134.3

An Active Microstrip Circuits Lab Course

Eric W. Bryerton*, Wayne A. Shiroma, and Zoya B. Popović
University of Colorado, Boulder, CO

Abstract

We describe a laboratory course in active microstrip circuits at the University of Colorado at Boulder. This course emphasizes the design and measurements of microwave (900 MHz–10 GHz) active circuits at the senior/graduate level. Experiments and design projects are described.

I. INTRODUCTION

THE WIRELESS communications revolution has recently created a strong demand for engineers with a background in radio-frequency (RF) and microwave circuit design. This paper describes a microwave laboratory course developed at the University of Colorado at Boulder to address this need. Although a number of microwave courses have been described in recent years [1]–[7], the distinguishing feature of this course is the strong emphasis on laboratory and project work. This course, *Active Microstrip Circuits*, is a senior/graduate-level course which emphasizes active microwave circuits, including design tradeoffs, fabrication techniques, and modern measurement techniques. It consists of one hour of lecture (using instructor-developed course notes) and four hours of lab per week. The lab is well-equipped with network analyzers (HP 8510B, HP 8702), synthesizers (HP 83620A), sweepers (HP 8350), spectrum analyzers (HP 8593), and power meters (HP 437B). In addition, a homemade PC-controlled anechoic chamber is available for antenna measurements.

II. LAB EXPERIMENTS

There are five 2–3 week long lab experiments in the course. Each student designs, fabricates, and measures his own circuit. Although our lab is equipped with advanced CAD packages (Hewlett-Packard Microwave Design System and Compact Software Supercompact), most students prefer to use *Puff* [8,9], a simple software package that runs on a PC. The fabrication procedure is simple. The circuit board is laid on an XY-plotter and the HPGL file generated by *Puff* is used to plot the circuit trace directly onto the board. The ink from the plotter pen serves as the mask. Resolution is limited to the width of the pen tip, which is 0.3 mm and is adequate for our purposes. Experiments 2–4 cover amplifier design. Each experiment uses the same transistor (HP-Avantek ATF-10736), so the student develops an understanding of how different matching networks are used to achieve different design objectives. The circuits are typically designed to operate between 2–10 GHz.

A. Experiment 1—Passive Microwave Circuits

Experiment 1 introduces the student to the software and fabrication process through the design and fabrication of simple microstrip circuits such as branchline couplers, lowpass filters, and bias tees. For students having no prior experience with vector network analyzer measurements, this lab offers the opportunity to gain that experience. The students are also introduced to the TRL calibration at this point. In this initial lab, a few of the students are told to intentionally ignore compensation of discontinuities in their circuits (*e.g.* tee junctions and open ends) to compare their effect with those that do compensate.

0-7803-4178-3/97/$10.00 © 1997 IEEE

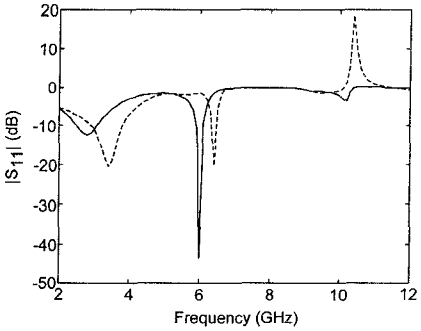


Fig. 1. Simulated $|S_{11}|$ of the amplifier with (dashed line) and without (solid line) the inclusion of a 0.7 nH source inductance.

B. Experiment 2—High-gain MESFET Amplifier

In this experiment, the transistor is conjugately matched at input and output for maximum gain. The design is based on the unilateral assumption and then optimized for bilateral operation. The student is encouraged to try different types of matching networks (*e.g.* quarter-wave transformer vs. single-stub) to observe their effect on bandwidth. To see the effects of saturation, a power sweep is performed on the amplifier using a HP70820A microwave transition analyzer.

The effects of source-lead inductance are deliberately not mentioned. So when the students' initial design operates at a different frequency than simulated or even oscillates, the student is forced to discover the problem on his own. This has been found to teach the students to account for these parasitics better than if they are simply told to do so ahead of time. Fig. 1 shows the effect of not including the source-lead inductance in the simulation. Ignoring this parasitic in a 6-GHz design results in a 10% frequency shift and possible oscillation near 10 GHz.

