Microwave Photonic Vector Modulator for High-Speed Wireless Digital Communications

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***Abstract*—This letter presents the design, realization, and experimental results of a microwave/photonic circuit suitable for high-speed direct digital modulation of microwave signals. The modulator employs a combination of microwave, photonic, and digital techniques to produce a discrete phase and amplitude (*i.e.,* vector) modulated carrier signal. The proof-of-concept demonstration presented in this paper was performed using a carrier frequency of 1 GHz and supports BPSK, QPSK, and 16-QAM. The paper also discusses ways to modify the modulator to simultaneously achieve data rates on the order of several hundreds of Mbs and wideband frequency hopping.**

***Index Terms*—Photonic phase shifting, vector modulation.**

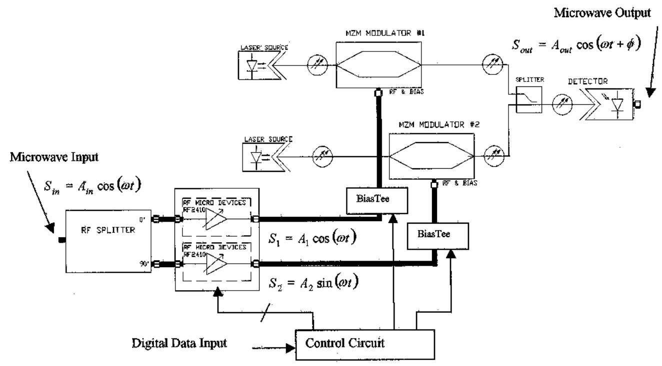

Fig. 1. Simplified system block diagram.

I. Introduction

THERE is a clear trend toward the use of both higher carrier frequencies and data transmission rates in wireless systems. As the wireless carrier frequency moves into the millimeter wave band, the data rate is moving toward 1 Gb/s [1]. While the conventional wireless transmitter employs modulation at an IF frequency followed by upconversion, previous work has shown that a considerable cost and complexity savings could be realized by direct modulation at the carrier frequency [2]. Direct modulation eliminates the spurious emissions and filtering requirements associated with upconversion, resulting in potentially increased modulation bandwidth and greater carrier tune-ability. In this paper, we present a microwave/photonic architecture whereby direct digital vector modulation can be performed at microwave frequencies The demonstration consists of 16-QAM, QPSK, and BPSK direct modulation of a 1 GHz microwave carrier.

II. Microwave Photonic Vector Modulator (MPVM) Approach

The use of photonics to perform vector modulation stems from applications related to analog phased array beamsteering systems [3]. Fig. 1. shows a block diagram of the microwave-photonic vector modulator (MPVM). The configuration is similar to that used for wideband analog phase shifting and serrodyne frequency translation as described in [4]; however, this enhanced design also includes amplitude control and is specifically intended for digital modulation. Furthermore, the Mach Zehnder modulators (MZMs) are configured to maintain quadrature bias at *all* constellation points, thereby suppressing modulator induced second order harmonic distortion [5]. The system is briefly described below.

For the proof-of-concept demonstration, a 1 GHz carrier frequency was selected based on availability of optical and microwave components. In this approach, the vector modulated signal is generated by combining two amplitude shift keyed (ASK) signals impressed on quadrature carriers. Hence, the carrier signal was split into in-phase (I) and quadrature (Q) channels by a 90-degree power divider. The modulation on each of the quadrature carriers is formed by a combination of amplitude scaling followed by bipolar phase shift keying (BPSK).

Amplitude scaling is provided 5-bit digital attenuators that have a total of 38 dB of adjustment range. The attenuators alone map out only one quadrant of vector modulation. The achievable vector locations (*i.e.,* constellation states) are a function of the attenuator discretization and typically only a subset of these are used in practice [6]. Fig. 2 shows the vector locations that are achievable in one quadrant using this approach. Only the subset of constellation points indicated by the arrows are required to support 16-QAM and the lower modulation orders, QPSK and BPSK; these are the target modulation formats for this proof-of-concept demonstration.

