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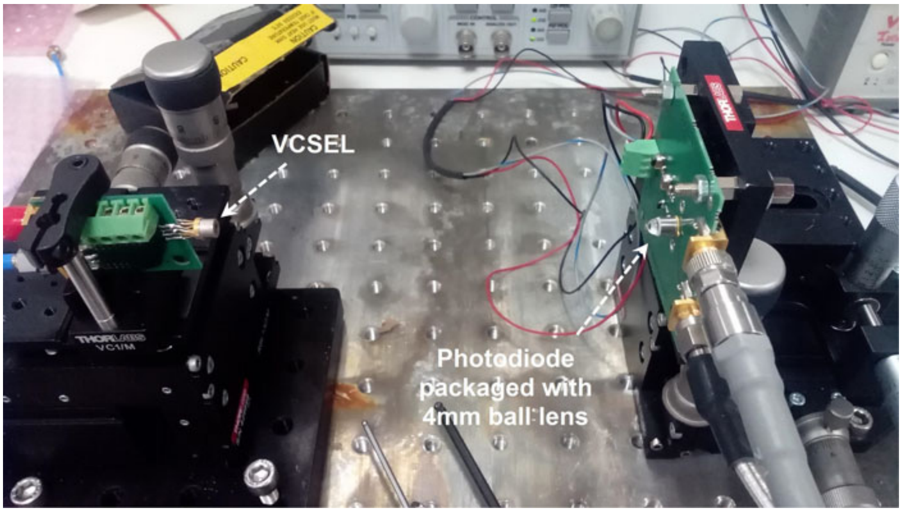

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Design and Assessment of a 2.5-Gb/s Optical Wireless Transmission System for High Energy Physics

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Abstract: We designed, realized, and tested a 2.5-Gb/s optical wireless communication (OWC) system prototype, that should be employed in high energy physics (HEP) experiments, such as the compact muon solenoid (CMS). The system consists of off-the-shelf components, mainly a vertical cavity surface emitting laser (VCSEL) and a PIN photodiode with a proper ball lens. Since it should be used to transmit data among particle sensors in neighboring rings of the CMS, its target distance is 10 cm. Its most attractive feature is that it does not require a (complex) active tracking system because its measured tolerance to misalignment is around $\pm$1 mm (at 10^{-12} bit error rate). We also report the X-rays irradiation tests of all components (Quartz lens, VCSEL, and PIN photodiode): None of them showed any degradation up till 238-Mrad (Si) dose. These results indicate that the designed OWC can be a viable solution for future HEP experiments.

Index Terms: Free-space optical, high energy physics (HEP) instrumentation.

1. Introduction

Compact Muon Solenoid (CMS) is one of the major experiments operating in the Large Hadron Collider (LHC) at CERN. The CMS inner tracker consists of about 10,000 silicon detector modules arranged in layers. These detector modules are fixed on concentric barrels, separated by around 10 centimeters [1]. In the current version of the tracker, the readout of the HEP events detected by the detector modules is performed by approximately 40,000 optical fiber links [2]. This large number results in a very high material budget and strong space limitations; it also introduces excessive labor cost for cables installation and management. The large amount of non-sensitive material may also reduce the detector performance because of multiple scattering. In addition, much larger data volumes are expected to be generated after future upgrades of the CMS and thus higher data rates will be required. Any possibility to route new cables is also difficult due to space limitations.

Wireless technology is an attractive option to reduce the need of optical fibers by providing radial connectivity between the layers of detector modules. This approach was presented by [3], where a millimeter wave (60 GHz signal) was considered for data transmission between the layers. The

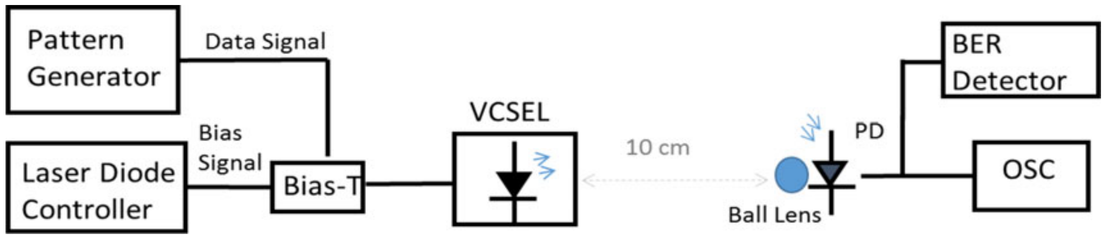


Fig. 1. OWC experimental setup at 2.5 Gb/s and 10 cm distance. OSC: Sampling oscilloscope; PD: PIN photodiode+TIA.

challenge of such systems is the non-availability of radiation-hard off-the-shelf electronic devices to generate millimeter waves.

