On Some Differences Between Wave Digital Models of Directional Couplers

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***Abstract*—The paper summarizes the development and applications of wave digital (WD) models for predicting the frequency response of four-port microwave passive circuits such as directional couplers. Models are developed and afterwards validated by commercial software tools. Differences between the equivalent circuit- and transmission line-based WD models are presented through analysis of multi-section couplers.**

***Index Terms*—Directional coupler, wave digital models, equivalent circuit, transmission lines.**

I. Introduction

ELECTROMAGNETIC (EM) simulation tools have become essential for circuit designers. Across industries and disciplines, simulation modeling solves real-world problems safely and efficiently and provides valuable solutions by giving clear insights into complex systems. It provides an important method of analysis which is easily verified, communicated, and understood. The designers have to be able to simulate and test their designs, and to provide accurate predictions of real-world performance of the design, before the design is fabricated in order to avoid major expenses committed to circuit construction and experimental verification.

Wave digital (WD) approach is based on A. Fettweis WD filter theory [1]-[2]. In recent years, it appears to be universal and has been successfully applied to digital modeling of a wider class of analog circuits (including microwave structures), systems and processes (including electromagnetic signals generation and radiation) [3]-[8].

On the one hand, this paper summarizes the development and applications of wave digital (WD) models for predicting the frequency response of four-port microwave passive circuits such as directional couplers. The advantage of the presented WD models is their ability to account for a wide frequency range very quickly, as well as to model different coupler geometries. Models are developed, built up in MATLAB/Simulink and afterwards validated by a commercial software tool. On the other hand, the agreement between suggested microwave device WD models is investigated.

The present paper is organized as follows. First, in Section II, an overview of WD models based on an equivalent circuit network that have been used to simulate frequency response in different four-port microstrip structures is given. Second, in Section III, WD models based on transmission lines (TLs) for the multiport structures are described. Third, in Section IV, a list of coupler models and their simulated frequency performance is provided and compared. The covered range is from two- or tri-section couplers to tri- and five-section wideband couplers with the defected ground structures (DGS). Finally, concluding remarks are included in Section V.

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II. Nutshell of the Equivalent Circuit-Based Wave Digital Models

Over the past years, for the purpose of the application of the WD modeling method, the authors have been generated WD models of different couplers based on their equivalent circuit networks [9]-[12]. All these models have been implemented with an in-house MATLAB algorithm. Simulink environment let one drag-and-drop blocks from its library and predifine modeling elements, connect them and create complex WD models.

The equivalent circuit parameters are not quoted at the beginning, therefore the initial step in the proposed technique is to synthesize the values of inductors and capacitors based on the frequency and the characteristic impedances of the individual coupler branches. The lumped equivalent circuit model for the conventional branch-line coupler is proposed in [13]. During modeling process, i.e. model synthesis, parts of the system representing multiport networks with inductors and capacitors in the equivalent circuit are replaced with their wave digital counterpart. One sub-block in the generated WD counterpart models a specific part of coupler layout; it represents one wave digital element (WDE). The main attention in the papers [11]-[12] is focused on generating so-called basic two-dimensional symmetric and asymmetric WDEs. So, a WD model of the device under consideration is based on basic multi-port WDEs and two-port adaptors for port impedance matching. Therefore, the developed WD model will be completely characterized by its parameters: port resistances and adaptor coefficients.

III. Transmission Line-Based WD Models (Development of New Models)

A transmission line-based wave digital model of the directional coupler is derived from its circuit diagram. A starting point for creation of a WD model of the observed four-port structure is to look on that structure as a connection of several individual arms (transmission lines) as shown in [14]. Interconnection networks are used to interconnect

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idendified TL segments. So, a TL-based WD model is synthesized by making use of basic wave digital building blocks. The boxes in the WD model contain the arithmetic operations and represent the interconnection network or contain the delay elements corresponding to the TL models.

A. Basic Wave Digital Buiding Blocks

Basic building blocks in the proposed TL-based WD model are unit elements (Fig. 1), circuit elements (like resistor shown in Fig. 2) and interconnection networks (Fig. 3) [5], [15]. Therefore, we describe the wave-flow equivalents to circuit elements and interconnection networks used in WD models.

