# A Monolithic Six-Port Module

Moise N. Solomon, *Member, IEEE*, Peter S. Weitzman, *Student Member, IEEE*, C. Phillip McClay, *Member, IEEE*, and Harry M. Cronson, *Fellow, IEEE*

*Abstract*—**The design and test of the first fully monolithic microwave integrated circuit (MMIC) implementation of a complete six-port module is described. The monolithic six-port module (MSPM) includes a six-port junction, matched FET diode detectors, high-dynamic range logarithmic amplifiers, and tunable Gunn-effect oscillators. The GaAs chip is 3 × 3 mm and the circuits operate from 7 to 9 GHz. In a reflectometer configuration, the MSPM demonstrates good agreement with National Institute of Standards and Technology (NIST) measurements on the same components. This MSPM can be used as a primary building block for a new generation of low-cost, very small, and highly reliable IC's for built-in-test applications.**

## I. Introduction

Six-port junction-based automatic network analyzers (ANA's), originally developed at NIST [1], are now used at primary standards laboratories throughout the world for very accurate measurements of amplitude and phase at microwave and millimeter-wave frequencies. Although there has been considerable work in six-ports since 1972, most of it has been in the design of coaxial and waveguide systems, and in developing various calibration techniques. The NIST measurement systems, like conventional heterodyne ANA's such as the HP8510C and Wiltron 360, cost about $200,000 and occupy an entire equipment rack. However, the six-port based systems could be much less expensive and considerably smaller because their main component, the six-port network, consists entirely of simple components, such as couplers, power dividers, and diode detectors, that can be easily fabricated as an integrated circuit.

For several years, we have been developing and miniaturizing critical components for microwave and millimeter-wave ANA's to eventually reduce cost and increase capability for built-in-test (BIT), automatic test equipment (ATE), and metrology applications [2]. Microwave integrated circuit (MIC) six-port junctions have been developed [3] but, to the authors' knowledge, this is the first reported monolithic six-port module (MSPM) with on-chip detectors, amplifiers, and an RF source.

This letter describes the design and initial measurement results for a 7- to 9-GHz MSPM fabricated using a standard MMIC foundry process. Innovative design features include a lumped-element monolithic six-port junction, matched FET diodes for power detection, high-dynamic range logarithmic amplifiers to compensate for diode nonlinearities and temperature effects, and a tunable Gunn-effect oscillator. In the initial measurements presented here, the on-chip Gunn-effect oscillators and low-frequency logarithmic amplifiers are not used. Additional equipment used in the reflectometer measurements include an external source, instrumentation amplifiers, a data acquisition system, and a personal computer.

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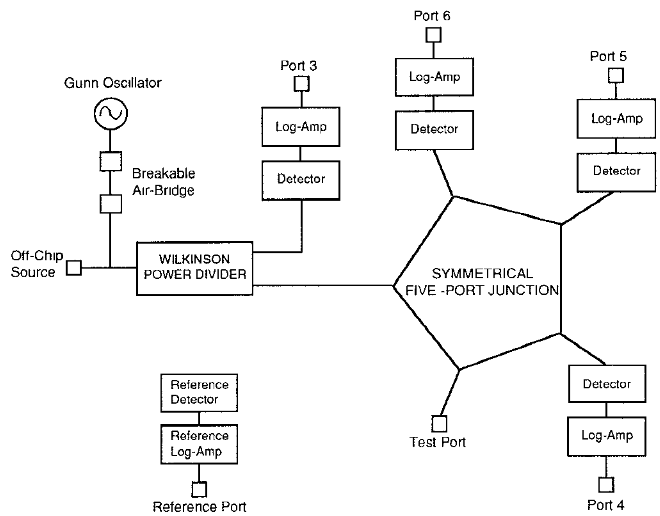



Fig. 1. Monolithic six-port module (MSPM) block diagram.

## II. Design

We implemented the MSPM chip with lumped-element components, resulting in a die area savings of approximately 400 times over an equivalent distributed element design. Fig. 1 is a block diagram of the entire MSPM chip. The source and device under test (DUT) ports are matched to a 50-ohm characteristic impedance. Each of the detection ports (ports 3 through 6) are connected to a power detector and logarithmic amplifier. The six-port junction itself consists of two parts: a Wilkinson power divider [4], and a symmetrical five-port coupler [5]. Three Gunn oscillators are included as optional on-chip sources. The breakable air-bridge shown in Fig. 1 is used to remove the Gunn oscillators from the circuit to enable testing with an external source. Fig. 2 is a layout of the MMIC chip indicating the locations of the symmetrical five-port coupler, Wilkinson power divider, Gunn diode source, power detectors, and logarithmic amplifiers.

