Interactive "Visual" Design of Matching and Compensation Networks for Microwave Active Circuits

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***Abstract* – A new interactive "visual" technique is presented for designing lossless two-port matching and passive two-terminal compensation networks used in different RF and microwave active circuits. It relies on a visual representation of design process. The technique allows the user to select a suitable network configuration and to directly control all the network elements for successful fabrication. Lumped, distributed noncommensurate-line and mixed (lumped-distributed) networks of moderate complexity can be designed. The approach is implemented in the software tool LOCUS, offering a simple and fast means to produce solutions without the need for complicated circuit theory and mathematics.**

I. INTRODUCTION

The term «visual design» denotes such the process in which the engineer through graphic interface tools directly controls the course of the design, actively intervening into it, and, simultaneously, observes design outcomes. Thus, here graphic tools are used not only for displaying and estimating results obtained at intermediate or final design stages, but rather serve as a direct design means.

In this paper, the implementation of the «visual» approach for designing lossless two-port matching/ equalizing and passive two-terminal compensation/ feedback networks, used in different RF and microwave active circuits (such as transistor amplifiers, mixers, multipliers, active filters, impedance converters, etc.), is described. We demonstrate the possibilities of the "visual" technique and compare it with the existing synthesis methods.

II. CURRENTLY-AVAILABLE APPROACHES TO DESIGNING MATCHING AND COMPENSATION NETWORKS FOR MICROWAVE ACTIVE CIRCUITS

Now there are two main approaches to synthesizing broadband matching and compensation networks for microwave active circuits. The first approach is based on the analytic theory by Fano and Youla, the second is the use of the real frequency techniques (RFTs) by Carlin and Yarman. Unfortunately, these approaches have several limitations:

1) It is difficult to apply them directly to designing complex linear active circuits (i.e., circuits with several matching/compensation networks) and, particularly, nonlinear active circuits. In the latter case, additional constraints are imposed on the input impedances of lossless matching networks and equalizers (i.e., impedances presented to active devices). These constraints may be caused by requirements for the output power, efficiency, etc., and are often represented as certain regions in the complex plane.

2) With the synthesis techniques above, network configurations and elements result from fully formalized, complicated numerical procedures. Therefore, the designer has only very limited possibilities to control these configurations and elements.

3) If distributed-element matching networks have to be designed, both the analytic procedures and RFTs lead to networks made from commensurate transmission lines. However, in practice it may be preferable to employ the networks consisting of noncommensurate lines, or the mixed networks with lumped and distributed elements.

In order to overcome some of the difficulties mentioned, a new decomposition synthesis approach [1,2] has been introduced for designing linear and nonlinear active circuits with passive matching/compensation networks. This method supposes that the design of active circuit is accomplished in two stages:

1) determination of acceptable regions of the matching/compensation networks' immitances at sample frequencies over a frequency band of interest, according to a set of circuit specifications;

2) synthesis of matching/compensation networks based on the acceptable immitance regions.

Recently, the decomposition synthesis method was applied to designing microwave active circuits with lossless matching networks [3,4] and ones with two-terminal compensation/feedback networks [5]. In these papers, some ways for determining acceptable regions of the network immitances have been presented.

In the practical design of RF and microwave circuits, rather simple matching/compensation networks (e.g., with the number of elements from one to six) are usually used.

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This paper presents an interactive procedure for computer-aided "visual" design of lossless two-port matching/equalizing (resistively terminated on one side) and passive two-terminal compensation/feedback networks based on acceptable immitance regions. The procedure allows designing lumped, distributed (non-commensurate) and mixed (lumped-distributed) networks of moderate complexity controlling network configurations and element values.

