*Progress In Electromagnetics Research Letters, Vol. 46, 89–94, 2014*

# A Novel Defected Ground Structure with Both Adjustable Center Frequency and Reconfigurable Bandwidth

**Xue Cao[1], Kai-Yu Zhao[2], Li-Li Yang[3], and Lin Li[4, *]**

**Abstract**—A new defected ground structure (DGS) with tunable working frequency and reconfigurable bandwidth is proposed in this paper. The prototype combines the conventional DGS with T-shaped patch featuring narrow bandwidth and two such units located symmetrically featuring wide bandwidth. The proposed structure is designed, simulated and measured. By embedding two reversely-set PIN diodes and four varactors, the proposed structure achieves a narrow bandwidth with a tuning range of 21.1% and a wide bandwidth with a tuning range of 24.6%. In comparison, the bandwidth ($-10$ dB) is about 13.6% for the narrowband state and 49.2% for the broadband state, where an approximately 4-times extension is obtained.

## 1. INTRODUCTION

Recently, the defected ground structures (DGSs) show increasing potential in several microwave applications. Since the dumbbell-shaped cell in [1] was firstly proposed with good bandgap features and band-rejection property, various modified DGSs have been presented [2–5]. All these DGSs fail to meet the multi-functional requirements of modern telecommunication systems. Consequently, the reconfigurable or tunable DGSs are highly desirable in the recent research. In [6], the conventional dumbbell-shaped DGS was modified by adding a T-shaped patch in the middle of the defected holes which showed tunable bandstop characteristics, as shown in Figure 1. In [7], several tunable dumbbell-shaped DGS were proposed to achieve a tuning range extending to 19% using commercially available diode varactors. In [8], a barium-strontium-titanate (BST) varactor chip was deployed to tune the open loop slot DGS resonator which obtained the tunable center frequency from 4.5 to 5.5 GHz. Though the research on reconfigurable DGSs has made obvious progress, however, to the best of our knowledge, most of these DGSs with tunable functions focus on frequency tunability and few papers about the reconfigurable bandwidth have been published. Although there have been some structure focused on switchable band [9], there is hardly no report reconfigurable DGSs with the switching capability between the narrowband state and the broadband state.

In this paper, a novel reconfigurable DGS structure with two symmetrically-located and mutually-coupled DGSs is presented. Compared to the conventional reconfigurable DGSs, the proposed design not only embeds varactors to obtain tunable working frequency but also uses PIN diodes to achieve the conversion between narrow bandwidth and wide bandwidth. In addition, the proposed DC low voltage control circuit allows an easy way to avoid the interference between the microwave signal and the controlling current by using two reversely-placed PIN diodes. In the main analyzing part of this paper, different working states of this novel reconfigurable DGS are exposed by equivalent circuit models, thus it can be easily applied to other DGSs requiring reconfigurable performances.

*Received 3 April 2014, Accepted 21 May 2014, Scheduled 5 June 2014*
* Corresponding author: Lin Li (lilin_door@hotmail.com).
[1] Department of Communication Engineering, Zhejiang Sci-Tech University, Hangzhou, Zhejiang 310018, China. [2] Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90007, USA. [3] Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou, Zhejiang 310027, China. [4] Department of Electronic Engineering, Zhejiang Sci-Tech University, Hangzhou, Zhejiang 310018, China.

