GaAs PHASE-COHERENT MICROWAVE MULTIPLE-SIGNAL GENERATION USING ALL-PASS NETWORKS

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ABSTRACT

All-pass network techniques have made it possible to realize very small monolithic lumped active phase shifters with decade bandwidth, high yield, and relative phase stability, even when the device parameters vary ±20%. We have successfully demonstrated fully monolithic first-order networks (at 250 MHz) and second-order networks (at 4 GHz).

INTRODUCTION

Microwave phased array systems traditionally have been designed with a binary set of phase shifters using distributed components, however applying those techniques to monolithic integrated circuits results in comparatively large chip size for frequencies below about 6 GHz. This problem has caused strong interest in using lumped circuit techniques that enable chip size to be drastically reduced. Yet lumped phase shifters that depend on precise absolute values of device parameters often have low yield. In searching for an alternative for monolithic implementation, we selected a pair of modulators driven by two sets of signals that maintain a 90° phase difference across the operating band. The modulators were constructed in segmented form and were described in previous papers [1, 2].

The constant phase difference networks are a monolithic version of a circuit first proposed by R.B. Dome in 1946 for generating single sideband modulation with audio frequencies [3]. The circuit consists of pairs of all-pass networks with only capacitors, resistors, and active elements. The poles and zeroes of the transmission function lie on the real axis of the complex frequency plane, and the number of such pole and zero pairs determines the relative bandwidth over which the network will function with a small phase error. A first-order network with a single pole-zero pair is a possibility for narrowband applications, while a second-order network can maintain a constant phase difference of 90° over a relative bandwidth of as much as 10 to 1, depending on the allowable errors in phase tracking.

An interesting property of the circuit is that the phase coherence of the multiple outputs is primarily dependent on the ratio of resistor or capacitor values. This characteristic is ideal for monolithic technology where the ratio of parameters is accurately determined by topological mask design, while the absolute value is a function of doping levels and deposition rates.

In addition, the magnitude of the needed capacitance decreases with increasing frequency. To implement the all-pass networks at 5 GHz, for example, capacitance values well under one picofarad are needed. In fact, only in a monolithic circuit are the unavoidable stray capacitances sufficiently small in comparison to make such a circuit feasible.

The following sections of this paper report the design, fabrication, and evaluation of a first-order network intended for the 220 to 280 MHz frequency range and a second-order implementation for the 3 to 5 GHz range. Both networks were designed to generate four output signals having relative phase of 0°, 90°, 180°, and 270°. Digitally-controlled on-chip RF switches enable the selection of four pairs of output signals, i.e., 0° and 90°; 90° and 180°; 180° and 270°; 270° and 0°. When either of the resulting vector generators are cascaded with the previously reported sine/cosine scalar element [1, 2], the result is a complete 0°-360°, five-bit phase shifter.

THEORETICAL CONSIDERATIONS

The four resistors and four capacitors, shown within the dotted lines in Figure 1, constitute a basic first-order all-pass network in which the relative RC time constants are designed to generate the required four signals which are 90° apart from one another in phase. The four signals are switched to the two output ports with digitally-controlled GaAs FET RF switches. The all-pass network must be driven by two balanced, complementary RF signal sources of relatively low impedance. GaAs FET source-followers are used to provide the low impedance sources. The symmetry of the configuration ensures that these input source-followers are loaded by equal impedances. The frequency dependence of this finite load impedance will result in a slightly frequency-

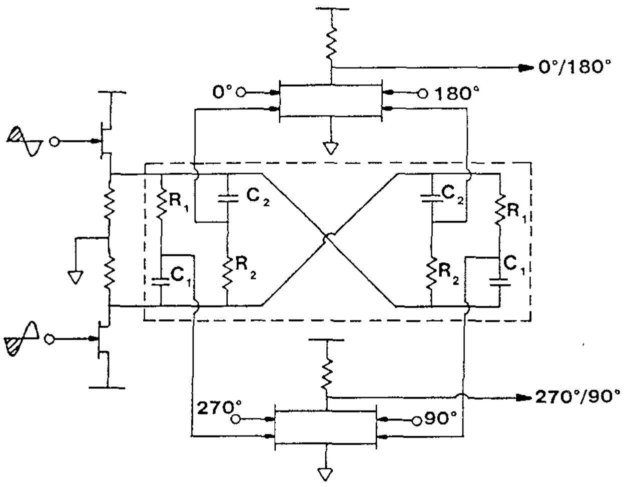

Figure 1. Vector Generator Using First-Order All-Pass Network

dependent amplitude response equally in all four output channels without affecting the relative phase and amplitude relationships among the channels.

