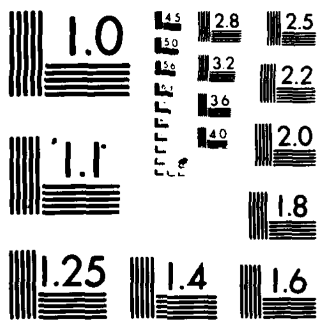
AD-A113 560 MICHIGAN UNIV ANN ARBOR ELECTRON PHYSICS LAB F/G 9/5
MICROWAVE CIRCUIT ANALYSIS AND SYNTHESIS.(U)
DEC 81 G I HADDAD, R K MAINS, D F PETERSON F33615-77-C-1132
UNCLASSIFIED AFWAL-TR-81-1219 NL

END
DATE
FILMED
5-82
DTIC



MICROCOPY RESOLUTION TEST CHART

AFWAL-TR-81-1219

MICROWAVE CIRCUIT ANALYSIS AND SYNTHESIS

G. I. Haddad et al.

Electron Physics Laboratory
Department of Electrical and Computer Engineering
The University of Michigan
Ann Arbor, Michigan 48109

December 1981

Final Report for Period July 1977-April 1981

Approved for public release; distribution unlimited.

AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

JON E. GRIGUS, CAPT, USAF
Project Engineer
Microwave Techniques &
Applications Gp

ALAN R MERTZ, CAPT, USAF
Chief, Microwave Techniques &
Applications Gp
Avionics Laboratory

FOR THE COMMANDER

DONALD S. REES, Chief
Microwave Technology Branch
Avionics Laboratory

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/AADM, W-PAFB, OH 45433 to help us maintain a current mailing list."

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-81-1219	2. GOVT ACCESSION NO. AD-A113 560	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MICROWAVE CIRCUIT ANALYSIS AND SYNTHESIS		5. TYPE OF REPORT & PERIOD COVERED Final July 1977-April 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) G. I. Haddad et al		8. CONTRACT OR GRANT NUMBER(s) F33615-77-C-1132
9. PERFORMING ORGANIZATION NAME AND ADDRESS Electron Physics Laboratory The University of Michigan Ann Arbor, MI 48109		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 20020351
11. CONTROLLING OFFICE NAME AND ADDRESS Avionics Laboratory (AFWAL/AADM-2) Air Force Wright Aeronautical Laboratories, AFSC WPAFB, OH 45433		12. REPORT DATE December 1981
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Air Force position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

X-band six-diode radially symmetric power combiner
FET modeling
FET circuits
Frequency tripling
Microwave varactor-tuned voltage-controlled oscillators
IMPATT diode properties
Millimeter-wave IMPATT devices
CATT devices

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report is a brief description of the work carried out under this program. In addition to the work reported here, several technical reports have been issued which describe in detail the work performed under this program. These reports are available and are considered as a part of this final report. The work carried out under this program included the following: properties of controlled avalanche transit-time (CATT) triode amplifiers, properties of high-efficiency X-band GaAs IMPATTs including single- and double-drift devices as well as CW and pulsed operation, power combining studies,

DD FORM 1 JAN 73 1473

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ABSTRACT CONT.

including fundamental and harmonic power combining, GaAs FET modeling, characterization and circuit studies, and development of a model to study the effects of energy and momentum relaxation effects on IMPATT device performance particularly at millimeter wavelengths.

FOREWORD

This report describes the microwave circuit analysis and synthesis studies at the Electron Physics Laboratory, Department of Electrical and Computer Engineering, The University of Michigan, Ann Arbor, Michigan. The work was sponsored by the Air Force Systems Command, Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract No. F33615-77-C-1132 (Project 2002, Task 03, Work Unit 51).

The work reported herein was performed during the period July 1977 to April 1981 by Drs. G. I. Haddad, R. K. Mains and D. F. Peterson and Messrs. R. Actis, J. R. East, R. K. Froelich, and D. Yang. The report was released by the authors in April 1981.

The authors wish to experess their appreciation to Captains Alan Mertz and Jon Grigus of the Avionics Laboratory for their input and discussions.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

The purpose of this program was to investigate various types of microwave device and circuit interactions in order to advance the state of the art and understanding of various types of circuits required in optimizing the performance of devices in oscillators, amplifiers, power combiners and other applications.

Several areas of investigation were carried out and included, in many instances, device modeling, device characterization, circuit design and evaluation, and device-circuit interactions. The major tasks which were active during the duration of the program and the results obtained are summarized in the following sections of this report. Several technical reports which describe in detail various aspects of the program have also been issued. The technical reports include:

1. "Design, Performance and Device/Circuit Limitations of N-Way Symmetrical IMPATT Diode Power Combining Arrays," by D. F. Peterson and G. I. Haddad, AFWAL-TR-81-1107.

2. "GaAs FET Modeling," by J. R. East and G. I. Haddad, AFWAL-TR-81-1191.

3. "Symmetrical Harmonic Power Combining," Abstract of New Technology, by D. F. Peterson.

4. "Properties of High-Efficiency X-Band GaAs IMPATT Diodes," by R. Mains and G. I. Haddad, AFWAL-TR-81-1066.

5. "Simulation of Pulsed IMPATT Oscillators and Injection-Locked Amplifiers," by R. K. Mains, G. I. Haddad and D. F. Peterson, AFWAL-TR-81-1177.

6. "Controlled Avalanche Transit-Time Triode Amplifiers," by S-W. Lee, AFWAL-TR-80-1185.

The areas of investigation included work on two- and three-terminal devices including modeling, prediction of properties and potential, device characterization, circuit requirements for optimum performance, dual-mode operation, power-combining techniques and the steady-state and transient properties of amplifiers and oscillators utilizing these devices.

