A VERSATILE VECTOR MODULATOR DESIGN FOR MMIC

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ABSTRACT

A single chip, MMIC vector modulator designed for use in an X band phased array radar system is described. The design principle is capable of addressing octave bandwidths and frequencies up into the mm wave region. The circuit is novel in that it is purely passive, using unpowered FETs as the control elements. It is therefore low noise and expected to be capable of handling relatively large RF signal levels of up to 1W. Analogue control of the vector extends over a range of more than 30 dB for amplitude and over 0-360 degrees for phase. Swept frequency, measured phase errors are lower than +/-10 deg for a 10% instantaneous bandwidth anywhere in X-band (8-12GHz).

INTRODUCTION

There is an increasing demand for high performance vector modulators in several types of modern microwave system. They are an essential component in phased arrays, in smart jammers and in certain types of FMCW radar. This paper describes a new type of vector modulator, two versions of which have been fabricated. The first is in hybrid technology and the second is a monolithic microwave integrated circuit (MMIC) on GaAs.

The hybrid version was a feasibility demonstrator for the MMIC and operates over approximately a 1 GHz frequency bandwidth from 9.5 to 10.5 GHz but the basic circuit concept is sufficiently versatile to be used over wider bandwidths and at frequencies up into the mm wave region. The monolithic version has been fabricated as a single chip measuring 3x4mm and can be set to operate over a 10% instantaneous bandwidth anywhere in the overall operating frequency range of 8-12 GHz. It offers considerable advantages in terms of size, cost and unit-to-unit performance tracking. Measured results and design details of both versions will be presented.

DESIGN PRINCIPLES

A block diagram of the basic vector modulator is shown in Fig 1. The first power splitter splits the input signal into two orthogonal components, I and Q. These two components (vectors) are adjusted in amplitude and sense by a pair of modified bi-phase modulators, each one of which comprises a quadrature power splitter and a pair of variable resistance terminations. When the terminations of the modulators are a low resistance, signals are strongly reflected with a phase inversion. When they are high in resistance, signals are strongly reflected with no phase inversion and when the resistances approach 50 ohms, the reflected signals tend to zero. Combining these two signal components in a simple power combiner completes the modulator function. A more general description of I-Q vector modulators can be found in reference 1.

The new modulator is a significant departure from previous designs in that it uses variable resistance elements instead of switches in the bi-phase modulators. This removes the need for an additional pair of variable attenuators which would consume an unacceptable area of GaAs on an MMIC. PIN diodes are an obvious first choice for the variable resistance elements but whilst these are available as discrete devices, they are not generally available in GaAs MMICs. FETs have therefore been used as an alternative and when DC biased with zero drain voltage, they have been shown to be capable of performing the same task. The drain/source port of the FET replaces the PIN diode and the gate becomes the control electrode. As a shunt element, the drain of the FET approximates a parallel combination of a variable resistor and capacitor (2). Changes in gate/source bias between zero and the pinch off voltage alter the thickness of the conducting channel which in turn changes the resistance. There are small changes in capacitance but most of the effects of the capacitance can be removed by suitable tuning. More design details will be given during the description of the MMIC in the following section.

The new design approach results in a modulator which has several important and attractive characteristics. Firstly, it is ideally suited to realisation as an MMIC on GaAs. Being accommodated on a single chip, it is both low cost and highly reproducible. Secondly, control of phase and amplitude is not quantised but is continuous over 0 to 360 degrees and -10 to -50dB respectively. Thirdly, no power from any supply is consumed by the modulator since it is a passive circuit. Although the control elements are microwave MESFETs, their drains are held at a DC voltage of zero. Control of the modulator is by application of negative bias voltage to the gates. Fourthly, as a passive circuit, the modulator is capable of handling large levels of RF input signal. It was designed to control input powers as high as 1 W, well in excess of the level an active circuit could be expected to handle. Fifthly, compared with an active circuit, the modulator has a superior noise performance. Being passive, it adds little excess noise over and above KTB. Finally, the modulator is high speed and capable of operating with wide modulation bandwidths (e.g several GHz).