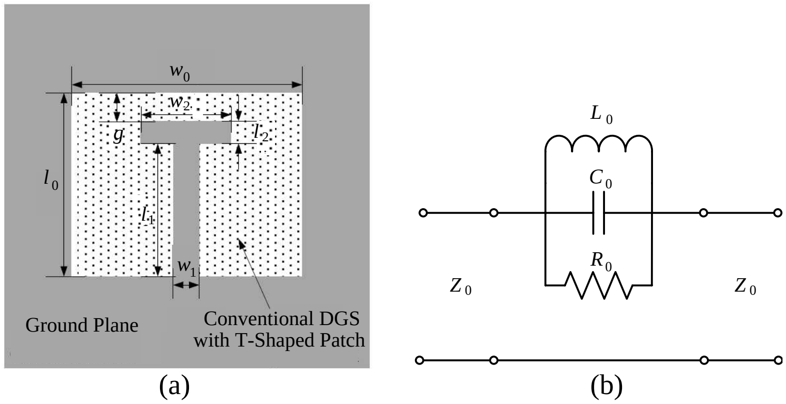


**Figure 1.** Conventional DGS with T-shaped patch. (a) Layout. (b) Its equivalent-circuit model.

## 2. DESIGN AND CHARACTERISTICS OF THE PROPOSED RECONFIGURABLE DGS

### 2.1. Basic Structures of Single DGS and Two Symmetrically-Located DGSs with Mutual Coupling

Figure 1(a) shows the conventional DGS with T-shaped patch in [6]. The frequency characteristic of the DGS can be modeled by its equivalent circuit, i.e., a parallel $R_0$, $L_0$ and $C_0$, as shown in Figure 1(b), which is similar to the presentation of the conventional DGS in [1].

The parameters of this equivalent circuit can be described as [5]:

$$C = \frac{\omega_c}{2Z_0\left(\omega_0^2 - \omega_c^2\right)} \tag{1}$$

$$L = \frac{1}{4\pi^2 f_0^2 C} \tag{2}$$

$$R = \frac{2Z_0}{\sqrt{\frac{1}{|S_{11}(\omega_0)|^2} - \left[2Z_0\left(\omega_0 C - \frac{1}{\omega_0 L}\right)\right]^2 - 1}} \tag{3}$$

where $\omega_0$ is the angular resonant frequency ($\omega_0 = 2\pi f_0$), $\omega_c$ the $-3\,\mathrm{dB}$ cutoff angular frequency, and $Z_0$ the characteristic impedance of the microstrip line. Thus, the relation among $R_0$, $L_0$, $C_0$ and $f_0$ can be easily drawn from (1), (2) and (3), which provides an applicable method to obtain the specific parameters for the lumped circuit of the proposed DGS.

Based on the above analysis for the single conventional DGS with T-shaped patch, the proposed structure with such two cells located symmetrically can be further explained. As shown in Figure 2(a), two identical DGSs are set in the opposite direction and separated by a metallic strip with the width of $s$. Considering the inductive mutual coupling between the adjacent DGS resonators [10], the equivalent lumped circuit is shown in Figure 2(b), where $L_0$ and $C_0$ are the self-inductance and self-capacitance respectively, and $L_{m0}$ represents the mutual inductance [11]. The magnetic coupling coefficient can be concluded as:

$$K_{m0} = \frac{L_{m0}}{L_0} = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \tag{4}$$

where $f_1$ and $f_2$ ($f_2 > f_1$) are two split resonant frequencies due to the mutual coupling [11]. To demonstrate the above analysis of the single DGS and two DGSs with mutual coupling, the sample units, as in Figures 1(a) and 2(a), have been simulated by using Ansoft HFSS. Figures 3(a) and 3(b) compare the simulated S21 by using HFSS and using the extracted lumped models for the two structures, respectively. In Figure 3(a), for the single DGS, good agreement can be seen that the resonant frequency. In Figure 3(b), however, for the two DGSs with mutual coupling, good agreement is seen at lower

