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Optical Data Links – Technology for Reliability and Free Space Links

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Abstract

We discuss the advantages of various kinds of light modulators with respect to Vertical Cavity Surface Emitting Lasers (VCSELs) in terms of potential reliability, radiation hardness, and low power consumption. We also discuss free space optical links which could use these modulators as well as MEMS mirrors and other technology which we are developing.

Keywords: Optical modulators, Free-space communnication, Optical communication, MEMS mirrors, Optical links for HEP

1. Technology

The detector elements of future High Energy Physics (HEP) experiments will collect large amounts of data and there is a need to find ways to get the data out of the detectors efficiently and reliably while at the same time reducing the mass of the communication electronics. In the long run, optics will be used for everything because of bandwidth. Also in the future Electro Optical Modulators (EOM) will be used instead of modulated lasers (e.g. VCSELs) because of bandwidth, low chirp [1][2], low power, and reliability. There are known radiation hard EOMs.

There are two basic kinds of EOMs of interest, electro-absorption (EAM), and Mach-Zhender (MZI). EOM uses a material with an electro-optic effect to modulate a beam of light with an electrical signal. A

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light beam can be modulated in phase, frequency, amplitude, or polarization. Lithium Niobate (LiNbO3) with various doping has been used in MZI based EOMs for a long time. In LiNbO3 crystals the refractive index changes as a function of the strength of the local electric field, so that if it is exposed to an electric field, light will travel slowly through it. Therefore, the phase of the light going through the crystal can be controlled by changing the electric field in the crystal. LiNbO3 has been tested for radiation hardness by several HEP groups [3]. The only disadvantage for LiNbO3 is size (few cm long). There are commercial modulators of small size, but some are polymer (not radiation hard) and some are too expensive at the present time. We may have found two vendors for small modulators who will work with us on ones which can be wire-bonded and have single-mode fiber connections. Radiation hardness tests need to be performed on these to determine suitability for HEP detectors.

Recently, with the improvements of semiconductor technologies, many EOMs have been developed based on semiconductors. These EOMs are extremely small in size, ultra low in power consumption and can be integrated into CMOS. Some light modulators are under development at IBM [4] and MIT [5] which could be good candidates for our implementation.

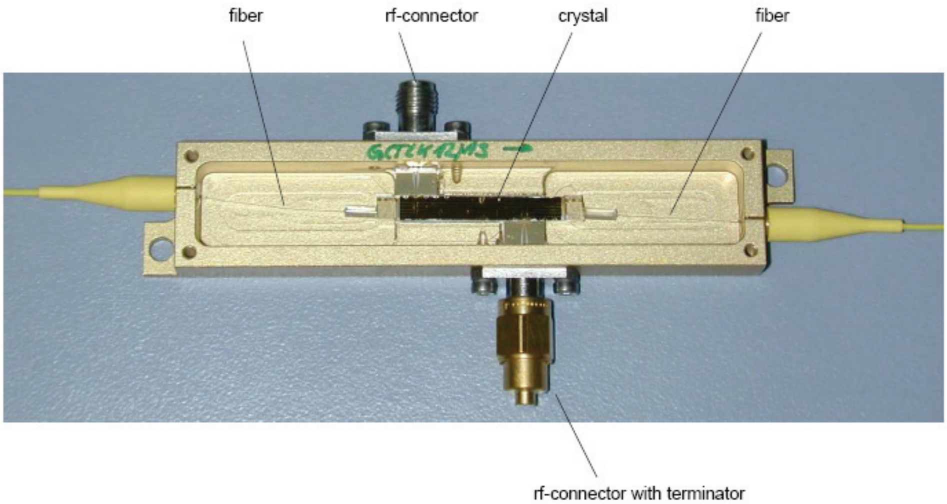

Fig. 1 A LiNO3 modulator from JenOptik: The required optical and electrical connections are small compared to the standard packaging. The modulator is about 3 cm long and very thin.

