FM-MRR Analog Audio System

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ABSTRACT

In this work, we describe a hybrid free-space infrared communications link that supports audio transmission. The technique combines conventional frequency modulation (FM) techniques with optical amplitude modulation (AM) with a Multiple Quantum Well (MQW) Modulating Retroreflector (MRR) technology. The method has produced a robust, low power system capable of transmitting high quality audio information over a free space infrared link extending to multiple kilometers, depending on the characteristics of the Transmit/Receiver (interrogator) and the sensor/ MRR unit at the data source.

Key Words: Free space optical communications, retromodulators, modulating retroreflector, analog modulation

1. INTRODUCTION

Typical free-space optical communications links transmit data in a digital format. In the case of source data such as analog video or audio, the source information must be digitized and (typically) compressed prior to transmission. The process of digitizing the data significantly increases the required transmission bandwidth. Digital compression techniques can reduce this effect but at the cost of increased power requirements. Eliminating the need for digitization and compression at the sensor would result in significant savings in both bandwidth and power. In this paper, we describe a technique to use frequency modulation FM) to transmit audio over a near-infrared carrier to address both of these issues.

At the heart of NRL's studies in compact, low power free space data links is the optical modulating retroreflector. We use Multiple Quantum Well (MQW) shutters which are fast, lightweight, and require very low voltages to shift absorbance. The operation of theses devices are detailed in the literature (1-2). A brief description of how they work and are implemented is shown in Figure 1. Overall operation of the corner cube device is shown in 1(a). When a voltage is applied to the MQW shutter, the absorbance wavelength is shifted as shown in (b) enabling ON-OFF-KEYING. The MQW shutter in these experiments is on the order of 6.3 mm in diameter as shown in (c). These units can be mounted in an array to open up the field-of-regard. A mounted unit is shown in (d) where it is driven by a wavelet compression unit and an impedance matching circuit. The mounted retromodulator is 10 grams and requires ~50 mW to support 4-6 Mbps, 30 fps of color video across links of kilometers.

NRL is developing two different MRR architectures: Corner Cube MRRs (CCMRR) and Cats-Eye based MRRs (CEMRR) (3). The former supports up to about 10 Mbps and the CEMRR promises to support 100 Mbps and higher. Both draw comparatively low power, are small, and lightweight. In fact, in our video links, most of the power required to support realtime transmission through the atmosphere, is needed to support the digitizer. Ironically, in the CCMRR links, the modulator itself requires only ~50 mW to support 30 fps of compressed color video while the digitizer requires on the order of 4W. This imbalance motivated us to consider alternative modulation techniques. In Figure 2, we compare the power requirements needed by MRR systems using compressed digitized components at the sensor to those using analog modulation (AM and FM). As can be seen from the figure, analog modulation promises significant advantage. The MQW devices, however, suffer some nonlinearities which can distort a recovered signal and AM modulation in particular is susceptible to the effects of

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14. ABSTRACT
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the atmosphere on links. To that end, we investigate FM techniques to both reduce the power and weight burden at the sensor/MRR end of a link and to maintain viable signal-to-noise over an atmospheric channel.

