Decomposition Synthesis Approach to Design of RF and Microwave Active Circuits

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***Abstract* – The paper presents a new decomposition synthesis method for designing linear and nonlinear active high - frequency circuits. This method allows the synthesis of passive correction (matching, compensation, feedback, etc.) networks from circuit performance specifications, with a circuit block diagram given. The method forms the basis of unified synthesis procedure for a wide range of RF and microwave active semiconductor circuits. Statements of problems at the synthesis stages are formulated and methods and algorithms for solving these problems are discussed. Also, we overview our research results with application to designing RF/microwave transistor amplifiers. CAD tools for transistor amplifiers and passive matching/compensation networks were implemented, they were used to design amplifiers of various types and structures.**

I. Introduction

The circuit synthesis software will be an important component of future generations of intelligent CAD systems used in electronics. However, the synthesis problem for RF/microwave active semiconductor circuits involves great difficulties. Currently - available methods of synthesis of high-frequency active circuits have essential restrictions. A general theoretical approach that solves the structural synthesis problem for RF/microwave active solid-state circuits of different types has not yet been developed.

In this paper, we briefly describe a new decomposition synthesis method for designing linear and nonlinear active high-frequency networks. It forms the basis of unified synthesis procedure for a wide range of RF and microwave active semiconductor circuits such as transistor amplifiers, mixers, multipliers, control circuits, active filters, immitance converters, etc. Also, we present the application of this method to designing transistor amplifiers of different types.

II. RF/Microwave Active Circuit Synthesis Problem

An efficient approach to the RF/microwave active circuit synthesis (design) problem should take into account its peculiar features. One feature is that active circuits contain unaltered blocks, namely, semiconductor devices whose parameters and models are predetermined. Thus, an active circuit can be represented as a connection of active unaltered part - semiconductor devices, and passive altered part - matching, compensation, feedback networks, etc., which we refer to as correction networks. Here, the correction networks are considered as a controllable circuit's part by choosing which one tries to get desired performances of a whole circuit.

The design of complex technical systems is generally based on the decomposition idea, i.e., on reducing a complicate design problem to a sequence of more simple tasks. Another feature of the active circuit synthesis problem is that it allows a natural two - level decomposition. Let $\mathbf{H} = (H_1, ..., H_n)$ be the vector of circuit performances such as the gain, noise figure, input and output return losses, output power, etc. Represent the circuit's passive part as a multiport. Let **w** be the vector of multiport (for instance, immitance or scattering) parameters of the passive part, and S_p and **e** be the structure and vector of elements of the passive part, respectively (the latter vector contains the resistances, capacitances, and inductances of lumped network elements, the characteristic impedances and lengths of microstrip lines, etc.).

Now, the active circuit can be described by the two - level model:

$$\mathbf{H}=\mathbf{H}[\mathbf{w}(S_p, \mathbf{e})], \quad \text{or } \mathbf{H} = \mathbf{F}_1(\mathbf{w}),\ \mathbf{w} = \mathbf{F}_2(S_p, \mathbf{e})$$

where $\mathbf{F}_1$ and $\mathbf{F}_2$ are some vector-functions (mappings).

When designing a broadband active circuit, the vectors **H** and **w** are functions of the frequency f. The circuit performance requirements can usually be represented in the form of system of inequalities at sample frequencies f_k (k=1, ..., m) over a prescribed frequency band:

$$H_i^-(f_k) \le H_i(f_k) \le H_i^+(f_k),\ i = 1, ... , n;\ k=1, ... , m$$

or

$$\mathbf{H}(f_k)\in E_H(f_k),\ k=1, ... , m \qquad (1)$$

where $H_i^-(f_k)$ and $H_i^+(f_k)$ are, respectively, the lower and upper boundary values of performance H_i at the frequency

f_k; $E_H(f_k)$ is the acceptable region of performances at f_k.

The active circuit synthesis problem can be decomposed into two stages: 1) determining the frequency dependence $\mathbf{w}(f)$ of the vector of multiport parameters, for which the conditions (1) are satisfied: 2) finding the passive part structure S_p and element vector $\mathbf{e}$ which realize the required dependence $\mathbf{w}(f)$.

In the familiar approaches, the dependence $\mathbf{w}(f)$ is often determined by solving the optimization problem for one of the circuit characteristics (say, H_1) at fixed frequencies f_k:

$$\mathbf{w}(f_k)=\mathbf{w}^0(f_k)=\arg \underset{\mathbf{w}(f_k)}{\text{extr}} \; H_1(f_k),\ \mathbf{H}(f_k)\in E_H(f_k);\ k=1,...,m.$$

A simple example is encountered in designing single-stage transistor amplifiers, when we determine the optimum matching networks' input impedances (i.e., optimum source and load impedances for active two-port) which correspond to the extremum (minimum or maximum) value of one of the amplifier performances at selected frequency. As a result, for each frequency f_k we obtain the only optimum point $\mathbf{w}^0(f_k)$; in a frequency band, this will be the only optimum «locus» $\mathbf{w}^0(f)$. However, in accordance with familiar circuit theory limitations [1,2], in the general case the optimum dependence $\mathbf{w}^0(f)$ cannot be exactly realized by any passive network over some bounded frequency range. Thus, the exact reproduction of this ideal locus may lead to unrealizable or unnecessarily complicated network.

