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Quadrature amplitude modulation in modulating retroreflector system

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It has been shown that the data throughput of an optical modulating retroreflector (MRR) system can be enhanced by use of spectrally efficient *M*-ary quadrature amplitude modulation (*M*-ary QAM). It has been demonstrated that this MRR system has sufficient dynamic range to support up to 64-QAM at 30 Mbit/s in a 6.75 MHz channel bandwidth.

Introduction: In many scenarios, free-space optical communication is desired between two platforms having different capabilities. For example, a small unmanned aerial vehicle (UAV) may have stringent weight and power constraints, while its ground station has no such restrictions. One approach that shifts almost all of the power, weight, and pointing requirements onto the ground station has been to configure the mobile node as a modulating retroreflector (MRR) [1]. Fig. 1 shows one example; an unmodulated (CW) interrogation laser illuminates a remote node that is composed of an absorptive modulator and a retroreflector. The remote node is known as a passive optical terminal (POT) because it does not require its own optical source. If the interrogation beam is within the field of view of the retroreflector (approximately ±15°), the beam will return to the interrogator with data impressed on it, having passed through the modulator twice.

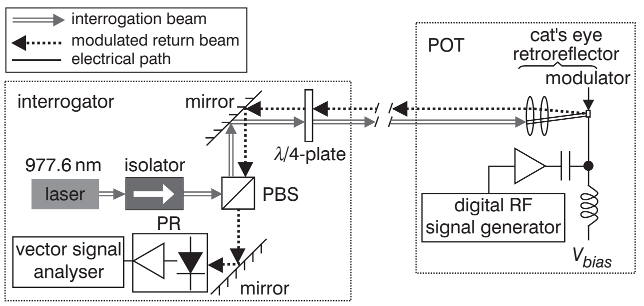

Fig. 1 *Modulating retroreflector system setup showing impression of data onto incident CW laser beam*

The surface-normal multiple quantum well (MQW) electroabsorption modulators used in these systems are *RC*-time limited. Practical modulating retroreflector links require relatively large area (hence large capacitance) modulators; consequently the available data channel bandwidth is limited to the low MHz range. Nonetheless, high data rates can be achieved by the use of spectrally efficient vector modulation formats such as *M*-ary quadrature amplitude modulation (*M*-ary QAM).

One of the driving forces for adopting vector modulation formats is the extensive commercial investment that has been made in wireless communication. This technology base, although designed for radio frequency (RF) free space links, uses well-developed techniques that are also directly applicable to optical free space links. For example, the IEEE 802.11a wireless modem standard provides for automatic adaptation to changes in the transmission medium. By monitoring the signal, it can adapt by adjusting the transmitter power, modulation rate/coding, or packet length.

Because of the bi-directional nature of MRR systems, the returned optical power in diffraction-limited MRR systems is inversely proportional to the fourth power of the range. As a result, the signal strength varies widely with range. Static nodes can also experience significant signal attenuation due to atmospheric conditions such as rain or fog. The various variable bit rate wireless protocols based on vector modulation formats are well suited to the wide range of received powers possible in typical scenarios. The adoption of a well-known standard could also ease the transition from RF to free space optical transmission.

With all of these advantages, the ability to use existing wireless components provides strong motivation to move towards that end. To make use of the commercial investment, the device must be capable of vector modulation, which is dependent on linearity of the modulator. This Letter describes the first measured performance of a modulating retroreflector operating with QAM modulation.

Test setup: Fig. 1 shows the setup of a retroreflector system. An external cavity tunable diode laser (New Focus Velocity) provided a maximum of 2.4 mW of optical power incident on the POT. The POT consisted of a 1 mm diameter MQW electroabsorption modulator [2] and a cat's eye retroreflector [3]. The MQW modulator consisted of InGaAs wells separated by AlGaAs barriers. The cat's eye retroreflecting optical system consisted of a telecentric Plossl lens with a flat reflector in the focal plane. The modulator was placed between the lens and the mirror, close to the focal plane. A polarising beamsplitter (PBS) and a quarter wave plate (λ/4-plate) formed an optical circulator, separating the interrogation beam and the return signal.