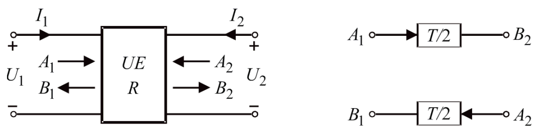

Fig. 1. Unit element and the corresponding wave-flow graph.

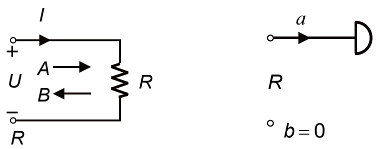

Fig. 2. Wave-flow equivalent for resistor, Zin = R.

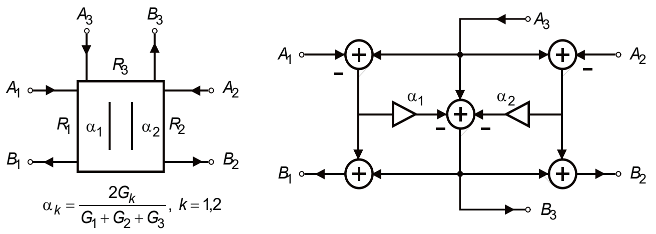

Fig. 3. Interconnection network: Three-port parallel adaptor with port 3 as the dependent port.

IV. LIST OF COUPLER MODELS (COMPARISON)

One of the most popular passive circuits used for various microwave and millimeter-wave applications is a branch-line directional coupler. In this section, digital models of several coupler structures are presented and discussed. Simple wave digital models are generated and simulated by use of MATLAB/Simulink environment. Also, the commercial Keysight Pathwave Advanced Design System (ADS) simulation software is used to generate ideal TL models of the designed couplers for comparison purposes.

To investigate the validity of the described WD models, comparison of the magnitude performance is given. The results of the illustrated examples in the frequency domain are presented here. The covered example range is from two- and tri-section couplers to tri- and five-section wideband couplers with DGS structures.

B. Case 1: A Single-Band Two-Section Coupler

The simplest coupler structure is composed of four quarter-wavelength transmission lines with different impedances. One such structure, i.e. a symmetric single-band coupler, which circuit diagram is shown in Fig. 4, with characteristic impedance of the main line $Z_1 = Z_0 / \sqrt{2}$, and for the branch line $Z_2 = Z_0 = 50\ \Omega$, is observed in [9], [12]. The electrical lengths of the TL segments are $\theta = \pi / 2$. The operating frequency is 2.45 GHz. Its model in ADS based on ideal transmission line is shown in [12]. That paper contains also its equivalent circuit-based WD model described in detail.

TL-based WD model is shown in Fig. 5 together with adaptor coefficients putted in Table I. Delays of all TLs are equal because of their equal electrical lengths and amounts to 102 ps. Simulated magnitudes are compared in Fig. 6. The comparison shows a coincidence between the *S*-parameter results obtained by EC-based WDM, TL-based WDM and ideal ADS model.

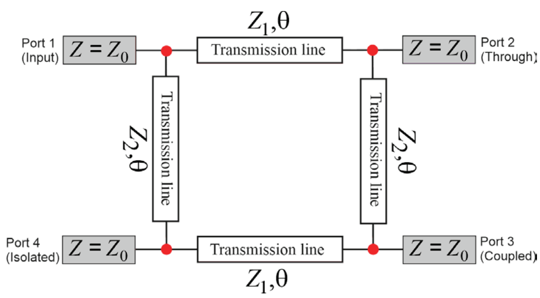

Fig. 4. Circuit diagram of a single-band two-section directional coupler. (Red dots show the locations of three-port parallel adaptors in the WD model).