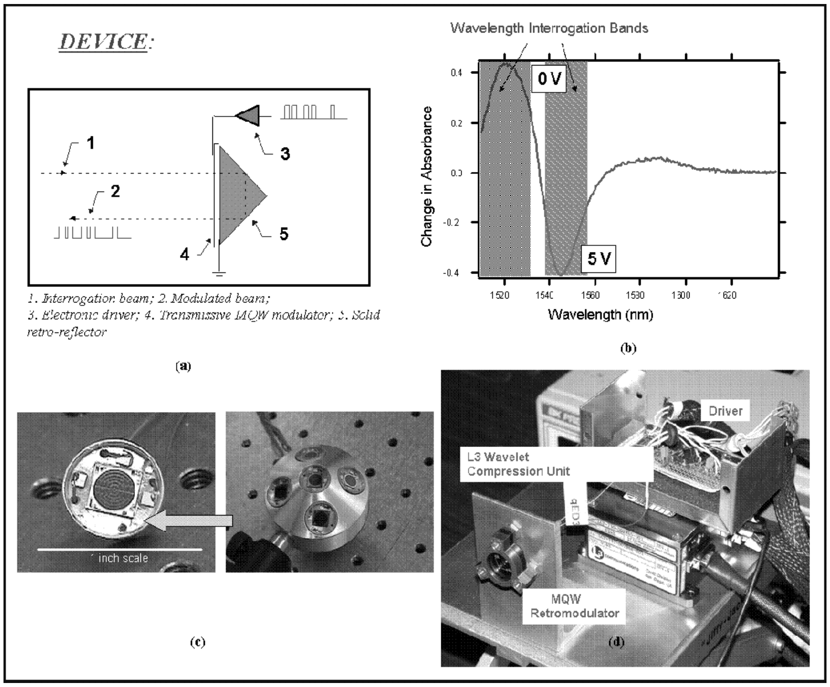

Figure 1. Multiple Quantum Well Corner Cube Modulating Retroreflectors (MQW-CCMRR): How they work.

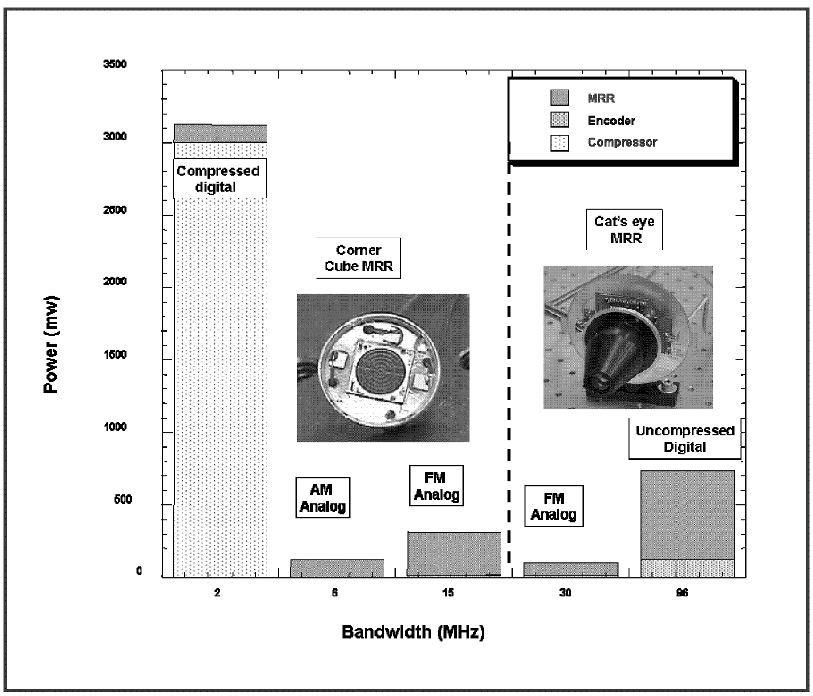

Figure 2. This comparison shows that digital compression is the dominant loading factor at the Sensor/MRR end of a given asymmetric link. Assumptions: transmission of real-time NTSC color video over a MQW CCMRR link with equivalent quality of service: Digital: 8 bits vs. Analog: 50 dB dynamic range. ***(Conversion: 8 bits x 6 dB/bit)***

3. EXPERIMENTAL CONFIGURATION

The FM-MRR audio system was tested in our lab using a 1 meter free space optical path. The input signal was taken from a PC sound card. Various types of audio signals were tested to determine the performance of the system including pure tones, human speech and music. The received signal was recorded on a second PC and output through a set of speakers. In addition, digital sound recordings were made for later analysis. Figure 3 shows the layout of the experiment.

