Proton-Induced Bit Error Studies in a 10 Gigabit per Second Fiber Optic Link

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Abstract-- We describe a stand-alone experiment with autonomous error checking and logging used to acquire proton induced bit error response of a 10 Gbps multi-mode fiber optic data link operating over a 100 meter fiber length. Comparisons with previously tested lower data rate data links indicate the primary source of bit errors arise in the link receiver's photodiode. The serial 10 Gbps results show relatively lower Bit Error Rate (BER) sensitivity to 63 MeV protons. Proton BER results of supporting high speed bipolar multiplexer and demultiplexer circuitry are also presented.

I. INTRODUCTION

In recent years numerous satellite missions have implemented the use of fiber-optic based local area networks for spacecraft telemetry and control busses as well as high data rate payload busses. Data transmission via optical fiber offers advantages in terms of power savings and reduced electromagnetic interference concerns, and these issues become increasingly important at data rates in the Gbps regime. Ongoing technology advances in support of terrestrial applications continue to offer attractive solutions for technology insertion into spacecraft. In particular, higher speed multi-mode transceiver sets have been introduced which support serial link rates of 10 Gbps, and multi-mode technologies offer advantages for ruggedized applications.

The optical signal level representing a digital "1" may contain very little energy. When received at the link's terminal and converted back to an electrical signal by an optoelectronic photo-detector, the signal level may be only a few hundred or thousand electrons prior to amplification. Several studies have demonstrated how the photodetector, by virtue of its low signal level, can be sensitive to false signals from direct ionization by incident protons. For details and additional information, please see the review [1, 2, and references therein]. One of the objectives of this study was to characterize state-of-the-art 10 Gbps serial multi-mode transceivers to gain an understanding of the link sensitivity to proton-induced bit errors, and we also examined the response to proton ionizing dose and displacement effects to a level of several krad(Si).

The work presented is sponsored by NASA Electronic Parts and Packaging (NEPP) Project, and the Defense Threat Reduction Agency (DTRA) under IACRO 02-4039I, and NASA Flight Projects.

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II. TEST HARDWARE AND EXPERIMENT SETUP

The optoelectronic transceivers were manufactured by Focused Research®, Inc. The H6101-01 10 Gbps transmitter module uses a AlGaAs laser with a bipolar Current Mode Logic (CML) electrical interface and a 50/125 mm multimode optical fiber output. The H6111-02 receiver module included a similar fiber pigtail which launched the optical signal onto a GaAs p-i-n photodiode, and electrical outputs were also at CML levels.

Often, the performance of optical transceivers is analyzed in the laboratory using commercial Bit Error Rate Test (BERT) equipment to provide signals and detect errors. With 10 Gbps data rates, this requires expensive test equipment and limits portability to radiation test facilities. Testing reported here was accomplished using a stand-alone custom test set that provided the 10 Gbps data traffic and examined the receiver's output to log any errors. Our proton test effort benefited from the additional objective of demonstrating performance in a stressing environment found in an aircraft, and this test required an autonomous test-bed.

Fig. 1 shows the block diagram of the high speed signal path elements of the test board. The receiver and transmitter sections used a multiplexer and demultiplexer pair manufactured by GIGA®, Inc. The GIGA® Si bipolar GD16584 demultiplexer and GD16585 multiplexer provided an interface to the Altera APEX (part number EP20K400EBC652-

1X) Field Programmable Gate Array (FPGA). The FPGA's LVDS data interface operated using a pseudo-random 127 bit data sequence at 622.02 Mbps, and the GIGA® mux/demux pair performed at a 16:1 and 1:16 ratio resulting in a serial data rate of 9.953 Gbps for compatibility of the test with the SONET OC-192 telecommunications industry standard. Operation of the Focused Research® transceivers was also verified at 10.66 Gbps, however the proton testing reported here was conducted at the slightly lower SONET rate. The autonomous test set included a PC-486 based controller for initialization of the test board and data logging. In addition to the optoelectronic transceivers, the GIGA® multiplexer and demultiplexer pair was also included in the testing. None of the other components comprising the test board shown in the Fig. 1 diagram were irradiated.

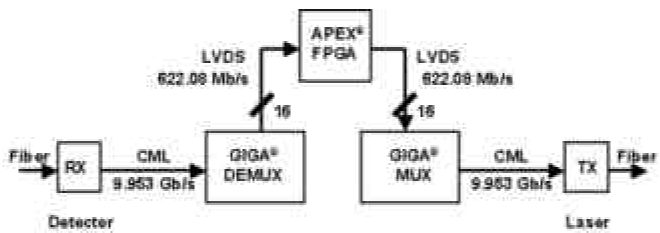

Fig. 1. This block diagram indicated the relation of the Tx and Rx modules as well as the high speed mux/demux pair and the controlling FPGA.

Proton exposures were conducted at the University of California Crocker Nuclear Laboratory cyclotron using 63 MeV protons. The test board was positioned in front of the beam with an aperture used to confine the beam to the device under test. The test configuration also included the 100 meter length of 50/125 mm multimode optical fiber, supplied by NetOptics®, Inc., and spooled around the chassis. The 100 meter fiber length was also not included as part of these radiation studies. Proton exposures of the high speed optoelectronics and mux/demux pair were conducted with the high speed test board mounted on a rotating stage so that precise measurements could be made versus the angle of arrival of the protons.

