Regards,
Eric Funk, Ph. D.
Partner, Red Mountain Radio LLC
eric@redmountainradio.com
970-325-2158 ×12

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Direct Carrier Modulation for Wireless Digital Communications Using an Improved Microwave-Photonic Vector Modulator (MPVM) Approach

Soumya Chandramouli, William D. Jemison, Eric Funk*

Department of ECE, Lafayette College, Easton, PA, 18042
*Naval Research Laboratory, Washington, D.C, 20375

Abstract — **This paper presents a demonstration of direct carrier modulation via the use of an improved microwave/photonic vector modulator (MPVM). This modulation approach is suitable for direct digital modulation of microwave and millimeter-wave signals and allows for tuning of the carrier frequency over wide bandwidths and dynamic reconfiguration of the modulation format. An all-optical control approach is used to achieve faster data rates and better carrier tune-ability than previously reported work in this area. Specifically, experimental results showing direct QPSK and 16-QAM modulation of carrier frequencies between 1.0 and 2.0 GHz with data rates to 8 Mbs are presented.**

I. INTRODUCTION

Conventional carrier modulation systems employ in-phase (I) and quadrature (Q) processing to achieve M-ary phase shift keying (*m*-PSK) and quadrature amplitude modulation (*m*-QAM). This I-Q processing typically requires the use of multiple up-conversions to the desired microwave or millimeter wave carrier frequency. Each of the up-conversions and its associated filtering requirements introduces complexity and imposes bandwidth limitations on the overall system. Direct carrier modulation using electronic or photonic vector modulation has advantages over traditional carrier modulation approaches using I-Q processing and multiple up-conversions [1-4]. Jemison, *et. al.* have recently demonstrated direct carrier modulation using a microwave/photonic vector modulator (MPVM) [5]. In this previous work, binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (16-QAM) were demonstrated at a carrier frequency of 1.0 GHz. The data rates achieved in this previous work were limited by the following: 1) the use of a bias-tee to combine band-limited data and the carrier frequency in a single elctrode MZM configuration, 2) the limited response time of the electronic microwave attenuators used for vector amplitude control, and 3) the speed of the prototype digital control circuit. Similarly, the carrier tune-ability of the previous system was limited by the bandwidth of the electronic microwave attenuators. This paper presents several significant improvements over the previous MPVM work by implementing an all-optical control approach to achieve higher data rates and wideband carrier tune-ability.

II. SYSTEM DESCRIPTION

The system block diagram is shown in Figure 1 and consists of a control circuit and the microwave photonic vector modulator (MPVM). The control circuit accepts a binary serial data stream from a HP8018A serial data source and generates the control signals for the MPVM. Control circuit functions include serial to parallel conversion, Gray-coding of the data, and providing proper MZM interface signal levels.

The MPVM directly modulates a microwave carrier signal, $S_{in}(t)$, based on the data encoded by the control signals. Two quadrature vectors, $S_I(t)$ and $S_Q(t)$, are obtained by splitting the carrier signal in a 90 degree microwave power divider. These signals are then applied to separate MZMs. The MZMs are Lucent 10 GHz 2624C (MZM 1 and 3) and 2623CSA (MZM 2 and 4) $LiNbO_3$ devices. These are driven by Lucent D2500 semiconductor lasers operated at 1.55 μm with a nominal optical power level of 2 mW. All four quadrants of the desired signal space can be accessed by using a combination of amplitude shift keying (ASK) and BPSK on the quadrature vectors. Each quadrature vector may be rotated 180 degrees from its initial state (*i.e.* BPSK) by changing the control signal voltage on MZMs 2 and 4 from + $V_\pi/2$ to $-V_\pi/2$. The amplitude of each quadrature vector may then be adjusted (*i.e.* ASK) by controlling the optical attenuation via MZMs 1 and 3. It should be noted that only MZMs 2 and 4 are required to operate at the carrier frequency since the function of MZMs 1 and 3 is to provide vector length modulation (ASK) at the symbol rate. The optical signals are then combined in a 3 dB optical power combiner. A high-speed phototdetector is used to recover the modulated microwave signal, $S_{out}(t)$.

