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A Wide-Band Equivalent Circuit Model for Single Slot Defected Ground Structures

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***Abstract*—Defected Ground Structures have multiple applications in the microwave domain, e.g., in the design of couplers, antennas, filters and filtennas. An accurate wide-band equivalent circuit model is proposed for Defected Ground Structures in this paper. This wide-band model can be used to model multiple resonances of a Defected Ground Structure with a single slot. Validation through measurements verifies the accuracy of the proposed model.**

***Index terms*—** Circuit modeling, Defected Ground Structure (DGS), slotlines.

I. INTRODUCTION

A Defected Ground Structure (DGS) has multiple applications in microwave fields. It can be used to improve or easily shape the Frequency Response Function (FRF) of passive components, to reduce the size of microwave circuits, to improve the performances of active circuits and antennas. Its potential has been already demonstrated in the design of couplers [1], antennas [2], [3], filters [4], [5] and filtennas [6], [7].

In this work, we consider the DGS shown in Fig. 1. It consists of a transmission line on the signal layer, with a resonating slot (called "defect") in the metallic ground-plane. The slot can have different shapes. In this work, we will focus on a rectangular slot.

A DGS is often designed using time-consuming electromagnetic (EM) simulations. Due to the large range of applications of a DGS, it becomes necessary to have an equivalent circuit model at disposal. An equivalent circuit provides more physical insight into the behavior of such a structure and the way this behavior is linked to its design parameters.

Equivalent circuit models for DGS have been proposed in the literature [8]–[10]. However, all these models lack accuracy because no losses have been taken into account in the models.

In [11] an accurate equivalent circuit model was proposed to model the fundamental resonance frequency for a DGS consisting of a single rectangular slot that was positioned perpendicularly to and symmetrically around the transmission line.

In this work, we extend this equivalent circuit model to a wide-band model that can accurately represent the higher-order harmonics besides the fundamental frequency. Section II discusses the DGS of interest. Section III introduces the equivalent circuit model. Section IV validates the proposed model by means of microwave measurements.

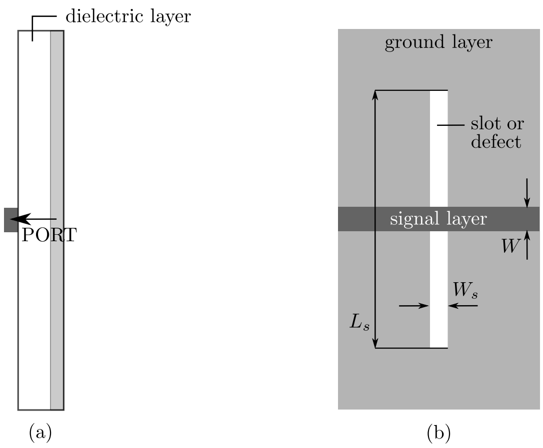

Figure 1. Layout of a DGS. Left: cross-section. Right: top-view of a DGS with a single slot.

II. DEFECTED GROUND STRUCTURE (DGS)

A slot in DGS is usually located directly underneath the transmission line for coupling to occur. The coupling effect introduces a transmission zero in the FRF of the structure. This implies that the DGS behaves as a bandstop filter. The fundamental resonance frequency of the filter depends on the shape and the size of the slot. Next to the bandstop behavior, the DGS has two other characteristics. Slots cause a slow-wave effect and increase the characteristic impedance of the transmission line [2], [12]. Slots also radiate, which means the structure could be used as a filtenna.

Besides the fundamental frequency, the DGS also displays higher-order harmonics. Which harmonics are excited and which are not can, at some extent, be selected by changing the position of the coupling between the slotline and the transmission line. This point is called the feedpoint.

Fig. 2 shows the electric field of the first 4 modes of the resonating slot. When the transmission line is positioned at $1/2$ of the slotline, the electric field of the even modes ($m = 2k$ with $k = 1 : \infty$) is zero at the feedpoint. In that case, the even modes are not excited since no energy coupling can occur between the transmission line and the slotline at these modes, resulting

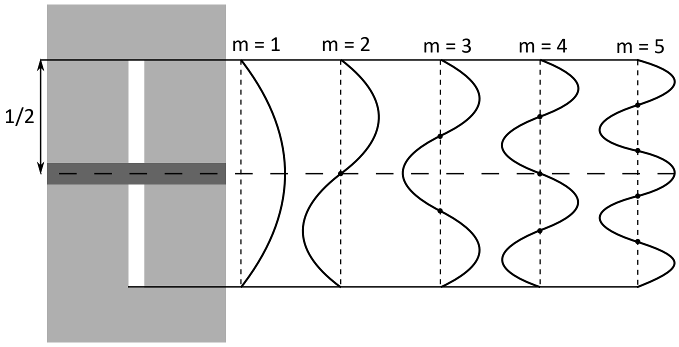

Figure 2. The position of the feedpoint between slotline and transmission line selects which modes of the electric field are excited and which are not excited.

in the absence of the corresponding harmonic frequencies in the FRF.

