A new approach to the design of low noise stable broadband microwave amplifier

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Abstract

In this paper a new approach to the design of stable broadband amplifier is shown. A new hybrid optimization algorithm based on Controlled Random Search (CRS) procedure for global optimization and Adaptive Complex "Acomplex" has been applied has been applied to the design of the broad-band microwave amplifier. Design method takes gain flatness, low noise factor, amplifier stability, loss factor associated with each reactive element and matching circuit realizability into account simultaneously.

Introduction

The main objective of a circuit design is to determine the parameters of the circuit so that it will provide the performance specified by the designer. The optimization problem in a design procedure is defined as the problem of finding the minimum of a given objective function depending on many interrelated parameters. Gradient methods have been successfully applied to optimization problems for some time. The direct application of such methods can be computationally intensive and the issue of convergence must be adressed. In order to guarantee the convergence of an optimization process, traditional algorithms are greedy and accept only those changes that can improve the cost of the objective function. One inherent drawback of this type of search is that it can be easily trapped into the local minima of an objective function if good initial values are not available. To tackle with these problems we have developed a new global optimization method [1]. New global optimization method is based on the combination of adaptive complex [2] and controlled random search (CRS2) [3] optimization methods. Using new hybrid optimization method we have designed a stable broad-band microwave amplifier. In this work, only the lumped lossy matching network is considered.

Optimization Procedure

Hybrid method 1 is based on Adaptive Complex Method "Acomplex" [1] and Controlled Random Search (CRS2) procedure [2] for global optimization. The description of the algorithm is as follows.

Given $F(x): R^n \rightarrow R$ s.t. $g \leq x \leq h$

Step 1: Set parameter a and k. Specify a "good" feasible starting point x_1 and randomly choose initial k-1 additional distinct points $x_2, x_3, .., x_k$ over V (initial search domain). Evaluate the objective function at each of the k points. Store the position and function value in A (an array).

Step 2: Adjust a, determine best point, x_L, (with least function value f_L) and worst point, x_H, (with largest function value f_H) in A.

Step 3: Compute centroid, x_c, of k-1 points, (omitting the worst).

$$x_{ic} = (k-1)^{-1}\left(\sum_{j=1}^{k} x_{ij} - x_{iH} \right) \quad i=1,2,..n$$

Step 4: Move the inferior point x_H, to $x_{new} = x_c + a(x_c - x_H)$ and compute $f(x_{new})$. If x_{new} is no longer the inferior point, then replace x_H by x_{new} in A and go to Step 10.

Step 5: Choose randomly n distinct points $R_2, .., R_{n+1}$ excluding x_L. Let $R_1 = x_L$. Determine the centroid G of points $R_1, .., R_n$. Compute the next trial point $P = 2G - R_{n+1}$.

Step 6: If P within V and satisfies other constraints, then evaluate f_P and go to Step 7; else, return to Step 5.

Step 7: If $f_P < f_H$ then replace x_H by P in A and go to Step 10.

Step 8: Move x_{new} half the distance to x_c.

Step 9: If x_{new} is no longer the inferior point, than replace x_H by x_{new} in A and goto Step 10; else ,return to Step 5.

Step 10: If the stop criterion is satisfied, then stop. Else, return to Step 2.

The adaptive scheme for the reflection factor a (typically in the interval [0.5,2]) was used. As the method proceeds the number of function evaluations required per iteration (fe/it) is computed at each step and exponantial smoothing is applied. An iteration is defined as the calculations required to compute a new point that is not inferior. A larger value for fe/it (greater than about 1.5) indicates that the method is overshooting as it seeks an improved point. This is due to an a value that is to large. On the other hand, if fe/it is small (in the neighborhood of one), the method is not aggressive enough in exploring new regions of the search space and this is caused by an a value which is too small. This method was operated with moderate value for k ($k=6(n+1)$). When the convergence is such that $f_H/f_L<1.001$ the algorithm stops. This criterion is arbitrary and can be modified by the user.

Design Principle

The transducer power gain function of a lumped lossy matching network must contain the lossy element which accompanies each lossy reactance of the matching network. As shown in Fig 1, the simplified model of a lumped inductor is considered as an ideal inductor in series with a resistor r, which is then specified in terms of the quality factor Q_L defined as

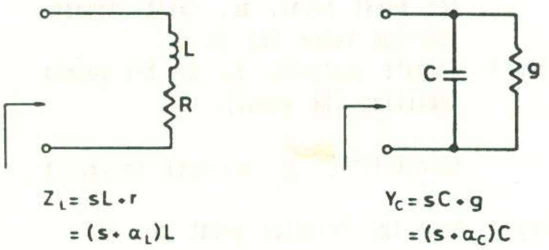


Fig.1. Simplified equivalent circuit for lumped reactive elements.