High speed Optical Wireless Communication (OWC) is a promising technology that could be used in the inner tracker due to the availability of off-the-shelf radiation-hard components [10]. Using OWC, the data will be transmitted from any inner layer of detectors to the next outer layer. The outermost layer of the tracker will be finally connected by optical fiber links. This will save several fiber links and will help in reducing both complexity and material budget besides providing high data rate connectivity. However, until today, only preliminary studies are reported about the OWC in HEP. An initial study was reported in [4], where OWC was demonstrated at 4 Gb/s to 10 Gb/s, for 21 cm and 11 cm transmission distance, respectively, through 2 mm silicon samples. Due to the proof-of-concept nature of the paper, limited experimental details were provided by the authors and no analysis was performed to prove that the proposed setup could effectively work in HEP environments. Many design constraints must be still investigated, i.e. proper selection of transmitter and receiver, misalignment tolerance, beam divergence of transmitter and its effect on the data rates.

Another conceptual idea was proposed in [5], where the designed transceiver is a Mach-Zehnder Modulator (MZM) with a laser source outside the irradiation zone. They proposed light beam steering for the system tolerance by deploying Micro Electro-Mechanical Systems (MEMS). However, this adds complexity because of the control electronics (based on FPGA and DAC/ADC) which are required to monitor the feedback. Moreover, the radiation tolerance of MZM's is still an open issue [6].

The mainstream research on laser-based OWC also used collimated beams with active alignment techniques [7], [8]. In the particle detectors only passively aligned OWC systems can be installed since the active tracking adds complexity and material budget. In addition, its control electronics may not be suitable for HEP environments. Therefore, in order to remove the active tracking issues, we designed and developed an OWC system that works with passive alignment, providing a higher misalignment tolerance than the CMS inner tracker requirement, which is 0.25 mm [9]. In order to achieve this tolerance, we performed a preliminary study of ray-tracing simulations of a 2.5 Gb/s OWC system [9].

In this paper, we present the realization of the 2.5 Gb/s OWC system using a single off-the-shelf Vertical Cavity Surface Emitting Laser (VCSEL) as the transmitter and a PIN photodiode with a ball lens as the receiver. We realized a low-cost and energy efficient system prototype. We also report the experimental assessment of the system, showing a tolerance to misalignment of ± 1 mm at 10 cm transmission distance, provided by a proper choice of the OWC components. Finally, we tested the viability of the optical components under X-rays irradiation.

2. Test-Bench Characterization and Results

Based on our previous ray-tracing simulations, in [9], we realized the experimental setup shown in Fig. 1. As discussed, we chose a VCSEL thanks to its low cost, its low divergence angle and circular beam waist, unlike edge emitting lasers. Moreover, VCSELs are attractive for HEP applications because they can be radiation resistant [10].

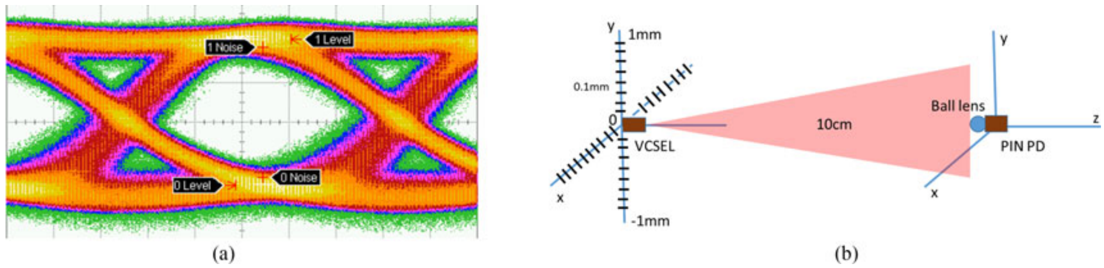


Fig. 2. (a): Eye diagram for the 2.5 Gb/s signal at 10 cm ; (b): tolerance measurement schematics.