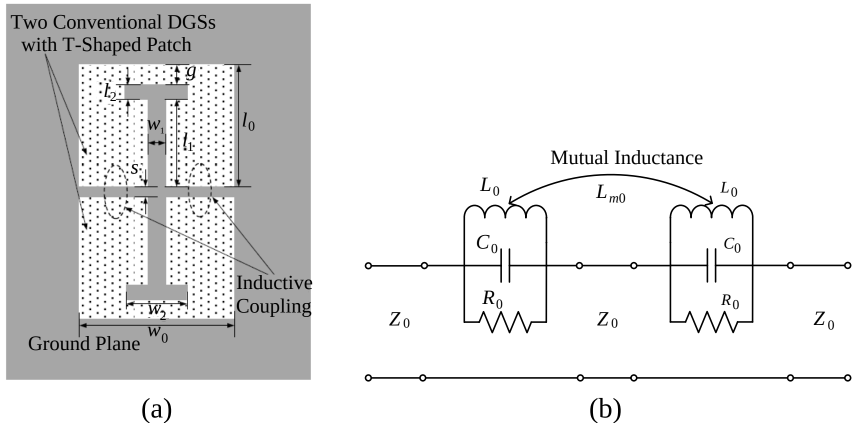


**Figure 2.** Two identical conventional DGSs with mutual coupling. (a) Layout. (b) Its equivalent-circuit model.

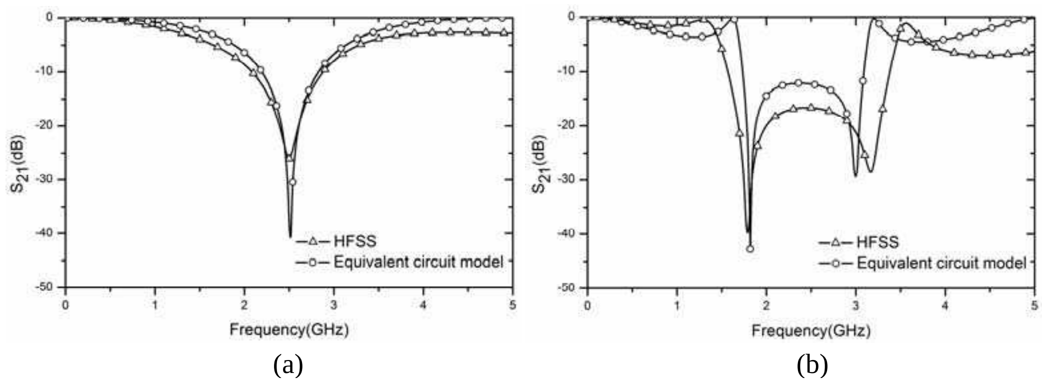


**Figure 3.** Comparison of the $S_{21}$ between the results by the full-wave simulation and the lumped models for: (a) single DGS, (b) two DGS with mutual coupling.

frequencies, but some discrepancies appear above 2.5 GHz. In the full-wave simulation, two split resonant frequencies of two DGSs with mutual coupling are $f_1 = 1.82$ GHz and $f_2 = 3.19$ GHz, respectively. The visible differences for the positions of $f_2$ and the value of $K_{m0}$ could be resulted from the simplicity of the equivalent lumped model that the distributed effects are not included in this model [10]. However, the broadband suppression behavior of the two DGSs with mutual coupling can still be predicted by this equivalent circuit model. Obviously, the single DGS achieves a narrow bandwidth, while the two DGSs with mutual coupling provide a wider bandwidth due to the coupling.

### 2.2. Reconfigurable Characteristics of the DGS

In order to obtain the proposed reconfigurable characteristics, the basic structures in Section A are modified. As shown in Figure 4, two reversely-placed PIN diodes, denoted as the PIN diodes group, are added and set across the gap between the edges of the lower T-shaped patch and the metallic ground plane. The reason not to apply a single PIN diode as a switch lies in that the PIN diode will be short-circuited by the metallic sides. An extra rectangular area with the size of $w_3 \times l_3$ is introduced set the PIN diodes appropriately in the microstrip configuration. Based on the assumption that the transmission lines are lossless and the on-resistance of PIN diodes is negligible, the whole structure can be defined by two states: firstly, two PIN diodes both conduct; secondly, two PIN diodes are both off.

For the first state of the PIN diodes group, the lower DGS with T-shaped patch is separated into two small identical parts. As a result, weak coupling between these two small parts is introduced. Accordingly, due to the effects of the PIN diodes group with ON state, the characteristic of the two DGSs in Figure 4 approximately returns to the narrowband state of the single DGS in Figure 3(a). For the second state, two PIN diodes are both off. Neglecting all the discontinuity effects, the expected

