High isolation of SPDT PIN diode switch using switchable dumbbell-shaped DGS in millimeter wave 28 GHz band

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ABSTRACT

This paper proposes a high isolation of single pole double throw (SPDT) PIN diode switch using switchable dumbbell-shaped defected ground structure (DGS). The proposed SPDT switch was designed for radio frequency (RF) front-end transceiver of antenna array multiple input multiple output (MIMO) in millimeter wave 28 GHz band. The switchable dumbbell-shaped DGS can be switched between allpass and bandstop responses where the bandstop response of the DGS can be utilized as a high isolation in the SPDT PIN diode switch circuit. A simple mathematical analysis is explained in this paper for the bandstop and allpass responses of the switchable dumbbell-shaped DGS. The propose SPDT switch was designed based on Roger RT/Duroid 5880 with 0.254 mm thickness and relative dielectric constant of 2.2. The simulated result showed that the proposed SPDT PIN diode switch produced an isolation of 36.36 dB at 27.3 GHz (center of 28 GHz band), which was 63% higher than the conventional SPDT design.

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1. INTRODUCTION

Single pole double throw (SPDT) switches are commonly used in radio frequency (RF) front-end systems of wireless communication. Its function is to switch between transmit and receive modes in time division duplex (TDD) communications as shown in Figure 1. This is an example use of the SPDT in RF phased–arrays for millimeter wave 5G applications [1]. High isolation is needed between transmitter and receiver where it is one of the key parameters in SPDT switch designs to minimize any high RF power leakage between transmitter to receiver. If the SPDT switch is unable to minimize the RF power leakage, it could distort the active circuits of the receiver, especially low noise amplifier (LNA).

In defected ground structure (DGS) design, currently it is commonly used in the application such as antennas [2]–[4], microwave filters [5]–[7], and the latest trend in microwave sensors [8], [9]. The progression of research works on the DGSs in RF and microwave for the last 10 years have shown evidences of improvement towards design realizations and performances. DGS has several advantages on the circuit design performances such as return loss or impedance matching improvement [10]–[12], unwanted frequency suppression [13]–[15], bandwidth enhancement of antennas [16], [17], size compactness [18], [19], high power handling capability [20], isolation in antenna designs [21]–[23], and compensating parasitic capacitance of switching element to improve isolation [24], [25].

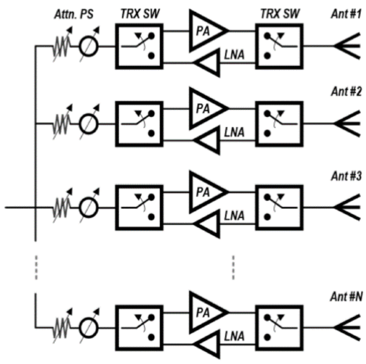


Figure 1. SPDT switch (TRX SW) in RF phased-arrays for millimeter wave 5G applications [1]

Therefore, in the application of RF front-end transceivers for antenna array multiple input multiple output (MIMO) [1], [26], this paper proposes an SPDT PIN diode switch design using switchable dumbbell-shaped DGS in millimeter wave 28 GHz band. The switchable dumbbell-shaped DGS is designed to be switched between allpass and bandstop responses where the bandstop response of the DGS can be utilized as a high isolation in the SPDT PIN diode switch circuit. As a background study, in RF switch designs using PIN diodes, high isolation can be easily obtained by focusing on the different circuit topologies as reported in [27]. Other high isolation techniques are discussed in [28] such as material with fabrication process design, resonant circuit, transmission line, and resonators. Besides, in this paper, for the high isolation performance comparison, a conventional series SPDT PIN diode switch was designed and simulated as a reference to the proposed SPDT switch.

2. THEORY AND CIRCUIT DESIGN

The theory and circuit design of switchable dumbbell-shaped DGS are explained and discussed. The discussion includes the mathemathical analysis of bandstop and allpass responses. Then followed by the discussion on the circuit design for the conventional and proposed SPDT switches.