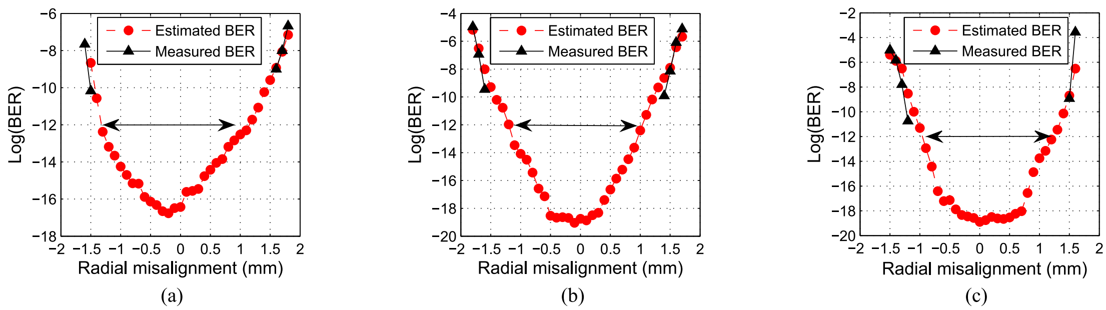
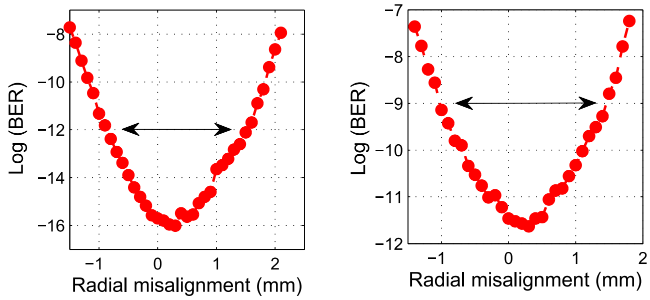


Fig. 3. Tolerance to misalignment: BER vs. radial misalignment for 3 mm (a), 4 mm (b), 5 mm (c) ball lens.

The VCSEL (1550 nm, 1 mW optical output power and 16° Full Width at Half Maximum divergence angle) was directly modulated at 2.5 Gb/s by a NRZ Pseudo Random Bit Sequence (PRBS length: 2^{15}-1 bits). In order to simplify the tolerance measurements, the VCSEL was placed on a 3-axis translator stage. The receiver consisted of a PIN photodiode and a ball lens. The photodiode has sensitive diameter of 60 μm, 3-dB bandwidth of 1.8 GHz with trans-impedance amplifier (TIA). A similar PIN photodiode was tested to be radiation hard [10]. The ball lens was placed in front of the photodiode to increase the collected light. Fused silica and quartz glass lenses were selected, since they can provide proper radiation hardness, i.e. much better than BK7 glass at 1550 nm [11]. The photodiode was placed on a similar 3-axis translator stage to precisely set its active area at the focal point of the ball lens. The transmission distance was fixed at 10 cm as required by the specification [1]. The TIA outputs (direct and inverted) were connected to a Bit Error Ratio (BER) detector and a sampling oscilloscope for the eye diagram analysis. Three ball lenses (3, 4 and 5 mm diameter) were characterized to choose the best one in terms of signal quality, tolerance values, required transmitted power and suitability for packaging. The signal quality of the OWC link was evaluated using Q factor [12]. BER of 10^{-12} was targeted according to the CMS experimental requirements.

