Performance of Cat's eye modulating retro-reflectors for free-space optical communications

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ABSTRACT

Modulating retro-reflectors (MRR) couple passive optical retro-reflectors with electro-optic modulators to allow free-space optical communication with a laser and pointing/acquisition/tracking system required on only one end of the link. In operation a conventional free space optical communications terminal, the interrogator, is used on one end of the link to illuminate the MRR on the other end of the link with a cw beam. The MRR imposes a modulation on the interrogating beam and passively retro-reflects it back to the interrogator. These types of systems are attractive for asymmetric communication links for which one end of the link cannot afford the weight, power or expense of a conventional free-space optical communication terminal. Recently, MRR using multiple quantum well (MQW) modulators have been demonstrated using a large area MQW placed in front of the aperture of a corner-cube.

For the MQW MRR, the maximum modulation can range into the gigahertz, limited only by the RC time constant of the device. This limitation, however, is a serious one. The optical aperture of an MRR cannot be too small or the amount of light retro-reflected will be insufficient to close the link. For typical corner-cube MQW MRR devices the modulator has a diameter between 0.5-1 cm and maximum modulation rates less than 10 Mbps. In this paper we describe a new kind of MQW MRR that uses a cat's eye retro-reflector with the MQW in the focal plane of the cat's eye. This system decouples the size of the modulator from the size of the optical aperture and allows much higher data rates. A 10 Mbps free space link over a range of 1 km is demonstrated. In addition a laboratory demonstration of a 70 Mbps MQW focal plane is described.

Keywords: Modulating retro-reflector, Retromodulator, Free space optical communication, Quantum well modulator, Cat's eye

1. INTRODUCTION

1.1. Modulating retro-reflectors

Modulating retro-reflectors (MRR) couple passive optical retro-reflectors with electro-optic modulators to allow long-range, free-space optical communication with a laser and pointing/acquisition/tracking system required on only one end of the link. In operation a conventional free space optical communications terminal [1], the interrogator, is used on one end of the link to illuminate the MRR on the other end of the link with a cw beam. The MRR imposes a modulation on the interrogating beam and passively retro-reflects it back to the interrogator. These types of systems are attractive for asymmetric communication links for which one end of the link cannot afford the weight, power or expense of a conventional free-space optical communication terminal. The MRR demonstrated to date have used a large area modulator placed in front of the aperture, or as one of the faces, of a corner-cube retro-reflector. MRR based on ferro-electric liquid crystals [2], MEMS devices [3] and multiple quantum well (MQW) electro-absorption modulators [4], [5] have been demonstrated recently

For both the liquid crystal and MEMS devices the maximum modulation rate is set by the intrinsic switching speed of the material, which are tens of KHz and hundreds of KHz respectively. For the MQW MRR however, the maximum

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modulation can range into the gigahertz, limited only by the RC time constant of the device. This limitation, however, is a serious one. The optical aperture of an MRR cannot be too small or the amount of light retro-reflected will be insufficient to close the link. For typical MQW MRR devices the modulator has a diameter between 0.5-1 cm and maximum modulation rates less than 10 MHz. This size device is sufficient to close a link at this rate at ranges over ten kilometers, depending on atmospheric conditions and the interrogator.

Recently we have developed a new kind of MRR that uses cat's eye retroreflectors and places the modulator in the focal plane of the cat's eye optic. In this paper we discuss different forms of cat's eye MRRs and their relevant figures of merit.