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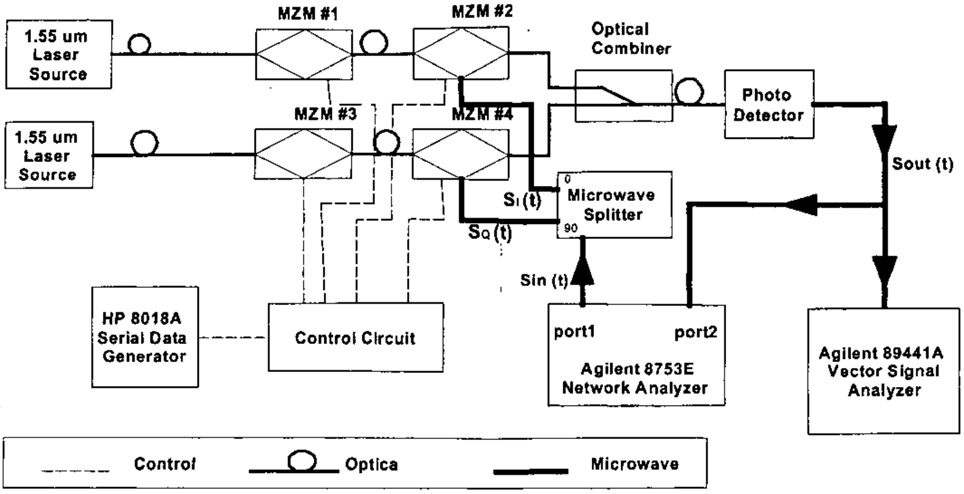


Figure 1. System block diagram

The output of the photodetector may then be amplified and used for wireless data transmission.

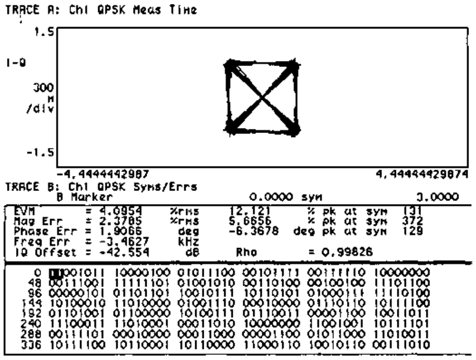
In the case of QPSK modulation, the signal has a constant envelope. Thus, the vector length is constant and ASK of the quadrature vectors is not required. This allows QPSK to be generated with only two MZMs. 16-QAM has a variable envelope, but requires only two vector lengths to achieve all signal constellation points. Therefore, 16-QAM can be achieved via a combination of BPSK on the first pair of MZMs and binary ASK applied to the second pair of MZMs. The decomposition of 16-QAM into two independent binary modulation types makes the control signal generation for 16-QAM convenient and simple.

III. EXPERIMENTAL RESULTS

The system was experimentally tested using QPSK and 16-QAM modulation. Experiments are presented to quantify: 1) basic system functionality and data transmission quality, and 2) wideband operation.

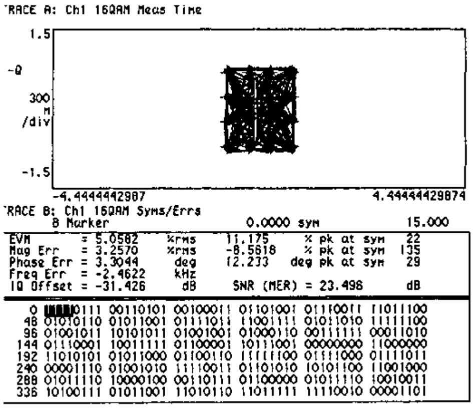
A. Basic Functionality and Data Transmission Quality

The purpose of this testing was to show that the MPVM can generate high-quality digitally modulated signals using multiple modulation formats. Figures 2 and 3 show the constellation diagrams and transmission statistics measured on an 89441A vector signal analyzer for QPSK and 16-QAM modulation at 1 Mbs using a 2^{20}-1 pseudo-random bit sequence (PRBS). The carrier frequency was 1.5 GHz in each case.


```
TRACE A: Ch1 QPSK Meas Time
  1.5
 I-Q
  300
    m
 /div
 -1.5
     -4.4444442987                                  4.44444429874
TRACE B: Ch1 QPSK Syms/Errs
       B Marker                    0.0000 sym              3.0000
 EVM        = 4.0954   %rms    12.121     % pk at sym  131
 Mag Err    = 2.3785   %rms    5.6656     % pk at sym  372
 Phase Err  = 1.9066    deg    -6.3678  deg pk at sym  129
 Freq Err   = -3.4627   kHz
 IQ Offset  = -42.554    dB     Rho          = 0.99826

     0 11001011 10000100 01011100 00101111 00111110 10000000
    48 00111001 11111101 01001010 00110100 00100100 11101100
    96 00000101 01101101 10010111 10110101 01000111 11110100
   144 10100010 11010000 01001110 00010000 01110110 10111100
   192 01101001 01100000 10100111 01110011 00001100 10011011
   240 11100011 11010001 00011010 10000000 11001001 10111101
   288 00111101 00010000 00011000 00001100 01011000 11010011
   336 10111100 10110001 10110000 11000110 10010110 00111010
```