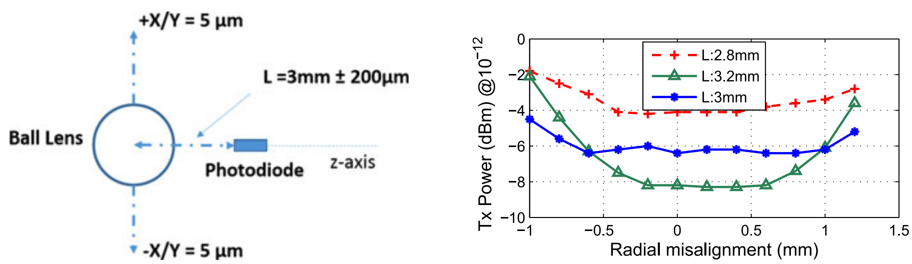
We started the characterization with the 5 mm ball lens to maximize the optical power at the photodiode, which helped to precisely align the OWC setup. Both the VCSEL and the photodiode were aligned by maximizing the eye opening. Bias current of the laser (4.7 mA) and peak-to-peak voltage from the pattern generator (1.130 Vpp) were also optimized in order to maximize the Q-factor value. Fig. 2(a) depicts the wide open eye diagram of 2.5 Gb/s at aligned position ($x = y = 0$). After that, we misaligned the VCSEL along the radial distance (X or Y axis, in both directions) by 0.1 mm step as illustrated in Fig. 2(b) and noted the BER and the Q-factor values. This process was repeated until the line of sight (LOS) was completely lost. The same procedure was performed for the 3 mm and 4 mm ball lenses.

Fig. 3(a)–(c) report the measured BER values (black triangles) as a function of the radial misalignment, depicting the alignment tolerance for the 3 lenses. The tolerance limit is defined as the misalignment range where the BER is $\leq 10^{-12}$. Due to the long measurement time (>30 mins for



(a) (b)

Fig. 4. Estimated BER vs. radial misalignment at 15 cm (a) and 20 cm (b) transmission distance.



(a) (b)

Fig. 5. (a): Scheme of packaging tolerance for the lens; (b): transmitted (Tx) power as a function of radial misalignment considering 5 μm deviation on X/Y axis and for different values of L (z-axis).

99% confidence level) for BER $\leq 10^{-10}$, we also report the BER values estimated from the Q-factor (red dots) [12].

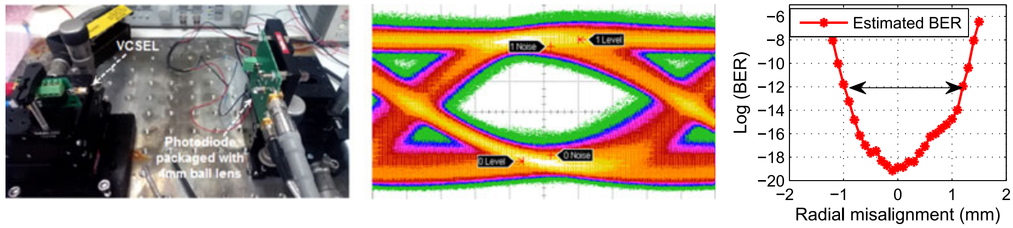
As can be observed from Fig. 3(a)–(c), the estimated BER values were slightly worse than the measured values because of the non-ideal Gaussian noise of the OWC system. We observe that all the three diameter ball lenses provide approximately ± 1 mm of tolerance values. These experimental tolerance ranges are in good agreement with the simulation results obtained in [9]. It is further deduced that 4 mm lens leads to optimized results providing high Q-factor and good tolerance values at BER of 10^{-12}. The 4 mm ball lens also provides the convenient packaging on top of the TO-46 header of the photodiode (which has a diameter of 4.7 mm).

We also report in Fig. 4 the results obtained by testing the system at longer distances (15 cm and 20 cm) with the 4 mm lens at the receiver. We achieved a tolerance range of ± 1 mm also at 15 cm (Fig. 4(a)), but with a lower BER margin (the minimum BER was 10^{-16}). At 20 cm distance, although the tolerance was similar to the previous cases, the BER was slightly lower than the target BER (Fig. 4(b)). Hence, in this configuration, the system is not suitable for the HEP experiment. Nevertheless, at 20 cm the designed OWC system can be used in board-to-board transmission system for applications where passive alignment of ± 1 mm at BER of 10^{-9} is required.

3. Receiver Prototype

Based on the previous results, we realized an OWC system receiver prototype. We designed the can cap for a 4 mm ball lens using the results of ray-tracing simulations. The critical task was to place the photodiode active area at the focal point of the ball lens, considering the precision of the packaging.

