Computer-aided design of microwave integrated circuits

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SUMMARY

This paper describes how an analysis/optimization program in current use may be adapted for the design of m.i.c.s. The optimization routine combines two different strategies to reduce the execution time and increase the accuracy of approach to the true minimum. The analysis routine incorporates an algorithm for junction parasitics, dispersion, conductor and dielectric loss in the microstrip lines. The effects of these parameters, together with design details, are given and optimized results presented for several amplifiers, including an X-band single stage version, employing GaAs Schottky-gate field-effect transistors. This amplifier achieves 7 dB ± 0·5 dB gain, with 2·5 : 1 input and output v.s.w.r., over the frequency range 8–11·6 GHz.

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1 Introduction

In the past few years several analysis programs have been adapted for microstrip circuits, assuming that the normal mode of operation for the microstrip line may be adequately described in terms of a TEM mode.[1-6] This approach works well up to S-band, but at high frequencies spurious propagating modes introduce dispersive effects which make the simple TEM model unacceptable. Discontinuity effects and junction parasitics are another problem making the analysis of microwave integrated circuits difficult. Some of these analysis programs are linked to optimization routines incorporating direct search techniques.[1-4] These are essentially sequential methods, in which successive points are determined by the previously generated data via the function values and/or gradient vectors.[5,6] Although such methods are often used, they are, however, efficient only in unimodal problems.

Mathematical functions which describe microwave circuit behaviour are in general non-linear, as well as being complex, often with many local minima. Incorporation of such functions into sequential search methods leads to convergence to the nearest local minimum, ignoring neighbours which may be superior.

As cost is also a very important consideration, particularly in the selection of an optimization algorithm for use in an industrial application, various modifications have been made to speed up the direct search methods by making the step size dependent on the degree of success or failure of each move.[1,2] The algorithms still have a tendency to slow down, particularly when the starting point is either far from the optimum or very close to it.

This paper describes how, by combining two or three different strategies of optimization, some of the problems may be overcome. GaAs f.e.t. small-signal amplifiers are also discussed as well as bipolar transistors, particular attention being given to their design and to the frequency dependent effects of various microstrip parameters at X- and C-bands.

2 Optimization

The non-unilateral properties of transistors in microwave amplifier circuits means that the elements all interact in some degree with each other in determining the overall response. With such effects in mind, the authors and their colleagues[7,8] have adopted a pseudo-random sequence procedure, similar to the Emery and O'Hagan 'spider' method.[2] This reduces the possibility of the optimum-following algorithm concentrating on certain variables to the exclusion of others, thereby causing false minima to be obtained. The variable to be examined is chosen by means of an algorithm in which a random number is obtained by multiplying the error between the computed and specified circuit performance by 10[6] and then selecting the last two integers. Since the chance that the error will be identical for any two values of variable are extremely

remote, this simple technique guarantees a number sufficiently random for the purposes of the program. Once the first element is chosen, a combination of successive error multiplication by 10^6 and modular arithmetic ensures that each of the remaining variables is examined once in as random a manner as possible.

The optimization method incorporates a large step direct search, mainly to deal with those starting points far from the optimum. Initially, element values are varied by 4% for distributed elements and 8% for discrete elements, but the step size is automatically varied within the program as a consequence of the success rate in minimizing the error function. Although very efficient in producing an acceptable result from a poor starting value for multivariable problems, the penalty paid here is that the convergence rate is slow when initial values are near to the optimum.

At this stage the program switches to one or more different strategies of optimization, thereby increasing the accuracy of approach to the true minimum and also tending to reduce the execution time. However, in this second stage the error function is optimized by a conjugate gradient pattern search.[9] Here each new direction of search is calculated as part of the iteration cycle, this method being inherently more powerful than those in which the directions are assigned in advance. Finally, to improve the chance of finding a global minimum solution to multi-modal problems, a limited number of random searches are employed.