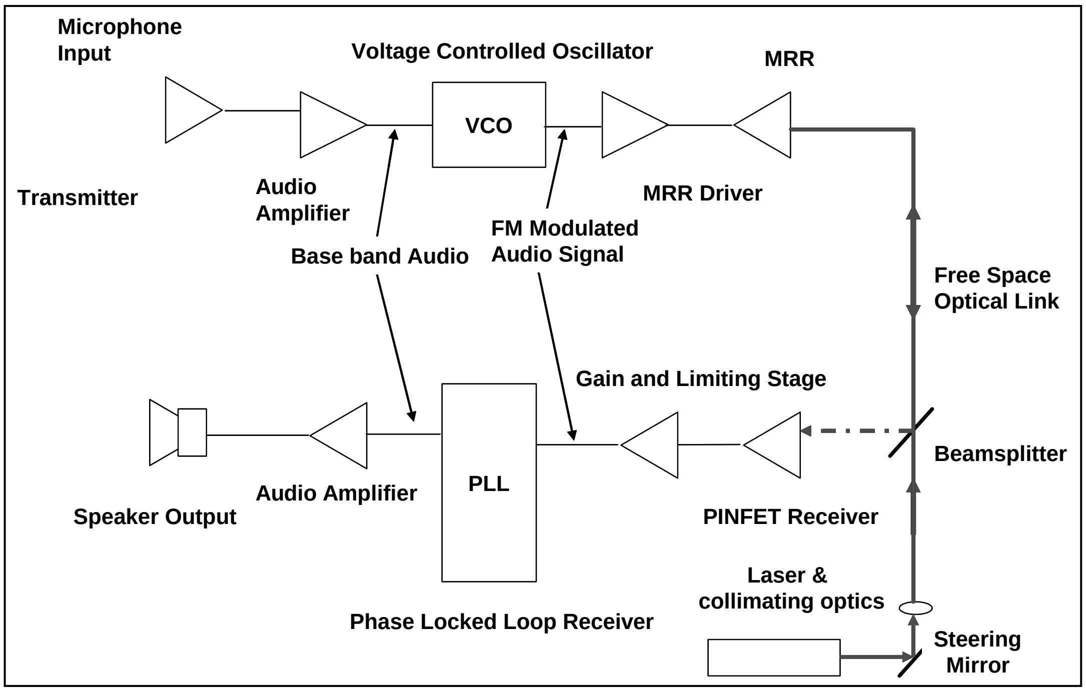

Figure 3: FM-MRR Audio System Block Diagram

The system is comprised of three major components: a transmitter module that converts the analog signal to FM and drives the MQW-MRR; an optical subsystem that includes the laser source and photodiode receiver, and a demodulator circuit that reconstructs the original signal from the received FM. As discussed above, the MQW-MRR functions as a shutter. The resulting retro-reflected optical signal is effectively ON-OFF keyed. This is ideally suited to transmitting a digital data stream. However, this property makes it nearly impossible to use the MQW-MRR as an analog amplitude modulator without introducing significant distortion to the signal. Such distortion requires a much more complex transmitter / receiver system to reconstruct the original signal.

In order to overcome the limitations of the MQW-MRR, an alternative method of encoding the analog signal had to be found. We chose to use a frequency modulation scheme similar to commercial FM radio transmission. However, there are several major differences between this approach and conventional FM. In a traditional FM system, the input is first converted to a frequency modulated signal by some form of voltage-to-frequency conversion. This FM signal is then impressed on a carrier frequency for transmission. In our case, the frequency modulated signal is used to drive the MQW-MRR directly. The result is an ON-OFF keyed optical signal with a varying frequency. The carrier signal is the amplitude modulated optical signal and the information is contained in the frequency of the AM carrier.

The transmitter is based on a simple voltage controlled oscillator (VCO). A VCO operates by generating an output frequency proportional to the input voltage. A typical frequency vs. voltage transfer curve for this type of device is shown in Figure 4.

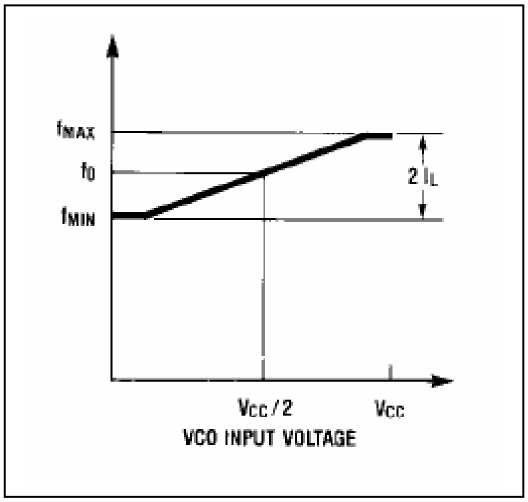

Figure 4: Typical VCO transfer function

The transmitter is based on a Fairchild 74VHC4046 CMOS device. In this case, we only used the VCO section of the chip. The receiver requires a minimum modulation frequency and we chose a center frequency of around 750 kHz with a maximum frequency deviation of approximately 30 kHz (see receiver discussion below). Thus, the minimum (f_{min}) and maximum (f_{max}) frequencies were 720 kHz and 780 kHz, respectively.

The audio input signal was amplified by OPA134 chip with a volume control. In order to obtain the best audio performance, the input signal required a peak-to-peak voltage of approximately 4.5V, within the input range of the VCO. By using the entire frequency range of the VCO, we minimized distortion and improved the signal-to-noise ratio. An example of voltages generated by the VCO which was used to drive the CCMRR is shown in Figure 5.