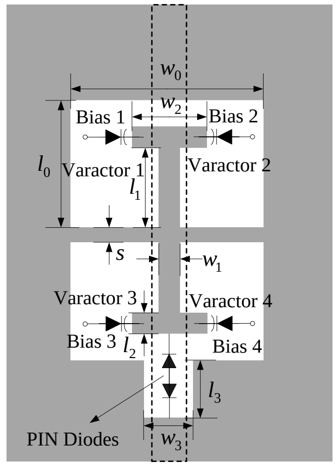


**Figure 4.** Layout of the proposed DGS with adjustable center frequency and reconfigurable bandwidth. ($l = 9.75\,\mathrm{mm}$, $w = 17\,\mathrm{mm}$, $l_1 = 8\,\mathrm{mm}$, $w_1 = 0.5\,\mathrm{mm}$, $l_2 = 1.2\,\mathrm{mm}$, $w_2 = 8\,\mathrm{mm}$, $l_3 = 3.75\,\mathrm{mm}$, $w_3 = 3\,\mathrm{mm}$, $s = 0.5\,\mathrm{mm}$ and $g = 0.55\,\mathrm{mm}$.).

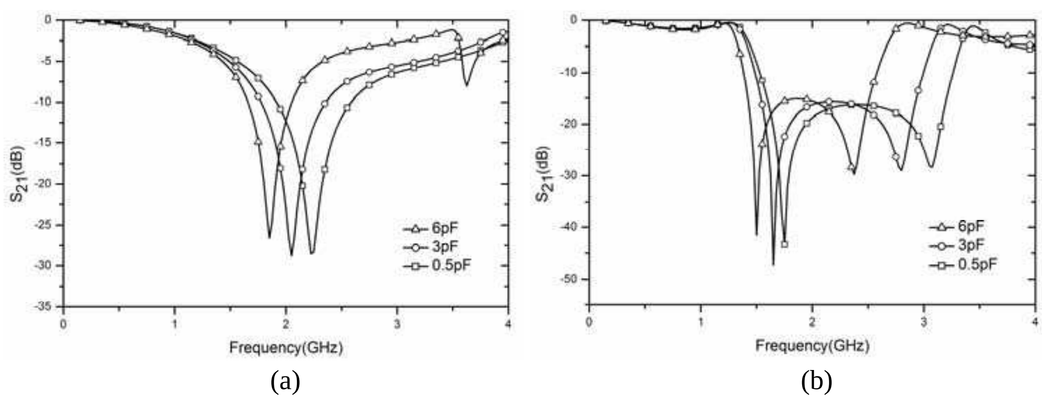


**Figure 5.** Simulated results for the proposed DGS with three different capacitance values of the varactors. (a) Two PIN diodes both ON. (b) Two PIN diodes both OFF.

performance should be the same as the structure in Figure 2(a), where a wide bandwidth was obtained. Thus the reconfigurable bandwidth of the structure can be achieved by modifying the ON and OFF states of the PIN diodes group.

Apart from the adjustable bandwidth, the proposed DGS can be further modified to obtain tunable working frequency by inserting varactors to each end of the arm of the T-shaped patch and applying DC biases at the open ends of the arms, as shown in Figure 4. The resonant frequency of the proposed cell shifts to lower range as the capacitance values of the varactors increase. Thus, with the varactors controlled electronically, the proposed characteristic of tunable resonant frequency can be achieved.

To demonstrate the above analysis of the proposed structure featuring both adjustable working frequency and reconfigurable bandwidth, the structure in Figure 4 was designed and simulated through Ansoft HFSS. The simulated results are plotted in Figure 5. In Figure 5(a), with two reversely-placed PIN diodes both on, the performance of the structure presents a narrow bandwidth with a single resonant frequency as expected. In addition, with four varactors controlled by a single biasing voltage, i.e., the DC biases 1 to 4 tuned simultaneously, the capacitances change from 0.5 pF to 6 pF and the resonant frequency shifts from 2.25 GHz to 1.85 GHz thus a 19.5% tuning range centered at 2.05 GHz is obtained.

In Figure 5(b), for the second state, i.e., two PIN diodes both off, the proposed structure is approximately equivalent to that in Figure 2(a). Similarly, as a result of the mutual coupling, a broadband performance with two resonant frequencies is obtained. Controlled by four varactors, the working frequencies can also be tuned. Thus a 21.6% tuning range centered at 2.18 GHz was obtained. Comparing the three curves of $S_{21}$ in Figures 5(a) and (b) respectively, it is obvious that the proposed structure in the second state broadens the bandwidth by creating an extra resonant frequency through mutual coupling.