PHYSICAL REALISATION & PERFORMANCE

A vector modulator has been fabricated as an MMIC using the commercial Philips Microwave GaAs Foundry. A photograph of the 4x3 mm chip is shown in Fig 2. An input carrier will enter the modulator at the left of the picture. It is split by the first of the Lange couplers into the two orthoganal components which then pass to the two variable bi-phase modulators. Another Lange coupler in each bi-phase element, then splits the signals yet again before delivery to the variable reflections loads. All the Lange couplers in the circuit have a -2.8 dB coupling ratio and length corresponding to a centre frequency of 9.5 GHz.

The variable reflection loads comprise a FET of 0.7 micron gate length and 600 micron gate width, together with tuning stubs both on the gate and drain terminals. Gate width is chosen such that the value of Idss (Ids @ Vgs=0) exceeds the current produced in a short circuit by 0.25 watts of incident power in a 50 ohm system. Network analyser RF measurements performed on similar 600 micron FETs with zero drain voltage lead to an approximate equivalent circuit model for the drain of the FET. The capacitive element of this is then tuned by the tuning stub connected to the drain, which at its remote end is connected to ground by a via hole. This particular tuning arrangement is largely responsible for the present 10% limit on instantaneous frequency bandwidth for the modulator. The gate of the FET is presented with an open circuit at RF by a quarter wavelength line which is de-coupled to ground by an MIM capacitor. Gate DC bias is applied at this point. The last element in the modulator is a conventional, in-phase power combiner complete with integral resistor.

The other version of the modulator in hybrid technology has been constructed with branch line couplers and this is shown in Fig 2. Branch line couplers have a more restricted bandwidth than Lange couplers but they are comparatively easy to fabricate.

Measurement procedures for vector modulators depend heavily on the practical application. However, before making application-specific measurements on the vector modulators, assessments can be made of their basic function as controllers of amplitude and phase using a microwave network analyser.

A series of measurements have been performed on the MMIC vector modulator with an HP 8510 network analyser. Measurements of terminal reflections showed input match to be better than 15 dB and output match to be better than 10 dB over the whole of X band (8-12 GHz).

An indication of the ability of the modulator to generate a vector of arbitrary phase and hold the value of phase over a band of frequencies, is given in Fig 4. Phase was measured over the frequency range from 8.5 to 10.5 GHz after setting phase to various different values at the centre of the band. The amplitude of the vector was set to -12 dB in each case. For a 10% instantaneous bandwidth, the variation in phase is less than +/- 10 degrees. Both I and Q control voltages were adjusted over a range of approximately 1.0 volts to achieve the full set of phase values. In a similar measurement over the same bandwidth, when phase is fixed for a number of amplitude settings, variation in amplitude is less than +/- 0.25 dB for amplitude settings between 0 and -20 dB. For higher levels of attenuation the amplitude variation increases slightly and at an amplitude setting of -30 dB the variation is about 2 dB at the edges of the band. This is shown in Fig 5.

The 10% instantaneous bandwidth of the modulators refers to specific limits on phase errors of +/- 10 degrees. Setting the position of the 10% window anywhere in X band is achieved by applying the appropriate control voltages. As verification that the modulator can operate in a different part of X band, measurements were also performed over 10.5-12.5 GHz. In an attempt to show simultaneously how vector amplitude and phase vary with frequency, the modulator was set, in turn, to eight arbitrary vector values. At mid band these were: 10 dB of attenuation with +45, +135, -45 and -135 degrees of phase shift, followed by 15 dB of attenuation with 0, +90, 180 and -90 degrees of phase shift. The variation from these settings across this frequency band can be seen in the polar plot Fig 6. It is interesting to note that the variations in amplitude and phase are different for different vector settings. This phenomenon is associated with the change in behaviour of the bi-phase elements of the modulator at different frequencies.

Fig 7 shows the variation in amplitude and phase of the 0 & 90 degree, I and Q vectors with control voltage, measured at 11.5 GHz. Each of the I and Q components of the output vector could be adjusted over more than a 30 dB dynamic range and by adjusting the controls for both vectors, the whole modulator demonstrated more than a 40 dB dynamic range.