First, we performed a simulation of the system misalignment at 10 cm distance, taking into account a radial (X/Y axis) and an axial (Z-axis, L) deviation of the ball lens position. On X/Y-axis, we considered a ± 5 μm deviation. On z-axis, we considered a deviation of ± 200 μm respect to a reference value of $L = 3$ mm (optimal position, see Fig. 5(a)). The assumed values were given



(a) (b) (c)

Fig. 6. (a): OWC experimental setup of 2.5 Gb/s; (b): eye diagram; (c): BER vs. misalignment.

to us by our packaging lab. The designed OWC system was limited by the VCSEL transmitted power of 1 mW (0 dBm). From Fig. 5(b), it was observed that, for our radial deviation, the tolerance range of approximately ± 1 mm could be obtained with ± 200 μm deviation on z-axis (all the curves are below the 0 dBm transmitted power). Finally, the ball lens holder was designed and realized according to TO-46 cap standards. The final prototype and setup is presented in Fig. 6(a).

3.1 Prototype Test and Results

The OWC system prototype was tested using the similar setup shown in Fig. 1. Both the VCSEL and photodiode packaged with 4 mm ball lens were placed on a 3-axis stage at distance of 10 cm from each other. As previously discussed, we properly aligned the transmitter and the receiver by maximizing the Q-factor value. Wide eye diagram for 2.5 Gb/s is shown in Fig. 6(b) for the aligned system position ($x = y = 0$).

Fig. 6(c) presents the BER values as a function of the radial misalignment, illustrating the tolerance range of the OWC prototype. We observed a tolerance range of ± 1.1 mm, matching with the results of the test-bench experiment, reported in Section 2. These results highlight the successful implementation of the 2.5 Gb/s prototype at 10 cm of distance with the misalignment tolerance value of ± 1 mm at 10^{-12} BER.

4. X-Rays Irradiation Test of the Prototype Components

In the past, other types of VCSELs and PIN photodiodes were tested under high irradiation fluence levels [10]. OWC mainly differs from fiber systems because in fibers the ionizing radiations (X-rays or Gamma rays) introduce Radiation Induced Attenuation (RIA). Off-the-shelf fibers introduce 0.06 dB/m attenuation at total ionizing dose of 65 Mrad [13], therefore negligible for short distance link. Wired and wireless optical links use quite similar transmitter and receiver, which thus have roughly similar radiation tolerance. However, the ball lenses for wireless links are not evaluated for dose rates required for HEP experiments. Future particle detectors will experience total ionizing dose of 100 Mrad (considering silicon material as a reference) [10]. The ionizing radiations such as X-rays and gamma rays strongly affect the glass transmission characteristics and refractive index [11], [14]. Therefore, a X-ray irradiation test was designed and conducted to study the performance of the quartz lens we used. As mentioned earlier, we selected the quartz glass because of its radiation hard behavior. Unlike glass material, VCSELs and PIN photodiodes are mainly degraded by non-ionizing radiations such as pions and neutrons [10]. However, in order to investigate the VCSEL and the PIN photodiode of OWC prototype we also analyzed their performance under high dose X-rays radiations. The devices used were procured with exactly the same specifications, that we utilized for the 2.5 Gb/s OWC system prototype.

4.1 Experiment

We designed a short distance LOS OWC experimental setup for the irradiation test of the optical components as shown in Fig. 7. The PIN Photodiode was without any trans-impedance amplifier

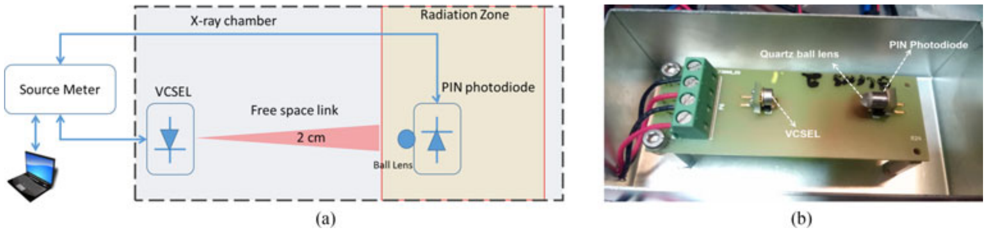


Fig. 7. (a): X-rays irradiation test setup; (b): PCB with the VCSEL and the photodiode with a ball lens.

