REPORT R-434 SEPTEMBER, 1969

CSL COORDINATED SCIENCE LABORATORY

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by

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This work was supported in whole by the Joint Services Electronics Program (U.S. Army, U.S. Navy, and U.S. Air Force) under Contract DAAB 07-67-C-0199.

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I. INTRODUCTION

In this paper a computer-aided design approach is developed for the broad-band matching of complex generator and load impedances to a network containing active elements. Both lumped or distributed elements can be used without difficulty, but herein only the distributed case is presented.

It is well known that at higher frequencies there is a point at which the lumped elements are no longer well defined and distributed models must be used. The mathematical description of these distributed parameter elements is complicated, and transcendental functions are involved in their description. For instance, a lossless transmission line is described by functions containing $\tanh(\ell s/c)$ where s is the usual complex frequency variable and ℓ/c is the ratio of the length of the transmission line element to the phase velocity of the wave in such an element. To eliminate the tanh function, a new variable can be introduced [1]

$$t = \tanh(\ell s/c),$$

but this requires that all lines in the network have the same ratio ℓ/c and the price of losing one parameter per line is paid for the convenience of describing the network by a rational function of the complex variable t.

Similar transformations can be applied for waveguides and RC distributed lines. This approach was and still is extensively used [2-5] because not only can the well-developed theory of lumped filters be applied, but also extensive tables are available. However, the synthesis is still quite complicated and elements not having direct lumped counterparts (unit elements) must be incorporated. To the knowledge of these authors, this approach was not used for matching problems and is probably unsuitable for networks containing transistors.

Some work has been done in matching a transistor to a resistive source and load by LC lossless transmission lines or by L and C lumped elements. In [6], a Smith Chart, lumped elements, and measured data of a transistor are used, whereas [7] attacks the problem by using a very simple mixed computer-aided graphic approach to match the transistor to a resistive load and source by means of LC lossless transmission lines. Minimization of the reflection coefficient was described in [8] to match a transistor to resistive source and load by means of lossless lines.

The method described in this paper is an optimization method allowing the use of several transistors, LC transmission lines (need not be lossless), lumped L, C, R elements and complex generator and load impedances. It has two parts:

1. The analysis of a special class of active distributed networks in terms of scattering parameters (cascade connection of series lines, stubs and transistors)
2. Optimization using Rosenbrock's minimization procedure which does not require knowledge of any derivatives.

The analysis of a cascade of networks with complex terminations requires a special redefinition of the transfer scattering parameters. This is done in the next section. In Section three the analysis program is discussed. Section four discusses the optimization criterion in which the lengths and characteristic impedances of the lines are adjusted within constrained bounds until the reflection loss is minimized and/or the power gain is flat over the specified frequency range. We conclude with several typical design problems, one of which is the matching of a slot antenna to a distributed line over a 2:1 frequency range.

II. TRANSFER SCATTERING PARAMETERS WITH COMPLEX NORMALIZATIONS

Basic Definition

The usual definition [9] of the scattering parameters for a two-port network normalized to complex loads is

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \tag{1a}$$

where

$$a_i = \frac{1}{2\sqrt{\mathrm{Re}Z_i}} [V_i + I_i Z_i]$$

$$b_i = \frac{1}{2\sqrt{\mathrm{Re}Z_i}} [V_i - I_i Z_i^*] \tag{1b}$$

*Denotes complex conjugate.

The above definitions can easily be extended to include n-port networks. However, in this paper we will only be concerned with two-ports.

We now wish to define a new set of parameters called the transfer scattering parameters which have the property that if T_A is the transfer scattering matrix for network A and if T_B is the transfer scattering matrix for network B in Figure 1, then the transfer scattering matrix for the cascade connection is

$$T_C = T_A T_B. \tag{2}$$

Let us write the transfer scattering parameters for network A as

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} t^a_{11} & t^a_{12} \\ t^a_{21} & t^a_{22} \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix}, \tag{3}$$

and for network B as

$$\begin{bmatrix} A_3 \\ B_3 \end{bmatrix} = \begin{bmatrix} t^b_{11} & t^b_{12} \\ t^b_{21} & t^b_{22} \end{bmatrix} \begin{bmatrix} A_4 \\ B_4 \end{bmatrix}. \tag{4}$$

We begin by defining the left hand quantities in (3) and (4) as being equal to the usual incident and reflected scattering waves, that is,

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_1}} \begin{bmatrix} 1 & Z_1 \\ 1 & -Z_1^* \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}, \tag{5}$$

and

$$\begin{bmatrix} A_3 \\ B_3 \end{bmatrix} = \begin{bmatrix} a_3 \\ b_3 \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_3}} \begin{bmatrix} 1 & Z_3 \\ 1 & -Z_3^* \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix}. \tag{6}$$

Now requirement (2) demands that

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \begin{bmatrix} A_3 \\ B_3 \end{bmatrix} = \frac{1}{2\sqrt{ReZ_3}} \begin{bmatrix} 1 & Z_3 \\ 1 & -Z_3^* \end{bmatrix} \begin{bmatrix} V_3 \\ I_3 \end{bmatrix} .$$

However, in the cascade connection

$$V_2 = V_3,$$

$$I_2 = -I_3,$$

and we must require $$Z_2 = Z_3$$

so that

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \frac{1}{2\sqrt{ReZ_2}} \begin{bmatrix} 1 & -Z_2 \\ 1 & Z_2^* \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

Note that in cascading two networks in order for relationship (2) to be valid <u>the connection ports must be normalized to the same complex impedance ($Z_2 = Z_3$)</u>. Hence, the complex normalized transfer scattering incident and reflected waves are defined as

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \frac{1}{2\sqrt{ReZ_1}} \begin{bmatrix} 1 & Z_1 \\ 1 & -Z_1^* \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} ; \tag{7}$$

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \frac{1}{2\sqrt{ReZ_2}} \begin{bmatrix} 1 & -Z_2 \\ 1 & Z_2^* \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} . \tag{8}$$

<u>Relation to S-parameters</u>

To obtain the relation of the complex-normalized transfer scattering parameters to the usual scattering parameters, we first express a_1 and b_1 as a function a_2 and b_2

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{s_{21}} & -\frac{s_{22}}{s_{21}} \\ \frac{1}{s_{21}} & \frac{s_{12}s_{21}-s_{11}s_{22}}{s_{21}} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} . \tag{9}$$

Since by definition (5)

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} \tag{10}$$

we have

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{s_{21}} & -\frac{s_{22}}{s_{21}} \\ \frac{s_{11}}{s_{21}} & \frac{s_{12}s_{21}-s_{11}s_{22}}{s_{21}} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} , \tag{11}$$

but from (1b)

$$\begin{bmatrix} b_2 \\ a_2 \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_2}} \begin{bmatrix} 1 & -Z_2^* \\ 1 & Z_2 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} , \tag{12}$$

and from (8)

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_2}} \begin{bmatrix} Z_2^* & Z_2 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} . \tag{13}$$

Substituting (13) into (12) we obtain

$$\begin{bmatrix} b_2 \\ a_2 \end{bmatrix} = \frac{1}{2\mathrm{Re}Z_2} \begin{bmatrix} 1 & -Z_2^* \\ 1 & Z_2 \end{bmatrix} \begin{bmatrix} Z_2^* & Z_2 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} , \tag{14}$$

and with the substitution of (14) into (11)

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = \left\{ \begin{bmatrix} \dfrac{1}{s_{21}} & -\dfrac{s_{22}}{s_{21}} \\ \dfrac{s_{11}}{s_{21}} & \dfrac{s_{12}s_{21}-s_{11}s_{22}}{s_{21}} \end{bmatrix} \frac{1}{2\mathrm{Re}Z_2} \begin{bmatrix} 2Z_2^* & Z_2-Z_2^* \\ Z_2^*-Z_2 & 2Z_2 \end{bmatrix} \right\} \begin{bmatrix} A_2 \\ B_2 \end{bmatrix} . \qquad (15)$$

The quantity constrained in the large brackets is the T matrix for the two-port in terms of the S-parameters. Note that if Z_2 is real (a special case), then $\begin{bmatrix} b_2 \\ a_2 \end{bmatrix} = \begin{bmatrix} A_2 \\ B_2 \end{bmatrix}$, and

$$T = \begin{bmatrix} \dfrac{1}{s_{21}} & -\dfrac{s_{22}}{s_{21}} \\ \dfrac{s_{11}}{s_{21}} & \dfrac{s_{12}s_{21}-s_{11}s_{22}}{s_{21}} \end{bmatrix} \qquad (16)$$

which is essentially the definition given in [9].

