Infrared Data Link using a Multiple Quantum Well Modulating Retro-reflector on a Small Rotary-Wing UAV

W. S. Rabinovich, G. C. Gilbreath, Chris Bovais, Kerry Cochrell, H. R. Burris, Mena Ferraro, Michael Vilcheck, Rita Mahon, Kim Goins, Ilene Sokolsky, John Vasquez, Timothy Meehan, Robin Barbehenn, D. S. Katzer, and K. Ikossi-Ansatasiou

US Naval Research Laboratory
Washington, DC 20375
202-767-9413
Rabinovich@nrl.navy.mil

Abstract— This paper describes a recent demonstration of an optical data link between a small rotary-wing unmanned airborne vehicle (UAV) and a ground based laser interrogator using the NRL multiple quantum well modulating retro-reflector (MRR).

MRR systems couple an optical retro-reflector, such as a corner-cube, and an electro-optic shutter to allow two-way optical communications using a laser, telescope and pointer-tracker on only one platform. The NRL MRR uses a semiconductor based multiple quantum well (MQW) shutter capable of modulation rates above 1 Mbps. The MQW modulating retro-reflector has the advantages of being compact, lightweight, and very low power. Up to an order of magnitude in onboard power can be saved using a small array of these devices instead of the RF equivalent.

In the demonstration a 400 Kbps optical link to a flying UAV at a range of 100-200 feet was shown. The device itself is capable of over 6 Mbps.

TABLE OF CONTENTS

1. INTRODUCTION[1]

Free space optical communication has emerged in recent years as an attractive alternative to conventional RF techniques. This has been due to the increasing maturity of lasers and compact optical systems as well as the inherent advantages of this approach, which include very large bandwidth, low probability of intercept, and immunity from interference or jamming. These features are inherent in the short wavelength of optics, but, to be exploited, require high quality telescopes and extremely accurate pointing and tracking. As a result, optical communication systems can have a large system impact in terms of weight, power and platform stability. Such a system is also inherently complex. These costs are acceptable in many systems, but if the platform is small, or has little available power, the requirements of a conventional optical communications link may be prohibitive.

The low divergence of optics is used in conventional optical communication systems to allow very high bit-rate (~Gbits/sec) links at long range. However, optics' low divergence can be used in another way: to enable a new kind of communication system that would be impractical at longer (RF) wavelengths. Rather than using two laser transmitters with their associated gimbaled telescopes and pointing/tracking systems it is possible to establish a two-way optical link using a single conventional laser transmitter. This transmitter is located on a large platform (or at a ground station) that has sufficient power, payload capacity and platform stability to operate it. It can communicate data to a second small platform conventionally, by modulating its laser with the desired signal. If the laser is strong enough the small platform can receive the data with a detector with a wide field of view, obviating the need for a large pointed receive telescope. However, such a system does not allow the small platform to transmit data back to the large platform. To enable the small platform to send data to the large platform we have examined using a modulating retro-reflector.

An optical retro-reflector is a passive optical system that reflects light incident upon it exactly back along its path of incidence. Retro-reflectors typically have a large field of view (about 20 degrees full angle) and very high efficiency. Retro-reflectors can be mounted in a hemispherical array to expand the field of view to as large a value as desired. A typical retro-reflector consists of three mirrors mounted in the shape of the corner of a cube. Optical retro-reflectors have been used in recent years to allow millimeter accuracy laser ranging of satellites.

Retro-reflectors can also act as optical communication systems. By mounting an electro-optic shutter in front of the corner-cube, the retro-reflected beam can be turned on or off (or at least modulated). By mounting a modulating retro-reflector on the small platform we can enable it to transmit data, without using a laser or pointer-tracker, to the large platform. In operation, the large platform would illuminate the small platform with a continuous-wave (unmodulated) laser beam. This beam would strike the modulating-retro and be passively reflected back to the large platform. The shutter would then be turned on and off with an electrical signal that carries the small platform's data. This impresses the data stream upon the retro-reflected beam, which then carries it back to the large platform. Fig. 1 shows a schematic of a modulating retro-reflector.

