Effect of a Discrete PIN Diode on Defected Ground Structure

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***Abstract*—This paper investigates the effect of a discrete PIN diode on Defected Ground Structure (DGS) where the different resonant frequency between ON and OFF state of the PIN diode is observed. Analytical modeling is determined and analyzed based on equivalent circuit of PIN diode and DGS. Then, a circuit simulation is performed using simulation software with different value of inductance and capacitance of DGS during ON and OFF state of the PIN diode. As a result, the resonant frequency of the PIN diode on the DGS shifted to higher frequency during ON state and shifted to lower frequency during OFF state. Besides, a larger value of inductance with a smaller value of capacitance of DGS will produce a larger range of resonant frequency between ON and OFF state and vice versa.**

Keywords—defected ground structure; DGS; PIN diode; resonant frequency; RF switch

I. INTRODUCTION

Over the years, Defected Ground Structure (DGS) provides a significant advantage by extending its applicability such in amplifiers [1, 2], filters [3, 4], power dividers [5], couplers [6, 7], and switches [8-10]. DGS is implemented by modifying guided wave characteristics where it changes the propagation constant and realized by etching only a few areas on the ground plane under a microstrip line [11]. The previous research works in [12, 13] reported the effects of lumped element on DGS. The selected lumped elements are chip type resistor, inductor and capacitor. However, there are other active components such as PIN diode, varactor diode or transistor which can be investigated its effects on DGS.

Therefore, this paper investigates the effect of discrete PIN diode on DGS. Fig. 1 shows a discrete PIN diode where it is placed on the dumbbell shaped DGS. Theoretically, the inductance and capacitance of DGS should create resonant response with the PIN diode during ON and OFF state. Two squares of etched area represent inductance while a gap between two squares represents capacitance [11].The investigation is the resonant frequency of discrete PIN diode on DGS based on analytical modeling and circuit simulation.

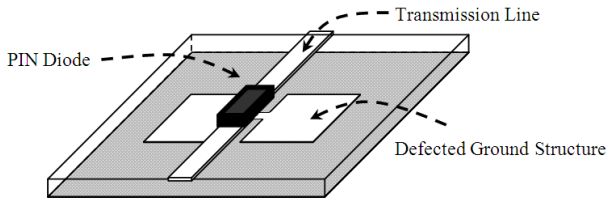


Fig. 1. Example of a discrete PIN diode on dumbbell shaped DGS.

II. ANALYTICAL MODELING

Fig. 2 shows the equivalent circuits of discrete PIN diode during ON and OFF state [14] on equivalent circuit of DGS [15, 16]. The total impedance of the equivalent circuit is derived. Then scattering parameter (S-parameter) between Port 2 and Port 1 (S_{21}) is explained using transmission (ABCD) matrix and conversion between ABCD to S-parameter in order to study the effect of discrete PIN diode on DGS.

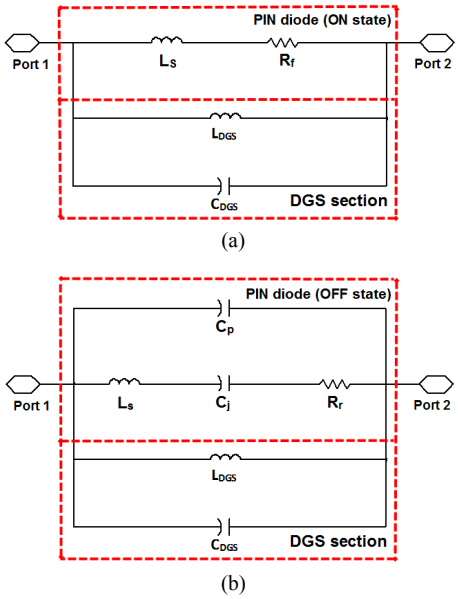


Fig. 2. Equivalent circuit of discrete PIN diode on DGS during (a) ON state and, (b) OFF state.

From Fig. 2(a) and 2(b), L_s and R_f denotes as a series inductance and forward resistance respectively during ON state while R_r is a reverse resistance and C_j is junction capacitance during OFF state of the discrete PIN diode. In DGS equivalent circuit, L_{DGS} and C_{DGS} refer to inductance and capacitance of DGS. Note that C_p value is very small, so it is neglected in analytical modeling. During ON or OFF state, the general total impedance of the equivalent circuit is

$$Z_T = R_T + j\omega L_T - \frac{j}{\omega C_T} \tag{1}$$

From (1), the total impedance of the equivalent circuit during ON state is

$$Z_{T(ON)} = \frac{1}{\frac{1}{j\omega L_D + R_D} - \frac{j}{\omega L_{DGS}} + j\omega C_{DGS}} \tag{2}$$