Renormalization of the Transfer Scattering Parameters

We see that the transfer scattering parameters are convenient for the analysis of a cascade connection of two-ports, since the transfer scattering matrix for the entire system is simply the resultant matrix product. However, ones ultimate goal is the acquisition of the S-parameters normalized to the complex terminating impedances Z_1 and Z_2 since these parameters have a definite meaning to us in terms of reflected and incident power. Thus, the analysis of a typical cascade of two-ports might proceed as follows: First we find the transfer scattering parameters of the two-ports all normalized to some arbitrary impedances Z_1' and Z_2'. One usually picks some convenient value, such as 50Ω's. We then find

$$[T'] = [T_1'][T_2'] \ \ldots \ [T_n'].$$

Thus,

$$\begin{bmatrix} A_1' \\ B_1' \end{bmatrix} = [T'] \begin{bmatrix} A_2' \\ B_2' \end{bmatrix} . \tag{17}$$

We now wish to relate T' to the S matrix normalized to the acutal port impedances Z_1 and Z_2. This is accomplished below.

Using (5) we have for the first port with primed normalizing impedances

$$\begin{bmatrix} A_1' \\ B_1' \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_1'}} \begin{bmatrix} 1 & Z_1' \\ 1 & -Z_1'^{*} \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} .$$

The same network, normalized to Z_1, Z_2 and expressed in terms of the usual scattering parameters, is described at port 1 by (1b)

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_1}} \begin{bmatrix} 1 & +Z_1' \\ 1 & -Z_1'^{*} \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} .$$

Because the voltage and current V_1, I_1 must be the same, elimination of the vector $\begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$ results in

$$\begin{bmatrix} A_1' \\ B_1' \end{bmatrix} = \frac{\sqrt{\mathrm{Re}Z_1}}{\sqrt{\mathrm{Re}Z_1'}} \begin{bmatrix} 1 & Z_1' \\ 1 & -Z_1'^{*} \end{bmatrix} \begin{bmatrix} 1 & Z_1 \\ 1 & -Z_1^{*} \end{bmatrix}^{-1} \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} . \tag{18}$$

We proceed similarly for the second port. From (6), in terms of the primed impedances

$$\begin{bmatrix} A_2' \\ B_2' \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_2'}} \begin{bmatrix} 1 & -Z_2' \\ 1 & Z_2'^* \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

and from (1b) in terms of the unprimed impedances

$$\begin{bmatrix} b_2 \\ a_2 \end{bmatrix} = \frac{1}{2\sqrt{\mathrm{Re}Z_2}} \begin{bmatrix} 1 & -Z_2^* \\ 1 & Z_2 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} .$$

Elimination of the vector $\begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$ results in

$$\begin{bmatrix} A_2' \\ B_2' \end{bmatrix} = \frac{\sqrt{\mathrm{Re}Z_2}}{\sqrt{\mathrm{Re}Z_2'}} \begin{bmatrix} 1 & -Z_2' \\ 1 & Z_2'^* \end{bmatrix} \begin{bmatrix} 1 & -Z_2^* \\ 1 & Z_2 \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} . \tag{19}$$

Insert now (18) and (19) into (17):

$$\frac{\sqrt{\mathrm{Re}Z_1}}{\sqrt{\mathrm{Re}Z_1'}} \begin{bmatrix} 1 & Z_1' \\ 1 & -Z_1'^* \end{bmatrix} \begin{bmatrix} 1 & Z_1 \\ 1 & -Z_1^* \end{bmatrix}^{-1} \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = [T'] \frac{\sqrt{\mathrm{Re}Z_2}}{\sqrt{\mathrm{Re}Z_2'}} \begin{bmatrix} 1 & -Z_2' \\ 1 & Z_2'^* \end{bmatrix} \begin{bmatrix} 1 & -Z_2^* \\ 1 & Z_2 \end{bmatrix}^{-1} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix}$$

This can be rewritten as

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = [U] \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} \tag{20}$$

where

$$U = \frac{1}{2\sqrt{\mathrm{Re}Z_1}\sqrt{\mathrm{Re}Z_1'}} \begin{bmatrix} Z_1'^*+Z_1 & Z_1'-Z_1 \\ Z_1'^*-Z_1^* & Z_1'+Z_1^* \end{bmatrix} [T'] \frac{1}{2\sqrt{\mathrm{Re}Z_2'}\sqrt{\mathrm{Re}Z_2}} \begin{bmatrix} Z_2+Z_2' & Z_2^*-Z_2' \\ Z_2-Z_2'^* & Z_2^*+Z_2'^* \end{bmatrix} . \tag{21}$$

At this point it is very important to note from (9) that

$$u_{11} = \frac{1}{s_{21}} \qquad u_{12} = -\frac{s_{22}}{s_{21}}$$
$$u_{21} = \frac{s_{11}}{s_{21}} \qquad u_{22} = \frac{s_{12}s_{21} - s_{11}s_{22}}{s_{21}} \tag{22}$$

and these S-parameters are now normalized to the complex terminating impedances Z_1, Z_2. One could use (5) and (15) to obtain the new T-matrix, normalized to Z_1 and Z_2, but we are actually interested in the S-parameters which have the usual connotation of power for matched terminations, that is,

$$|s_{jk}|^2 = \frac{\text{power delivered to } z_j}{\text{max power available from port k}}, \tag{23}$$

$$|s_{jj}|^2 = \frac{\text{power reflected from port j}}{\text{power incident on port j}}. \tag{24}$$

For the two-port we note that

$$s_{11} = \frac{u_{21}}{u_{11}}, \tag{25}$$

$$s_{21} = \frac{1}{u_{11}}, \tag{26}$$

$$s_{22} = -\frac{u_{12}}{u_{11}}, \tag{27}$$

and

$$s_{12} = \frac{u_{11}u_{22} - u_{21}u_{12}}{u_{11}}. \tag{28}$$

Therefore Equations (25) - (28) are the quantities which will be optimized in some sense.

