INTEGRATED APPROACH TO MICROWAVE POSTPRODUCTION TUNING

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We present a new, integrated, theoretically justifiable approach to postproduction tuning. The approach addresses the determination of a set of sampling points at which measurements should be made, the specification of the circuit response of interest, the determination of the parameters to be tuned and the tuning algorithm itself. It utilizes a highly effective nonlinear programming notation which can be applied to any circuit design problem. We present its application in tuning a matching amplifier circuit, utilizing highly efficient optimization algorithms, which are available as documented computer program packages.

Introduction

Tolerances, parasitic effects and uncertainties in a circuit model cause deviations in the manufactured circuit performance and violation of the design specifications may result. Postproduction tuning is included in the final stages of a production process to readjust the network performance in an effort to meet the specifications.

Tuning has formally been considered as an integral part of the design process [1], the objective being to relax the tolerances and compensate for the uncertainties in the model parameters. We summarize here an integrated approach to postproduction tuning, which relies on least pth optimization with p=1 and p=∞, subject to suitable constraints. The approach utilizes the information gained during the design process in specifying both the frequencies at which tuning should be monitored and the tunable parameters. The required changes in the tunable parameters are computed using a functional tuning algorithm.

Mathematical Formulation

Selection of Nominal Design

A network design problem can be formulated as a minimax optimization problem as follows.

$$\underset{\phi,\, z}{\text{Minimize}}\ z \tag{1a}$$

subject to

$$f_i(\phi) \leq z, \quad i \in I_c, \tag{1b}$$

where $I_c \triangleq \{1, 2, \ldots, m_c\}$, ϕ is the n-vector of design components, f_i is a designer defined error function and z is an additional independent variable.

Selection of Worst Cases

The solution of problem (1) provides us with theoretically justifiable critical functions $f_j(\phi^0)$, $j \in I_c^*$, where $I_c^* \subseteq I_c$ is the index set of the critical functions. Normally, each critical function corresponds to a sample frequency. Consequently, we determine, using (1), the frequencies to be monitored during tuning and the nominal design values ϕ_i^0, $i \in I_\phi$, where $I_\phi \triangleq \{1, 2, \ldots, n\}$.

Parasitic effects are often neglected or approximated during the design problem (1). The parasitic effects could be represented by additional variables ϕ_{n+i}, $i \in I_p$, where $I_p \triangleq \{1, 2, \ldots, p\}$.

The design parameters are subjected to tolerances ε_i. The tolerances produce the region [1]

$$R_\varepsilon \triangleq \{\phi \mid \phi_i = \phi_i^0 + \varepsilon_i \mu_i, \ -1 \leq \mu_i \leq 1, \ i \in I_\phi\} . \tag{2}$$

A manufactured outcome of the circuit would be a point of R_ε. Worst-case analysis is carried out to identify the critical points of this region. A worst case point is assumed to occur at one of the 2^n vertices of R_ε indexed by ϕ^i, $i \in I_v$, where $I_v \triangleq \{1, 2, \ldots, 2^n\}$.

For every function $f_i(\phi)$, $i \in I_c^*$, one or more vertices are selected [2]. Let $I_{vi} \subset I_v$ be the index set of worst-case vertices corresponding to the function $f_i(\phi)$, $i \in I_c^*$, and let

$$I_v^* \triangleq \bigcup_i I_{vi}, \quad i \in I_c^* \tag{3}$$

define the index set of critical vertices, $I_v^* \subseteq I_v$.

Selection of Tuning Variables

To compute the tunable parameters, we solve the following optimization problem [1].

$$\text{Minimize} \sum_{i \in I_t} t_i \tag{4a}$$

w.r.t. t_i, ρ_i^r, $i \in I_t$, $r \in I_v^*$, where

$$t_i \geq 0, \ i \in I_t , \tag{4b}$$

$$-1 \leq \rho_i^r \leq 1 , \ i \in I_t, \ r \in I_v^* , \tag{4c}$$

such that

$$\phi \in R_c^*, \tag{4d}$$

for all $r \in I_v^*$, where

$$\phi_i = \begin{cases} \phi_i^r, & i \notin I_t , \\ \phi_i^r + t_i \rho_i^r, & i \in I_t \end{cases} \tag{4e}$$

and

$$R_c^* \triangleq \{\phi \mid f_i(\phi) \leq 0, \ i \in I_c^*\} . \tag{4f}$$

This problem is a least pth optimization problem with p=1. It finds the minimum <u>number</u> k of tunable parameters required to tune all worst-case vertices. At the solution we obtain

$$I_t^* \triangleq \{i \mid t_i \neq 0 \text{ and } i \in I_t\} . \tag{5}$$

Functional Tuning Algorithm

A functional tuning technique is applied to find the required changes in the tunable elements. The actual response is assumed to be given by

$$F^a = F^0 + F^{\varepsilon p}, \tag{6}$$

where a refers to the actual values, 0 to the nominal

This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grant A7239.

design values and εp to the deviational effect due to tolerance effects and parasitics.