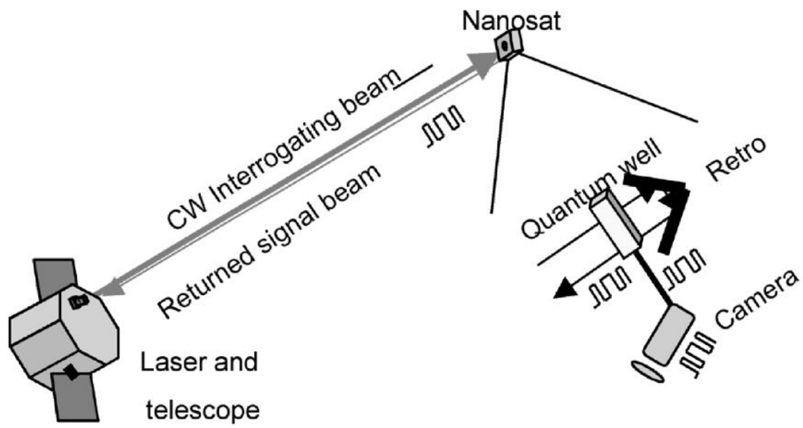


Figure 1. A modulating retro-reflector link

1.2. Modulating retro-reflector links

Modulating retro-reflector links have similarities and differences from conventional free space optical links. As with conventional links, MRR links depend on laser power, beam divergence, pointing accuracy and receiver diameter, but for an MRR link these parameters are all determined by the interrogator. Unlike conventional free space optical links, MRR links must transit the atmosphere twice, so atmospheric attenuation is higher and in addition they fall off as $1/R^4$ instead of $1/R^2$. The MRR parameters that affect the link are the MRR's optical antenna gain, its modulation efficiency, and it modulation bandwidth.

To overcome, its large propagation losses the MRR must exhibit a high optical antenna gain (also called its optical cross-section). The MRR acts as a receiver, intercepting the light of the interrogator, and a transmitter, remitting the light as its retro-reflects it. Thus its optical antenna gain is the product of the classical formulas for receiver gain and transmitter gain. The retro-reflector antenna gain is

$$G_{MRR} = \left[\frac{\pi D_{retro}}{\lambda}\right]^4 S \tag{1}$$

where D_{retro} is the optical aperture of the retro-reflector, λ is the wavelength of light and S is the Strehl ratio of the optic. As can be seen the gain has a very strong dependence on retro-reflector aperture. In fact since both the antenna gain and the range dependence scale as fourth powers, doubling the aperture of an MRR doubles its range. It is also important to maintain near diffraction limited performance from the optic.

In considering an MRR link it is important to consider the nature of the optical receiver used on the interrogator terminal. At data rates of a few Mbps, typical optical telecommunication detectors such as Erbium pre-amplified photodiodes do not work effectively. Instead InGaAs PIN diodes or avalanche photodiodes are used. As a result the noise in the optical receiver is generally dominated by the noise of the electronic pre-amplifier circuit. Unlike quantum limited systems in which the noise level increases as the optical contrast ratio decreases the noise level in this case is independent of the optical contrast ratio. The optical signal to noise ratio (OSNR) can then be defined as,

$$OSNR = \frac{P_{On} - P_{Off}}{P_{noise}} = P_{\mathrm{Re}t} \frac{e^{-\alpha_{On}} - e^{-\alpha_{Off}}}{P_{noise}} \quad (2)$$

where P_{On} is the optical power returned by the MQW MRR when it is in its on-state, P_{Off} is the power returned in the off-state, P_{noise} is the noise equivalent power of the detector, P_{Ret} is the optical power returned by the MRR excluding losses in the MQW modulator, α_{On} is the double-pass absorption-length product of the MQW in it's on-state and α_{Off} in its off-state. From equation 2 it can be seen that maximizing the OSNR depends on both the optical contrast ratio and the optical transmission of the MQW. This can be seen more clearly by defining a figure of merit for the MQW, its modulation efficiency,

$$M = e^{-\alpha_{On}} - e^{-\alpha_{Off}} = e^{-\alpha_{Off}} \cdot \left[C_{MQW} - 1\right] \quad (3)$$

where M is the modulation efficiency and CMQW is the optical contrast ratio of the MQW. The OSNR of an MQW MRR link is then simply MP_{Ret}/ P_{noise}.