III. The "Visual" Design Procedure

The formulation of the problem under solution is as follows. Assume that at the first active circuit design stage, the acceptable regions E_k of the matching/compensation network impedance have been determined at sample frequencies ω_k ($k = \overline{1,m}$) over a prescribed band (they are graphically represented as certain regions in the complex plane) [3-5]. We need to find a passive two-terminal network (i.e., a network configuration and elements) so that its impedance $Z(j\omega)$ at all the frequencies ω_k falls into the respective regions E_k:

$$Z(j\omega_k) \in E_k,\ k = \overline{1,m}. \qquad (1)$$

When designing matching networks, the two-terminal network must be in the form of a lossless two-port terminated in a resistor. Certainly, the task can equivalently be formulated in terms of the network admittance or reflectance.

The design procedure includes two steps:

1) selection of a network configuration;

2) determination of element values of the network with chosen structure.

The problem at the first step is solved by comparing a location of acceptable regions in the immitance plane with families of immitance locuses plotted for networks of different configurations. For this, we have compiled the catalogue of immitance locuses for typical lumped- and distributed-element matching/compensation networks.

After selecting a configuration of two-terminal network, element values can be found by solving a respective system of equations. This system is created by equating the network impedance at one or several frequencies ω_i, $i \in \{1, 2, \ldots, m\}$, to desired (reference) values Z_i selected within the corresponding acceptable regions E_i. Once the element values are determined, the network impedance locus $Z(j\omega)$ may be plotted. Now, one can visually verify whether the impedance values at the other frequencies $\omega_k \neq \omega_i$ belong to the respective acceptable regions E_k.

Unfortunately, the equations are highly nonlinear in terms of the unknown elements, therefore the system can analytically be solved only for simple networks (e.g., with two or three elements). For more complicated networks, to simplify the solution, it is worthwhile to assign values of certain network elements. The values of assigned elements will affect a shape of the network impedance locus $Z(j\omega)$ which has to pass through one or more prescribed (reference) points Z_i. With this, the network design takes an interactive form – specifying different values of desired impedances Z_i and assigned elements, one can control a shape of the locus $Z(j\omega)$ and attain falling the network impedance at all frequencies ω_k within the respective regions E_k.

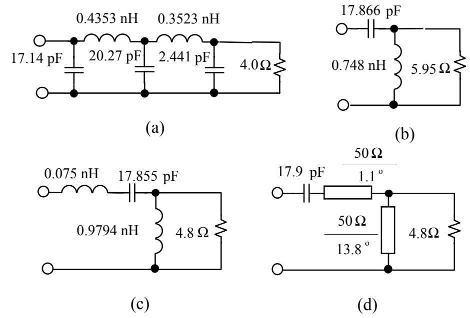

Fig. 1. Circuit diagrams of synthesized CTNs.

We display the acceptable regions and the network immitance locus on the computer terminal. Assigned (controlled) elements are varied with the sliders on the parameter scales whereas reference impedance points can directly be captured and moved within the regions E_i by the "mouse" manipulator. The computation of remain (unknown) network elements is very fast due to analytic close-form solution of the equations. Therefore, as assigned elements and reference impedances are varied, the change of a locus shape can be observed in real time. Immediate values of assigned and calculated network elements are continuously displayed, this makes possible the direct control of these elements during the design process.

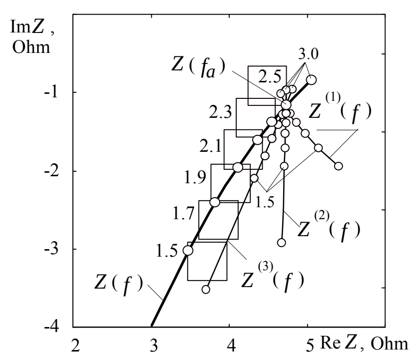

Fig. 2. Acceptable regions and locuses of impedance for the network of Fig. 1(b). $Z(f)$: R=5.95Ω; $Z^{(1)}(f)$: R=4.5Ω; $Z^{(2)}(f)$: R=4.75Ω; $Z^{(3)}(f)$: R=5Ω (the numbers near the circles on the locuses denote the frequencies in GHz).

The approach presented is implemented in LOCUS, a program of interactive "visual" design of matching/compensation networks for active RF and microwave circuits. When designing microwave active circuits with matching/compensation/ feedback networks, acceptable regions of the network impedance or reflectance are determined directly from the circuit performance specifications using our other CAD tools [3-5], then they are transmitted to LOCUS as data files.