Coverage of all four quadrants of the vector modulation space can be achieved by the addition of a BPSK modulator to each channel. The BPSK modulation is performed by optical intensity modulation of a CW laser in an MZM. The transfer function of the MZM is a periodic function of the voltage at its bias port and the bias points of $V\pi/2$ and $3V\pi/2$ lead to transfer functions that are equal in magnitude, but opposite in slope. Hence, by switching the bias voltage between these two values, BPSK modulation is performed on each quadrature vector. Since the amplitude scaling for 16-QAM is performed electronically, *all*

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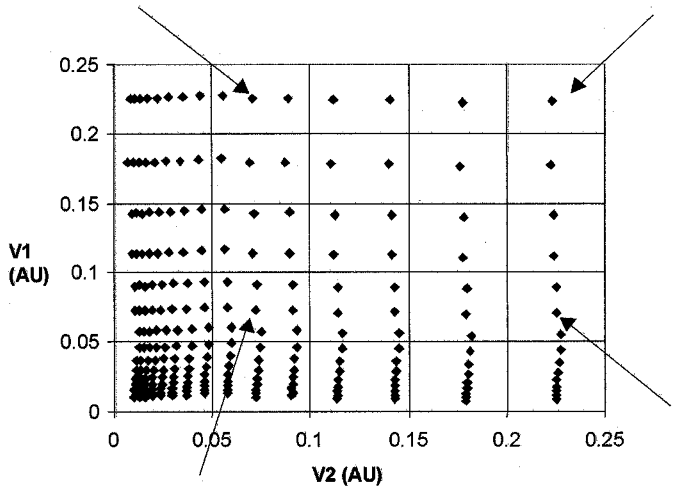

Fig. 2. Achievable single-quadrant vector locations (arrows indicate locations used for BPSK, QPSK, and 16-QAM).

signal constellation points for each modulation format considered in this work (BPSK, QPSK, and 16-QAM) are obtained with the system MZMs biased optimally in the linear region of their small signal transfer function. While a detailed dynamic range assessment of the MPVM is not presented here, the dynamic range characteristics of externally modulated analog fiber optic links are well documented [7].

In this work, Lucent Technologies 2623CSA MZMs with a 3-dB bandwidth of 10 GHz were used. Each MZM was driven at a nominal power level of 3 mW by a Lucent Technologies D2500 1.55 μm laser diode. The optical signals at the outputs of the MZMs were combined in a 3-dB fiber optic coupler and the signal was detected using an Agilent Technologes 83 440C 20 GHz photodiode. The resulting signal is a vector modulated microwave carrier. A 1 GHz LNA with 10 dB of gain was used after the photodiode to amplify the signal. No attempt was made to minimize the overall microwave insertion loss of the system that was measured to be 37 dB. Note that coherent mixing effects are eliminated by using two separate free-running (*i.e.,* nonfrequency-locked) lasers [4].

The digital control circuit, realized using a field programmable gate array (FPGA), processes the incoming data stream from a serial data generator to produce the appropriate control signals to dynamically drive the microwave attenuators and MZMs. The specific modulation obtained is a function of the mapping of the incoming serial data stream to the available vector locations. The control circuit was configured to produce Gray-coded BPSK, QPSK, or 16-QAM modulation. The FPGA outputs drove the microwave attenuators directly while high speed buffer amplifiers were used between the FPGA and the MZM bias tee.

III. Experimental Results

The system described in the previous section was tested dynamically using an Agilent 89 441A vector signal analyzer to assess the error vector magnitude (EVM) [8] of the modulated signal. Prior to performing these measurements, the system was calibrated to eliminate amplitude and phase imbalances associated with the various microwave and optical components. The small phase imbalance of the system was removed by phase trimming in the microwave path with a passive phase shifter. The small amplitude imbalance was removed by adjusting the drive level of the lasers to obtain equal vector lengths.

