DC-Preserving Passivity Enforcement for S-Parameter Based Macromodels

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***Abstract*—Rational approximation of frequency responses is important for the modeling and design of microwave systems. An exact match of the dc value is crucial to ensure the accuracy and reliability of circuit and system simulations. This paper presents a novel approach to compute dc-compliant macromodels that are both accurate and uniformly passive at the same time. Several examples illustrate the effectiveness of the approach.**

***Index Terms*—DC compliant, frequency domain, macromodeling, passivity enforcement, system identification, vector fitting.**

I. Introduction

Vector fitting is a robust macromodeling algorithm to compute a rational function approximation of frequency-domain responses that are obtained from full-wave electromagnetic simulations or high-frequency measurements [1]–[8]. Although the resulting macromodels are stable and accurate, the extrapolation of the model at lower frequencies may indicate an incorrect dc value due to fitting errors. Nevertheless, an exact match of the dc value is crucial because minor inaccuracies may compromise the accuracy and reliability of all circuit and system simulations [9]. It is possible to modify an incorrect dc value by adding an external correction term to the model. Although this offset can be effective to compensate small errors, it introduces an unnecessary broadband deviation, which is often undesired. An alternative approach is shown in [10], where an exact correspondence of the dc value is obtained by modifying the functional form of the rational approximation model. This modification ensures that the model has an exact agreement of the dc value, but it frequently occurs that the resulting model is not asymptotically passive or uniformly passive. When combined with nonlinear terminations, a nonpassive model may lead to unstable simulations in an unpredictable way. Even though standard passivity enforcement techniques can be applied from literature, they do not preserve the dc value and often introduce additional deviations that contribute further to the problem [11]. This paper introduces a reliable solution to the resolve these difficulties. A modified version of the vector-fitting algorithm is proposed to compute dc-compliant macromodels, and a robust algorithm is proposed to enforce overall passivity while preserving the dc value. Several examples illustrate the advantages of this approach.

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II. DC-Compliant Macromodeling

A. Model Representation

To compute a dc-compliant macromodel, the vector-fitting algorithm is modified to calculate a proper macromodel with a modified complex diagonalized state space representation

$$sX(s) = AX(s) + BU(s) \tag{1}$$
$$Y(s) = sCX(s) + DU(s). \tag{2}$$

The transfer function of the model $S(s)$ is then defined as

$$S(s) = sC(sI - A)^{-1}B + D. \tag{3}$$

The advantage of this representation is that the model response at dc is exactly equal to the elements of the feedthrough matrix D. Thus, by setting the elements on the mth row and nth column of D equal to the correct dc value $\{\mathrm{dc}\}^{mn}$ of the corresponding scattering element S_{mn}, a perfect agreement is guaranteed [10]. Each element $S_{mn}(s)$ of (3) can be recasted into a partial fraction expansion, assuming that each element has a distinct set of coefficients γ_p^{mn} and common poles θ_p

$$S_{mn}(s) = \sum_{p=1}^{P} \frac{s\gamma_p^{mn}}{s - \theta_p} + \{\mathrm{dc}\}^{mn}. \tag{4}$$

It is also evident from (4) that $S_{mn}(0) = \{\mathrm{dc}\}^{mn}$, and thus a dc-compliant macromodel is obtained. A reliable procedure to calculate the remaining model coefficients γ_p^{mn} and θ_p is described in Section II-B. It is largely based on a modified procedure of the standard vector-fitting routine [10].