III. Equivalent circuit model

In [11], a circuit model was proposed for a DGS with one slot, modeling only the fundamental frequency, f_0 ($k = 1$ in Fig. 3). In this work, we extend this equivalent circuit model to a wide-band model that can accurately represent the higher-order harmonics besides the fundamental frequency.

After a de-embedding step to remove a delay contribution of the signal transmission line, the transmission line of the DGS was modeled by the Telegrapher's equation representation (L, C and $R(f)$). The shunt conductance, G, was not modeled because the dielectric losses were negligible. The complex series impedance $R(f)$ represents the skin effect [13]

$$R(f) = K\sqrt{j(2\pi f)} \tag{1}$$

The slot itself was modeled by an RLC-resonator (L_{res}, C_{res} and $R_{res}(f)$) of which the resistor is frequency-dependent. This resistor mainly represents the radiation losses of the slot and is defined as

$$R_{res}(f) = R_{rad}\left(\frac{f}{f_0}\right)^{\alpha} \tag{2}$$

Introducing losses in this model was necessary to achieve a high accuracy [11]. These frequency-dependent impedances can be simulated in a SPICE environment, e.g. LTspice®.

Modeling an extra harmonic requires an extra LC-resonator. Cascading LC-tanks to model multiple resonances has been proposed in the literature [9], [10]. If the radiation losses are taken into account, the LC-tanks can be replaced by an RLC-tank structure. Since the resistor representing the slot losses is frequency-dependent in our case, this resistor is sufficient to model the losses over a wide frequency band. Hence, per extra harmonic to be modeled we only need 2 extra circuit parameters (L and C), while a single RLC-tank that requires 3 parameters (L, C and R) can be used to model only the fundamental frequency. The wide-band model that we obtained is shown in Fig. 3 and can model k resonances.

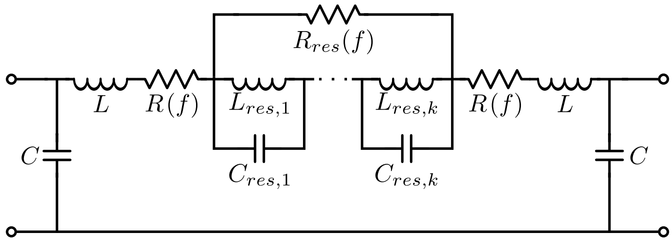

Figure 3. Wide-band circuit model that models resonances 1 to k of a DGS.

IV. Measurement validation

The wide-band model, shown in Fig. 3, is validated using microwave measurements of a DGS. The prototype of the DGS with a symmetrical slot, as shown in Fig. 4, was designed on a Rogers 4003 substrate with $\varepsilon_r = 3.55$, $\tan(\delta) = 0.0022$ at 2.5 GHz and a dielectric height $h = 60$ mil. The scattering (S) parameters of the DGS were measured with a Vector Network Analyzer (VNA).

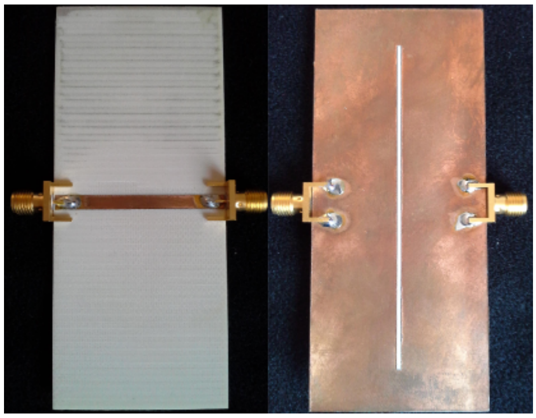

Figure 4. The prototype of a DGS. Left: top view. Right: Bottom view.

To validate the accuracy of the proposed wide-band model, we consider an example up to the third harmonic (measured up to 5 GHz). To obtain an accurate circuit model up to the third harmonic, the model needs to include the first resonance (at f_0) as well as the second resonance (at $3f_0$) ($k = 2$ in Fig. 3). We note that the second harmonic (at $2f_0$) is not excited as previously explained. The values of the circuit parameters are extracted by an optimization step based on the measured S-parameters.