From (2), using ABCD matrix and conversion between ABCD to S-parameter the S_{21} is derived as

$$S_{21(ON)} = \frac{2}{2 + \frac{1}{\left(\frac{1}{j\omega L_D + R_D} - \frac{j}{\omega L_{DGS}} + j\omega C_{DGS}\right) Z_o}} \tag{3}$$

The same steps are used on the equivalent circuit during OFF state where

$$Z_{T(OFF)} = \frac{1}{\frac{1}{j\omega L_D - \frac{j}{\omega C_j} + R_D} - \frac{j}{\omega L_{DGS}} + j\omega C_{DGS}} \tag{4}$$

Then, from (4), the S_{21} is derived as

$$S_{21(OFF)} = \frac{2}{2 + \frac{1}{\left(\frac{1}{j\omega L_D - \frac{j}{\omega C_j} + R_D} - \frac{j}{\omega L_{DGS}} + j\omega C_{DGS}\right) Z_o}} \tag{5}$$

During OFF or ON state, by refering to (1), a resonant frequency of discrete PIN diode on DGS occurs when

$$j\omega L_T - \frac{j}{\omega C_T} = 0 \tag{6}$$

From (6), the resonant frequency can be calculated as

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_T}} \ Hz \tag{7}$$

From (3) and (5), it is found that the resonant frequency during ON and OFF state will be different to each other due to the presence of $C_j$during OFF state of PIN diode. Thus, the resonant frequency during OFF state is theoretically will be shifted to lower frequency due to larger value of C_T compared with resonant frequency during ON state.

III. Circuit Simulation

The circuit simulation is performed in Advanced Design System (ADS) software based on the equivalent circuit in Fig. 2(a) and 2(b). In the simulation, PIN diode model is based on commercialized PIN diode from NXP Semiconductors (part number: BAP64-02). The +5 V and -5 V of voltage supplies are used to turn ON and turned OFF the PIN diode respectively. The PIN diode model in ADS software has parameters of C_j= 0.35 pF, L_s= 0.6 nH, R_r= 5 Ω and R_f= 1 Ω.

For the equivalent circuit of DGS, it is well known that the effective inductance of the dumbbell shaped DGS pattern increases with larger square areas (*a* and *b*), while its effective capacitance increases with a narrower gap width in the middle (*g*) [17]. The DGS design is obtained through parametric study as reported in [18-19] since there is no specific synthesis to obtain the layout size of DGS. This technique is also very popular in antenna designs [20-22].

Therefore, inductance and capacitance of DGS are varied to be resonated at 4.0 GHz where five values of inductance are chosen; 10 nH, 8 nH, 6 nH, 4 nH and 2 nH. Then, the capacitance of DGS is tuned at 4.0 GHz. Fig. 3 shows simulation results of DGS at resonant frequency of 4.0 GHz. Table 1 shows the different values of inductor and capacitor at 4.0 GHz for Fig. 3.

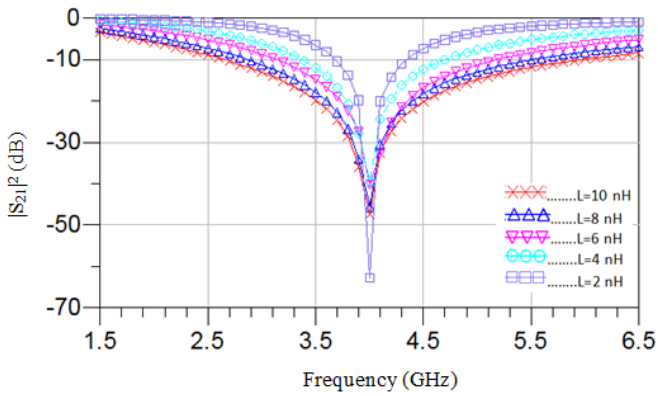


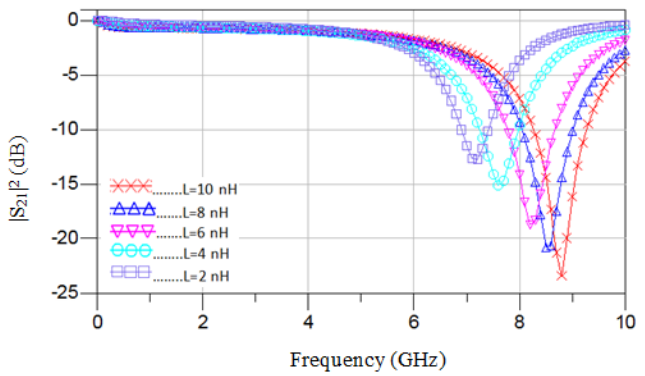
Fig. 3. Resonant frequency of DGS at 4.0 GHz.