The feature of our approach is that the *whole acceptable regions* $E_w(f_k)$ of the vector $\mathbf{w}$ at f_k are determined at the first design stage, instead of the *only optimum points*:

$$E_w(f_k)=\{\mathbf{w}(f_k):\mathbf{H}(\mathbf{w}(f_k))\in E_H(f_k)\},\ k=1,\ ...,\ m. \quad (2)$$

At the second design stage, we synthesize the circuit's passive part from these regions. The problem can be formulated as follows: find the set $E_{S,\mathrm{e}}$ of structures S_p and element vectors $\mathbf{e}$ such that

$$E_{S,\mathrm{e}} = \{\ S_p,\ \mathbf{e} : \mathbf{w}(S_p,\ \mathbf{e},\ f_k)\in E_w(f_k),\ \ k=1,\ ...,m\}. \quad (3)$$

The problem (3) can have many solutions, the simplest or easily producible network is selected. Thus, the «acceptability region» concept allows for synthesizing the most appropriate broadband correction networks from a simultaneous set of active circuit requirements. In addition, a spread of active and passive element parameters and influence of external factors (such as temperature) can be taken into account.

III. Decomposition Synthesis Method for RF and Microwave Active Circuits

The decomposition method implements the synthesis scheme (1)-(3). It offers a general approach to the design of linear and nonlinear active circuits which can be represented in the form of connection of semiconductor devices and passive correction networks. In order to facilitate the synthesis problem and to obtain practical solutions, we further decompose an active circuit, i.e., present its structure in more detail via a block diagram. On this diagram, the types of blocks (for example, semiconductor devices, oneport and twoport, lossless and lossy correction networks and so on) and the links between blocks are supposed to be exactly known. Parameters of some blocks (semiconductor devices, networks with known structure and elements) are given. The rest of blocks (correction networks) are "black boxes", their structures and elements must be discovered during the synthesis process.

The decomposition synthesis method assumes a definite sequence of steps: 1) selection of a block diagram (structural scheme) of an active circuit; 2) constructing a mathematical model of circuit of chosen block diagram; 3) determining the limit (extremely achievable) circuit performances within the frame of chosen block diagram and assigning performance specifications; 4) determining acceptable regions of correction networks' parameters (for instance, immitance or scattering parameters) at sample frequencies over a frequency band of interest, according to a simultaneous set of circuit performance specifications; 5) finding correction networks' structures and elements from the acceptable parameter regions.

It should be recognized that the method presented does not provide a full structural synthesis of active high-frequency circuits. It only allows the synthesis of passive correction networks according to active circuit requirements, with a given circuit block diagram. However, this is often an advantage of the method because for many RF/microwave active circuits, reasonable block diagrams, applicable at high frequencies, are known from the practice. Also, based on the decomposition synthesis method, the problem of finding (selecting) expedient block diagram of a circuit can in principle be solved as well. This task is solved by looking over feasible block diagrams and comparing their extremely achievable performances.

IV. Methods, Algorithms, and Application of Decomposition Synthesis Approach

Let us consider the statements of problems at the synthesis stages as well as the methods and algorithms for solving them. Also, we overview our research results with application to designing microwave transistor amplifiers.

In the first stage, one is to construct a circuit's mathematical model that describes a dependence of circuit performances upon the immitance/scattering parameters of correction networks. For structurally simple linear circuits, this model can be derived in the analytical form by means of general matrix methods of microwave circuit analysis. A solution of this problem can be automatized by using the programs of symbolic circuit analysis or computer algebra packages (such as Mathematica, MapleV, etc.). Using this approach, we have obtained and investigated mathematical models of some commonly used structures of linear RF/microwave circuits with two-port matching/equalizing and two-terminal compensation/feedback networks [3-7].

For structurally complex linear circuits and nonlinear circuits, more general approaches can be used, such as the model identification, behavioral and neural network modeling, linearization, etc.

A key problem of the decomposition synthesis is finding acceptable regions of the correction networks' immitance/scattering parameters. From a mathematical (algebraic) viewpoint, it may be reduced to solving nonlinear systems of inequalities in the multidimensional space of complex or real variables (i.e., the correction networks' parameters) [3,8,9]. The geometric interpretation of the latter problem is to find a projection of multidimensional acceptable region on the subspace of smaller dimension (e. g., the plane of two real variables) [8-10].