III. ANALYSIS OF CASCADED NETWORKS

In this particular work we are interested in finding the power delivered to a complex load through a cascade connection of series lines, shorted stubs, transistors, and possibly lumped elements. Thus, we will be concerned with finding the transfer scattering parameters for the above two-ports (series line, shorted stubs, etc.) and finding their product in the sequence in which they are connected. As we mentioned in Section II the normalizing impedances Z_1' and Z_2' are completely arbitrary; hence we will choose $Z_1' = Z_2' = R$, a real number. In particular we set $R = 50\Omega$'s. Then the final matrix can be renormalized to the complex terminating impedances Z_1 and Z_2 by the expression

$$[U] = [ML][T'][MR] \tag{29}$$

where from (21)

$$[ML] = \frac{1}{2\sqrt{R\ \mathrm{Re}Z_1}} \begin{bmatrix} R+Z_1 & R-Z_1 \\ R-Z_1^* & R+Z_1^* \end{bmatrix}, \tag{30}$$

and

$$[MR] = \frac{1}{2\sqrt{R\ \mathrm{Re}Z_2}} \begin{bmatrix} Z_2+R & Z_2^*-R \\ Z_2-R & Z_2^*+R \end{bmatrix}, \tag{31}$$

since $Z_1' = Z_2' = R$. The power delivered to the load is then computed by (26) and (23).

The T-matrices for some typical networks are given in Figures 2 and 3. Figure 2 shows the results for two basic lumped sections, and Figure 3 gives the T-parameters for two typical distributed sections. The scattering parameters for the transistors are measured for a 50Ω normalization, and a subroutine converts them to transfer scattering parameters normalized to 50Ω's.

IV. DESIGN OF BROAD-BAND AMPLIFIERS

A typical design problem might be to match an antenna to a transistor over a 2:1 frequency range. A certain cascade connection of series lines, shorted stubs, and transistors is chosen to do the job. One does not know whether or not this particular topology is the best suited for the task at hand; one can only guess. Some initial lengths and characteristic impedances are chosen for the transmission lines. The network is analyzed for these initial conditions at a finite number of frequencies ω_i, i=1,2,...,n where $\omega_i \in \Omega_o$ and Ω_o is the frequency range of interest. At each frequency the scattering parameters and the augmented admittance matrix of the network are computed. The augmented admittance matrix is used to check the stability of the two-port. In addition the error function

$$E = \sum_{i=1}^{n} \{a(|s_{11}^i|^2 + |s_{22}^i|^2) + b(|s_{21}^i|^2 - |s_{21}^v|^2)^d\} \tag{32}$$

is formed, where s_{11} and s_{22} are the reflected losses and $|s_{21}^i| - |s_{21}^v|^2$ is the deviation of the power gain from some predetermined average value s_{21}^v. The quantities a, b, and d are weighting factors. For example, if $a \neq 0$ and $b = 0$, then in minimizing E we are trying to obtain a good match. However, if $a = 0$, and $b \neq 0$, then we are trying to achieve a flat power gain over the frequency range Ω_o. These two criteria are not necessarily the same when transistors are present that have a gain characteristic which is not constant in Ω_o.

E is minimized using a modified version of Rosenbrock's minimization procedure [10]. Thus we do not need to use any finite difference techniques to compute the rate of change of E with respect to the various parameters. The characteristic impedances and lengths of the lines are simply varied in the direction of the maximum rate of change of E and directions orthogonal to it. The parameters are constrained to lie within certain bounds. For example, the characteristic impedance might be required to lie in the range 30Ω to 130Ω so that the design is practical. Some typical design examples follow.

V. RESULTS

Resistive Source and Load

Figure 4 illustrates a typical broad-band matching problem. The network consists of an L-section, a transistor, and a T-section. The generator and load impedances are both 50Ω's in this example. The problem is to adjust the length (L_i) and the characteristic impedance (Z_{oi}) of each line to achieve flat power gain or the best match over a certain frequency range. In this paper we will restrict ourselves to the 2:1 range of 150 MHz to 300 MHz. The selection of the circuit topology was arbitrary, and one could have any reasonable number of series lines, stubs, and transistors, and in any order.

The results of our computer-aided design are illustrated in Table I and Figures 5 through 9. In Table I the result of the initial guess is shown

Table I

	L_i^*	Z_{01}	L_2^*	Z_{02}	L_3^*	Z_{03}	L_4^*	Z_{04}	L_5^*	Z_{05}	Average Gain(dB)	Ripple (dB)
Initial Result	0.50	50Ω	0.50	50Ω	0.50	50Ω	0.50	50Ω	0.50	50Ω	7.0	8.5
Optimized Result IA	.086	28Ω	.982	55Ω	0.444	84Ω	.799	90Ω	.462	104Ω	11.3	0.2
Sensitivity Result IB	.080	25Ω	1.00	50Ω	0.420	77Ω	.800	80Ω	.452	95Ω	11.0	0.2
Sensitivity Result IC	0.50	50Ω	1.00	50Ω	.420	77Ω	.800	80Ω	.450	95Ω	11.1	0.4
Optimized Result II	0.95	36Ω	.978	79Ω	.845	100Ω	.595	60Ω	.997	40Ω	12.5	0.45
Optimized Result III	.136	67Ω	.94	64Ω	.999	129Ω	.983	90Ω	.059	34Ω	14.5	5.6
Optimized Result IV	.897	37Ω	.873	97Ω	.620	100Ω	.523	87Ω	0	-	11.3	0.25
Optimized Result V	.722	29Ω	.458	125Ω	.730	133Ω	.496	92Ω	0	-	12.4	0.25

L_i^* is the normalized length of the line. The actual length $\ell_i = \dfrac{L_i}{2\pi\sqrt{\mu\epsilon}\, f_N}$ where

f_N = 212 MHz.

first. Initially the normalized lengths were set equal to 0.5 and the characteristic impedances were set equal to 50Ω's. Note that the average gain was quite low (7.0 dB) and the variation in gain from the highest gain to the lowest gain was very large (ripple = 8.5 dB). Rosenbrock's minimization procedure was then applied to the function (32) for a variety of different weights. Optimized Result IA was obtained by trying to achieve a flat power gain with a reasonable minimization of the reflection losses, and Optimized Result II was obtained by weighting the reflection loss term a little heavier, and thus, sacrificing some of the flatness in gain. Optimized Result III was achieved by only minimizing the reflection losses. All four of these results are illustrated in Figure 5. An experimental comparison with Optimized Result IA is shown in Figure 6 on an exaggerated scale. Note that the experimental results are within approximately 0.5 dB of the computed result. Since the measurement of the S-parameters for the transistor appear to be the only weak link in our analysis procedure, the transistor was removed from the circuit and a comparison made between the experimental and computed results. Figure 7 shows that this suspicion was correct. The gain in the experimental circuit was slightly below the computed results; but this is to be expected, since we were assuming lossless lines in our program.

Other errors that might effect the results could be due to inaccuracies in the actual length of the lines and in the characteristic impedance of each line. A sensitivity study was done on Optimized Result IA and these results are denoted in Table I as Sensitivity Results IB and IC. A graphical comparison is shown in Figure 8. We note that the optimized result is fairly insensitive, that is, the local minimum seems to be fairly flat; a fact that we noted consistently throughout our studies.

Finally, Optimized Results IV and V illustrate the effect of changing the network topology. Note that the last series line was deleted, and yet the consequences are almost negligible. The reason that Optimized Result V appears to be so good is that we constrained the characteristic impedance to be less than 150Ω's, whereas in most of the other results we constrained it to be less than 100Ω's or 130Ω's. These results are compared to Optimized Results I and II in Figure 9.

Resistive Source and Complex Load

Next, the renormalization scheme in Section II was applied in an attempt to match a slot antenna to a strip line containing one or more transistors over the frequency band 150 MHz to 300 MHz. The antenna impedance is plotted in Figure 10. Note that its impedance varies considerably in this band, so it appears that we have an impossible task. The generator impedance was assumed to be 50Ω's.

