High-Speed Microwave-Photonic Vector Modulator (MPVM) with Wideband Carrier Tuning and Spectral Control

Guangxi Wang, William D. Jemison

Department of ECE, Lafayette College, Easton, PA, 18042

Abstract — **A microwave/photonic vector modulator (MPVM) has been demonstrated previously by one of the authors using direct QPSK and 16-QAM modulation at carrier frequencies between 1.0 and 2.0 GHz with data rates to 8 Mbs. This paper significantly extends this work in several areas to include greater than three octaves of carrier tunability, greater than 70 times increase in data rates to 600 Mbs, and 27 dB of modulated waveform sidelobe level suppression; the latter being critically important for fiber radio applications requiring wireless transmission.**

I. INTRODUCTION

Chandramouli, *et. al.* have recently demonstrated direct carrier modulation using a microwave/photonic vector modulator (MPVM) [1]. In this previous work, octave-band carrier tuning of quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (16-QAM) were demonstrated. The data rate achieved in this previous work was limited to 8 Mbs by the electronic Mach Zehnder Modulator drivers used in the MPVM. This paper presents several significant improvements over the previous MPVM work including: 1) multi-octave carrier tunability, 2) a factor of greater than 70 increase in the data rate, and 3) spectral control of the modulated microwave signal. Specifically, experimental results are presented that demonstrate greater than three octaves of carrier tuning (485 MHz < f_c < 3900 MHz) and digital data transmission to 600 Mbs. In addition, both simulated and experimental results are presented that demonstrate significant improvement (27 dB) in the spectral control of the modulated microwave waveform using a combination of baseband data filtering and MZM bias adjustment. Spectral control of the modulated signal is a critical issue in hybrid fiber optic/wireless or fiber radio applications where the photodetected signal will be amplified and transmitted wirelessly [2,3,4].

II. SYSTEM DESCRIPTION

The block diagram of a simplified MPVM capable of BPSK modulation is shown in Figure 1. It consists of a single Lucent 2624C 10 GHz Mach Zehnder Modulator (MZM) that is simultaneously driven by a continuous wave (CW) microwave carrier frequency and a binary serial data stream. The nominal voltage swing of the serial data is adjusted such that a logical "0" is set at $-V_\pi/2$ while a logical "1" is set at $+V_\pi/2$ [1]. The opposite slope polarity of the MZM transfer function of these two points results in binary phase shift keyed (BPSK) modulation (i.e. the carrier vector is modulated between 0 and 180 degrees) [1,5]. A DC source is used to obtain the proper DC bias point since the transfer function maximum of the MZM being used is not at zero volts.

The baseband serial binary data stream is a 2^{23}-1 psuedo-random bit sequence (PRBS) generated by a bit error rate (BER) test-set transmitter. Proper MZM interface signal levels are achieved by amplifying the data stream with a Watkins Johnson WJSA1137-2 10 GHz MZM driver amplifier. Optionally, the data may be filtered prior to being applied to the MZM using low-pass filters matched to the data rate. Section III.B will show how this baseband data filtering can be used in conjunction with additional MZM bias adjustment to provide spectral control of the modulated output signal.

The microwave carrier signal is generated by an Agilent 8753E Network Analyzer at a nominal power level of +15 dBm. A Lucent 1550 μm D2500 semiconductor laser operated at a nominal optical power level of 3 mW provides the optical input to the MZM.

A high-speed phototdetector is used at the output of the MPVM to recover the BPSK-modulated microwave signal. The output of the photodetector is amplified by a 38 dB linear power amplifier. The output of this amplifier may be connected directly to a microwave spectrum analyzer to observe the microwave spectrum. Alternatively, the output may be mixed with a sample of the unmodulated microwave carrier to recover the baseband data signal. The mixer output may be fed into a bit error rate receiver to make BER measurements or to a sampling oscilloscope to obtain eye diagrams.

