Network Oriented Modeling of the One-Port Antenna Structure

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Abstract

The application of network oriented methods for passive microwave structures simulation allows one to construct compact model of the circuits and leads to the reduction of the computational efforts. Splitting the simulation results into two parts representing a lumped element model and distributed parameters model can be provide using poles stability criterion. The system identification procedure has been applied to the estimation of the lumped element model parameters. The lumped element network realization for the input impedance of the planar patch antenna is presented as the demonstration of proposed technique.

1. Introduction

A network oriented modeling of the passive microwave structures provides a useful description and characterization of different microwave devices. The main reason for such an approach to the modeling is its simplicity and visibility of the representation through the equivalent circuit containing only lumped elements (inductance, capacitance and resistance). Another reason is a possibility of the reduction of the computational efforts for the full wave 3-D simulation, implementing the finite-difference time-domain (FDTD), transmission line matrix (TLM) or some other approach [1]. The time-domain reaction of the high-Q microwave circuits for the shot impulse excitation has very long duration, thus system identification (SI) procedure applied to the simulation results allows to constructs a lumped element model (LEM) at the beginning of the simulation process. As a result the replacing of the huge time-domain numerical simulation process by the predicted reaction gives the reduction of the required computer time and memory capacity.

The rest of the paper is organized as follows. The concept of network approach to electromagnetic structures representation can be found in Section 2. Section 3 explains the system identification procedure for LEM part estimation through physical poles extraction using stability criterion. The principles of elementary synthesis for the given impedance or admittance expressed by rational functions are described in Section 4. The application of the proposed technique to the TLM simulation result of two patch antennas (non-optimized and optimized) is represented in Section 5. In the conclusion the finally results are discussed.

2. Electromagnetic Structures Representation

The conventional approach for the network oriented methods is a fitting of the system transfer function in the frequency-domain by the rational function. The criterion of this fitting is a root mean square error (RMSE) between the simulated or measured date and the pole or rational function model. The parameters of the model are the number of poles and there positions in the complex frequency plane. The SI procedure results in such parameter estimation which minimizes the RMSE criterion. In fact this procedure implements the best approximation, it has no physical meaning. The obtained poles positions do not represent real quasistatic processes inside the microwave circuit. To overcome this problem we proposed to split the whole model of the microwave circuit into two parts.

The simplified diagram of the incident waveform $a(t)$ propagation inside the microwave structure is shown in fig.1. The scattered waveform $b(t)$ can be considered as a sum of two parts. The one is a scattered waveform $b_D(t)$ corresponding to the distributed parameter model (DPM) which represents the processes describing by the geometrical theory of diffraction. The other is $b_L(t)$ which combines in-series delay line and the circuit carried out with only lumped electrical elements.

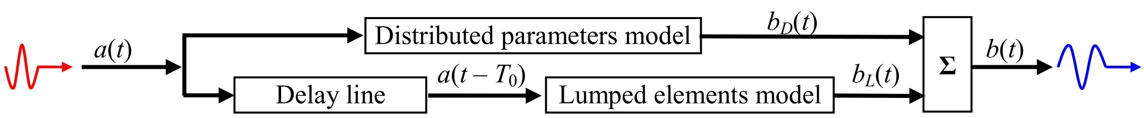

Fig.1. The model of microwave circuit

The subdivision of the pulse response into LEM and DPM parts can be applied to the scattering parameters **S** of the microwave circuits. Let us consider the simplest case. The scattering matrix of one-port microwave device (e.g. antenna) consists of the single element. It can be described by the complex function $S_{11}(f) = H(f)$. The driving-point scattering transfer function corresponding to the proposed model consists of two parts:

$$H(f) = \frac{B(f)}{A(f)} = H_D(f) + H_L(f) \cdot \exp(-j2\pi f T_0), \tag{1}$$

where $A(f)$ and $B(f)$ are the Fourier spectra of the incident $a(t)$ and return $b(t)$ waveforms; $H_D(f) = B_D(f)/A(f)$ is the input transfer function for the distributed parameters model describing by a geometric diffraction theory only; $H_L(f) = [B_L(f)/A(f)]\times\exp(j2\pi f T_0)$ is the input transfer function for the lumped elements model describing by a quasi-static electromagnetic field theory; T_0 is a time lag of the delay line. The important condition of divisibility is the requirement that both LEM and DPM part belong to primary passive device. The condition of device passivity demands the rational functions in (1) to be $|H(j\omega)| \le 1$, $|H_D(j\omega)| \le 1$ and $|H_L(j\omega)| \le 1$ for every frequency value ω.

3. System Identification Procedure

Results of the full-wave electromagnetic simulation or time domain field measurements can be considered as initial data for the SI which consists of the following steps. The first proceeding step is the obtaining of impulse response (IR) by the deconvolution in the required frequency range [2]. The estimation of such IR provides the microwave structure description which is free of ill-condition problems. Thus the frequency response (or the Fourier transform of the IR) describes the structure in pre-chosen frequency bandwidth. The restored IR has been used for solving the problem of late-time border estimation and choosing the pole model order. The stability criterion allows searching two-parametric solution which provides stable set of poles. The application of the approximation quality criterion (such as RMSE) consists in the comparison of the reconstructed late time part of IR and the late time part of the IR restored by the deconvolution. However the present scheme does not demand the RMSE value to be a very small number so in practice it should be unit of percents.