## 3. EXPERIMENTAL RESULTS OF THE PROPOSED STRUCTURE

To demonstrate the feasibility of the above-mentioned method, the structure was fabricated and measured on a 0.5 mm substrate with a relative dielectric constant of 2.65 for an experimental demonstration, as depicted in Figure 6. Two Skyworks SMP1345-079LF PIN diodes are used as the switch to change the two working states and four high-performance Infineon BB837 vatactors with the minimum diode capacitance about 0.45 pF at 28 V are chosen to tune the working frequency. DC biases 1 to 4 are set to tune the voltage of varactors and DC bias 5 is to switch the ON and OFF states of the PIN diodes group. To avoid the interference between the microwave signal and the controlling current of varactors, RF chokes are needed between the DC voltage source and the RF current path, which are set on the signal plane to have minimum impact on the metallic ground plane, as shown in Figure 6(b).

The measured results are plotted in Figure 7 and carried out by Agilent E8358A Network Analyzer. Considering the maximum forward current of the BB837 vatactors, the tuning range for the DC controlling voltage of the varactors is set 1.4 V to 15 V and the corresponding capacitances of the varactors is about 6 pF to 0.7 pF. When the PIN diodes are both on, the center frequency of the narrow bandwidth can be tuned from 1.82 GHz to 2.25 GHz by four varactors, where a 21.1% tuning range is obtained, as shown in Figure 7(a). For the OFF state of the PIN diodes group, the center frequency of the wide bandwidth can be tuned from 1.78 GHz to 2.28 GHz and the tuning range is 24.6%, as shown in Figure 7(b). In addition, the bandwidth (−10 dB) is about 13.6% for the narrowband state and 49.2%

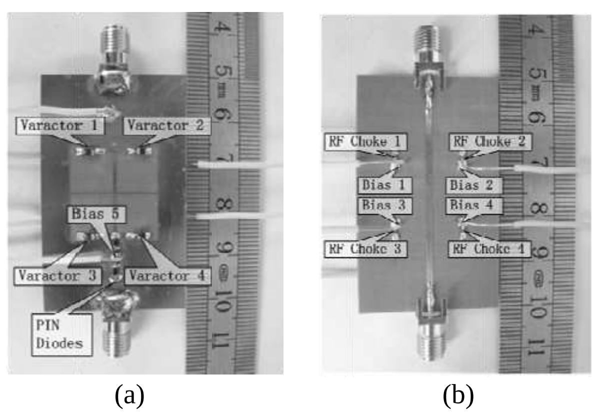


**Figure 6.** Proposed DGS with adjustable center frequency and reconfigurable bandwidth. (a) View of the ground plane. (b) View of the signal plane.

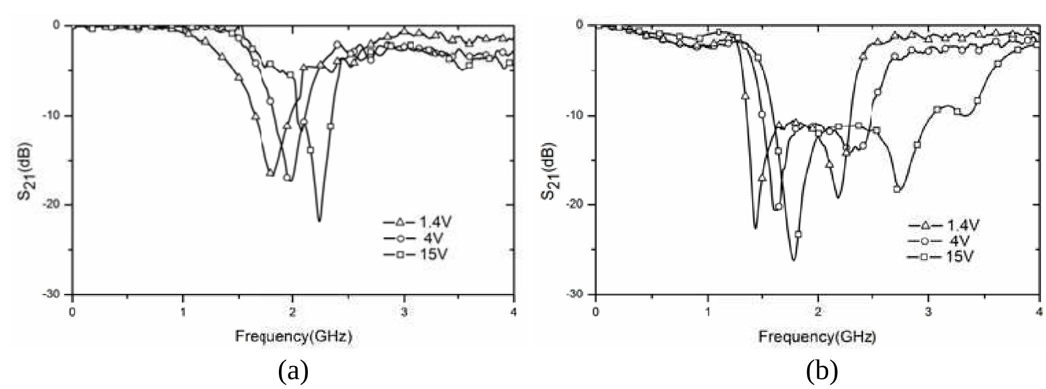


**Figure 7.** Measured results for the proposed DGS with three different biasing voltages of the varactors. (a) Two PIN diodes both ON. (b) Two PIN diodes both OFF.

