A FULLY MONOLITHIC 4-18 GHZ DIGITAL VECTOR MODULATOR

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ABSTRACT

A fully monolithic vector modulator covering the entire 4-18 GHz band is presented that features independent direct digital control of amplitude and phase. The modulator output amplitude can be varied over a 25 dB range with 32 steps of resolution and the phase can be independently varied over 360° with 32 steps. The vector modulator chip set consists of a miniaturized 5 bit MMIC phase shifter and a 5 bit MMIC segmented dual gate distributed variable gain amplifier/attenuator. The chips are assembled on a carrier measuring less than 0.4" x 0.5" and require no supporting RF hybrid or DAC circuitry. The vector modulator demonstrates state-of-the-art performance with ultrawide (instantaneous) bandwidth, high uncorrected accuracy and resolution, and direct digital control with a potential transition time of a few nanoseconds. In addition, the individual MMIC chip performance is the best reported to date for ultrawide bandwidth phase and amplitude control functions.

INTRODUCTION

Amplitude and phase modulation of microwave signals is needed for phased arrays, electronic warfare systems, digital communications, and measurement systems. The performance, size, and cost of this vector modulator enable improved systems solutions to be realized. For example, the vector modulator could function in a digital communications system with a wide modulation bandwidth by choosing appropriate states to accommodate quadrature amplitude modulation (QAM) techniques. This permits direct encoding of data on the RF carrier, simplifying the system. Other benefits to the system include the potential for multiple band coverage and frequency agility, such as for frequency-hopped spread spectrum modulation, with fewer components. Benefits to an ECM or radar system include a greatly reduced need for complicated driver circuitry incorporating look up tables, and wideband modes of operation previously unavailable.

The vector modulator is implemented by a direct cascade of three MMIC chips. As shown in Figure 1,

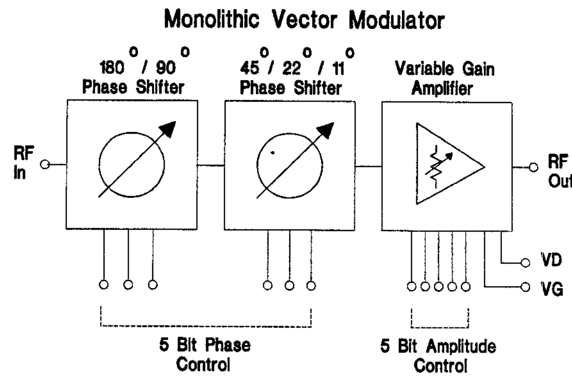

Figure 1. Block Diagram of the Vector Modulator

this consists of two and three bit phase shifters followed by a variable gain amplifier, all with direct digital (0V or -5V) control inputs. Unlike narrow band approaches [1,2], separate phase and amplitude functions are typically required for broadband performance with independent control of amplitude and phase [3-6]. Each of the MMIC chips was optimized for high phase or amplitude resolution with minimal relative variation over frequency, high instantaneous bandwidth, low VSWR, minimum insertion loss, and minimum incidental phase or amplitude change with desired amplitude or phase setting. In addition, high transition speed, small physical size, low power consumption, minimal need for component matching, low cost, and minimal control complexity are important systems considerations and are well served by the all MMIC approach. A major advantage of this approach is that it does not require hybrid couplers together with close MMIC chip matching to achieve good performance (at a penalty of large size and high cost) nor does it require extensive error correction routines to compensate for performance inadequacies such as phase/amplitude control interdependency or variation with frequency.

5 BIT MMIC PHASE SHIFTER

The phase shifter used in this vector modulator is a redesign of previously reported work [3]

