Transmitter Optical Sub-Assembly (TOSA). On the receiver side the Receiver Optical Sub-Assembly (ROSA) includes a commercial PIN photodiode and the radiation-tolerant GigaBit TransImpedance and limiting Amplifier (GBTIA) [4]. Due to the need for radiation tolerance the ASICs are sourced from the GigaBit Transceiver (GBT) project [5].

This paper will summarize the development of the VTRx prototypes and the testing of its components. We will show test results demonstrating the performance of different transceiver variants. The radiation tolerance of lasers and photodiodes has already been verified and tests results have been published in [6]. The single-event upset testing of fully assembled VTRx modules has also been carried out [7].
2 Printed circuit board

According to the Versatile Transceiver specifications [8], the VTRx will have to operate at 4.8 Gbit/s, a limit set by the current GBT chipset. However, to allow testing of 10G compliant commercial devices the Printed Circuit Board (PCB) has been designed to operate at higher frequencies. The first version of the PCB had some limitations and we observed more jitter and more amplitude noise when compared to a commercial laser driver evaluation board [9]. In multi-gigabit optical links, these parameters can greatly affect the overall link performance and must be carefully controlled.

In order to improve the PCB, the new design was optimized using CAD tools specialized for Signal Integrity (SI) simulations. These tools were used at different phases during the design process. In the pre-layout phase, performance critical PCB structures were laid out and simulated in an SI tool. These structures were then used as a starting point for the layout design. Changes during the layout process could be verified at any time by exporting the design from the layout tool to the SI simulator. Finally, the finished design was analyzed before sign-off. Advanced post-layout simulations were carried out using active device models to optimize the matching between the laser driver and the laser. The performance of the re-designed PCB will be shown in section 5.

3 Optical connector latch

Since the VTRx will be used in tracking detectors its mass has to be minimized to avoid unwanted particle interactions that would degrade the overall experiment performance. Unlike commercial transceivers, the VTRx module must not contain large metallic parts like for example the EM shielding. The required mass reduction can be achieved by using a custom-designed plastic connector latch. The purpose of the plastic adapter is to ensure good optical connection between TOSA/ROSA and the LC-type optical connector, which requires tight manufacturing tolerances. The 3-D CAD models have been tailored for the selected TOSA and ROSA packages. Small prototype series were produced using 3-D printing techniques. The use of low cost, rapid prototyping allowed us to optimize the connector design and to produce samples using different materials. The feasibility of using radiation tolerant polymers and the possibility of making large production series with 3-D printing are currently being investigated.
4 Component testing

4.1 TOSA tests

Several commercial TOSA components from different vendors have been tested to verify that they meet the Versatile Link specifications [8]. The so-called LIV curve is obtained by measuring the light intensity (L) and forward operating voltage (V) as a function of DC bias current (I). Using the LIV curve we can extract some basic device parameters, such as threshold current and slope efficiency. The experimental setup, shown in figure 2, consists of a Laser Diode Controller (LDC), which drives the Device Under Test (DUT) and measures the forward voltage drop across the laser. The intensity of the output light is measured using an Optical Power Meter (OPM). The instrument control and the data logging are implemented in LabVIEW running on a computer. Figure 3 shows some LIV curves obtained by measuring various Vertical Cavity Surface Emitting Laser (VCSEL) devices from different manufacturers.

The Relative Intensity Noise (RIN) measurement is performed in the frequency domain. In addition to the characterization of the noise performance, the results can also provide information about the high-frequency properties of the device. During the RIN test the stochastic variations of the steady-state light intensity are measured at different bias conditions using an experimental setup shown in figure 4. It consists of a laser diode controller, (LDC) which provides a DC current for the laser, a reference optical receiver (RX), which performs the optical to electrical conversion, and an electrical spectrum analyser (ESA). The instrument control and the data logging were implemented.
Figure 4. Experimental setup used for measuring laser RIN.

Figure 5. Laser RIN measured at bias currents ranging from 3 to 13 mA (left) and extracted relaxation oscillation frequency ($f_r$) as a function of bias current above threshold (right).

The raw results contain noise (e.g. thermal and shot noise) produced by the instruments. The laser RIN can be obtained by removing these unwanted noise components from the spectrum. The relaxation oscillation ($f_r$) and damping ($\Gamma_d$) frequencies can then be extracted by fitting the laser RIN to equation (4.1), where $A$ and $B$ are device-dependent constants [10].

$$RIN(f) = \frac{A + B(2\pi f)^2}{16\pi^4(f^2 - f_r^2) + (2\pi f)^2\Gamma_d^2}$$  \hfill (4.1)$$

Figure 5 shows the results of a measurement carried out on a single-mode VCSEL device. Traces on the left plot show the laser RIN measured at drive currents from 3 and 13 mA in steps of 0.5 mA. The extracted relaxation oscillation frequency, which is related to the maximum modulation bandwidth of the device, as a function of the drive current above threshold is displayed on the right plot of figure 5. The results can be used to define the optimal laser bias conditions in order to achieve the required noise performance and modulation bandwidth.

