Investigation of hermetically sealed commercial $LiNbO_3$ optical modulator for use in laser/LIDAR space-flight applications

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ABSTRACT

This paper is the first in a series of publications to investigate the use of commercial-off-the-shelf (COTS) components for space flight fiber laser transmitter systems and LIDAR (laser imaging detection and ranging) detection systems. In the current study, a hermetically sealed COTS $LiNbO_3$ optical modulator is characterized for space flight applications. The modulator investigated was part of the family of "High-Extinction Ratio Modulators" with part number MXPE-LN from Photline Technologies in Besancon, France. Device performance was monitored during exposure to a Cobalt^{60} gamma-ray source. Results from the testing show little change in device operation for a total accumulated dose of 52 krad.

Keywords: Optical Modulator, Space Flight, Qualification, $LiNbO_3$, Radiation, Fiber Laser

1. INTRODUCTION

Ever-expanding applications in telecommunications, sensing, and related fields demand new and improved devices for optical manipulation. This is especially true of next-generation optical systems for space flight that must endure harsh environments. Starting in 2003, the NASA Electronic Parts and Packaging (NEPP) program began investigation of fiber laser systems and components to raise the technology readiness level (TRL) for incorporation on future planetary missions.[1] Two areas of concern in a fiber laser system, for applications such as a LIDAR transmitter requiring pulsed output, are the active gain medium and the modulator.[2] Therefore, studies of these two components are being performed to increase confidence needed for use on future missions.

Due to its favorable optical properties, lithium niobate ($LiNbO_3$) is a commonly used material for electro-optic and acousto-optic devices. Various optical components and integrated devices, such as, lenses, polarizers, couplers, modulators, interferometers, etc., can be fabricated from bulk $LiNbO_3$ or as surface/ thin-film devices. But in order for these to be considered for use in a space flight mission, they must be able to survive the harsh space environment over the life of the mission.

Components used on space flights experience a wide variety of radiation types and intensities throughout their mission profile. The strength of the radiation and type (gamma, X-ray, neutron, proton, etc.) depends on many factors, including, spacecraft orbit, flight pattern, location of component, and shielding. When considering the use of optical components in these types of environments, the response to energetic protons, gamma, and hard x-rays is of particular concern. Unlike electrical components which are usually most sensitive to radiation that can cause large amounts of displacement damage (like neutrons or heavy ions), optical components are often most sensitive to energetic particles (protons and gamma or x-ray photons) that excite electrons that can then lead to color center formation. Thus, radiation testing of optical components for space flight usually begins with gamma radiation exposure to investigate induced loss in transmission and any annealing that takes place subsequent to the exposure.

Many applications being considered for upcoming space missions will require a stable, highly reliable method of generating and modulating an optical signal. It is also desirable to use commercial-off-the-shelf (COTS) technologies whenever possible to help alleviate tight schedule and budget constraints. Thus, a $LiNbO_3$ optical modulator was chosen for the current study. Initial testing, reported here, consisted of in-situ monitoring of the modulated optical output at 1550 nm during exposure of the modulator to gamma radiation from a Co^{60} source. In addition to this initial screening, an expanded radiation test program will be used and the device will be tested in a thermal vacuum chamber since hermetically sealed optical devices have shown to be especially sensitive to this type of testing.

2. EXPERIMENTAL SETUP

The $LiNbO_3$ modulator chosen for testing was a high extinction ratio intensity modulator from Photline Technologies. The devices are part of their MXPE-LN series that are specified with extinction ratios of 40 dB and power handling of 500 mV. The modulator waveguides are created using the proton exchange process that results in polarizing waveguides. Packaging allows separate DC and RF biasing of the crystal. The $LiNbO_3$ crystal is an X-cut Y-propagating orientation, which minimizes operating bias. Input and output fibers packaged on the modulator housing are polarization maintaining (PM) fibers that are 1.5 m in length.

The experimental setup is shown in Figure 1. Optical input signal came from a Santec TSL-210 tunable optical power source, set at 1550 nm with a 4 mW output. This was coupled to the modulator with an 8 µm core PM fiber from Oz Optics (part number PMJ-3A3U-1550-8/125/3/15/1). An identical fiber was used to transmit the optical signal from the modulator to the detection system. The modulated optical signal was collected using a Tektronics P613 optical-to-electrical converter and recorded on an Agilent 8722ES high-speed oscilloscope. A LabView program was written to capture the data from the oscilloscope at set time intervals and store it on a laptop computer. The modulator was DC biased using an HP E3610A power supply. RF modulation was accomplished using a Tektronics 1103-Tekprobe signal generator.

