High Isolation of Single Pole Single Throw Switch using Defected Ground Structure

M. H. Abdul Hadi, B. H. Ahmad, Z. Zakaria, N. A. Shairi

Abstract*— *In this paper, a high isolation of Single Pole Single Throw (SPST) switch using Defected Ground Structure (DGS) is proposed. A discrete PIN diode was used as switching element in the SPST switch design. First, the resonant frequency of the discrete PIN diode on DGS, which is based on mathematical modeling and circuit simulation is analyzed. The results showed that the resonant frequency of the discrete PIN diode on the DGS was shifted to higher frequency during ON state and was shifted to lower frequency during OFF state. Then, by realizing the SPST switch circuit using FR4 substrate in 1.5 GHz frequency band, the measured result clearly showed that high isolation (>30 dB) of the proposed SPST switch during OFF state was produced by using DGS compared to a SPST switch without DGS.

Index Terms*—*defected ground structure (DGS), PIN diode, resonant frequency, isolation, RF switch, SPST switch.

I. INTRODUCTION

Until now, discrete PIN diodes are still desirable for higher power application used in military, satellite communication and base station [1]. In these applications, high isolation is one of the key parameters in RF switch designs. For low frequency application, especially in L-band (1 - 2 GHz) and S-band (2 - 4 GHz), the discrete PIN diodes are usually in standard packaging such as SOT23, SOT323, SOD323 or SOD523 [2]. As reported in [3], [4], it is difficult to get high isolation if using just a single discrete PIN diode in RF switch designs.

On the other hand, Defected Ground Structure (DGS) provides a significant advantage by extending its applicability such in filters [5], [6], power amplifiers [7], power dividers [8], switches [9], [10], and couplers [11]. DGS is implemented by modifying guided wave characteristics where it changes the propagation constant and it is realized by etching only a few areas on the ground plane under a microstrip line [12]. The previous research works in [13], [14] reported the effects of lumped element on DGS.

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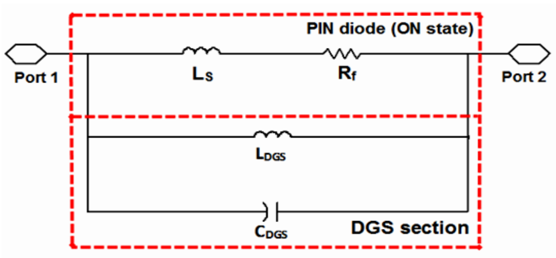
The selected lumped elements are chip type resistor, inductor and capacitor. However, there are other active components such as PIN diode, varactor diode or transistor that can be potentially investigated its effects on DGS. Therefore, this paper starts with the analyses of the resonant frequency of discrete PIN diode on DGS, which is based on mathematical modeling and circuit simulation. Theoretically, the inductance and capacitance of DGS could produce a resonant response with the PIN diode during ON and OFF states. This is due to the fact that in the square dumbbell shape of DGS, two squares of etched area represent as an inductance while a gap between two squares represents a capacitance [12]. Then, the high isolation of Single Pole Single Throw (SPST) switch using square dumbbell DGS is proposed. This could be one of the other techniques of isolation improvements such as material with fabrication process design, circuit design, resonant circuit, transmission line and resonator [15]. Most of these techniques were applied in SPST and Single Pole Multi Throw (SPMT) switches.

This paper is organized as follows. In Section II, a discrete PIN diode on DGS is analyzed based on mathematical modeling and circuit simulation, while Section III presents the circuit realization of a SPST switch with DGS for high isolation performance. Then, followed by experimental results in Section IV. Finally, the future works and conclusion are in Section V and VI respectively.

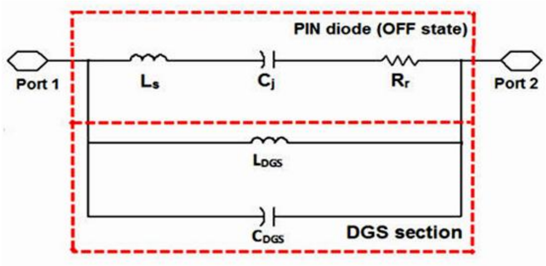
II. ANALYSES OF DISCRETE PIN DIODE ON DGS

The equivalent circuits of a discrete PIN diode during ON and OFF states [16] on the equivalent circuit of DGS [17] are depicted in Fig. 1. The total impedance of the equivalent circuit was derived using equations of scattering parameter (*S*-parameter) and transmission (*ABCD*) matrix. Thus, in order to study the effect of discrete PIN diode on DGS, the *S*-parameter between Port 2 and Port 1, (S_{21}) in Fig. 1(a) and (b) is described based on *ABCD* matrix and the conversion between *ABCD* to *S*-parameter.