The MIT prototype uses Si stressed with Ge which has an absorption peak which is used to modulate the light. The radiation hardness of GeSi in general has been studied [6] and shown to be adequate for use in future HEP experiments. This device is fabricated with 180 nm CMOS technology. It has a very small footprint (30 μm^2). Operation spectral range of the device is 1539-1553 nm (half of the C-band) with extinction ratio of 11 dB at 1536 nm and 8 dB at 1550 nm. More features of the device include ultra-low energy consumption (50 fJ/bit, or 50 µW at 1 Gb/s), GHz bandwidth, 3V p-p AC and 6 V bias. Radiation hardness of the material was tested to 3×10^{17} electrons/cm^2 [7].

The IBM prototype is an extremely small MZI based EOM. Some of the features of this device include 10 Gb/s bandwidth, power consumption of 41 mW at 5 Gb/s, footprint of 100 µm × 10 µm × ~1 µm, broad working spectrum, 7.3 nm at 1550 nm, 80 µm long delay line internal, 1V p-p AC, and a 1.6V bias.

A conventional laser transceiver uses about 300 mW of power at 1 Gb/s. A VCSEL with its driver can be of ~100 mW. An MIT prototype modulator used 50 µW of electric power. This is a huge improvement in power consumption (and heat generation). The existing VCSEL and driver ASIC is ~ cm long, but the prototype modulators from both MIT and IBM are about 10^{-2} cm long (100 μm), a volume ratio of ~10^{-4} and a mass ratio of similar order.

Many commercial systems which work faster than 10 Gb/s already use EOMs and CW lasers. EOMs enable one to get the lasers out of tracking volume.

2. The Comparison of VCSELs and EOMs

The current schemes of optical communication in both ATLAS [8] and CMS [9] detectors use VCSELs to generate the laser light both on-detector and off-detector to transmit the data as illustrated in Fig. 2(b).

Since each VCSEL must be operated at a critical operating point, a radiation hard Application Specific Integrated Circuit (ASIC) has been developed for use with VCSELs close to pixel detectors.

Particular VCSELs were chosen after studying the radiation hardness of the commercial VCSELs [10] which may or may not satisfy the radiation hardness required for the future HEP experiments. Since there is evidence of high failure rates of VCSELs [11], which may or may not be associated with particular manufacturers or particular designs, it is becoming clear that it is important to move the lasers used for data transmission out of areas inaccessible after closing of the detector to run the experiment. In a free space beam concept all the laser sources are moved outside the detector and EOMs are used to transfer the data into light beams as shown in Fig. 2(a). This not only reduces the current required inside the detector but also removes the necessity to develop complex radiation hard current driver ASICs. Also we use CW laser sources instead of VCSELs. Some of the advantages of EOM could also be realized by using fibers as well.