The circuit model response fits the DGS measured response quite well. Fig. 5-6 show the magnitude and phase of the S_{11} and S_{21} parameters of the measured DGS (full black line) and of the simulated wide-band circuit model (dashed dark gray line). The absolute model error is shown in light gray. The Root Mean Square Error (RMSE) is equal to −28.8 dB and −27.7 dB for S_{11} and S_{21}, respectively.

V. Conclusion

We have proposed a wide-band circuit model for DGS structures with a single slot. This model can be used to de-

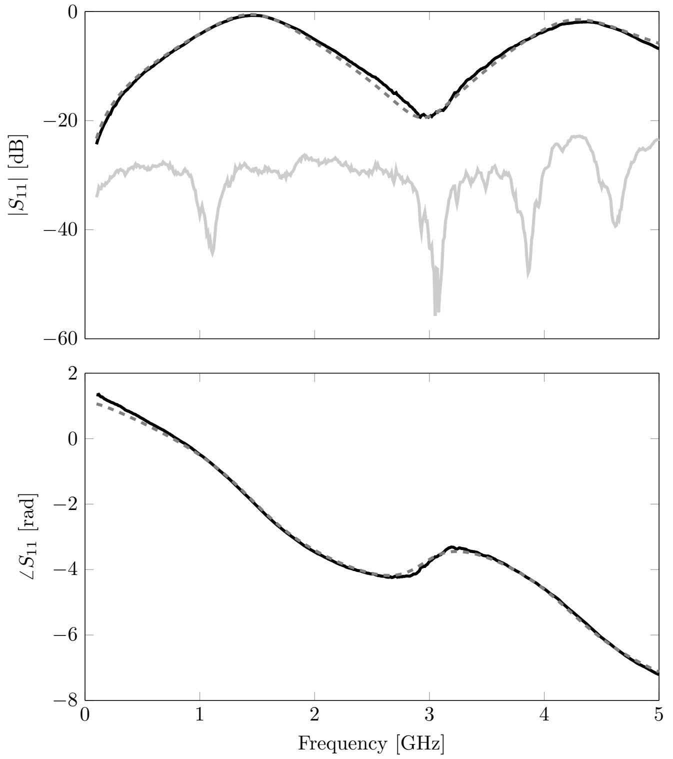

Figure 5. Comparison of the S_{11}-parameter of the measured DGS (full black line) and the simulated wide-band circuit model (dashed dark gray line). The absolute model error is shown in full light gray. The RMSE is $-28.8\,\mathrm{dB}$. Top: amplitude comparison. Bottom: phase comparison.

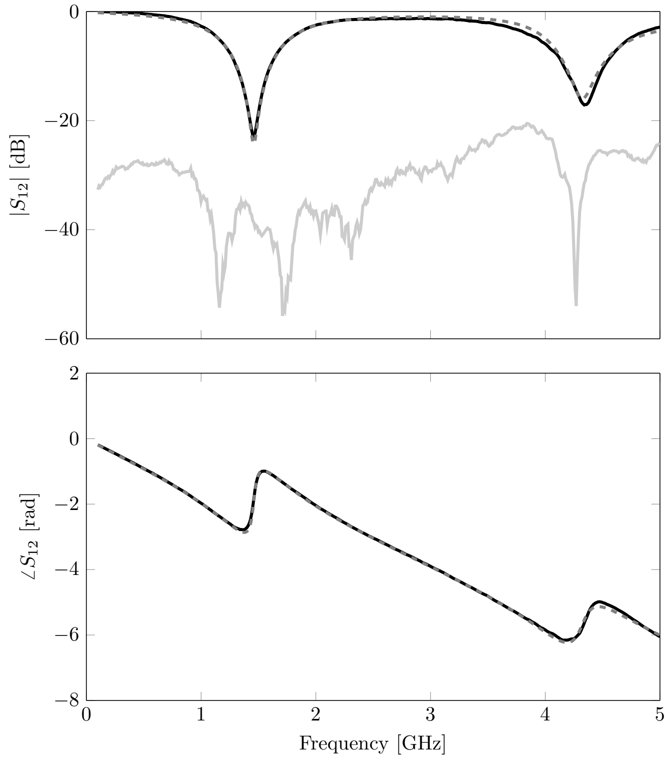

Figure 6. Comparison of the S_{21}-parameter of the measured DGS (full black line) and the simulated wide-band circuit model (dashed dark gray line). The absolute model error is shown in full light gray. The RMSE is $-27.7\,\mathrm{dB}$. Top: amplitude comparison. Bottom: phase comparison.

scribe multiple resonances of the DGS response. The proposed model was validated by measurements, which confirm a good accuracy. Future work will focus on extending this model representation towards more general DGS configurations.

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