Given an MRR's antenna gain and modulation efficiency, an MRR link can be expressed in terms similar to a conventional optical link as

$$P_{sig} = P_{Las} G_T L_T L_R T_{atm} G_{MRR} L_{MRR} M L_R T_{atm} G_{\mathrm{Re}c} L_{rec} \quad (4)$$

where P_{sig} is the retro-reflected signal power. Conventional definitions are used for G_T, the optical antenna gain of the interrogator's transmit optics, L_T, the loss in the transmit optics, $L_{R,}$, the free space propagation loss, T_{atm}, the atmospheric transmission, L_{MRR} the optical loss of the MRR excluding modulator loss, G_{rec}, the optical antenna gain of the receiver on the interrogator and L_{rec}, the optical losses in the receiver.

The strong dependence of the MRR optical antenna gain on aperture motivates using a large aperture retro-reflector. But for corner cube based MRRs the modulator diameter must equal the retro-reflector aperture. For multiple quantum well modulators, as well as many other types of modulators, the maximum modulation rate drops, and the maximum power consumption increases as the modulator capacitance goes up. The capacitance is directly proportional to the area, so larger modulators are slower and more power-hungry. It is possible to speed up a modulator up by sub-dividing it into pixels and driving the pixels separately, but this does not decrease the power draw. This power consumption can become large for high data rates and the heating it induces in the MQW may distort the retro-reflected beam ruining the link.

1.3. Cat's eye modulating retro-reflectors

Given the scaling rules described above there is an obvious problem in achieving long range, high data rate MRR links. These links require high MQW modulation speed, driving one towards smaller modulators, while at the same time requiring a higher retro-reflected optical signal, driving one towards larger optical apertures. This is impossible for a corner-cube based MRR for which the modulator size must equal the optical aperture.

One idea that suggests itself is using a lens to increase the optical aperture. It should then be possible to place the modulator in the focus of the lens and maintain a larger optical aperture and a small modulator aperture simultaneously. However, any optics added to the MRR must have several characteristics, two of which are:

1. An MRR must preserve the retro-reflective properties of the system.

2. An MRR should have as high an optical antenna gain as possible.

3. Most MRR systems need a wide field of view to be of application interest.

A class of optical systems called cat's eye retro-reflectors can provide these characteristics if properly designed.

There is no one form of cat's eye retro-reflector, but all contain some sort of focusing optics. A classic form for a cat's eye is shown below in Figure 2.

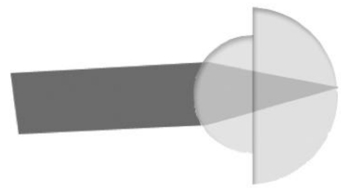


Figure 2. A spherical cat's eye retro-reflector

While this kind of cat's eye has a large field of view (FOV) it also has very large spherical aberration thus violating characteristic 2. This aberration can be avoided by using the optic at high f number (about f/10). This, however, leads to a problem maintaining characteristic 3. If the cat's eye MRR is to operate over a wide field of view, then a high f-number optic implies a large modulator in the focal plane. This is because the focal spot will move as the angle of incidence changes. The range of motion of the spot determines the modulator size,

$$D_{\text{mod}} = f\#D_{retro}\theta_{retro} \tag{5}$$

where D_{mod} is the modulator diameter, f# is the f-number of the cat's eye and θ_{retro} is the FOV that the cat's eye must work over.

Since we'd like to keep the modulator as small as possible this leads to a fourth desirable characteristic for a cat's eye optic:

4. A cats' eye MRR must have as low an f number as possible.

Even a sophisticated cat's eye optic will have an f-number of about 2. If the optic is to cover the same field of view as a corner cube (about 0.5 radians) then $D_{mod}=D_{retro}$, the same situation as with a corner cube. However, a cat's eye MRR can offer two advantages: If the required FOV is not large a cat's eye MRR can have a small modulator, whereas the modulator size for a corner cube MRR is independent of the FOV. Second, while the focal spot does wander over a large area for a wide FOV, it only covers a small part of the focal plane at any one time. Thus if the angle of arrival can be determined, and if the modulator is divided into sub-pixels, then only a small part of the modulator needs to be driven at any one time, greatly reducing the power draw.