The symmetrical five-port coupler was designed as a lumped-element version of the equivalent distributed circuit. This coupler, at its center frequency, has the following properties: each port is matched to 50 ohms, the power into each port is divided equally to the other four ports, and the phase difference between the transmission coefficient to an

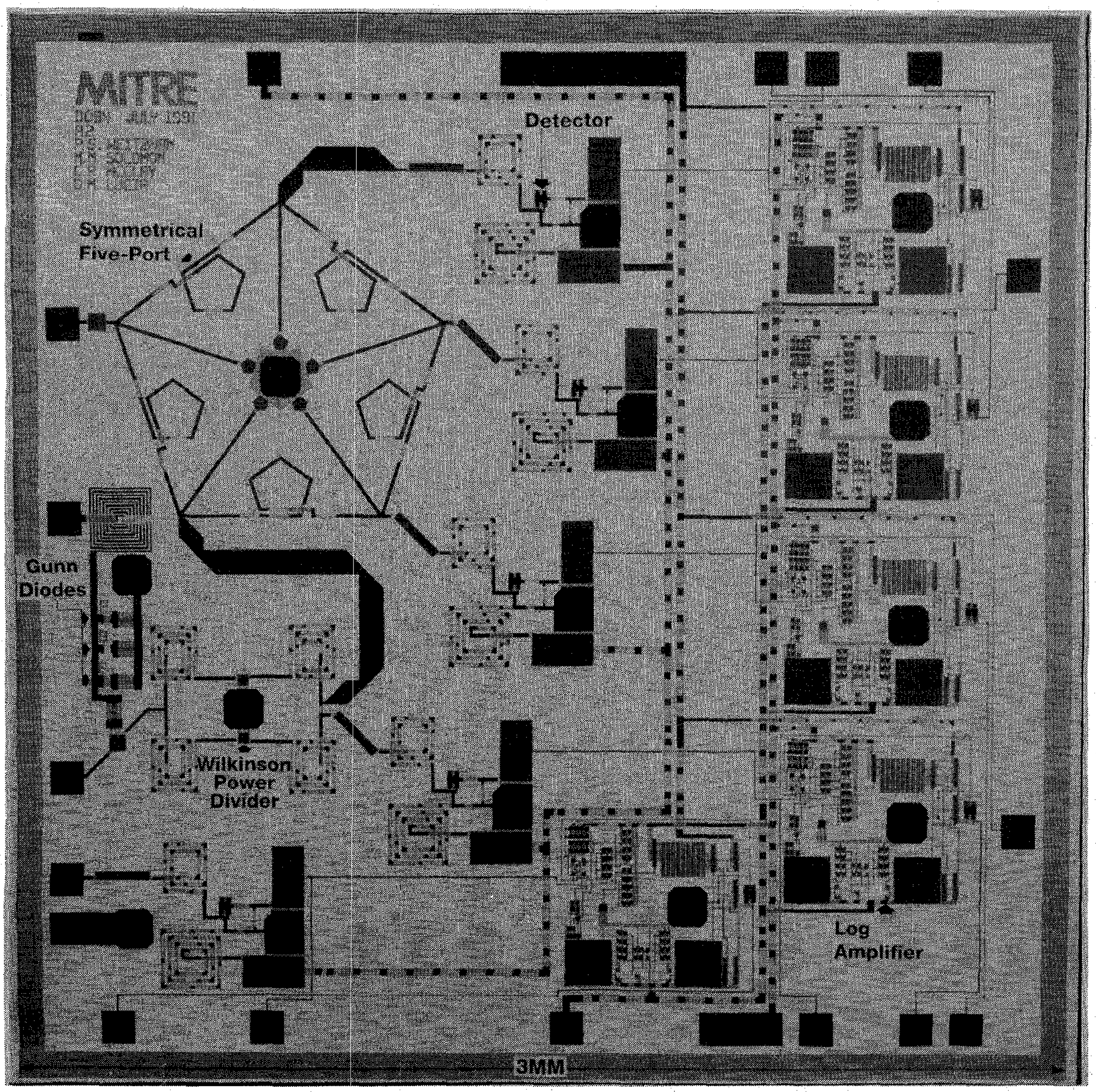



Fig. 2. Layout of MMIC chip.

adjacent port ($S21$) and an offset port ($S31$) is 120 degrees. The required five 46.6-ohm, 75.5-degree transmission lines for the five-port coupler are implemented in MMIC using lumped-element $T$-section low-pass filters with a shunt capacitor and two series inductors.

The Wilkinson power divider is a lumped-element equivalent of a conventional distributed power divider. The 90-degree, 70.7-ohm transmission lines are also realized using $T$-section low-pass filters with a shunt capacitor and two series inductors. The shunt 100-ohm resistor is fabricated using NiCr thin-film metallization.