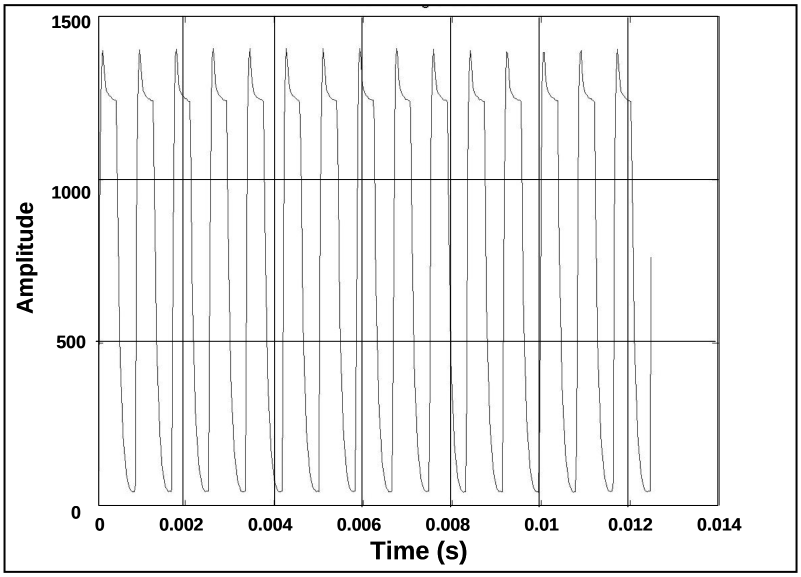

Figure 5. FM signal Waveform used to drive CCMRR.

We have used several different optical interrogator designs in our work with MQW-MRR devices. The Specifics of the optics depend largely on the intended range of the optical link. For this work, we used a simple lab bench system with a maximum range of about 10 meters The interrogator was a mono-static design where the transmit and receive portions share a single aperture. This is necessary due to parallax inherent in a short range link. The beam retro-reflected by the MQW-MRR returns along the path of the output beam. The transmit and receive beams are differentiated using a 50/50 beam splitter. A gold coated steering mirror eases alignment.

The laser interrogator was a fiber-coupled 1550 nm source with a maximum output of 1.5mW. The output of the laser was collimated. The return beam was captured by a lens and coupled into a single mode fiber which was pigtailed to a PINFET detector. The detector has a nominal bandwidth of 4 MB/s, and was AC coupled with a low frequency cut-off of approximately 200 kHz. The output of the PINFET detector was then coupled to the demodulator circuit.

The demodulator circuit was a simple phase locked loop (PLL). The circuit operates by comparing the phase of the received FM signal to an internal frequency reference. The resulting phase error signal is used to adjust the reference frequency, minimizing the error. We matched the modulator and used a Fairchild 74VHC4046 CMOS Phase Lock Loop chip. This chip contains both the phase comparator and frequency reference. Figure 6 below shows a block diagram of the 74VHC4046 (4).