C. Experiment 3—Broadband MESFET Amplifier

In Experiment 3, the amplifier is designed for broadband performance by adding resistive feedback. The students design and simulate three different broadband amplifier topologies—balanced, distributed, and feedback. For the distributed case, the student simulates an increasing number of sections to see the limitations of this approach. The students fabricate the resitive feedback design and compare its performance with the high-gain amplifier built in the previous experiment.

D. Experiment 4—Low-noise MESFET Amplifier

Experiment 4 involves matching for noise. The student first learns how a hot-cold Y-factor measurement is used to measure the noise figure of a two-port. An amplifier matched for low noise is then designed and built. An HP 8593E Spectrum Analyzer/Noise Figure Meter is used for the noise figure measurement.

E. Experiment 5—Resonators and Oscillators

In Experiment 5, a Gunn diode oscillator is fabricated using the MA-49139 packaged Gunn diode. The students measure both the *I-V* and free-running oscillation characteristics, noting that oscillation takes place only in the negative-resistance region. Injection locking is also introduced at this point, and is shown how this can stabilize the oscillator.

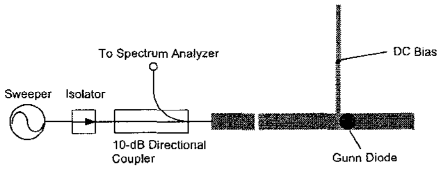


Fig. 2. Experimental setup for measuring the injection-locking characteristics of the Gunn diode oscillator. The Gunn diode is mounted in a gap-coupled microstrip resonator.

Phase noise is also measured. Fig. 2 shows the measurement setup for the injection locking experiment. A low-level signal is injected into the oscillator from the sweeper and the spectrum analyzer shows the student how the injected signal cleans up the spectrum of the oscillator. The oscillators are designed to operate at 5 GHz and typically produce about -3 dBm of output power.

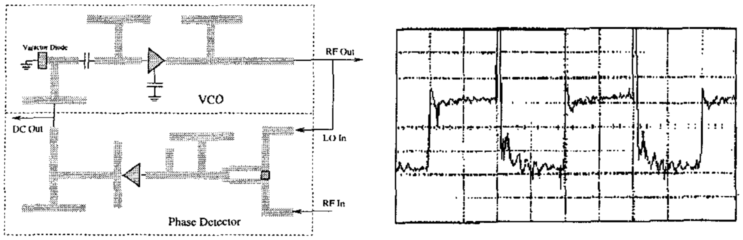
The experiment also involves designing a MESFET oscillator. The MESFET oscillator is designed on *Puff* by seeing if the S-parameters of the circuit form a counter-clockwise loop outside the unity Smith chart. This indicates a closed-loop gain of greater than unity. Injection locking as well as FM modulation at the gate is demonstrated.

III. PROJECTS

At the end of the term, each student works on a project. Teams of two work on those projects which are fairly complex. Some projects are listed below and a few are described in more detail. As indicated by the citations, some projects have led to journal publications.

- *A Microwave Coupler with Thermal Isolation* — A thermally isolated microwave coupler at 905 MHz is designed and demonstrated with 15.4 dB return loss and 1.8 dB insertion loss. The coupler consists of two fork-shaped antennas separated by a dielectric. [10]
- *Passive and Active Quasi-Microstrip Antennas* — Passive and active versions of a quasi–microstrip antenna [11] exhibiting 14% 2:1 VSWR bandwidth at 2 GHz were designed. The design of an active quasi–microstrip antenna which employs a single-stage MESFET amplifier with nominal gain of 8 dB is described. Measured and predicted values of VSWR, radiation patterns, and gain are provided for the active antenna. The amplifier is found to increase the gain of the antenna by an average of 8 dB and to reduce the variance of the gain over the bandwidth from 2 dB to 0.5 dB.
- *Microwave Phase Lock Loop* — A microwave phase lock loop at 3.5 GHz with a 9 MHz locking bandwidth is designed and built. The circuit as fabricated in microstrip is shown in Fig. 3(a). A phase detector, filter, and voltage-controlled oscillator are each individually constructed, tested, and finally combined. The phase noise of the PLL is -105 dBc/Hz at 100-kHz offset as compared to the -86 dBc/Hz phase noise of the VCO alone at the same offset. FM demodulation of a 500-kHz square wave is also demonstrated and shown in Fig. 3(b).