$$r = \omega_o \frac{L}{Q_L} \tag{1}$$

where L is the value of the ideal lossless inductor and w_0 is the frequency at which the Q_L is defined. The impedance of the lossy inductor is then given by

$$Z_L = r + sL = \omega_o \frac{L}{Q_L} + sL = (s + \alpha_L)L \tag{2}$$

where $a_L = w_0/Q_L$ is the inductor loss or dissipation factor. Similarly, a simplified model of a lossy capacitor is considered as an ideal lossless capacitor C in parallel with a resistor with conductance g. If this conductance is specified in terms of the quality factor Q_C as

$$g = \omega_o \frac{C}{Q_C} \tag{3}$$

then the admittance of the lossy capacitor is given by

$$Y_C = g + sC = \omega_o \frac{C}{Q_C} + sC = (s + \alpha_C)C \tag{4}$$

where $a_C = w_0/Q_C$ is the capacitor loss factor. It is clear that the basic transformation of variable from s to (s+a) will incorporate the losses of the L's and C's.

The y parameters of the transistor can be denoted by

$$y_{ik} = g_{ik} + jb_{ik}, \quad i,k=1,2. \tag{5}$$

Then the transducer power gain, G_T, of the amplifier (Fig.2.) can be written as follows [3].

$$\frac{4|y_{21}|^2 G_s G_L}{|(y_{11}+Y_s)(y_{22}+Y_L) - y_{12}y_{21}|^2} \tag{6}$$

where G_S and G_L are related to Y_S and Y_L, respectively, as follows:

$$Y_S = G_S + jB_S \tag{7}$$

$$Y_L = G_L + jB_L \tag{8}$$

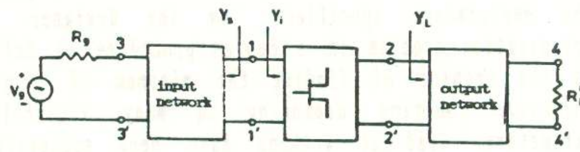


Fig.2. An amplifier with input-and-output-port-matching networks.

Y_S and Y_L are unknown functions to be found such that the transducer gain, $G_T(i)$, evaluated at a passband sample frequency w_i, approaches a desired gain $G_0(i)$ in the sense that the sum of squared errors, E, defined in the following equation is minimized:

$$E = \max|G_T(i) - G_o(i)|, \quad i = 1,2\ldots m \tag{9}$$

where m is the number of sample frequencies selected. Physical realizability for Y_S and Y_L requires that, for all frequencies,

$$G_S>0 \qquad G_L>0 \tag{10}$$

And to maintain amplifier stability when a potentially unstable transistor is employed, the following inequalities must hold [3]:

$$G_s + g_{11} > 0 \qquad (11a)$$

$$G_L + g_{22} > 0 \qquad (11b)$$

and

$$(G_s + g_{11})(G_L + g_{22}) > \frac{M}{2}(1 + \cos\theta) \qquad (11c)$$

where

$$M = |y_{12} y_{21}| \qquad (12)$$

and

$$\theta = \text{phase of}(y_{12} y_{21}) \qquad (13)$$

If condition in (10) hold, then the stability conditions (11a) and (11b) will hold in most cases since both g_{11} and g_{22} are positive for most transistors. Inequality (11c) can be replaced by an equation if positive constanat K, Stern's stability factor, is employed:

$$K = \frac{(G_S + g_{11})(G_L + g_{22})}{\frac{M}{2}(1 + \cos\theta)} \qquad (14)$$

where it has been assumed that

$$\frac{M}{2}(1 + \cos\theta) > 0$$

As an input or output matching networks three-element π- or T-sections can be used. A π-section has two parallel elements and the T-section has two series elements as shown in Fig.3a and Fig.3b respectively. The bandwidths of π-and T-sections are also determined by the transformation Q-factors ($f_{-3dB} = f_0 + f_0/Q_{max}$) [4].

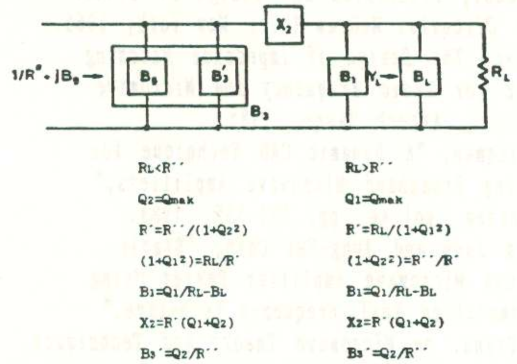


Fig.3a. The design of π section.

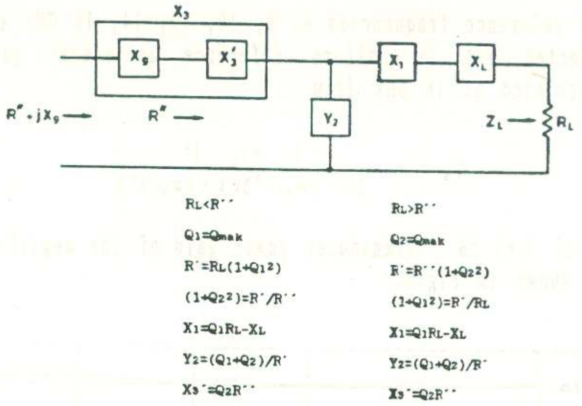


Fig.3b. The design of T section.