B. Model Identification

To identify the coefficients γ_p^{mn} and θ_p in (4), the transfer function of scattering element $S_{mn}(s)$ is defined as the ratio of a numerator $\rho S_{mn}(s)$ and a common denominator $\rho(s)$. Both expressions are expanded as a linear combination of rational basis functions that are based on a common set of poles a_p. These poles are initially prescribed, and they are selected according to a heuristical scheme in [1]. The first step of the identification process consists of finding the optimal values of the coefficients

c_p^{mn} and $\tilde{c}_p$ such that the least squares distance between the rational model and data samples is minimized

$$S_{mn}(s) = \frac{\rho S_{mn}(s)}{\rho(s)} = \frac{\sum_{p=1}^{P} \frac{s c_p^{mn}}{s-a_p} + \{\mathrm{dc}\}^{mn}}{\sum_{p=1}^{P} \frac{s\tilde{c}_p}{s-a_p} + \tilde{c}_0}. \quad (5)$$

The calculation of coefficients c_p^{mn} and $\tilde{c}_p$ leads to a nonlinear identification problem that can be hard to solve using standard optimization techniques. Therefore, a linear approximation of the problem is found by minimizing Levi's cost function [12]

$$\sum_{p=1}^{P} \frac{s c_p^{mn}}{s-a_p} + \{\mathrm{dc}\}^{mn} = S_{mn}(s) \left(\sum_{p=1}^{P} \frac{s\tilde{c}_p}{s-a_p} + \tilde{c}_0 \right). \quad (6)$$

The trivial null solution in (6) is avoided by setting the coefficient $\tilde{c}_0 = 1$. This choice ensures that $S_{mn}(0)$ in (5) equals the exact dc value, whereas $\rho(s)$ approaches unity at the low frequencies. This leads to the following expression:

$$\sum_{p=1}^{P} \frac{s c_p^{mn}}{s-a_p} - S_{mn}(s) \sum_{p=1}^{P} \frac{s\tilde{c}_p}{s-a_p} = S_{mn}(s) - \{\mathrm{dc}\}^{mn}. \quad (7)$$

Once the coefficients c_p^{mn} and $\tilde{c}_p$ are solved, it is clear that (5) can be simplified by cancelling out the prescribed poles a_p. It follows that the relocated poles $\theta = \{\theta_1, \ldots, \theta_P\}$ of the transfer function are, in fact, the zeros of $\rho(s)$. These zeros are easily calculated by solving an eigenvalue problem that is based on the minimal state space realization $(A_\rho,\ B_\rho,\ C_\rho,\ D_\rho)$ of $\rho(s)$. The easiest way to construct this realization is to reformulate $\rho(s)$ from (5) into the standard partial fraction form such that

$$\rho(s) = \sum_{p=1}^{P} \frac{s\tilde{c}_p}{s-a_p} + \tilde{c}_0 = \sum_{p=1}^{P} \frac{\bar{c}_p}{s-a_p} + \bar{c}_0 \quad (8)$$

provided that $\bar{c}_p = \tilde{c}_p a_p$ and $\bar{c}_0 = \tilde{c}_0 + \tilde{c}_1 + \cdots + \tilde{c}_P$. This way, the state space realization can be constructed using the same procedure as in [1, App. B]. The zeros of $\rho(s)$ are directly found by solving the following eigenvalue problem:

$$\theta = \mathrm{eig}(A_\rho - B_\rho D_\rho^{-1} C_\rho). \quad (9)$$

The prescribed poles a_p in (5) are replaced by the relocated poles θ_p, and this procedure is iteratively repeated until they are converged to some quasi-optimal position [1]. Stability of the model is ensured by a simple pole-flipping scheme that inverts the sign of unstable poles during the iterations. It is shown in [13] that this pole relocation process is equivalent to the Sanathanan–Koerner iteration using implicit weighting. Once the relocated poles θ_p are converged, the corresponding coefficients γ_p^{mn} of the model are solved as a linear problem

$$S_{mn}(s) = \sum_{p=1}^{P} \frac{s\gamma_p^{mn}}{s-\theta_p} + \{\mathrm{dc}\}^{mn} \quad (10)$$

where the coefficient $\{\mathrm{dc}\}^{mn}$ is equal to the exact dc value.