TABLE I. Inductance and Capacitance of DGS at Resonant Frequency of 4.0 GHz

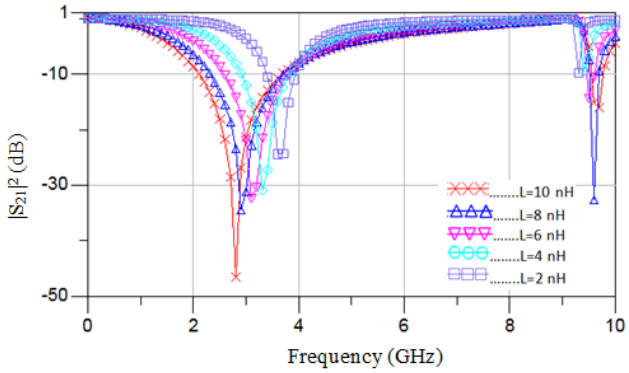
Values of Inductance and Capacitance of DGS	
Inductance, L (nH)	***Capacitance, C (pF)***
10.0	0.16
8.0	0.20
6.0	0.26
4.0	0.40
2.0	0.78

From Table I, values of L and C of DGS are used to investigate the resonant effect of PIN diode during ON and OFF state due to DGS. Thus, Fig. 4 shows the simulation results of discrete PIN diode on DGS during ON and OFF state.

It can be seen that different resonant frequencies are produced during ON and OFF state of PIN diode. During ON state, the resonant frequency is shifted to higher frequencies while during OFF state it is shifted to lower frequencies. Three samples are picked up from Fig. 4 to observe the different range of resonant frequency between ON and OFF state with different inductance and capacitance of DGS as shown in Fig. 5. The samples are taken for the largest, medium and small ranges of resonant frequencies.

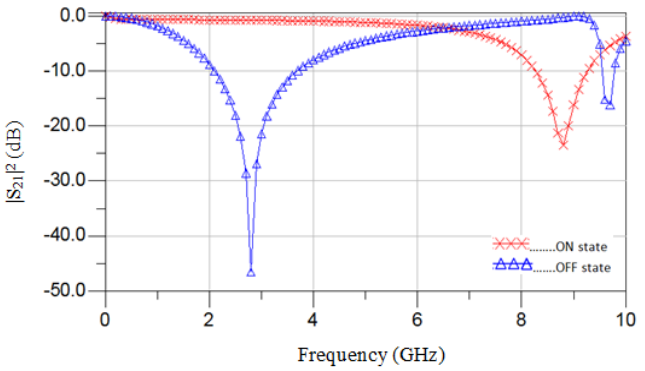


(a)

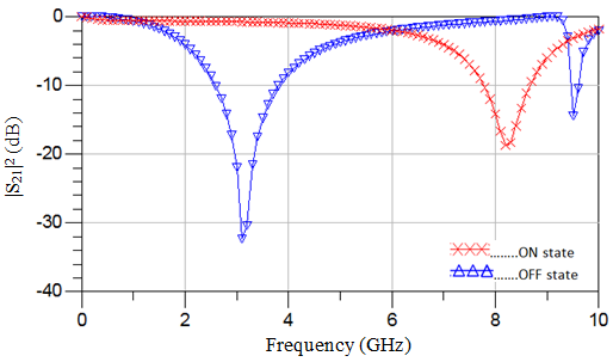


(b)

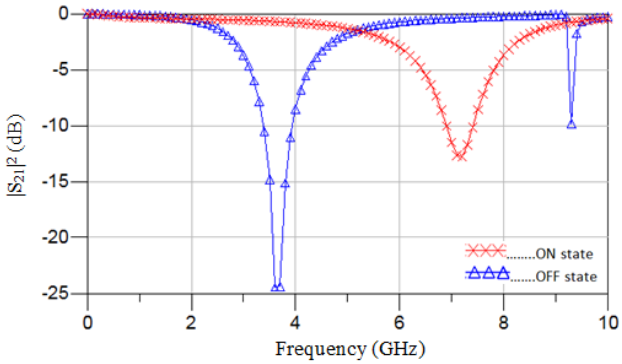
Fig. 4. Simulation results of equivalent circuit during (a) ON state and, (b) OFF state.



(a)



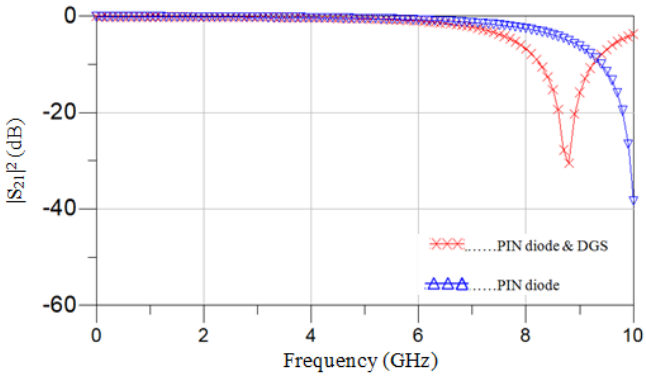
(b)