Design Procedure

A design procedure based on the principle described and the formulas above is as follows.

Step 1. Select passband reference frequencies w_i, $i=1,2,\ldots,m$. Prescribe the passband reference transducer power gain $G_0(i)$. Obtain transistor y parameters, $y_{jk}(i), j,k=1,2$.

Step 2. Obtain an initial guess for optimization designing π- or T-sections input and output matching networks incorporating the loss factor associated with each reactive element.

Step 3. Using new hybrid method minimize the objective function E defined by (9) under the stability and physical realizability constraints and obtain element values.

Design Example

In this section, an 6-16 GHz stable broad-band amplifier design example is presented. The transistor y parameters are calculated from the S parameters given in Table 1.

Table 1: Scattering parameters of HFET-2001

Frequency (GHz)	S11		S21		S12		S22	
6	0.88	-65	2	125	0.05	60	0.71	-22
8	0.83	-85	1.81	109	0.06	53	0.68	-30
10	0.79	-101	1.64	95	0.06	51	0.66	-37
12	0.76	-113	1.48	84	0.06	52	0.66	-43
14	0.73	-126	1.39	73	0.06	54	0.64	-48
16	0.71	-141	1.32	61	0.07	55	0.63	-56

Linear Power Bias $V_{DS}=4.0$ V, $I_{DS}=0.5I_{DSS}$

Six reference frequencies 6, 8, 10, 12, 14, 16 GHz are selected with a uniform reference unilateral gain calculated at 16 GHz from

$$G_o = \frac{|\ s_{12}\ |^2}{(1-|s_{11}|^2)(1-|s_{22}|^2)}$$

G_o of 7.65 dB. Transducer power gain of the amplifier is shown in Fig.3.

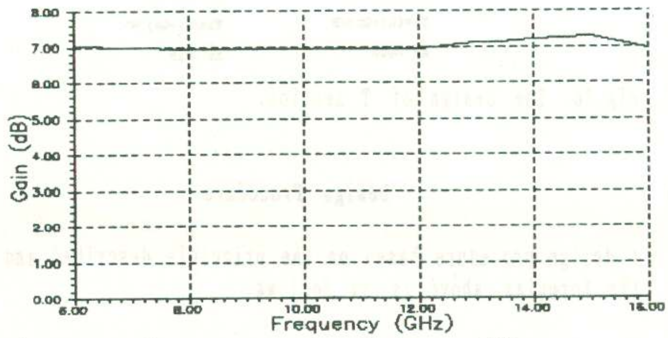
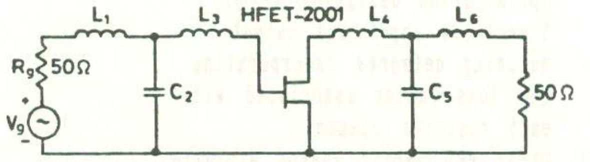


Fig.3. Transducer power gain of the amplifier.

Fig.4 shows a schematic diagram of the amplifier. Stern's stability factor for the amplifier is listed in Table 2.



L_1=.234 C_2=.333 L_3=.454 L:nH
L_4=1.302 C_5=.164 L_6=.490 C:pF

Fig.4. Schematic diagram of the amplifier.

Table 2: Stern's stability factor of the amplifier in Fig.4

FREQUENCY GHz	GAIN dB	K
6	7.04	35.74
7	6.97	29.22
8	6.94	24.53
9	6.94	22.63
10	6.93	21.26
11	6.94	20.17
12	6.95	19.18
13	7.09	17.62
14	7.21	15.99
15	7.28	12.34
16	6.93	9.67

The lumped inductors in the matching network are assumed to have Q's of 25 while capacitors have Q's of 50 to 16 GHz. The solution required 313 function evaluations over 24 sec. The computer used was an 33 MHz AT class machine with an 80386 processor. In the literature it was reported that the transducer gain value obtained by the best supercompact, by the dynamic CAD technique and by the simplified real frequency technique were 6.81∓0.57 dB, 7.35∓0.33 dB [6], and 7.42∓0.34 dB [7] respectively. In [7] it was reported that the minimum stability factor was 7.9 found at 16 GHz. The transducer power gain and the minimum stability factor obtained in the example by this method are 7.105∓0.175 dB and 9.67 respectively.

Conclusions

A new hybrid optimization method based on adaptive complex and controlled random search methods has been developed and applied to the design of broad-band amplifier. Design method takes gain flatness, amplifier stability, loss factor associated with each reactive element and matching circuit realizability into account simultaneously. A 6-16 GHz amplifier design example has also been presented to demonstrate the application of the new method. New algorithm doesn't require any gradient information. It can be implemented easily. Thus it is possible to use this new global hybrid optimization algorithm for the design of any linear or nonlinear microwave circuits.

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