Cat's eye modulating retro-reflectors for free-space optical data transfer

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Using short range free space optical interconnects can be attractive for on-board data transfer in spacecrafts. Such links do not require long wiring harnesses, have no susceptibility to RF interference, can provide point-to-point connectivity and can, in some cases, be self-configuring. However most schemes for free space optical interconnects rely on arrays of small lasers and/or modulators directed via microlens arrays or gratings to a detector plane. These systems have very tight alignment tolerances both positionally and angularly and may be difficult to employ reliably on a spacecraft.

An alternative approach for free space optical data transfer uses modulating optical retro-reflectors (MRR). An optical retro-reflector is a passive optical device that reflects light exactly back along its path of incidence over a large field of view. An MRR couples an electro-optic modulator to the retro-reflector. In operation a cw interrogating beam paints the MRR with light which the retro-reflects back to the interrogating source. By driving the modulator with a signal the retro-reflected light is modulated and carries that data back to the interrogator with no need for pointing or tracking on one end of the link.

We will discuss an MRR system that works between two fixed points and greatly relaxes the alignment requirements for the link while at the same time preventing cross-talk between nodes. This system uses nodes consisting of cat's eye modulating retro-reflectors that contain semiconductor multiple quantum well modulator/receivers. The nodes also have cw diode laser emitters. In operation each node sends out a broad cw beam to an identical node. The second node retro-reflects the broad beam in a narrow cone that contains the desired information. The designs and preliminary evaluations of the optical and electro-optical components of the system will be discussed and some sample links calculated

I. Project Goals

Data transfer on-board a spacecraft is typically done using wiring harnesses (where the wires may be copper for electrical signals or fiber optic for optical signals) using a serial protocol such as 1553 or 1773. This approach has several limitations. The wiring harnesses themselves are undesirable because of their mass and large moment of inertia. Also having an astronaut repair or add new connections once the spacecraft has been launched is quite difficult. The nature of the serial bus is also limiting because only one instrument can talk at a time limiting the aggregate data rate of the network.

The object of the Cat's Eye Modulating Retro-reflector program is to develop the components for a new type of spacecraft data network that utilizes free space optical data transfer. This free space optical network will allow the elimination of long wiring harnesses, enable point-to-point data connections, allow new data nodes to be added to a spacecraft after launch with relative ease, be immune to RF interference and allow data networks to easily extend outside of the spacecraft or to parts of distributed spacecrafts. In addition the network will not have the very accurate alignment tolerances between nodes that is generally required by free space optics.

II. Background

A Optical data transfer

Optical data communications using fiber optic connections is rapidly becoming the standard method of data transfer, particularly when high bandwidth or RF interference issues are important. Free space optical data transfer is also commonly used for short range, relatively low data rate links between portable or handheld computers (IRDA) or, even more commonly, in a variety of remote controls for consumer devices such as televisions or cameras. These broad-beam free space interconnects generally link a single transmitter device to a single receiver device. In fact such an interconnect can in principle allow a device to communicate with several receiver nodes at once but not in a point-to-point fashion. As shown below in Figure 1, in such a link the transmitter sends the same signal to all nodes.

Broad beam free space interconnects generally have moderate data rates (less than 10 Mbps) because they use low power emitters such as LEDs and because they spread their light over such a large area that there are insufficient received photons to support a high-speed link. Nonetheless such links are attractive because they have low sensitivity to alignment. Indeed the simplest replacement for a 1553 bus on a spacecraft would be a set of broad beam free space links.