The mode of operation for this type of network can be explained with the help of the voltage vector diagram of Figure 2. The amplitude of the output vector is independent of freqency. When the two networks are designed properly, one network has a phase shift of 45° and the other of 135° at the center of the operating frequency band.

A circuit configuration using a first-order network shows a phase response with a single peak. By selecting the element values so that the phase difference between the two branches exceeds the desired value of 90° by a small amount at the center, the circuit will operate over a certain band of frequencies without the phase error exceeding this amount. For example, for a one degree error at the center, the circuit will cover a 1.7 bandwidth ratio.

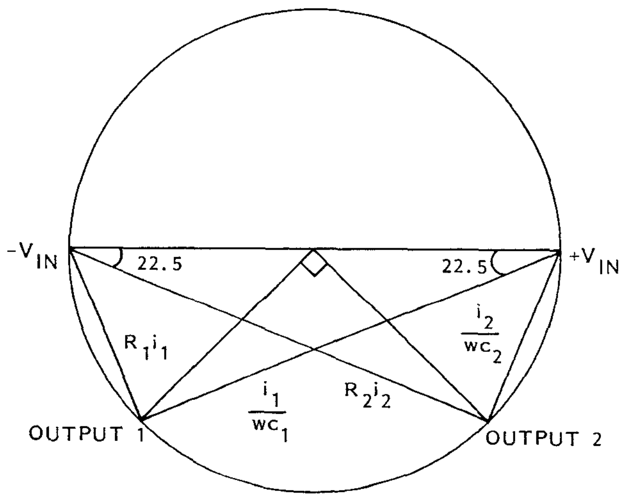

Figure 2. Voltage Vector Diagram of an RC All-Pass Filter

A second-order network can be created by cascading two first-order networks or by replacing the network shown within the dotted lines in Figure 1 with the network shown in Figure 3. However one disadvantage of this network is its greater insertion loss. On the other hand its apparent greater complexity is of little concern in a monolithic realization, since the small resistors and capacitors consume little room on the substrate.

The theory for computing the location of the poles and the zeroes of the transfer function has been described in previous papers [1, 4, 5]. In particular Donald Weaver shows a systematic numerical approach for deriving their locations [5]. For applications in which second-order networks satisfy the bandwidth requirements, simpler, more direct iterative computer programs can be used, since a second-order network has only two independent numerical values that must be selected. These independent values are, first, the ratio between the pole locations of both networks and, second, the ratio of the center frequencies of the two networks.

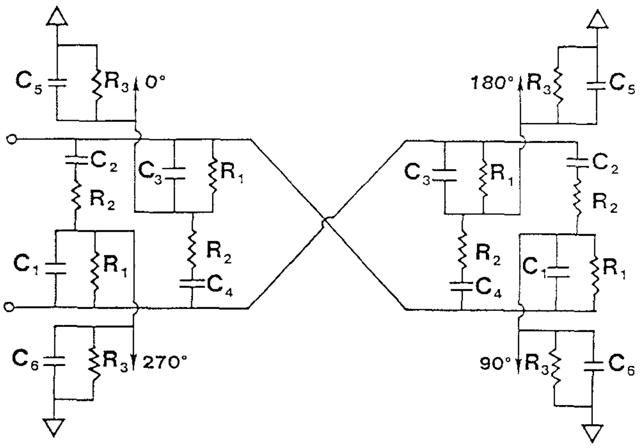

Figure 3. Second-Order All-Pass Network

THE PHASE SPLITTER

The phase splitter that generates the two out of phase signals, shown in Figure 4, consists of an initial approximate phase splitter followed by differential pairs that have more gain for the odd mode than for the even mode. Since the even mode component represents the deviation from a perfect split, the quality of the signal improves with each stage of differential gain. The initial split load-resistor phase splitter gives a less than perfect split as a result of the presence of a finite gate current. However the capacitance component of this gate current is partially compensated for by the small capacitor shunting the source load-resistance.