The proposed stability criterion is founded on the fact that the positions of physical poles can be extracted from the finite duration IR segment. The changing of the location of this segment inside the late-time part of the IR results in the stable positions of the estimated poles if the order of the extracting MPM corresponds to the number of the physical poles [2, 3]. The realization of the stability criterion needs specific tools which allow to automate pole set comparison by evaluating the degree of nearness one poles set to another one. It was shown in [3] that signature comparison technique mapping a set of K poles into the point of complex K-dimensional space has sufficient advantage as such kind of tools. After the pole extraction is applied the transfer function of the LEM part can be expressed as a conventional rational function of the complex frequency with real α_k and β_k coefficients

$$H_L(s) = \frac{\sum_{k=0}^{K-1} \beta_k s^k}{\sum_{k=0}^{K} \alpha_k s^k} = \frac{\prod_{k=1}^{K-1} (s - s_{0k})}{\prod_{k=1}^{K} (s - s_k)}, \tag{2}$$

where s_{0k} and s_k are correspondingly zeroes and poles which must be present as real values or conjugate pairs.

4. Approach to Elementary Synthesis

The lumped element model represents a circuit assembled by the passive electrical elements only. To make such realization possible the input impedance of the circuit has to be positive real function (PRF). The necessary and sufficient conditions for the PRF $Z(s)$ are the following:

1) $Z(s)$ must be real for real s;

2) the real part of the impedance must be non-negative $\mathrm{Re}(Z(s)) \ge 0$ for $\mathrm{Re}(s) \ge 0$;

3) the poles of $Z(s)$ have the real parts which are negative or zero (only simple poles with real positive residues are permitted in the imaginary axis).

The driving-point impedance of the one-port microwave device can be represented through its refection transfer function as

$$Z(s) = \frac{1}{Y(s)} = Z_0 \frac{1 + H_L(s)}{1 - H_L(s)}, \tag{3}$$

where Z_0 is characteristic impedance of the transmission line. Taking under consideration expression (2) the degrees of polynomials in the numerator and denominator are assumed to be equal in general case.

The concept of the circuit synthesis procedure is to break up the whole PRF Z(s) into a combination of simpler partial PRFs $\{Z_i(s)\}$, connected in series and/or in parallel [4]. The simplest partials which can be constructed by only one element are constant, linear function and inverse proportionality implemented by resistance, inductance and capacitance correspondingly. Each pole or the pair of conjugate poles can be expressed by the rational fraction of the first (for real) or second (complex-conjugate pair) order. The first order rational fractions can be realized as a parallel connection of R-C or R-L circuits. The pair of complex conjugate poles can be implemented by the resonant circuit which transfer function is expressed by the second order partial fraction. The same approach with a few corrections is generally valid for the admittance $Y(s)$ given in (3). So the elementary synthesis procedure for a given impedance or admittance can be implemented by subsequent extractions of the realizable simple partials while the rest part is still realizable. The impedance can be transformed into admittance on any step if there is no possibility to implement a series connection of realizable partials and vice versa. It is important to notice that some driving-point functions have several possible realizations while the others have the only one.

5. Network Modeling of Patch Antenna

There we demonstrate the application of network oriented approach to the analysis of two antennas. The combined TLM-GA (Transmission Line Matrix and Genetic Algorithm) optimization method was used on the patch antenna structure shown in Fig. 2. The initial patch antenna exhibits its first two resonances at 6 GHz and 12 GHz. For the optimization the frequency range was specified from 5 GHz to 10 GHz. The optimization goals and process are explained in detain in [5].

The proposed SI method was applied to the TLM simulation results. Figure 3 shows the amplitude characteristics for LEM parts of the non-optimized (initial) and bandwidth optimized patch antennas. It can be seen that the optimized antenna has additional resonant frequencies. These provide a larger impedance bandwidth compared to the initial antenna with two resonances. It has to be mentioned that additional resonances may destroy the group delay properties. Therefore the impedance bandwidth criterion used here applies well to wideband antennas for several narrowband services. However, antennas optimized in that way may not be suitable for ultrawideband pulse transmission.