SECTION II

POWER COMBINING STUDIES

2.1 Introduction. The objective of this phase of the program was to develop new and innovative techniques for the circuit-level power combining of negative-resistance devices for applications at both microwave and millimeter-wavelength frequencies. The use of IMPATT devices in radially symmetric power combining structures has been investigated primarily and both device and circuit constraints for optimal performance of these combiners have been derived. This approach is somewhat different from other previous methods of combining and it predicts wider band operation. A detailed theoretical analysis and predictions for realistic devices and circuits are provided in an accompanying technical report entitled "Design, Performance and Device/Circuit Limitations of N-Way Symmetrical IMPATT Diode Power Combining Arrays," AFWAL-TR-81-1107.

Associated with the theory, an experimental, X-band six-diode combiner is being constructed to verify the theoretical predictions. A summary of the state of this effort is included here. This portion of the program can be summarized at this point by indicating that an IMPATT diode, circuit-level power combining technique has been proposed and analyzed in detail. The approach seems applicable to millimeter wavelength in integrated circuit form, and an experimental model at X-band is being constructed for performance evaluation.

2.2 Construction of an X-Band Six-Diode Radially Symmetric Power Combiner. In this phase of the program, an experimental version of a radially symmetric six-diode power combiner is being developed at

X-band frequencies. Theoretical predictions have indicated promising results for this particular power combining scheme. The experiment is designed to test the theoretical predictions and to characterize the nonideal nature of a practical implementation of the theory.

The construction of the experimental six-diode power combiner is proceeding in three stages: (1) construction of a six-way radially symmetrical test fixture to investigate interline coupling and other effects of the circuit configuration, (2) device characterization to determine appropriate circuit combining lengths and characteristic impedances, and (3) characterization of the device-circuit performance. The work has currently progressed to Stage 2. A summary of the construction and testing completed to the present time is presented.

A radially symmetric six-way X-band power combiner test circuit has been constructed using microstrip transmission lines. Six 50-Ω TEM lines join at the center of a hexagon-shaped substrate board to form the "combining point" which attaches to a 50-Ω coaxial output line as shown in Fig. 2.1. Initial investigations of this structure have dealt with the nonideal nature of this combining scheme. In particular, it is of interest to know the extent of interline coupling between adjacent devices, since this could degrade combiner performance and stability criteria.

One method of determining interline coupling is to measure the transmission coefficient between any two device ports when the combining port is terminated in a short circuit and the remaining ports are terminated in matched loads. In this way, certain frequencies will reflect the short circuit, terminating the combining port to a virtual short at the combining point. A comparison of the isolation between

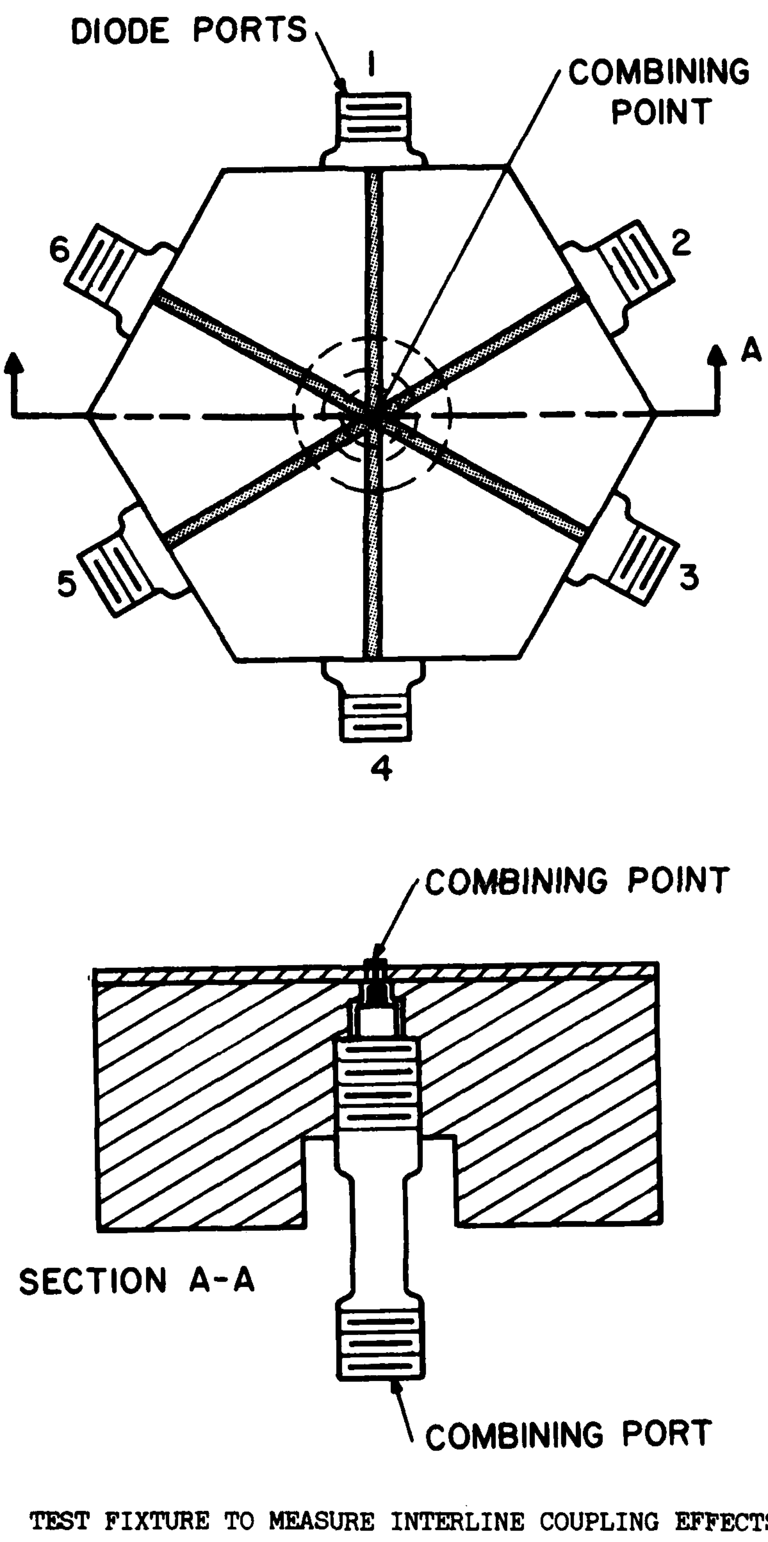


FIG. 2.1 TEST FIXTURE TO MEASURE INTERLINE COUPLING EFFECTS.

adjacent lines can be made by examining the transmission coefficient at these frequencies. Figure 2.2 illustrates the transmission coefficient S_{41} and S_{21} over the band of frequencies, 3.5 GHz to 8.5 GHz. Virtual short circuits appear at the combining point at approximately 4 GHz and 8 GHz. At these "virtual short" frequencies, a minimum of 22 dB of isolation is present between adjacent lines. More isolation is present between nonadjacent lines. At these levels of interline coupling, no problems are expected with stability.