From Fig. 1(a) and (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 the DGS equivalent circuit, L_{DGS} and C_{DGS} are the inductance and capacitance of DGS.



(a)



(b)

Fig. 1. Equivalent circuit of discrete PIN diode on DGS during (a) ON state and, (b) OFF state

During ON or OFF state, the general total impedance of the equivalent circuit is

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

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

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

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

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

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

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

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

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

Meanwhile, by refering to (1), a resonant frequency of discrete PIN diode on DGS occurs when

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

Therefore, from (6), the resonant frequency can be calculated as

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

From (3) and (5), the resonant frequency during ON and OFF states would be a different resonant frequencies 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 would be shifted to lower frequency due to larger values of C_T compared to the resonant frequency during ON state.

In the next step, a circuit simulation was performed in Advanced Design System (ADS) software based on the equivalent circuits in Fig. 1(a) and (b). In the simulation, the PIN diode model was based on commercial PIN diode from NXP Semiconductors (part number: BAP64-02). The voltage supply of +5 V and -5 V were used to turned ON and turned OFF the PIN diode respectively. The PIN diode model has the parameters of $C_j = 0.35$ pF, $L_s = 0.6$ nH, $R_r = 5\ \Omega$ and $R_f = 1\ \Omega$.

Meanwhile, for the equivalent circuit of DGS, it is well known that the effective inductance of square dumbbell DGS increases with larger square areas (a and b), while its effective capacitance increases with a narrower gap width in the middle (g) [18] (see Fig. 5(b)). Therefore, the DGS design was only obtained through parametric studies as reported in [19], [20] and can be found in the other designs as well like antennas [21], [22] and microwave absorber [23]. This is due to no specific synthesis to obtain the actual layout size of the DGS.

The inductance and capacitance of the DGS were varied in the simulation to be resonating at 4.0 GHz where five values of inductance were chosen as follows; 10 nH, 8 nH, 6 nH, 4 nH and 2 nH. Then, the capacitance of the DGS was tuned at 4.0 GHz. Fig. 2 shows the simulated results for the resonant frequency of the DGS while Table I tabulates the calculated different values for the inductance and capacitance at 4 GHz.

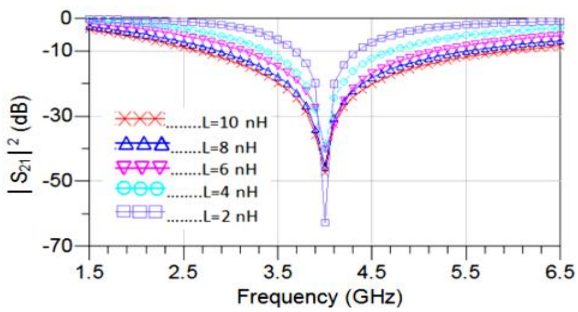
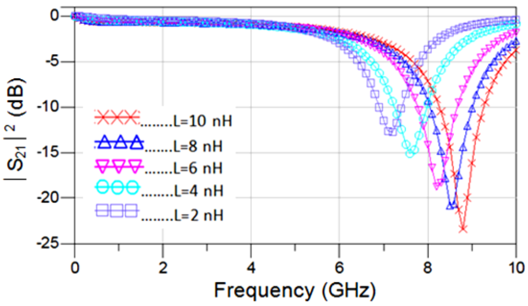


Fig. 2. Resonant frequency of DGS at 4.0 GHz with different values of inductance and capacitance according to Table I.

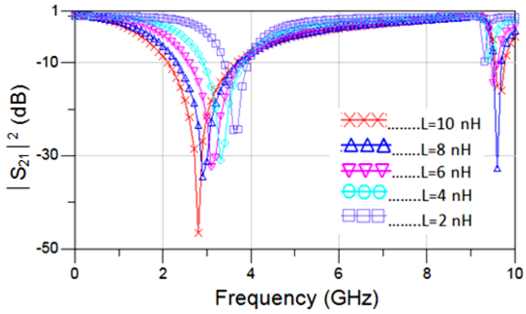
TABLE I. Inductance and capacitance values of DGS at resonant frequency of 4.0 GHz.

