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MMIC LINEAR-PHASE AND DIGITAL MODULATORS FOR DEEP SPACE SPACECRAFT X-BAND TRANSPONDER APPLICATIONS

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ABSTRACT

This article summarizes the design concepts, analyses and the development of GaAs monolithic microwave integrated circuit (MMIC) linear-phase and digital modulators for the next generation of space-borne communications systems. The design approach uses a very compact novel lumped element quadrature hybrid and MESFET-varactors to provide low loss and well-controlled phase performance for deep space transponder (DST) applications. The measured results of the MESFET-diode show a capacitance range of 2:1 under reverse bias, and a Q of 38 at 10 GHz. Three cascaded sections of hybrid-coupled reflection phase shifters have been modeled and simulations performed to provide an X-band (8415 ± 50 MHz) DST phase modulator with ± 2.5 radians of peak phase deviation. The modulator will accommodate downlink signal modulation with composite telemetry and ranging data, with a deviation linearity tolerance of ± 8% and insertion loss of less than 8 ± 0.5 dB. The MMIC digital modulator is designed to provide greater than 10 Mb/s of bi-phase modulation at X-band.

I. INTRODUCTION

GaAs MMIC analog linear-phase and digital modulators have been analyzed and investigated to provide the capability to directly modulate an X-band (8415 MHz) downlink carrier for deep space transponder (DST) applications [1]. The design specifications [1, 2] for the analog and digital phase modulators are given in Tables 1 and 2, respectively. The analog phase modulator [2] must be capable of large linear phase deviation, low loss, and wideband operation with good thermal stability. In addition, the phase modulator and its driver circuit must be compact and consume low dc power. The design is to provide ± 2.5 radians of peak phase deviation to accommodate downlink modulation of telemetry and ranging signals. The tolerance on the phase deviation linearity is ± 8%. The insertion loss should be less than 8 dB and its variation with phase shift should be within ± 0.5 dB. The phase delay variation specifications over the transponder hardware qualification environment, - 30°C to + 85°C is less than 0.5 ps/°C for the phase modulator. This investigation will consider the reflection type phase shifter for the GaAs MMIC implementation of the hardware. The digital modulator is designed to provide a binary phase shift Keying (BPSK) modulation of 10 Mb/s. The organization of the article is as follows. The modulator design and circuit configurations are presented in Section II. The test data is presented in Section III. The conclusions are presented in Section IV.

II. GaAs MMIC LINEAR-PHASE AND BI-PHASE MODULATORS

A. GaAs MMIC Linear-Phase Modulator Design

The X-band MMIC linear-phase modulator is based on a reflection type hybrid coupled phase shifter design approach [3, 4]. A basic building block of a single-section continuously variable reflection phase shifter is shown in Fig. 1. It consists of a pair of MESFET-varactors coupled to a lumped element quadrature coupler [5] with a series inductor and a parallel resistor. The X-band lumped element 3 dB hybrid coupler consists of a multi-turn bifilar spiral transformer and capacitors. The design equations for this lumped element coupler are given in the references, [5] and [6]. The capacitors were implemented using a standard metal-insulator-metal (MIM) structure with silicon nitride as the dielectric insulator material. The MESFET used in this application is a standard 0.5X600 micron depletion mode MESFET from Triquint analog MMIC process. The gate length of the MESFET is equal to half micron. The MESFET-varactors are designed by shorting the source and drain electrodes to form the cathode. The MESFET-varactors are readily integrable with inductors, capacitors, and resistors needed for the rest of the MMIC circuit. The model of the MESFET-varactors used in the CAD simulations is based on the measured capacitance-voltage (C-V) characteristics over 0.1 to 10 GHz frequency range. The measured C-V characteristics showed greater than 2:1 capacitance change over the bias range of -2 V to -6 V. The MESFET-varactor quality factor (Q) is approximately equal to 38, and the estimated cut-off frequency is 380 GHz. The MESFET-varactor, series inductor L1 and lumped hybrid are optimized to provide a linear phase shift of 100 degrees. A resistor is shunted across each diode to minimize insertion loss variation as the phase is varied.