The experimental work in the future will concentrate on Stage 2, i.e., the characterization of diodes to be used in the combiner circuitry. Some high-power IMPATT diodes have been obtained and will be evaluated for their suitability and to establish combining line lengths and characteristic impedances. Once device characterization is complete, the diodes will be placed in the combiner circuit and the combiner performance will be evaluated.

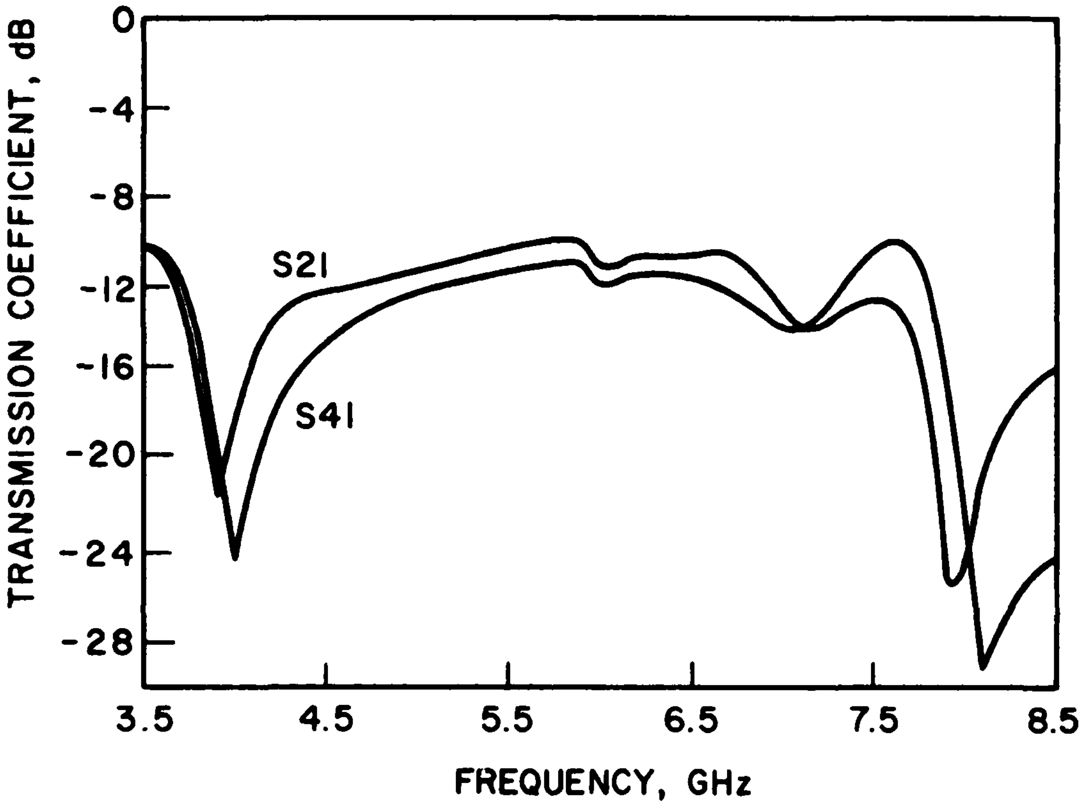


FIG. 2.2 TRANSMISSION COEFFICIENTS VS. FREQUENCY FOR THE POWER COMBINING CIRCUIT.

SECTION III

FET MODELING

3.1 Introduction. The objective of this phase of the program was to develop approximate, yet realistic, models which can be employed to predict the properties of FET devices (particularly GaAs MESFETs) as a function of various parameters including geometry, doping profile and operating point. Such a model has been developed and can be used, without needing an exorbitant amount of computer time, to predict the properties of such devices and to study the effects of the various parameters.

A detailed technical report describing the model and the results obtained to date has been prepared and issued as Report No. AFWAL-TR-81-1191 entitled "GaAs FET Modeling" by J. R. East and G. I. Haddad.

3.2 The FET Model. A computer model which can be employed to determine the operation of Schottky-barrier field-effect transistors has been developed and is used to study a variety of transistor structures. A summary of the major elements of the model and the results obtained to date are summarized here.

1. A quasi-two-dimensional computer model has been developed and the results obtained from it have been compared with other full, two-dimensional simulations. Excellent agreement has been obtained, yet this model is much simpler, easier to utilize and less costly to employ.

2. The effect of various depletion-layer approximations has been studied. Although the usual depletion-layer approximation gives reasonable agreement with other two-dimensional results, a new sloping potential methods models charge and potential distribution within the channel better and yields better agreement.

3. A very simple model which neglects space charge in the channel can be used to describe the FET terminal characteristics.

4. Simulations of silicon and GaAs FETs have been compared with full, two-dimensional results. The best match between the two types of model was for X-band GaAs FETs. Drain current vs. drain-source voltage curves matched to approximately 15 percent. The simple quasi-two-dimensional model predicts currents higher than the two-dimensional models. The predictions for charge and potential distribution are also approximately correct.

5. The effects of varying the low field mobility and saturated velocity on the drain current vs. drain-source voltage have been studied. Devices with mobilities and saturated velocities ± 20 percent of the nominal values were studied. The resulting drain current charge was always less than ± 20 percent, ranging from 7 to 15 percent. The effect of the electron velocity-field curve on the current can be roughly described by the space-charge-free model.

