obtains [2] the excess carrier density distribution within the gapwidth w:

$$\Delta n(x) \simeq \Delta p(x) = g\tau \left\{1 - \frac{\cosh(x/L_a)}{\cosh(w/2L_a) + Q_c{}^{-1}\sinh(w/2L_a)}\right\} \quad \ldots \quad (1)$$

where g is the bulk rate of carrier generation, τ is the intensity-dependent excess carrier lifetime, L_a is the ambipolar diffusion length and $Q_c = s\tau/L_a$ is the contact figure of merit with regard to recombination effects, i.e. the ratio of contact recombination velocity s to bulk recombination velocity L_a/τ. By assuming the dark conductivity σ_d to be much smaller than the excited photoconductivity $\Delta\sigma(x) = q(\mu_n + \mu_p)\Delta p(x)$, even at the contacts at $|x| = w/2$, the sensor photoresistance may be calculated from

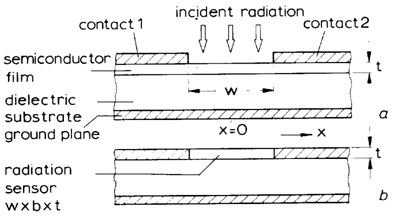

Fig. 2 *Cross-section of integrated radiation sensor and its contacts*
a Real configuration
b Simplified model, admissible for $t \ll L_a$

$$R = 2\int_0^{w/2} dR = \frac{2}{q(\mu_n + \mu_p)bt}\int_0^{w/2}\frac{dx}{\Delta p(x)}$$

$$= \frac{2D}{\Delta\sigma_{max}\,bt}\int_0^{w/2}\frac{dx}{D - \cosh(x/L_a)} \qquad (2)$$

where $D = \cosh(w/2L_a) + Q_c{}^{-1}\sinh(w/2L_a)$ and

$$\Delta\sigma_{max} = q(\mu_n + \mu_p)g\tau.$$

Solving eqn. 2 yields R as a function of D and w, respectively:

$$R\{D(w)\} = R_0\frac{2D}{(D^2-1)^{\frac{1}{2}}}$$

$$\times \ln\left\{\frac{[1 - D - (D^2-1)^{\frac{1}{2}}][\exp(w/2L_a) - D + (D^2-1)^{\frac{1}{2}}]}{[1 - D + (D^2-1)^{\frac{1}{2}}][\exp(w/2L_a) - D - (D^2-1)^{\frac{1}{2}}]}\right\} \quad \ldots \quad (3)$$

where $R_0 = L_a/\Delta\sigma_{max}\,bt$.

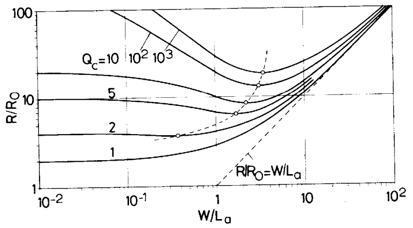

Fig. 3 *Plot of normalised sensor photoresistance R/R_0 against normalised gapwidth w/L_a with contact figure of merit Q_c as parameter*

Results: Calculated from eqn. 3, the plot of R/R_0 as a function of w/L_a at various Q_c is shown in Fig. 3. Since the modulation factor increases with decreasing R, the minimum of each curve will indicate the most suitable gapwidth causing the highest possible modulation factor at a given Q_c. For good ohmic contacts having a $Q_c \geqslant 10^4$, these calculations result in an optimum gapwidth of $w \simeq 4L_a$. Further, from eqn. 3, one obtains $\lim_{w \to 0}\{R(w)\} = 2R_0\,Q_c$ and

$$R(w \gg L_a) \simeq R_0\,w/L_a = w/\Delta\sigma_{max}\,bt.$$

Investigations on a CdSe–Al_2O_3 shunt modulator system[2] with an excess carrier lifetime $\tau \simeq 4 \times 10^{-4}$ s produced by an incident radiation density of about 2 W/cm² and with an ambipolar carrier mobility $\mu_a \simeq 10\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ yielded experimentally an optimum gapwidth of about 0·2 mm. Indeed, this value is somewhat smaller than the optimum mentioned above, which can be calculated for the CdSe–Al_2O_3 system as $4\,L_a \simeq 0{\cdot}4$ mm. But it still verifies the theoretical results fairly well, considering the silver conductor past contacts on the CdSe film which were deposited by silk-screen printing and therefore will merely produce a Q_c of about 10 to 100.