III. Passivity Conditions

Although the calculated macromodels are dc compliant, they are not guaranteed passive by construction. The exact definition of passivity for stable S-parameter-based macromodels in the frequency domain stipulates that the singular values σ of the scattering matrix $S(j\omega)$ are unitary bounded [14]

$$(I - S^H(j\omega)S(j\omega)) \geq 0 \qquad \forall\omega \quad (11)$$

which leads to the following equivalent expression:

$$\max_{\omega} \sigma(S(j\omega)) \leq 1 \qquad \forall\omega. \quad (12)$$

In order to apply some algebraic passivity tests to the model, the state space realization (1) and (2) is reformulated as follows:

$$sX(s) = \bar{A}X(s) + \bar{B}U(s) \quad (13)$$
$$Y(s) = \bar{C}X(s) + \bar{D}U(s). \quad (14)$$

Real matrices $\bar{A}$, $\bar{B}$, $\bar{C}$, and $\bar{D}$ are obtained by applying a similar transformation as (8) to each element $S_{mn}(s)$ in (4). The passivity can then easily be verified algebraically by computing the eigenvalues of an associated Hamiltonian matrix [15]

$$H = \begin{bmatrix} \bar{A} - \bar{B}\bar{R}^{-1}\bar{D}^T\bar{C} & -\bar{B}\bar{R}^{-1}\bar{B}^T \\ \bar{C}^T\bar{Q}^{-1}\bar{C} & -\bar{A}^T + \bar{C}^T\bar{D}\bar{R}^{-1}\bar{B}^T \end{bmatrix} \quad (15)$$

where $\bar{R} = \bar{D}^T\bar{D} - I$ and $\bar{Q} = \bar{D}\bar{D}^T - I$. If $j\omega_k$ is an imaginary eigenvalue of H, then the corresponding frequency ω_k may denote the crossover between a passive and a nonpassive frequency band [16]. By computing the slopes of the singular value curves at the purely imaginary eigenvalues, it is possible to pinpoint the exact boundaries of a passivity violation. If all the eigenvalues of H have a nonvanishing real part, then the system is passive. Theoretical proofs about this procedure are reported in [15]. In the case of reciprocal systems, a smaller passivity test matrix can be derived that is half the size of the Hamiltonian matrix H [17].

IV. Asymptotic Passivity Enforcement

Asymptotic passivity of the model requires that the singular values $\sigma(S(j\omega))$ of the scattering matrix are unitary bounded for $s \to \infty$. This can easily be verified by computing the singular value decomposition of the $\bar{D}$ matrix such that

$$S(\infty) = \bar{D} = U\Sigma V^* \quad (16)$$

where Σ is a positive real-valued diagonal matrix that contains the singular values, and U and V are unitary matrices. If the model is not asymptotically passive, then one (or several) of the singular values in Σ will exceed unity. To compensate this violation, a new set of violation parameters S_{viol} is constructed

$$S_{\mathrm{viol}}(\infty) = \bar{D}_{\mathrm{viol}} = U\Sigma_{\mathrm{viol}}V^* \quad (17)$$

with

$$\Sigma_{\mathrm{viol}} = \Sigma\Upsilon - \Psi \quad (18)$$

where Υ and Ψ are square diagonal matrices

$$\Upsilon|_{ii,\Sigma_{ii}\leq\delta}=0 \quad \Upsilon|_{ii,\Sigma_{ii}>\delta}=1$$
$$\Psi|_{ii,\Sigma_{ii}\leq\delta}=0 \quad \Psi|_{ii,\Sigma_{ii}>\delta}=\delta. \tag{19}$$

The value of the parameter δ is chosen exactly equal to 1. To make the model asymptotically passive, a new set of residues C_{viol} is computed by fitting $S_{\text{viol}}(\infty)$ using the same set of poles A that were used in the original macromodel (1). This leads to the following underdetermined problem:

$$S_{\text{viol}}(\infty)=\lim_{s\to\infty} sC_{\text{viol}}(sI-A)^{-1}B=C_{\text{viol}}B. \tag{20}$$

A combination of two terms is formed to preserve complex conjugacy of the residues corresponding to a complex pole pair. While solving the equations, one can impose additional nonlinear constraints that minimize the deviation to the input–output port response of the macromodel (see [18] for details). The violations are then removed by subtracting C_{viol} from the residue matrix C, leading to a new set of residues C_{asymp}

$$C_{\text{asymp}}=C-C_{\text{viol}}. \tag{21}$$

It is noted that the D matrix in (2) remains unaffected since this matrix contains the dc values that should be preserved.