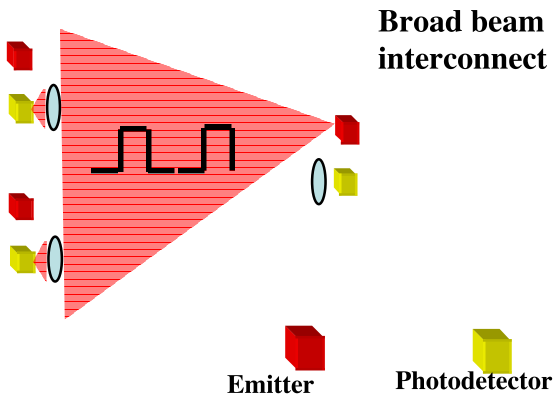


Figure 1 A broad beam free space optical interconnect

There are other applications in which high single channel data rate, point-to-point links are desired. These include data transfer between boards or even chips in a computer or from high data rate imaging sensors. For these applications another free space optical approach has been investigated intensively over the past decade[1]. This approach uses combinations of emitters, modulators and detectors arranged in planar arrays combined with micro-optics. As shown below in Figure 2 in such a system, a transmitter in one plane is tightly imaged onto a receiver in a second plane. Two forms of transmitters are used. In one case a single laser is split into multiple beams each of which is modulated by a pixel in a modulator array. Alternatively the transmitter may be a small laser such as a VCSEL which is directly modulated. These systems have the advantage of very high single channel data rates (hundreds of Mbps) because they are very efficient in their use of light. They are also true point-to-point systems with no cross talk between nodes. The net result is a potential of extremely high aggregate date rates exceeding terabits per second. The downside of this approach is extremely precise positional and angular alignment requirements of about 100 microns and 100 microradians (for a 1 meter long link) respectively. Such requirements are difficult to manufacture and maintain in equipment destined for use in the controlled environment of a terrestrial computer room and may be impossible to meet for spacecraft systems that must survive launch and work without maintenance for years[2].

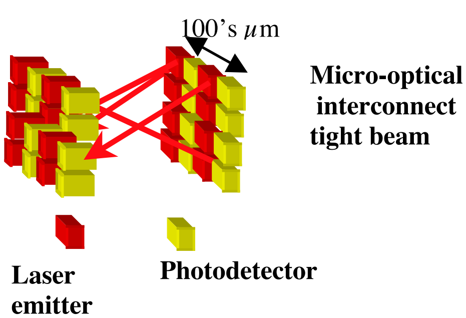
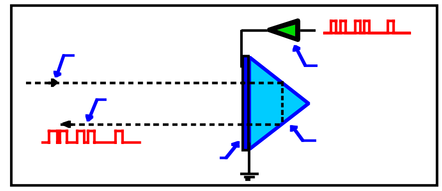


Figure 2: A micro-optical free space interconnect

B. Modulating retro-reflectors

An alternative to the broad-beam or micro-optical free space optical interconnects is a new approach based on cat's eye modulating retro-reflectors. As shown in Figure 3, a modulating retro-reflector (MRR) combines a passive optical retro-reflector with an active electro-optic shutter.



1. Interrogation beam 2. Modulated beam
3. Electronic driver 4. Transmissive MQW mod.
5.
Solid retro-reflector

Figure 3: A corner cube based modulating retro-reflector

These systems have been proposed and in some cases demonstrated over many years using different types of electro-optic shutters and corner-cube retro-reflectors. The proposed systems generally involved the MRR on one end of the link and a conventional free space optical communications terminal on the other. The conventional terminal consisted of a laser, telescope and active pointer-tracker. This interrogator was pointed at the modulating retro-reflector illuminating it with a cw beam. This beam was then modulated and retro-reflected back to the interrogator. Such a system allows two way free space optical communications with pointing and tracking on only one end of the link. An example link between a mothership and nanosatellite is shown below in Figure 4.

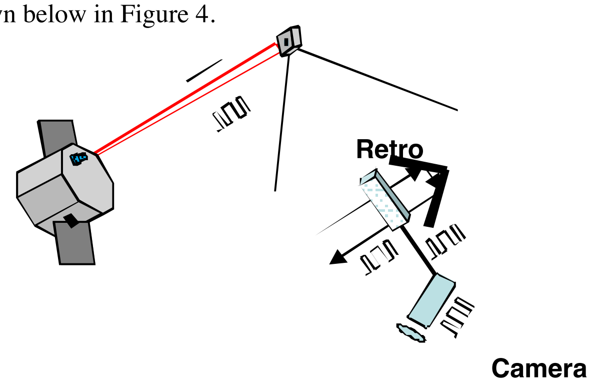


Figure 4: A modulating retro-reflector link between a mothership and nanosatellite

The Air Force Research Laboratory demonstrated a modulating retro-reflector link to a balloon in 1997. Their MRR used a liquid crystal shutter, which was limited to a top data rate of about 10 Kbps, and a corner-cube retro-reflector[3].

C. Multiple Quantum Well Modulators

Since 1998 the Naval Research Laboratory has investigated corner-cube based modulating retro-reflectors based on semiconductor multiple quantum well (MQW) based electro-optic shutters[4]. These types of shutter have the advantage of having very high intrinsic switching times (greater than 10 GHz), and in practice are limited in their modulation rate only by RC time. For typical sized systems with apertures between 0.5 and 1 cm MQW modulating retro-reflectors can sustain data rates of up to 10 Mbps. These devices have been used to close a free space optical link to a UAV.

As shown in Figure 5 a multiple quantum well modulator is a PIN diode with multiple layers of thin layers of alternating semiconductor alloys in the intrinsic region. These layers consist of a lower band-gap material, the well, and a higher bandgap material the barrier.