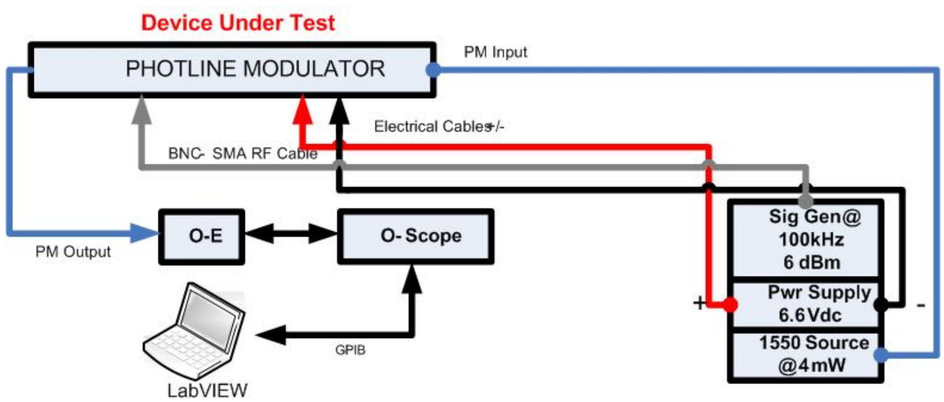
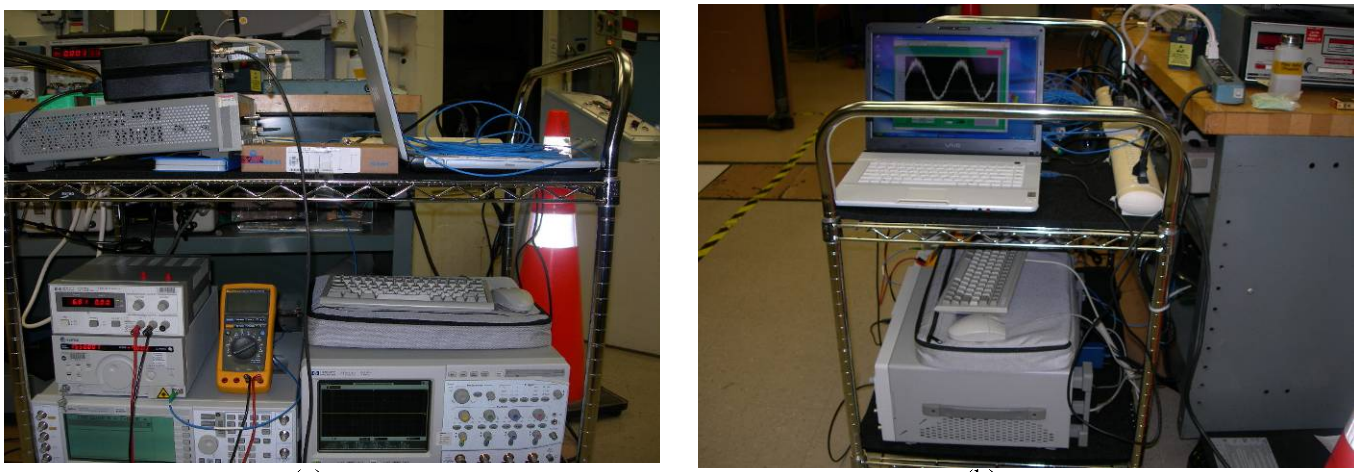


Figure 1: Modulator experimental setup

Modulator testing was conducted in three stages. The first was to test the as-received modulator in the lab for 24 hours to observe any drift or change in RF performance. Next, the modulator was subjected to gamma radiation exposure with in-situ monitoring. This was followed by another test in the lab to monitor for any annealing due to recovery of radiation-induced defects.

The gamma radiation exposure was conducted at NASA Goddard Space Flight Center. Figures 2 and 3 show the experimental setup and arrangement of the modulator during testing. A dose rate of 13 rad/min was chosen with a total exposure time to yield 52 krad total dose. The device under test was placed inside a lead-lined box to minimize stray radiation resulting from gamma ray interaction with the walls and fixtures inside the test cell. The lead shielding was taken into consideration when choosing the location from the source to give the desired 13 rad/min exposure conditions. Due to the highly directional nature of the source as a result of the Co^{60} housing configuration, the input and output fibers from the modulator were routed outside of the exposure area. Thus, due to the minimal amount of fiber being subjected to the gamma radiation, no additional fibers were needed to monitor for loss in the fiber cables themselves.