V. Uniform Passivity Enforcement

If algebraic passivity tests indicate that the model is nonpassive, then the passivity enforcement algorithm [11] is modified to compensate the violation without affecting the dc value. The residues in the output matrix C_t (for $t=0,\ldots,T$) are iteratively corrected by a simple least squares fitting procedure until all violations are removed. In the first iteration step $t=0$ of the algorithm, $C_0=C_{\text{asymp}}$ in (21).

A. Nonpassive Residuals of Scattering Matrix

First, a dense set of frequencies Ω_{eval} is determined from dc up to about 20% above the highest relevant frequency. This highest relevant frequency is the maximum of the highest crossing from a nonpassive to a passive region on one hand and the maximum frequency of interest on the other hand. For each frequency s_{eval} in the set Ω_{eval}, a singular value decomposition of the scattering matrix is performed as follows:

$$S(s_{\text{eval}})=D+sC_t(s_{\text{eval}}I-A)^{-1}B=U\Sigma V^* \tag{22}$$

where Σ is a positive real-valued diagonal matrix that contains the singular values, and U and V are unitary matrices. The inversion of $(s_{\text{eval}}I-A)$ in (22) is computationally fast because it is a complex diagonal matrix. It is clear that one (or several) of the singular values in Σ will exceed unity in the areas where the model is nonpassive. Therefore, a new set of violation parameters S_{viol} is constructed as follows:

$$S_{\text{viol}}(s_{\text{eval}})=U\Sigma_{\text{viol}}V^* \qquad \forall s_{\text{eval}}\in\Omega_{\text{eval}} \tag{23}$$

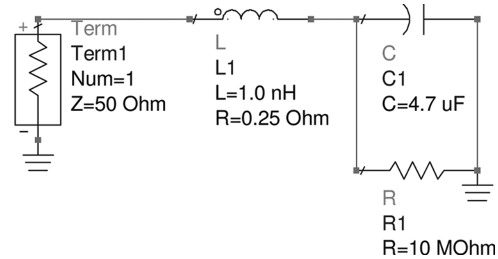

Fig. 1. Shunt capacitor: schematic.

where Σ_{viol}, Υ, and Ψ are defined as in (18) and (19). In this case, the value of δ is a predefined tolerance parameter that is chosen, in practice, slightly smaller than 1 (such as, e.g., 0.999).

B. Adjustments of Residues

In order to make the initial state space model passive, a new set of residues C_{viol} is computed by fitting the violation parameters S_{viol} over the frequency sweep Ω_{eval} using the same set of poles A that were used in the original model (1)

$$S_{\text{viol}}(s)=sC_{\text{viol}}(sI-A)^{-1}B. \tag{24}$$

It is noted that the solution of (24) is found by solving an overdetermined least squares matrix. The computational cost of this residue identification step is very small because it does not require any pole relocations. The calculated residues C_{viol} are then subtracted from the previous residue matrix C_t in order to suppress the passivity violations; hence,

$$C_{t+1}=C_t-C_{\text{viol}}. \tag{25}$$

This process is repeated until all violations are compensated.

