110 GHz Vector Modulator for Adaptive Software-Controlled Transmitters

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***Abstract*—A 110 GHz MMIC vector modulator for use in low-cost, high-performance, radar and communication transmitters is presented. The circuit consists of two push–pull (bi-phase) attenuators arranged in phase quadrature and has dimensions of 1.7×1.4 mm^2. The fabricated MMIC has been characterized by means of static S-parameter measurements and shows a minimum insertion loss of 12 dB at 110 GHz. Using these measurements, the required baseband input levels for a 64-QAM static constellation were determined. These levels were then applied at 10 MSample/s, by an arbitrary waveform generator, to demonstrate a 60 Mb/s data rate transmitter operating at 110 GHz. To date, this represents the highest reported RF frequency for direct multilevel carrier modulation using monolithic technology.**

***Index Terms*—Millimeter-wave integrated circuits, MMICs, vector modulation, W-band.**

I. INTRODUCTION

A GREAT deal of work has been undertaken recently on direct carrier modulation at millimeter-wave frequencies using monolithic technology [1]–[3]. This is because of its potential for reduced front-end hardware complexity, lower cost and increased modulation flexibility. By using an RF vector modulator, it is possible to generate arbitrary bandpass signals directly at the carrier frequency without the need for large and expensive upconverter chains. For short-range millimeter-wave radars and communications applications, the transmitter is further simplified because it would not require a power amplifier if a medium power diode source is used for the local oscillator. Moreover, with spectral sidelobe filtering performed by the vector modulator [4] there may also be no need for millimeter-wave filtering. By eliminating costly power amplification and filtering, the direct conversion approach using a vector modulator offers considerable cost savings.

Another major benefit of the vector modulator is its capacity to provide adaptive, multifunctional operation under software control. For example, the I–Q vector modulator can be used to perform: multilevel digital modulation, small-shift frequency translation, spectral sidelobe filtering, and even power amplifier linearization. Furthermore, it has been demonstrated that some of these functions can be performed simultaneously and that they can be made adaptive, under software control, for channel selection or switching between standards [4].

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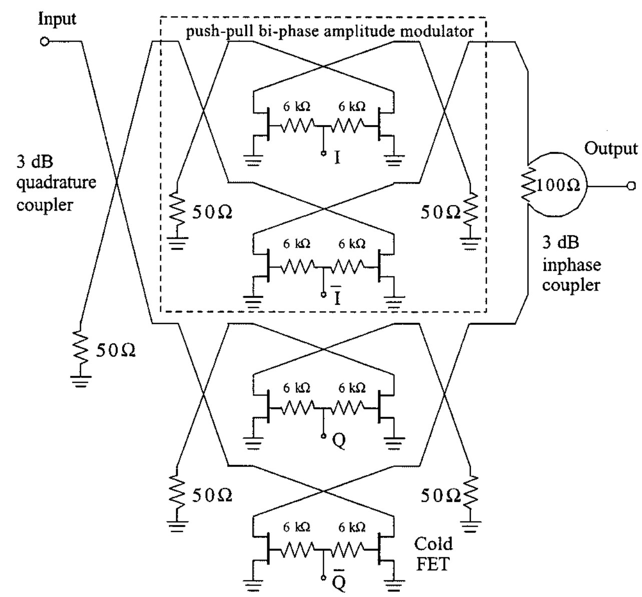


Fig. 1. Schematic of the I–Q (push–pull)vector modulator.

In this letter, a 110 GHz four-channel I–Q (push-pull) vector modulator is presented. The design employs two independently biased push–pull (bi-phase) amplitude modulators connected in phase quadrature. The basic biphase amplitude modulators themselves are based on an analog reflection topology [5] with cold-pHEMT's used as variable resistance terminations. This design approach has proven very successful up to frequencies as high as 76.5 GHz [1] and has been used to demonstrate a variety of direct carrier modulations; namely, 256-QAM, 32-PSK, and small-shift frequency translation [1]–[3].