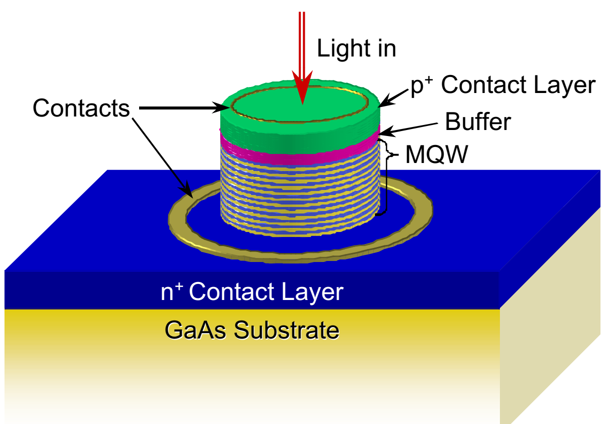


Figure 5. The layer structure of an MQW modulator

Because the semiconductor layers are very thin the conduction and valence bands becomes quantized and the exciton absorption feature at the band-edge becomes narrower in linewidth and enhanced in absorption. The center wavelength of the exciton is determined by the composition of the well material as well as the width of well. When a reverse bias is applied across the MQW the electric field changes the quantum well potential, shifting the exciton feature to the red and reducing the magnitude of the absorption. Thus, as shown in Fig. 6 a varying voltage on the quantum well is converted into a varying optical absorption over about a 10 nm bandwidth.

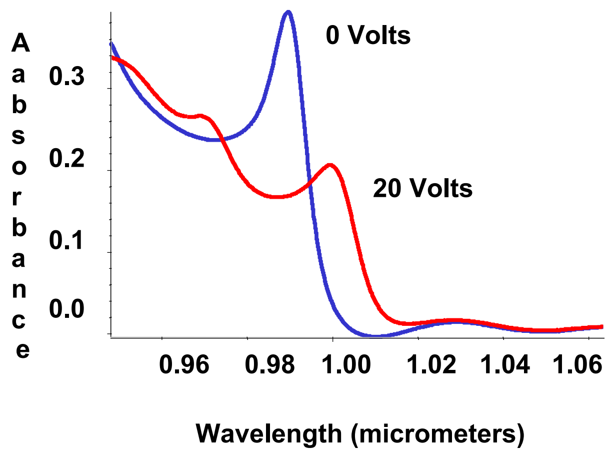


Figure 6. The band-edge optical absorption of an MQW for 0 and 20 V reverse bias

This sort of modulator is attractive for modulating retro-reflector applications because it can have a large area and its modulation characteristics are essentially free of angle dependence. Using InGaAs/AlGaAs MQW structures grown on GaAs substrates operating wavelengths between 0.8-1.06 μm can be accessed[5]. Using InGaAs/InAlAs MQW structures grown on InP the wavelength region around 1.55 μm can be accessed.

D. Cat's eye modulating retro-reflectors

In almost all applications of modulating retro-reflectors considered to date the platform carrying the MRR is asymmetric with the platform carrying the interrogator. Generally the interrogator platform can handle more weight and has more available power, so it can carry a pointed laser interrogator. The situation for on-board data transfer is quite different since each data node is a peer of the other nodes. None of the nodes can use active pointing to maintain a link in the presence of environmental perturbations. The challenge then is to make us of the retro-reflection characteristics of an MRR to relieve pointing requirements on *both* ends of the link. We can do this by combining the MRR concept with the broad beam free space interconnect describe earlier. Such a system allows point to point interconnects because no information is carried on the broad angle beam, only on the narrow divergence retro-reflected beams, thus there is no cross-talk.

To implement such a system we examined the use of a different form of MRR using a cat's eye retro-reflector. There is no one form for a cat's eye retro-reflector, but they generally combine lenses and mirrors and incorporate an optical focus. A spherical cat's eye is shown below in Figure 7.

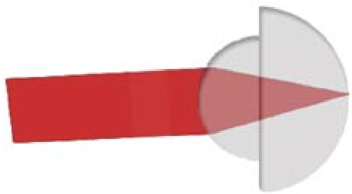


Figure 7: A spherical cat's eye retro-reflector.

We can use the fact that a cat's eye retro-reflector has an optical focus whose position varies based on the incidence angle of light upon the cat's eye to channelize the return from multiple nodes and allow point to point links. We have designed an alternative form of cat's eye retro-reflector that uses a custom lens, a flat mirror and a MQW modulator/receiver array inserted into the optical system in front of the mirror. This cat's eye modulating retro-reflector (CEMRR) node also has an emitter, a fiber coupled laser diode reflected from a dot coupler placed in front of the cat's eye aperture. A diagram of a CEMRR node is shown below in Figure 8.