A vector signal generator (VSG, Agilent E4431B) provided a QAM modulated signal at a 9 MHz carrier frequency. This signal was amplified to 15.0 dBm (measured into 50 Ω) and delivered to the MQW modulator. A DC offset of 7.5 V was added to reverse bias the modulator as required. The VSG was configured to deliver QAM modulation at a symbol rate of 5 MHz. A root raised cosine (RRC) filter with a roll-off factor of 0.35 was used for spectral shaping. Signals from the photoreceiver (PR, New Focus 1811) were demodulated with an Agilent 89441A vector signal analyser (VSA). The VSA was configured to measure the modulation error ratio (MER), which is the ratio of average power in the transmitted signal to the average power in the error signal. The error signal is the vector difference between the ideal and actual received signals. The operating wavelength and MQW reverse bias were fine tuned to maximise the MER.

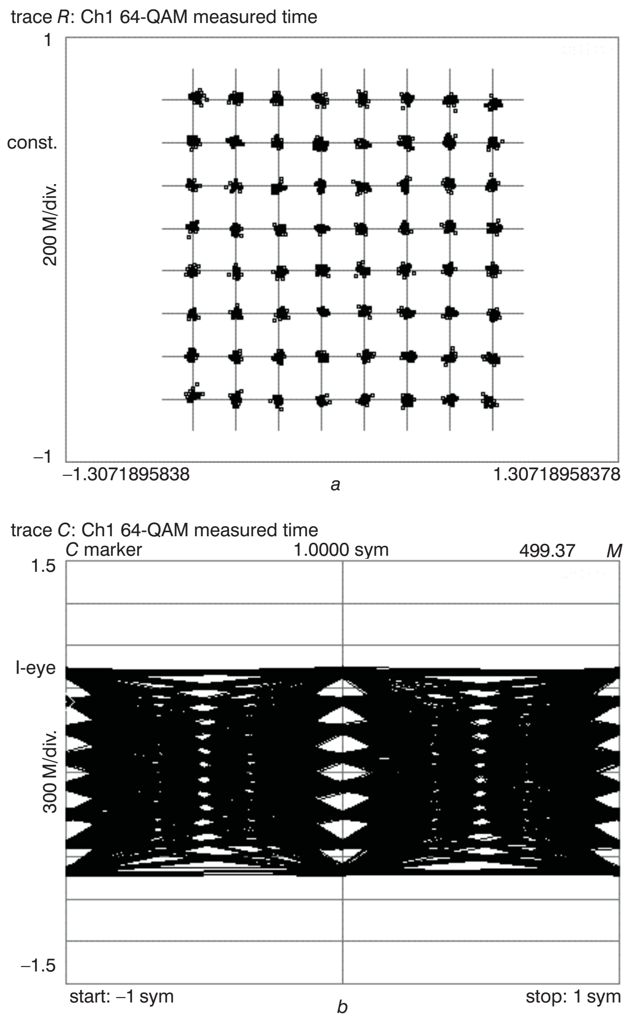

Fig. 2 *64 QAM (6 bit/symbol) as transmitted through our modulating retroreflector*

a Received signal constellation
x- and *y*-axes represent in-phase (*I*) and quadrature (*Q*) components of 9 MHz carrier. EVM=2.1164% rms, MER=29.817 dB
b Eye pattern for in-phase channel (*I*-branch)

Results: The setup described was tested with 64-QAM modulation. The received signal constellation and eye diagram for the in-phase channel are shown in Fig. 2. As expected, the in-phase and quadrature eye diagrams were indistinguishable from each other.

Since M-ary QAM generally requires higher signal to noise ratio (SNR) and much better linearity than the RZ and NRZ formats, QAM data links are often designed to tolerate uncorrected bit error rates (BER) as high as 10^{-4}. Forward error correction (FEC), typically Reed–Solomon, then provides correction to $<10^{-9}$ levels.

Assuming an additive white Gaussian noise channel, the probability of a symbol error can be found from the average SNR per symbol [4]:

$$P_M = 1 - \left[1 - \left(1 - \frac{1}{\sqrt{M}}\right)\mathrm{erfc}\left(\sqrt{\frac{3}{M-1}\frac{E_{AV}}{2N_0}}\right)\right]^2 \qquad (1)$$

where P_M is the probability of a symbol error for M-ary QAM, M is the order of the QAM (e.g. 64 or 256), and E_{AV}/N_0 is the average SNR per symbol. Assuming the use of a Gray encoded symbol map, the BER will be:

$$\mathrm{BER} \cong \frac{P_M}{m} \quad m = \log_2 M \qquad (2)$$

where m is the number of bits per symbol. According to (1) and (2), a MER of at least 24.3 dB is required in order to achieve a BER of 10^{-4} with a 64-QAM signal.