6. Other potential device materials have been modeled to predict FET operation.

From these results, the properties of dc FET operation can be described. The next step is to model RF operation of FETs. The steps in this process are:

1. Study the small-signal operation of FETs. This involves a small-signal expansion of the dc results. The equations for this model have been derived and must be programmed into the dc program.

2. Study the effect of velocity overshoot on FET operation.

3. Study the large-signal operation for a variety of conditions. This will include frequency and power limitations under large-signal operation.

SECTION IV

FET CIRCUITS

4.1 Introduction. The objectives of this phase of the program were to investigate the use of FETs in a variety of useful microwave and millimeter-wave applications. This portion of the program has been active during the past year and work has primarily concentrated on the large-signal characterization of FETs for use in VCOs.

A two-signal measurement technique is being implemented in conjunction with the calculator-controlled network analyzer to determine the large-signal, two-port network properties of FETs. The data provided by this method can be used to determine circuit conditions for the device such that optimum oscillator performance is achieved in the form of maximum output power, widest tuning bandwidth, or other criteria. This approach is also useful in the design of amplifiers using three-terminal devices and is also useful for checking the accuracy of device models. The characterization of devices using this method is presently underway, and the basic measurement hardware and software requirements have been developed.

Based on the results of the power combining study and the use of simple FET VCO circuits, a new technique has been conceived to extend the operating frequencies of transistor VCOs. This method uses three-fold (or generally n-fold) symmetry to accomplish power combining frequency tripling (n-fold multiplication) and provide a separate, isolated output port. A patent application has been filed for this technique and is included in Section 4.2. In addition, the Abstract of New Technology (ANT) is included.

To summarize the efforts for this portion of the program, new measurement techniques are being used to improve the characterization of FETs for design and modeling purposes and the use of FETs in frequency tripling circuits are being investigated. Enhanced performance of this and other FET components will be possible from the extensive experimental characterizations being performed on the devices.

4.2 Symmetrical Frequency Tripling of Microwave Varactor Tuned Voltage-Controlled Oscillators. The object of this invention is to triple the output frequency of certain existing fundamental frequency microwave varactor-tuned oscillators while providing comparable performance with respect to tuning bandwidths, voltage-to-frequency tuning linearity and oscillator noise levels. Additionally, the invented technique uses symmetry to reduce the circuit design complexity and filtering requirements over conventional methods.

The conventional approach for achieving a threefold increase (tripling) in oscillator frequency is to use a fundamental voltage-controlled oscillator cascaded with a separate varactor-diode or step-recovery-diode times-three frequency multiplier (tripler) circuit. The disadvantages of this approach are those primarily associated with the design and realization of the frequency-tripler circuit. Conventional frequency multiplier design requires selective filtering requirements and specified circuit boundary conditions at the various harmonics involved which are difficult to realize, particularly over a wide bandwidth. Therefore, the conventional approach usually results in narrowband operation of the voltage-controlled oscillator in addition to low output power caused by the losses and efficiency associated with frequency multiplication.

In the invention, fundamental-frequency voltage-controlled oscillation and frequency tripling are accomplished in the same circuit, and threefold symmetry is used to separate the various frequencies such that no filtering is required to provide the frequency-tripled output at a separate port. The construction of the invention using bipolar junction transistors is shown in Fig. 4.1. It makes use of three identical fundamental common-collector transistor oscillator circuits of the type shown in Fig. 4.2 connected in a wye configuration. Each of the three transistor oscillators in Fig. 4.1 is designed for fundamental frequency operation assuming points A and B are virtual short circuits. The element values L_t, C_o, and the varactor capacitance C_v are adjusted for a desired frequency range of oscillation. Because of symmetry each oscillator then operates with the same electrical waveforms displaced in time by a third of the fundamental period or 120 electrical degrees. Hence, the three fundamental frequency currents at nodes A and B add to zero to produce the required virtual short circuits. The nonlinearities associated with the varactor and the transistor will provide frequency multiplication and produce higher harmonic currents. The second-harmonic currents will differ in phase by twice that of the fundamental currents, resulting in these three currents again being 120 degrees out of phase with each other and adding to zero at the nodes A and B. Hence, A and B appear as virtual short circuits at the second harmonic. Third-harmonic currents will differ in phase by three times that of the fundamental currents and hence will all be in phase at the nodes A and B. Therefore, only