Using the actual measurements $F^{\varepsilon p}$ is modeled by a transfer function over the frequency range of interest. The model is used to simulate the actual response. The tuning problem is formulated as a linearly constrained minimax optimization problem, where the variables are the changes in the tunable parameters, namely,

$$\text{minimize } z \tag{7a}$$

w.r.t. $\phi_i, i \in I_t^*$ and z subject to

$$\bar{f}_i(\phi) \leq z\,, \quad i \in I_c\,, \tag{7b}$$

$$\ell_i \leq \phi_i \leq u_i\,, \quad i \in I_t^*\,, \tag{7c}$$

$$\phi_i = \phi_i^0\,, \quad i \notin I_t^*\,, \tag{7d}$$

where ℓ_i and u_i define limits on the k tunable parameters, z is an additional independent variable and $\bar{f}_i$ accounts for the modelled deviational effects.

The tunable elements are adjusted by the amounts indicated by solving (7) and the process is repeated until the circuit meets its design specifications.

Example

We have applied our approach to the amplifier circuit shown in Fig. 1.

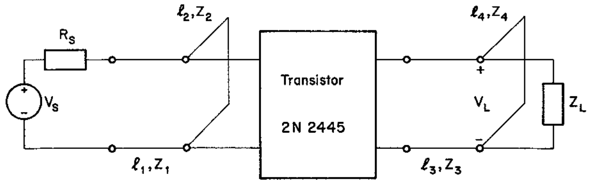

Fig. 1 The broad-band amplifier.

Using (1) the nominal parameters of the circuit were reoptimized to a 10 dB power gain over the frequency range 150 MHz to 300 MHz. We utilized the optimization package MMLC [3,4]. The characteristic impedances are assumed to be not greater than 200 ohms. The response achieved is superior over that obtained earlier in [5]. This is partly because we relaxed the bounds on the design parameters. The new and previous nominal design parameters are given in Table 1. From

Table 1
Nominal Element Values and Tunable Amounts

Element	Orig. Nom. Values	New Nom. Values	Relat. Tunable Amounts
ℓ_1	2.012	1.741	0.0
Z_1	86.76	68.778	0.0088
ℓ_2	0.976	1.534	0.0
Z_2	97.57	200.0	0.0
ℓ_3	0.833	1.140	0.0
Z_3	125.	181.252	0.0
ℓ_4	0.927	1.280	0.079
Z_4	132.	105.105	0.0

ℓ is the normalized length. The actual length equals $\ell\lambda_n/2\pi$, where λ_n is the wavelength at 230 MHz.
Z is the characteristic impedance in ohms.

Table 2
The Optimum Nominal Response and Worst-Case Response for ± 5% Tolerance

Frequency (MHz)	Power Gain (dB)	Worst-Case Vertex	Worst-Case Response (dB)
150	10.058 *	123	11.318
160	9.926 *	134	8.559
170	10.072 *	123	11.274
180	10.043	107	11.155
190	10.053	107	11.189
200	10.006	107	11.095
210	10.028	104	11.053
220	9.926 *	153	8.794
230	10.031	104	10.894
240	10.028	112	10.765
250	10.072 *	80	10.726
260	10.031	80	10.640
270	9.965	189	9.313
280	9.926 *	189	9.302
290	9.983	61	9.392
300	10.072 *	212	10.657

* identifies critical frequencies

power gain = $4 R_S G_L |V_L|^2/|V_S|^2$

the vertex no. is given by the formula

$$r = 1 + \sum_{j=1}^{n} \left[\frac{\mu_j^r + 1}{2}\right] 2^{j-1}\,, \quad \mu_j^r \in \{-1, 1\}.$$

the response obtained, the frequencies identified in Table 2 are candidates for the critical frequencies.

We assume that the design specifications tolerate ± 1 dB deviation from the specified value of 10 dB. Worst-case analysis is performed using ± 5% tolerances. Considering only the previous identified critical frequencies the set I_v^* consists of {123, 134, 153} (Table 2). We performed optimization problem (4) using these three critical vertices to determine the tunable parameters. The results of this optimization problem is given in Table 1. Z_1 and ℓ_4 are the tunable parameters. The MFNC package, which implements the Han-Powell algorithm [6], is utilized in solving this nonlinear programming problem [7].