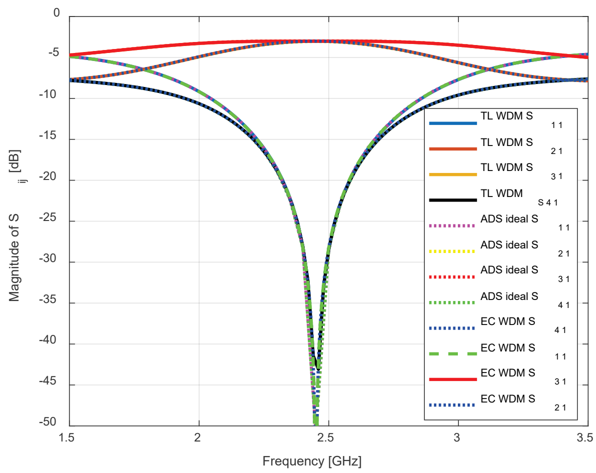

Fig. 6. Simulated magnitude performance of a single-band two-section coupler (TL-based WDM versus EC-based WDM and ADS ideal TL model).

TABLE I
PORT SIGNAL ORDERING FOR INTERCONNECTION NETWORKS

Three-port adaptors	**Port 1**	**Port 2**	**Coeff. α_1**	**Coeff. α_2**
ADP-Z0Z1Z2	Z0	Z1	α1=2/Z0/*SG*	α2=2/Z1/*SG*
			SG=1/Z0+1/Z1+1/Z2	
ADP-Z1Z0Z2	Z1	Z0	α1=2/Z1/*SG*	α2=2/Z0/*SG*
Two-port adaptors	**Port 1**	**Port 2**	**Coefficient α**	
ADP-S	Rg	Z0	(Rg-Z0)/(Rg+Z0)	
ADP-L	Z0	RL	(Z0-RL)/(Z0+RL)	

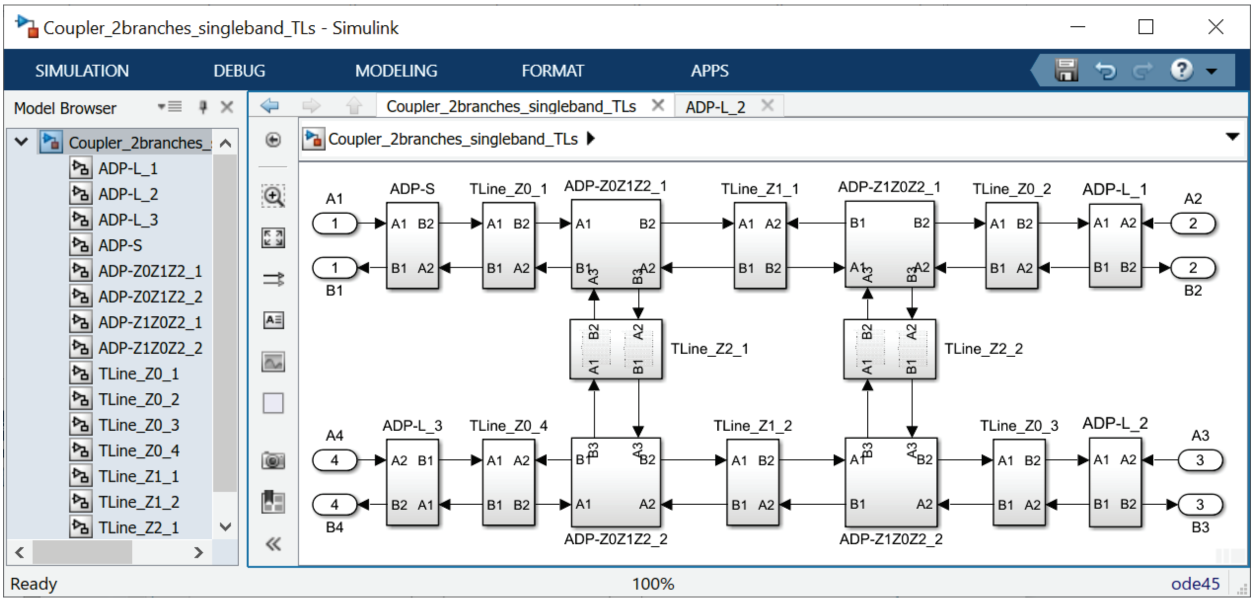

Fig. 5. Simulink model of TL-based WDM of a single-band two-section coupler.