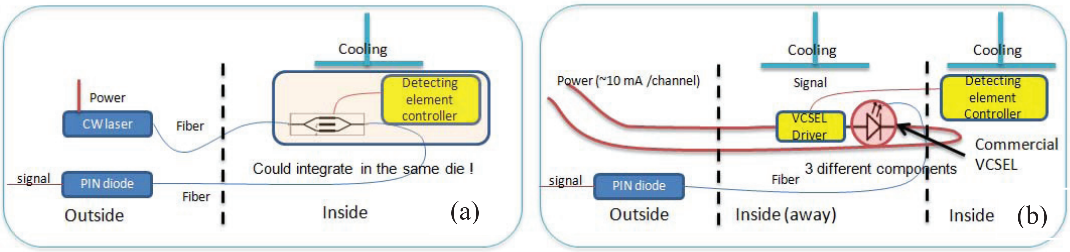

Fig. 2 Topology of connecting (a) EOM and (b) VCSELs based communication link

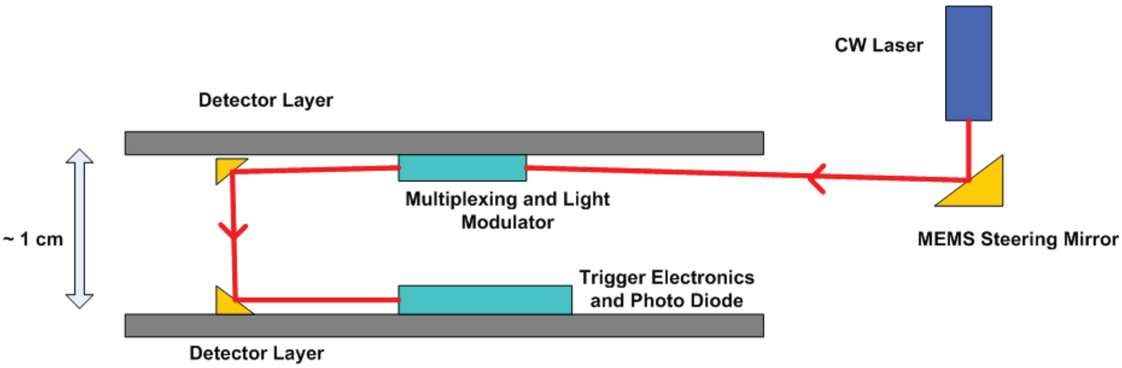

Fig.3 Concept of communication between ID layers for trigger decisions

3. Triggering

On-board triggers would reduce the amount of data to be transmitted out of the tracking detectors. This is essential for LHC upgrades. We show a concept for interlayer communication [7] which would function for the spacing of tracking layers from roughly 1 cm to several cm as shown in Fig. 3. This would allow some momentum cut on track stubs.
A major improvement beyond even the conventional form of optical links could be made by using optical modulators so that the lasers are not in the tracking volume.

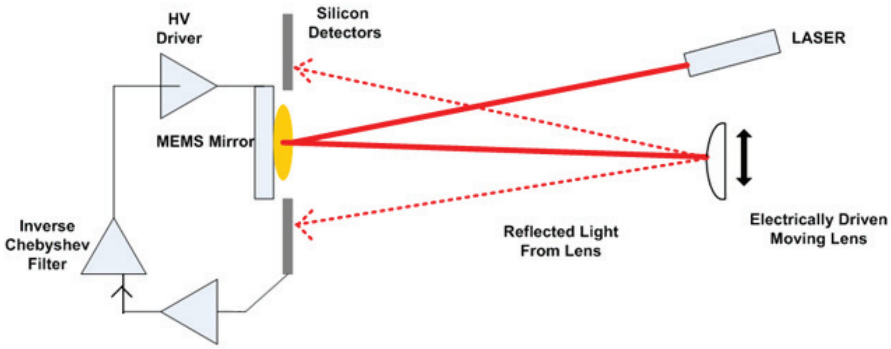

Fig.4. Concept of direct feedback to establish and maintain stable alignment

4. Free Space Data Links

Instead of fibers the light beams could be steered in air into the modulators by using MEMS mirrors and special light couplers. Since fibers are radiation sensitive, particularly in areas where there is very high rate of exposure, the free space beam suffers no consequence over the lifetime of the experiment. Also free space beams reduce the complexity of fiber routing while it reduces the latency due to velocity factors and delay drift due to thermal effects compared to fibers. There are also areas where fiber connectors are too large and too massive.

Due to diffraction, there is an optimum diameter for a beam for a given distance in order to not be in the $1/r^2$ loss region. The Rayleigh distance relates waist size and divergence, and it depends on wavelength. If we start with a diameter too small for the distance of interest, the beam will diverge, and will become $1/r^2$ at the receiver, and we will have large losses. This is typical of space, satellite, etc. applications. If we start with an optimum diameter, the waist can be near the receiver, and we can capture almost all the light and focus it to a small spot. Examples are ~ 1 mm for 1 m and ~ 50 mm for 1 km.