VI. Examples

A. Shunt Capacitor

As a first example, the algorithm is demonstrated by computing a passive dc-compliant macromodel of a one-port shunt decoupling capacitor. The schematic of a simple model with representative behavior (see Fig. 1) is used to generate the S-parameters so the reader can easily verify the computations. The data samples are computed from dc up to 4 GHz, as shown in Fig. 2. Since $Z(0)=10\ \text{M}\Omega+0.25\ \Omega$ and $Z_0=50\ \Omega$, it is clear that the S-parameter at dc equals

$$S(0)=\frac{(Z(0)-Z_0)}{(Z(0)+Z_0)}\approx 0.99999000005025. \tag{26}$$

The modified vector-fitting algorithm in Section II-B is used to compute an exact dc-compliant macromodel with two poles. Unfortunately, the model is not asymptotically passive because

$$S(\infty)=\bar{D}\approx 1.000000001400475. \tag{27}$$

In order to make the macromodel asymptotically passive, the procedure in Section IV is applied to compute a small correction to the residues C in (2) without modifying the dc values in D.

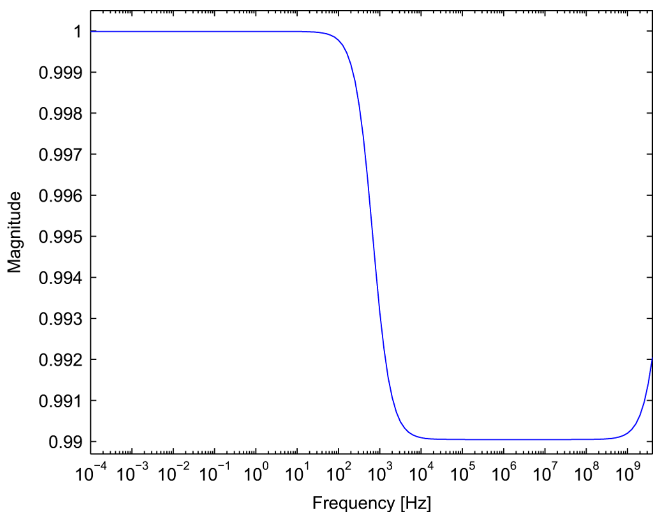

Fig. 2. Shunt capacitor: magnitude of S-parameters.

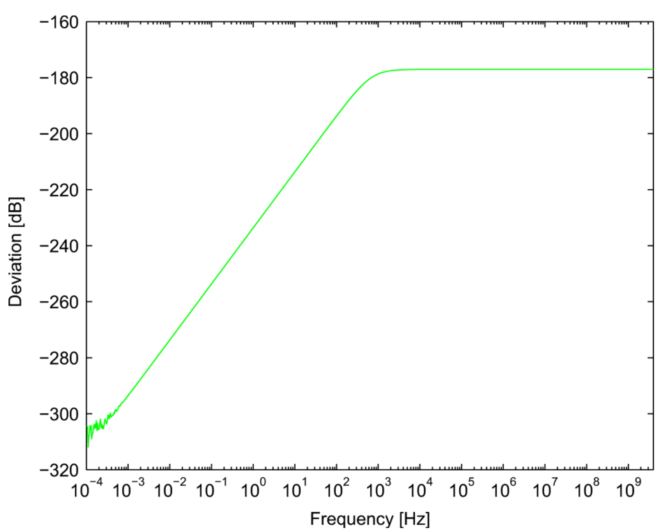

Fig. 3. Shunt capacitor: deviation passive dc-compliant macromodel.