III. Test Results Overview

63 MeV proton-induced SEU measurements of the GIGA® mux and demux pair showed some sensitivity to errors. Exposures to the GD16585 multiplexer resulted in a total of 27 errors after exposure to 1.20 x 10^{10} protons/cm^2. All except one error involved a single bit, and the resulting error cross-section was 1.8 x 10^{-9} cm^2. No performance degradation was noted after all exposures which corresponds to 3.7 krad(Si). The GD16584 demultiplexer showed comparable sensitivity with 11 errors during exposure to 2.49 x 10^9 63 MeV protons resulting in a cross-section of 4.4 x 10^{-9} cm^2. No degradation was noted after a cumulative 2.1 krad(Si) exposure. We expect that the ionizing dose and displacement damage of this bipolar technology would far exceed the levels that we tested to, however we followed a test strategy to gain characterization results of these devices with minimal risk of device failure. We did not have the luxury of multiple copies of the test board, and refurbishing the test hardware in the event of failure was not an attractive option.

A relatively low cross section for errors was verified for the Focus Research® H6101-01 10 Gbps transmitter. Only one error was noted after exposure to 1.4 x 10^{10} protons/cm^2 resulting in a cross section of 7.14 x 10^{-11} cm^2. Again, no degradation was noted after 1.4 krad(Si). As this component included only a bipolar laser driver and VCSEL, we would not expect either high single event cross-section sensitivity or susceptibility to ionizing dose or displacement damage at these levels. Similar insensitivity to proton induced transients and also resistance to proton damage has been reported previously in VCSEL-based transmitters [3].

As expected, the Focused Research® H6111-02 10 Gbps receiver showed much higher sensitivity to bit errors induced by incident protons, and this is consistent with the mechanism associated with direct ionization from protons incident on the receiver photodiode [1 and references therein]. Data supporting this claim were acquired by measuring the sensitivity to bit errors versus proton incidence angle relative to the plane of the GaAs p-i-n photodiode. Fig. 2 shows measured bit error cross-sections versus angle, with the 90 degree trajectory corresponding to grazing incidence and maximum pathlength through the receiver's photodiode.

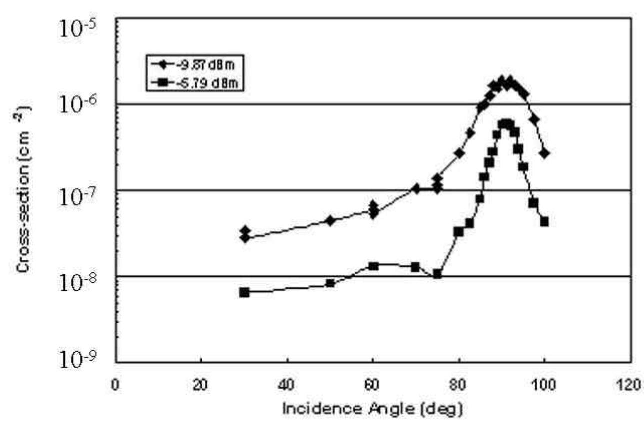

Fig. 2. The Focus Research H6111-02 10 Gbps receiver showed much higher sensitivity to bit errors from protons when incident near the plane of the receiver's p-i-n diode.

Fig. 2 indicates a two order-of-magnitude enhancement in the sensitivity at grazing incidence, and this is consistent with results of other similar studies in lower bandwidth optical data links [1]. The link is more sensitive to errors when operated at the lower level of incident optical power, and this result is also consistent with previous studies. This power was monitored and controlled during test, and the -9.87 dBm level was within half a dB of the limit at which spontaneous errors would have corrupted the test. At -9.87 dBm, a bit error ratio of better than 10^{-13} was measured without incident protons

IV. Comparison with Literature Data

One objective of this study was to examine the relative performance of serial fiber optic links versus parallel links operating under otherwise similar conditions. The demonstration of 10 Gpbs operation of a serial multi-mode link over a 100 meter fiber length is remarkable in itself, and we believe we are the first to show that this can be done in a ruggedized demonstration. By comparing our results with the previous study in [3], we can assess the relative impact of proton induced bit errors in a serial versus a 10 channel parallel link operating at 10 Gbps. This link, manufactured by Honeywell®, also operated over multi-mode fiber, and each of its 10 channels was designed of operate at 1 Gbps to provide an aggregate of 10 Gbps, with 2 spare channels unused. Fig. 3 reproduces results that were first reported in [2] for this parallel ruggedized link that also uses a VSCEL-based transmitter and GsAs based receiver.