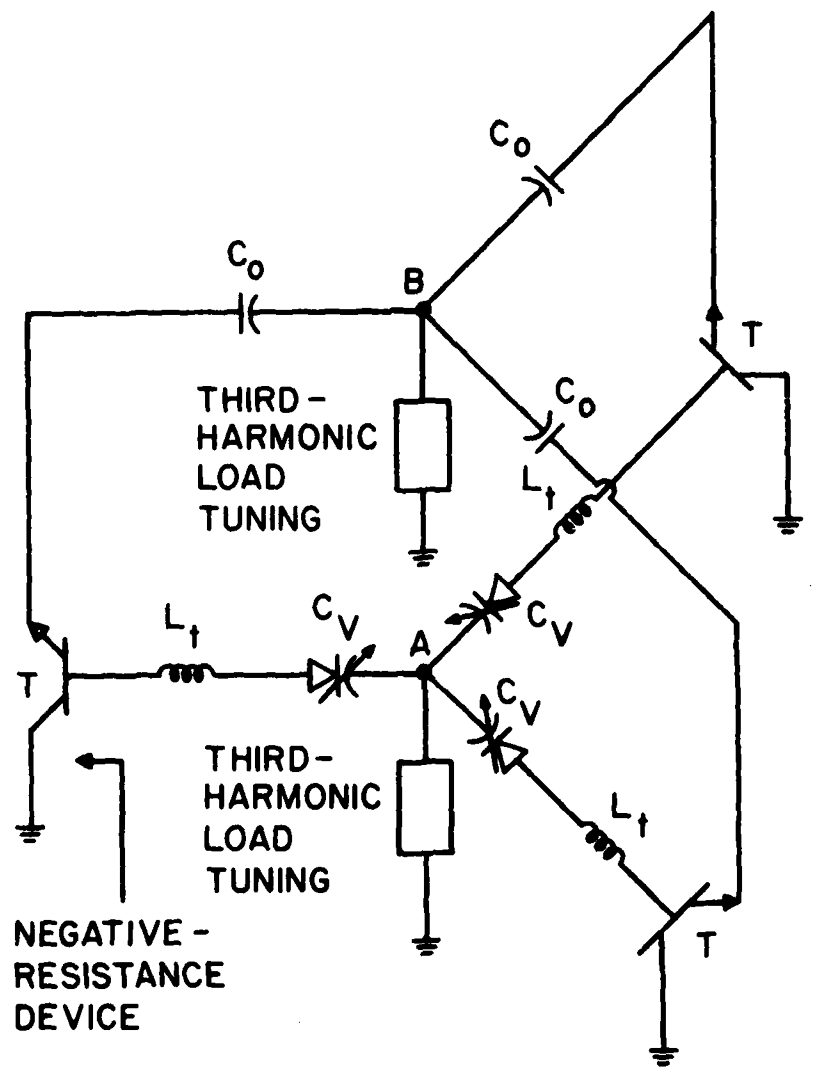


FIG. 4.1 A SYMMETRICAL, THREE-PHASE, THIRD-HARMONIC, POWER-COMBINING, VARACTOR-TUNED TRANSISTOR OSCILLATOR.

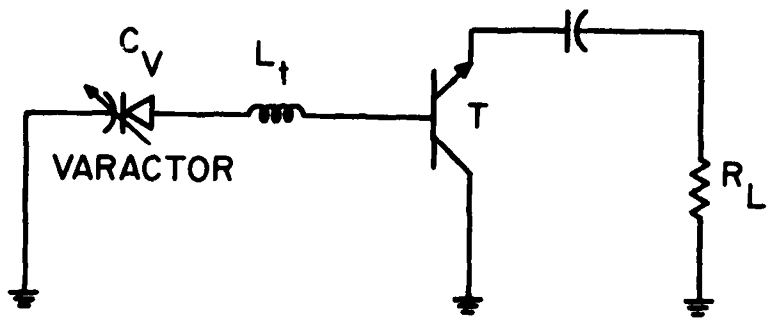


FIG. 4.2 A FUNDAMENTAL-FREQUENCY TRANSISTOR VARACTOR-TUNED VOLTAGE-CONTROLLED OSCILLATOR USED AS THE BUILDING BLOCK FOR THE TRIPLING OSCILLATOR OF FIG. 4.1 (BIASING NOT SHOWN).

third-harmonic output power will appear at these two nodes because of the symmetry. Phasor diagrams of the currents at the fundamental, second harmonic, and third harmonic at the node A and B are shown in Fig. 4.3.

There are several advantages of this multiplying oscillator circuit over the conventional approach. First, harmonic filtering is obtained by the use of symmetry, so that wideband operation is possible as long as the symmetry and balance of the three circuits can be preserved. Second, the varactor accomplishes the dual role of controlling the oscillator frequency and contributing to harmonic generation. It is well known that varactor diodes can produce efficient harmonic generation in the proper circuit environment. Third, the idling current at the second harmonic can be controlled by the nature of the varactor and its polarity with respect to the active device. For example, if each varactor is replaced by a back-to-back varactor pair, the second-harmonic current can be reduced if desired. The second-harmonic idling current can have a substantial effect on the third-harmonic output level. Fourth, there are two points of symmetry (A and B in Fig. 4.1) in the circuit where the third-harmonic output power can be extracted. This allows either node to be used as an output port with the other serving as a third-harmonic tuning location for enhanced performance. Normally, the highest harmonic content is expected at node A in Fig. 4.1. Last, the circuit is also combining the power output from three devices, so that higher output power levels can be expected over the conventional approach.

This method of achieving voltage-controlled oscillation is not constrained to use microwave bipolar transistors as indicated in Fig.