3 Analysis and Evaluation of Microstrip Parameters

Analysis—The use of microstrip amplifiers implies essentially simple circuitry, for which the S-parameter [S] approach is well suited.[10] As S-parameters cannot be used in chain matrices, transmission parameters [T], which have properties similar to those of the [ABCD] set, have been used in the analysis routine. Furthermore, the calculations required for the transformation from [S] to [T] are slightly less complex than the corresponding ones from [S] to [ABCD] parameters.

Junction Parasitics—The majority of computerized methods for discontinuity effects have resulted in numerical procedures, but these are somewhat difficult to incorporate. In consequence, there have been developed a number of empirical equations for the evaluation of junction reactances associated with the abrupt change in the centre conductor of microstrip.[11] As the parasitics for a step change may be embodied in series inductance and shunt capacitance, the empirical formulae evaluate these reactances in terms of microstrip widths for a fixed dielectric constant (alumina). The reactance associated with an open-end termination is treated in a manner as described in Ref. 12.

Dielectric Loss—This may be calculated if both the loss tangent and the electric field distribution are known.

Computation of the electric field is complicated and not practicable for present purposes, so an empirical method has been used here to evaluate the dielectric loss.[13]

Dispersion—Of the many experimental and theoretical approaches reported, we have chosen Getsinger's model[14] as being the most appropriate for computer analysis.

Conductor Loss—Schneider's approximation,[15] being simple and explicit, has been adopted for estimating conductor losses in the strip and ground plane.

4 Design Examples

The design procedures and results for some optimized amplifiers are illustrated in this Section. Three different circuits of varying complexity were considered. The aim for the first one was to optimize for a 7 dB power gain and 2·5 : 1 v.s.w.r. at both input and output, over a frequency range of 8–11·6 GHz. The GaAs f.e.t. amplifier utilized Plessey Schottky-barrier type GAT 3, the transistor chip being mounted on a 1-mm diameter post protruding through a hole drilled in the alumina. The flange of this post was bonded to the microstrip ground plane, thereby providing a low-inductance d.c. return for the source contact.[16] Initially, unilateral input and output matching networks were designed by filter synthesis, using high-low impedance sections,[17] and extra circuit elements were then added for the purpose of meeting the required specification. The final optimized values are indicated on the circuit arrangement shown in Fig. 1(a), whilst Fig. 1(b) shows the frequency response for the initial and the final designs, using air line. The initial circuit performance gave 1·2 dB gain at 8 GHz, rising to 5·8 dB at 8·8 GHz, and falling to −6 dB at 11·6 GHz. This was improved by optimization to give a calculated gain of 7 dB ± 0·5 dB and a v.s.w.r. better than 2:1 over the desired bandwidth.

Experimental results obtained by using the microstrip line dimensions from the optimized circuit are also included in Fig. 1(b), using alumina substrate. Although the measured response follows the predicted gain in shape, there are significant differences between the two curves. These have been traced to dispersion, losses and junction parasitics, for which no corrections were made. Figure 1(c) shows in more detail the optimized power gain with and without taking into account the above parameters. The results indicated by the solid line were obtained by including conductor and dielectric losses, as well as dispersion effects. The dotted line resulted when, in addition to these parameters, junction effects were taken into account. The diagram shows that the parasitic junction effects were of much smaller importance here than losses and dispersion in the microstrip.
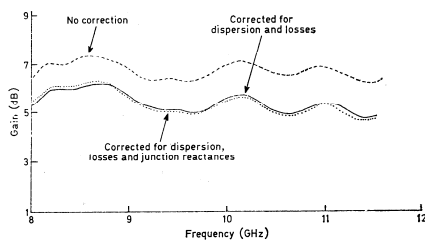
If the input and output matching networks consist of only a few sections, then the junction introduces mismetching as illustrated in Ref. 18, tending to enhance the effects of parasitic reactance. Here, however, multi-
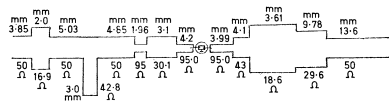
(a) X-band GaAs f.e.t. amplifier circuit.
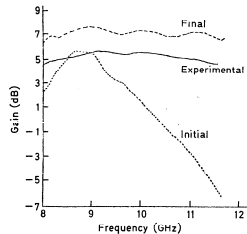
(b) Frequency response of X-band amplifier—initial, final (computed) and experimental.

