Accurate Modeling of a Patterned Ground and its Application to Microwave Filters

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Abstract **─** A patterned ground and its exactly equivalent lumped circuit model are analyzed in depth in this paper. Characteristics of the introduced patterned ground include providing the finite attenuation pole and reflection pole near the cutoff frequency, thus effectively improving the frequency-response selectivity. The basic unit cell and its performance are first studied. A circuit theory-based lumped model is then introduced. To verify the developed equivalent model, a prototype low-pass filter using three cascaded cells is designed. Results of the prototype filter show a good consistency between the experiment and theory.

Index Terms **─** Attenuation pole, lumped element model, patterned ground, reflection pole.

I. INTRODUCTION

In general, the patterned ground is obtained by etching some shapes/structures on a ground plane of a microwave planar circuit. It is also called defected ground structures (DGSs) or in some cases split ring resonators (SRRs). It can exhibit a bandgap, slow/fast-wave or negative index refraction characteristics. In recent decades, many researchers have been devoted to studying such kinds of structures, and many characteristics/performances are exploited. These properties have been imposed to many applications in microwave engineering such as balun [1], directional coupler [2], antenna [3] and so on, while the most common application is for microwave filters including lowpass type [4-11], bandpass type [10-18], bandstop type [19], UWB type [20,21] and multi-band filters [22,23]. Basic advantages in introducing these structures in the microwave circuits are extending operation bandwidth [1], reducing circuit area [2,4,6-8], achieving wide stopband [7,11-13], generating required multi-band responses [22,23], implementing reconfigurable function [24], etc.

On the other hand, the patterned ground is a special structure that cannot be found in classic microwave engineering. Thus, studying and designing such a structure generally involves full-wave electromagnetic (EM) simulations with try and error. In this process, an equivalent circuit model that is either circuit theory-based or physical structure-based or a combination between them is important in studying and designing, especially, when many etched patterns are cascaded. The cascaded patterns are necessary and important to further improve the circuit performance in applications. To date, many equivalent circuit models are presented [1,4-9,12,23,24], but no general models are found to be suitable for all patterns due to the complexity and variety of the patterned shape. Moreover, many models developed are only applicable to only one unit cell. Their accuracy may be greatly degraded, or even failed, when they are applied to the cascaded cells.

In this article, we study a patterned ground and its equivalent lumped circuit model. EM characteristics of the studied structure are first investigated. Results indicate that the presented pattern can provide attenuation and reflection poles near the cutoff frequency, thus greatly improving the frequency selectivity for filter applications. To model this pattern, a circuit

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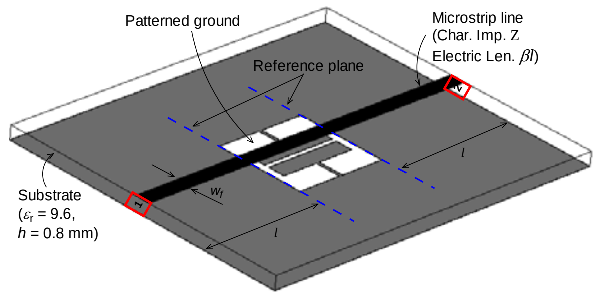
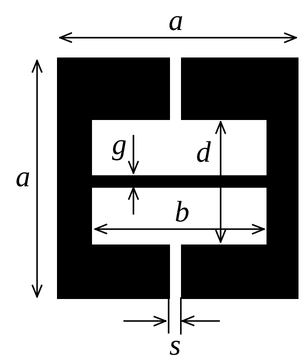
theory-based lumped element model is proposed. The developed model is simple and accurate. Moreover, it is suitable not only for the unit cell but also for the cascaded patterns. To verify the study, a five-order filter is investigated and confirmed. Demonstration on the prototype filter is also performed, theoretically and experimentally, with a good consistency.