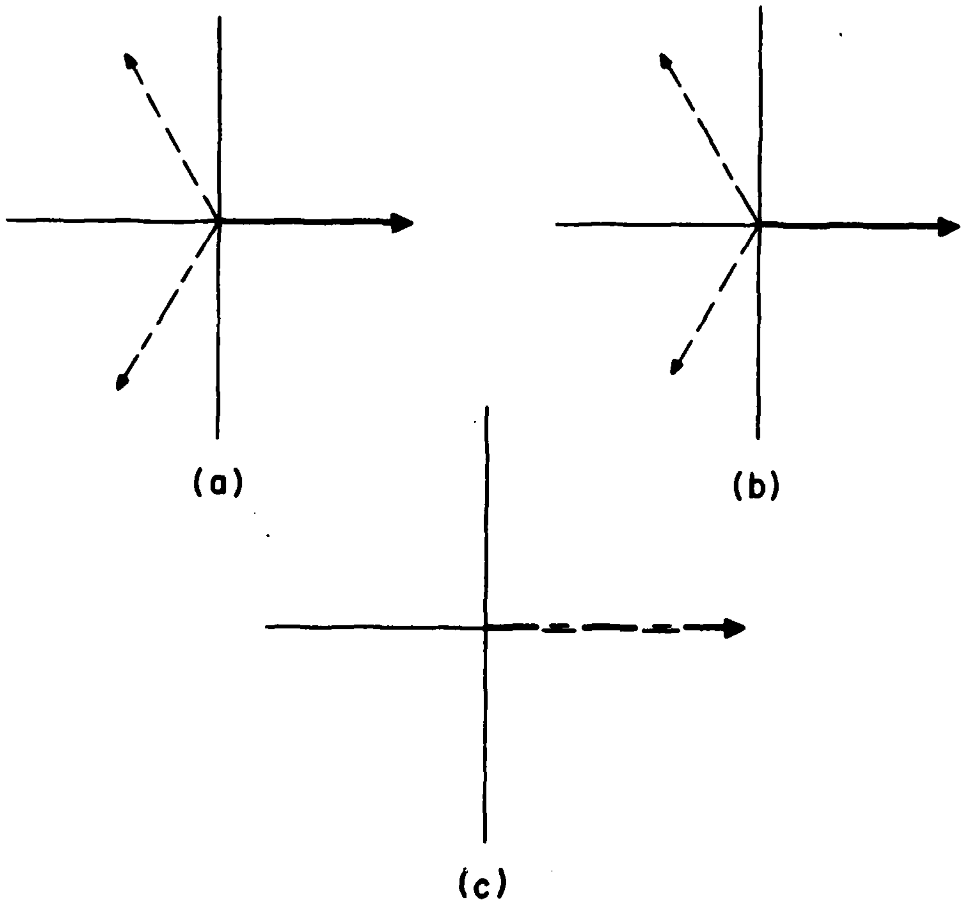


FIG. 4.3 PHASOR DIAGRAMS OF THE CURRENTS ENTERING MODE A OR B OF FIG. 4.1 (a) AT FUNDAMENTAL FREQUENCY, (b) AT SECOND HARMONIC AND (c) AT THIRD HARMONIC.

4.1. Other transistors, such as microwave field-effect transistors can also be used in the common drain configuration, for example. In addition, two-terminal devices such as Gunn or IMPATT diodes can be used in place of the transistors, in which case only one third-harmonic output port will be available. Finally, when transistors are used, the wye connection of capacitors C_o on the third terminals can be replaced by an equivalent delta connection at the sacrifice of the second third-harmonic output port. This connection may be more easily realized in a planar circuit geometry.

The feature believed to be new in this invention is primarily the use of threefold symmetry of simple fundamental oscillators to provide one or two points of symmetry where the fundamental and second harmonic cancel and where the third harmonic is available. This feature is significant in that it simplifies design and eliminates the need for frequency selective harmonic filtering requirements while allowing great design flexibility at the two isolated third-harmonic nodes. Furthermore, the circuit automatically combines the power from three devices for improved power level at the output while extending the effective range of operating frequencies of fundamental-frequency microwave transistor oscillators by a factor of three.

SECTION V

IMPATT DIODE PROPERTIES

5.1 Introduction. The purpose of this phase of the program was to investigate in detail the various properties of IMPATT devices for both steady-state and pulsed operation as oscillators and amplifiers. Detailed results have been obtained for various types of profiles including single- and double-drift devices and for various operating points. The detailed results are included in two technical reports. The first, which is concerned with the steady-state properties has been issued as Report No. AFWAL-TR-81-1066 entitled "Properties of High Efficiency X-Band GaAs IMPATT Diodes" by R. Mains and G. I. Haddad. The second is Report No. AFWAL-TR-81-1177 entitled "Simulation of Pulsed IMPATT Oscillators and Injection-Locked Amplifiers" by R. Mains, G.Haddad and D. Peterson. A summary of the work performed is given in the next section.

5.2 IMPATT Devices. The research carried out on theoretical IMPATT investigations may be divided into two main categories. The first was to simulate numerous single- and double-drift GaAs structures at X-band as well as to investigate operation at higher frequencies and to look at some Si IMPATT structures. Second, a program was developed to study the dynamic behavior of pulsed IMPATT oscillators and amplifiers which utilize this simulation data. The work performed in each of these areas is described next.

To simulate IMPATT structures, the finite difference programs developed by Bauhahn[1] were used. These programs were modified so that total current boundary conditions are imposed for the minority carriers (corresponding to a constant reverse saturation current). The dc, small-signal and large-signal programs were all modified in this manner. Next, an exhaustive series of runs was carried out for many GaAs IMPATT structures designed for X-band operation which yielded information concerning impedance and power levels as a function of RF voltage, dc current density and temperature. Several structures which yield high efficiencies due to the precollection mode were given special attention. The single-drift structures studied were: uniformly doped, high-low, and low-high-low doping profiles. Double-drift devices studied were: uniformly doped, hybrid, and double Read profiles. For some of these simulations, dynamic temperature effects were included to determine device characteristics when the restrictive assumption that the temperature remains constant as the RF voltage is varied is relaxed.

In addition, simulations for GaAs and Si double-drift structures were performed in the 35- to 40-GHz range. The intent here was to explain the high efficiencies reported in the literature[2] for GaAs and to assess the performance of Si devices for comparison. It was found that by suitable adjustment of the high-field diffusion coefficient in GaAs, experimentally obtained efficiencies were duplicated.

---

1. Bauhahn, P. E., "Properties of Semiconductor Materials and Microwave Transit-Time Devices," Tech. Report No. 140, Electron Physics Laboratory, The University of Michigan, Ann Arbor, October 1977.

2. Masse, D., Chu, G., Johnson, K. and Adlerstein, M., "High Power GaAs Millimeter Wave IMPATT Diodes," Microwave J., vol. 22, No. 6, pp. 103-105, June 1979.

During the second phase of the research, a program was developed to study the dynamic behavior of IMPATT oscillators and amplifiers utilizing the quasi-static approximation. This approximation assumes that the RF voltage across the device at any time may be expressed as a sine wave whose amplitude and phase vary slowly with respect to the RF period. Solving for the complex frequency S at each time step determines the rate of change of amplitude and phase. Temperature variation effects are included and a thermal time constant consistent with published values at X-band is used. The circuit is currently chosen to model the cylindrical resonant cavity structure. The circuit model includes package parasitics, a transmission line to model the quarter-wave transformer near the diode, a second transmission line to model the 50-Ω line between the transformer and the resonant cavity, and a parallel resonant lumped-element circuit to model the cavity in series with the 50-Ω stabilizing load.

This quasi-static program is being used to inexpensively investigate many aspects of pulsed operation including: the delayed start effect and how it is affected by circuit design and locking signal amplitude, frequency drift of pulsed oscillator/amplifier during operation, how to design for dual mode operation, the effects of varying dc current and pulse width, and a comparison of the operating characteristics of different IMPATT diode structures.