4.2 ROSA tests

The specially-designed radiation-tolerant receiving amplifier, the GBTIA [4], was assembled with 60 $\mu$m diameter InGaAs and 70 $\mu$m diameter GaAs photodiodes. We tested 10 ROSA devices from each variant to measure their sensitivity. During the measurement the Device Under Test (DUT)
was fed with a Pseudo-Random Bit Sequence (PRBS) typically operating at the target bit-rate of 4.8 Gbit/s generated by serial Bit Error Rate Tester (BERT). The electrical signal from the BERT was converted into an optical signal by the transmitter (TX) portion of a reference transceiver module. The optical signal passed through a Variable Optical Attenuator (VOA) before reaching the DUT. The average optical power was measured via a tap coupler in the VOA. The electrical output of the DUT was fed back to the BERT for analysis. Bit Error Rate (BER) curves were obtained by plotting the error rate at different input optical power levels. Optical Modulation Amplitude (OMA) at the receiver is calculated using the measured average optical power and the pre-measured extinction ratio of the reference transmitter. The test setup is shown in figure 6.

The BER curves for all devices are overlaid for ease of comparison on the left plot of figure 7. We have extracted a sensitivity based on the measurements at a BER of $10^{-9}$ and these values are shown on the right plot of figure 7. DUT 2 is clearly an outlier when used with both single- and multi-mode fibre inputs. We can see that the InGaAs device at 1310 nm and the GaAs device at 850 nm meet the single-mode and multi-mode specifications, respectively. However, the InGaAs device only marginally meets the multi-mode specifications at 850 nm.
5 Module testing

Four different VTRx variants have been assembled using the GBTIA ROSA and shortlisted TOSA components. Since the current version of the GBLD has some performance limitations, two VTRx versions were built with commercial laser drivers to validate the PCB design and to dynamically test the selected TOSA candidates. In addition, these prototypes offered the possibility to directly compare the results of measurements carried out earlier on commercial evaluation boards. The available VTRx variants are listed in table 1.

The transmitter portion of standalone modules was tested by measuring the optical eye at various bias and modulation current settings with the experimental setup shown in figure 8. The DUT, plugged into a commercial Module Compliance Board (MCB), was driven by a BERT which was configured to generate a repeating PRBS pattern at 4.8 Gbit/s. The optical output of the DUT was connected to the optical head of a sampling oscilloscope. The sub-rate clock required by the oscilloscope was also provided by the BERT. After reconstructing the eye diagram the oscilloscope extracts the amplitude and jitter parameters. The control of the oscilloscope and the data logging were implemented in LabVIEW.

Figure 9 shows some results of the measurement carried out using the single-mode VTRx variants. The bias and modulation current settings were chosen to be similar in the two cases. However, the differences between the laser drivers and the lasers used on the two prototypes mean
that the actual operating points of the two lasers cannot be identical. While this makes a direct comparison of the measured amplitude and average power difficult, it does allow us to gain some insight into the relative performance of the two VTRx variants. The eye diagram of variant 3 (left) confirms that the GBLD has some bandwidth limitations resulting in slower rising/falling edges and more data dependent jitter, but the eye remains reasonably wide open. Some ringing can be observed on the eye diagram of variant 1 (right) due to the sub-optimal resistor values in the laser matching network chosen according to the best compromise found in order to maximize the modulation amplitude.

The transmit eye diagrams of the multi-mode VTRx variants are shown in figure 10. Since a VCSEL requires less modulation current than an edge emitter laser, the GBLD-based variant 4 has faster edges, but it is still slower than a commercial laser driver on variant 2. In addition, there is an important difference in jitter between the rising and falling edges in case of the GBLD.

The receiver section of the VTRx prototypes has been verified by measuring the bit error rate using the experimental setup shown in figure 6. BER curves were recorded while the transmitter part was disabled, and also while the transmitter was enabled and sending data. Some VTRx prototypes were also tested with the plastic LC connector latch. The results in figure 11 show that operating the transmitter has no negative influence on the receiver performance, which can be slightly improved by properly mating ROSA and LC connector ferrule with the help of the optical connector latch.

![Figure 10](image_url). Transmit optical eye of the multi-mode VTRx prototypes: variant 4 using the GBLD (left) and variant 2 using a commercial laser driver (right).

### Table 1. Available VTRx variants.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Laser Driver</th>
<th>TOSA type</th>
<th>ROSA type</th>
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<tbody>
<tr>
<td>1</td>
<td>ONET1101L</td>
<td>Edge Emitter Laser</td>
<td>60 µm InGaAs</td>
</tr>
<tr>
<td>2</td>
<td>ONET8501V</td>
<td>VCSEL</td>
<td>70 µm GaAs</td>
</tr>
<tr>
<td>3</td>
<td>GBLD v3</td>
<td>Edge Emitter Laser</td>
<td>60 µm InGaAs</td>
</tr>
<tr>
<td>4</td>
<td>GBLD v3</td>
<td>VCSEL</td>
<td>70 µm GaAs</td>
</tr>
</tbody>
</table>
### 6 Summary

New versions of the Versatile Transceiver PCB have been designed using techniques to ensure good performance at 5 Gbit/s. The feasibility of using rapid 3-D printing for producing different optical connector variants has been demonstrated. Candidate TOSA and ROSA components have been tested and shown to meet the Versatile Link specifications. Using these components different flavours of transceiver prototypes have been built and functionally tested. The test results show that these VTRx prototypes operate according to specifications.

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### References