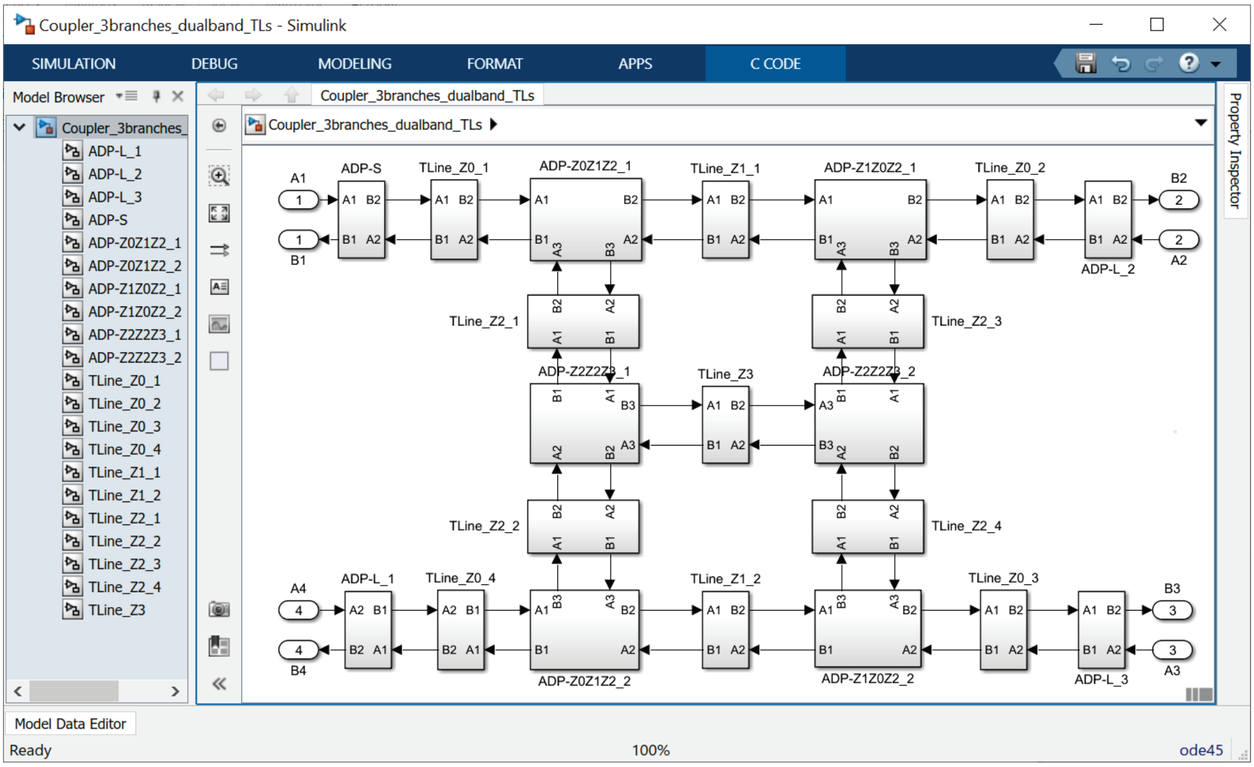

Fig. 8. TL-based WDM of a dual-band tri-section coupler.

C. Case 2: A Dual-Band Tri-Section Coupler

A dual-band branch-line coupler structure with three parallel lines which schematic diagram can be found in Fig. 7 is analyzed in [12]. It is design to operate at 1.0/2.5 GHz. For the characteristic impedance Z_0 set to $50\ \Omega$, the calculated line impedances are $Z_1 = 49.48\ \Omega$, $Z_2 = 79.21\ \Omega$, and $Z_3 = 132.66\ \Omega$ having the power ratio of 3dB. This example is specific, because of different electrical lengths of transmission lines, $\theta = 51.43^{\text{o}}$ and 2θ.

TL-based model of this structure is shown in Fig. 8. The blocks corresponding to individual TLs are assigned as TLine_*Zx* (*x*=0,1,2,3). Delay of the corresponding TLs with the electrical length θ is 143 ps, and for 2θ is 286 ps at the frequency of 1 GHz. Ordering of port signals for used interconnection networks (two- and three-port parallel adaptors) and relations for multiplier coefficients are presented in Table I. Additional adaptor ADP-Z2Z2Z3 has two equal multiplier coefficients $\alpha_1 = \alpha_2 = (2/Z2)/SG$, where $SG = 2/Z2 + 1/Z3$.