The optimized results are illustrated in Figures 11 and 12. Figure 11 presents the results for one common-emitter transistor stage. The comparison between the experimental and the computed results is very good except at the high frequency end of the scale. It was found that different transistors in the circuit could shift the gain curve by one dB or more. However, the shape of the gain characteristic did not change significantly. Therefore, it was felt that the discrepancy at the end of the line must be due to an error in the measurement of the load impedance or inaccuracies in the manufacture of the line. Note that the output section consists of a rather long narrow line with a characteristic impedance of 130Ω's. This line was difficult to cut accurately without the aid of precision tools which we lacked. Figure 13 appears to support the latter hypothesis. The transistor was removed from the line and the line was terminated in 50Ω's. A comparison of the experimental and computed gain curves in Figure 13 shows that initially the experimental loss was slightly greater than the computed loss, as it should be since we assumed lossless lines in our program. However, at 220 MHz the lines cross and the computed loss becomes greater than the experimental loss. Such is the case in Figure 11. Figure 12 presents the matched results for two common-emitter stages. The gain variation is only $\pm$ 1.5dB about the average of 28 dB. This is an extremely good result considering the given load impedance. It should be noted that the network configurations in Figures 11 and 12 were arrived at by trial and error. Various other configurations were tried and they gave poor and sometimes unstable results.

VI. COMMENTS

Additional problems being studied are the design of broad-band low noise receivers and the design of distributed filters. Also, other minimization techniques which use gradient techniques are being studied. It should be noted that the single stage designs with ten or less parameters were very straightforward. However, amplifiers with two or more stages and with ten or more parameters become increasingly difficult to design, and it appears that for any large problem more network theory needs to be brought to bear on the problem; or, perhaps each stage needs to be adjusted separately (something we did not try). Each of our designs took from 2 to 5 minutes of 360/75 time.

ACKNOWLEDGMENTS

We would like to express our gratitude to Mr. Fred Ore of the University of Illinois Antenna Laboratory for conducting the experimental measurements and to Mr. M. E. Mokari-Bolhassan of the Coordinated Science Laboratory for doing some of the programming.

REFERENCES

1. P. I. Richards, "Resistor-Transmission-Line Circuits," Proc. IRE, Vol. 36, pp. 217-220, Feb. 1948.

2. H. Ozaki and J. Ishii, "Synthesis of a Class of Strip-Line Filters," IRE Transactions on Circuit Theory, CT-5, pp. 104-109, June 1958.

3. R. Levy and I. Whiteley, "Synthesis of Distributed Elliptic-Function Filters from Lumped-Constant Prototypes," IEEE Transactions on Microwave Theory and Techniques, MTT-14, pp. 506-517, Nov. 1966.

4. H. J. Carlin and W. Kohler, "Direct Synthesis of Band-Pass Transmission Line Structures, IEEE Transactions on Microwave Theory and Techniques, MTT-13, pp. 283-297, May 1965.

5. R. Levy, "A General Equivalent Circuit Transformation for Distributed Networks," IEEE Transactions on Circuit Theory, CT-12, pp. 457-458, Sept. 1965.

6. R. W. Anderson, "S-Parameter Techniques for Faster, More Accurate Design," Hewlett-Packard Journal, Vol. 18, No. 6, Feb. 1967.

7. V. G. Gelnovatch and T. F. Burke, "Computer Aided Design of Wideband Integrated Microwave Transistor Amplifiers on High Dielectric Substrates," IEEE Transactions on Microwave Theory and Techniques, MTT-16, July 1968, pp. 429-439.

8. F. E. Emery and M. O'Hagan, "Optimal Design of Matching Networks for Microwave Transistor Amplifiers," IEEE Transactions on Microwave Theory and Techniques, MTT-16, Dec. 1966, pp. 696-689.

9. H. J. Carlin and A. B. Giordano, Network Theory: An Introduction to Reciprocal and Nonreciprocal Circuits, Prentice-Hall, Inc., 1964.

10. H. H. Rosenbrock, "An Automatic Method for Finding the Greatest or the Least Value of a Function," The Computer Journal, Vol. 3, p. 175, 1960.

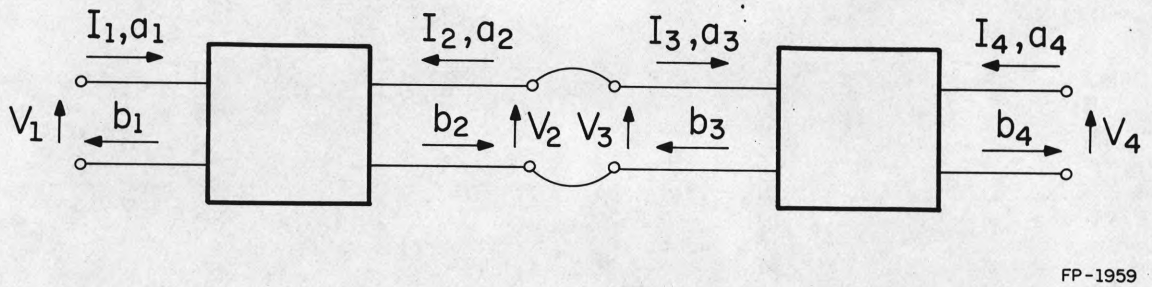
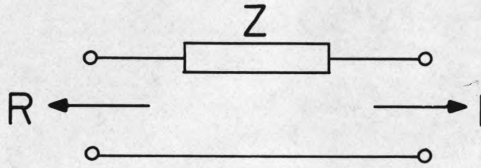
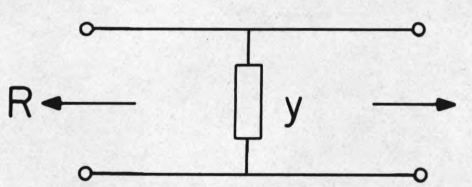


Figure 1. Cascade connection of two-ports.



$$T = \begin{bmatrix} 1+\frac{Z}{2R} & -\frac{Z}{2R} \\ \frac{Z}{2R} & 1-\frac{Z}{2R} \end{bmatrix}$$

(a) Series Element

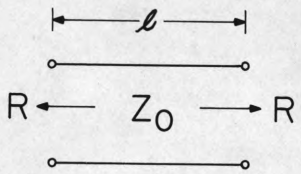


$$T = \begin{bmatrix} 1+\frac{Ry}{2} & \frac{Ry}{2} \\ -\frac{Ry}{2} & 1-\frac{Ry}{2} \end{bmatrix}$$

(b) Shunt Element

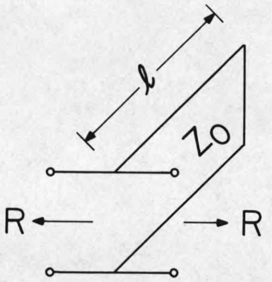
FP-1960

Figure 2. Transfer-scattering parameters for some lumped two-ports.



$$T = \begin{bmatrix} \cos\beta\ell + j\dfrac{Z_0^2+R^2}{2Z_0R}\sin\beta\ell & -j\dfrac{Z_0^2-R^2}{2Z_0R}\sin\beta\ell \\ j\dfrac{Z_0^2-R^2}{2Z_0R}\sin\beta\ell & \cos\beta\ell - j\dfrac{Z_0^2+R^2}{2Z_0R}\sin\beta\ell \end{bmatrix}$$

(a) Lossless Series Line



$$T = \begin{bmatrix} 1 - j\dfrac{R}{2Z_0}\cot\beta\ell & -j\dfrac{R}{2Z_0}\cot\beta\ell \\ j\dfrac{R}{2Z_0}\cot\beta\ell & 1 + j\dfrac{R}{2Z_0}\cot\beta\ell \end{bmatrix}$$

(b) Lossless Shorted Line

FP-1961

Figure 3. Transfer-scattering parameters for some distributed two-ports.