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, the values of *L* and *C* of DGS were used to investigate the resonant effect of the PIN diode model (BAP64-02) during ON and OFF states on DGS. Thus, Fig. 3 shows the simulation results of the discrete PIN diode on DGS during ON and OFF states. It was found that different resonant frequencies were produced during ON and OFF states of the PIN diode. During ON state, the resonant frequency was shifted to higher frequencies while during OFF state it was shifted to lower frequencies. During ON state (in Fig. 3(a)), the resonant frequency of the PIN diode on DGS had shifted to higher frequencies due to parallel L_s and L_{DGS} that produced smaller total inductance, L_T. In Fig. 3(b), during OFF state, the resonant frequency of the PIN diode on DGS had shifted to lower frequencies due to parallel C_j and C_{DGS} that produced larger total capacitance, C_T.



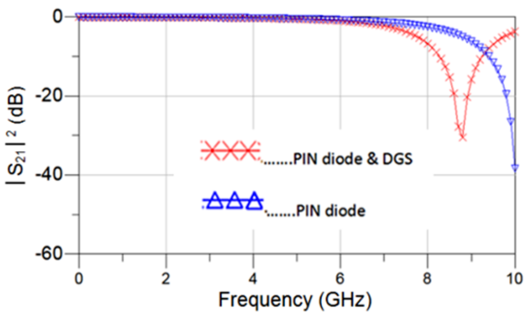
(a)



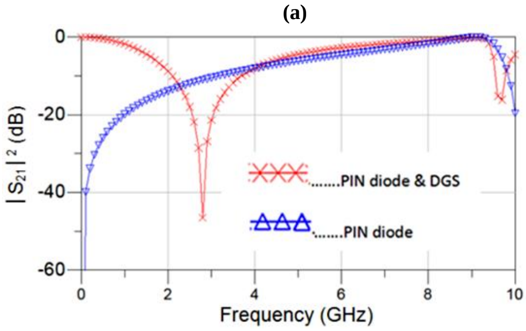
(b)

Fig. 3. Resonant frequency of equivalent circuit during (a) ON state and, (b) OFF state.

To further the analyses, a circuit simulation was carried out by comparing the performance of PIN diode with and without DGS during ON and OFF states. A pair of inductance, L = 10 nH and capacitance, C = 0.16 pF (refer Table 1) were chosen by incorporating it with the PIN diode. Hence, Fig. 4 shows the simulation results of PIN diode with and without DGS during ON and OFF states.



(a)



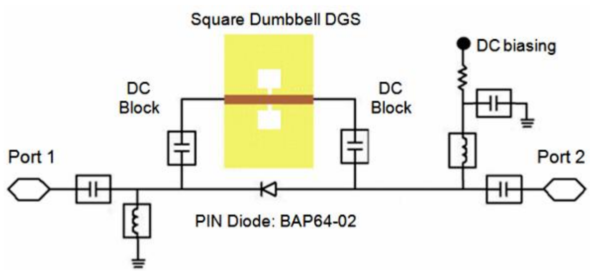
(b)

Fig. 4. Response of S_{21} of PIN diode with and without DGS during (a) ON state, and (b) OFF state.

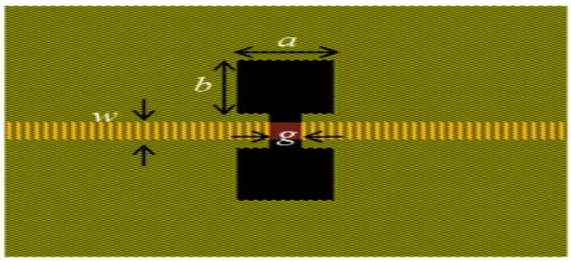
At low frequencies (e.g. 1 to 5 GHz), it obviously showed that the insertion loss was low during ON state (in Fig. 4(a)). This is due to the fact that the insertion loss of PIN diode is depending on the series resistance during ON state whereby it has a relatively small series resistance value. Meanwhile, as shown in Fig. 4(b) the circuit simulations of PIN diode on DGS (during OFF state) effectively improved the isolation performance compared to PIN diode itself (at low frequencies from 2 to 4 GHz) . This is due to larger values of C_T (the total capacitance of C_j and C_{DGS}) as compared to the resonant frequency during ON state. The detailed analyses of the discrete PIN diode on DGS were reported in [24].