Our measured MER of 28.6 dB exceeded this requirement. With receiver equalisation activated, the MER improved further to 29.8 dB. Utilising spectrally efficient 64-QAM allowed us to achieve a notable channel bit rate of 30 Mbit/s at a symbol rate of only 5 MHz (6 bit/symbol). Actual system throughput (bit rate minus FEC overhead) would be approximately 27 Mbit/s, which corresponds to a usable spectral efficiency of 4.0 bit/s/Hz. This is sufficient, for example, to support 6 channels of digital NTSC live video as broadcast over commercial digital cable [5]. We expect higher symbol rates would be possible with a VSG/VSA setup capable of larger bandwidths.

It is noteworthy that a MER of 29.0 dB was measured with equalised 256-QAM. Although this falls short of the 30.23 dB MER required to achieve an uncorrected BER of 10^{-4}, it would be acceptable for video transmission with appropriate error control coding and/or error concealment [6]. A more linear modulator design or higher laser power would further improve the MER.

It is important to realise that while 64-QAM modulation is spectrally efficient, this format performs poorly when noise or distortion reduce the MER below 24 dB. The modulators used in this experiment were originally designed strictly for on–off keying (OOK), with no concern for linearity of operation. In spite of this, a very linear region of operation was found by optimising the bias voltage, signal amplitude, and laser wavelength. Compared to optimised values for the same modulator used with OOK, the signal amplitude was decreased, while the bias level was increased. The optimal wavelength was also different for OOK and QAM. OOK performed best at 980 nm, whereas with QAM the highest MER was obtained at a wavelength of 977.6 nm.

Using the parameters optimised for QAM, our current MQW modulator is linear enough to support the 64-QAM format with minimal distortion. The results from this work are very encouraging, and we plan to design new modulators with improved linearity and operating voltages. These changes could allow an increase in data throughput. One could envision extending this approach to either higher symbol rates or multiple frequency division multiplexed channels for even higher throughputs.

Conclusions: We have shown that spectrally efficient M-ary QAM modulation formats can be used to extend the data rate of modulating retroreflectors. A test link with a MQW modulator provided faithful transmission of a 64-QAM constellation, at 4 bit/s/Hz spectral efficiency. The technique can provide data rates well in excess of the RC-limited bandwidth of the modulator. Future MQW modulators will be designed for improved linearity and lower signal voltage. This will enable higher order modulation formats to be used.

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References

1 GILBREATH, G.C., RABINOVICH, W.S., MEEHAN, T.J., VILCHECK, M.J., MAHON, R., BURRIS, R., FERRARO, M., SOKOLSKY, I., VASQUEZ, J.A., BOVAIS, C.S., COCHRELL, K., GOINS, K.C., BARBEHENN, R., KATZER, D.S., IKOSSI-ANASTASIOU, K., and MONTES, M.J.: 'Large aperture multiple quantum well modulating retroreflector for free space optical data transfer on unmanned aerial vehicles', *Opt. Eng.*, 2001, **40**, (7), pp. 1348–1356

2 RABINOVICH, W.S., GILBREATH, G.C., GOETZ, P.G., MAHON, R., KATZER, D.S., IKOSSI-ANASTASIOU, K., BINARI, S., MEEHAN, T.J., FERRARO, M., SOKOLSKY, I., VASQUEZ, J.A., and VILCHECK, M.J.: 'InGaAs multiple quantum well modulating retro-reflector for free space optical communications' *in* VOELZ, D.G., RICKLIN, J.C. (Eds.): 'Free-Space Laser Communications and Imaging', 2002, Vol. 4489, pp. 190–201 (Proc. SPIE)

3 RABINOVICH, W.S., MAHON, R., GOETZ, P.G., WALUSCHKA, E., KATZER, D.S., BINARI, S.C., and GILBREATH, G.C.: 'A cat's eye multiple quantum well modulating retro-reflector', *IEEE Photonics Technol. Lett.*, 2003, **15**, (3), pp. 401–403

4 PROAKIS, J.G.: 'Digital communications' (McGraw-Hill, New York, NY, 1995, 3rd edition), pp. 280–281

5 RYBA, M., and MATUSZAK, P.: 'Testing 256 QAM transmission of data over HFC', *Commun. Eng. Des.*, December 1996

6 MICHELSON, A.M.: 'Reliable ATM transmission of multimedia in wireless networks'. IEEE 1998 International Conference on Universal Personal Communications, 1998. ICUPC'98, Florence, Italy, 5–9 Oct. 1998, Vol. 2, pp. 1021–1027