2.1. Switchable dumbbell-shaped defected ground structure

Figure 2 is a proposed switchable dumbbell-shaped DGS. As shown in Figure 2(a), the switching of the dumbbell-shaped DGS is performed by using discrete PIN diode to allow the switching between bandstop and allpass responses. The DGS is located at the bottom layer of a printed circuit board (PCB). The dimensions of the proposed DGS are a=1.7 mm, b=0.24 mm, d=0.33 mm, m=1.13 mm, and n=1.6 mm. Capacitor (C) is used as a DC block to create a small positive (*+ve*) area of voltage supply to the anode of the PIN diode (D). The PIN diode is operated by two distinct states which are ON state (+5 V) for allpass response and OFF state (-5 V) for bandstop response.

Meanwhile, as shown in Figure 2(b), it is an equivalent circuit of the proposed DGS that consists of capacitor (*C*) and inductor (*L*) that paralleled with a PIN diode (*D*). This equivalent circuit can be used to mathematically analyze the bandstop and allpass responses. Therefore, according to Othman *et al*. [29] for the mathematical analysis of a bandstop response, the S_{21} of switchable dumbbell-shaped DGS (during OFF state of the PIN diode) was derived as (1):

$$S_{21} = \frac{2}{2+\frac{j\omega L}{(1-\omega^2 LC)Z_0}+Z_0} \qquad (1)$$

where Z_0 is a characteristic impedance of the input and output of the DGS. If Z_0=1 which is a normalize impedance, *L* and *C* will produce a bandstop response. Therefore, a resonant frequency is produced when:

$$j\omega L - \frac{j}{\omega C} = 0 \qquad (2)$$

For the allpass response, the proposed DGS is short circuited due to ON state of the PIN diode. Then, let C is zero and Z_0=1 (a normalized impedance). The S_{21} of (1) becomes (3):

$$S_{21} = \frac{2}{2+\frac{j\omega(0)}{(1-\omega^2(0)C)}+1} \approx 1 \tag{3}$$

From (3), it shows that an ideal zero insertion loss can be achieved, where allpass response is produced.

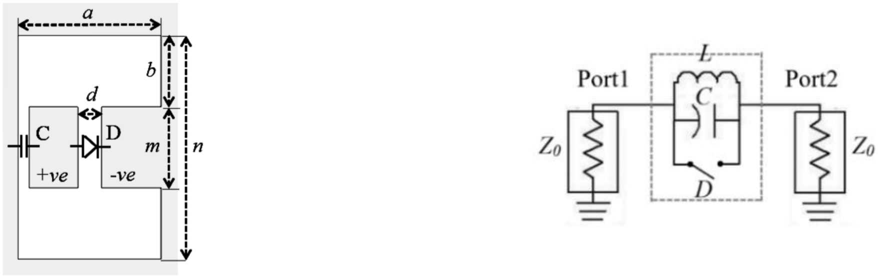


Figure 2. The proposed switchable dumbbell-shaped DGS, (a) bottom view of the layout and (b) its equivalent circuit

A complete switchable dumbbell-shaped DGS with biasing line is shown in Figure 3. The biasing line (at bottom layer) uses a wire bonding that is attached between copper layer (+*ve*) in the middle of the DGS and radial stub of the biasing line. Take note that the wire bonding is a part of the RF choke to block RF signals (particularly 28 GHz) from entering to the biasing line. The top layer is a microstrip line with 50 Ω impedance in 28 GHz band.