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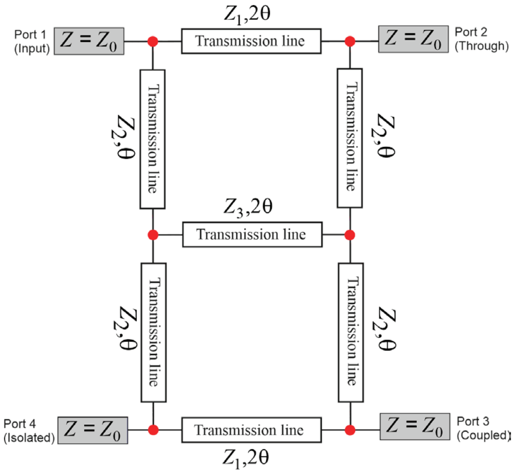

Fig. 7. Circuit diagram of a dual-band tri-section coupler. (Red dots show the locations of three-port parallel adaptors in the WD model).

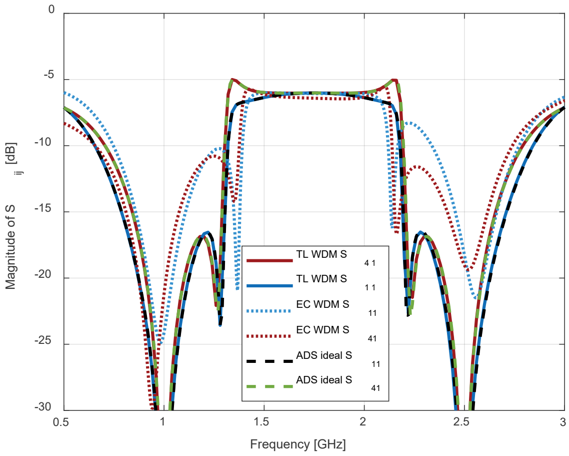

Fig. 9. Comparison of the simulated magnitudes of S_{11} and S_{41} parameters.

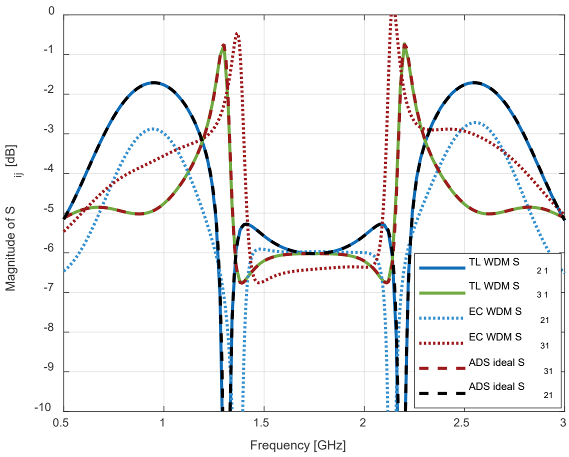

Fig. 10. Comparison of the simulated magnitudes of S_{21} and S_{31} parameters.

Comparison of simulated magnitudes of the *S*-parameters obtained by WD models (EC-based and TL-based) and ADS model are given in Figs. 9 and 10. TL-based model curves from MATLAB and ADS are barely distinguishable. There is a slight disagreement with results from EC-based model.

D. Case 3: A Tri-Section Wideband DGS Coupler

An example of a tri-section wideband branch-line hybrid for operating at center frequency of 2.4 GHz has been design and fabricated by authors in [10]. The characteristic impedances of the stubs are $Z_s = 99.86\,\Omega$, $Z_{s1} = 41.13\,\Omega$ and the main line impedance is $Z_1 = 34.74\,\Omega$. All TLs are $\lambda/4$ long (λ is the wavelength at the operating frequency). Their delays are calculated as 104 ps. Fig. 11 contains layout of DGS coupler and Fig. 12 its circuit diagram.