II. PETTERNED GROUND AND ITS UNIT EQUIVALENT CIRCUIT MODEL

Figure 1(a) shows the 3-D view of the introduced patterned ground, while its physical parameters are illustrated in Fig. 1(b). The pattern area is denoted by $a\times a$, so it is a square contour in shape. Within the etched region, a narrow strip with width s loads a capacitive patch. The capacitive patch is represented by length b and width $(d-g)/2$. Basic operation principle of this kind of structure, taking a hole on the ground as an example, is that due to the ground etching, the ground perfection is disturbed, and therefore, the etched ground creates current path surrounding to the contour of the hole, corresponding to lengthened current lines. The lengthened current lines can be equivalent to a lumped inductance. Moreover, the imperfect ground also creates the charge accumulation, and this phenomenon can be analyzed based on the capacitance effects. Consequently, a hole on the ground can be formulated as an LC network to generate resonance (notch response) at some frequencies. On the other hand, in view of transmission lines, it is known that a high impedance microstrip line exhibits inductance effect while a microstrip patch corresponds to an equivalent capacitance. Therefore, we introduce narrow strips loading capacitive patches within an etched hole, where the narrow strip functions as an enhanced distributed inductance and the capacitive patch corresponds to an enhanced equivalent capacitance. Thus, this improved structure can create the larger equivalent inductance and capacitance within a given area compared to a standard hole. It will be shown latter that with this improvement, not only the resonance is lowered but also good responses including a sharp transition skirt are observed, making the studied structure be interesting for application to some kinds of microwave components. The pattern is etched beneath a microstrip line (line width w_f) and the substrate utilized has a thickness h = 0.8 mm and relative permittivity ε_r = 9.6 in this study.



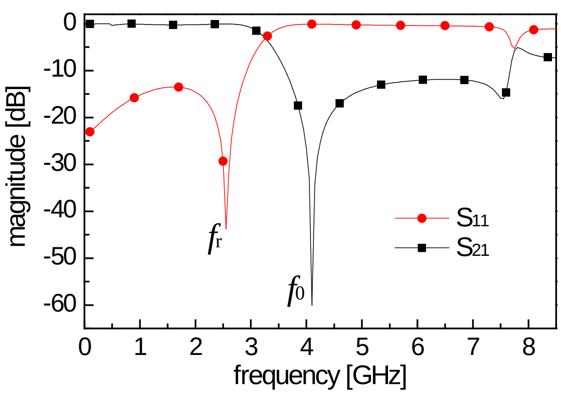
(a) 3-D view.



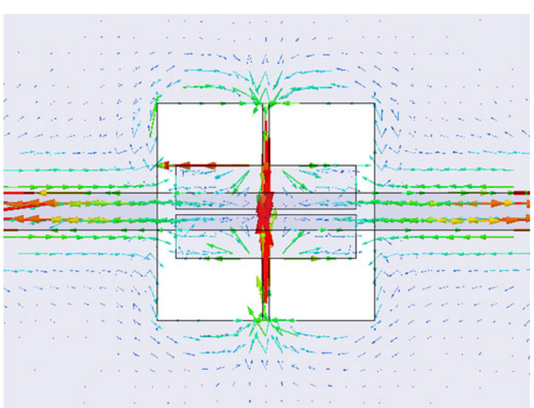
(b) Detailed parameter formulation.

Fig. 1. Studied patterned ground.

To investigate the electric performance of the unit patterned ground, the reference plane should be placed at the two edges of the pattern as given in Fig. 1(a). However, if so, drastic discontinuity will be suffered from and the simulation results cannot be convincing for the utilized full-wave EM simulator (Ansoft Ensemble 8). Therefore, the excitation ports are selected as 5 mm (l = 5mm in Fig. 1(a)) away from the reference planes when performing the EM simulations. Figure 2(a) describes the simulated responses where the physical parameters referring to Fig. 1(b) are a = 7mm, b = 5.8mm, d = 3mm, s = 0.2mm, g = 0.2mm and the strip width w_f = 1.2mm in Fig. 1(a). Based on the EM simulations, it is obvious to see that the studied pattern exhibits a reflection pole f_r that is close to the resonance f_0, and above the f_r, a fast slew rate is observed. Near the resonance f_0, the pattern has a sharp roll off at the lower transition skirt; while at the upper band, it has a relatively wide attenuation band. For the observed responses, it is interesting to note that this structure can provide a reflection pole f_r near the resonance f_0 compared to most patterned grounds. It is believed that the generated reflection pole f_r primarily results from the narrow strip loading capacitive patch. This loading greatly compensates for the equivalent inductance because for an etched hole alone, its equivalent inductance is generally smaller than its equivalent capacitance and hence, it is difficult to be matched to the characteristic impedance of a transmission line based on $Z_0 = (L_0/C_0)^{0.5}$. But for the studied patterned ground, its equivalent inductance can be effectively enhanced. Thus, in this case, idea matching is possible at some frequencies. To confirm this analyses, current distribution from EM simulations is provided at the reflection pole frequency f_r. As shown in Fig. 2(b), the current near and within the patterned region is continues and provides a good circulation path, indicating that the matching condition is good at the frequency of f_r.