APPLICATION TESTING

Tests specific to two different applications have been carried out on the hybrid modulator. These are described below. Similar tests will be carried out on the MMIC modulator which, owing to the closer tracking of the I and Q channels, should demonstrate still better performance.

The hybrid vector modulator has been tested in a signal cancellation loop of the type used in an FMCW radar. It is the function of the loop to cancel the miss-match reflection from the antenna and with the hybrid modulator installed, the loop suppressed reflections by approximately 50 dB. Its ability to handle large signal levels was demonstrated in the experiment during which input power to the modulator was 1 W.

In connection with the second application, the modulator was tested as a single sideband upconverter. For this two quadrature sinusoidal control voltages were applied to the modulator, one for each of the I and Q components. If a carrier, at frequency fc, is applied to the input of the modulator and the sinusoid control voltages are at frequency fm, then a single side-frequency is produced at the output of the modulator at a frequency of either fc-fm or fc+fm, depending on which of the two control voltages is leading. Several experiments of this kind have been performed on the hybrid modulator. One of the results is given Fig 8 which shows the measured output spectrum of the modulator for an input signal of 9.5 GHz and a modulation frequency of 1.1 MHz. The original carrier component is at the centre of the picture and is at a level of -40 dB with respect to the new side-frequency. These measurements have demonstrated the modulator's capability to generate false, or ghost targets in ECM applications.

CONCLUSIONS

Practical, passive vector modulator designs in both hybrid and MMIC technology have been described. Measurements of the modulators have verified the performance advantages that were expected to be gained from the new design concept. Low amplitude and phase errors have been demonstrated. Realisation of the modulator as an MMIC offers advantages in terms of size, cost, weight, reproducibility and channel tracking. These factors are critical to multi-channel systems such as phased arrays.

The new vector modulator design has already demonstrated its potential for use in an FMCW radar. In the near future, it should also find itself employed in other important microwave systems.

ACKNOWLEDGEMENTS

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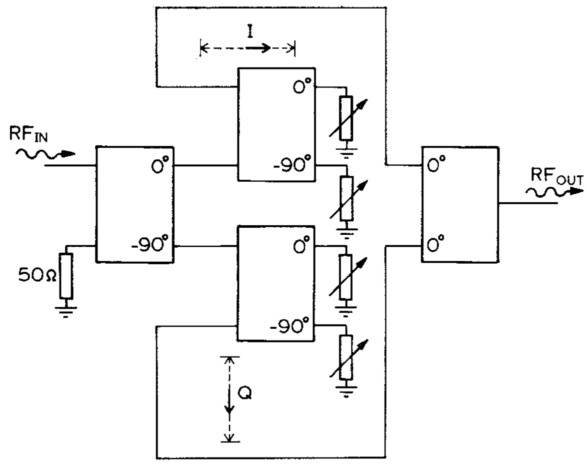

Figure 1. Basic I-Q Vector Modulator.

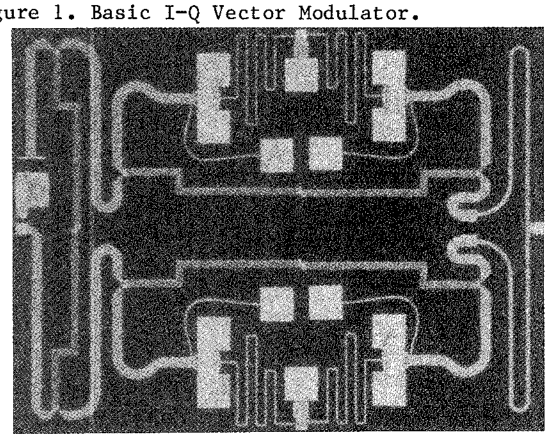

Figure 2. Photograph of an MMIC Vector Modulator.

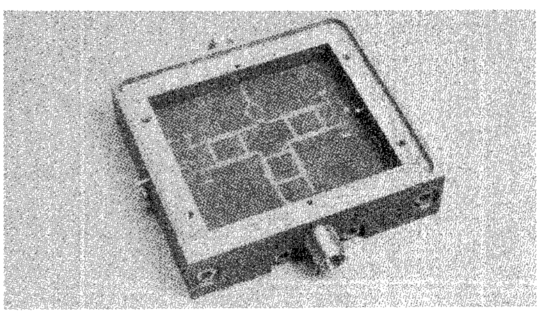

Figure 3. Photograph of the MIC Vector Modulator.