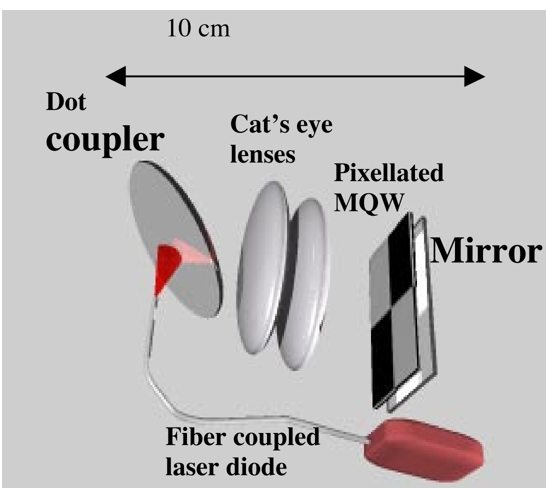


Figure 8: A cat's eye modulating retro-reflector transmitter/receiver node

A set of CEMRR nodes can exchange data in a point-to-point fashion by interrogating each other with broad cw laser beams and receiving narrow divergence retro-reflected signal containing data streams. Below, in Figure 9, a typical set of CEMRR nodes is shown. The node on the right will act as an interrogator, while the nodes on the left will act as transmitters.

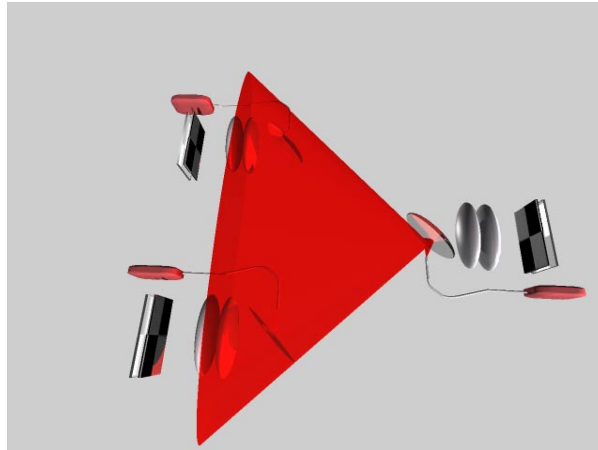


Figure 9: A set of cat's eye modulating retro-reflector nodes

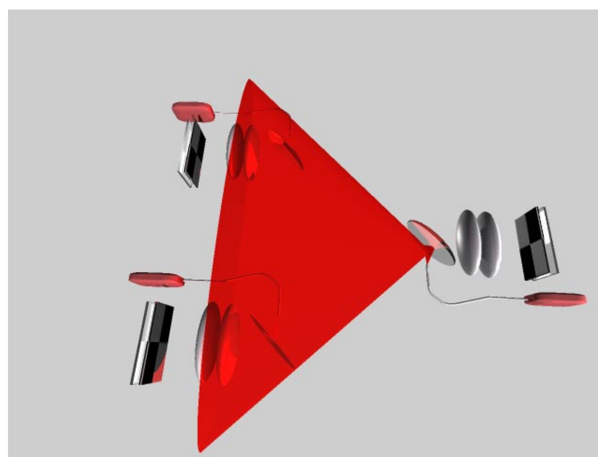


Figure 10: A cat's eye interrogator node paints two cat's eye transmitter nodes

In operation, as shown in Figure 10, the transmitter node emits a broad cw laser beam that paints both of the transmitter nodes. This beam carries no information so the fact that it intercepts two nodes causes no cross talk. Its broad angular divergence and large footprint ensures that the interrogation beam has little positional or angular sensitivity. As shown in Figure 11, the portion of the interrogation beam that intercepts each interrogator node is focused by the lenses and passes through a pixel in the MQW array. The particular pixel that the light passes through depends on the relative spatial positions of the interrogator and transmitter. In a properly designed CEMRR system each pair of nodes will have a unique pixel associated with it. This is what allows point-to-point links.

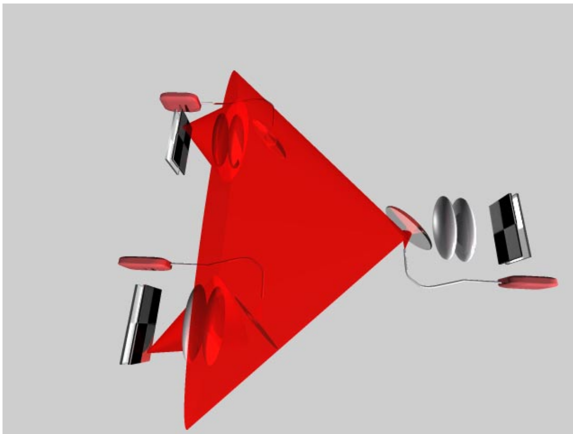


Figure 11: The beam path upon interrogation in the transmitter nodes of a CEMRR system

The light passes through the transmitter node MQW pixel twice (once on entering and once on reflection). This pixel has a modulated voltage placed upon it. This modulates the cw light with the signal which the transmitter node wishes to send back to the interrogator. As shown in Figure 12 this light then retro-reflects in a narrow divergence beam back to the interrogator.