Other projects include *A 3–D Grid Oscillator* [12], *Bi-directional Quasi-Optical Amplifier Unit Cell* [13], *A 5-GHz High-Efficiency Class-E Oscillator* [14], *CPW Oscillator* [15], *Single Balanced Diode mixer*, *Microstrip MESFET Power Combining A Quarter-Wave Shorted-Patch Planar Transmission Wave Amplifier*, *1-GHz Lumped Element Oscillator*, *Design, Analysis, and Comparison with Experimental Results for a Balanced Ampli-*



(a) (b)

Fig. 3. Layout of microwave phase lock loop (a). Time-domain plot of demodulated 500-kHz square wave (b).

fier, Active Patch Antenna Receiver, A Microstrip VCO, Two-stage Amplifer, Nonlinear Modeling of a Self-Biasing Oscillator, Quasi-Optical Lens Amplifiers, A Frequency Multiplier Using a Nonlinear Transmission Line, Low-Noise Optical Receiver, Varactor-Tuned Meander-Line Bandstop Filter, Impedance Measurements of Scaled Self-Complementary Antennas, Cheap Horn Antennas.

IV. ACKNOWLEDGMENT

The success of this course is largely due to the generous equipment donations by Hewlett-Packard, substrate donations by the Rogers Corporation, and active device donations by Hewlett-Packard and MA/COM. Portions of this course were funded by the University of Colorado Undergraduate Excellence Fund.

REFERENCES

[1] D. R. Hertling and R. K. Feeney, "RF and microwave design courses at Georgia Tech," *IEEE Trans. Education*, vol. 32, no. 4, pp. 430–435, Nov. 1989.

[2] D. M. Pozar, "A modern course in microwave engineering," *IEEE Trans. Education*, vol. 33, no. 1, pp. 129–134, Feb. 1990.

[3] K. C. Gupta, "Teaching CAD to microwave students," *IEEE Trans. Education*, vol. 33, no. 1, pp. 140–144, Feb. 1990.

[4] G. R. Branner, "An elective microwave course sequence with integrated laboratory," *IEEE Trans. Education*, vol. 33, no. 1, pp. 145–148, Feb. 1990.

[5] D. B. Rutledge, EE153 classnotes, Caltech, 1991.

[6] R. C. Compton and R. A. York, "A hands-on microwave laboratory course using microstrip circuits," *IEEE Trans. Education*, vol. 33, no. 1, pp. 161–163, Feb. 1990.

[7] P. H. Young, "Microstrip design laboratory," *IEEE Trans. Education*, vol. 34, no. 1, pp. 113–117, Feb. 1991.

[8] S. W. Wedge, R. C. Compton and D. B. Rutledge, *Puff: Computer Aided Design for Microwave Microwave Integrated Circuits, version 2.0.* A *Puff* manual and diskette may be ordered for $10 from Puff Distribution, Electrical Engineering M/S 116-81, California Institute of Technology, Pasadena, CA 91125.

[9] S. W. Wedge and D. B. Rutledge, "Wave computations for microwave education," *IEEE Trans. Education*, vol. 36, no. 1, pp. 127–131, Feb. 1993.

[10] R. Brown, P. Ensaf, T. Marshall, M. Piket-May, B. Popović, and Z. B. Popović, "Printed microwave couplers with thermal isolation," to be presented at the *1997 IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, June 1997.

[11] B. D. Popović, J. Schoenberg, and Z. B. Popović, "Broadband Quasi-Microstrip Antenna," *IEEE Trans. Antennas Propagat.*, vol. 43, pp. 1148–1152, Oct. 1995.

[12] W. A. Shiroma, B. L. Shaw, and Z. B. Popović, "A 100-transistor quadruple grid oscillator," *IEEE Microwave and Guided Wave Lett.*, vol. 4, no. 10, pp. 350–351, Oct. 1994.

[13] S. Hollung and Z. B. Popović, "A bi-directional quasi-optical lens amplifier," to be presented at the *1997 IEEE MTT-S Int. Microwave Symp. Dig.*, Denver, CO, June 1997.

[14] E. W. Bryerton, W. A. Shiroma, and Z. B. Popović, "A 5-GHz high-efficiency oscillator," *IEEE Microwave and Guided Wave Lett.*, vol. 6, no. 12, pp. 441–443, Dec. 1996.

[15] V. Radisić, "CPW oscillator configuration for an electro-optic modulator," *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 9, pp. 1645–1647, Sep. 1993.