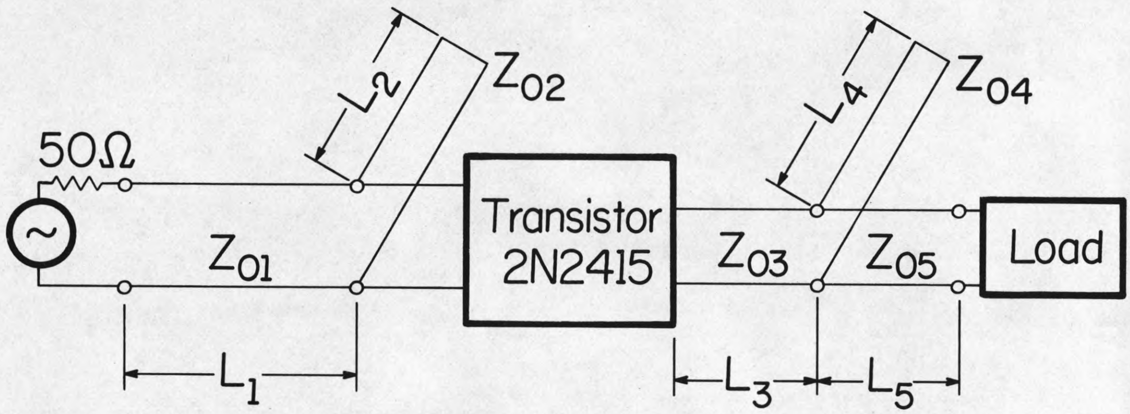
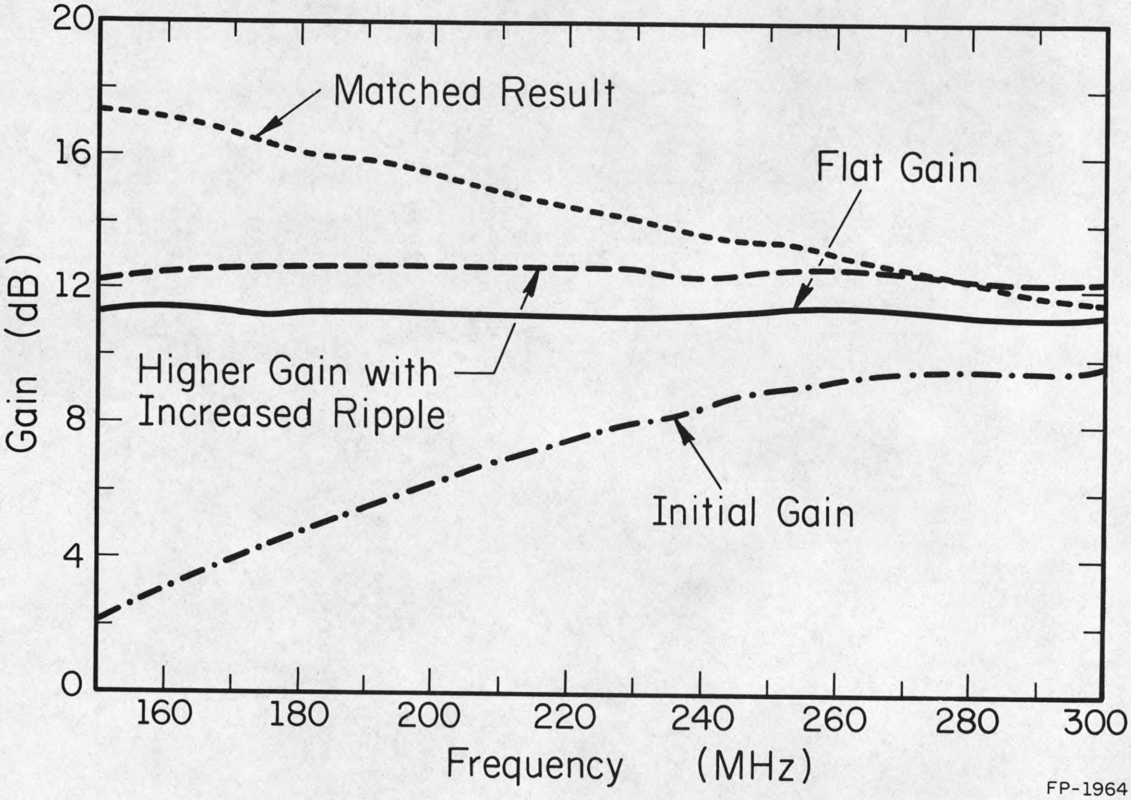


Figure 4. Typical matching configuration.



FP-1964

Figure 5. Initial gain and the dependence of the optimal gain on the weighting factors.

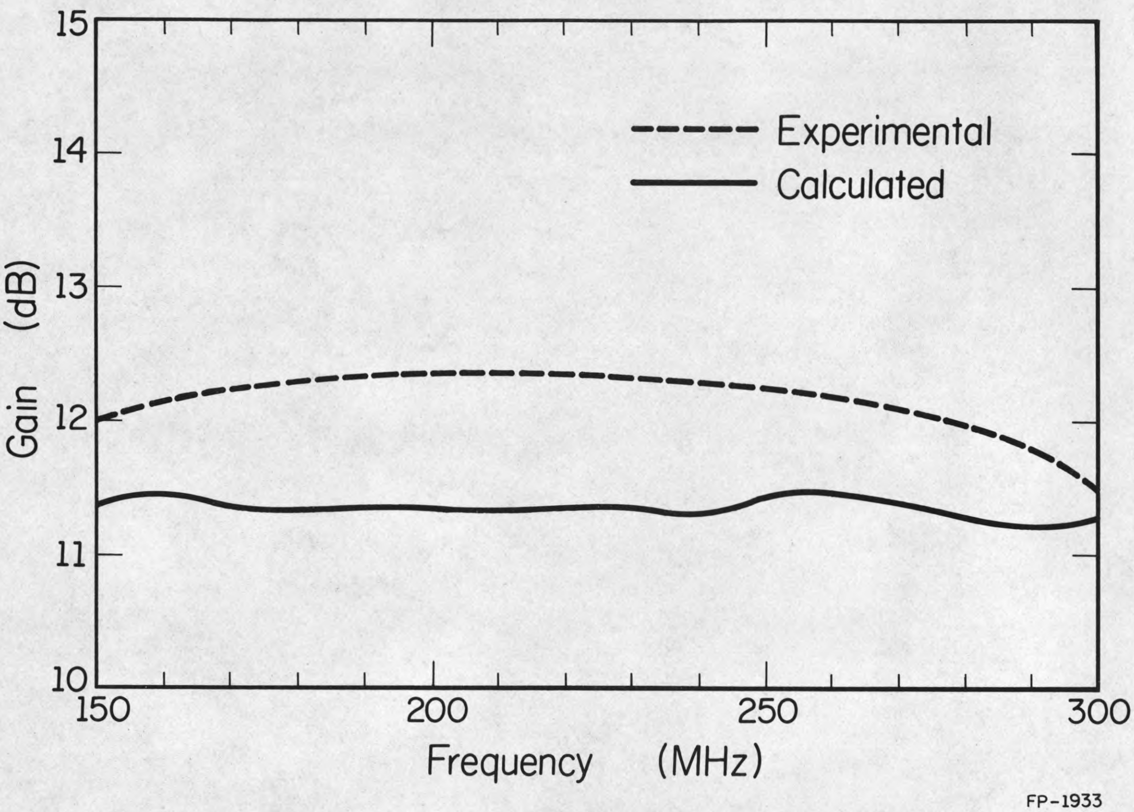


Figure 6. A comparison of experimental and computed results.