An X-band ± 2.6 radians (300 degree) analog phase shifter was designed and fabricated using a cascade of three single-section hybrid coupled phase shifter circuits as shown in Fig. 2. Buffer amplifiers are used to provide an isolation of about 38 dB between sections. The buffer amplifiers use 0.5X200 micron MESFETs in a cascode amplifier circuit configuration. This linear-phase modulator [Fig. 2] has been simulated using CAD tools to have ± 2.6 radians of continuous phase shift in the 8.4 to 8.6 GHz range with the variation of the MESFET-varactor control voltage from -2 V to -6 V. The simulated insertion loss is 0 dB, with ± 0.5 dB variation over the control voltage. The input and output return losses were better than 15 dB in simulation.

The X-band linear-phase modulator [Fig. 2] chip measures 96X36 mils. This compact layout using lumped elements is about one-quarter the size of the conventional distributed element design approach.

B. GaAs MMIC Bi-Phase Modulator Design

The block diagram of the MMIC bi-phase modulator is shown in Fig. 3. It consists of a lumped element quadrature hybrid and MESFET switches. The design is based on the reflection phase shifter approach [3 - 5]. When the MESFET switches are "on", the phase modulator is in the minimum phase state and vice versa. By switching the MESFETs from "on" to "off" state, one can theoretically achieve 180 degrees differential phase shift in the 8 GHz to 9 GHz band. Both input and output return losses are better than 15 dB at both states. The insertion loss variation between the two states was simulated as ± 0.2 dB.

The bi-phase modulator design resulted in a small chip size of 36X36 mils. To the best of our knowledge, this is the smallest chip size reported for an X-band BPSK modulator.

III. MEASURED RESULTS

The measured phase shift for the X-band linear-phase modulator [Fig. 2] is shown in Fig. 4. The phase measured at 2 V reverse bias was used as the reference. From 2 V to 6 V reverse bias, a linear phase shift of ± 2.6 radians (300 degrees) was obtained between 8.2 to 8.7 GHz. The phase shift as a function of the bias voltage is shown in Fig. 5 for frequencies 8.4 GHz and 8.5 GHz. The phase shift linearity is better than ± 2% over the frequency band of interest for DST application; 8.4 GHz to 8.5 GHz. For reverse bias, the measured insertion loss over this frequency band was - 2 ± 1.5 dB. The insertion loss variation needs to be reduced to ± 0.5 dB to satisfy the specified requirements [Table 1]. A second design/fabrication iteration has been planned. The device models will be revised to fit the experimental data, and the circuit components will be optimized to meet the specifications in the next iteration.

The measured phase shift performance and insertion loss for the bi-phase modulator are shown in Figs. 6 and 7, respectively. The 180 degrees phase shift has a maximum of ± 4 degrees of phase error over the frequency range 8.2 GHz to 8.7 GHz. The measured phase shift is 180 ± 2 degrees, and insertion loss is 7 dB ± 0.3 dB over the DST downlink frequency range from 8.4 GHz to 8.5 GHz. As shown in Figs. 8 and 9, the input port return loss for the bi-phase is greater than 13 dB, and the output port return loss is greater than 10 dB. The bi-phase modulator does not meet the return loss requirement of 14 dB or better [Table 2] at its input and output ports. It will be optimized to meet this requirement in the next iteration.

IV. CONCLUSIONS

The development and performance X-band GaAs MMIC linear-phase and bi-phase modulators for the deep space transponder and space-borne communications systems applications are presented. The linear-phase modulator design is based on the reflection phase shifter approach and utilizes a novel lumped element quadrature hybrid and MESFET-varactors for each section. Three such sections have been used in tandem to achieve a linear phase shift in excess of ± 2.6 radians over 8.2 to 8.7 GHz frequency range. The insertion loss variation over the phase change is - 2 ± 1.5 dB over this frequency range, and it does not meet the desired specification. The shunt resistor across the MESFET-varactors will be adjusted and the circuit will be optimized in the second iteration to provide ± 0.5 dB insertion loss variation over the phase change. The chip size of the fabricated linear-phase modulator is 36X96 mils.

The GaAs MMIC bi-phase modulator is also based on the reflection phase shifter approach, and is composed of a lumped element quadrature hybrid and MESFET switches. The bi-phase modulator chip measures only 36X36 mils. The measured phase shift performance is 180 ± 2 degrees, and the insertion loss is 7 dB ± 0.3 dB over the frequency band from 8.4 to 8.5 GHz.

Potential commercial applications include phased arrays, and satellite communication systems. Commercial microwave systems which require continuous phase control in trimming multiple channels also benefit from this design.