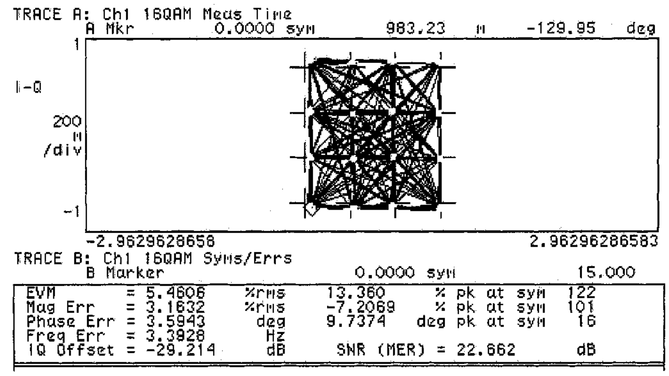

Fig. 3. Experimentally measured 16-QAM signal constellation diagram.

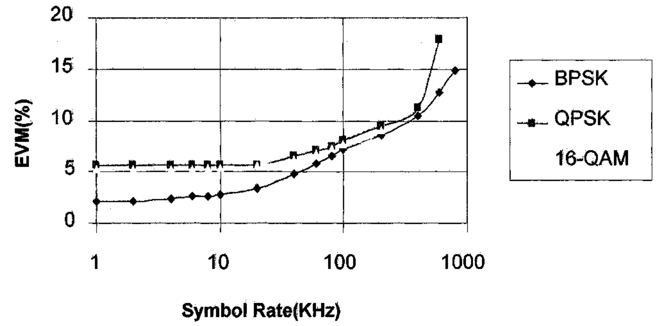

Fig. 4. Experimentally measured Error Vector Magnitude (EVM) for BPSK, QPSK, and 16-QAM.

The system was tested with BPSK, QPSK, and 16-QAM modulation and full functionality was obtained in all cases. The data rate was incremented from 1 kbs to 3.2 Mbs and was limited by the speed of the FPGA control circuit and the frequency response of the bias tees used with the MZMs. No attempt was made to control spectral emissions via baseband data filtering; this will be addressed in future work. A signal constellation diagram of the 16-QAM mode is shown in Fig. 3 at the 80 kbs data rate. Fig. 4 summarizes the measured EVM performance as a function of the symbol rate. At symbol rates of less than 100 kSymbols/sec, the 16-QAM EVM is only 7% rms, which would yield an acceptable bit-error-rate [8] for most digital wireless applications. However, at symbol rates of greater than 500 kSymbols/sec, there is a marked rise in the EVM of the BPSK mode that was correlated to the limited bias tee bandwidth. Similarly, the QPSK and 16-QAM modes show a sharp EVM degradation at approximately 500 kSymbols/sec. and 250 kSymbols/sec., respectively, corresponding to an input data rate of 1 Mbs in both cases. This degradation was correlated to the limited speed of the FPGA control circuit that ran with only a 2 MHz clock speed. The current speed limitations are easily circumvented by using a faster FPGA or custom control circuit and MZMs that have separate electrodes for the microwave and bias signals.

IV. Conclusion

This letter reports on a microwave photonic implementation of a vector modulator suitable for direct digital modulation of microwave carriers for high-speed wireless digital communications. BPSK, QPSK, and 16-QAM modulation were demonstrated at a carrier frequency of 1 GHz. The data rate of this proof-of-concept experiment was limited to approximately 3.2 Mbs due to hardware component availability. The data rate can be significantly increased by using MZMs that have separate electrodes for the microwave and bias signals and a faster control circuit. Moreover, it is possible to implement the amplitude control function in the optical domain via the use of optical intensity modulation of the I and Q signals. This may be accomplished by external intensity modulation or direct modulation of the semiconductor lasers enabling both the amplitude and phase control of the MPVM to be implemented photonically. This would result in speed performance improvements of at least two orders of magnitude and, due to the wide bandwidth of the MZMs, will simultaneously allow wideband frequency hopping of the carrier signal. Moreover, since MZMs can be designed for operation to 70 GHz [9], the technique can be used for direct digital modulation of millimeter wave carriers, thus greatly simplifying transmitter design at these frequencies. To the best of the author's knowledge, this level of performance has not been demonstrated using traditional microwave design. Finally, the MPVM lends itself to a high level of optical integration since the MZMs and the optical combiner may be integrated into a single optical circuit, thus greatly reducing the size and cost of the implementation. These features make the performance and cost benefits of the MPVM attractive as data rates and carrier frequencies constantly are pushed higher.

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