(a) (b)

Figure 2: Experimental setup used for radiation testing of Photline Modulator

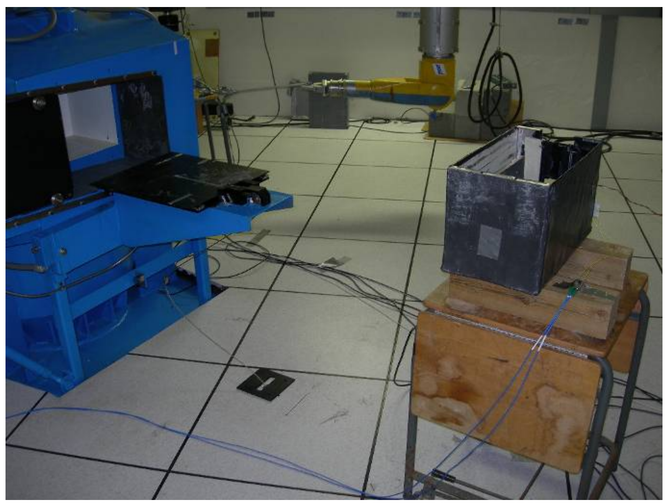


Figure 3: $LiNbO_3$ Modulator in radiation test cell

3. RESULTS AND DISCUSSION

Due to its many advantageous electro-optic properties, $LiNbO_3$ has been studied for more than 30 years. For a historical overview of radiation effects studies on $LiNbO_3$, the reader is referred to ref. 3, which gives a good background and contains an extensive reference list.

A material's response to radiation can vary greatly depending on how it was grown, dopants that were intentionally or unintentionally incorporated, crystal orientation, geometry of the device, whether it is used in thin film or bulk format, wavelength of operation, and many other factors. For example, the radiation response of bulk $LiNbO_3$, as would be used for laser Q-switching, was shown to be very sensitive to crystal structure and doping.[4-5] The material exhibits a strong induced absorption at 1064 nm under large dose rate exposure, but doping with greater than 6 mol% MgO nearly eliminates the radiation-induced absorption. This is due to a change in the $LiNbO_3$ crystal structure and defect structure or congruently grown crystals at this doping concentration. The radiation-generated attenuation is also wavelength dependent, with a larger response in the visible wavelength range than in the near-IR. Thus, based on previous testing and data presented in literature, it is possible to develop a set of device specifications, but it is prudent to test new $LiNbO_3$-based devices in a representative radiation environment.

In basic terms, the optical modulator allows the control of intensity, phase, or polarization of an optical signal by application of an electric field. The intensity modulation for a surface layer waveguide device, as addressed in this paper, is achieved by splitting the incoming signal into two separate waveguides and then recombining the signals after some distance. The interference of the two signals, either constructively or destructively, leads to the change in intensity. By applying a voltage to electrodes applied beside the waveguide device, thus generating an electric field across the waveguide, the refractive index of the waveguide can be altered, thereby changing the intensity when the signals are recombined. The reader is referred to ref. 6 for a more detailed discussion of $LiNbO_3$ modulators.

Historically, waveguides were formed in $LiNbO_3$ slabs by in-diffusion of Ti at high temperature. While this resulted in the refractive index change needed for waveguide fabrication, the Ti can also contribute to radiation induced loss.[3,7] In addition, Ti in-diffusion tends to result in waveguides that allow both the TE and TM modes to propogate. Taylor et al. showed that this can lead to crosstalk between the waveguides during radiation exposure that can change the device output.[3] An alternate method of waveguide fabrication is through annealed proton exchange (APE), in which the Li ions are exchanged with protons from an acid bath. The altered regions have an increased extraordinary index, with virtually no change in the ordinary index, thus leading to polarizing waveguides. The APE process is relatively simple and inexpensive with a relatively high index change, and so it is therefore the preferred industry method for waveguide fabrication in $LiNbO_3$. The modulators used in this study were fabricated using the APE process. But, as has been reported by Fedorov and Korkishko, the growth and exchange conditions can alter the crystal structure[8-9], which can affect the radiation response of a material.