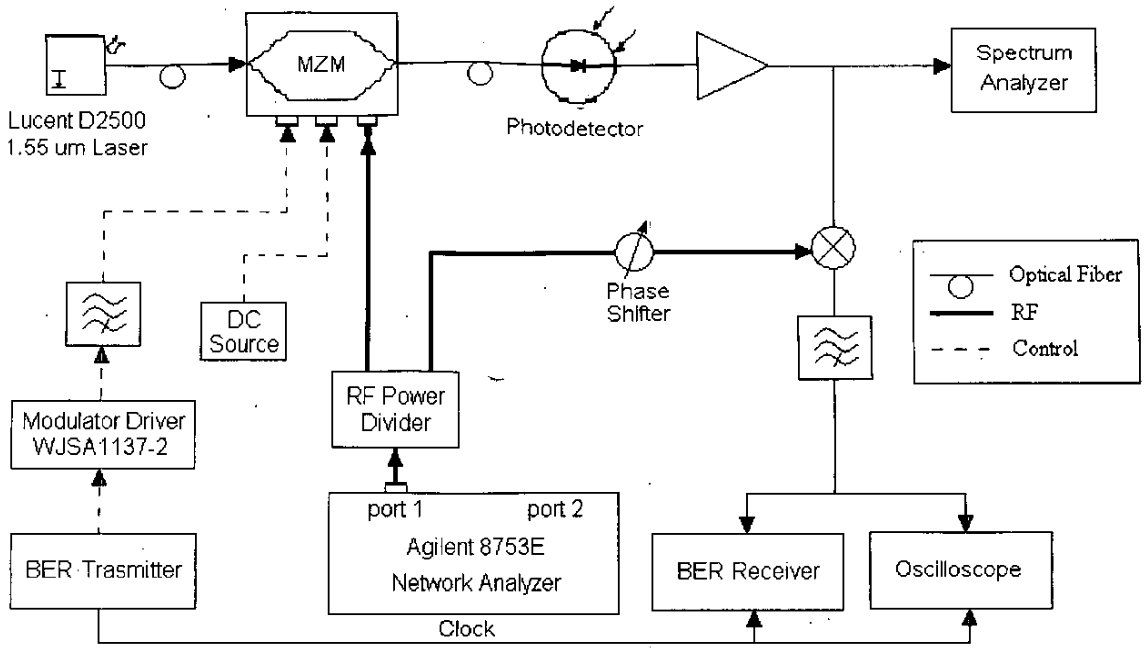

Figure 1. System Diagram

III. EXPERIMENTAL RESULTS

The system was experimentally tested using BPSK modulation to demonstrate: 1) enhanced carrier tunability, 2) improved data rate performance, and 3) spectral control of the microwave signal.

A. Enhanced carrier tunability and improved data rate performance

The purpose of this testing was to significantly extend the tuning range of the carrier frequency and to increase the data rate, thus demonstrating the promise of the MPVM for wideband Gbs digital data links. It should be emphasized that while the results presented in this section show greater than three octaves of carrier tuning and better than 70 times improvement in error-free data rate, the performance limitations in these areas are not limited by anything inherent in the MPVM architecture, but rather by equipment availability. Specifically carrier tuning is limited by the 4 GHz 3dB frequency of the power amplifier.

Figure 2 shows the eye diagram of a 600 Mbs BPSK baseband signal that is downconverted from a 1.6 GHz carrier frequency. An extension to QPSK operation, which has been shown previously [1], would result in a 1.2 Gbs data rate.

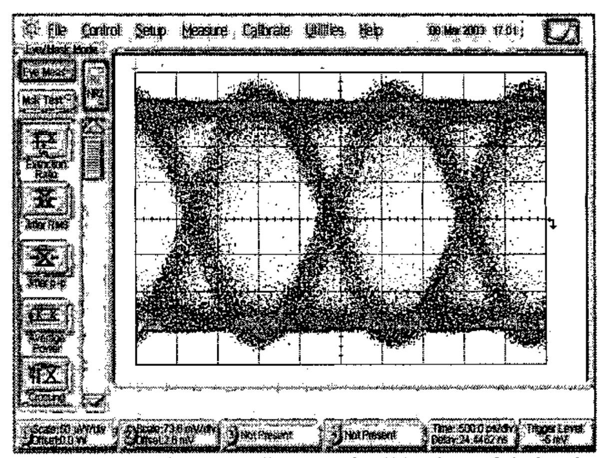

Figure 2. Baseband eye diagram of a 600 Mbs BPSK signal downconverted from a 1.6 GHz carrier frequency

In order to show the wideband tuning capability of the MPVM, the carrier frequency was adjusted from 485 MHz to 3,900 MHz. In each case, the modulated microwave frequency was downconverted and the baseband data was analyzed using the BER test-set. Table 1 lists a subset of these carrier frequencies and shows that slightly greater than 3 octaves of tunability was achieved while maintaining error-free data transmission.