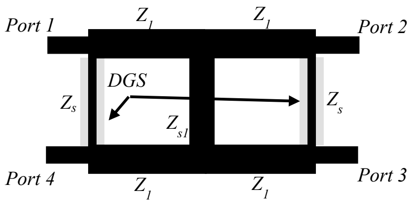

Fig. 11. Layout of a tri-section wideband DGS hybrid designed in [10].

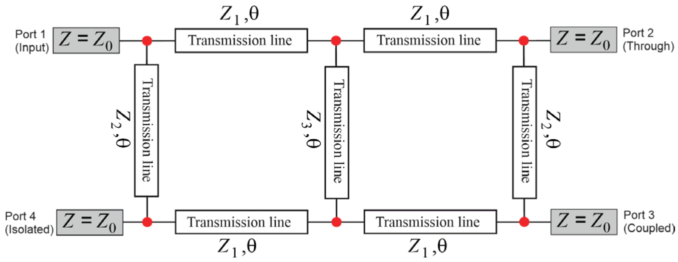

Fig. 12. Circuit diagram of a tri-section wideband DGS hybrid. (Red dots show the locations of three-port parallel adaptors in the WD model).

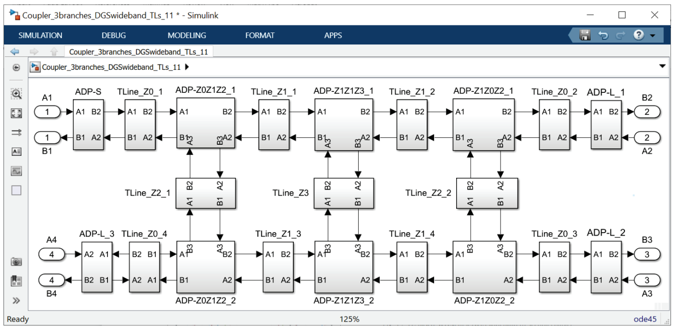

Fig. 13. TL-based WDM of a DGS wideband tri-section coupler.

Coefficient relations in three-port parallel adaptors used as interconnection networks in TL-based WDM drawn in Fig. 13 are presented in Table I. Additional adaptor ADP-Z1Z1Z3 has the multiplier coefficients with equal value calculated by relation $\alpha_1 = \alpha_2 = (2/Z1)/SG$, where $SG = 2/Z1 + 1/Z3$.

The simulated magnitude responses of this coupler example are compared in Fig. 14. Slight disagreement between EC-based model and other models is evident. The corresponding equivalent circuit-based model is validated by measurements and full-wave simulation results in [10].

E. Case 4: A Five-Section Wideband DGS Coupler

Different aspects of five-section wideband 3 dB branch-line hybrid with 90° phase difference which operates at center frequency of 2.5 GHz are presented in [11]. The proposed hybrid configuration, shown in Fig. 15, having symmetric nature with defected ground structures is designed and fabricated. The hybrid is also simulated and measured, and its wave digital model based on multimethod technique and an equivalent circuit is created there.

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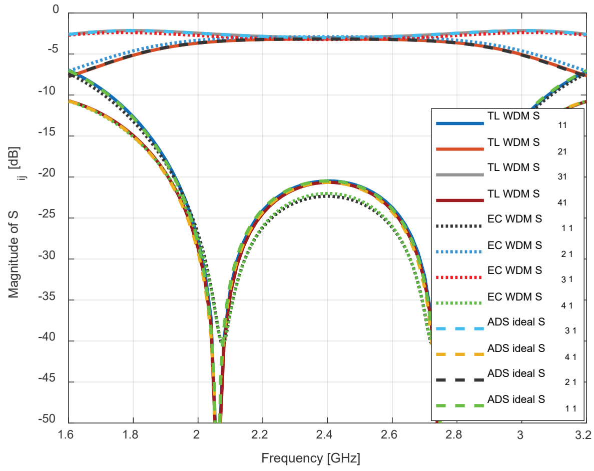
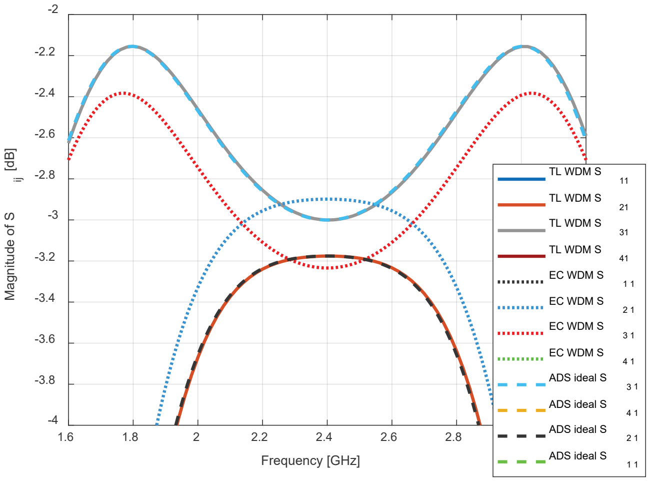


