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Harmonica (a CAD program) and a new circuit analysis program called Puff have been used to develop a computer-aided design/fabrication system. Using this system, one can design, simulate and build simple microwave circuits in less than a day. The system was used to develop a 3 GHz amplifier based on a Fujitsu packaged transistor and microstrip matching networks The measured performance results agreed closely with those that the simulation predicted.

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BRIEF OUTLINE OF RESEARCH FINDINGS

Since the last progress report in January, I have continued using Harmonica, written here by Ken Kundert, in addition to a new circuit analysis program called Puff, designed at CalTech, to develop a computer-aided design/fabrication system. Using this system, one can design, simulate and build simple microwave circuits in less than a day. I used the system to develop a 3 GHz amplifier based on a Fujitsu packaged transistor and microstrip matching networks. The measured performance results agreed closely with those that the simulation predicted.

I also used Harmonica and Puff as well as a commercially available circuit simulation program that runs on the IBM AT called Pspice to study the very high frequency (near the zero current gain frequency) behavior of a darlington connected pair of transistors with a third transistor acting as a current mirror to the output transistor in the darlington configuration. The presence of the third transistor eliminates the excess phase rolloff while the darlington pair gives much higher dc current gain. These two factors suggested that this transistor configuration would make a very useful microwave device. Unfortunately, the simulations proved otherwise—as a power amplifiying device with 50 ohm input and output impedances, this transistor configuration performed comparably to a single transistor.

AUTHOR: Eric Copeland

PERIOD: 1/1/87 - 6/30/87

BRIEF OUTLINE OF RESEARCH FINDINGS

Submitted by Eric Copeland

I have been working under the ARO Fellowship since October 1986. Initially, I concentrated on assisting another graduate student, Ken Kundert, develop a CAD program, called Harmonica, useful for microwave and millimeter wave circuits. Ken works under the supervision of Professor Sangiovanni-Vincentelli of the Electrical Engineering Department here. I assisted Ken by testing his program and looking for inconsistent results, making suggestions for additions to the program, and by producing a comprehensive user's manual so that others could use the program. Harmonica uses frequency domain analysis to quickly analyze complex circuits operating in the microwave to millimeter wave frequency range; Harmonica could lend itself particularly well, therefore, to the design of MICs and MMICs.

I have, in the interim, begun to build and measure the response of simple active and passive circuits to test the consistency of Harmonica's predictions with experimentally obtained data. All of these circuits have been built with passive elements and microwave transistors on either Coplanar Waveguide or Microstrip lines on artificial dielectric. My hope is to produce an undergraduate laboratory experiment in which students will become familiar with the use of as well as advantages of using CAD techniques to design active circuits at very high frequency.

Submitted by Professor S. E. Schwarz (for Dylan F. Williams)

Between July 1 and October 1, 1986 this position was held by Dylan F. Williams. Dr. Williams has now received his Ph.D. degree and is presently with Ball Aerospace Corp., Boulder, Colorado. The title of his doctoral thesis was "Millimeter-wave Integrated Circuit Technology."

The final portion of his research has recently been published. The bibliographical citation of his final publication under this grant is:

D.J. Ehrlich, D.F. Williams, J.H.C. Sedlacek, M. Rothschild, and S.E. Schwarz, "High-accuracy Tuning of Planar Millimeter-wave Circuits by Laser Photochemical Etching." Electron Device Letters EDL-8, 110-113, (March, 1987).

AUTHORS: Eric Copeland & S. E. Schwarz

PERIODS: 7/1/86 - 12/31/86

BRIEF OUTLINE OF RESEARCH FINDINGS

In the last period, work on adjustable tuning of millimeter-wave integrated circuits was completed. The most promising method investigated involves the laser-assisted etching of a metal film to change the electrical length of a CPW section. The is the planar analog of a sliding backshort in rectangular-metal waveguide. The problems with fabricating devices suitable for demonstrating laser-assisted tuning of millimeter wave integrated circuits were solved and the tuner was successfully demonstrated on an operating millimeter-wave detector circuit. This is the first demonstration of a tuner compatible with millimeter-wave integrated circuits.

AUTHOR: Dylan S. Williams

PERIOD: 1/1/86 - 6/30/86

BRIEF OUTLINE OF RESEARCH FINDINGS

Previous work on planar millimeter wave integrated circuits demonstrated the need for tunable elements in these circuits if performance comparable to circuits realized in waveguide (in which tunable elements are available) is to be obtained. Thus, methods of tuning millimeter wave integrated circuits were investigated in this period. Two methods have been demonstrated and work is continuing on a third.