ACKNOWLEDGMENTS

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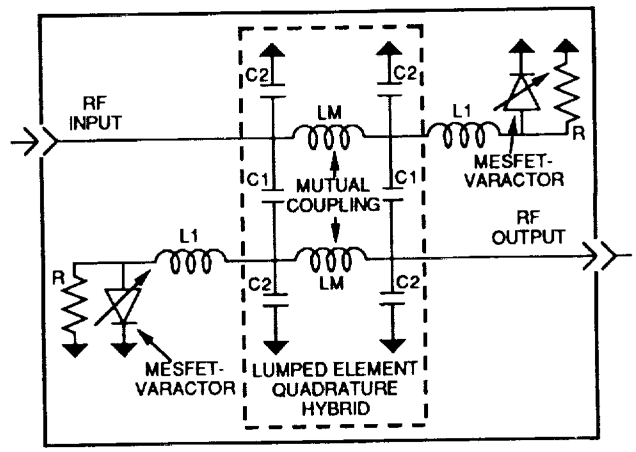
Table 1. MMIC Linear-Phase Modulator Specifications

PARAMETERS	SPECIFICATIONS
1. RF FREQUENCY	8415 ± 50 MHz
2. INSERTION LOSS	8 dB (MAX)
3. LOSS VARIATION	± 0.5 dB (MAX)
4. INPUT RETURN LOSS	14 dB (MIN)
5. OUTPUT RETURN LOSS	14 dB (MIN)
6. LINEAR PHASE SHIFT	± 2.5 RAD PEAK (285.5°)
7. MODULATION PHASE LINEARITY	± 5% BSL TO ± 2 RADIANS PEAK ± 8% BSL TO ± 2.5 RADIANS PEAK
8. MODULATION SENSITIVITY	2 RADIANS PEAK/VOLT PEAK
9. RF INPUT LEVEL	+ 10 dBm (MAX)
10. DC POWER	± 6V, 120 mW
11. DESIGN TEMP. RANGE	- 30°C TO + 85°C

Table 2. MMIC Bi-Phase Modulator Specifications

PARAMETERS	SPECIFICATIONS
1. RF FREQUENCY	8415 ± 50 MHz
2. INSERTION LOSS	7 dB (MAX)
3. LOSS VARIATION (AM)	± 0.5 dB (MAX)
4. INPUT RETURN LOSS	14 dB (MIN)
5. OUTPUT RETURN LOSS	14 dB (MIN)
6. RF INPUT LEVEL	+ 10 dBm (MAX)
7. PHASE SHIFT	180° ± 5°
8. BI-PHASE MODULATION	> 10 Mb/s
9. DESIGN TEMP RANGE	- 30° to + 85°C



R: RESISTOR
C1, C2: CAPACITORS
L1: INDUCTOR
LM: MUTUALLY COUPLED INDUCTORS

Figure 1. Single-section lumped element quadrature hybrid coupled phase shifter with MESFET varactors.