II. VECTOR MODULATOR DESIGN

The 110 GHz I–Q (push-pull) vector modulator, shown in Fig. 1, is a passive circuit comprising a combination of three basic circuit elements; namely, nine Lange couplers, one in-phase power combiner, and eight cold-pHEMT terminations. The RF signal entering the input port is split into two orthogonal (i.e., I and Q) channels and modulated independently by two push–pull (bi-phase) amplitude modulators. The resulting signals are then recombined in-phase at the output. In principle, any arbitrary transmission amplitude and phase can be obtained with a minimum theoretical insertion loss of 6 dB. Due to ohmic and radiation losses and imperfections in the terminations, the minimum insertion loss can be much higher. The fundamental component in this vector modulator is a basic

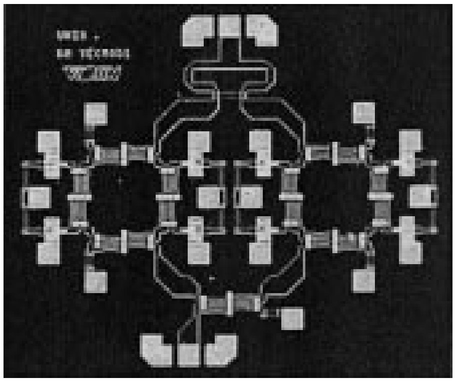
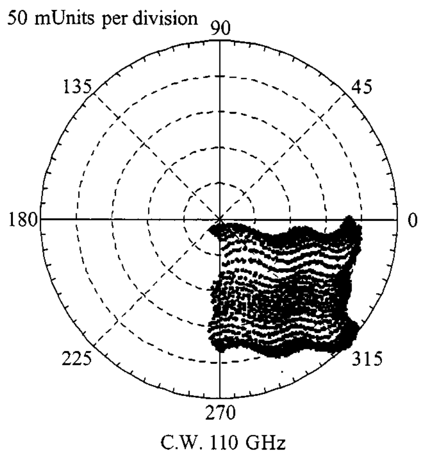
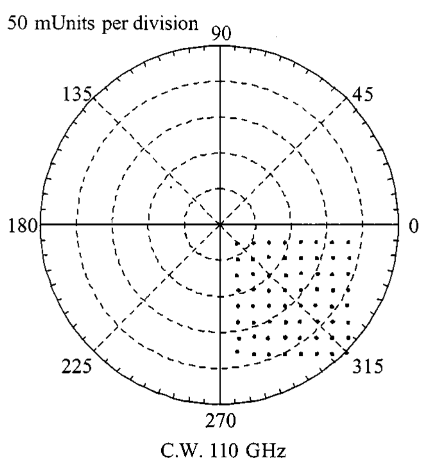


Fig. 2. Microphotograph of the 110 GHz I–Q (push-pull) vector modulator.

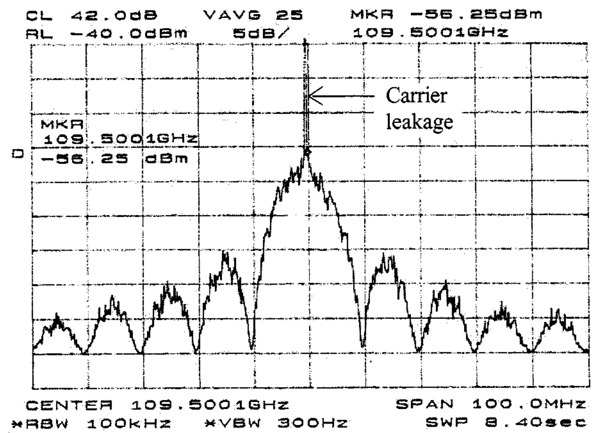


(a)

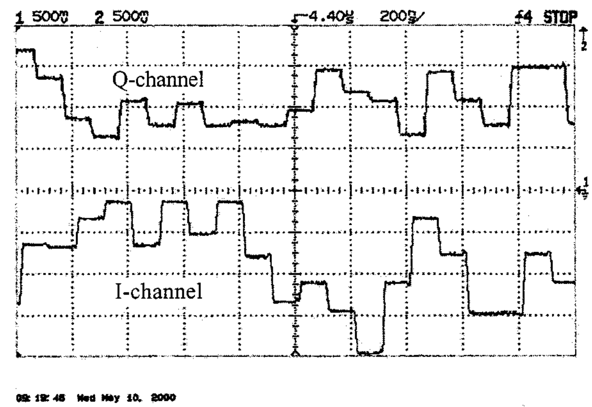


(b)

Fig. 3. Measured static constellation of the vector modulator (a) with swept bias voltage control (b) software selected and generated 64-QAM.