(a)



(b)

Fig. 2. (a) EM simulated results of the studied pattern. (b) Current distributions at the frequency of f_r.

From Fig. 2(a), it is also observed that the response exhibits another passband around the frequency of 8GHz. The phenomenon results from the periodicity of microwave transmission lines. And we will show below that this spurious passband is also modeled exactly for the cascaded patterns.

Therefore, the introduced pattern features an enhanced frequency selectivity and a widened attenuation compared to some other patterns [5,7-9]. From these responses, one can see that the studied structure is potentially useful to microwave filter applications with enhanced performance.

To give a further insight into this structure, here we sweep the physical parameter *b* to investigate its frequency responses. Intuitively, decreasing *b* corresponds to reducing the equivalent capacitance and therefore, its resonance f_0 will shift to higher frequencies. Figure 3 presents the EM simulations of the sweeping results. It is seen that the resonances do shift to the lower frequencies with a larger *b*, while the reflection poles are lowered. From the frequency responses for three different *b* values (*b* = 5.0, 5.8 and 6.6mm respectively), it is seen that a greater *b* lowers both resonances f_0 and reflection poles f_r, while the attenuation band maintains a similar level. Moreover, a greater *b* results in a steeper transition skirt, however, the attenuation bandwidth under this case is reduced slightly. Therefore, these results give us useful insights that if the transition skirt is the first consideration in design specifications, one can choose a greater *b* to achieve the goal. Sweeping other physical parameters can provide different responses, but similar insights can be obtained and these investigations are not presented here for brevity.

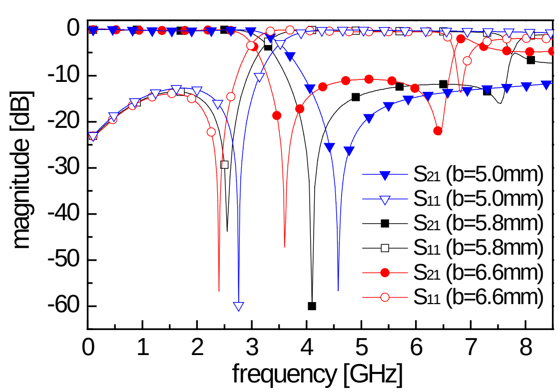


Fig. 3. Sweeping responses of parameter *b*.

Based on the above results, an equivalent lumped element model is proposed. Figure 4 describes this model, where its key part is represented by a parallel LC network (L_0 and C_0) that determines the basic resonance, f_0. Notice that this model does not include any resistance element because the investigated pattern is assumed to be lossless in the study. In Fig. 4, transmission line models with characteristic impedance Z and electric length βl formulate the microstrip-line section from excitation port to the reference plane in Fig. 1(a). To extract the lumped LC-parameter values, S-parameters of the patterned ground with a unit cell are obtained from EM simulations. By using the relationship between S-parameter and ABCD-matrix, equivalent LC-element values can be extracted. Figure 5 compares the performance resulting from the EM simulation and the lumped circuit simulation. As can be found, the shunt L_0 and C_0 clearly predict the resonance f_0 when L_0 = 1.2512nH and C_0 = 1.2093pF under physical parameters of a unit cell presented before. To more accurately predict the reflection pole f_r, a shunt capacitor C_1 is introduced as shown in Fig. 4. With this improvement, the pole f_r between EM and circuit simulations reasonably matches when C_1 = 0.5041pF, as illustrated in Fig. 5(a). Finally, the wide attenuation is considered by introducing a T-network with inductors L_1 and L_2 in series and then a capacitor C_2 in shunt between them as shown in Fig. 5(b). And the T-network is in series to the above equivalent circuit. Therefore, the entire lumped LC model is proposed as described in Fig. 4. By extracting the lumped parameter values, well matched responses between the EM and circuit simulations are observed as illustrated in Fig. 5, where L_0 = 1.2512nH, C_0 = 1.2093pF, C_1 = 0.5041pF, L_1 = 2.5422nH, L_2 = 1.1176nH, and C_2 = 1.6855pF.