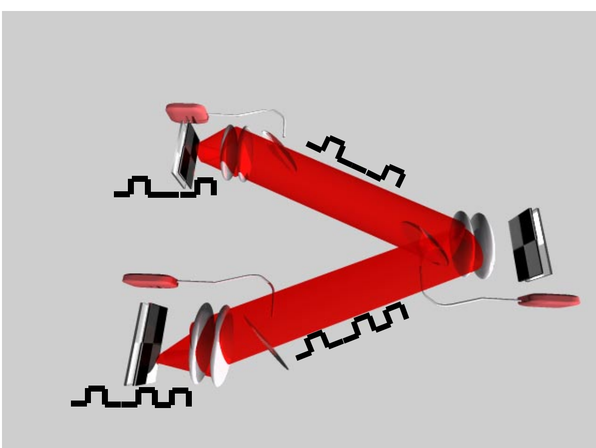


Figure 12: The transmitter nodes retro-reflect their data back to the interrogator node.

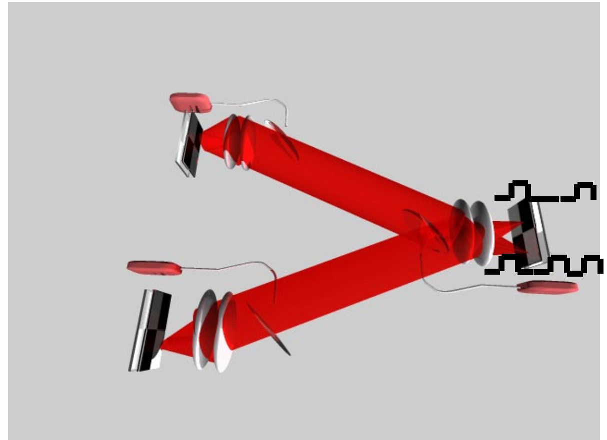


Figure 13: The retro-reflected signals are detected by the interrogator.

Finally the retro-reflected beams intercept the lenses of the interrogator node where they focus onto the interrogator's MQW array, again onto a particular pixel determined by the relative positions of the interrogator node and the transmitter node. In this case however, we bias the MQW with a constant voltage and detect the photocurrent produced by the retro-reflected beam. Because an MQW is a PIN diode it can act as a photodetector. As shown in Figure 13 the retro-reflected signals from each transmitter focus onto different interrogator MQW pixel.

A system of CEMRRs has a variety of sensitivities to angular or positional misalignment. If the interrogator position shifts the broad interrogating beam will shift with it, but as long as the interrogator shift is less than the footprint of the interrogating beam the link will be maintained. Similarly if the position of either of the transmitters shifts by less than the interrogating footprint the link will be maintained. If the angle of the interrogator shifts the position of the interrogating beam will shift, but if this angular shift is smaller than the angular width of the interrogating beam then the transmitter nodes will still be painted with the interrogating beam. If the angle of a transmitter node shifts it will have no effect on the link, because of the retro-reflection, for shifts within the field of view of the cat's eye retro-reflector (typically about 30 degrees).

A more subtle alignment sensitivity occurs upon retro-reflection if the positions of any of the nodes shift. For shifts smaller than the interrogator footprint retro-reflection will still occur but the focal positions on the MQW arrays in both the interrogator and the transmitters will shift. Because of the demagnification of the cat's eye lenses the focal plane shift is much smaller than the physical shift of the nodes. This shift can be handled in two possible ways. First, if the pixels are sufficiently large then these positional shifts will not move the focal spots off the proper pixel. For a typical system, a 1mm pixel would allow for 5 cm node shift. An alternative approach is to overfill the MQW array with more pixels than nodes. Then if a shift occurs pixels can be reassigned to different node pairs. An advantage of the second approach is the possibility of adding more nodes later on. This opens up the possibility of networks that can automatically add new physical point-to-point connections as new nodes are added.

The net result of the CEMRR system is one which combines some of the features of both broad beam and micro-optical free space interconnects. The system has the low alignment sensitivity of the broad beam system but has the point-to-point connectivity of the micro-optical system. It is less efficient in its handling of light than the micro-optical system but more efficient than the broad beam system (because all the nodes that fall within the footprint of the interrogator beam have their own data channel)

III. Components for Cat's eye modulating retro-reflectors

To demonstrate the utility of a cat's eye modulating retro-reflector we have been developing a free space optical 1553 bus using CEMRR nodes. The 1553 protocol is not optimal for using CEMRRs but it is ubiquitous on spacecraft and so is a good first step towards more flexible architectures.