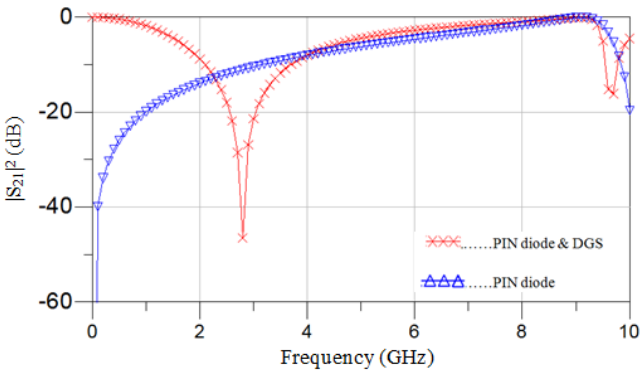
(c)

Fig. 5. Range of resonant frequency between ON and OFF state at different value of L and C of DGS; (a) L = 10 nH, C = 0.16 pF (b) L = 6 nH, C = 0.26 pF and (c) L = 2 nH, C = 0.78 pF.

To further the investigation, a circuit simulation is carried out to compare the performance of PIN diode with and without DGS during ON and OFF state. A pair of inductance, L = 10 nH and capacitance, C = 0.16 nH (refer Table I) is chosen to incorporate with the PIN diode model. Fig. 6 shows simulation results of PIN diode with and without DGS during ON and OFF state.



(a)



(b)

Fig. 6. Simulation results ofPIN diode with and without DGS during (a) ON state, and (b) OFF state.

IV. Discussion

From the simulation results in Fig. 4, 5 and 6, they are obviously seen that insertion loss is low during ON state because PIN diode has relatively small series resistance during

ON state which explains the low insertion loss[23].Furthermore, during ON state, it removes the parasitic capacitance and leaves PIN diode in low impedance state [24].

During OFF state, by incorporating DGS to PIN diode, it enhances the isolation performance of PIN diode where the DGS resonates out parasitic capacitance of PIN diode. It is shown in Fig. 6(b) where the circuit simulation of PIN diode with DGS (during OFF state) effectively improve isolation performance compare with PIN diode itself. Inductance and capacitance of DGS are able to resonate at any desired frequency as shown in Fig. 3.Note that the second resonance can be seen in Fig. 4 and 5. This scenario is not due to the effect of DGS but the characteristic of commercialized PIN diode from NXP Semiconductor.

In Fig. 4(a), during ON state, the resonant frequency has shifted to higher frequencies due to parallel L_s and L_{DGS} that produces smaller total inductance, L_T (refer Fig. 2(a)). In Fig. 4(b), during OFF state, the resonant frequency has shifted to lower frequencies due to parallel C_j and C_{DGS} that produces larger total capacitance, C_T (refer Fig. 2(b)). Besides, it can be observed that both Fig. 4(a) and 4(b) have different resonant frequency locations due to different values of L and C of DGS. Furthermore, the different values of L and C of DGS have produced different range of resonant frequency between ON and OFF state. In Fig. 5(a), 5(b) and 5(c), the range of resonant frequency between ON and OFF state are 6.8 GHz, 5.1 GHz and 3.6 GHz respectively. Thus, larger value of inductance with smaller value of capacitance of DGS (e.g. L = 10 nH and C = 0.16 pF) produces a larger range of resonant frequency between ON and OFF state.

V. FUTURE WORK

The next step is to verify this investigation with EM simulation and S-parameter measurement. The PCB substrate material will be based on FR4 material which is low cost as reported in [25, 26].In term of application, we found that it has a potential to be applied in RF switch design. Since the DGS is also acts as a resonator, it will have a similar solution for isolation improvement of FET or PIN diode switches as reported in [27-30]. The FET or PIN diode switches can be applied in wireless communication [31, 32], microwave imaging [33, 34] and test system [35, 36].

VI. CONCLUSION

Analytical modeling and circuit simulation of discrete PIN diode on DGS have been presented in order to investigate the resonant frequency of the circuit. Different value of inductance and capacitance of DGS are determined for different resonant frequency during ON and OFF state of PIN diode. Therefore, we conclude that resonant frequency of the PIN diode on DGS has shifted to higher frequency during ON state and shifted to lower frequency during OFF state. Besides, a larger value of inductance with a smaller value of capacitance of DGS produces a larger range of resonant frequency between ON and OFF state and vice versa.

ACKNOWLEDGMENT

We would like to acknowledge the contribution of our colleagues from Faculty of Electronics and Computer Engineering, UTeM of the research work. This work is funded by Fundamental Research Grant Scheme (FRGS), Ministry of Higher Education, Malaysia (project number FRGS/2012/FKEKK/TK02/03/2/F00128).

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