Figure 2. Constellation Diagram and Transmission Statistics for QPSK


```
TRACE A: Ch1 16QAM Meas Time
  1.5
 -Q
  300
    m
 /div
 -1.5
     -4.4444442987                                  4.44444429874
TRACE B: Ch1 16QAM Syms/Errs
       B Marker                    0.0000 sym              15.000
 EVM        = 5.0582   %rms    11.175     % pk at sym   22
 Mag Err    = 3.2570   %rms    -8.5618    % pk at sym  135
 Phase Err  = 3.3044    deg    12.233   deg pk at sym   29
 Freq Err   = -2.4622   kHz
 IQ Offset  = -31.426    dB     SNR (MER) = 23.498       dB

     0 11110111 00110101 00100011 01101001 01110011 11011100
    48 01010110 01011001 01111011 11001111 01011010 11111100
    96 01001011 10101011 01001001 01000110 00111111 00011010
   144 01110001 10011111 01100001 10111001 00000000 11000000
   192 11010101 01011000 01100110 11111100 01111000 01111011
   240 00001110 01001010 11110011 01101010 10101100 11001000
   288 01011110 10000100 00110111 01100000 01011110 10010011
   336 10100111 01011001 11010110 11011111 11110010 00001101
```

Figure 3. Constellation Diagram and Transmission Statistics for 16-QAM

Figure 4 shows the spectrum of the 1 Mbps (250 kSymbols/sec) 16-QAM signal. The main lobe width correlates exactly with the symbol rate and a well-defined sidelobe structure was obtained since no baseband data filtering was applied. Optimal filtering of the MPVM control signals for minimizing intersymbol interference (ISI) and providing spectral control needs to be addressed in future work.

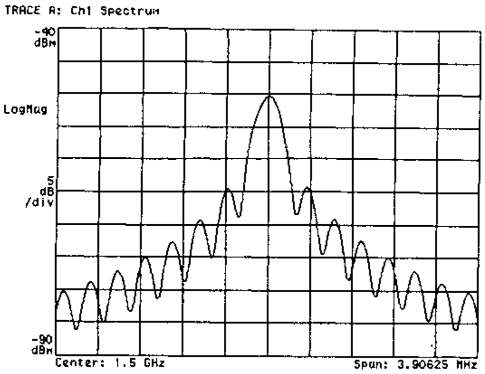


Figure 4. Spectrum of 1 Mbs 16-QAM (no MPVM baseband filtering)

Figure 5 shows the measured Error Vector Magnitude (EVM) for the QPSK and 16-QAM signals as a function of symbol rate. The EVM provides a quantitative measure of modulation performance [6].

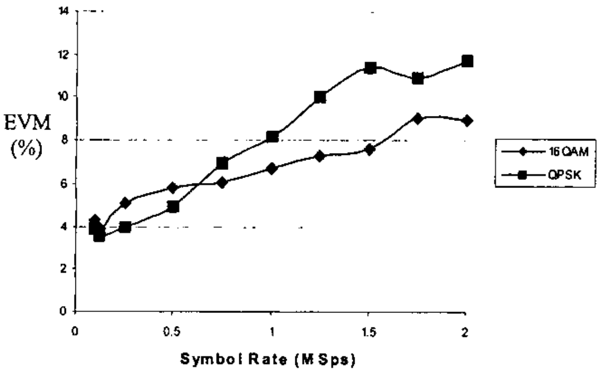


Figure 5. EVM vs. Symbol Rate for QPSK and 16-QAM using a 2^{20}-1 pseudo-random bit sequence (PRBS)

These data rates are more than one order of magnitude higher than the data rate achieved previously [5]. Thus, the speed limitations associated with single-port MZMs and the digital attenuator in the previous MPVM have been eliminated. The control circuit remains the only significant data-rate limiting factor and an improved implementation should extend the MPVM performance above 100 Mbs.

B. Wideband Testing

The purpose of this testing was to quantify the MPVM performance over the full design bandwidth of 1.0 – 2.0 GHz. This bandwidth was selected based on microwave component and test equipment availability. However, it should be noted that, since the 2623CSA MZMs operate to 18 GHz, the system easily can be reconfigured to support operation in dc - 18 GHz range by changing the microwave power divider and using a higher speed photodetector.