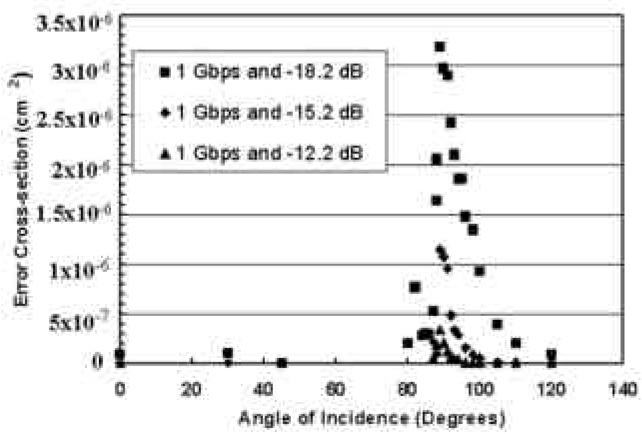

Fig. 3. From [3], the Honeywell receiver's sensitivity changed dramatically with both incidence angle and with the link's optical power. This is expected for errors caused by proton hits to the receiver's photodiode.

Results reproduced form [3] in Fig. 3 show the expected trends for proton-induced errors from direct ionization both in terms of the sharp increase in cross section near grazing angle and also in terms of the importance of incident optical power as a means of mitigating proton sensitivity.

Comparison of the cross section data of Figs. 2 and 3 are possible to assess the relative sensitivity of the serial 10 Gbps link reported here with the 10 Gbps link described in [3] which is actually 10 parallel 1 Gbps links. Obviously, careful consideration of several issues is important, but we note that the physical layer is similar in the two cases since both operate with VCSEL transmitters at 850 nm and both use GaAs p-i-n detectors for multimode operation.

Since the error cross section is so critically important on incident optical power, we recommend comparing the BER sensitivity in on the basis of optical power required per bit of data transmitted. The data presented as Fig. 4 show test results for the two links as compared on this basis. Note that the two link's error cross-sections are essentially identical, even though their operational speeds differ by a factor of 10, and so do their operating link powers. Therefore, if the two links were operated with identical link power on a per bit basis, then the BER cross sections can be compared. Recall that the error cross-section is defined as the number or errors per proton fluence at a given operating rate. As long as the proton fluence and number or errors match, as they do in the Fig. 4 comparison, then the proton induced cross-section is the same.

It is very important to realize that equivalent error cross sections for two links operating at data rates that differ by 10x would result in BERs that also differ by 10x for the two links, even though they have essentially identical error cross-sections. This follows from the fact that the BER is calculated as the number of bits in error divided by the number of bits transmitted. So, assuming that single bit errors dominate, the BER for the 10 Gbps serial link would be 0.1 x the BER for the 1 Gbps link. Furthermore, if 10 1 Gbps links are operated in parallel to achieve an aggregate 10 Gbps data rate, then both the total data rate and the number of proton hits would scale by the factor of 10, and the BER remains unchanged. So comparison of proton induced errors in the parallel versus the serial links would still favor the serial solution by a factor of 10.

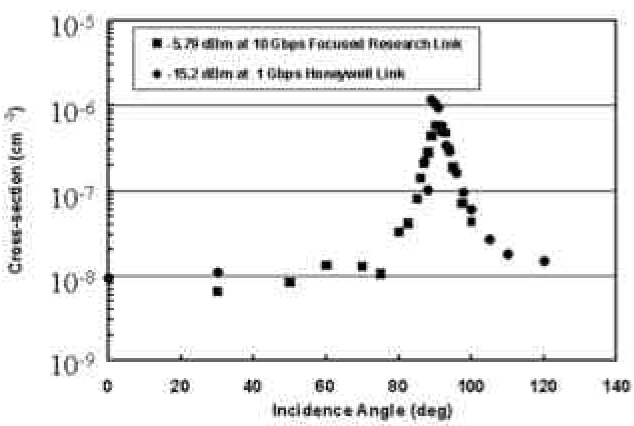

Fig. 4. 63 MeV proton cross section data from the 10 Gbps serial link at 10 Gbps are compared with the 1 Gbps results from [3] on the basis of equal optical power per bit of data transmitted.

Another extenuating circumstance would matter for the two serial versus parallel links just compared. The possible use of additional link margin could be used in either link to mitigate the proton-induced error rate and improver the BER. Relative to Fig. 4, the 1 Gbps parallel linked approach could apparently operate with -12.2 dBm, and this would improve the BER by about 7x as indicated by the data of Fig. 3. This is in comparison to the 4 dB margin available for the 10 Gbps case for which the higher operating power appears to improve the BER by approximately 3x.

V. Summary

We report results of proton-induced bit error measurements in a 10 Gbps serial multimode fiber link using a custom and novel test approach. The link proves that 10 Gpbs rates are attainable over distances of up to 100 meters of 50/125 *mm* optical fiber, and our measurements indicated a link budget with about 4 dB above the required minimum. The VCESL based transmitter and GaAs based p-i-n receiver performed well in the presence of ionizing dose and displacement damage, and this was also the case for the GIGA high speed Si multiplexer and demultiplexer pair. As expected, the GaAs p-i-n device is sensitive to bit errors from direct ionization from protons. Our analysis and comparison with previously tested lower rate link hardware indicates that the 10 Gbps serial solution can result in about an order of magnitude reduction in the BER when compared on the basis of average optical power per bit of transmitted data.

VI. References

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