This is because the focal spot of the cat's eye will move as the relative angle between the MRR and the interrogating laser changes. There are several ways to deal with this motion that will be described below, but in all cases it is desirable for the range of possible focal spot positions to be as small as possible. The focal plane size will be proportional to the field of view of the MRR and its focal length. Since we want as large an aperture as possible, we need a low f number to keep the focal length short.

2. CAT'S EYE OPTICS

2.1. Telecentric cat's eye retro-reflectors

Any cat's eye optic will involve some compromises of desirable characteristics versus cost, size, complexity and weight. A very simple cat's eye optical system uses a telecentric lens coupled to a flat mirror in its focal plane. As shown in Figure 2 the telecentric condition assures retro-reflection because, over the effective FOV, a symmetric ray bundle is produced in the focal plane regardless of the input angle of the beam. The flat mirror in the focal plane, when oriented normal to the axis of the lens then inverts the ray bundle so that it retro-reflects.

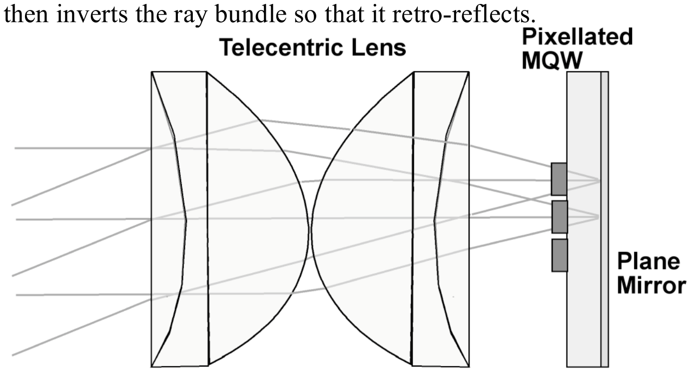


Figure 3. A telecentric cat's eye modulating retro-reflector

This form of cat's eye has several advantages. It is based on telecentric lenses, which are commonly available, and, in addition, it has a flat focal plane. That means that the mirror can be made by coating the back surface of an MQW modulator with metal making integration simple. Its primary disadvantage is its low Strehl ratio of about 0.06, reducing its optical antenna gain. It also has a moderate field of view of about 20 degrees.

We constructed a telecentric cat's eye MRR using a 1 cm aperture Plossl objective. A photograph of the device is shown below in figure 4.

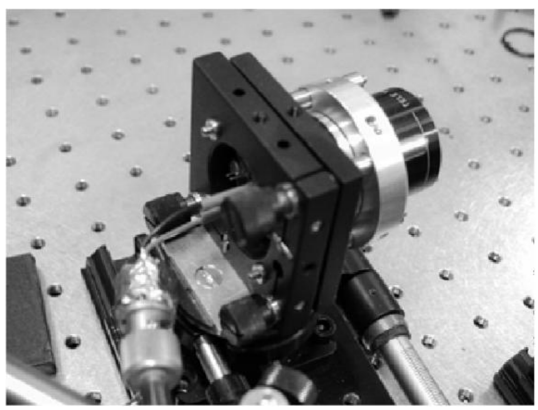


Figure 4. Prototype telecentric cat's eye modulating retro-reflector

2.2. Aspheric curved focal plane diffraction limited cat's eye retro-reflector

When optimum performance for a cats' eye MRR is desired a custom optic must be designed. There are many different sorts of designs that are possible each emphasizing different metrics. We developed a lens based on catadioptric[6] design optimized for wavelengths around 1.55 µm. The objective consists of four refracting elements. The first surface of the first refracting element is parabolic, all other surfaces are spherical. The aperture stop is between the second and third elements, and the secondary mirror acts as the field stop in the system.