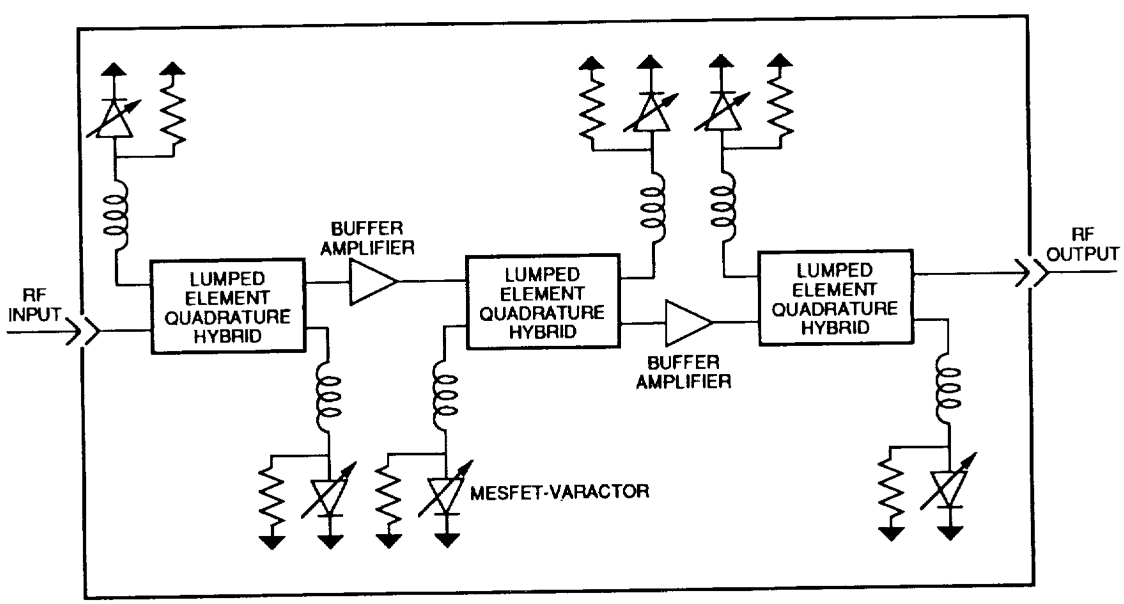


Figure 2. Block diagram of the three-stage linear phase modulator with two isolation amplifiers.

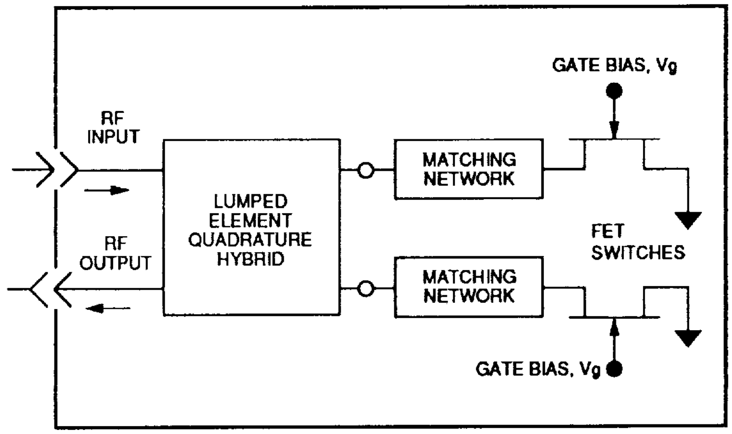


Figure 3. Block diagram of the bi-phase modulator with lumped quadrature hybrid.

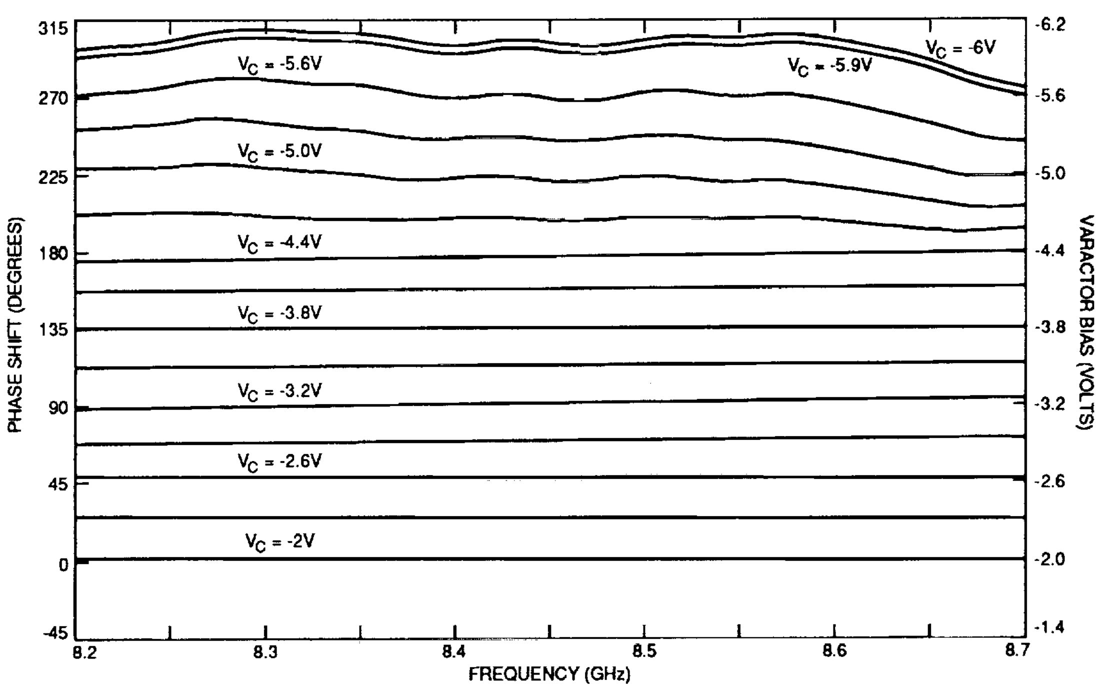


Figure 4. Measured phase shift as a function of the frequency at different dc bias levels. V_C is the dc bias control voltage.