IV. Examples

A. Example 1: Designing Two-Terminal Compensation Network for MMIC Simulated Inductor

The problem is to synthesize a compensation two-terminal network (CTN) for MMIC simulated inductor [6]. Such the inductor represents an active two-port (gyrator) terminated at its output in a passive load (i.e., CTN). In order to obtain the circuit input impedance close to preassigned response over a specified frequency band (e.g., to the reactance of inductance), the CTN has to possess a proper impedance-frequency characteristic within this band.

In [6], the desired impedance response $Z_0(f)$ of the CTN has been derived to achieve 5-nH inductance using Meunier gyrator built on nonideal active elements (MMIC GaAs FETs). In that paper, the lumped 6-element CTN (Fig.1(a)) has been synthesized with MATCHNET program to fit $Z_0(f)$ in the band 1.5-2.5 GHz.

TABLE 1 - COMPARISON OF SEVERAL TWO-TERMINAL NETWORK SYNTHESIS TECHNIQUES

Network №	Fig.	Synthesis Technique	ΔR_{max}, Ohm	ΔX_{max}, Ohm	n
1	1(a)	MATCHNET	0.94	0.60	6
2	1(b)	Visual (LOCUS)	0.25	0.26	3
3	1(c)	Visual (LOCUS)	0.12	0.11	4
4	1(d)	Visual (LOCUS)	0.12	0.11	4

Using these impedance data, we have designed lumped, distributed, and mixed-element CTNs with LOCUS. Fig. 2 shows the acceptable regions of the CTN impedance constructed at several frequencies f_k around $Z_0(f_k)$ for the real and imaginary part deviations $\Delta R=\Delta X=\pm 0.25\Omega$. The design results are presented in Fig.1 and Table 1 (here, ΔR_{max} and ΔX_{max} are the maximum absolute deviations of real and imaginary parts of the CTN impedance about $Z_0(f)$, n is the number of elements). It can be seen that the «visually» designed CTNs comprise a lesser number of elements (3 or 4) and yield lesser errors in fitting the desired impedance response $Z_0(f)$ as compared to the network of Fig. 1(a). In Fig. 2, the impedance locuses $Z(f)$ for the network of Fig. 1(b) are displayed, they are presented for different values of the resistance R (controlled element) with the reference impedance point $Z(f_a)$ selected within the acceptable region at f_a=2.5 GHz.

B. Example 2: Matching of a LCR Load

The example presents the classical single-matching problem introduced by Fano. A lossless matching network is to be synthesized to maximize the transducer power gain (TPG) between a resistive generator and the *LCR* load (Fig.3) over the frequency band $\omega\in[0; 1]$.

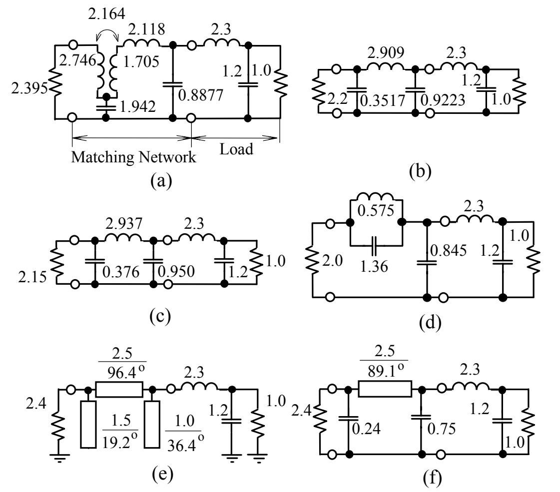

Fig. 3. Circuit diagrams of synthesized matching networks (the characteristic impedances of microstrip lines are normalized to the resistance R=1Ω, electrical lengths are presented for the frequency ω=1).