The first (and simplest) method involved simply thermo-compression bonding a series of gold straps across a section of CPW. The gold straps were then removed one at a time, changing the electrical length of the CPW section.

The second method involved tinning a section of CPW with indium solder and sliding a heated gold plate through the molten solder. The heat is removed after the gold plate has been positioned properly. After the solder has solidified, the apparatus which adjusts the position of the gold plate is also removed. This method is advantageous if the position of the tuner must be changed continuously back and forth. Both of these methods of tuning have proved to be quite successful.

The third method, upon which work is still in progress, involves laser assisted etching of a metal film to change the length of the CPW section. I plan to publish these results as soon as the work on laser assisted etching is finished.

AUTHOR: Dylan S. Williams

PERIOD: 7/1/85 - 12/31/85

In previous report periods, an integrated circuit receiver technology was investigated. A technology was developed utilizing coplanar waveguide transmission lines, integrated capacitors, and plated gold posts. During this period, a deomonstration receiver was fabricated by ion milling 1um thick gold conductors on a 200um thick sapphire substrate. Plated gold posts were used to fabricate high frequency T junctions and to suspend the beam lead diodes above the substrate surface, reducing radiation losses. The receiver was designed for a 10 GHz instantaneous bandwidth centered at 71 GHz and a local oscillator frequency of 32.2 GHz. The GaAs beam lead diodes were supplied by Dr. J. A. Paul of the Hughes Aircraft Company's Electron Dynamics Division and had a cutoff frequency of 600 GHz. The single sideband gain of the receiver was measured by comparing the power at the intermediate frequency of 6.55 GHz with that of a standard gain horn at the signal frequency of 70.95 GHz. The lack of a swept source prevented measurement of the gain at other frequencies in the receivers instantaneous band-width. The measured single sidband gain of +4.25 dBi compares well with the expected gain of +4.65 dBi.

In previous periods it was shown that it is possible to reduce the loss of CPW by a factor of four by employing grooved substrates. While the receiver construction is compatible with this loss reduction scheme, it was not employed. In addition, no attempt was made to tune out the diode capacitances, although doing so with a sliding short is also compatible with the receivers construction techniques. Further calculations indicate that if the loss reduction scheme were employed and if the diode capacitance were tuned, an overall receiver gain of +7.825 dBi would be achieved with this design. This figure corresponds to a conversion efficiency of -5.0 dB and an overall ohmic loss of -.675 dB. These improvements will be considered in the next period.

center box; l n. Antenna Gain +13.5 dB (antenna efficiency is 65%) Antenna ohmic loss - 1.5 dB

RF bandpass filter loss
Ohmic loss - .2 dB
Radiation loss - .2 dB

Mixer conversion loss - 6.5 dB

IF low-pass filter loss - .45dB --------- Estimated Receiver Gain + 4.65dB

Measured Receiver Gain + 4.25dB

Table I. Receiver preformance estimates. The signal, local oscillator, and IF frequencies are 70.95 GHz, 32.2 GHz, and 6.55 GHz respectively.

AUTHOR: Dylan S. Williams

PERIOD: 1/1/85 - 6/30/85

BRIEF OUTLINE OF RESEARCH FINDINGS

In the previous progress reports, the design and fabrication of a planar millimeter-wave integrated circuit was described. In this period, I have performed further testing on the receiver. Extensive experiments have revealed that the planar capacitators used in the mixer section of the receiver radiate strongly into the substrate material. This greatly degrades the response of the receiver and seems to be responsible for the previous inability to obtain the expected conversion loss. This surprising phenomena is not fully understood at this time, although a relatively simple scheme has been devised to eliminate it. This phenomena emphasizes the need for a better understanding of the radiation properties of planar devices. The mixer has recently been redesigned to eliminate this problem and I have resumed fabrication. Also in this period, I modified a computer program written by Peter Siegel and Anthony Kerr for analyzing a single ended mixer. The modifications allow the subharmonic mixer employed in this receiver to be analyzed. Extensive S-parameter measurements of the embedding circuit have been performed. This data is used by the computer program to predict the performance of the mixer section of the receiver. I obtained reasonable agreement between the computed and the measured performance of a scale model of the mixer. I have used the program to pinpoint areas where further improvement might be made.