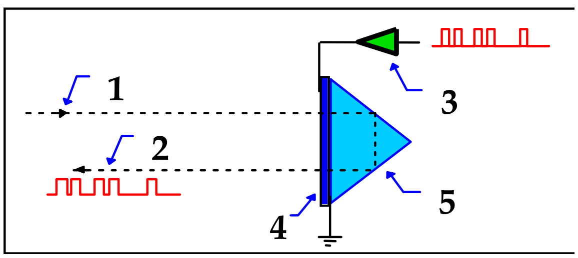

FIGURE 1. Device illustrated where: (1) interrogation beam; (2) reflected modulated beam;

Such a system can be very light and consume small amounts of power. In addition, if an array is used, the small platform need only be pointed toward the large platform with an accuracy equal to the field of view of the array, which can be as large as 100 degrees. The retro-reflection is insensitive to platform jitter as well. Despite this very generous pointing tolerance on the small platform, the retro-reflected beam has a divergence equal to the diffraction-limit of the retro-reflector (typically about 200 micro-radians). Thus the small platform maintains the low probability of intercept of a conventional optical communications link, but gains the loose pointing advantage of an omni-directional RF link.

The concept of a modulating retro-reflector is an old one. The impediment to implementation has been the availability of a laser transmitter for the large platform and a suitable shutter for the small platform. The development of conventional optical communication systems has made high quality laser transmitters available. Using such a system there has been a recent demonstration of a modulating retro-reflector link from the ground to a balloon using a ferro-electric liquid crystal as a shutter. This link transmitted data from the balloon at 20 Kbps[1]. Unfortunately, liquid crystal technology is very limited for data transmission. Physically, liquid crystal switching times are limited to data rates of 100 Kbps or less, and even this rate is very hard to achieve.

To extend modulating retro-links to data rates of mega-bits per second and higher, NRL has pursued the use of a different type of electro-optic shutter: a semiconductor-based optical switch based on GaAs multiple quantum wells (MQW)[2]. Semiconductor MQW technology is the basis for commercially available laser diodes. When used as a shutter, MQW technology offers many advantages. It is robust and all-solid state. In addition it operates at low voltages (less than 20 V) and low power (less than 1 Watt). Most importantly it is capable of very high switching speeds. MQW modulators have been run at data rates as high as 40 Gbps. In practice, for a modulating retro system, the link rather than the modulator limits the data rate. For a conventional corner-cube modulating retro-reflector, MQW technology should allow data rates in the tens of mega-bits per second, depending on range and the laser transmitter on the large platform.

The characteristics and appropriate applications of a MQW modulating retro-reflector link are determined by two scaling laws: the optical link budget and the power consumption curve of the MQW shutter. The optical power, and hence the maximum communications rate, retro-reflected from the small platform back to the large platform scales as

$$\frac{P_{laser} \cdot D_{retro}{}^{4} \cdot D_{rec}{}^{2}}{\theta_{div}{}^{2} \cdot R^{4}}$$

Where P_{laser} is the power of the laser transmitter on the large platform and θ_{div} is its divergence, D_{retro} is the diameter of the modulating retro-reflector on the small platform, D_{rec} is the diameter of the receive telescope on the large platform and R is the range between the two platforms.

The strongest dependencies are on the range and the retro-reflector diameter, both of which scale as fourth powers. Retro-reflector links fall off more strongly with range than conventional links because of their bi-directional nature. The strong dependence on retro-reflector diameter occurs because increasing the size of the retro-reflector both increases the optical power intercepted and decreases the divergence of the returned optical beam.

The electrical power consumption of a MQW modulating retro-reflector scales as:

$$D_{retro}{}^{4} \cdot V^{2} B^{2}$$

Where V is the voltage applied to the modulator (fixed by the required optical contrast ratio) and B is the data rate of the link.

In general then, any link is a compromise between keeping the retro-reflector large to maximize the returned optical power and keeping it small to reduce the electrical power consumed by the modulator.

2. Multiple Quantum Well Modulators

While the idea of a modulating retro-reflector is not a new one, it has in the past not been possible to implement a high-speed, low power link due to the lack of an appropriate electro-optic shutter. That shutter must have several characteristics to make a link possible. The shutter must have a high switching speed, low power consumption, large area, wide field of view and high optical quality. In addition it must work at wavelengths where good laser sources are available, be radiation tolerant (for space applications) and rugged.