TABLE 2 - COMPARISON OF SEVERAL MATCHING NETWORK SYNTHESIS TECHNIQUES

Network №	Fig.	Synthesis technique	G_{min}	n
1	3(a)	Classical (Fano)	0.826	4
2	3(b)	Line-segment RFT (Carlin)	0.848	3
3	3(c)	Visual (LOCUS)	0.850	3
4	3(d)	Visual (LOCUS)	0.881	3
5	3(e)	Visual (LOCUS)	0.805	3
6	3(f)	Visual (LOCUS)	0.813	3

The circular acceptable regions of the input network impedance have been produced by LOCUS according to the formulas in [3]. The matching networks designed by several synthesis techniques as well as their performances are presented in Fig.3 and Table 2 (G_{min} is the minimum value of the TPG over the band $\omega\in[0; 1]$; n is the order of the matching network, which is equal to the number of energy storage elements).

While designing Network 3, we have taken the usual three-element low-pass configuration that was previously used by Carlin to demonstrate his RFT. However, observing the location of acceptable impedance regions, we have found the superior three-element network topology (Network 4) with a greater TPG, which is rather not obvious for this classical problem. Also, the distributed and mixed networks (Networks 5 and 6) have been synthesized with LOCUS.

C. Example 3: Design of Stable Broadband Microwave Transistor Amplifier

The example has been introduced by Yarman. The problem is to synthesize the front-end and back-end lossless equalizers for single-stage broadband transistor amplifier. The passband is 6–16 GHz, in the amplifier the Hewlett-Packard HFET-2001 transistor is used. The design goal is to maximize the flat amplifier TPG in the passband, simultaneously providing the amplifier stability.

The information concerning the amplifiers designed by several CAD techniques is presented in Fig. 4 and Table 3. Amplifiers 4 and 5 have been designed by the "visual" technique with our CAD tools, REGION [4] and LOCUS. The performances of Amplifier 4 are very close to those resulted from RFTs (Amplifiers 2 and 3). However, considering the acceptable regions' location in the impedance plane, we have found the superior topology of the front-end equalizer containing additional shunt inductance L_{12} (Amplifier 5).

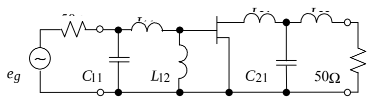

Fig. 4. Amplifier circuit diagram.

TABLE 3 -
COMPARISON OF SEVERAL AMPLIFIER DESIGN TECHNIQUES

Amplifier №	Design Technique	G, dB
1 (Fig.4, L_{12}=∞)	Optimization with Super-Compact (Yarman)	6.81±0.57
2 (Fig.4, L_{12}=∞)	Dynamic RFT (Yarman)	7.35±0.33
3 (Fig.4, L_{12}=∞)	Modified RFT (Jang, Chiu)	7.42±0.34
4 (Fig.4, L_{12}=∞)	Visual (LOCUS)	7.35±0.2
5 (Fig.4, L_{12}≠∞)	Visual (LOCUS)	7.90±0.2

The Examples 1-3 have shown that a location of the acceptable immitance regions suggests appropriate network configurations to the user. Owing to this, in these examples we have discovered the network structures with superior performances. In order to arrive at these results with the analytic or real frequency techniques, one would have to look over many different types of network functions (configurations), this would take plenty of the computational time.

V. CONCLUSION

In this paper, a new "visual" technique is presented for designing lossless two-port matching/equalizing and passive two-terminal compensation/feedback networks used in different RF and microwave active circuits. In comparison to the currently available synthesis methods, the "visual" technique offers some advantages. In particular, it uses no complicated circuit theory, the design procedure is simple and looks somewhat like a computer game. Thus, even the user with insufficient grounding in the circuit theory and synthesis techniques, can quite successfully employ the "visual' CAD tool.

The examples presented show that for networks of moderate complexity, this approach leads to results which are comparable to or even better than those obtained by the existing synthesis techniques. However, the "visual" technique offers the capabilities that are unavailable with the analytic or real frequency synthesis methods. First, it allows the user to select a suitable network configuration and to directly control all the network elements for successful fabrication. Also, distributed noncommensurate-line and mixed (lumped-distributed) networks can be designed.

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