The RF power detectors are conventional Schottky diodes, implemented using full MESFET structures to ensure uniformity across the die. The detectors are biased to improve their sensitivity at low signal levels, and are wideband matched to 50 ohms using a resistive-reactive lumped-element network. For a practical MSPM design, it is necessary to temperature compensate the detectors since their quiescent operating point changes considerably with ambient temperature variations. Therefore, we applied two independent compensation techniques, both employing matched diodes to track temperature and processing variations. The most straightforward technique used is to measure the detector voltage differentially with respect to an identically biased reference detector. This also increases the dynamic range of the detectors since the common-mode dc-bias voltage is rejected. A logarithmic amplifier, using a feedback diode identical to the detector diode, also provides compensation since its voltage transfer characteristic is the inverse of the exponentially varying detector output.

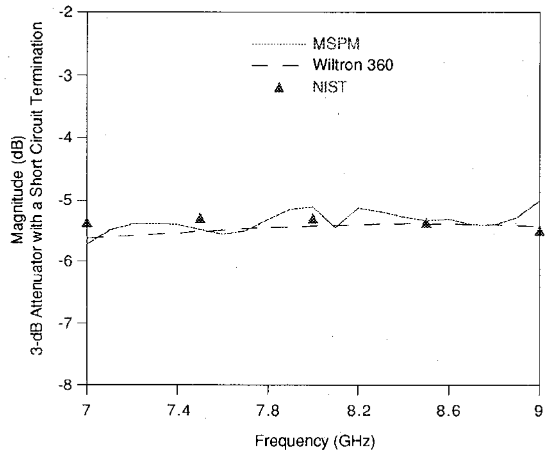
A tunable Gunn effect oscillator is included as an on-chip experimental source. Its compact size and wide tunability make it attractive for BIT and ATE applications. These Gunn diodes have an active region that varies in width to produce an oscillator whose frequency is bias dependent [6], [7]. Three different Gunn oscillators are included on-chip to provide broad frequency range coverage.

## III. Measurements

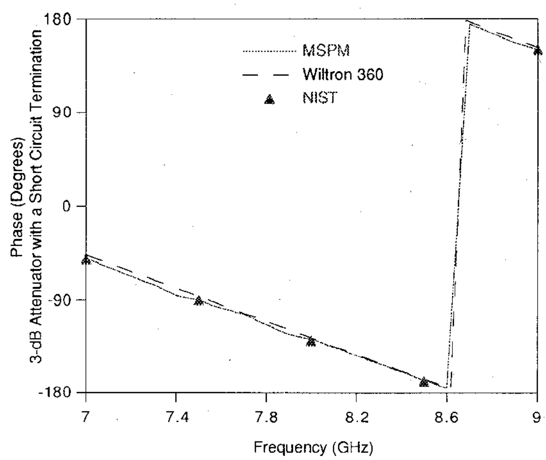
In our initial MSPM test configuration, an HP8341 synthesizer was used as an external microwave source. The detector voltages were measured directly using an HP3852A data acquisition system. (A preliminary characterization of the logarithmic amplifiers indicate that external filtering of their outputs will be necessary to reduce the additional noise added by the amplifiers, and therefore, only the direct detector measurements are presented here.) The calibration procedure is a version of Engen's original sliding termination procedure [8] written in Pascal. This program runs on an Apple Macintosh computer, which also controls the synthesizer and data acquisition system via the IEEE-488 bus.

A comparison between the MSPM, a Wiltron 360 ANA, and a NIST measurement of the reflection coefficient of a short-circuit terminated 3-dB attenuator from 7 to 9 GHz is shown in Fig. 3(a) and (b). The DUT (3.5-mm female coaxial connector) was measured by NIST using their six-port reflectometer. The MSPM measurement of both magnitude and phase is in close agreement with the other measurements. Specifically, the magnitude measurement is within 0.2 dB of the NIST measurement in the 7.1–8.9-GHz band. Also, the MSPM phase measurement is within 3 degrees of the NIST measurement in the same frequency band.

The tunable Gunn oscillator sources included on the MSPM chip oscillated out of the MSPM frequency band. Therefore, tests using this source were not performed. A future MSPM will include an oscillator in the correct frequency band.




(a)




(b)

Fig. 3. Reflection coefficient measurement of a shorted 3-dB attenuator, comparison between the MSPM, Wiltron 360, and NIST. (a) Magnitude. (b) Phase.

## IV. Conclusion and Plans

The design of an innovative MSPM was presented and good measurement correlation was shown. Planned work includes more extensive characterization of the MSPM using the on-chip logarithmic amplifiers over a temperature range. We are now designing millimeter-wave MSPM's that could be mounted directly in a waveguide fixture or on-wafer probe for highly accurate $S$-parameter measurements. Also, it is possible to increase the bandwidth of the six-port junction by using different six-port topologies. Additionally, multichip module packages with higher gain amplifiers, an analog-to-digital converter, and multiplexer are desirable for BIT applications.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