AUTHOR: Dylan S. Williams

PERIOD: 7/1/84 - 12/31/84

BRIEF OUTLINE OF RESEARCH FINDINGS

In the previous progress reports a design for a planar millimeter-wave integrated circuit was described. In this period I have refined the fabrication procedure. Several circuits have been built and one circuit has been tested. The 9 GHz mixing product of an incident R.F. field at 69 GHz and the second harmonic of the local oscillator at 30 GHz was observed, but the conversion efficiency was lower than expected. The rectified local oscillator current was as high as 8 mA at a low pulse duty ratio, indicating that the local oscillator power was sufficient. The most likely cause of this low efficiency is two-fold. First, one of the diodes in the diode pair was defective. Second, the diodes used were silicon schottky diodes with a low cut-off frequency. I hope that the use of high cut-off GaAs schottky diodes will improve the conversion efficiency.

I have also begun an investigation of radiation on planar substrates. The motivation for this study is the large amount of power generated at higher harmonics of the R.F. and the local oscillator in the mixing process, which is then radiated into substrate modes. This is a major loss mechanism in the mixing process. I hope that a better understanding of these radiated fields may lead to a method of improving the overall efficiency of the mixing process. I have built a probe with highly resistive leads which allows accurate measurement of field amplitudes in free space without appreciably disturbing the field amplitudes. The probe has been tested by measuring the radiated field intensity and polarization at 2 GHz from a microstrip line terminated in an open circuit.

AUTHOR: Dylan C. Williams

PERIOD: 1/1/84 - 6/30/84

BRIEF OUTLINE OF RESEARCH FINDINGS

In this period a millimeter-wave integrated circuit receiver was designed. The subharmonically-pumped mixer circuit is compatible with either beam-lead or monolithic diode technology. Coplanar waveguide (CPW) is used throughout the receiver to allow convenient shunt connections, reduce radiation losses, and to relax the tolerances required of the substrate material. Lowpass and bandpass filters, realized in CPW [1], are used to separate the various mixer frequencies.

The receiver is shown in Fig. 1. Two antennas ("a" in Fig. 1), composed of arrays of slots [2], serve to couple incident energy at the signal frequency into a CPW mode. Conventional wirebonds at the 'antenna junction' ("b") suppress the "even" mode of the guide [3]. The two quarter-wavelength sections which make up the 'antenna matching circuit' of ("c") match the antenna and diode impedances. The single-section 'RF bandpass filter' ("d") provides reactive terminations at the antenna port at the intermediate (IF), image, and local oscillator (LO) frequencies. The two bypass capacitors in ("e") allow the anti-parallel mixer diodes to be separately biased for optimum conversion loss. The ability to separately bias each diode is important at millimeter wave frequencies as it allows a certain degree of compensation for differences in the electrical parameters of the two diodes [4]. Adjustable ground planes above the antenna and the 'RF Bandpass filter' may also be used to compensate for differences in the impedances of separate diode pairs when those differences are large. Finally, a multiplexer circuit consisting of the 'LO/IF filter' ("f"), the 'LO filter' ("g"), and the 'IF filter' ("h") allows injection of the LO signal and extraction of the IF. Again, wirebonds are used to suppress the even CPW mode at the various junctions in the multiplexer.

The performance of the receiver has been simulated in the microwave region. The antenna has a measured directivity of 13.5 dB. Losses of the 'antenna junction' and the 'antenna matching circuit' were included in this measurement. The half power beam widths in the E and H planes for the antenna are 29° and 45° respectively. In microwave simulations a conversion loss of -5.5 dB was obtained for the 'mixer circuit,' which includes the losses of the 'RF band pass filter' and the 'LO/IF multiplexer.' A millimeter-wave version is currently being fabricated.

In addition, a theoretical study of the loss mechanisms in CPW was performed in this period. A reduction in propagation losses by as much as a factor of four has been predicted when grooves are etched into the dielectric substrate, as in Fig. 2. Work on experimental verification is in progress. A similar evaluation of fin-line is currently in progress.

References

[1] D. F. Williams and S. E. Schwarz, "Design and Performance of Coplanar Waveguide Band-Pass Filters," IEEE Microwave Theory and Tech., vol. MTT-31, pp 558-566,

[2] A. Nesic, "Slotted Antenna Array Excited by a Coplanar Waveguide," Electronic Letters, vol. 18, no. 6, pp. 275-276, March 1982.

[3] J. Paul, private communication.

[4] R. G. Hicks, P. J. Khan, "Numerical Analysis of Subharmonic Mixers Using Accurate and Approximate Models," IEEE Microwave Theory and Tech. vol. MTT-30, no. 12, pp. 2113-2119, December 1982.