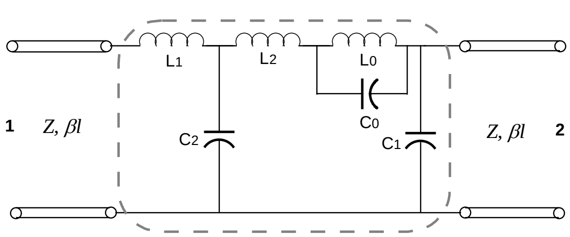
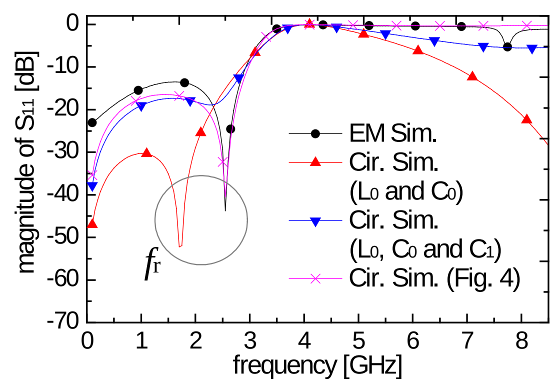
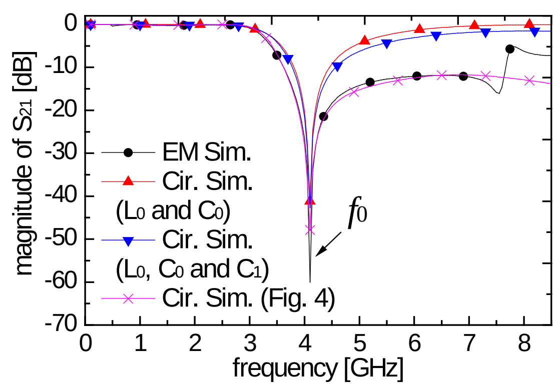


Fig. 4. Developed equivalent circuit model.



(a) Reflection responses

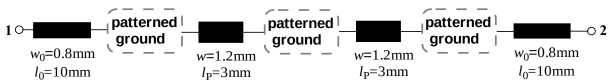


(b) Attenuation (or transmission) responses

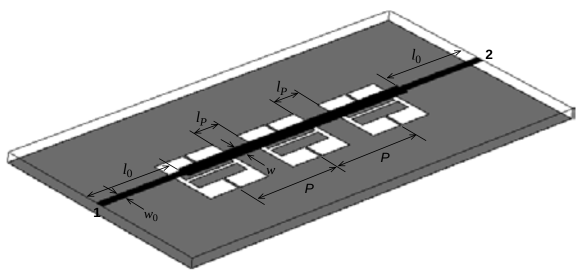
Fig. 5. Influence of the equivalent circuit element on the performance.

III. A FIVE-ORDER FILTER BASED ON THE STUDIED PATTERNED GROUND

To illustrate the introduced pattern for microwave filter applications and validate the effectiveness of its equivalent model, a five-order filter is demonstrated by cascading three unit cells of the studied pattern. In this case, the microstrip feed lines are set as width w_0 = 0.8mm (corresponding to characteristic impedance Z_0 = 50Ω) and length l_0 = 10mm for the input and output. Block diagram of the filter is shown in Fig. 6(a), where the patterned ground is described by the equivalent model given in the dashed box in Fig. 4. The microstrip-line width of the coupling region is the same as w_f in Fig. 1(a), i.e., w = 1.2mm. Figure 6(b) depicts a 3-D view of the physical structure of the filter. It is designed based on the proposed equivalent model and the coupling separation between two unit cells is found as l_P = 3mm, corresponding to a periodicity P, a quarter guided-wavelength at the cutoff frequency. The optimized LC parameters are: L_0 = 1.3061nH, C_0 = 1.2295pF, C_1 = 0.2271pF, L_1 = 2.4429nH, L_2 = 1.1977nH, and C_2 = 1.3061pF, which correspond to a resonance at 4 GHz approximately.



(a) Block diagram of the filter.



(b) 3-D view of the filter.

Fig. 6. Five-order filter based on the studied patterned ground.

Figure 7 presents the simulated frequency responses based on the equivalent circuit parameters and full-wave EM simulator. From the simulated responses, the circuit model not only predicts the reflection poles clearly, but also formulates the attenuation pole precisely. More importantly, the spurious resonance is predicted exactly. The results show a very good agreement between them. These results also indicate that the proposed lumped element model is efficient to model the studied patterned ground for cascaded cells.