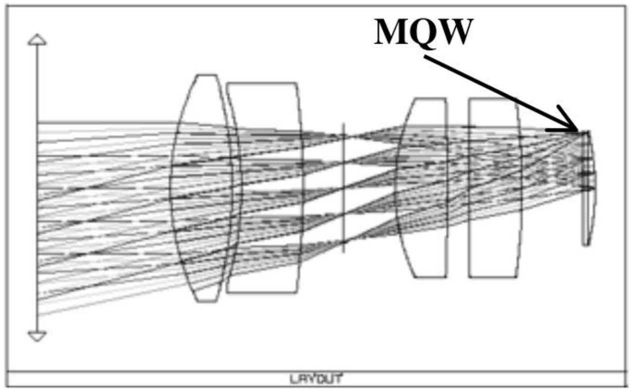
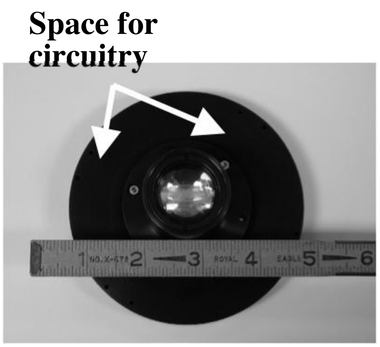


Figure 6. Ray trace of the diffraction limited cat's eye.

When used as an MRR, a transmissive modulator inserted just in front of the secondary mirror would serve as the field stop. Unlike the telecentric cat's eye described above this optic uses a curved reflector. In this case then the MQW must be transmissive and placed in front of the back mirror.

A ray trace of the optic is shown in figure 6. It provides diffraction limited return over a 30 degree FOV with little vignetting. The effective f number of the system is f/2. The focal plane size necessary to cover the entire FOV is about 1.4 cm. While the system is not telecentric, the combination of the refractive elements and the curved reflector produce a system that is in effect locally telecentric.

We fabricated this optic including a housing with space for focal plane circuitry. A photograph of the diffraction limited cat's eye MRR is shown in figure 7.



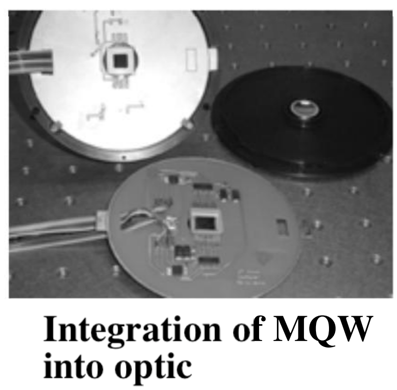


Figure 7. Fabricated diffraction limited cat's eye optic and circuitry housing

The optical performance of the cat's eye was evaluated using an optical interferometer. A flat wavefront was sent into the optic and an interferogram of the retro-reflected beam was recorder as a function of incident angle. Over the full FOV the retro-reflected wavefront was flat, indicating near-diffraction limited performance. Interferograms at normal incidence and 6 degrees off normal incidence are shown in figure 8.

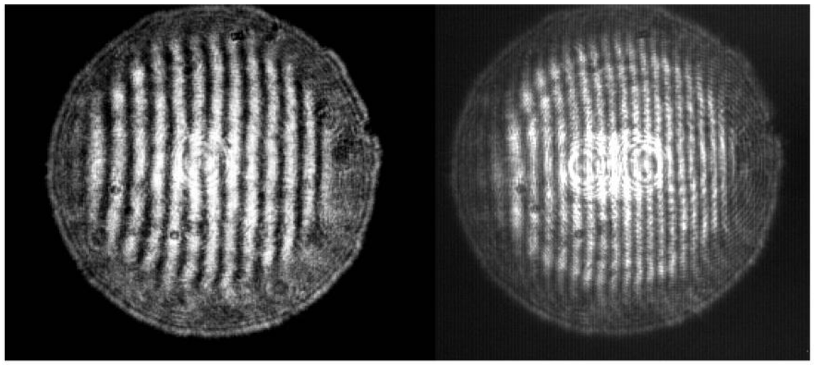


Figure 8. Optical interferograms of the cat's eye optic at various angles of incidence

2.3. Aspheric flat focal plane diffraction limited cat's eye retro-reflector

The curved focal plane optic has many desirable properties but the necessity of using a transmissive modulator in front of the back mirror can be limiting. Using a flat focal plane device such as the telecentric lens described in section 2.1, the modulator can be used as the back mirror allowing both easier addressing of pixels and, as will be described below, better heat dissipation.