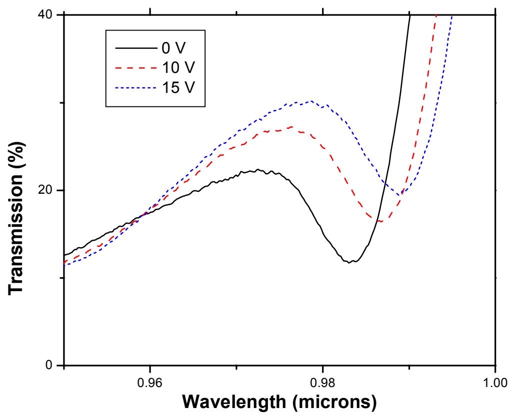

Figure 2. Transmission versus voltage for an InGaAs based MQW Modulator

Semiconductor multiple quantum well (MQW) modulators are one of the few technologies that meet all these requirements[3]. These devices are based upon the same materials technology as laser diodes. They consist of several hundred very thin (~10 nm) layers of semiconductor material, such as GaAs, deposited on a large (3 inch diameter) semiconductor wafer. Electrically they take the form of a P-I-N diode. Optically the thin layers induce a sharp absorption feature at a wavelength that is determined by the constituent materials and the structure that is grown. When the device has a moderate (~15V) voltage placed across it in reverse bias the absorption feature changes, both shifting to longer wavelengths and dropping in magnitude. Thus the transmission of the device near this absorption feature changes dramatically. This is shown in Fig. 2 for an InGaAs based MQW modulator that we have designed and grown for use in a modulating retro-reflector system

The modulator consists of 75 periods of InGaAs wells surrounded by AlGaAs barriers. The device is grown on an n-type GaAs wafer and is capped by a p-type contact layer, thus forming a P-I-N diode. It is a transmissive modulator designed to work at a wavelength of 980 nm, compatible with many good laser diode sources. We have also grown GaAs/AlGaAs modulators that work at 850 nm. These materials have very good performance, but have the disadvantage of working only in reflection, which is somewhat less convenient than transmission mode devices. Other wavelengths matched to 1-micron rare-earth lasers and 1.5 micron eye-safe lasers are also possible.

Once grown the wafer is fabricated into discrete devices using a multi-step photolithography process consisting of etching and metallization steps. A typical device has a 5-mmaperture, though larger devices are possible. It is important to point out that while MQW modulators have been used in many applications to date, modulators of such a large size are very uncommon and require special fabrication techniques A fabricated and mounted modulator is shown below in Fig. 3.

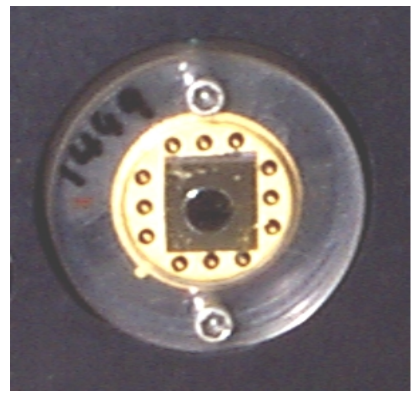

Figure 3. Fabricated MQW Modulator

An important characteristic of the modulator is the optical wavefront quality that can be maintained transmitting

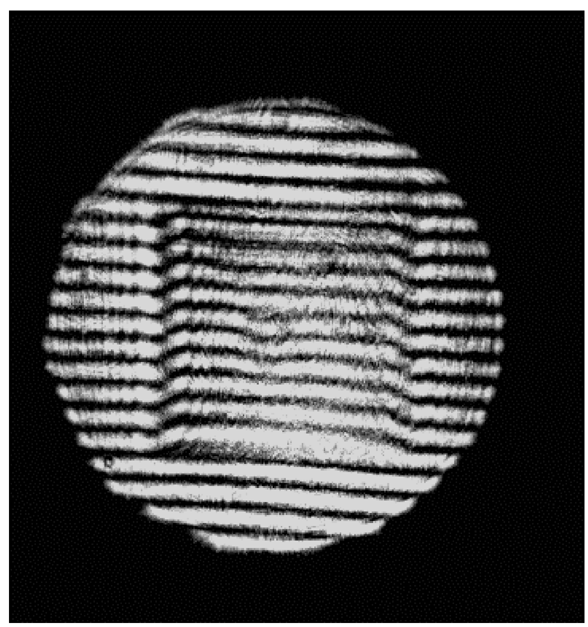

Figure 4. Interferogram of InGaAs modulator

through it. If the modulator abberates the beam, the returned optical signal will be attenuated and insufficient light may be present for the link. In Fig. 4 below we show an infrared interferometric measurement of a 1-cm piece of the InGaAs modulator. As can be seen its optical quality is good.