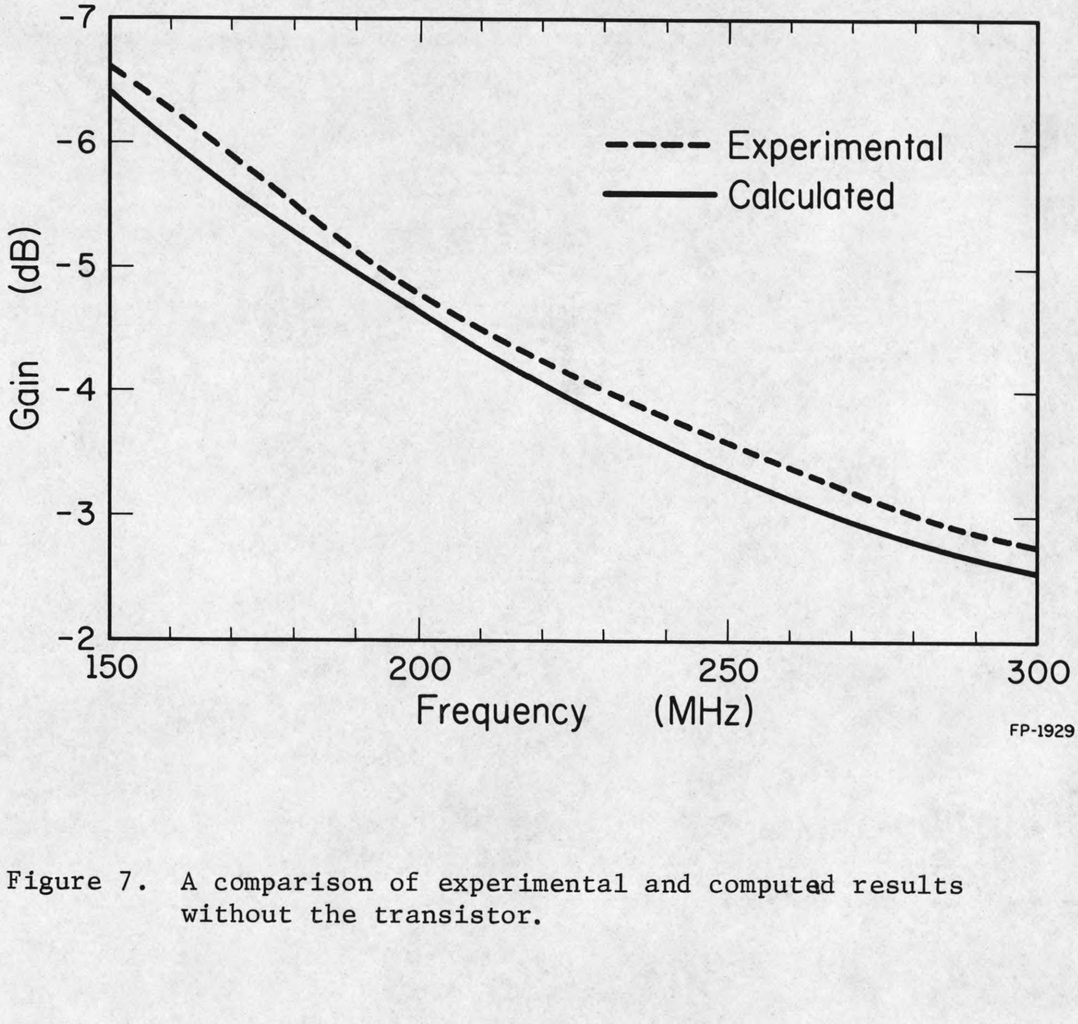


Figure 7. A comparison of experimental and computed results without the transistor.

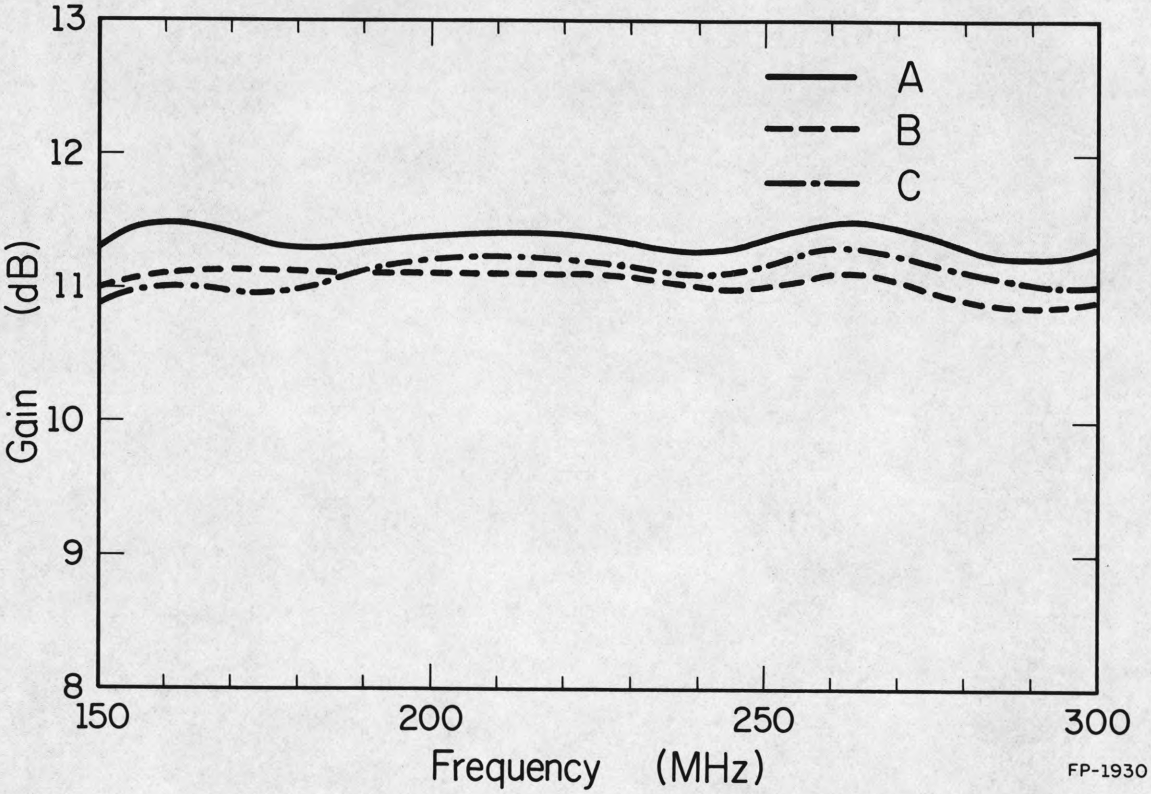


Figure 8. Variation of gain with parameters.