4.1. MEMS Mirrors

We demonstrate steering of a free space beam carrying data which has been done using MEMS mirrors at Argonne. If there are relative movements of the sender and receiver, for example vibrations caused by pumps, some sort of method to compensate for the movement must be incorporated into the steering. A steering feedback loop utilizes a position sensitive detector which senses the reflected beam from the mirror at the receiving side. This is illustrated in Fig. 4. Laser light is reflected off of a MEMS mirror and onto a partially (> 50 %) silvered lens [12]. The lens is chosen to produce a large enough reflection at four simple Si photo detectors rigidly coupled around the MEMS mirror. The change in response is then used as a feedback to move the beam back to the receiver accurately. An analog control loop was used to implement the feedback. Our prototype setup uses a commercial MEMS mirror from Mirrorcle Tech [13].

In order to simulate the relative vibrations, the reflecting lens is mounted on a small rigid structure which can be driven at variable frequencies and amplitudes in a single axis. An analog filter was introduced to reduce the vibrations associated with a mechanical resonance of the MEMS mirror. The design and behavior of the analog filter is further explained in [12]. This setup is capable of constraining beam motion relative to target to about 5 μm, when the reflecting lens is moving 700 μm at 5 Hz [12].

There are several issues with this scheme in getting the light beam captured after it passes through the partially silvered lens. The first issue is that both the size of the reflection on the silicon detectors and the size of the beam at the receiving lens are dependent on the size of the beam at the reflecting lens. The second issue is that the reflected light pattern on the silicon detectors is not proportional to the movement of the reflecting lens if the movement is large (~mm).

In order to solve the issues with the direct feedback the setup was changed. Instead of an analog feedback with inverse Chebyshev filter we used a lookup table on an FPGA to convert the reflected signal on the silicon detectors to the actual position of the receiver. Here it was essential to introduce a separate laser to do the alignment since the lookup table depended on the location (There is a degeneracy of solutions at large angle if the reflection depends on the MEMS–steered beam). With the separation of the laser, the reflecting lens was moved to the side of the receiving lens. An illustration of the new setup is shown in Fig. 5 and photos of the actual setup are shown in Fig. 6. The lookup table is filled initially by mapping the reflection patterns to the actual location of the receiving system.

4.2. The lens system

With the free space data link over a distance of ~1 m, we investigated the ability of different types of lenses to form the beam and capture the beam at various angles and positions. To build a complete link without major optical losses, it is essential to optimize both beam launch and capture. We found that aspheric lenses produce narrow beams but have very narrow acceptance angles (< 2 mr). Also we found that GRIN (Gradient-Index)lenses have wide acceptance angles (>20 mr) if a multi mode fiber is attached. With these findings our setup used an aspheric lens to launch the beam and a GRIN lens to capture the beam. The improved setup is shown in Fig. 5.

5. Prototype Setup

A prototype was built to test the lens system, MEMS mirrors and feedback all together, as illustrated in Fig. 5. A pseudo random data electrical signal was generated from an FPGA board at 1.25 Gb/s and that signal was used to modulate a 1550 nm CW laser beam. For this setup we are using a LiNbO3 MZI type EOM. The modulated light is then launched (in air) using an aspheric lens. The beam is reflected off of a MEMS mirror in the direction of the GRIN lens in the receiving setup. The light captured by the GRIN lens is then fed to a 1550 nm Small Form-factor Pluggable (SFP) transceiver to convert the optical signal back to electrical, which is fed back to the FPGA board to compare with the original signal to check the Bit Error Ratio (BER).

An 850 nm laser was used for the alignment link in order to use inexpensive Si detectors. The alignment laser is reflected from a silvered lens which is rigidly coupled to the receiving system of the data link. Any vibration in the receiving system also vibrates this reflecting lens and that changes the reflected pattern at the Si detectors. The Si detectors are connected to an amplifier and digitizer. The digitized signal is then fed to an FPGA, which we used to lookup the MEMS mirror voltages required to steer the beam directly in to the receiving GRIN lens. These electrical signals then pass through Finite Impulse Response (FIR) low pass digital filters also implemented in the same FPGA. These filters are required to reduce any 1 kHz signal, which is caused by a resonance of the MirrorcleTech MEMS mirrors. Finally the signals are converted to analog and amplified to drive the MEMS mirror.