Unlike liquid crystal modulators, MQW modulators have very high switching speeds. Small devices have been operated at speeds in the tens of GHz. In practice the speed is limited primarily by the RC time of the device. Thus the large area devices we use for modulating retro-reflectors typically have speeds between 1 and 10 Mbps. Higher speeds are possible however, depending on range and the sophistication of the fabrication process. In practice data rates like these are appropriate for many of the sensors carried on the small platforms for which these devices are appropriate.

While a full set or radiation tests have not yet been performed on these devices we have done a preliminary experiment. A GaAs/AlGaAs and an InGaAs/AlGaAs modulator were characterized optically and electrically and then exposed to a 20 kRad does of 20 Mev protons. There was no effect upon the modulator characteristics. A more detailed set of tests is planned for the near future.

2. Bench-top link tests

Once fabricated the modulators are mounted onto a corner-cube retro-reflector and the bit-error rate performance of a bench-top link is characterized. The set-up is shown below in Fig. 5.

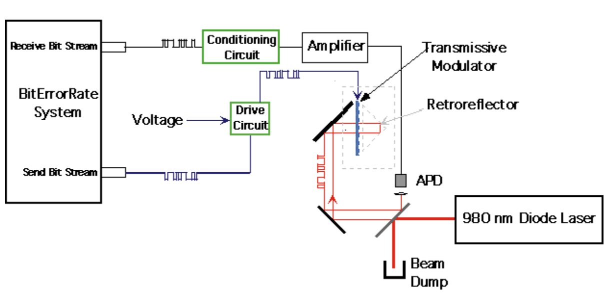

Figure 5. Bench-top Bit Error Rate test set-up

MQW modulators are inherently quiet devices, faithfully reproducing the voltage applied to them up to their RC response time limit. The bit error rate of a communications link that uses them depends primarily on the received photon flux, the noise in the receive circuit and the contrast ratio of the modulator. Typically the modulators we have fabricated have had contrast ratios between 1.75 to 1 to 4 to 1 depending on the structure. The contrast ratio depends upon the applied voltage, increasing as the voltage goes up until a saturation value is reached, typically at an applied voltage between 15 and 25 V. In Fig. 6 we show the BER measured in our bench-top set-up for a 1 Mbps link using an InGaAs modulator in which the photon flux was dropped down to the point where the signal was near the noise in the detector. The BER was then measured as a function of voltage applied to the modulator. As expected the BER drops as the voltage increases.

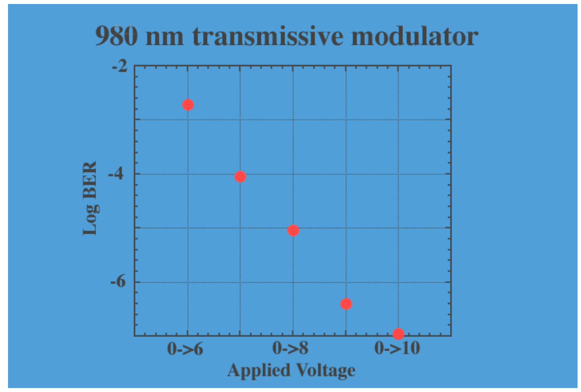

Figure 6 BER vs. Applied voltage

4. Field Test

Successful implementation of a modulating retro-reflector link requires the integration of the device onto a platform as well as the ability to place a narrow divergence laser beam onto the platform while in flight. As a first step in an operational modulating retro-reflector communications link we packaged a 0.5 cm diameter InGaAs MQW modulating retro-reflector and mounted it on a small rotary-wing unmanned airborne vehicle. The modulating retro-reflector

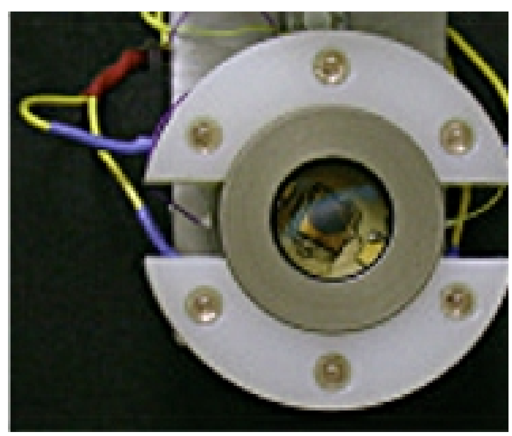

Figure 8. Modulating retro-reflector flight assembly

was placed on the tail of the UAV pointing down. Also mounted on the UAV was a camera, microprocessor, frame grabber and electrical drive circuitry for the modulator. The microprocessor could be programmed to send a pseudo-random bit stream to the modulating retro-reflector.