CIRCUIT IMPLEMENTATIONS

Figure 5 presents a photograph of the VG-2 cell, which is an implementation of the first-order

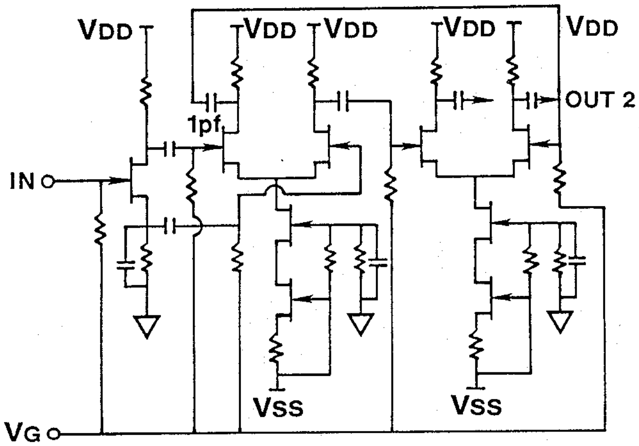

Figure 4. Phase Splitter

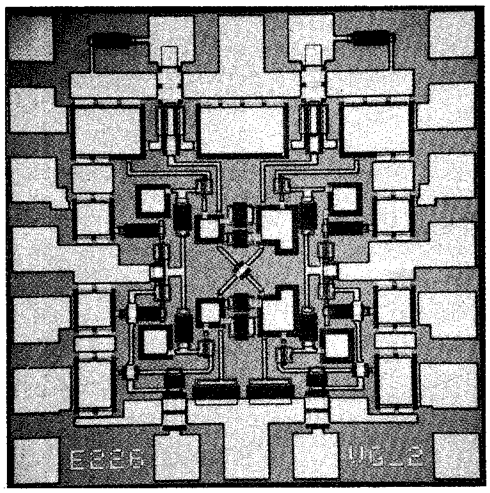

Figure 5. Vector Generator at 250 MHz

circuit shown in Figure 1. The circuit was designed for operation at center frequency of 250 MHz. The cell was fabricated using an epitaxial GaAs process with air-bridge cross-overs, metal-insulator-metal (MIM) capacitors, bulk GaAs resistors, and one micron gate length MESFET active devices. The chip size is 1.2 × 1.2 mm. Figure 6 shows the RF performance over the 180 to 340 MHz band measured at wafer level on a co-planar RF probe station.

Figure 7 shows a VG-3 second-order constant phase difference network, which was shown schematically in Figure 3. It is combined on the same chip with a PSP-1 phase splitter. The composite device was fabricated with a selectively ion-implanted process with air-bridge cross-overs, MIM capacitors, thin film resistors, and one micron gatelength MESFET active devices. The chip size is 1.2 × 2.4 mm. Figure 8 presents the experimental results of wafer-level RF testing for only the phase splitter portion of the circuit (the left half of Figure 7). The phase splitter demonstrated excellent performance over the 200 MHz to 5 GHz range

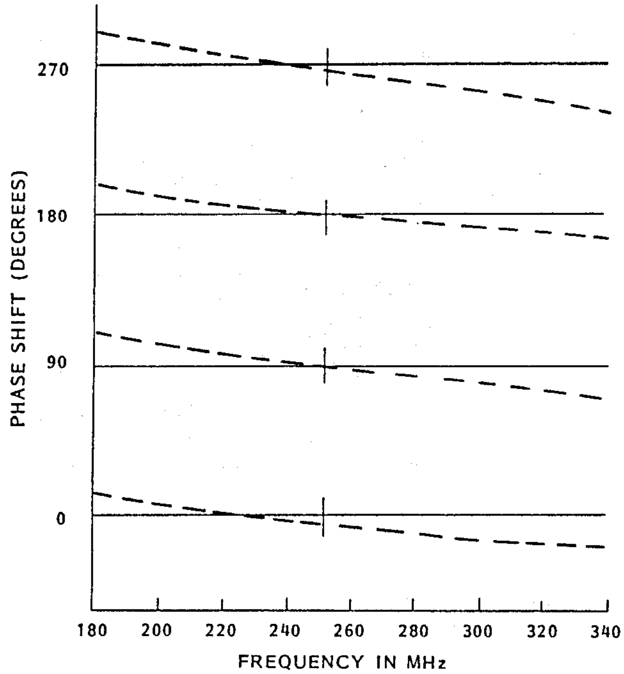

Figure 6. RF Performance of 250 MHz Vector Generator

(± 0.25 dB amplitude match and ± 0.60 phase coherence between the two outputs). Figure 9 shows the composite response of both cells of Figure 7 over 3 to 5 GHz.