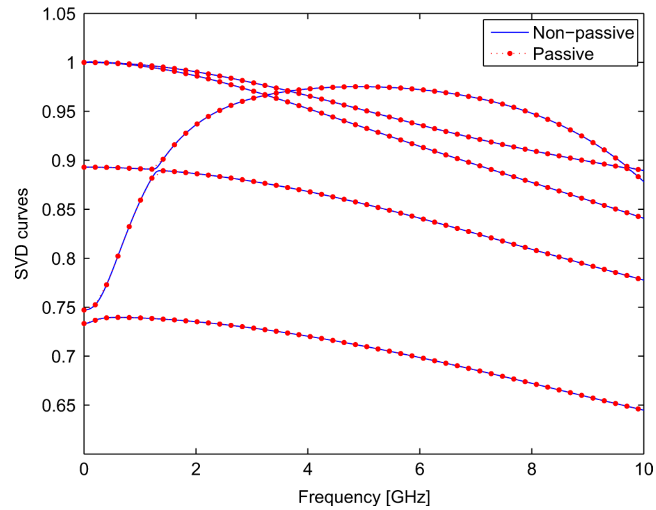

Fig. 4. Balun: singular value curves of passive and nonpassive model.

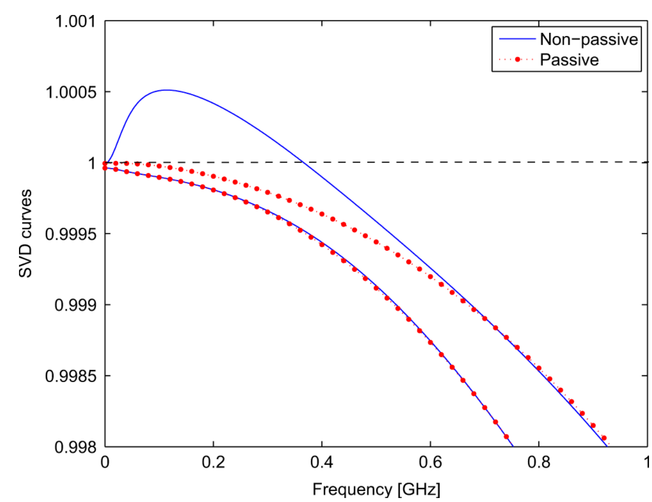

Fig. 5. Balun: zoom of Fig. 4 at lower frequencies from dc to 1 GHz.

This correction offsets the passivity violation in such a way that $S(\infty) = \bar{D}$ becomes exactly equal to 1.

Although asymptotic passivity is enforced, it is not guaranteed that the macromodel is uniformly passive. Uniform passivity can be verified by checking the eigenvalues of the Hamiltonian matrix (15). However, since $\bar{D}$ is now exactly equal to 1, this test cannot be applied because both $\bar{Q}$ and $\bar{R}$ become singular. To resolve this problem, a modified passivity test (based on the realization of the reciprocal system) is used, as in [19]. It is found that the conditions for uniform passivity are satisfied, and no further compensations are needed.

Fig. 3 shows the deviation of the passive dc-compliant macromodel, and it turns out that the maximum absolute deviation caused by asymptotic passivity enforcement is approximately −178 dB. It is also noted that there is no deviation at dc because the proposed macromodeling and passivity enforcement procedure preserves the exact dc values.

B. Balun Transformer

As a second example, the procedure is applied to compute a passive dc-compliant macromodel of a five-port planar microwave balun transformer. The S-parameters of the component are simulated with ADS Momentum [20] over the frequency range of interest from dc up to 10 GHz. The modified vector-fitting procedure in Section II-B is used to compute an accurate ten-pole macromodel with an exact match of the dc value. Accurate modeling of the dc value is often critical to capture the late-time (steady state) response of the system [21]. It is verified by checking the singular values of $\bar{D}$ that the model is asymptotically passive; however, a Hamiltonian passivity check indicates that the model is not uniformly passive. To visualize possible passivity violations, the singular value curves of the scattering matrix are shown in Fig. 4. A zoom of Fig. 4 near dc is shown in Fig. 5, and it is seen that a small passivity violation is detected. The iterative passivity compensation procedure in Section V is applied to remove the violation, and a passive macromodel is obtained in ten iterations. It is seen from Fig. 6 that the size of the maximum violation decreases monotonically in each iteration step, and convergence to a passive macromodel is obtained.