Figure 7 below shows the UAV, which is about 1 meter long.

Figure 7 The UAV

The modulator used in the demonstration was a 75 period InGaAs/AlGaAs MQW with an exciton resonance at 981 nm. The modulator was affixed to a mount centered above a corner-cube retro-reflector. Wire bonds to the p and n contact layers on the modulator were used to bias the modulator. The modulator/retro-reflector assembly, shown below in Fig. 8, was also ringed by infrared LEDs that were used to provide a beacon for acquisition and tracking of the UAV.

In addition to the modulator the UAV carried video and driving electronics. The challenge in the design of the payload electronics was to design a flexible payload that could meet the unique requirements of our demonstration

- harsh environment: vibration, oil mist, shock

- light weight,

- small outline

The modulator used in our UAV setup requires an ~ 15 Volt swing to achieve a sufficient optical contrast between the on and off states. Electrically the modulator can be modeled as a ~ 2 nF capacitor in series with a ~ 5Ω resistor. The drive circuitry consists of a 15 - 17 volt power source, the Elantec 7202 driver and a 0.1 μF bypass capacitor. The Elantec part was chosen for its ability to drive a capacitive load at 1 - 10 MHz.

A FPGA is used to encode the data. In addition, the FPGA performs framing functions on the data, generation of the pseudo random code for bit error tests and the encoding of the video data needed for DC balance. The user can modify the FPGA quickly to change encoding method, to add error correction, to change the frame format, etc.

An off the shelf frame grabber card collects the video data and prepares it for transport. The card receives an NTSC signal from an on board camera and passes the data via the PC/104 bus to the FPGA card.

The payload electronics for the modulating retro experiment are broken into two sections. The modulator and its drive electronics and the electronics used for generating and encoding data. We chose a PC/104 form factor for the data generating and encoding electronics because of the ample supply of off the shelf PC/104 cards available on the market. These cards both meet the stringent requirements of cost and vibration survivability as well as enabling the user to make quick changes in the lab and the field. The PC/104 stack consists of a FPGA card that is used to encode, frame and send the data to the modulator, a frame grabber card which collects video data from a camera and a x86 class card. The x86 card, which runs Linux, is used to boot the FPGA card, to run scripts, to collect and store video data and to provide a communication link to the outside world via a PPP link connected to the serial port.

This setup created a very flexible platform that can be quickly be re-configured to meet requirements of different tests. This platform can be used to test any new configurations before implementation in a small and compact package.

To close the optical link a cw laser must illuminate the UAV, and the returned optical signal must be collected and focused onto a detector. We used a very simple optical configuration. A 100 mW distributed Bragg reflector laser diode operating at 976 nm was fiber coupled to a collimator. The beam was collimated to a relatively broad divergence of 3 milliradians to avoid laser safety issues with low flying aircraft. The outgoing beam passed through a 3-inch diameter 50 percent beam splitter. Half the light went out and half went into a beam dump. The retro-reflected light was reflected by this beam splitter to a 2-inch diameter lens where it was focused onto a silicon avalanche photodiode. A 10 nm bandwidth optical filter was used to remove background sunlight. The resulting signal was amplified by a 3 MHz bandwidth amplifier and read out on an oscilloscope or fed into a computer for video reconstruction. The optical set-up is shown below in Fig. 9

The optical assembly was mounted on a motorized gimbal to allow for active tracking of the UAV. The entire video tracking system utilized for the modulating retroreflector demonstration contains two subunits. The first is a DBA Systems Video tracker with a computer controller. A Dell Laptop serves as the controller, and it communicates with the tracker over an RS 232 line. The second system consists of a Sagebrush pan-and-tilt gimbal controlled by another Dell laptop computer via RS 232. The gimbal contains the optics along with two cameras. The tracking camera is a narrow FOV Supercircuits CCD camera with an 830 nm long pass filter and an 880 nm bandpass filter. The visual acquisition camera is a wide FOV miniature CCD camera from Marshal Electronics. This camera is unfiltered. The UAV carries a six element, 880 nm LED array surrounding the modulator. Light is emitted from this array at a half angle of 15^{o}. This array serves as a beacon for the tracking camera.