AUTHOR: Dylan Williams

PERIOD: 8/24/83

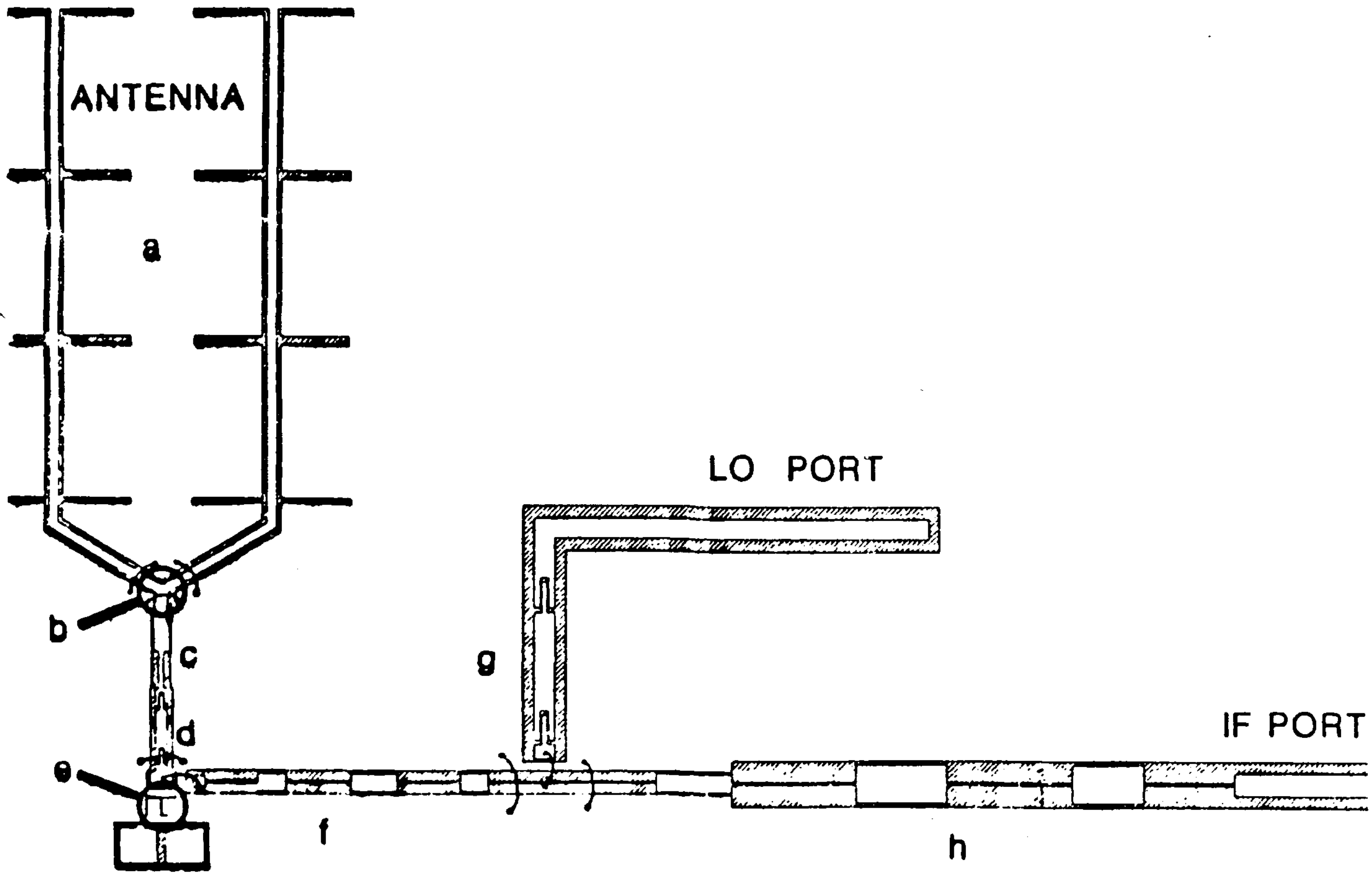

Fig. 1. Subharmonically Pumped Millimeter-Wave Integrated Circuit Receiver.