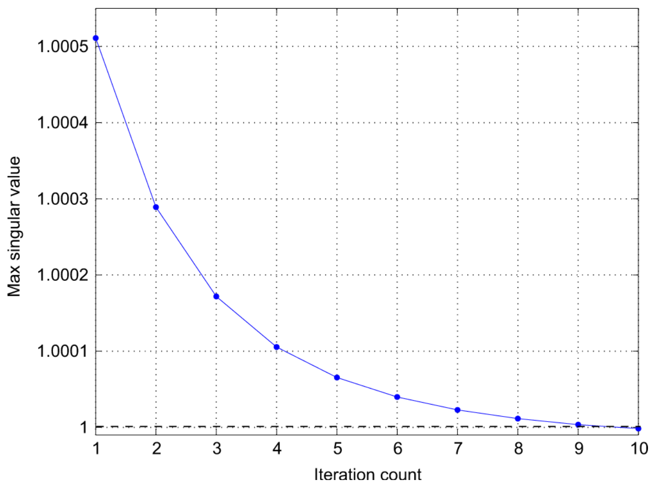

Fig. 6. Balun: maximum singular value in each iteration step.

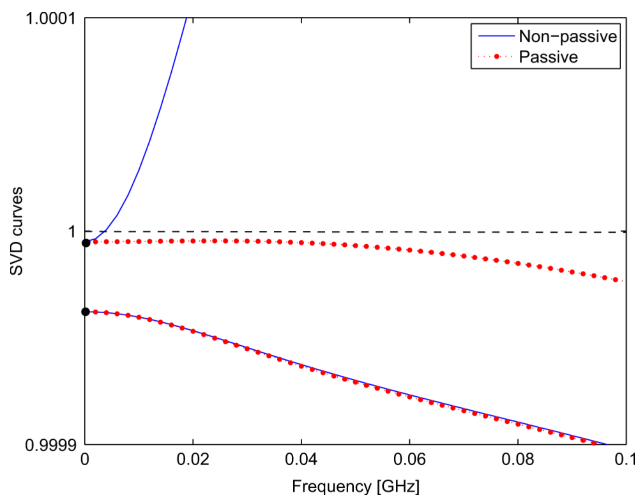

Fig. 7. Balun: zoom of Fig. 4 at lower frequencies from dc to 100 MHz.

Fig. 7 shows a more detailed zoom of the singular value curves, and a closer inspection reveals that the passivity compensation algorithm preserves an exact agreement of the singular values at dc (marked by black dots), as desired. Fig. 8 shows the magnitude of the S-parameter response of the passive dc-compliant macromodel, and it turns out that the maximum absolute deviation is bounded by approximately -80 dB over the frequency range of interest, which is a highly accurate result. It is also noted from Fig. 8 that the deviation at dc is exactly equal to 0 since the passivity enforcement procedure ensures that the dc values remain unaltered.

As a comparison, the standard vector-fitting technique from [1] is used to compute a similar ten-pole macromodel. The frequency sample at $s = 0$ is included in the fitting process; however, dc compliance (as described in this paper) is not enforced. Table I lists the exact dc values and the dc values of the standard vector-fitting model, and it is seen that a nonnegligible deviation is introduced. Fig. 9 shows the singular value curves of the model and confirms that the singular values of the exact dc solution (marked by black dots) are indeed missed, even before any kind of passivity enforcement is applied. Such a deviation is undesired, as it may lead to wrong bias currents at dc. The new dc-compliant macromodeling procedure described in this paper completely resolves this problem, as it enforces an exact match of the dc value and preserves the dc value of the macromodel during the passivity enforcement.