The tracker controller sets the tracking threshold and gate area along with the line-of-sight offset. This offset is picked to maximize return from the modulator. It then commands the tracker to work in "Auto Track" mode, which causes the tracker to begin tracking a target as soon as it is acquired without further command. Once the tracker is set up for the demonstration, changes through the computer controller are no longer needed.

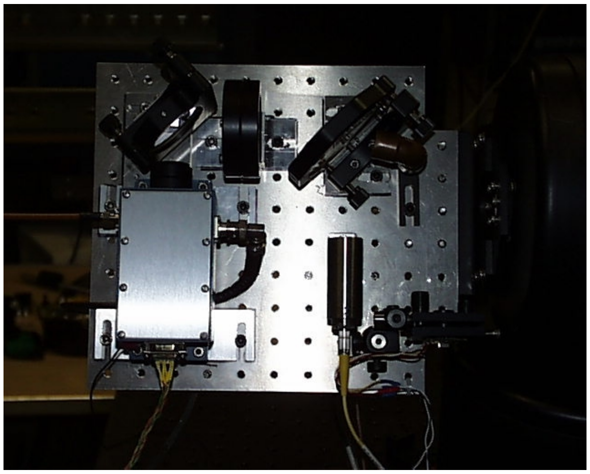

Figure 9 Optical transmit receive assembly

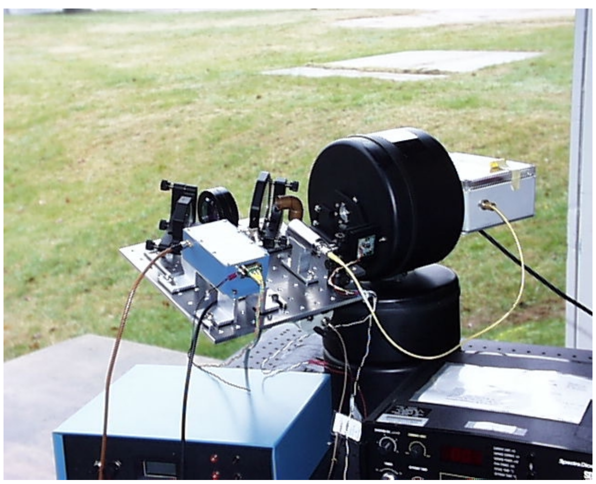

Figure 10 Telescope with pointer/tracker

The tracking software begins in manual mode. In this mode, the user moves the gimbal using the computer mouse or joystick. The operator uses the acquisition camera to find the UAV target. Once the tracker acquires the target, it begins to track it, and it sends a TTL signal to the gimbal controller. This signal is fed to the computer through a National Instruments analog to digital data acquisition board. Once the computer receives the "On Track" signal, it will automatically enter the software track loop when the user releases the mouse or joystick.

When the tracker achieves track on the target, it maximizes all of the pixels above the threshold set by the controller. It then finds the centroid of these maximized pixels and calculates the offset of the centroid from the line-of-sight point. The tracker outputs a voltage on each of two lines. One line corresponds to azimuth offset, and the other line corresponds to elevation offset. Both lines vary from –5V to +5V, and the signal is linearly related to the distance of the centroid from the line-of-sight point on each axis. Zero V corresponds to the line-of-sight point (i.e. no offset), and a maximum signal corresponds to the edge of the tracking gate. The tracker updates these voltages at a 60 Hz rate.
The entire transmit/receive assembly is shown in Fig. 10.

We have conducted one field test using this system. The on-board computer was programmed to drive the modulator with a 400 Kbps pseudo-random bit stream. The UAV was flown at an altitude of 50-100 feet and a range of 100-200 feet from the transmit/receive laser. The conditions for the test were somewhat adverse with a light rain, fog and low visibility. Nonetheless, due to the short range and the infrared wavelength of the laser no atmospheric effects were observed.