SECTION VI

MILLIMETER-WAVE IMPATT DEVICES

6.1 Introduction. This phase of the program was concerned with computer modeling of millimeter-wave IMPATT diodes. Since the applicability of the conventional drift and diffusion, or static, transport model to millimeter-wave devices is uncertain, a more general model is needed. The new model should be of a form which allows economical large-signal simulation of IMPATT devices. Work under this phase of the program falls into the categories of simulation development and application. Objectives of the development work are to develop a suitable device model and corresponding computer program. Objectives of the simulation work are to confirm the agreement between the conventional and the new models at sufficiently low frequencies, to learn under what circumstances the conventional model breaks down, and to develop design guidelines for millimeter-wave IMPATT diodes.

6.2 Work Performed to Date. A transport model which conserves carrier energy and momentum has been chosen as appropriate for the present work. The model is based on transport equations, given by Blotekjaer,[3] which are the first three velocity moments of the Boltzmann transport equation. A computer program which applies the model to Si devices is now in operation. While the cost of running the program is generally from three to ten times as large as that of

---

3. Blotekjaer, K., "Transport Equations for Electrons in Two-Valley Semiconductors," IEEE Trans. on Electron Devices, vol. ED-17, No. 1, pp. 38-47, January 1970.

running a conventional simulation, numerical methods are under investigation which may reduce the cost.

A study comparing the results of a conventional simulation developed at the Electron Physics Laboratory[4] with those of the new simulation is underway. The two models give similar results when applied to a Si device operating near 100 GHz, as can be seen from the large-signal admittance data given in Fig. 6.1. The results appear to confirm that the models are in close agreement with each other for frequencies below 100 GHz. Some results at near 300 GHz have also been obtained. Disagreement between the two models is great, but may be due in part to differences between the diffusion coefficient which is implicit in the new model and that which is used in the conventional model. The coefficient used in the conventional model will be adjusted to minimize these differences. It was thought that disagreement between the two models might also be due to the use of differing boundary conditions, but changing the conditions used in the new model do not affect its results significantly.

6.3 Summary and Conclusions. A millimeter-wave Si IMPATT simulation has been developed which is based on an improved transport model. As expected, results from the new model are close to those of the conventional drift diffusion model at sufficiently low frequencies. The new model should provide a means of determining where the conventional model breaks down and of predicting the performance of millimeter-wave devices at very high frequencies.

4. Bauhahn, P. and Haddad, G. I., "IMPATT Device Simulation and Properties," IEEE Trans. on Electron Devices, vol. ED-24, No. 6, pp. 634-642, June 1977.

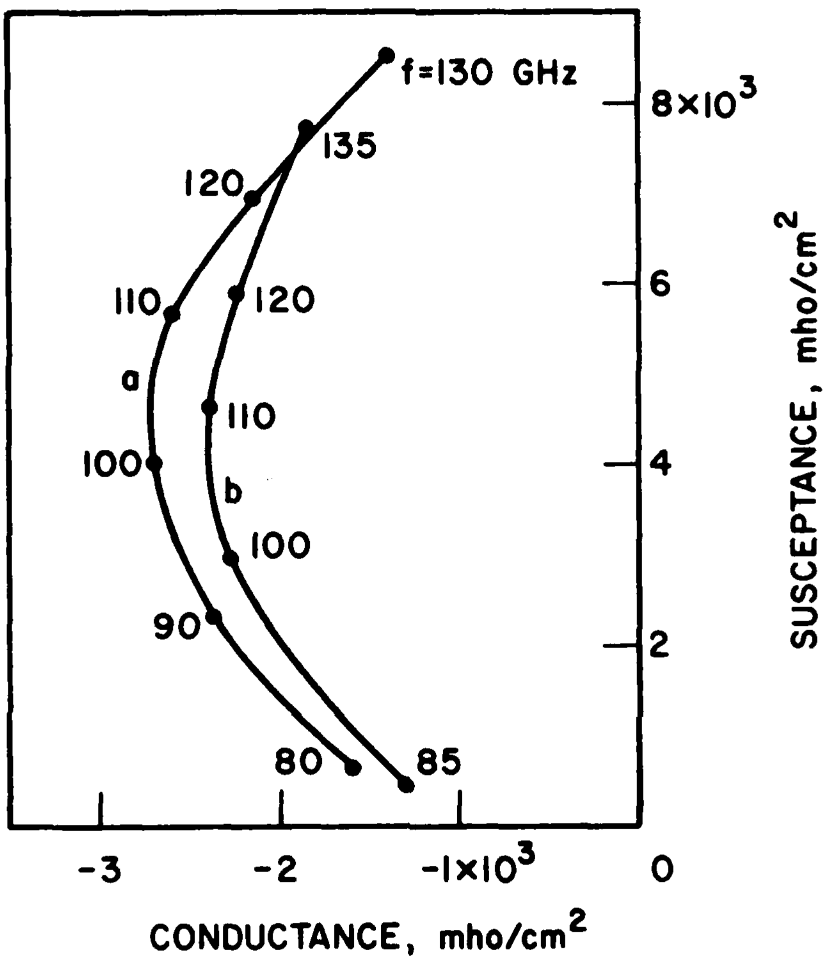


FIG. 6.1 RF ADMITTANCE AT VARIOUS FREQUENCIES PREDICTED BY (a) ENERGY AND MOMENTUM CONSERVING SIMULATION AND (b) CONVENTIONAL SIMULATION. (SILICON DOUBLE-DRIFT DIODE, J_{dc} = 60,000 A/cm² AND V_{RF} = 10 V)

SECTION VII

CONTROLLED-AVALANCE TRANSIT-TIME TRIODE AMPLIFIERS

7.1 Introduction. The purpose of this phase of the program was to evaluate the properties of controlled-avalanche transit-time devices, their application in amplifiers, and their comparison with conventional BJT devices. This work was completed about a year ago and a technical report[5] describing the results has been issued. The abstract from this report and the summary and conclusions are included here for completeness.