A cat's eye modulating retro-reflector system requires an integrated set of optical, electronic and photonic components. The optical system must retro-reflect light (though diffraction limited beam quality and accuracy is not needed for short-range links). It must also allow for the insertion of an MQW modulator/receiver array into the optical chain. The MQW device must balance the requirements of optical modulation with photoresponse. It must also be robust enough to survive launch and operate in a spacecraft environment. The interface to the 1553 bus presents a set of challenges. The 1553 signal must be converted to the appropriate driving voltage for the MQW when the MQW is used as a modulator. When the MQW is used as a receiver a DC bias must be put on the device and the photocurrent must be amplified up to the point where it can be reinserted into the electrical 1553 bus. The logic and components must encompass these needs as well as at least simulate a peer-to-peer bus. In the subsections below we will describe our progress to date on these goals.

A. Optical Design

Unlike a typical cat's eye retro-reflector the optics in the CEMRR nodes must accommodate a planar MQW array. We approached this problem by using a custom lens design.

The experimental setup and spot diagram are shown below.

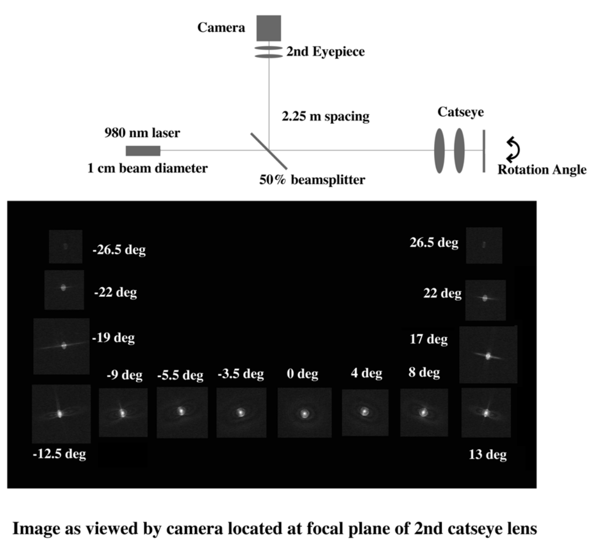


Figure 14: Cat's eye spot diagrams

In this same setup the change in the focal spot position as a function of entrance angle into the cat's eye was measured. A graph of this data is shown in Figure 15.

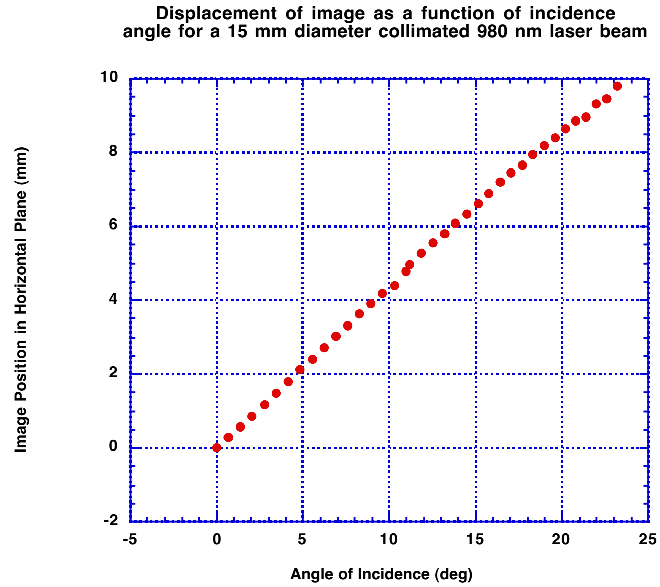


Figure 15: Shift of focal spot with incidence angle

The field of view of the cat's eye is about 30 degrees. The focal spot is approximately 140 microns in diameter. The divergence of the retro-reflected beam was less than 1 milliradian.

B. MQW Modulator/Receiver

A multiple quantum well structure consists of multiple thin layers of semiconductor alloys. The alloy with the lower energy band-gap is called the well and the alloy with the higher energy-band-gap is called the barrier. The alloy composition and width of the well material determine the operating wavelength of the modulator.

The MQW devices for the CEMRR nodes must act as both optical modulators and photodetectors. This places some additional restrictions on the design of the MQW layers. In particular to maintain good photodetector responsivity the barriers must not be too thick, but if the barriers are too thin the optical modulation contrast will be low. We designed a MQW structures using a self-consistent transfer matrix code. The MQW was designed for operation at 980 nm and were grown via molecular beam epitaxy at NRL.

We chose 980 nm as the operating wavelength. 980 nm laser diodes are used to pump 1550 nm Erbium doped optical amplifiers used by the telecommunications industry. The use of 980 nm diode lasers allows us to leverage the high investment by industry in making these lasers powerful and reliable.