III. SPST Switch Design

According to the analyses results in the previous section, several possible circuits of SPST switch with DGS were designed based on the equivalent circuit. The most practical and successful realization of the circuit is illustrated in Fig. 5(a). The SPST switch was realized using a discrete PIN diode (BAP64-02) that connected in parallel with square dumbbell DGS by positioning it side-by-side to each other. It was fabricated on FR4 substrate with thickness of 1.6 mm and relative dielectric constant, ε_r of 4.7.



(a)



(b)

Fig. 5. (a) Circuit diagram of SPST switch with square dumbbell DGS and (b) the 2D view of square dumbbell DGS in ADS software.

The square dumbbell DGS (see Fig. 5(b)) was designed as a layout and simulated in 2D electromagnetic (EM) simulator in the ADS software. All the FR4 substrate parameters were included in the substrate model of the layout. The selected square dumbbell DGS layout was obtained through parametric studies. The DGS is placed on the ground plane under the microstrip line where w denotes the width of microstrip line. The isolation performance simulation was run in the ADS software by applying voltage of +10 V and 0 V for ON state and OFF state on the SPST switch circuit respectively.

Finally, the proposed SPST switch was fabricated for verification with simulation results. Fig. 6 shows a photograph of fabricated SPST switch with square dumbbell DGS. The selected resonant frequency of the fabricated square dumbbell DGS was at 4 GHz. Based on the parametric studies in the simulation, there are several different sizes of the area and the gap of the square dumbbell DGS that could be resonated at 4 GHz. Therefore, the dimensions of the square dumbbell DGS; $a = b = 6$ mm and $g = 1$ mm were chosen in the experimental work of the proposed SPST switch circuit.

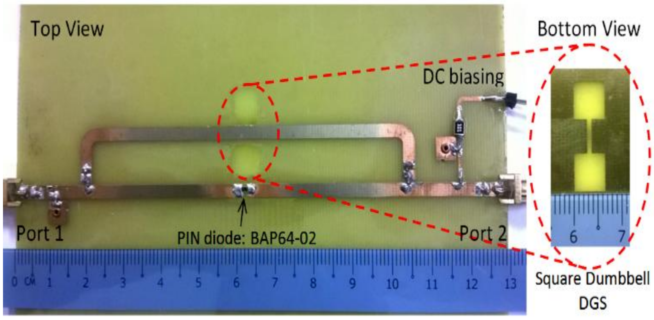
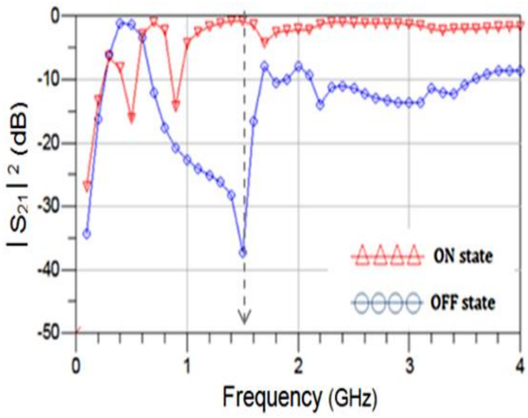


Fig. 6. Photograph of SPST switch with square dumbbell DGS (top and bottom view).

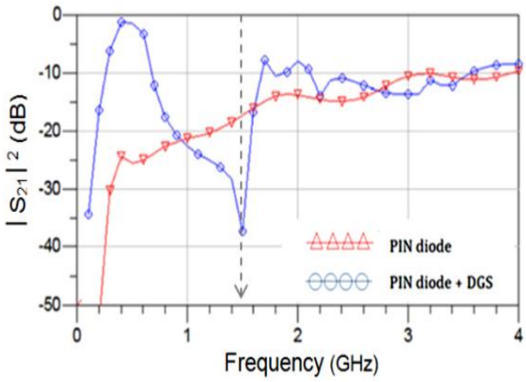
IV. Experimental Results

Fig. 7(a) and 8(a) show the simulation and measurement results respectively for the SPST switch with square dumbbell DGS during ON and OFF states. Meanwhile, Fig. 7(b) and 8(b) show the isolation performance of the SPST switch (during OFF state) with and without square dumbbell DGS.