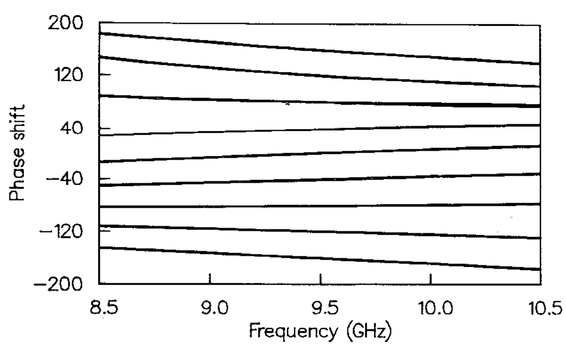

Figure 4. Measured Phase Shift of MMIC with Frequency.

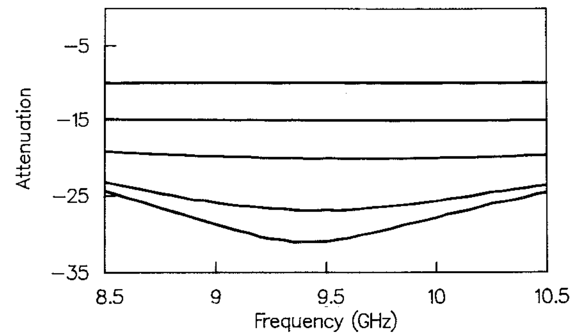

Figure 5. Measured Amplitude Variation of MMIC with Frequency.

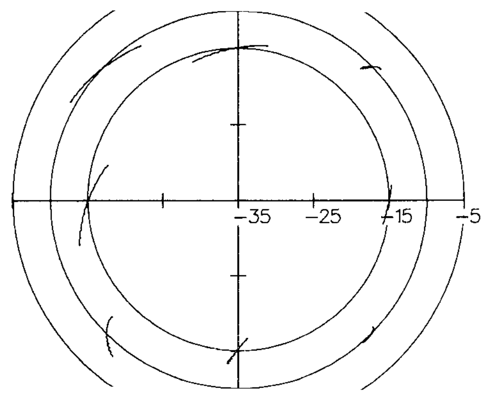

Figure 6. The Variation of Arbitrary Vectors with Frequency (10.5 - 12.5 GHz).

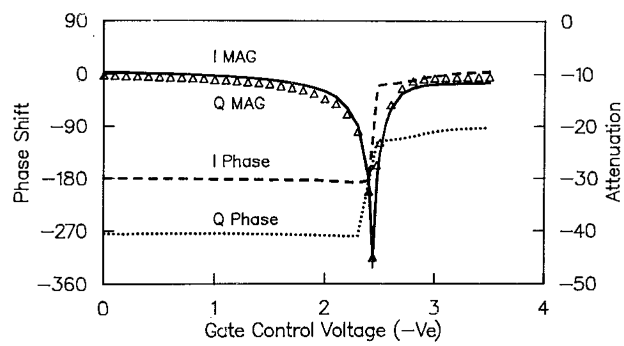

Figure 7. Variation of the I and Q Vectors with Control Voltage (11.5 GHz).

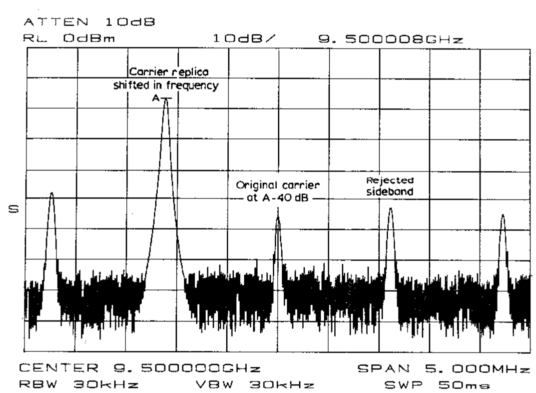

Figure 8. Vector Modulator Performing Frequency Translation.