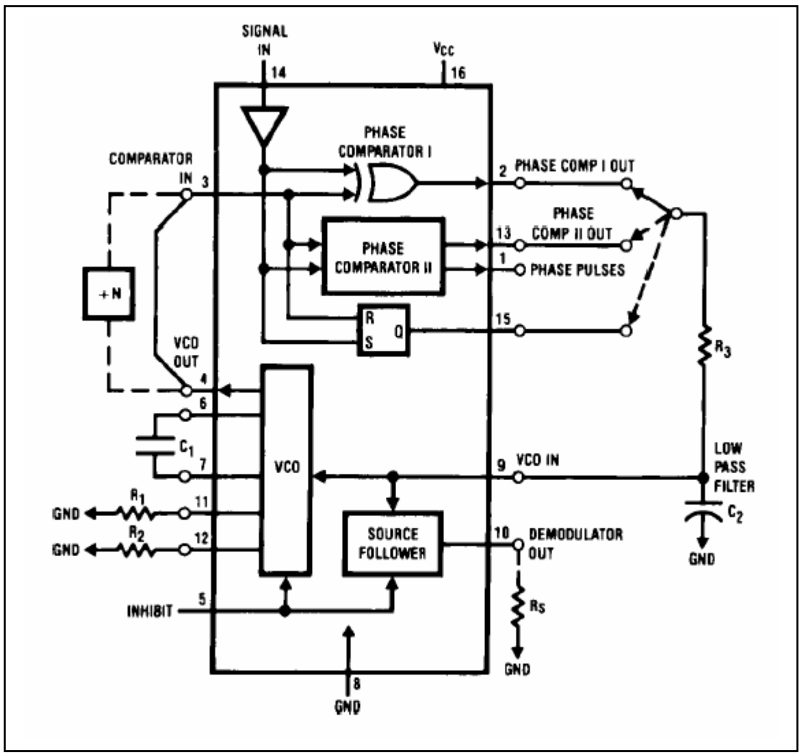

Figure 6. Block diagram of Fairchild 74VHC4046 (Ref. 4)

As the figure above shows, the 74VHC4046 consists of a phase comparator section and a voltage controlled oscillator (VCO) for the frequency reference. The circuit forms a complete FM receiver with the addition of a small number of passive components.

The VCO behavior is controlled by 2 resistors and 1 capacitor. Referring to the diagram above, R1 and C1 control the center frequency of the VCO. This is the output frequency when the input to the VCO is VCC/2. R2 controls the frequency offset. This is the minimum frequency the VCO will produce when the input to the VCO is 0 V. If R2 is omitted, the minimum frequency is essentially 0 Hz. For this experiment, we set the center frequency to approximately 750 kHz, which was compatible with the photodiode's low frequency cutoff of around 200 kHz and its being AC-coupled.

The VCO is driven by the output of the phase comparator after being low pass filtered. R3 and C2 control the cutoff frequency of the filter. This frequency is chosen match the bandwidth of the original analog signal. In this case, the bandwidth was set at around 50Hz, ensuring negligible distortion of normal audio signals.

The 74VHC4046 contains three separate phase comparator circuits. Each one is best suited to a particular type of input signal. In our case, the input signal has a fixed duty cycle of 50%, making Phase Comparator I the best choice.

The final component of the receiver circuit is a simple audio amplifier to allow the receiver to drive a small speaker, headphones, or other audio device. We chose the Texas Instruments OPA134 operational amplifier in combination with a Texas Instruments BUF364 voltage buffer. The OPA134 is tailored for audio applications and the BUF364 provides additional output current, allowing the circuit to drive a small speaker, headphones or other audio device. Note that the BUF364 is placed inside the feedback loop of the OPA134. This helps to minimize the offset voltage of the BUF364.

4. RESULTS

The results of testing of the FM-MRR audio system are summarized in Figures 7 and 8 . Figure 7 shows the effect of driving the VCO with a real audio signal compared with no input. The audio information is carried in the frequency spectrum of the VCO output. We can see that the signal falls within the bandwidth defined. The noise outside the bandpass is effectively suppressed as well.

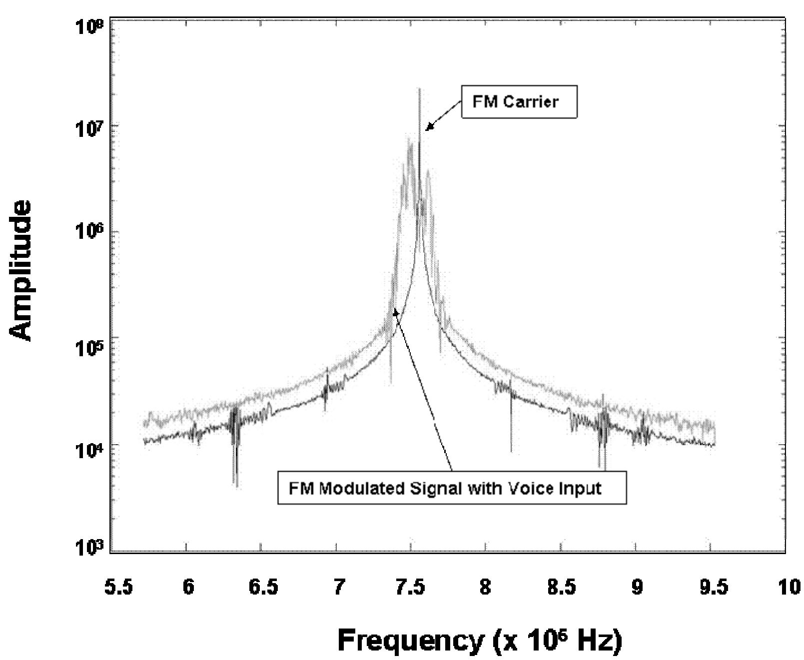

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Figure 7. Spectra of FM Modulated Signals with and without audio input.