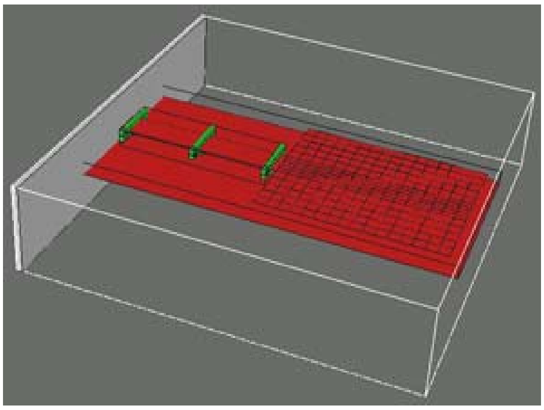

Fig. 2. CAD rendered view of the simulated and optimized patch antenna

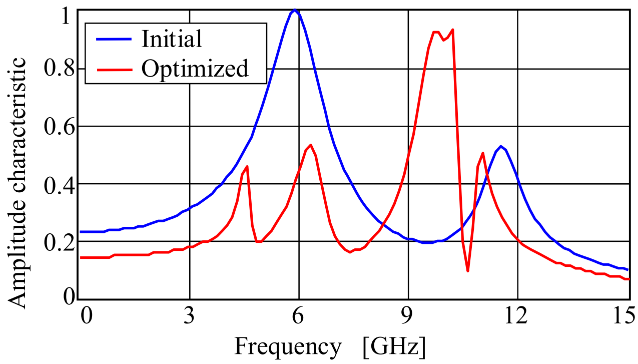

Fig.3. Modeled patch antenna amplitude spectral response

The impedances for extracted LEM part for both initial and optimized antennas are shown in fig. 4. There one can see the PRF requirements carrying out. This fact means that according LEM part which the impedance belongs to can be realized by only passive electrical elements. The LEM for initial (non-optimized) patch antenna contains 2 complex conjugate pairs of poles and zeroes. Its network realization built by subsequent Brune's synthesis method is presented in fig. 5. The elements values are rounded off. Note that the mutual inductances of close-coupled coils give the unity coupling coefficients. The network for optimized antenna (here is omitted) implements 5 conjugate pairs of poles and zeroes using the Brune's realization cycles. Thus the network consists of 5 unity-coupled inductances.

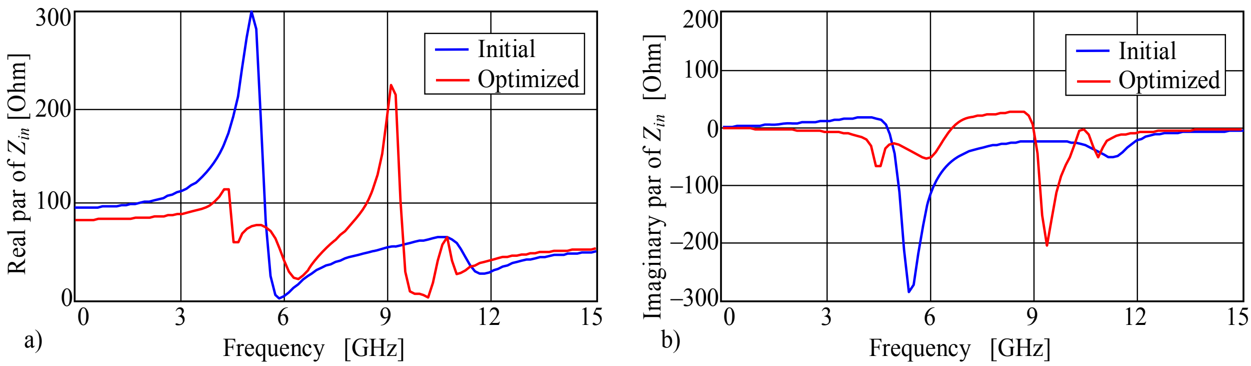

Fig. 4. Modeled patch antenna input impedance

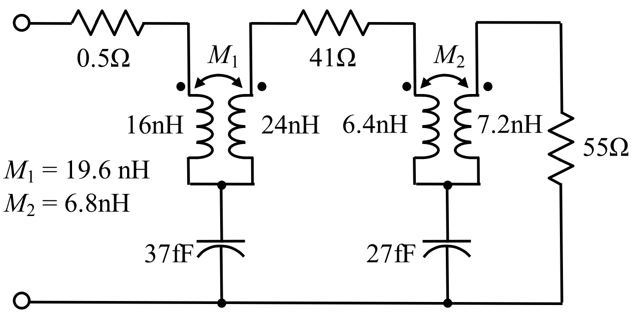

Fig. 5. The lumped element equivalent network for non-optimized patch antenna

6. Conclusion

As stated above, the application of methods conventionally used in network analysis can be done to improve the time-domain simulation performance and to simplify the representation of simulated microwave structures. Network oriented modeling of passive distributed microwave structures can be accomplished in a more efficient way and yielding more compact models by subdivision of the model into two parts. One of them is the distributed parameters model while the other one is the lumped elements model with a delay line. The LEM part of the model can be totally identified by the order of the pole model and positions of poles and zeros on the complex frequency plane. The time lag of the delay line can be defined in accordance with the stability criterion. The TLM simulation results for the optimization process made for patch antenna has been used as initial data for extracting LEM part which is intended for further network realization. Consequently the equivalent network schemes consisting of electric lumped elements have been constructed for non-optimized and optimized patch antennas and the former is presented.

7. References

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