(c) Frequency response of X-band amplifier—with and without correction. (Computed).

Fig. 1.

section microstrip arrangements were used to reduce the v.s.w.r.s.

The second example is that of a three-stage amplifier for the frequency range 2·5–3·5 GHz, utilizing bipolar transistors, as illustrated in Fig. 2(a). The results for optimized power gain are shown in Fig. 2(b) as a solid line and as a dashed line, corresponding to correction for microstrip parameters and junction reactances and to no correction, respectively. It is to be noted that the corrected power gain has been reduced by almost 1 dB. The junction reactance had virtually no effect on the power gain but resulted in slightly increased input and output v.s.w.r.

The third and final example comprises a simple narrow band amplifier, again utilizing Plessey GaAs f.e.t.s. The circuit arrangement illustrated in Fig. 3(a) is relatively simple, involving only two stubs. The dotted and solid lines in Fig. 3(b) are computed for initial and final optimized power gain using air line, respectively. Figure 3(c) shows the results of substituting both alumina and polyguide substrate in place of the air line. In the case of

polyguide, the power gain of the amplifier is seen to be higher than with alumina. This is explained by the dispersion and spurious propagating modes having a larger effect on account of the higher dielectric constant ($\epsilon_r = 9·8$).
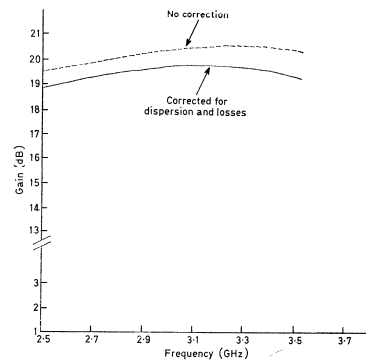
5 Conclusions

An analysis/optimization program has been described which includes an algorithm for junction parasitics, dispersion and losses in microstrip. The optimization routine combines pseudo-random and conjugate gradient pattern-search techniques to improve the chance of finding a global solution to multimodal problems. The optimization of GaAs f.e.t. and bipolar transistor amplifiers illustrates the ability of the program to produce good results from poor starting values.

A unilateral design approach utilizing filter synthesis and optimization has been successfully applied to a single stage X-band amplifier. As the input and output matching networks contain a multi-section arrangement of microstrip lines, the junction parasitics have negligible effect on the amplifier performance, although dispersion and losses reduced the gain by almost 1·5 dB over the bandwidth 8–11·6 GHz. At S-band the junction parasitics had no effect on the amplifier performance, but dispersion and losses again reduced the gain, by almost 1 dB in fact, for the three-stage amplifier. The dispersive effect, which makes the simple TEM model inaccurate, has been demonstrated by using different substrate materials and the effect on overall performance was found to be very significant for a substrate of high permittivity.
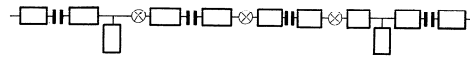
(a) A three-stage S-band amplifier circuit.

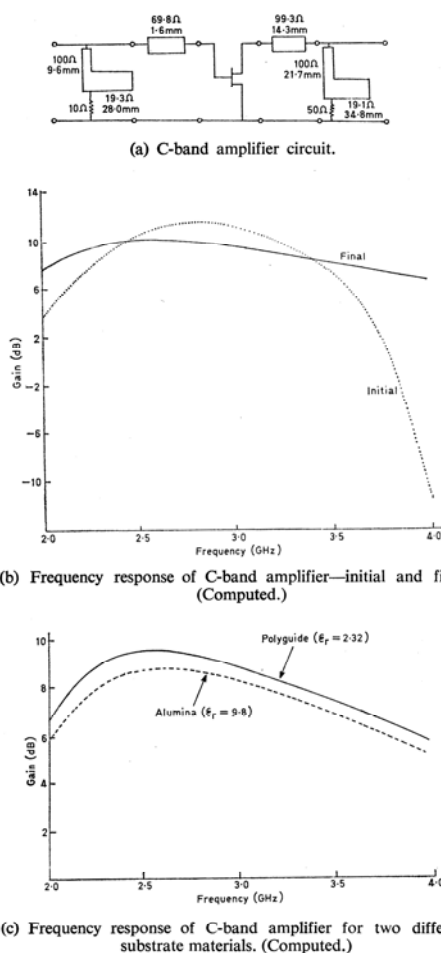(b) Frequency response of S-band amplifier. (Computed).