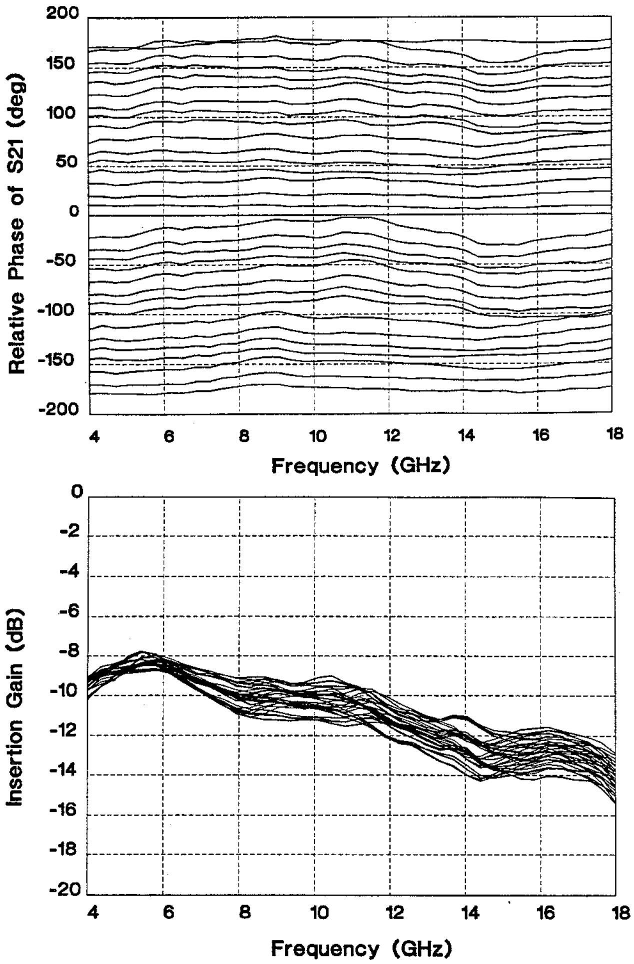

Figure 2. Measured Phase Shift in degrees (a) and Insertion Loss in -dB (b) of the Compact MMIC 5 Bit Phase Shifter Chip Set over all 32 states.

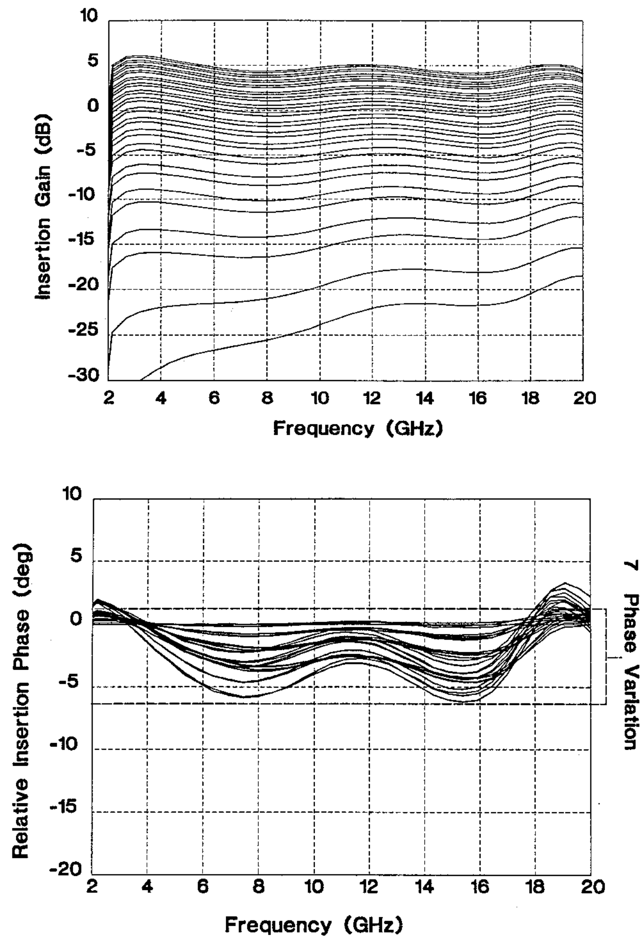

Figure 3. Insertion Gain in dB (a) and Incidental Phase Shift in degrees (b) of the MMIC Variable Gain Amplifier/Attenuator Chip. The Phase Shift is shown over 26 states (14 dB of dynamic range).

undertaken to significantly reduce the circuit die size. The 5 bit phase shifter was designed on two chips, one containing the 180° and 90° bits, the other containing the 45°, 22.5°, and 11.25° bits. The two chip approach increases both the processing yield and the circuit application versatility, and provided less risk for the size reduction redesign. The area of the new chip set is half the size of the previous version, measuring 251 x 133 mils. The measured performance of the compact 5 bit phase shifter is shown in Figure 2, and is similar to the current state-of-the-art results for the larger version. This chip set utilizes direct digital inputs to control switching MESFETs and dissipates negligible levels of power for control.

MMIC VARIABLE GAIN AMPLIFIER/ATTENUATOR

The variable gain amplifier/attenuator utilizes ion implanted 0.5 micron segmented dual gate FETs in a distributed amplifier configuration. Each FET is divided into 5 individual segments whose peripheries are 6.5, 13, 26, 52, and 104 microns. The first gate is fed by an RF input bus while each second gate is individually grounded via separate thin film capacitors to provide a cascode FET with separately controllable segments. Control voltages applied to the second gates completely turn each segment on or off. This provides a FET transconductance characteristic which is highly linear with respect to a digital control word formed directly from the set of high or low second gate biases [4]. Digital control reduces sensitivity to FET gate recess variations when compared to analog control of a standard dual gate FET. The incidental phase shift with gain control state is minimized, allowing the straightforward implementation of a vector modulator with independent phase and attenuation sections.