(a)



(b)

Fig. 14. Simulated magnitude performances of a tri-section wideband DGS coupler (TL-based WDM versus EC-based WD and ADS ideal TL models): (a) all S-parameters and (b) zoom on S_{21} and S_{31} parameters.

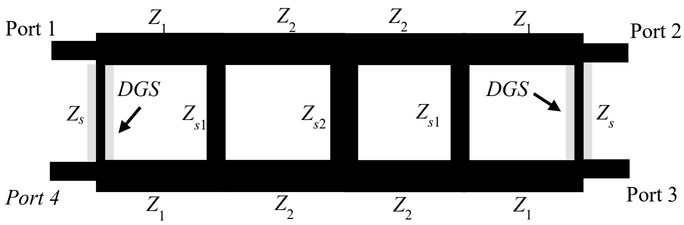


Fig. 15. Layout of a five-section wideband DGS hybrid designed in [11].

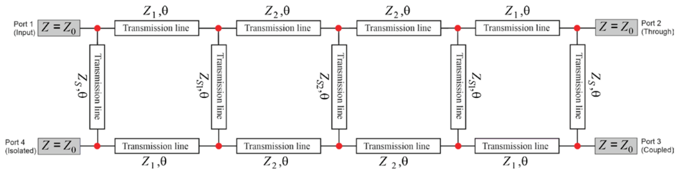
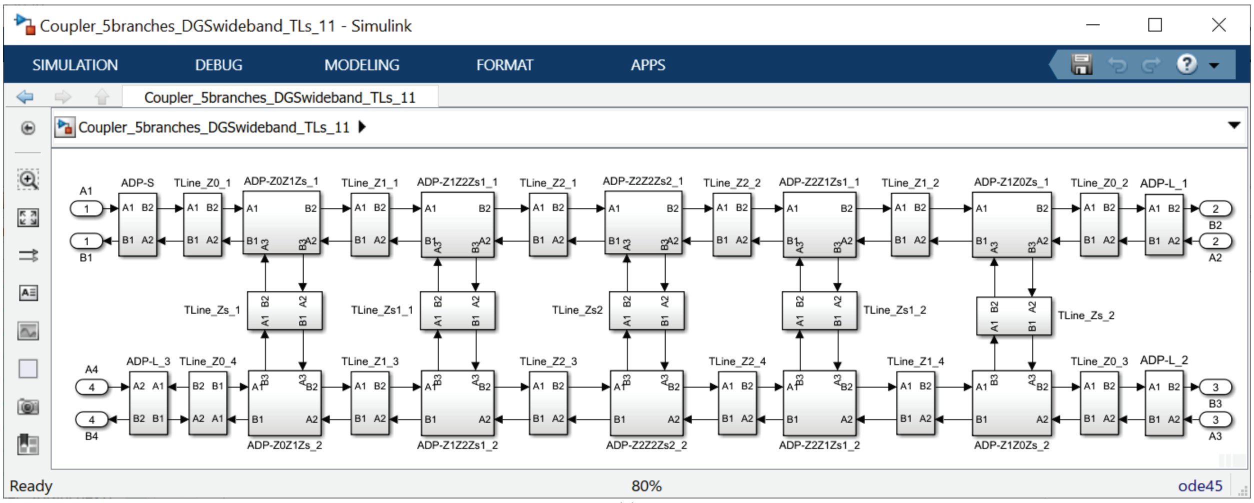


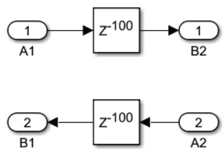
Fig. 16. Circuit diagram of a five-section wideband DGS hybrid. (Red dots show the locations of three-port parallel adaptors in the WD model).