for the broadband state, where a 4-times deference for the bandwidth is achieved. Due to the parasitic effect of varactors, there are visible spurious responses in the measured results, which are especially significant when the varactors are tuned to small capacitance value. However, the measured results are fully able to represent the expected results for the proposed DGS with both adjustable center frequency and reconfigurable bandwidth. Thus the designing method for the proposed structure is confirmed by the measurement.

## 4. CONCLUSION

A novel defected ground structure including two oppositely-located conventional DGSs with T-shaped patch is proposed in this paper. The proposed structure achieves a narrow bandwidth with a tuning range of 21.1% and a wide bandwidth with a tuning range of 24.6%, and presents an effective way to switch the coupling states between closely-located DGSs, thus it can be extended into other ranges of reconfigurable microwave components or antenna arrays.

## ACKNOWLEDGMENT

This work has been supported by the National Natural Science Foundation of China under grants (61101052).

## REFERENCES

1. Ahn, D., J.-S. Park, C.-S. Kim, J. Kim, Y. Qian, and T. Itoh, "A design of the low-pass filter using the novel microstrip defected ground structure," *IEEE Trans. Microw. Theory Tech.*, Vol. 49, No. 1, 86–93, Jan. 2001.
2. Lim, J. S., C. S. Kim, D. Ahn, Y. C. Jeong, and S. Nam, "Design of low-pass filters using defected ground structure," *IEEE Trans. Microw. Theory Tech.*, Vol. 53, No. 8, 2539–2545, Aug. 2005.
3. Mandal, M. K. and S. Sanyal, "A novel defected ground structure for planar circuits," *IEEE Microw. Wireless Compon. Lett.*, Vol. 16, No. 2, 93–95, Feb. 2006.
4. Geng, J. P., J. J. Li, R. H. Jin, S. Ye, X. L. Liang, and M. Z. Li, "The development of curved microstrip antenna with defected ground structure," *Progress In Electromagnetics Research*, Vol. 98, 53–73, 2009.
5. Woo, D. J., T. K. Lee, J. W. Lee, C. S. Pyo, and W. K. Choi, "Novel U-slot and V-slot DGSs for bandstop filter with improved $Q$ factor," *IEEE Trans. Microw. Theory Tech.*, Vol. 54, No. 6, 2840–2847, Jun. 2006.
6. Wang, X. H., B. Z. Wang, H. Zhang, and K. J. Chen, "A tunable bandstop resonator based on a compact slotted ground structure," *IEEE Trans. Microw. Theory Tech.*, Vol. 55, No. 9, 1912–1918, Sep. 2007.
7. Safwat, A. M., F. Podevin, P. Ferrari, and A. Vilcot, "Tunable bandstop defected ground structure resonator using reconfigurable dumbbell-shaped coplanar waveguide," *IEEE Trans. Microw. Theory Tech.*, Vol. 54, No. 9, 3559–3564, Sep. 2006.
8. Chun, Y.-H., J.-S. Hong, P. Bao, T. J. Jackson, and M. J. Lancaster, "Tunable slotted ground structured bandstop filter with BST varactors," *IET Microw. Antennas Propag.*, Vol. 3, No. 5, 870–876, 2009.
9. Mohamed, H. A., H. B. El-Shaarawy, E. A. Abdallah, and H. El-Hennawy, "Compact reconfigurable dual mode resonator with switchable band using RF PIN diodes," *PIERS Proceedings*, 1072–1076, Stockholm, Sweden, Aug. 12–15, 2013.
10. Wu, S.-J., C.-H. Tsai, T.-L. Wu, and T. Itoh "A novel wideband common-mode suppression filter for gigahertz differential signals using coupled patterned ground structure," *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 4, 848–855, Apr. 2009.
11. Hong, J.-S. G. and M. J. Lancaster, *Microstrip Filter for RF/Microwave Applications,* 245–249, Wiley, New York, 2001.