We have combined the desirable properties of both the telecentric optic and the aspheric curved focal plane optic and fabricated an aspheric flat focal plane cat's eye. The design has a 1.6 cm effective aperture and diffraction limited performance. The design does involve some compromises. This optics field of view is only 20 degrees, not 30 as with the curved focal plane optic. In addition, it is an f/3 optic, requiring a larger modulator focal plane to cover the same field of view.

Design of flat focal plane cat's eye MRRs puts an additional restriction on the modulator. Since the modulator is used as the back mirror its flatness becomes important in determining the Strehl ratio of the system. This is particularly critical for this design, since it is near diffraction limited. For MQW modulators it is easier to preserve wavefront flatness using a transmissive modulator than a reflective modulator. This is because stresses that might bend the wafer have little effect on the optical path length of the wafer but can have strong effects on its radius of curvature when used in reflection. We are currently evaluating the performance of this optic to examine these and other effects. A photograph of the assembled optic and modulator plane is shown in figure 9. In addition we have fabricated a smaller version of this optic with a 1 cm aperture. The smaller optic has a lower f/-number of 2.4.

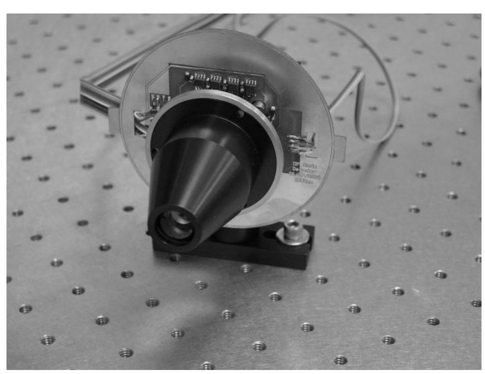


Figure 9. Aspheric flat focal plane cat's eye with MQW modulator plane

2.4. Summary of optical properties of cat's eyes

Design	Aperture	f/#	G_{retro}	Field of view	Focal plane
Telecentric Plossl	1 cm	4	160 dB	20°	Flat
Aspheric Curved	1.6 cm	2	179 dB	30°	Curved
Aspheric Flat	1.6 cm	3	179 dB	20°	Flat
Aspheric Flat	1 cm	2.4	171 dB	20°	Flat

Table 1. the optical characteristics of various cat's eye retro-reflector designs

3. MULTIPLE QUANTUM WELL FOCAL PLANE

3.1. Multiple quantum well modulators

Many types of modulators are possible for cat's eye MRRs. In general practical systems will require modulator technologies that allow for wide-angle surface normal operation and the ability to configure compact, power efficient arrays that can cover areas of about 1 cm for wide field of view operation.

Wide-angle surface normal operation is needed because good cat's eye optics will have low f-numbers, implying a broad ray bundle at the focal plane. In addition if a wide *system* field of view is desired then the modulator focal plane will extend over 1-2 cm for an optical aperture on the order of a centimeter. To allow high speed operation, an array of modulators will be needed.

At low data rates (~Kbps) both MEMS and liquid crystal technology are attractive. Both of these modulators types can be used in surface normal arrays.

At higher data rates (Mbps and up), both these technologies become limited by their intrinsic switching speeds. We have investigated surface normal MQW modulators for these data rates. MQW modulators are limited only by their RC time up to Gbps. They are thus ideally suited for cat's eye MRRs since the cat's eye allows a design trade of pixel size (and hence drive complexity) versus RC time (and hence data rate). We have used absorptive surface normal MQW modulators instead of two other approaches: waveguide modulators and asymmetric Fabry-Perot MQW modulators. Waveguide modulators offer high speed and high contrast ratio, but are almost impossible to efficiently configure into large area arrays, thus limiting the system FOV. Asymmetric Fabry-Perot MQW modulators can be configured into large area arrays and offer high contrast, but do not have wide field of view operation, limiting the choice of cat's eye optics to high f-numbers.