In order to determine acceptable regions of the immitances/reflectances of matching and compensation networks incorporated into linear active circuit, we have used several different approaches:

- mapping of functions, describing circuit performances, into the complex immitance/reflectance plane [4-7];
- analytic solution of systems of inequalities [3];
- finding a projection of multidimensional acceptable region on the plane or three-dimensional subspace using numerical algorithms [8-10].

For some nonlinear active circuits with lossless matching networks (for instance, power amplifiers, mixers, and multipliers), acceptable regions of the networks' input immitances/reflectances (i.e., the immitances/reflectances presented to device terminals) can be obtained using familiar performance contours in the source/load plane. Such the contours for the large signal gain, output power, efficiency, intermodulation distortions, etc., may be produced from device load-pull measurements or computer modeling [11].

The problem of determining performance limits for a circuit of chosen structure at fixed frequencies can be solved by analogous methods. Also, in particular cases, we can account for peculiarities of a circuit structure. By this way, we have investigated the performance limits of amplifiers with feedback and matching networks [4,5].

The synthesis of passive correction networks from acceptable regions of the immitance/scattering parameters is an important problem of decomposition synthesis as well. We develop two approaches to solve this problem [5,6,12-14]:

- the use of general synthesis procedures which assume the stages of approximation and network realization;
- interactive "visual" design of networks.

The first approach [5,12,13] is based on the approximation of acceptable immitance regions by minimum - phase functions. The general synthesis procedures are universal and generate a wide range of network structures. They allow the estimation of the synthesis problem solvability as well as determination of limit circuit performances over a prescribed frequency band [2,5,15]. However, the synthesis procedures are cumbersome, also, it is hard to control network configurations and elements with this approach.

The interactive "visual" procedure for the network design [6,14] involves two stages: 1) selection of correction network structure in a set of standard structures, according to the location of acceptable regions in the network immitance/reflectance plane; 2) computation of network elements by solving a corresponding system of equations or inequalities. The "visual" design technique can be applied to designing networks of moderate complexity. However, it allows the user to select appropriate network configurations and to directly control all the network elements, which leads to real-world design. Also, it uses no a complicated circuit theory and intrinsic computations.

We have applied this general decomposition synthesis method to designing RF and microwave transistor amplifiers. A unified design approach for amplifiers with lossless two-port matching/equalizing networks and amplifiers with passive two-terminal compensation/ feedback networks has been developed [3-8,12,13]. For these amplifier configurations, methods and algorithms of the passive correction network synthesis have been elaborated taking into account a simultaneous set of performance specifications.

Also, based on the decomposition synthesis method, we have implemented CAD tools for RF/microwave transistor amplifiers and passive matching/compensation networks [4-8,12-14]. These programs were used to design amplifiers of various types and structures (amplifiers with lossless and lossy matching/equalizing networks; amplifiers with two-terminal compensation and feedback networks; wide - band, ultrawide - band, pulse, low - noise, and power amplifiers) [3-8,12-14]. When synthesizing, requirements for the amplifier gain, noise figure, input and output VSWRs, stability, etc., were simultaneously taken into account. It was demonstrated that our approach can produce novel amplifier configurations with better performances [3,7,16]. Many amplifier and receiver circuits designed have been manufactured.

V. CONCLUSION

We have presented a new decomposition synthesis approach to the design of wide range of RF and microwave active semiconductor circuits. It assumes the representation of active circuit as a generalized structure consisting of unaltered active and altered passive part. An initial complicate design problem is decomposed into a sequence of more simple tasks. First, specifications for a whole active circuit are transformed into specifications for passive (matching, compensation, feedback, etc.) networks. Then, the passive networks are synthesized from their own specifications. The feature of our approach is that passive network requirements are presented as acceptable regions of the networks' immitances/ reflectances at sample frequencies.

Such the synthesis concept of RF/microwave active circuits seems to be of great importance for developing CAD techniques because it formalizes the design process and allows the solution of different design problems for various circuit types and structures on the common ground. The method takes into account a simultaneous set of circuit performance specifications, uses exact models of active devices, and enables the synthesis of the most simple (suitable) network configurations for prescribed specifications.

The application of the decomposition synthesis method to designing microwave transistor amplifiers is found to be considerably encouraging. This approach may be used as the basis for developing a family of computer - aided synthesis programs which will allow the design of different types of RF/microwave active circuits (such as low-noise, linear and power transistor amplifiers, mixers, multipliers, control circuits, active filters, immitance converters, inductance and negative resistance simulators, active amplitude and phase equalizers, etc.) in accordance with specifications.

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