(a)



(b)

Fig. 4. The 64-QAM modulation with 60 Mb/s pseudo-random data at 110 GHz: b(a) spectral response and (b) I and Q baseband signals.

bi-phase reflection-type modulator [5], which consists of a 50 Ω Lange coupler and two cold-pHEMT's. If the gate-to-source biases applied to the pHEMT's are varied identically and the coupler is ideal, the modulator will always be perfectly matched and will have a transmission response exactly equal to the reflection coefficients presented by the terminations. Consequently, the modulator's performance is largely dictated by the range over which the drain-to-source impedance of the pHEMT's can be varied.

Ideally, for devices with a large drain-to-source resistance variation and small capacitance variation, full bi-phase operation with negligible insertion phase variation is possible. However, at W-band frequencies, the observed variation in resistance for most conventional pHEMT devices is small and the capacitance is quite significant. Consequently, the range of attenuation is small and the insertion phase varies substantially with applied bias. If two basic (i.e., non-ideal) bi-phase reflection-type amplitude modulators are arranged in a push–pull configuration, requiring two additional quadrature couplers, and they are supplied with complimentary control signals, the range of attenuation can be improved and the insertion phase variation suppressed.

Based on the preceding principles, a 110 GHz vector modulator was designed with microstrip on 100-μm thick GaAs and 0.25-μm gate length AlGaAs/InGaAs pHEMT devices, with two-finger by 50-μm gate width geometry. Although it might appear preferable to have a device with a shorter gate length, this does nothing to increase the range of variation of the critical drain-to-source impedance. The only advantage is a lower gate capacitance, which would permit higher rates of modulation. The final chip, shown in Fig. 2, was fabricated with EONCOM

Ltd.'s GaAs pHEMT MMIC foundry process and has dimensions of 1.7×1.4 mm^2.

III. RESULTS

The static constellation and frequency response of the vector modulator were measured using the new Agilent 8510XF network analyzer at the University of Surrey. The complete transmission response for the vector modulator is shown in Fig. 3(a), where the I and Q control voltages have been swept from -2 V to 0 V, in steps of 0.016 V. The response is shifted into the fourth quadrant by a bias-invariant "leakage" vector arising from inadequate isolation in the Lange couplers. At 110 GHz, the length of the couplers decreases with respect to the width and spacing of the interdigitated fingers. Airbridges and port connections, which are insignificant at lower frequencies, become electrically larger and now contribute to the coupler's characteristics. These problems could be completely eliminated by using a branch-line coupler, but at the expense of a reduced bandwidth.

From the swept values above, a 64-QAM constellation was extracted and appears, as shown in Fig. 3(b). Assuming the constellation is centered at the origin, the minimum insertion loss for the device is 12 dB, with a ± 0.4 dB variation over a 2 GHz bandwidth. This is significantly greater than the 6 dB theoretical minimum, because the variation in the real component of the drain-to-source impedance of the pHEMTs' is still quite small. The worst-case input return loss is 8 dB and the worst-case output return loss is 11 dB, over all states. Fig. 4 shows the 64-QAM spectral response of the vector modulator along with the predistorted baseband signals for a symbol rate of 10 MSample/s (or 60 Mb/s data rate). The presence of the carrier is due to the signal leakage effect described above.

IV. CONCLUSIONS

A 110 GHz vector modulator, based on two push–pull (biphase) attenuators, has been fabricated and tested. This indicates that a design approach, previously intended for microwave frequencies can be applied successfully to the edge of D-band. The circuit itself is a relatively simple and compact design. Since the devices are biased in a resistive mode, it also promises to be a high yield circuit with little sensitivity to temperature and production spread. The vector modulator has the potential for improving the performance of low-cost millimeter-wave radar and communications applications. By demonstrating real analog signal processing at 110 GHz, this work opens up new possibilities for terahertz electronics.

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