The measured performance of the amplifier/attenuator is shown in Figure 3. The device provides 4.5 $\pm$ 0.5 dB of gain in the maximum gain state with better than 9 dB output return loss and 8 dB input return loss. The maximum attenuation range is better than 25 dB over the entire 4-18 GHz band. The device maintains monotonic attenuation control for all

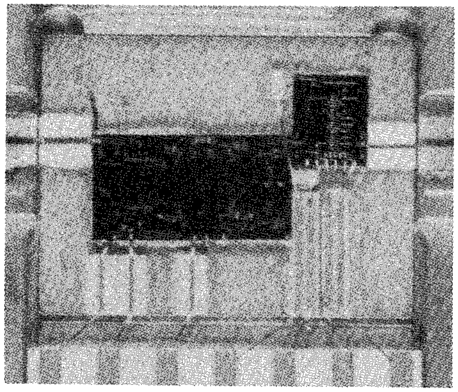

Figure 4. Photograph of the 4-18 GHz Vector Modulator Chip Set on CuW Carrier.

states. Over a dynamic range of 12 dB, 26 gain/attenuation states are available with an incidental phase shift variation of less than 8°. The variable gain amplifier/attenuator operates with 5V of drain voltage and typically draws 80-100 mA of current when operated at approximately 1/2 of I_{dss}. The chip measures 97 by 118 mils.

VECTOR MODULATOR PERFORMANCE

A photograph of a prototype vector modulator assembly is shown in figure 4. The three chips of the vector modulator were eutectically die attached to a 0.38" x 0.5" carrier, which was packaged in an available housing that provided 9 pins for application of DC bias, phase shifter control, and gain control. While this number of control pins did not permit the testing of every available state, 16 states using 2 phase shifter bits and 2 amplitude control bits of the vector modulator were measured.

The performance of the 16 measured states of the vector modulator is shown in Figure 5 from 4-18 GHz and is not corrected for package effects. In Figure 6, the measured complex S21 for each of the 16 states is normalized with respect to one state of the device over the 4-18 GHz band and plotted on a polar chart. The measured minimum loss of the vector modulator was less than 13 dB worst case, and the input and output VSWRs were less than 3:1.

A full analysis of the vector modulator was performed by cascading the measured data of the phase shifter and variable gain amplifier chips to show the performance of the vector modulator in every state. The analysis was verified by comparison to the 16 measured states. The results are plotted in Figure 7 at 6 GHz and 15 GHz showing the insertion phase and gain at each state. The RMS phase and amplitude errors for the vector modulator chip set are shown in Figure 8 and are less than 9° (6° typical) and 1.5 dB across the 4 to 18 GHz band. Note that the RMS phase errors are the highest for the data plotted in Figure 5b. The independence of the amplitude and phase controls is evident. While modulation frequencies are currently limited by low pass RC

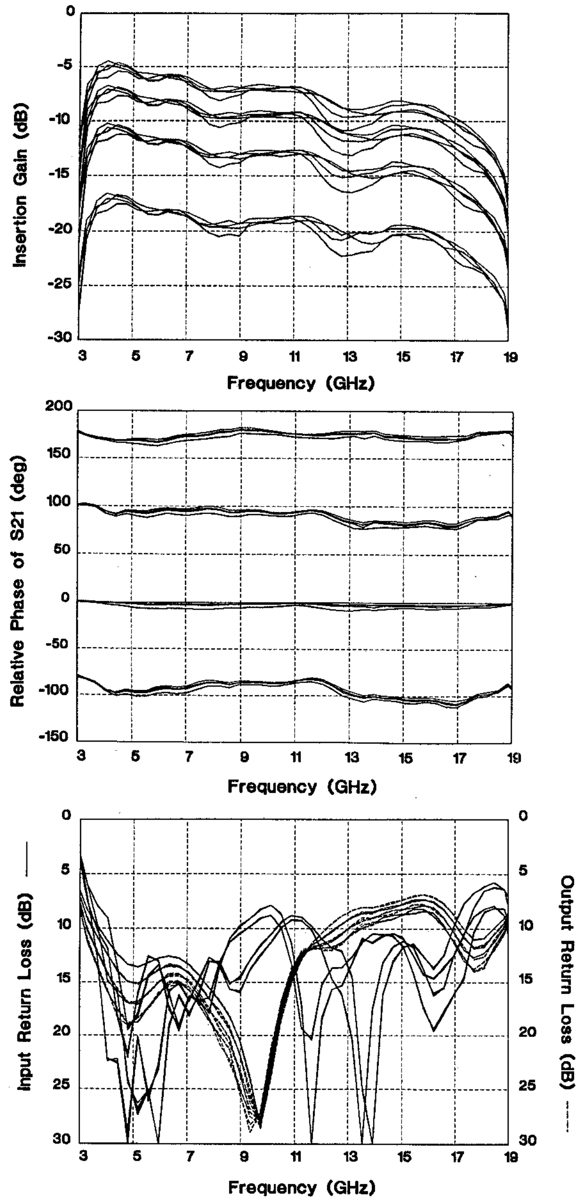

Figure 5. Measured S-Parameters of the Vector Modulator over 16 States (4 Phase x 4 Amplitude) from 4 to 18 GHz.

filtering on each MMIC chip to roughly 25MHz, transition times of several nanoseconds are easily obtainable with reduced resistance values without compromising RF performance.