Carrier frequency (MHz)	Error-free locking
485	Yes
535	Yes
585	Yes
635	Yes
685	Yes
885	Yes
970	Yes
1,110	Yes
1,170	Yes
1,260	Yes
1,330	Yes
1,600	Yes
1,940	Yes
2,220	Yes
2,420	Yes
2,800	Yes
3,180	Yes
3,710	Yes
3,900	Yes

Table 1. Multi-octave carrier tuning with error-free locking on a 340 Mbs 2^{23}-1 pseudo-random bit sequence

B. Spectral control

The purpose of this testing is to significantly improve the spectral characteristics of the modulated microwave waveform. This is critically important for fiber radio or hybrid fiber optic/wireless applications that use wireless transmission [2,3,4]. Without spectral control, the output of the MPVM is unacceptable for wireless transmission as it exhibits a strong sin(x)/(x) sidelobe structure with the first sibelobe level only 13 dB down from the main lobe as shown in Figure 4.

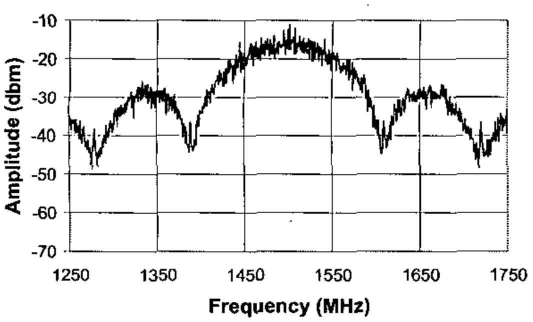

Figure 4. Spectrum of MPVM output signal: fc = 1.5 GHz @ 110 Mbs; No Baseband Filtering; Input baseband data voltage swing at 100% of Vπ

For lower data rate applications spectral control is achieved using digital signal processing (DSP) to implement baseband data filtering. However, at data rates approaching Gbs, DSP techniques become impractical and hardware approaches become necessary. To improve the spectral characteristics, a combination of analog baseband data filtering and MZM bias control was used. First, an analog low pass filter was inserted between the MZM and the MZM driver amplifiers as shown in Figure 1. Two commercially available Chebychev filters with 100 MHz 1dB cutoff frequencies were cascaded to perform this operation. The data rate was then set to 110 Mbs which sets the first null of the baseband data spectrum at the –12 dB point of the cascade filter combination. Higher data rates could easily be achieved by using a different filter. Initially, the peak-to-peak voltage of the serial data signal was maintained at its nominal value of Vπ. Figure 5 shows the spectrum of the resulting BPSK signal at a carrier frequency of 1.5 GHz. A reduction in the first sidelobe level of 12 dB (-13 dBc to –25 dBc) relative to an unfiltered case of Figure 4 is obvious.

Figure 6 shows the eye diagram of this signal after downconversion to baseband. When this signal was applied to the BER receiver, error-free performance was achieved.

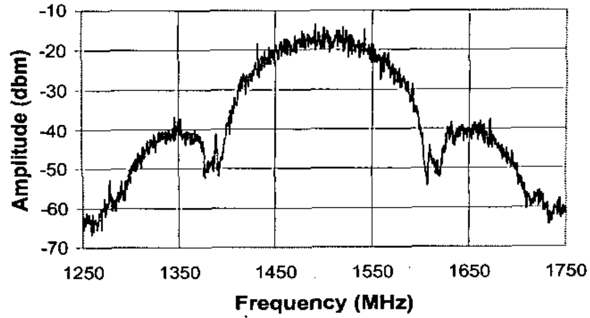

Figure 5. Spectrum of MPVM output signal: fc = 1.5 GHz @ 110 Mbs; Baseband filtering; Input baseband data voltage swing at 100% of Vπ

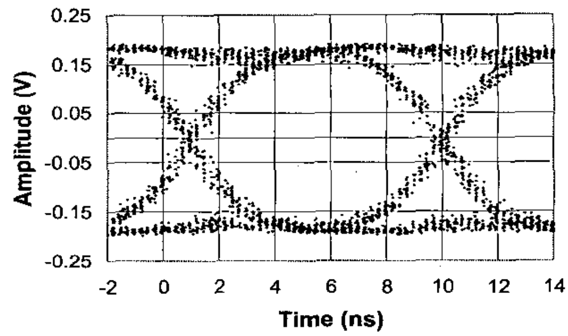

Figure 6. Eye diagram of a downconverted 110 Mbs BPSK baseband signal; Baseband filtering; Input baseband data voltage swing at 100% of Vπ