A photolithography mask was created and a set of 1mm MQW structures was produced by metallization and wet chemical etching.

We evaluated the resulting device's DC photoresponse by placing the structure under a DC reverse bias. illuminating it with a calibrated, tunable, laser diode and measuring the current. A dark current measurement was also taken. The subtraction of the two curves gives the DC photoresponse shown below in Figure 16.

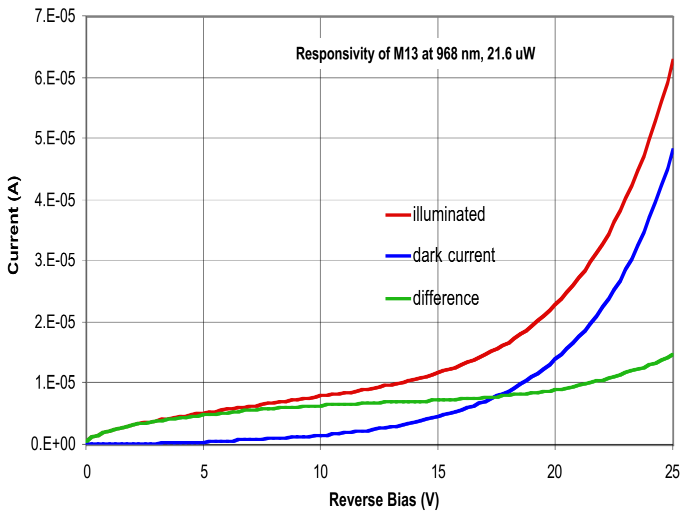


Figure 16: DC Photoresponse of 980 nm MQW structure

The responsivity, shown by the green curve, becomes relatively flat by about 8 V reverse bias at about 0.3 A/W. At biases above about 20 V the responsivity climbs again, perhaps due to avalanche gain.

The modulation contrast of the MQW was measured using a similar set-up to that used for measuring the photoresponse. In this case the light passing through the MQW was focused onto a silicon photodetector. A modulated bias was placed upon the structure and the resultant modulated optical signal was measured.

The rise time of the modulation was faster than the response time of our measuring apparatus (10 MHz). From the measured capacitance (50 pF) and sheet resistance (50 Ohms) of the device we estimate a maximum modulation rate of 50-100 Mbps. A modulation trace is shown below in Figure 17.

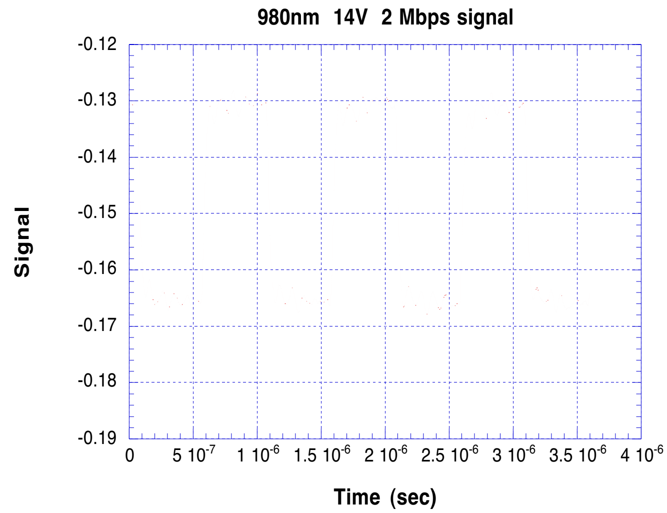


Figure 17: Optical modulation of MQW device illuminated at 980 nm with a 14 V applied bias

The modulation contrast is also a function of wavelength. The 3 dB bandwidth of the modulation is about 10 nm as shown in Figure 18.

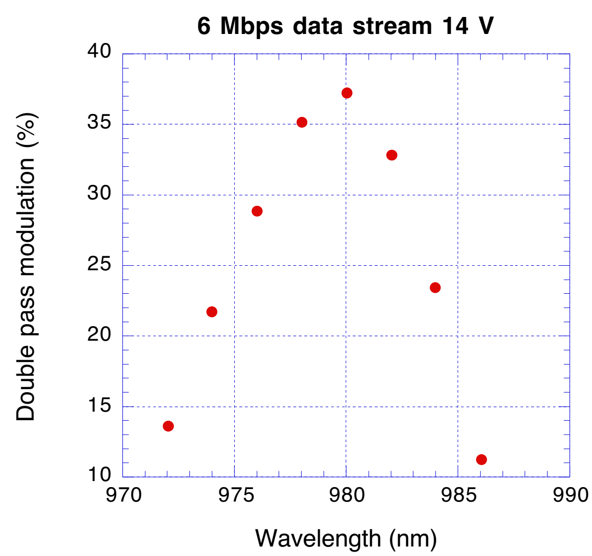


Figure 18: Double pass modulation contrast for 14 V applied voltage and a function of wavelength.