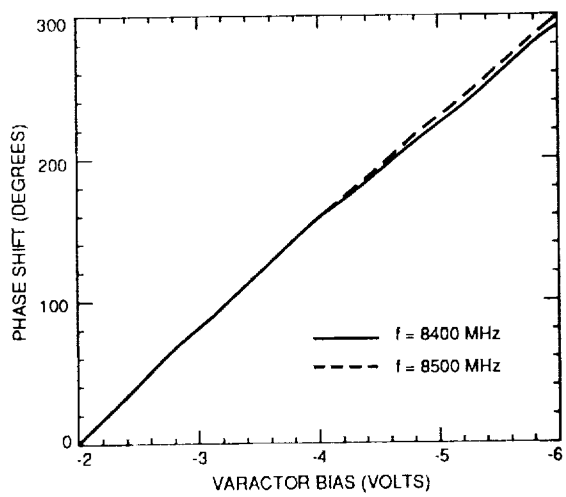


Figure 5. Measured phase shift as a function of the dc bias voltage at frequencies 8400 MHz and 8500 MHz.

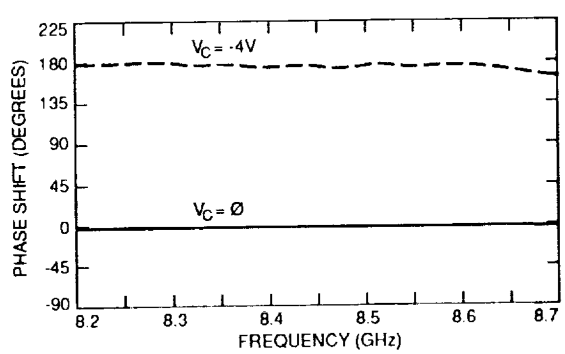


Figure 6. Measured phase shift performance of the bi-phase modulator as a function of the frequency.

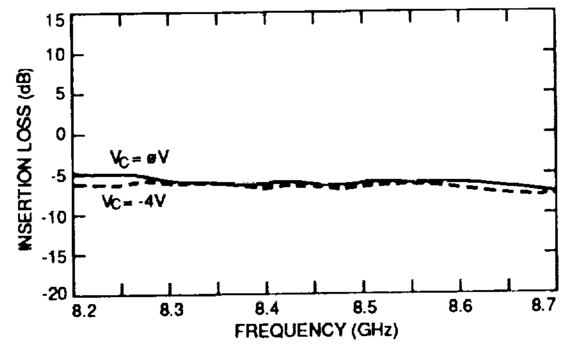


Figure 7. Measured insertion loss of the bi-phase modulator as a function of the frequency.

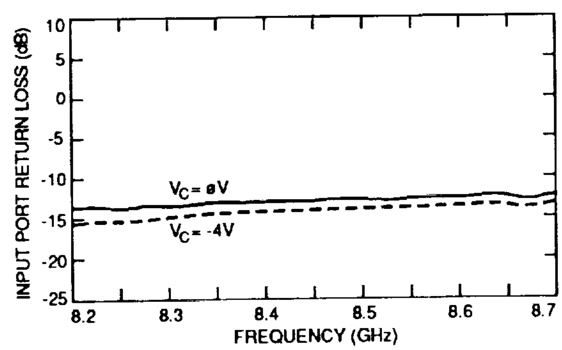


Figure 8. Measured input port return loss of the bi-phase modulator as a function of the frequency.

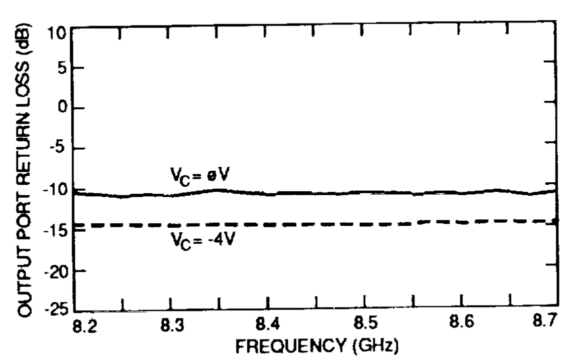


Figure 9. Measured output port return loss of the bi-phase modulator as a function of the frequency.