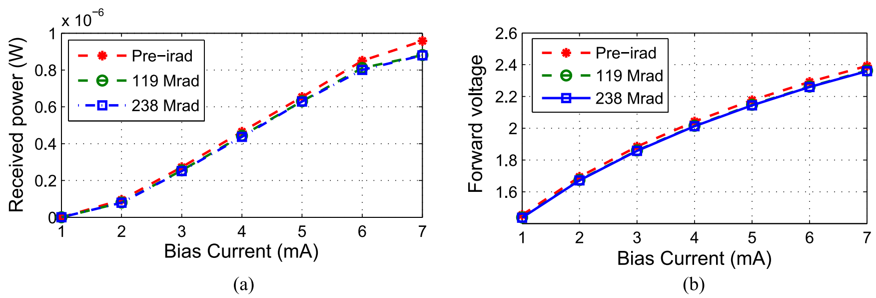


Fig. 8. (a): L-I curve of the VCSEL; (b): I-V curve of the VCSEL under X-rays.

(TIA) for X-rays test. The TIA was avoided to reduce the test complexity, because it could be difficult to analyze the TIA and the photodiode together if one or both degrade under the X-rays. In addition, custom radiation hard TIA is already designed for particle detectors experiments [15]. We used the VCSEL as a Continuous Wave (CW) source. To test the quartz glass material under X-rays, a 4 mm quartz ball lens was packaged with the PIN photodiode (utilizing the ball lens cap designed in Section 3). The distance between the photodiode and the VCSEL was adjusted at 2 cm. The short distance was kept to characterize the components with high received power at the photodiode.

The test was conducted at the irradiation facility of the University of Padua. The 8 keV X-rays irradiation setup was calibrated to place the device at 14 mm distance from the source. At this distance, the X-ray beam waist was approximately 2.5 mm and the dose rate was 10.8 Mrad/hour (Si). The board was fixed in a box, covered with an aluminum and a zinc plate to shield other parts on the board. Thus we irradiated only the component under test. Both the VCSEL and the photodiode were connected with a source-meter remotely controlled by a PC. Each component was irradiated continuously for 22 hours with total dose of 238 Mrad (Si). We recorded the bias current and the forward voltage of the VCSEL together with the dark/received current of the photodiode at every 15 min interval. The dark current was measured by switching off the VCSEL while the received current at the photodiode was monitored by fixing the VCSEL bias current at 7 mA. For each component, the X-ray beam was initially aligned using a laser installed in the X-ray chamber. The VCSEL and the photodiode were irradiated without any packaging to avoid the shielding of X-rays.

4.2 Irradiation Results

First we irradiated one VCSEL. We present the results in Fig. 8, which shows the L-I and I-V curves of the VCSEL under test in three different conditions: before irradiations (red), after 119 Mrad (green) and after 238 Mrad of irradiation (blue). A slight change in the L-I slope was observed. However, this variation was negligible enough to affect the performance of the designed OWC system. The shift in slope was probably because of the increase in temperature as also reported in previous ionizing radiation tests by [18]. No change in the threshold current of the VCSEL was detected because of the irradiation. Also, no degradation in the VCSEL I-V curve was recorded.

We then irradiated the photodiode. We present in Fig. 9(a) the photodiode current (I_{PD}): the current generated from the received optical power) as a function of time. This shows no

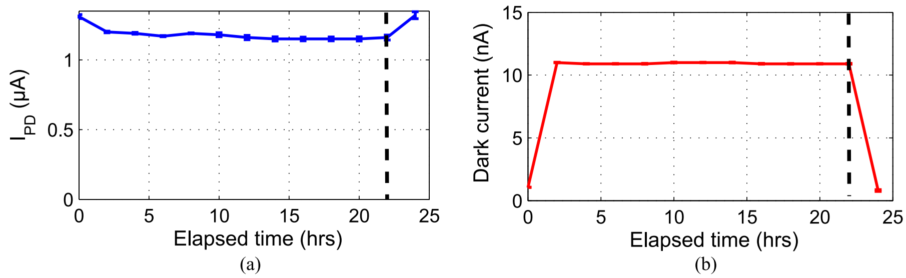


Fig. 9. (a): Received current at the photodiode as a function of time; (b): dark current of the photodiode at a reverse bias of 4 V as a function of time with 10.8 Mrad/hour dose. Bar line shows end of irradiation test.