To characterize the pre-irradiation performance of the modulator, a 24 hour test was conducted. To determine the DC bias condition, a curve of the optical output versus DC bias was obtained; this is shown in Figure 4. The quadrature point around 6.0 volts was chosen to allow for maximum drift without encountering effects due to clipping on the top or bottom of the transfer function. It is common practice to use a feedback photodiode located near the modulator output to lock the output by adjusting the DC bias during operation. The Photline modulator being tested has this option, but it was not used since the photodiode is within the radiation exposure area and radiation-induced changes in the photodiode would lead to erroneous effects on the modulator performance. Therefore, a constant DC bias was used, but no feedback was attempted to correct for standard modulator drift characteristics.

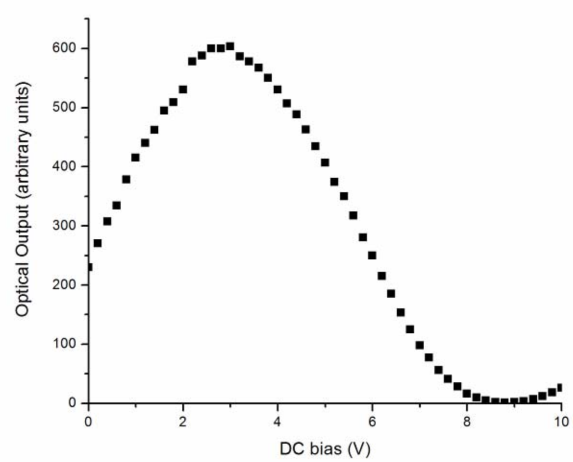


Figure 4: DC bias versus optical output from modulator with no RF bias applied

Figure 5 shows the results of the 24 hour pre-irradiation test. Modulation was done at 100 kHz with a 6 dBm sine wave from the signal generator. As expected, the modulator drifted slightly during the test, but there was no change in the frequency or peak-to-peak voltage of optical output.

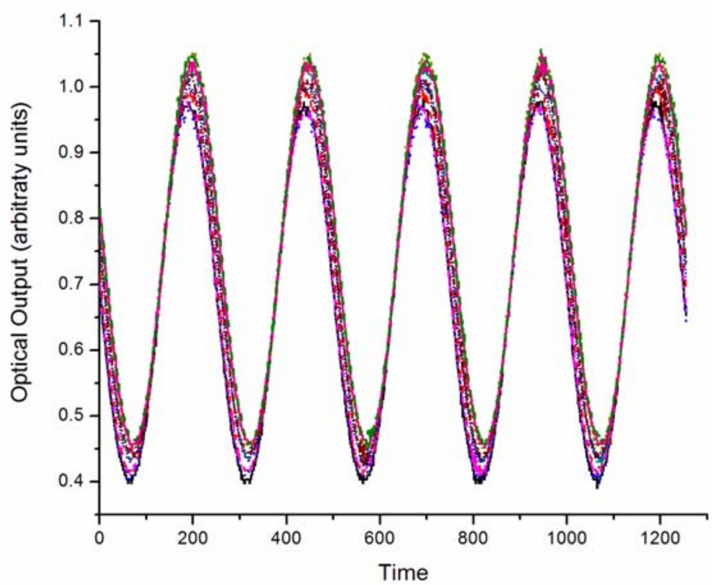


Figure 5: Benchtop test of modulator before radiation testing. Data show normal drift with no change in peak-to-peak voltage or frequency.

The modulator was exposed as described above to a Co^{60} gamma source. The experiment location was chosen to give a 13 rad/min dose rate inside a lead-lined box. Operating parameters were identical to those used for the previous test. Results are shown in Figures 6 and 7.