C. Radiation effects on the MQW modulator/receiver

The radiation tolerance of the MQW modulator/receiver was evaluated by performing a stepped bombardment of 1 MeV protons. 3 MQWs were tested, one under a 15 V bias while being bombarded and 2 unbiased. After each bombardment the optical transmission, modulation contrast, modulation rise time and dark current were measured.

The bombardment sequence is shown in Table 1. Up to a dosage of $10^{14}/cm^2$ no degradation of modulation performance was observed though the dark current did increase.

Exposure	Cumulative Fluence (cm^{-2})	Equivalent D_d (MeV/g)	Equivalent # of Years in LEO Orbit
1	**8×10^{11}**	**5.40×10^{9}**	**3.5**
2	**4×10^{12}**	**4.32×10^{10}**	**28.0**
3	**8×10^{13}**	**2.16×10^{11}**	**140.2**
4	**1×10^{14}**	**2.16×10^{12}**	**1402.4**
5	**4×10^{14}**	**5.40×10^{12}**	**3505.9**

Table 1: Radiation exposure schedule

D. MQW Modulator Temperature Dependence

MQW modulators have a limited operating wavelength bandwidth. Because the band-edge of the semiconductor material shifts with temperature the MQW modulator has a temperature window in which it can operate if the laser used in the CEMRR system is not tunable. We measured the temperature dependence of the MQW by measuring its absorption spectrum as a function of its temperature. The measured shift, is about 0.33 nm/°C. Given the operating bandwidth shown in Figure 18 the temperature window is about 30 °C.

E. Cat's eye link budget

Given the optical losses measured in the cat's eye optic and the modulation characteristics of the MQW we can estimate a link budget for CEMRR nodes. A sample budget is shown below. This budget assumes a 1 cm cat's eye, 3 meter range, 500 micron MQW pixels, 15 cm diameter interrogator footprint, and 10 MHz receiver bandwidth.

Source	20 dBm
Geometric loss	-23.5 dB
Transmitter cat's eye optical loss	-3 dB
MQW loss	-5 dB
MQW modulation contrast	-4 dB
Geometric loss (transmitter to interrogator)	-3 dB
Interrogator cat's eye optical loss	-1.5 dB
Total	**-20 dBm**
Estimated receiver sensitivity	-30 dBm
Margin	10 dB

F. 1553 Logic and Interface

In a true point-to-point network any node can talk to any other node. In a 1553 network nodes must talk through a bus controller. We modified the bus logic to simulate a point-to-point link and allow a remote terminal to talk to a remote terminal. In addition a free-space optical 1553 bus was constructed by passing a cw laser beam through an MQW modulator and focusing that light onto a photodetector. The MQW modulator was driven with a 1553 signal. This signal was received by the photodetector and reinserted into the electrical 1553 bus. Some sample data waveforms are shown in Figure 19.

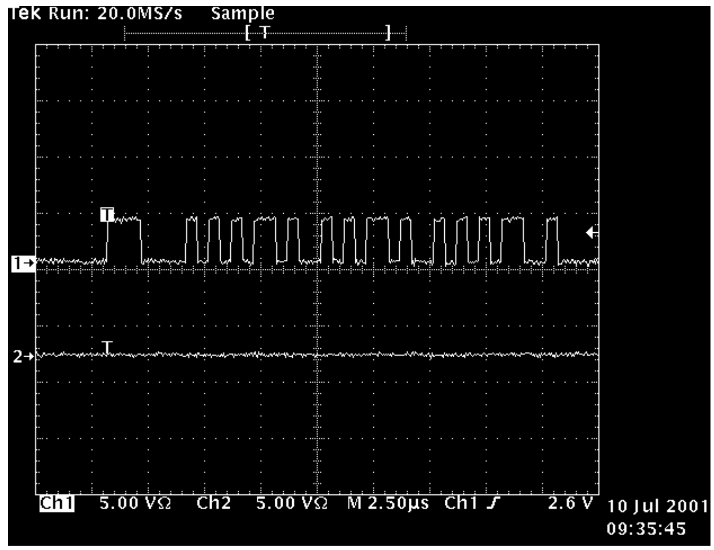


Figure 19: 1553 data signal carried on a free space optical

IV. Future Plans

The next step in developing cat's eye modulating retro-reflectors for optical data interconnects is integration of the MQW modulator with the cat's eye optics. These nodes will then be assembled into a 1553 network configuration using the logic circuitry already developed.

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