Fig. 2.

N. M. HOSSEINI and H. V. SHURMER

(a) C-band amplifier circuit.

(b) Frequency response of C-band amplifier—initial and final. (Computed.)

(c) Frequency response of C-band amplifier for two different substrate materials. (Computed.)

Fig. 3.

6 Acknowledgments

7 References

1 Gelnovatch, C. G. and Chase, L. L., 'DEMON—An optimal seeking computer program for the design of microwave circuits', *IEEE Trans. on Solid-State Circuits*, **SC-5**, p. 303–9, December 1970.

2 Emery, F. E. and O'Hagan, M., 'Optimal design of matching network for microwave transistor', *IEEE Trans. on Microwave Theory and Techniques*, **MTT-14**, pp. 696–8, December 1966.

3 Trick, T. N. and Vlach, J., 'Computer-aided design of broad-band amplifiers with complex loads', *IEEE Trans.*, **MTT-18**, pp. 541–7, September 1970.

4 Cisco, T. C., 'Design of Microstrip Components by Computer', NASA-Contractor Report (NASA-CR-1982), p. 205, March 1972.

5 Sanchez-Sinencio, E. and Trick, T. N., 'CADMIC—computer-aided design of microwave integrated circuits', *IEEE Trans.*, **MTT-22**, pp. 309–16, March 1974.

6 Herrick, D. L., 'NOVA—network optimization via adjoints', *IEEE Trans.*, **MTT-23**, pp. 849–50, October 1975.

7 Soares, R. A., 'Amplifier design using bipolar transistor', London University Ph.D. Thesis, 1974.

8 Hosseini, N. M., Shurmer, H. V. and Soares, R. A., 'OPTIMAL—a program for optimizing microstrip networks', *Electronics Letters*, **12**, No. 8, pp. 190–2, 15th April 1976.

9 Fletcher, R. and Reeves, C. M., 'Function minimization by conjugate gradients', *Computer J.*, **7**, No. 2, p. 149, 1961.

10 Hewlett-Packard, 'S-parameter design', Application Note 194, April 1972.

11 Hosseini, N. M., 'The application of computer-aided design to microstrip circuits', Ph.D. Thesis, University of Warwick, July 1977.

12 Hammerstad, E. O., 'Equation for microstrip circuit design', in Proc. 1975 European Microwave Conf., Hamburg, Germany, pp. 268–271.

13 Hosseini, N. M. and Shurmer, H. V., 'MICPA—evaluation of microstrip line parameters', *Electronics Letters*, **12**, No. 19, pp. 496–7, 15th September 1976.

14 Getsinger, W. J., 'Microstrip dispersion model', *IEEE Trans.*, **MTT-21**, pp. 34–9, January 1973.

15 Schneider, M. V., 'Microstrip lines for microwave integrated circuits', *Bell Syst. Tech. J.*, **48**, pp. 1421–44, May–June 1969.

16 Soares, R. A. and Turner, J. A., 'Tunable X-band GaAs f.e.t. amplifier', *Electronics Letters*, **11**, No. 19, pp. 474–5, 18th September 1975.

17 Slaymaker, N. A., Soares, R. A. and Turner, J. A., 'GaAs m.e.s.f.e.t. small-signal X-band amplifiers', *IEEE Trans.*, **MTT-24**, pp. 329–37, June 1976.

18 Akello, R. J., Easter, B. and Stephenson, I. M., 'Effects of microstrip discontinuities on GaAs m.e.s.f.e.t. amplifier gain performance', *Electronics Letters*, **13**, No. 6, pp. 160–2, 17th March 1977.