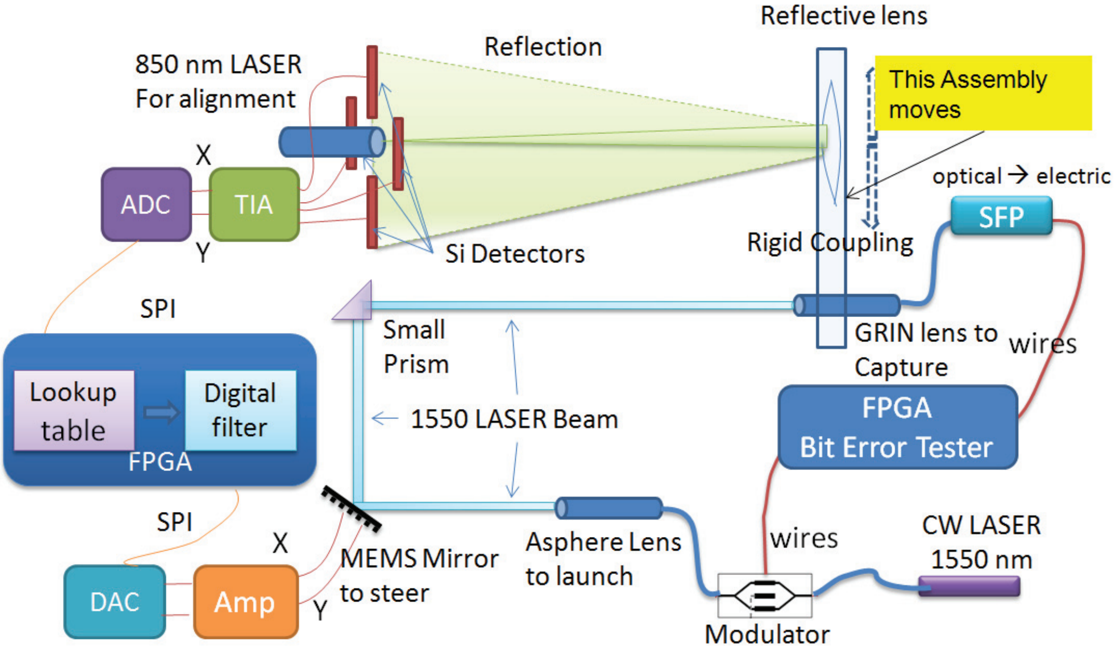

Fig.5. An illustration of demonstration setup

6. Performance of the System

To measure the static performance (Limitations of capture lens when steering with MEMS) of the full system the receiver was first moved very slowly in both x and y directions. The Full Width Half Maximum (FWHM) of the received optical power was found to be at ~10 mm displacement. The BER at ±10 mm is 10^{-14}. To measure the dynamic performance the receiving system was mounted on a speaker (Fig. 6(a)) at some random angle. We observed 10^{-14} BER with the speaker oscillating at 10 Hz with approximately 5 mm amplitude. With a constant delay FIR filter, this system starts producing errors if the speaker moves faster than 10 Hz and with large amplitude (> 1 mm). The analog Inverse Chebyshev filter does not have these limitations. This working range should be adequate for real detector environments. It seems clear that the digital filter phase delay significantly affects the working range of the system and we have replaced the digital filter with the optimized analog filter we designed for the direct feedback.

7. Conclusions

We have made a number of advances in free space optical data transmission at ANL-HEP. Among these are steering using reflections from the receiver system without wires. We made a major improvement by separating data link and the alignment link. We have found ways to form beams and receive beams that reduce critical alignments, reducing time and money for setup. A free space system is operating at 1.25 Gb/s over 1550 nm, using a modulator to compose data, and an FPGA to check for errors, a $<10^{-14}$ error rate with target moving about 1 cm x 1 cm at 1 m. We have control of a MEMS mirror which has high Q resonance (using both analog and digital filters). Although not mentioned in this paper, we have demonstrated a long range, 80 m, data telescope using low power (0.5 mW vs 250 mW commercial) by means of near diffraction limited beams. In addition we have done some radiation testing of SiGe modulator material.