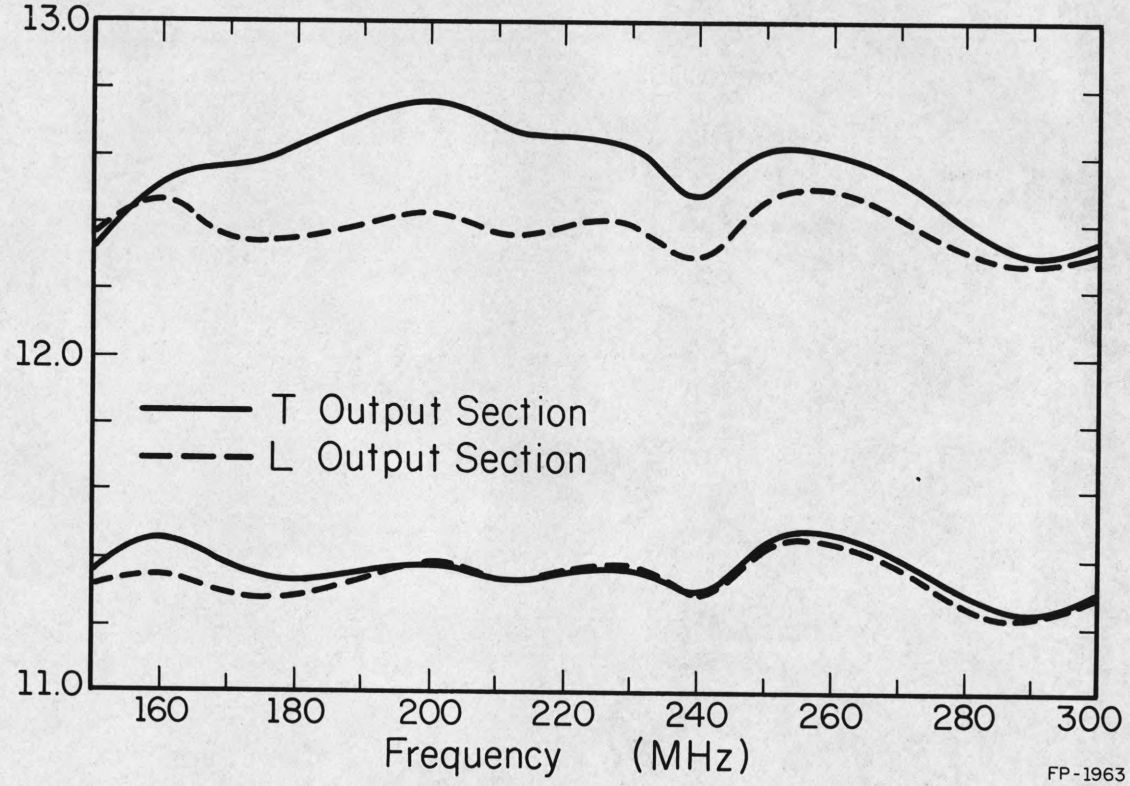


Figure 9. Gain comparison for different output sections.

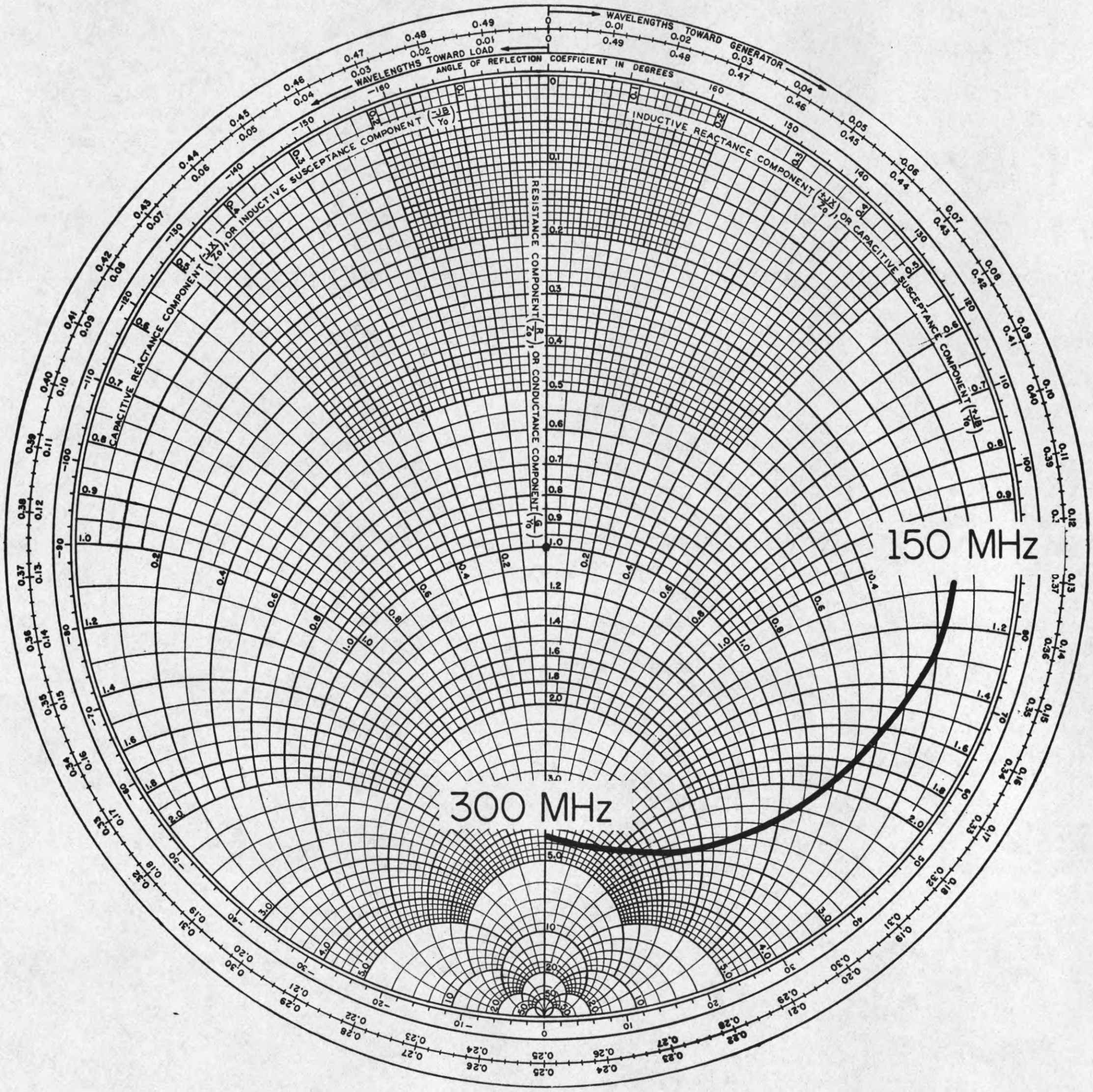


Figure 10. Impedance of the antenna load normalized to 50Ω's.