In flight, the angle between the laser and the UAV changed rapidly due to the short range. In addition the attitude of the UAV also changed rapidly. Despite this we received a strong return signal as long as the laser beam fell into the acceptance angle of the retro-reflector, approximately 20 degrees. The beam returned from the modulating retro-reflector had a divergence of approximately half a milliradian but was passively directed back to the transmit/receive assembly without any need for pointing on the UAV. Future test will use an array of retro-reflectors to broaden the acceptance angle.

An optical return from the test is shown if Fig. 11. The modulation rate is 400 Kbps, but the modulator and detector bandwidth and the returned signal level were sufficient for a 3 Mbps link. The modulator consumed 40 mW of electrical power at this modulation rate.

Further tests will demonstrate higher data rates and video transmission from the UAV.

5. Conclusion

We have shown that a multiple quantum well based modulating retro-reflector can enable a very small platform to passively close an optical data link. The use of such modulators can allow much higher bandwidth communications than such platforms are usually capable of. In addition the link is both covert, very difficult to jam and immune from the frequency congestion problems to which RF communications are susceptible.

Many applications will require much longer range links than we have demonstrated. Such links will require narrower outgoing beam divergence and larger receive telescopes.

The effect of the atmosphere will also play a much larger

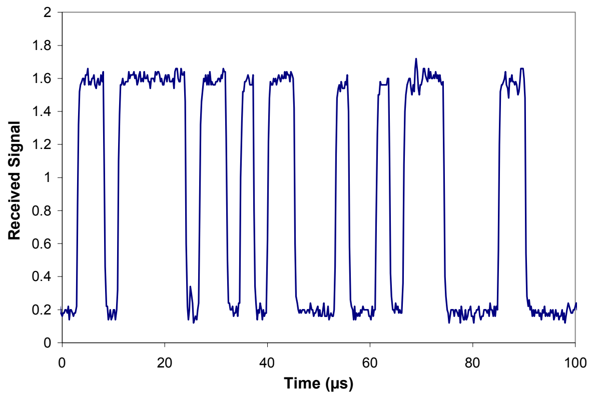

Figure 11 . Optically returned data stream from the UAV in flight

role in long distance terrestrial links. Nonetheless, link analyses based upon this technology show that with modest power lasers terrestrial links with ranges of tens of kilometers and data rates from 1 to 10 Mbps are possible. An optical communications link is always susceptible to cloud cover and heavy rain or fog. But many applications for this device, such as surveillance, are often done in clear weather conditions or below the cloud deck. In addition, air to UAV data links may avoid these problems. Modulating retro-reflectors may also be useful as communications relays. An interesting benefit of this technology is that, unlike conventional optical communications, it is not necessarily point to point. One modulating retro-reflector can be interrogated simultaneously by many lasers, allowing one node to distribute information to many sites.

For space to space applications, where the atmosphere does not play a part possible ranges for retro-reflector links increase to a few hundred kilometers for flyable lasers and telescopes.

As small platforms proliferate in both scientific and military applications we believe that modulating retro-reflector systems will find many applications for communications.

Acknowledgements

The authors acknowledge the support of the Office of Naval Research.

6. Reference

[1] Charles M. Swenson, Clark A. Steed, Imelda A. A. DeLaRue, and Robert Q. Fugate, "Low power FLC-Based Retromodulator Communications System", SPIE Proceedings 2990, pp. 296-310 (1997)

[2]G. Charmaine Gilbreath, W. S. Rabinovich, Rita Mahon, D. S. Katzer, K. Ikossi-Anasatasiou, Michael R. Corson, John F. Kline, Joshua Resnick, H. C. Merk, Michael J. Vilcheck, "Modulating retro-reflector architecture using multiple quantum wells for free space optical communications", Proc. SPIE Vol. 3491, p. 581-586, December 1998.

[3] D.A.B. Miller, J. S. Weiner and D. S. Chelma, IEEE J. Quantum Electron., QE-22, 1816 (1986)

7. Biography

William S. Rabinovich was born in New York, NY in 1961. He received a B.S. in Physics from the State University of New York at Stony Brook in 1982, an M.S. in Physics from Brown University in 1984 and a Ph.D. in Physics from Brown University in 1987. He has been with the Optical Science Division of the U. S. Naval Research Laboratory since 1987. His research interests include optical properties of semiconductor nanostructures and free-space optical links.