Some future directions are to develop at least a 5 Gb/s free space link (with combined digital mapping and analog bandpass), incorporate more than one MEMS mirror in our setup, and pursue a more robust long distance optical link using steering feedback and micro-motors. We will evaluate MEMS mirrors supplied by Argonne CNM, and do radiation tests on commercial modulators.

In addition, we have submitted a proposal to apply optical readout to an actual detector in the Fermilab test beam using the Argonne DHCAL [14], which would be an ideal test-bed with 400K channels.

During the course of our studies it has become evident that the use of light modulators would eliminate many of the reliability problems associated with VCSEls, whether with free space transmission or with fibers.

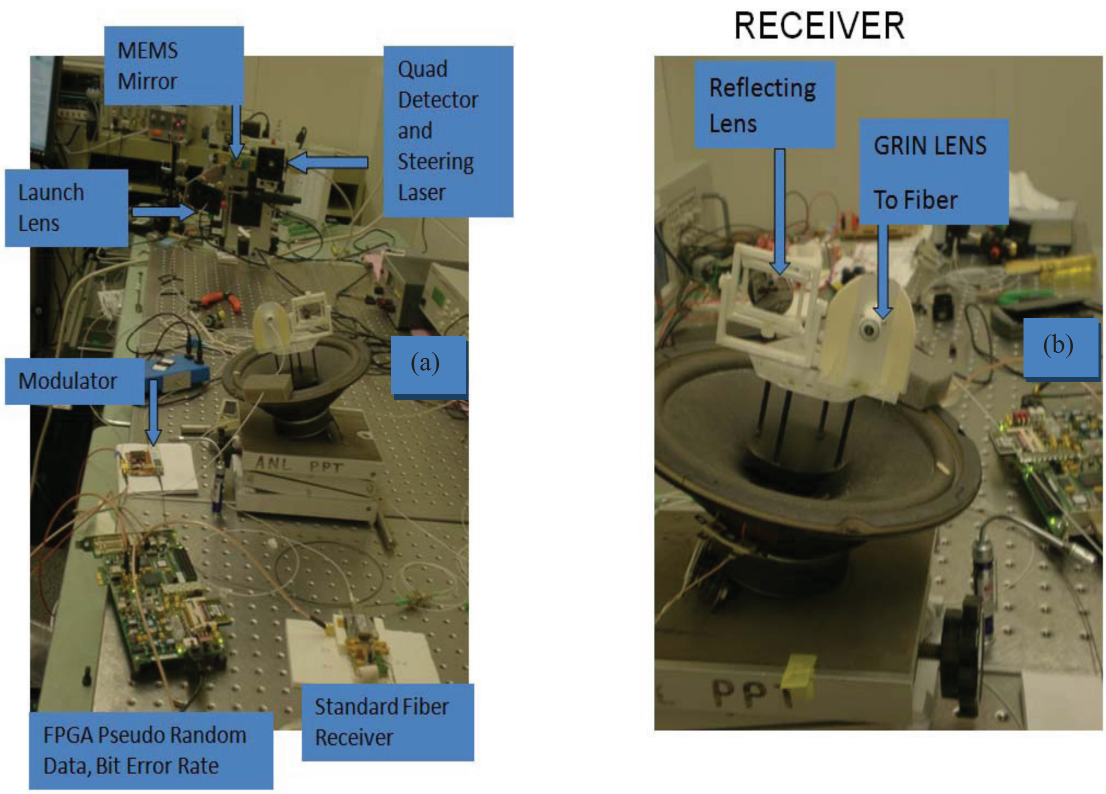

Fig.6. The prototypes setup with all the components (a) full setup. (b) A closer look at the receiving system and its mounting

Acknowledgements

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