3.2. MQW Modulator Focal Plane for Cat's eye MRRs

We have used an NRL designed coupled well MQW modulator that can run at less than 5 V of drive and produce a 2:1 contrast ratio and MQW modulation efficiency, M, of about 0.25. The low drive power is critical to reduce both the power consumed and the heat load produced by the MQW array, which scales as V^2. An 8 mm x 8 mm array was fabricated for the focal plane. This is sufficient to cover an FOV of 17 degrees in the aspheric curved focal plane cat's eye and about 10 degrees in the aspheric flat focal plane cat's eye.

An early version of this array had a maximum modulation speed of about 10 Mbps, primarily limited by contact and sheet resistance. We integrated that array into the curved focal plane aspheric cat's eye and close a 1 Km link at 10 Mbps at NRL's Chesapeake Bay lasercomm testbed. The retro-reflected data from that link is shown below in figure 10. To the best of our knowledge, this is the first long-range cat's eye MQW MRR data link ever demonstrated.

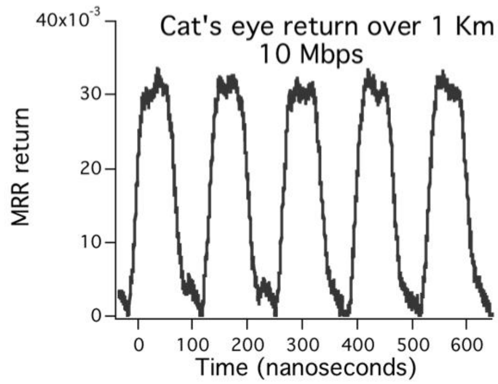


Figure 10. 10 Mbps retro-reflected data stream returned by the aspheric curved focal plane cat's eye MRR at a range of 1 Km.

We have continued to improve the array design of the 8 mm x 8 mm MQW array and have recently demonstrated in the laboratory a 8 mm x 8 mm array with a top data rate of about 70 Mbps. A waveform from this array taken on a probe station in a single pass geometry is shown in figure 11.

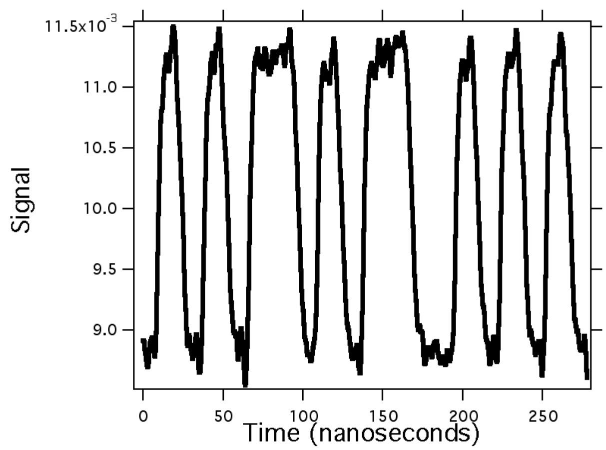


Figure 11. 70 Mbps data stream from a cat's eye array measured in the laboratory. The array was measured on a probe station in single pass mode. The contrast ratio in MRR operation would be the square of that shown here.

The high modulation rate attainable with a relatively few pixels indicates that cat's eye MQW MRR technology has the capacity to scale to very high bandwidths, while still maintaining simple construction and operation. However, other factors may limit modulation speed. Pixellating the focal plane and running those pixels with individual drivers does increase speed, but if the whole array is driven, does not decrease power consumption. The capacitance of the 8 mm x 8 mm array is about 3 nF. So if the entire array is driven with 5 V it consumes about 400 mW at 10 Mbps and about 3 Watts at 70 Mbps when the data signal is a square wave. When driven with an NRZ data signal, the power consumption is about half these values. This power consumption can result in considerable heating of the MQW array. Since the optical properties of the array shift with temperature and degrade at high temperatures (greater than 50 C) this self-heating is undesirable. The peak operating wavelength of an MQW modulator shifts at a rate of about 0.7 nm per degree C.