The functional tuning method of (7) is carried out on the previous three critical vertices. The results of tuning for these cases is given in Table 3. The responses before and after tuning are shown in Figs. 2,

Table 3
Results of Tuning

	Case 1	Case 2	Case 3
Vertex No.	123	134	153
No. of Iterations of Functional Tuning Algorithm	1	1	1
Tunable Element Values	Z_1 = 66.66	Z_1 = 70.616	Z_1 = 66.66
	ℓ_4 = 1.209	ℓ_4 = 1.331	ℓ_4 = 1.154

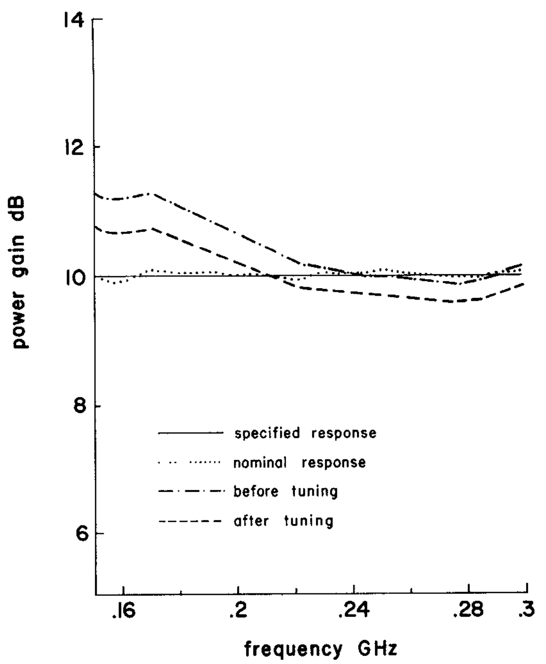

Fig. 2 The responses for Case 1.

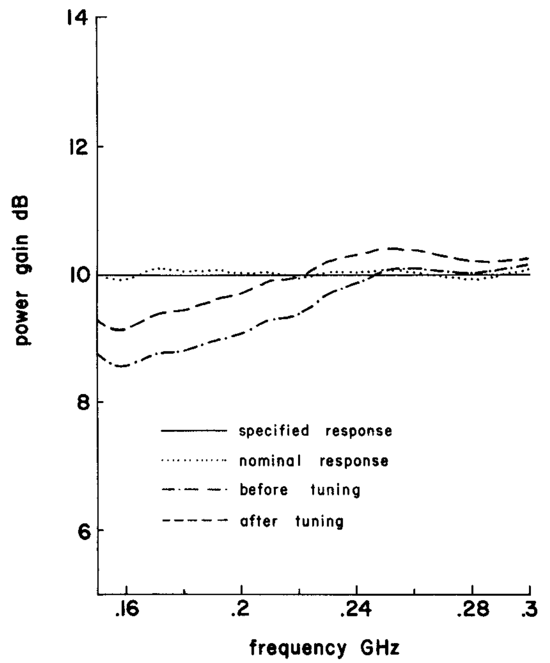

Fig. 3 The responses for Case 2.

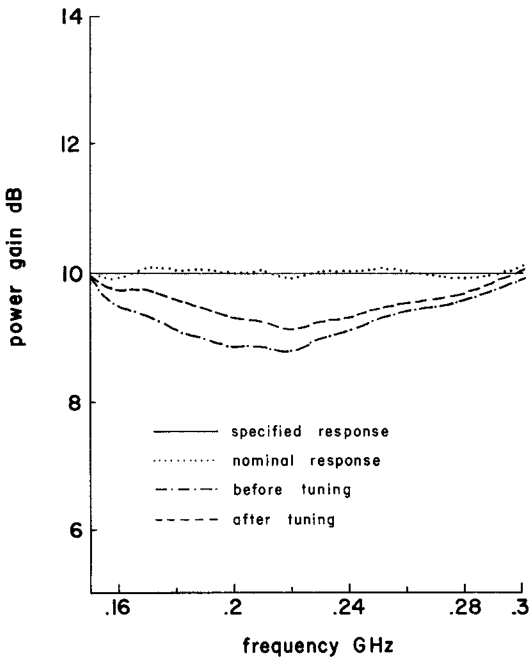

Fig. 4 The responses for Case 3.

3 and 4. The solution of (7) is obtained using the optimization package MMLC [3].

Conclusions

Our approach optimally utilizes the information obtained at the design stage in specifying both the minimal number of tunable elements and the essential tuning frequencies.

A functional tuning method is then applied to determine the required tunable amounts using the response measurements.

The approach has integrated a number of concepts and techniques to produce an efficient postproduction tuning procedure. It is general enough to be applied to any type of microwave circuit and can efficiently tune the response.

Acknowledgment

The authors are grateful to Mr. W. Kellermann of McMaster University for useful discussions on the theoretical formulation of this work.

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