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COMPUTER-PROGRAM DESCRIPTION

OPTIMAL: A PROGRAM FOR OPTIMISING MICROSTRIP NETWORKS*

Indexing terms: Electronics applications of computers, Microwave amplifiers, Optimisation, Solid-state microwave circuits, Striplines

An optimisation program OPTIMAL is described which includes algorithms for dispersion and loss in microstrip. The optimisation routine combines pseudorandom and conjugate gradient pattern-search techniques to improve the chances of finding a global-minimum solution to multimodal problems. The optimisation of a GaAs f.e.t. amplifier shows the program's ability to produce good results from poor starting values.

Introduction: Microstrip, because of its light weight, small dimensions and easy processing capability, is being increasingly used for microwave circuit design up to J-band. General-purpose transmission-line analysis programs have been adapted for microstrip circuits by specifying microstrip elements as operating in a TEM mode. This approach works well up to S-band,[1, 2] but at higher frequencies spurious propagating modes introduce dispersive effects which make the simple TEM model inaccurate.

Many optimisation programs are now available which make use of these general circuit analysis programs.[3] In general, the optimisation programs are based on 'sequential' or 'linear search algorithms', in which previously generated points are used to determine the new direction of search. Although extremely efficient in determining the minima of unimodal functions, for multivariable, multimodal problems, such as those encountered in amplifier optimisation, a sequential search program will converge to the nearest local minimum, ignoring neighbouring, but possibly better, minima.

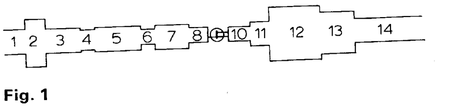

Fig. 1

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* The program listing and accompanying documentation are held in the IEE Library, Savoy Place, London WC2R 0BL, England. For further information, please contact the Library, quoting CP151

Table 1

Elements		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Initial values	Ω	50	−16	50	−43	50	95	−30	95	Tr.	−95	−43	−19	−30	50
	mm	3·8	−4·4	−5·4	−4·1	−5·1	1·9	−5·2	−2·5		−1·2	−4·4	−2·8	−8·6	13·6
Final values	Ω	50	23	50	49·9	50	95	46	95	Tr.	100	44·5	20·9	27·5	50
	mm	3·8	2·8	5·5	2·4	8·7	1·9	6·6	2·9		4·3	2·1	8·8	7·2	13·6

This letter describes a microstrip analysis and optimisation program OPTIMAL which has several novel features:

(*a*) The analysis routine incorporates Getsinger's model for microstrip dispersion[4] and includes an algorithm for determining conductor loss in microstrip lines.

(*b*) The optimisation routine makes use of a large-step pseudorandom search technique to increase the chances of finding a global minimum.

(*c*) Having located a promising valley, the program switches to efficient conjugate gradient technique to converge quickly to the minimum.

As this program is designed mainly to deal with active 2-port devices, the letter concludes by showing the results of the optimisation of an X-band GaAs f.e.t. amplifier design.

Program description: The program OPTIMAL has been written for cascades of 2-port circuit elements. It employs a least *p*th objective function based on the following network responses: (*a*) transducer gain, (*b*) ripple gain and (*c*) input/output reflection coefficient.

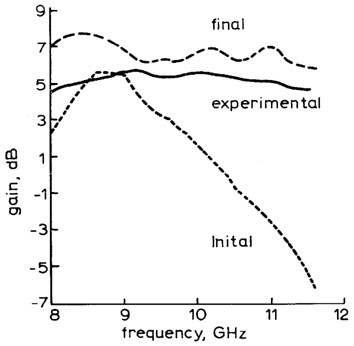

Fig. 2

Eight basic types of circuit element are available. They include transistors which are not optimised and represented by their *s*-parameters, transmission lines, short- or open-circuited shunt stubs, series series, series parallel, shunt series, shunt parallel of inductor-capacitor-resistor, L-section of transmission line. A negative initial value for any parameter indicates that this parameter is to be varied during optimisation and thus a lower and upper bound for each varied element will be punched afterwards in the same card (see also program details).