CONCLUSION

Constant phase difference networks based on RC all-pass networks are a viable means of implementing monolithic multiple phase-coherent signal generators, which can be an integral part of monolithic active phase shifters. Such signal generators can be fabricated using very small chip area even at lower microwave frequencies. Also the balanced signals needed to drive the balanced all-pass networks can be monolithically implemented using a differential amplifier technique.

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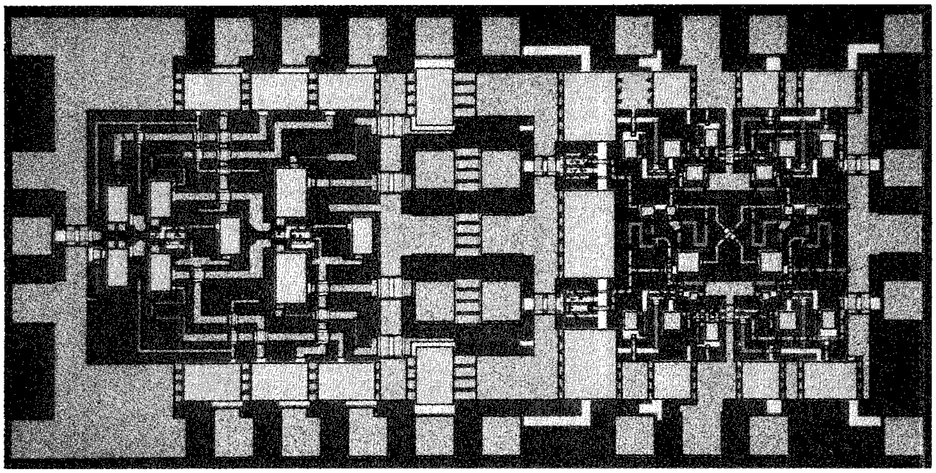

Figure 7. Phase Splitter and Vector Generator (3-5 GHz)

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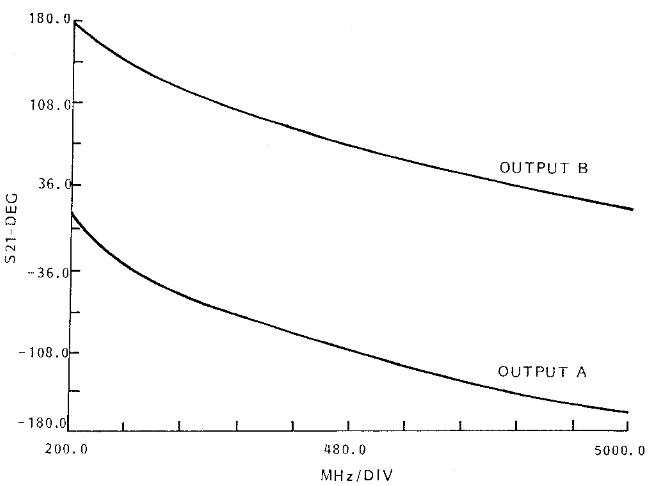

Figure 8. Waver-Level RF Test Results for Differential Phase Splitter Circuit PSP-1

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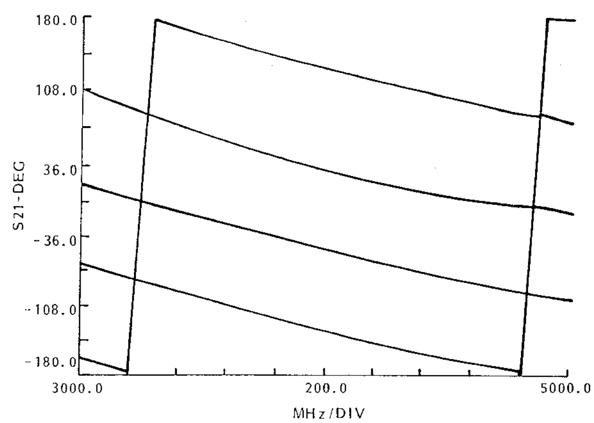

Figure 9. Composite Results of Both Cells over 3-5 GHz