TABLE II
PORT SIGNAL ORDERING FOR THREE-PORT ADAPTORS

Three-port adaptors	Port 1	Port 2	Coeff. α_1	Coeff. α_2
ADP-Z0Z1Zs	Z0	Z1	α1=2/Z0/*SG*	α2=2/Z1/*SG*
			SG=1/Z0+1/Z1+1/Zs	
ADP-Z1Z0Zs	Z1	Z0	α1=2/Z1/*SG*	α2=2/Z0/*SG*
ADP-Z1Z2Zs1	Z1	Z2	α1=2/Z1/*SG*	α2=2/Z2/*SG*
			SG=1/Z1+1/Z2+1/Zs1	
ADP-Z2Z1Zs1	Z2	Z1	α1=2/Z2/*SG*	α2=2/Z1/*SG*
ADP-Z2Z2Zs2	Z2	Z2	α1=α2=2/Z2/*SG*	
			SG=2/Z2+1/Zs2	



(a)



(b)

Fig. 17. (a) TL-based WDM of a five-section wideband DGS coupler and (b) model of one TL segment with used Delay block from Simulink Library.

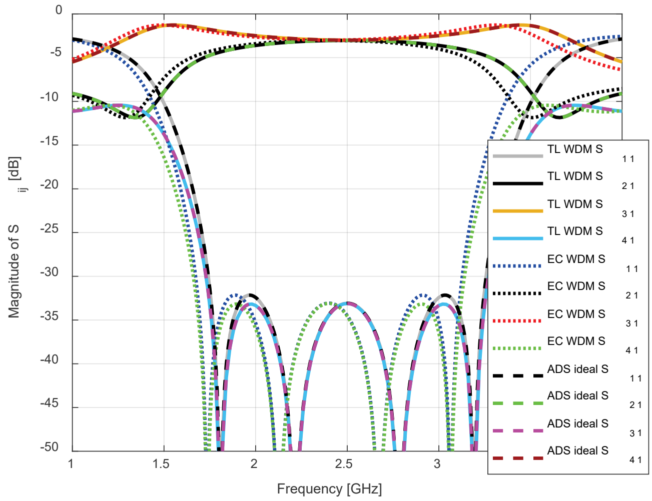


Fig. 18. Simulated magnitude performances of a five-section wideband DGS coupler (differences among TL-based WD, EC-based WD and ADS ideal TL models).

A circuit diagram of the analyzed DGS coupler is presented in Fig. 16. This circuit diagram contains some red dots which show places where three-port parallel adaptors are used in a TL-based WDM given in Fig. 17. Each TL block is presented by 100 UEs corresponding to 100 ps delay, Fig. 17b. Ordering of port signals for three-port adaptors is given in Table II.

Once again, comparison in Fig. 18 confirms matching of TL-based model results from WDM and ADS, and slight non-matching of EC-based model results. The corresponding equivalent circuit-based model is validated by measurments and full-wave simulation results in [11].

V. Conclusion

The paper confirms potential of a WD approach for the simulation of given directional couplers. We have investigated the differences between equivalent circuit-based and transmission line-based WD models of these four-port microwave devices. The simulations demonstrate that the proposed TL-based WD model behaves exactly the same as model generated in ADS by ideal TLs. The differences between EC-based models and abovementioned models are evident except in the case of the simplest coupler design. To conclude, there is progress, but still more to do in this WD modeling approach. The next step is to find a way to include losses in the models in order to get closer to real measurements.

On the other hand, comparing the circuit diagrams with the TL-based WDMs clearly shows their great similarity. Due to the advantages of the nature of generating the TL-based model, this approach can be easily adopted by researchers for simulation purposes of wide range of branch-line couplers. In comparison with the equivalent circuit-based modeling approach a TL-based approach is more intuitive.

Acknowledgment

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