It showed that both the simulation and measurement results at 1.5 GHz in Fig. 7(a) and Fig. 8(a) have shown a low insertion loss during ON state and a high isolation (> 30 dB) during OFF state. As depicted in Fig. 7(b) and Fig. 8(b), the isolation of the SPST switch with square dumbbell DGS is higher than the SPST switch without DGS. Although the isolation of the measurement result is lower than the simulation result, it is still higher than 30 dB.

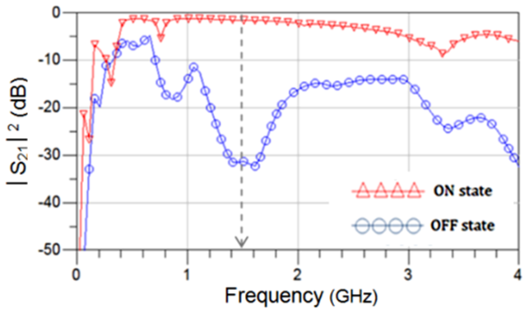


(a)

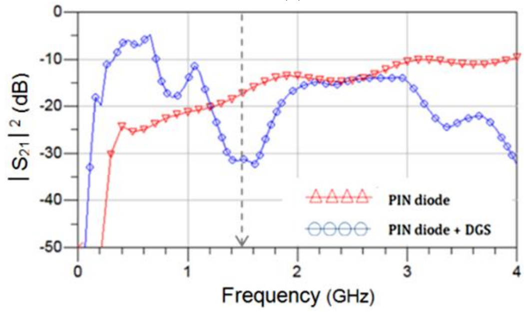


(b)

Fig. 7. Simulation results of (a) the SPST switch with DGS during ON and OFF states, (b) the SPST switch (OFF state) with and without DGS.



(a)



(b)

Fig. 8. Measurement results of (a) the SPST switch with DGS during ON and OFF states, (b) the SPST switch (OFF state) with and without DGS.

If compared the results in Fig. 7(b) and Fig. 8(b) with (5), it was proven that during OFF state, the presence of C_j in the discrete PIN diode during OFF state would cause the resonant frequency of the DGS (at 4 GHz) be shifted to lower frequency due to larger values of total capacitance ($C_j + C_{DGS}$). The comparison of the simulation and measurement result of isolation at 1.5 GHz is shown in Table II.

TABLE II. Comparison of isolation between simulation and measurement at 1.5 GHz

SPST Switch	Simulation	Measurement
Discrete PIN Diode	17.3 dB	18.6 dB
Discrete PIN diode with square dumbbell DGS	37.3 dB	31.3 dB

V. Future Works

This work could be further extended for high isolation of Single Pole Double Throw (SPDT) switch as reported in [25], [26]. To reduce the circuit size of the proposed SPST switch, the DGS structures that reported in [27], [28] could be used in the design.

Moreover, the authors in [29], [30] had demonstrated that the DGS was implemented successfully in monolithic microwave integrated circuit (MMIC) or radio frequency integrated circuit (RFIC). Thus, for application in the millimeter wave region, this work is recommended to be implemented in MMIC or RFIC technology. Moreover, the proposed SPST switch with DGS has a potential to be used as RF switches in test instruments [31]–[33], microwave imaging devices [34], [35], and wireless data communications [36]–[38].

VI. CONCLUSION

The mathematical modeling and its circuit simulation of discrete PIN diode on DGS have been carried out in order to investigate the resonant frequency response of the circuit. As results, different resonant frequencies during ON and OFF states were produced due to the presence of C_j during OFF state of the discrete PIN diode. The resonant frequency during OFF state shifted to lower frequency due to larger values of C_T (the total capacitance of C_j and C_{DGS}) as compared to the resonant frequency during ON state. Based on these analyses, it has been proposed for high isolation of SPST switch using DGS The proposed SPST switch was realized in ADS software using discrete PIN diode model and square dumbbell DGS layout for analysis of isolation performance simulation. Further verification was made by fabricating the proposed circuit using FR4 substrate and measured using microwave network analyzer. Therefore, from the simulation and measurement results, this work successfully demonstrated that the square dumbbell DGS could be used to produce a high isolation of SPST switch during OFF state.

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