Analysis: In the course of development of any computer program, two conflicting requirements emerge: one is to perform the analysis as quickly as possible, by making the program highly specific, the other is to relate the method of computation to the general usage capability of the program. The *s*-parameters (*S*) approach was chosen, since it is ideally suited to these requirements. It is obvious that the inability to use *s*-parameters in chain matrices is the result of the decision to take reflected waves as dependent variables and incident waves as independent. Therefore transmission parameters (*T*), which have properties similar to those of the (*ABCD*) set, have been used in the analysis routine.

The calculations required for the transformation from (*S*) to (*T*) are slightly less complex than those required from (*S*) to (*ABCD*). For a higher calculation efficiency, the (*T*) set have therefore been used for cascading; thus the analysis program deals with elements connected in cascade and terminated with 50 Ω loads at the inputs and outputs. It also contains algorithms for dealing with loss and dispersion in microstrip elements for a variety of dielectric substrates. A facility also exists within the program for converting transmission-line elements from their air lengths and characteristic impedances to dimensions compatible with microstrip substrates.

Optimisation: This section of the program has two parts; the large-step pseudorandom search algorithm known as PRANCE and a conjugate gradient search to locate the final minimum.

PRANCE: The nonunilateral properties of the GaAs f.e.t. and bipolar transistor in microwave amplifier circuits means that no element is entirely isolated from any other in its effects on the overall response. For this reason the authors have used an approach similar to Emery and O'Hagan's 'spider method',[5] in which the variables are chosen in a pseudorandom sequence. This reduces the possibility of the

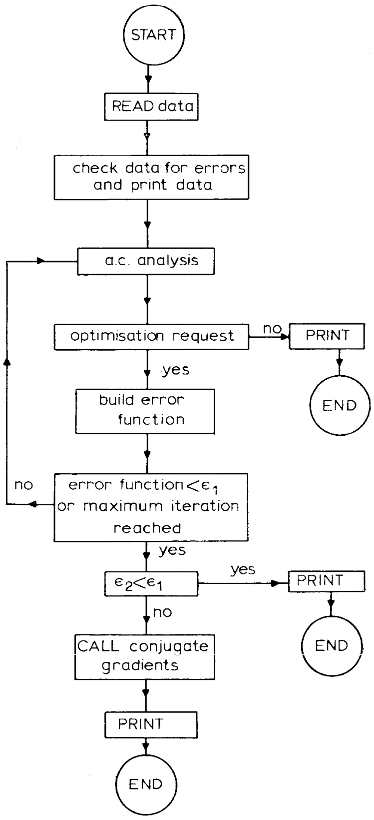

Fig. 3 *Flow diagram*

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 an algorithm in which a random number is obtained by multiplying the error between computed and specified circuit performance by 10^6 and selecting the last two integers. Since the chances 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 PRANCE.

Once the first element is chosen, a combination of successive error multiplication by 10^6 and modular arithmetic will ensure that each of the remaining variables will be examined once in as random a manner as possible.

The objective function is the least pth form, where p can have any value between 6 and 60. Initially, element values are varied by 4% for distributed elements and 8% for discrete elements, although this step size is automatically varied within the program, depending on the success rate in minimising the objective function.

Conjugate gradient: In the last stage, the objective function is minimised by the Fletcher-and-Reeves algorithm[6] which the new circuit values select, by a conjugate gradient pattern search. By this technique, each new direction of search is calculated as part of the iteration cycle. The method is inherently more powerful than those in which the directions are assigned in advance.

OPTIMAL application to GaAs-f.e.t.-amplifier design: This provides a good example of the ability of OPTIMAL to produce results from poor starting values. The amplifier circuit is shown in Fig. 1. The goal was to achieve a flat 7 dB power gain and 1·5:1 v.s.w.r. at both input and output over the range 8–11·6 GHz. In Table 1, the initial parameter values, together with the final values of the elements, are shown. Fig. 2 shows the frequency response of both the initial and the final design. The initial circuit performance gave 1·2 dB gain at 8 GHz, going up to 5·8 dB at 8·8 GHz, and falling to −6 dB at 11·6 GHz. This was improved by OPTIMAL to give a gain of 7 dB ± 0·5 dB and a v.s.w.r. of better than 2:1 over the band.