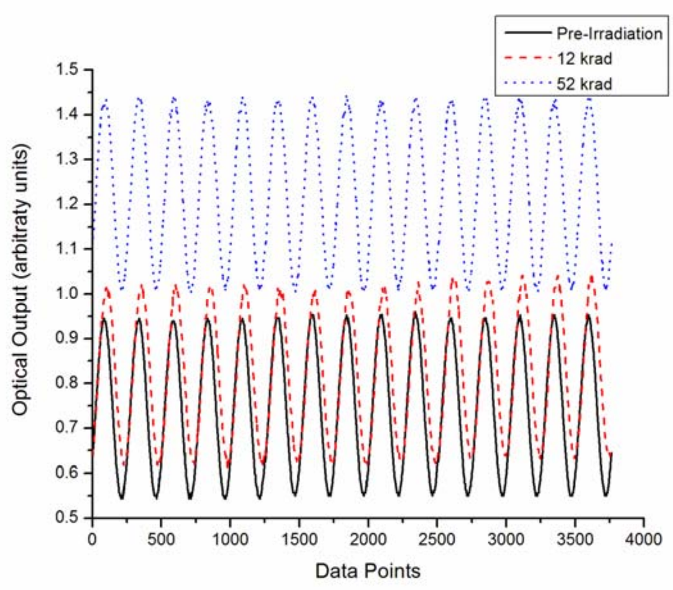


Figure 6: Modulator output pre-irradiation and at 12 krad and 52 krad exposure to gamma radiation

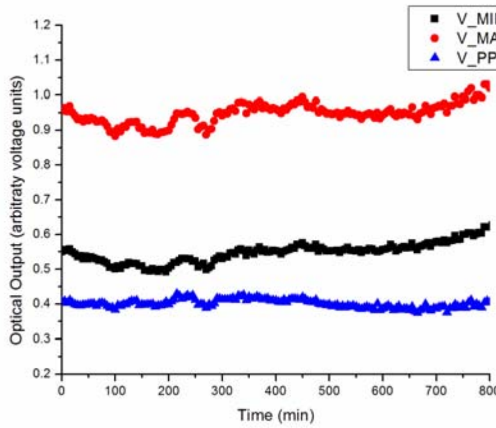


Figure 7: Modulator output during first 800 minutes of radiation test. Maximum and minimum voltage are shown in top two curves. The bottom curve is the peak-to-peak voltage difference, which remained constant throughout the remainder of the test.

From the data, it can be seen that the modulator output drifted during the test, but there was no change in the peak-to-peak voltage of the frequency. Since no photodiode feedback was being used to actively adjust the DC bias, the drift is expected. The constant frequency and peak-to-peak voltage indicates that the gamma irradiation had no effect on the modulator performance. Since the optical waveguides pass both the DC and RF biasing electrodes, any changes due to radiation exposure would have to affect both the DC and RF response. However, changes due to temperature or photobleaching would cause the output to drift with no change in RF modulation characteristics. Therefore, for the Photline modulator under test, there was essentially no change in performance during this 52 krad gamma radiation exposure. To confirm this, the modulator was again run in the lab one month after the radiation exposure. Results are shown in Figure 8. As can be seen in the figure, the modulator operated the same as it did during the pre-irradiation test, with a drift in the DC bias but no change in frequency or peak-to-peak voltage.

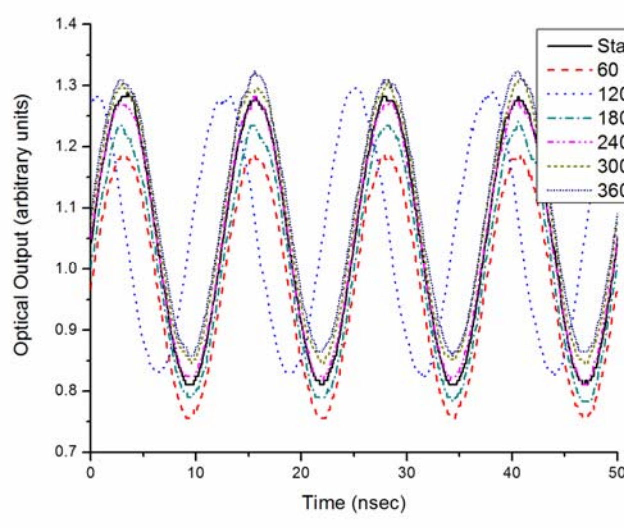


Figure 8: Modulator output after radiation test. Data were collected a month after completion of radiation test. Drift in output is similar to pre-irradiation results. No change in frequency or peak-to-peak output was observed.

CONCLUSION

Lithium niobate optical modulators are finding increasing application for future space flight missions. The current work reports on initial testing of a COTS $LiNbO_3$ optical modulator purchased from Photline Technologies. The modulator was exposed at 13 rad/min for a total accumulated dose of 52 krad. While the modulator output showed an expected drift in output DC level, no change in the RF performance was measured. The DC drift was expected since no photodiode feedback was incorporated into this initial test. Based on the favorable results from this initial screening test, further space flight qualification testing (an expanded radiation test sequence and thermal vacuum testing) will be conducted on COTS $LiNbO_3$ optical modulators.

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