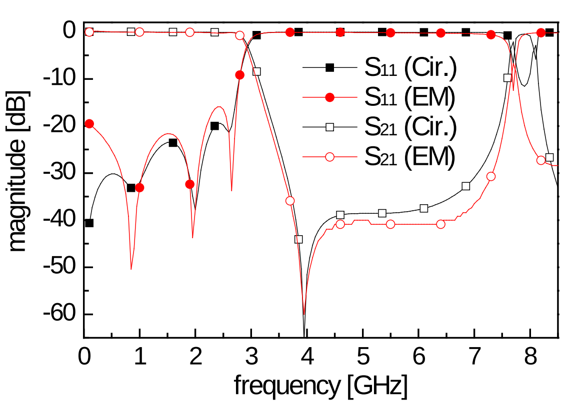


Fig. 7. Circuit design and EM results of the filter.

IV. EXPERIMENTAL VALIDATIONS AND RESULTS

Based on the above designs, the five-order prototype filter is fabricated on a substrate with a relative permittivity of 9.6 and a thickness of 0.8mm. Figure 8 shows the photograph of the built circuits, where the upper section denotes the front side of the circuit, and lower section represents the back side of the circuit. Experimental studies of the circuit are carried out on an Agilent E5071C ENA series network analyzer (frequency range 100kHz-8.5GHz). It is calibrated based on the through-reflection-line (TRL). Figure 9 describes the measured performance of this prototype filter. It is found from measurements that there are three reflection poles at 1.04, 2.11, and 2.60GHz with levels over 45, 30 and 40dB, respectively; an attenuation pole locates at 3.66GHz with an attenuation level over 60dB that is close to a reflection pole of 2.60GHz, thus resulting in a sharp transition skirt of $|S_{21}|$ curve. Measurements also indicate that the attenuation band is better than 35dB from 3.39 to 7.37GHz, and a spurious resonance at approximate 7.85GHz is found. Within the passband, the measured insertion loss is around 0.5 dB and group delay is about 0.8ns.

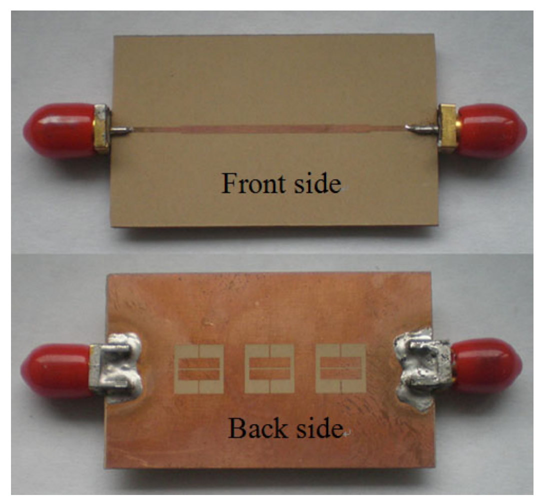


Fig.8. Photograph of the patterned ground filter.

From the measured and simulated results of the demonstrator, some discrepancies are also found. These discrepancies primarily exhibit a slight frequency shift, which can be attributed to the fabrication uncertainties. In general, the measurements match simulations well. These results confirm that the studied patterned ground structure is capable of implementing microwave filters with high performance, and more importantly, the developed lumped LC network can accurately model the cascaded patterns.

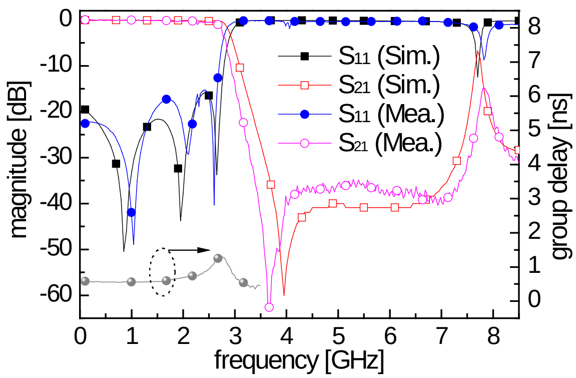


Fig. 9. Performance of the prototype filter.

VI. CONCLUSION

In this paper, we have studied a patterned ground and its accurately equivalent circuit model for microwave filter applications. The introduced structure exhibits both reflection pole and attenuation pole placed near the cutoff frequency and a wide attenuation band. A circuit model suitable not only for a unit cell but also for the cascaded cells is proposed. The model is simple and accurate. To verify the study, a demonstration circuit by cascading three patterned cells has been investigated. Results from the circuit model, EM simulations and experiments validate the studies with a good agreement. The introduced patterned ground and its equivalent model are interesting to be potentially applied to the modern microwave engineering.

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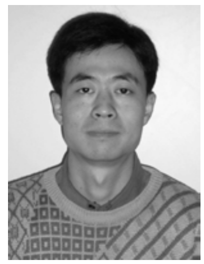

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