Experimental results obtained by using the microstrip line dimensions obtained from OPTIMAL are also included in Fig. 2. Although the experimental results follow the predicted gain response shape there are significant differences between the two curves. These have been traced to junction parasitics and radiation losses for which no corrections have been made in OPTIMAL. Work is at the moment being carried out to obtain accurate models for standard microstrip discontinuities and these will be included in a new version of OPTIMAL.

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Program details

(*a*) FORTRAN IV

(*b*) A maximum of 60 network types

(*c*) Complex and only single precision arithmetic

(*d*) 963 cards, including comments

Performance guide

(*a*) It is loaded on the XDS-Sigma 5 computer by using overlay

(*b*) Core-size requirements: 50896 bytes

(*c*) Input medium: cards

(*d*) Output medium: line printer

(*e*) Work or data files needed: None

(*f*) Time taken to run submitted example: compilation 4·10 min, run 19·20 min

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GaAs POWER F.E.T.S WITH SEMI-INSULATED GATES

Indexing terms: Field-effect transistors, Ion implantation, Power transistors, Solid-state microwave devices

GaAs semi-insulated-gate f.e.t.s (s.i.g.f.e.t.s) have been fabricated by Ar^+ bombardment in the gate region. The d.c. characteristics and microwave performance are compared with those of conventional power m.e.s.f.e.t.s fabricated from the same slice. Up to 2·9W output power with 4 dB gain has been obtained from s.i.g.f.e.t. devices at 8 GHz.

Small-signal GaAs f.e.t.s with semi-insulated gates (s.i.g.f.e.t.s) have been fabricated by proton bombardment of the region between the source and drain to reduce gate leakage current.[1] Recently, conventional GaAs Schottky-barrier-gate f.e.t. (m.e.s.f.e.t.) amplifiers have yielded output powers in the 1 to 2 W range at X-band.[2–4] In the present work, semi-insulated gates created by Ar^+ bombardment have been used on power f.e.t.s in an attempt to improve performance. In addition to lowering the leakage current, the semi-insulated gate may also redistribute the electric fields beneath the gate contact (in a lower-maximum-field configuration) so as to permit the use of larger drain bias voltages and thus give higher r.f. output powers. In the present letter, the direct-current/voltage (I/V) characteristics and microwave performance of GaAs s.i.g.f.e.t.s are described and compared with those of conventional m.e.s.f.e.t.s fabricated simultaneously from a portion of the same slice.

The device structure shown in Fig. 1 differs from that of Pruniaux *et al.*,[1] in that only the region directly under the gate is subjected to ion bombardment. The fabrication procedure is similar to that for conventional m.e.s.f.e.t.s,[4, 5] except for creation of the semi-insulated region. Active layers having $n = 5$ to $15 \times 10^{16}\,cm^{-3}$ are grown by a $AsCl_3/Ga/H_2$ vapour-phase-epitaxy process on semi-insulating GaAs substrates and thinned by anodic oxidation to about 0·4 μm, which is about 0·1 μm thicker than for conventional m.e.s.f.e.t.s. Following mesa etching and source/drain ohmic-contact formation, the gate pattern (2 μm gate lengths) is defined in AZ 1350J photoresist. Rather than continuing with gate metal evaporation and liftoff as with the m.e.s.f.e.t., the slice is now bombarded with $10^{14}/cm^2$ Ar^+ ions at 30 keV. The photoresist, which confines the bombarded area to the exposed gate region, is not significantly affected by bombardment and is subsequently employed for gate evaporation and liftoff. The remainder of the device fabrication and mounting is identical to the conventional m.e.s.f.e.t. process.[4, 5] Since the bombardment is limited to the gate region, the thicker epitaxial layers used give lower parasitic source-gate, drain-gate and contact resistances. Argon ions are employed rather than protons to obtain the