SUMMARY

A vector modulator has been demonstrated with highly independent direct digital control of amplitude and phase over an instantaneous 4 to 18 GHz bandwidth. State-of-the-art performance was measured for this MMIC-based device. The vector modulator has potential for improving the performance and reducing costs of a wide variety of systems.

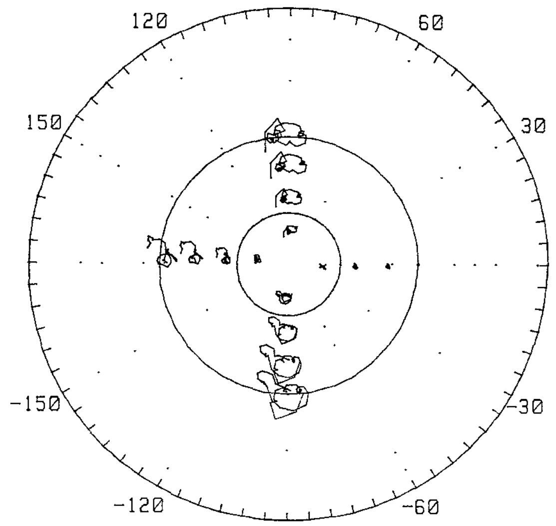

Figure 6. Measured S21 of the Vector Modulator in 16 States Normalized to the Phase and Gain of One of the States at each Frequency. The Reference Circles are at 0 and -8 dB and the Frequency Range is 3.3-18.9 GHz.

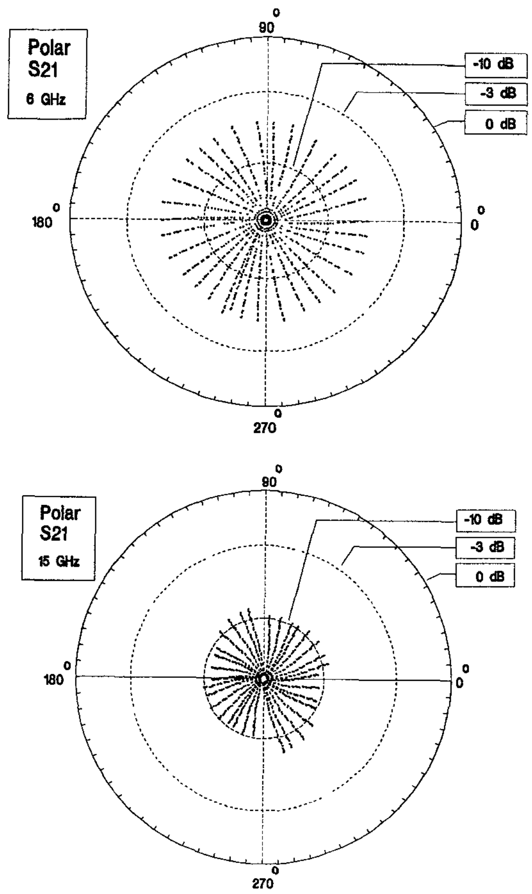

Figure 7. Cascaded Measured Chip Data to Show Vector Modulator Performance in Every State (1024 States) at 6 GHz (a) and 15 GHz (b).

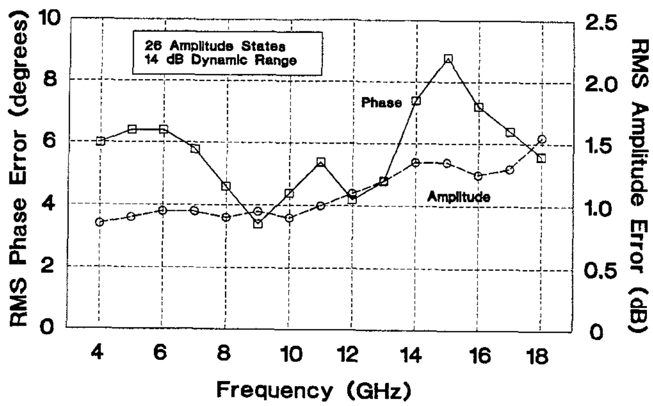

Figure 8. Uncorrected RMS Phase and Amplitude Errors of Cascaded Vector Modulator Chip Set averaged over 32 Phase and 26 Amplitude States.

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