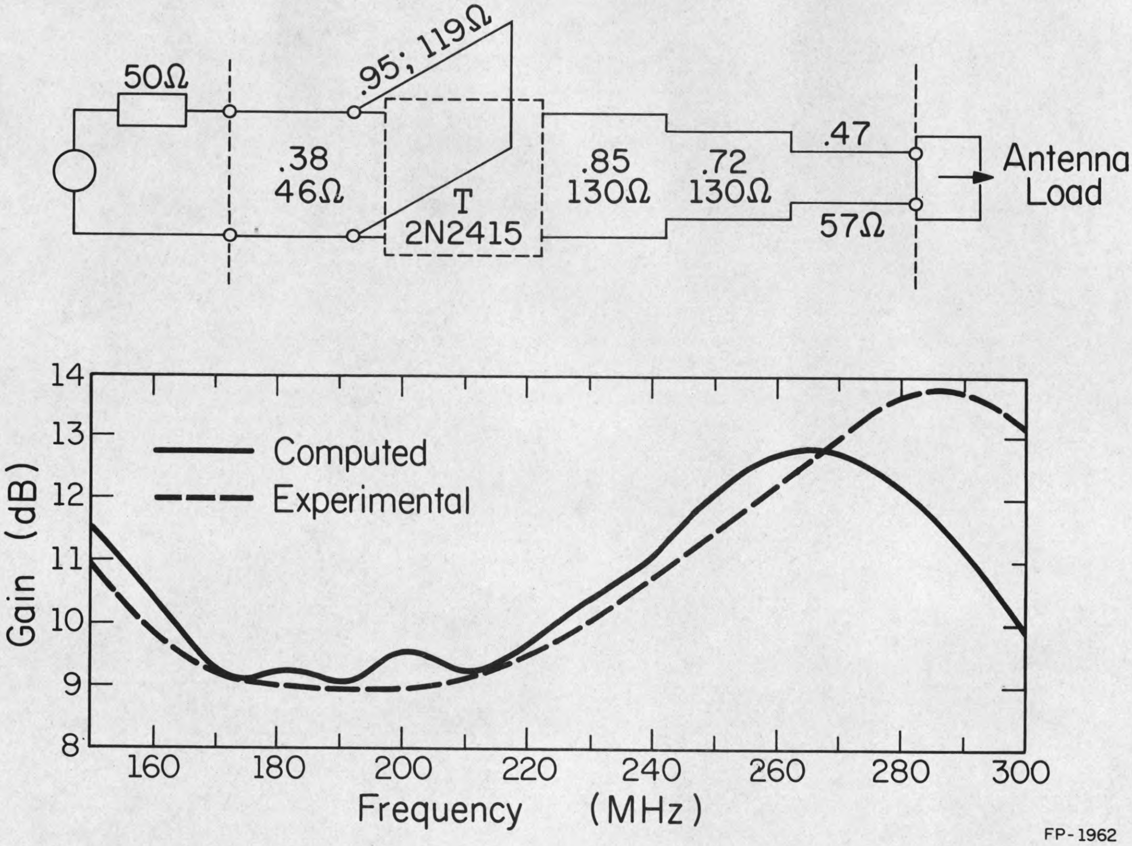


Figure 11. Comparison of experimental and computed optimal gains for an antenna load and one transistor.

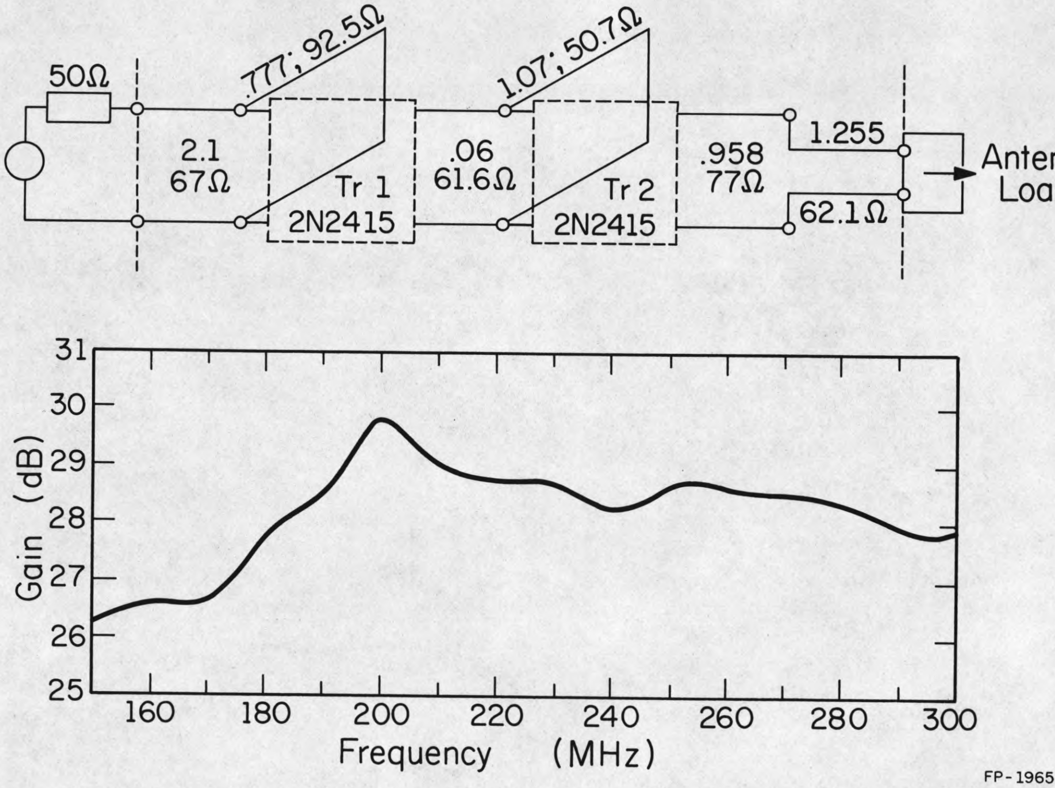


Figure 12. Optimal gain for an antenna load and two common-emitter stages.

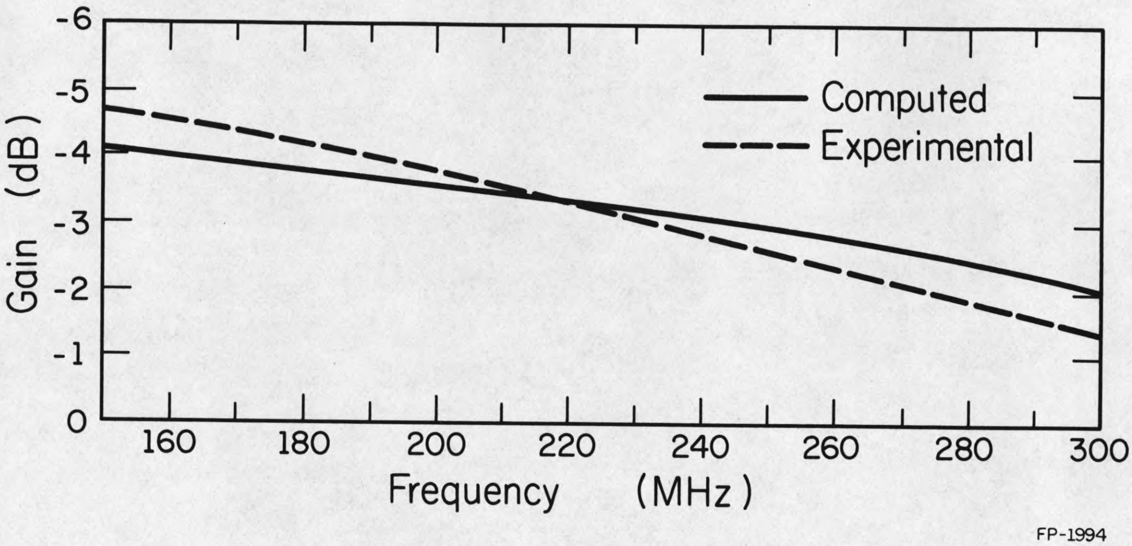


Figure 13. Comparison of experimental and computed loss for the line in Figure 11 without the transistor and with a 50Ω load.

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
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13. ABSTRACT

In this paper a computer-aided design approach is developed for the broad-band matching of complex generator and load impedances to a network containing active elements. Both lumped or distributed elements can be used without difficulty, but herein only the distributed case is presented.

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