The MPVM system was calibrated at 1.5 GHz to minimize quadrature phase error and amplitude imbalance. The phase error and amplitude imbalance of each quadrature vector (*i.e.* 0, 90, 180, and 270 degrees) were then measured over the full system bandwidth. The results are shown in Figures 6 and 7. Results for all four of the signal vectors are shown on each graph.

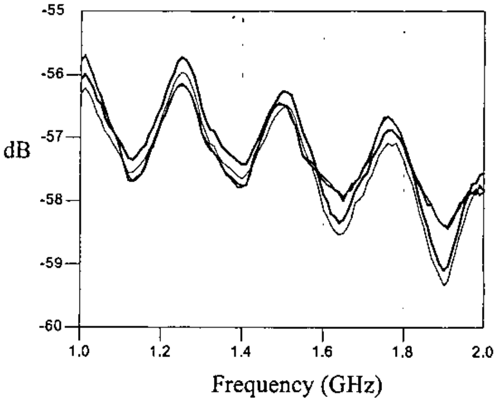


Figure 6. MPVM Quadrature Amplitude Error

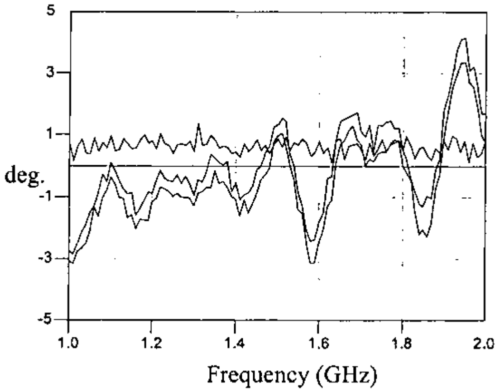


Figure 7. MPVM Quadrature Phase Error

At the 1.5 GHz calibration frequency, the maximum amplitude and relative phase error between any two adjacent quadrature vectors is less than +/- 0.15 dB and +/- 0.65 degrees, respectively. The maximum amplitude and relative phase error at any other frequency in the band is +/- 0.47 dB at 1.9 GHz and +/- 2 degrees at 1.95 GHz, respectively. The maximum amplitude phase variation across the full octave bandwidth, is less than +/- 1.81 dB and +/- 3.5 degrees, respectively. Large magnitude and phase deviations are evident outside the 1.0-2.0 GHz frequency range (not shown), however, this is expected since the 90 degree microwave power divider used in this work is designed for 1.0-2.0 GHz. In fact, most of the amplitude and phase error of the MPVM can be traced to the microwave power divider performance and input VSWR of the MZMs. However, these results are still excellent and the MPVM may be used over the full octave bandwidth. Table 1 shows the measured EVM performance of the 1 Mbs 16-QAM at several points across the frequency band. The results indicate that the EVM is less than 5.4% over the design bandwidth. The 10% EVM at 2.2 GHz occurs at a frequency outside the design bandwidth. Given this wideband performance, the carrier frequency could be tuned or dynamically hopped over this octave bandwidth in order to support multiple wireless bands or frequency hopped or chirped spread spectrum.

TABLE I

16 QAM EVM AT 1 MBS

RF Frequency (GHz)	EVM (%)
1.1	5.1
1.5	5.1
1.8	5.4
2.0	5.2
2.2	10.0

IV. CONCLUSION

This paper presents an experimental demonstration of direct carrier modulation via the use of a microwave/photonic vector modulator. Specifically, experimental results were presented that demonstrate full-functionality, octave-band operation for QPSK and 16-QAM modulation. Since photonic components can be designed to operate over extremely wide bandwidths [7], this direct modulation approach is suitable for direct digital modulation of microwave and millimeter-wave signals and allows for both tuning of the carrier frequency over wide bandwidths and dynamic reconfiguration of the modulation format. The results presented demonstrate significantly higher data rates and better carrier tune-ability than previously reported work in this area [5]. These improvements were achieved using an all-optical control method that eliminates most of the performance barriers associated with the previous MPVM approach. While four MZMs are used in this demonstration, only two of them are required to operate at the carrier frequency as the remaining two are used for intensity control at the symbol rate. Multiple MZMs may be realized in integrated optics to simultaneously increase performance and significantly reduce the size and cost of the MPVM. Alternatively, the use of direct laser modulation or electroabsorbtive modulators may be used to provide the intensity control required for vector length control.

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