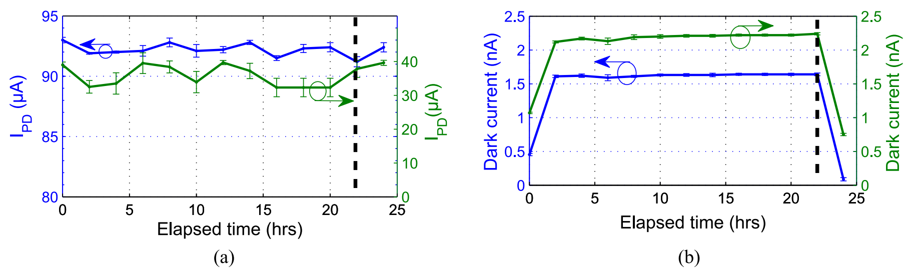


Fig. 10. Received current (a) and dark current (b) of the photodiode with the quartz ball lens as function of time (Xrays dose : 10.8 Mrad/hour).

degradation for total dose of 238 Mrad (10.8 Mrad /hour) with the post-irradiation current (after bar line) approximately equal to the pre-irradiation value (0th hour). The dark current as a function of time was also evaluated (Fig. 9(b)) depicting a constant trend during the irradiation time. The increase in the dark current during the irradiation was mainly due to the PIN photodiode sensitivity to the X-rays because after irradiation the dark current drops to pre-irradiation value. Any ionizing damage could have resulted in permanent dark current rise after irradiations, as reported by [16] which, however, was not observed in this test. Therefore, the results show that the photodiode under test remained in working condition after 238 Mrad of X-rays dose.

The robust behavior of the VCSEL and the photodiode under ionizing radiations (Gamma rays) is also reported previously in [17], [18] for lower ionizing dose (10 Mrad).

Finally, we irradiated the quartz ball lens. For results verification, we tested two boards with the PIN photodiodes packaged with the quartz ball lens. Fig. 10 presents the received and dark current of the PIN photodiode as a function of time. Fig. 10 (a) shows that the I_{PD} remained stable throughout the test for both boards. No change was observed after post irradiation. The little fluctuation of the I_{PD} for the second board (green line) was probably due to unstable behavior of the VCSEL which was also observed during pre-irradiation testing. Although the photodiode was packaged and properly shielded in this experiment, yet the dark current was monitored to observe the photodiode performance for correctly investigating the quartz lens behavior. Fig. 10 (b) shows the dark current for the two boards and depicts similar trend to the photodiode test, as explained earlier. The difference in the pre- and post-irradiation values of the dark current is due to the different environment conditions for both the measurements. The pre-irradiation reading was taken outside the chamber with slightly more ambient light.

In addition, no darkening effect was observed on the glass surface. The stable results without any degradation of the received current depicts that there was no change in the transmission and refractive index properties of the quartz lens due to 238 Mrad(Si) dose of X-rays radiations. Through this test, we conclude that the quartz lens is suitable for the 2.5 Gb/s OWC link aimed to be deployed in particle physics experiments.

Furthermore, in the real environment of inner CMS tracker, all the components will be irradiated simultaneously. However, the 238 Mrad of X-rays introduced very small effects on each of the tested device (several order of magnitude lower than the operating conditions); hence, we can expect that the total effect of the irradiation on the OWC system was negligible.

5. Conclusion

We reported design, realization and test of an OWC system prototype for HEP applications. It provides the 2.5 Gb/s data rate at 10 cm distance with a misalignment tolerance of ± 1 mm, which is complaint with passive alignment. The results lead to realize a system prototype with a packaged receiver. We carefully selected the optical components i.e. a VCSEL as the transmitter and an InGaAs photodiode with quartz ball lens as the receiver to make it suitable for the HEP particle detectors. Finally, we tested all the components under X-rays for 238 Mrad (Si) of dose. The test was important to analyze the quartz ball lens resistance under high ionizing dose levels. We observed that none of the components showed any degradation. Both the tolerance range and the X-rays test satisfy the requirements for establishing the wireless link between the layers of silicon detector modules in the CMS inner tracker.

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