Several approaches can be used to minimize this self-heating. First better passive techniques can help. Figure 12 compares the wavelength shift of our original, slower, 8 mm x 8 mm array at different data rates for two different mounting approaches. The first uses conventional epoxy to attach the MQW to its carrier and the second uses a thermally conductive epoxy. The thermal conductive epoxy reduces self-heating by 60% indicating that the principle thermal impedance is from the MQW to its carrier. This impedance is further limited by the fact that the array was designed for the curved focal plane cat's eye and hence needed to be transmissive. As a result the thermal path from wafer to mount is only at the edges. A flat focal plane cat's eye would allow thermal contact over the entire wafer further reducing heating.

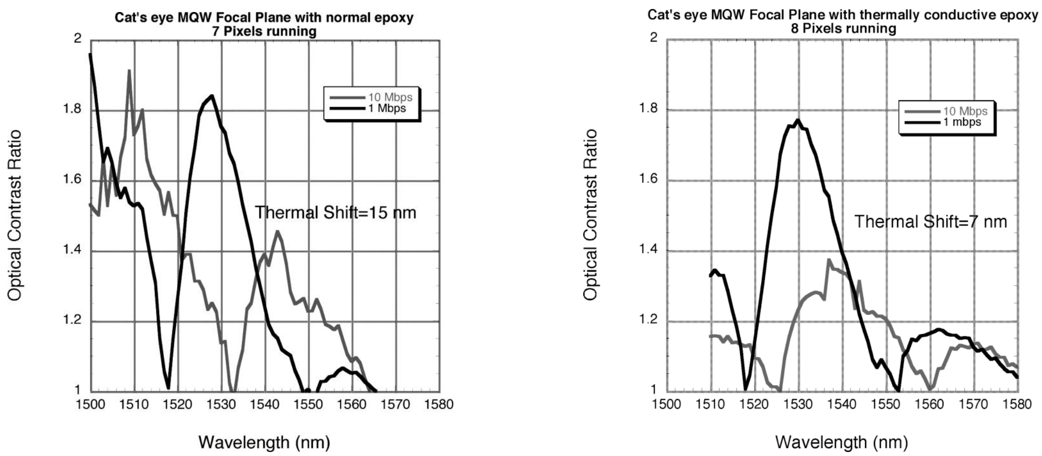


Figure 12 MQW Modulator self-heating demonstrated by shift in peak modulation wavelength as a function of data rate for two different mounting schemes.

Even with the more efficient heat sinking the modulator focal plane heats at a rate of 1.5 C/Mbps. Thus running at the full 70 Mbps rate of our newer array would cause about 100 C heating, an unacceptable amount. Heating can be further reduced by only driving that portion of the modulator array that the incoming interrogation beam is focused upon. This can be done by sensing the angle of arrival of the incoming beam and switching modulation to that area of the array. This approach has the possibility of reducing power consumption by an order of magnitude or more, allowing high speed operation. We are currently implementing such an angle of arrival sensing system for our cat's eye MRRs.

Another possibility is to actively cool the MQW focal plane. This solves many problems but comes at the expense of greater system power dissipation.

4. CONCLUSION

Cat’s eye multiple quantum modulating retro-reflectors have the potential to increase the maximum data rate of MRR systems by more than an order of magnitude over corner cube systems. This increased data rate comes at a cost of increased optical and in some cases MQW complexity. The form of a cat’s eye MRR depends a great deal on how it will be used and what field of view it must cover, but using the right combination optical and photonic components makes it possible to craft optimal solutions to a variety of problems.

The principle virtue of a cat's eye device is the greater flexibility to trade system parameters as compared to a corner cube MRR. In particular when used with an angle of arrival sensor, we can almost arbitrarily increase data rate without decreasing optical aperture or greatly increasing power, by using larger numbers of pixels in the focal plane. It is also possible to trade system field of view for speed without using a large number of pixels.

A cat's eye MRR can operate at a high data rate with few pixels if is field of view is restricted. This may be allowable in some applications (for example building to building communication) or if the MRR is mounted on a coarse tracking gimbal. This approach however can only be taken so far before it compromises one of the chief virtues of an MRR, the abilty to work with no moving parts over a wide field of view.

5. ACKNOWLEDGEMENTS

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