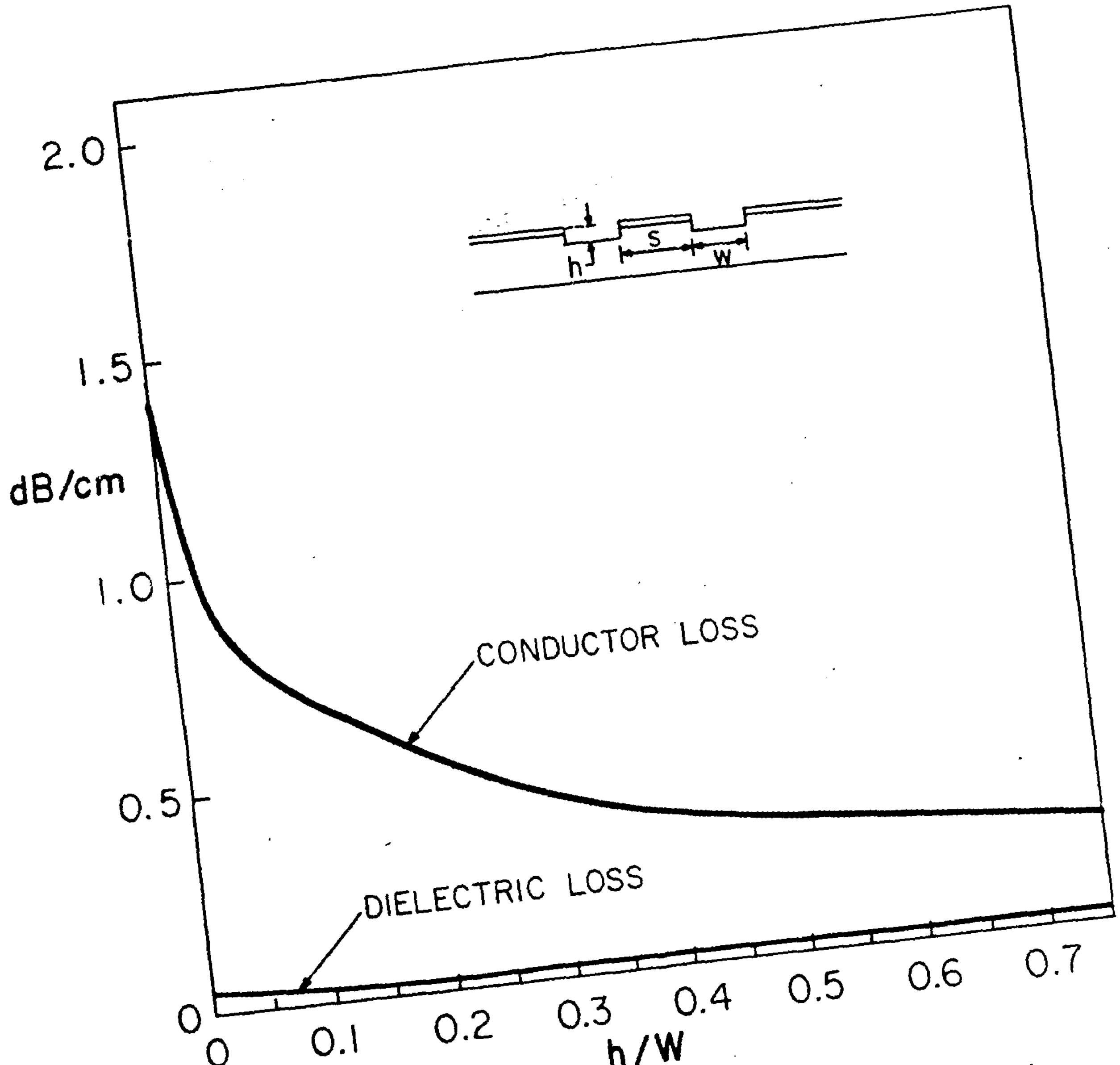

Fig. 2. Conductor and dielectric losses in 50Ω CPW as a function of groove depth h at 100 GHz from computer calculations (ε_r = 10, R_s = .0826Ω/□, tan δ = 2×10^{-4}, S + 2W = 200 μm).

BRIEF OUTLINE OF RESEARCH FINDINGS

My efforts have been devoted for the most part to coursework. I have been acquiring a general background in the areas of network flow theory, graph planary theory, number theory with emphasis on cryptographic applications, and concrete complexity.

A large portion of my work has been in the applications of network flow theory to other graph theoretic problems, specifically those involving matchings. My other work has involved deriving lower bounds on the complexity of specific problems in dynamic data structures. As I continue my coursework and research, I plan to emphasize these areas, particularly the area of dynamic data structures.

AUTHOR: Joel Mick
PERIOD: 8/24/83