To achieve additional spectral control, the peak-to-peak voltage swing of the input serial data signal applied to the MZM is reduced from the nominal level of Vπ to a fraction of Vπ. This reduction affects both the mainlobe signal level and the sidelobe level of the modulated microwave spectrum. Figure 7 shows both experimental and simulated mainlobe signal level loss and first sidelobe level (relative to the mainlobe) as a function of the percentage reduction of Vπ. The simulated results were obtained using a circuit-based modeling approach for MZMs similar to that described by *Zandano, et. al.* [6] with baseband filter models that were extracted from measured data. The simulation was performed using Agilent ADS. The agreement between the experimental and simulated results is good with a worst-case difference of 0.7 dB between simulated and experimental mainlobe levels and a worst-case difference of 3.1 dB between simulated and experimental sidelobe levels. It should be stressed that these results apply only to the case where baseband filters are used and are specific to the type of filter used.

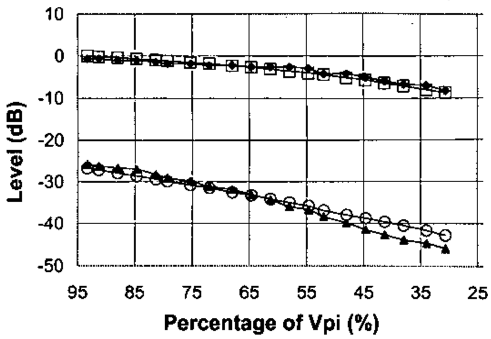

Figure 7. Upper curves: Mainlobe Reduction (♦- Exp., □- Sim.); Lower curves: 1st Sidelobe Level (▲- Exp., O- Sim.)

Based on the results of Figure 7, a tradeoff may be made between the acceptable signal loss and the spectral control. Figure 8 shows the spectrum of the resulting BPSK signal when the input peak-to-peak data swing is set for maximum sidelobe suppression (i.e. data voltage swing at 31% of Vπ). The 7.5 dB mainlobe level reduction and 15 dB sibelobe level reduction compared to Figure 5 is evident. Compared to the unfiltered case (Figure 4) the sidelobe level has been reduced by 32 dB.

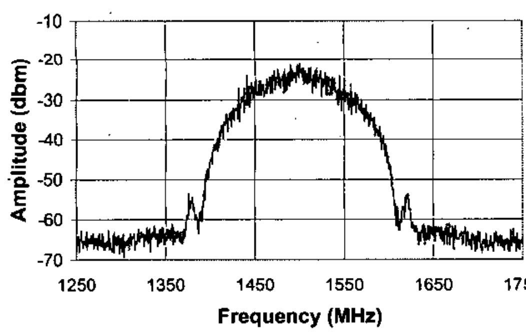

Figure 8. Spectrum of MPVM output signal: fc = 1.5 GHz @ 110 Mbs; Baseband filtering; Input baseband data voltage swing at 31% of Vπ

Figure 8 shows the eye diagram of the downconverted baseband signal. When this signal was applied to the BER receiver, error free performance was achieved.

CONCLUSION

Several significant MPVM performance enhancements have been demonstrated including improved spectral control, multi-octave carrier tunability, and increased data rates. These enhancements demonstrate the promise of the MPVM for giga-bit per second microwave and millimeter-wave transmitters and fiber radio applications as well as for advanced communications applications such as multi-band or ultrawideband frequency hopped spread spectrum. A peak data rate of 600 Mbs is demonstrated in this paper use BPSK modulation, and this implies a 1.2 Gbs speed when QPSK modulation is used.

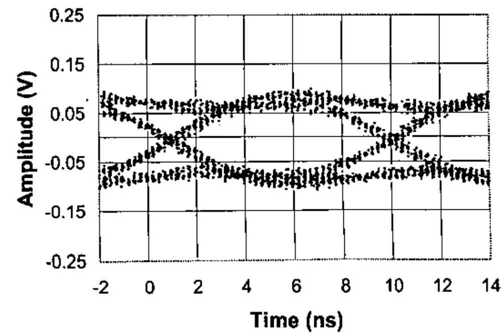

Figure 9. Eye diagram of a downconverted 110 Mbs BPSK baseband signal; Baseband filtering; Input baseband data voltage swing at 31% of Vπ

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