Figure 8 shows a comparison of the input audio signal and the recovered signal after transmission over a free space optical link of approximately one meter on the optical bench in the laboratory. The output signal is offset from the input for clarity. The comparison shows that the output signal shows very little distortion and tracks the input with fidelity.

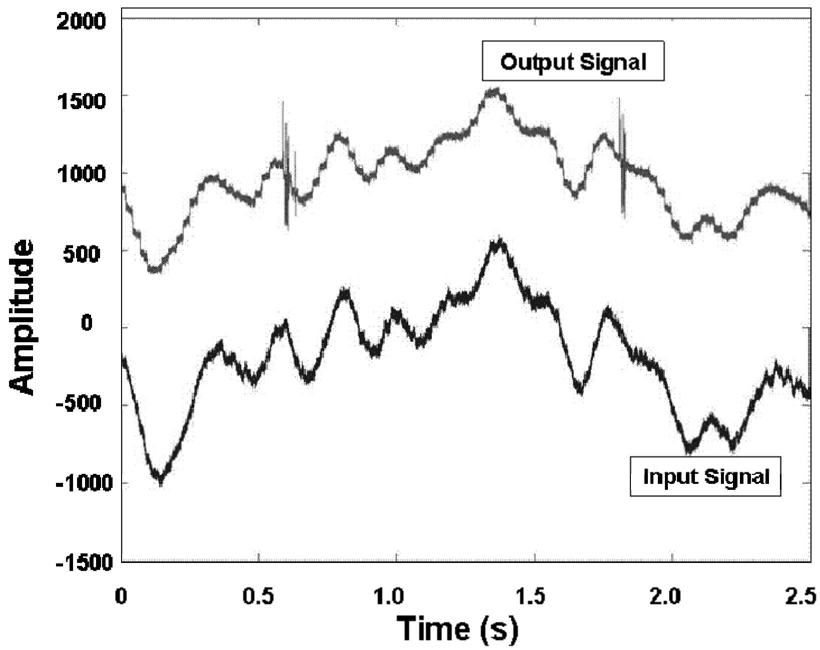

Figure 8. Comparison of input and output voice signals

The complete transmitter circuit, including MRR, consumes less than 200_mW (40mA at 5V) at full load. This compares to several watts required to digitize, compress and transmit the same signal using digital techniques. This low power consumption makes the approach ideal for battery or solar powered applications.

5. SUMMARY

Transmission of an FM audio signal has been demonstrated using a CCMRR-based asymmetric free-space link. The concept shows that such a configuration presents several advantages over conventional digital techniques. FM transmission requires a much less complex system, consisting only of an amplifier, VCO and MQW-MRR unit. This reduction in complexity leads to a similar reduction in the power required to transmit the same information. Several watts can be required to digitize, compress and transmit the same signal using digital techniques. The bandwidth required to transmit the FM signal is intrinsically lower than in a digital system as well and does not require compression to reduce bandwidth. Thus, the greatly reduced power requirements make this approach ideal for low and micro-power applications.

This technique is not limited to audio data only. The same approach can be used to transmit any analog data stream provided the data bandwidth does not exceed the modulation bandwidth of the MQW-MRR. Currently, that limit is around 20 MHz for corner cube devices. With advanced cat's eye designs, that bandwidth increases to as much as 100 MHz or greater. This means that the techniques described in this work can be applied to much more complicated signals than simple audio. (5)

REFERENCES

1. G.C. Gilbreath, et. al., “Progress in development of multiple quantum well retromodulators for free-space data links”, *Optical Engineering*, **42**(6), 1611-1617 (2003).

2. W. S. Rabinovich, et.al, “Free-space Optical Free-Space Communications Link at 1550 nm using Multiple Quantum Well Modulating Retroreflectors in a Marine Environment”, Optical Eng., **44(5**), pp. 056001-056012 (2005).

3. Mark. L. Bierman, et. al., "Design and analysis of a diffraction limited cat's eye retroreflector", Opt. Eng., **41**(7), pp. 1655-1660 (2002).

4. 74VHC4046 CMOS Phase Lock Loop Specification Sheet, www.fairchildsemi.com (2003).

5. James L. Murphy, et. al., “Frequency Modulated Modulating Retroreflector Analog Audio System”, patent pending (2005).