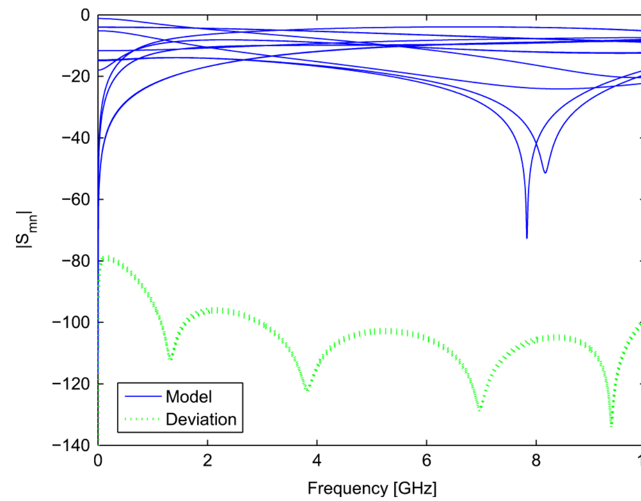

Fig. 8. Balun: singular values passive dc-compliant macromodel and deviation.

TABLE I
DC VALUES—UPPER TRIANGULAR ELEMENTS OF $S(0)$

Element	DC (exact)	DC (standard VF)	Deviation
S_{11}	-0.184901699841	-0.184839387277	$6.231256400 \times 10^{-5}$
S_{12}	0.551210045042	0.551266571409	$5.652636643 \times 10^{-5}$
S_{13}	-0.000001491559	0.000050601538	$5.209309820 \times 10^{-5}$
S_{14}	-0.000022099361	0.000059681755	$8.178111763 \times 10^{-5}$
S_{15}	0.633656141148	0.633718887156	$6.274600852 \times 10^{-5}$
S_{22}	-0.179447486896	-0.179379530608	$6.795628833 \times 10^{-5}$
S_{23}	-0.000011089670	0.000059794682	$7.088435261 \times 10^{-5}$
S_{24}	0.000002390237	0.000050881571	$4.849133399 \times 10^{-5}$
S_{25}	0.628197292194	0.628263860432	$6.656823816 \times 10^{-5}$
S_{33}	0.126438292257	0.126522747136	$8.445487870 \times 10^{-5}$
S_{34}	0.873533552444	0.873609217132	$7.566468838 \times 10^{-5}$
S_{35}	0.000032478851	0.000060296875	$2.781802465 \times 10^{-5}$
S_{44}	0.126449954354	0.126526855758	$7.690140391 \times 10^{-5}$
S_{45}	0.000039902918	0.000063277412	$2.337449373 \times 10^{-5}$
S_{55}	-0.261839167897	-0.261805781711	$3.338618576 \times 10^{-5}$

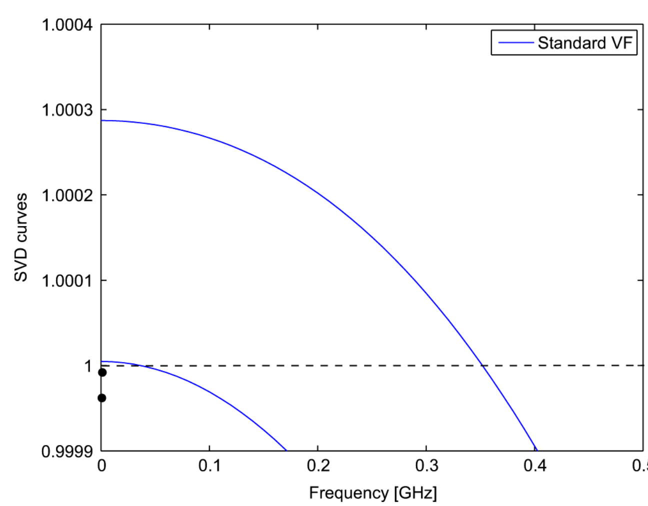

Fig. 9. Balun: singular values standard VF macromodel (non dc compliant).

VII. Conclusions

The calculation of macromodels with an exact match of the dc values are important since minor inaccuracies can lead to unreliable circuit and system simulations. A robust approach is described to compute macromodels that are dc compliant, and a reliable passivity enforcement procedure is proposed to ensure asymptotic and uniform passivity of the model. Several examples illustrate that this method yields accurate results.

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