7.2 Abstract from the Technical Report. "The purpose of this work is to study the theoretical effects of avalanche multiplication and collection transit time on microwave controlled avalanche transit-time triode (CATT) devices. The objectives of this report are to obtain a better device model, develop a complete one-dimensional large-signal simulation computer program, calculate the large-signal performance of Class C CATT amplifiers and make a comparison between Class C CATT and Class C BJT amplifiers. The following studies were carried out in order to achieve these objectives.

"A dc computer program was developed which calculates the dc avalanche multiplication factor vs. base-collector dc bias characteristics. The results provide an estimation of the suitability of various semiconductor materials, optimum collector geometrical structures and doping densities.

---

5. Lee, S-W., "Controlled Avalanche Transit-Time Triode Amplifiers," Tech. Report No. AFWAL-TR-80-1185, Electron Physics Laboratory, The Univeristy of Michigan, Ann Arbor, November 1980.

"Analytical models of dc and small-signal characteristics for Read-type collector structures are given which incorporate both the avalanche multiplication and collector transit-time mechanisms. Contrary to previous findings, the small-signal characteristics indicate that a large avalanche multiplication factor decreases the RF power gain of small-signal Class A CATT amplifiers. The results are given and discussed.

"A large-signal computer simulation was developed which consists of three computer programs: the emitter-base computer program (EBCP), the large-signal simulation program (LSSP), and the collector circuit comptuer program (CCCP). The effects of high impurity doping level in the emitter, high injection level inthe base, time-varying width of the neutral base region, carrier-induced drift field in the base, nonzero minority carrier concentration at the edge of the base-collector depletion region in the base, and the feedback hole current are incorporated in EBCP. Computer program LSSP models the semiconductor region through a set of difference equations of the semiconductor equations. A current-conserving boundary condition is given. The simulation includes the velocity-electric field, diffusion-electric field, and avalanche ionization rate-electric field characteristics in the collector region. The computer program CCCP incorporates the displacement current in the collector semiconductor region and the effects of the external load impedance.

"Large-signal results of Class C CATT amplifiers are obtained and are presented. Effects of base-collector dc bias, load, collector structure, and operating frequency are discussed. The simulation calculates amplifier output power, gain, and efficiency. It also gives the emitter-base current and voltage waveforms; avalanche multiplication factor; waveforms of voltage across the base-collector depletion region and collector terminal current; and spatial distributions of electrons, holes, and electric field at any time instant. Large-signal output power, gain, efficiency, dynamic range, and inherent bandwidth of Class C CATT and BJT amplifiers are compared and suggestions for further studies are given."

7.3 Summary and Conclusions from the Technical Report. "The purpose of this study was to investigate the effects of avalanche multiplication and transit time in the collector region of a BJT. Analytical equations, circuit models, and computer simulations were used to determine dc, small-signal, and large-signal behavior of CATT amplifiers.

"In Chapter II a dc computer program was developed which determines the dc avalanche multiplication factor vs. V_{bias} characteristics for any Si or GaAs collector structure. The results provide an estimation of device large-signal performance capability. The optimum collector parameters, i.e., w_{av}, N_{av}, N_c, obtained from the dc computer program correspond well to the results of large-signal simulation. Results also indicate that an n-type Si CATT amplifier is superior to p-type Si and n-type GaAs CATT amplifiers due to its favorable M_{A_o} vs. V_{bias} characteristics.

"In Chapter III analytical models of dc and small-signal characteristics for CATT devices with Read-type collector structures were given which incorporated both the avalanche multiplication and the collector transit-time mechanisms. Contrary to previous findings, the small-signal characteristics of Class A CATT amplifiers indicated that a larger avalanche multiplication factor results in a smaller RF power gain and an increase in M_{A_o} does not necessarily imply a significant increase in f_{max}. Results were given and discussed. One conclusion was the inapplicability of CATT devices as Class A amplifiers.

"In Chapter IV a large-signal computer simulation was developed which incorporated several improvements over the large-signal simulation previously reported, i.e., high injection level effects region, Early effect, effect of high impurity level in the emitter, nonzero minority carrier concentration at the edge of the base-collector depletion region on the base side, minority carrier induced electric field in the base region, current conserving boundary condition for minority carriers in the collector region, and diffusion current in the collector depletion region.

"In Chapter V large-signal results of Class C CATT amplifiers were given. Effects of base-collector dc bias, load, operating frequency and collector structures were examined and discussed. The simulation calculates output power, power gain, and efficiency of the amplifier. It also gives emitter-base current and voltage waveforms; avalanche multiplication factor; J_T and V_T waveforms; and spatial distributions of electrons, holes, and electric field in the collector depletion region at any time instant. Various Si n-type CATT and BJT Class C amplifiers operating at 12.75 GHz were compared in terms of output power, power gain, efficiency, and dynamic range. Optimum collector impurity doping level and optimum width of the collector region of both the CATT and BJT amplifiers were determined and discussed.

Carrier multiplication and long collector transit time do increase power gain, but at the expense of lower efficiency and smaller dynamic range. Avalanche multiplication does help to increase the device inherent bandwidth."

SECTION VIII

SUMMARY AND CONCLUSIONS

Several significant contributions were made during this program toward a better understanding of microwave solid-state devices and their behavior in oscillator and amplifier applications. In particular, several devices were considered including CATT, IMPATT and GaAs FET devices. Computer models were developed for analyzing the properties, capabilities, and potential of these devices as well as determining the types of circuits they require in order to optimize their performance in oscillators and amplifiers under both CW and pulsed conditions. Experimental measurements were also performed on some of these devices to obtain comparison with the theoretical results. Due to these investigations, we presently have the best computer programs available anywhere for determining device properties, assessing their capabilities and providing information as to the type of circuit impedances required for operation of these devices as oscillators and amplifiers as a function of frequency, geometry and doping density.

Novel schemes for power combining of devices at fundamental and harmonic frequencies were conceived, analyzed and tested. These schemes should lead to improved performance for combining the power output from two- and three-terminal microwave devices and will also prove useful in extending the frequency of operation of these devices.

MED

-8