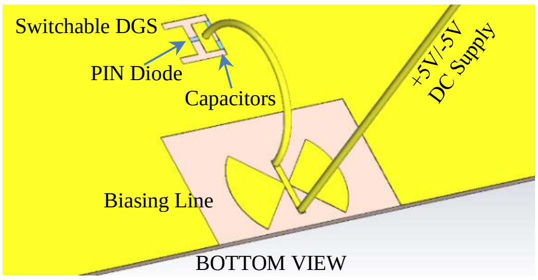


Figure 3. Three dimensional (3-D) of switchable dumbbell-shaped DGS with biasing line

2.2. Single pole double throw switch design

Figure 4 is SPDT switch circuit designs whereas depicted in Figure 4(a) is the conventional series SPDT switch and Figure 4(b) is the the proposed SPDT switch. To compare the proposed SPDT switch's isolation performance, the conventional series SPDT was designed and simulated. Figure 4(a) demonstrates how the isolation of the series SPDT switch in transmit mode (during which RF signals travel from port 1 to port 2) is entirely dependent upon the PIN diode's OFF state in the receiving arm. At the meantime, the PIN diodes on DGS is turned off in the transmit arm during transmit mode operation of the proposed SPDT switch Figure 4(b). The DGS then produce an allpass response. The PIN diode on DGS is turned ON in the receive arm. At this point, the DGS begin to produce a bandstop response. In the transmit mode, the isolation between port 3 and port 1 (S31) is depending on the bandstop response along with the OFF state of the PIN diode in the receiving arm.

RF signals travel from port 2 to port 3 during receive mode operation of the proposed SPDT switch. As a result, the PIN diode in the DGS is turned OFF in the receive arm. The DGS in the receiving arm then becomes an allpass response. The PIN diode in the DGS is turned ON while in the transmit arm. The DGS in the transmit arm then becomes a bandstop response. In this receive mode, the bandstop response along with the OFF state of the PIN diode in the transmit arm determines the isolation between port 1 and port 3 (S31). Table 1 provides a summary of these operations for the transmit and receive modes.

By using computer simulation technology (CST) software, the proposed SPDT switch circuit shown in Figure 4(b) was created. All the parameters of Roger RT/Duroid 5880 substrate such as relative dielectric constant of 2.2 and a thickness of 0.254 mm were included in the circuit design. The PIN diode model was based on MA4AGBLP912 by MACOM. The circuit was simulated for its insertion loss, return loss, and isolation. Figure 5(a) is the final layout of top view and Figure 5(b) is the final layout of bottom view with the total layout area of 62.03×29.86 mm.

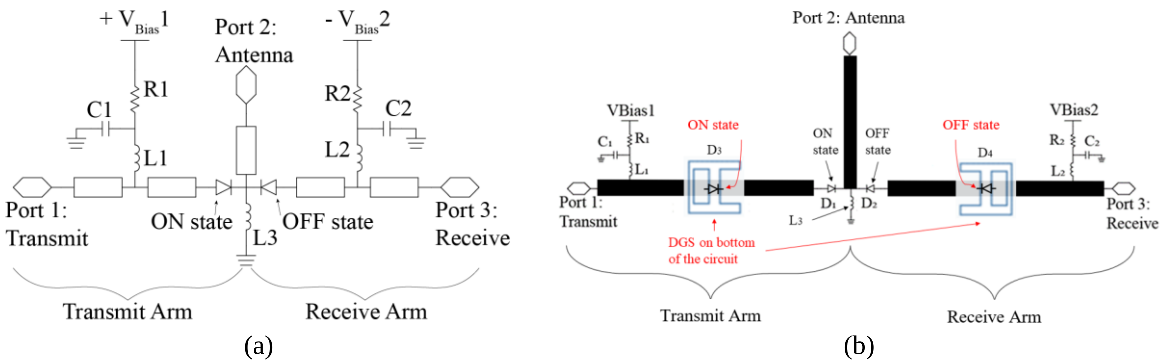


Figure 4. SPDT switch designs for; (a) conventional circuit and (b) proposed circuit

Table 1. Operation of transmit and receive modes in the proposed SPDT circuit design

	Transmit mode	Receive mode
$V_{Bias}1$	+5 V	-5 V
$V_{Bias}2$	-5 V	+5 V
Series PIN diode (transmit arm)	ON state	OFF state
Series PIN diode (receive arm)	OFF state	ON state
Switchable DGS (transmit arm)	Allpass response	Bandstop response
Switchable DGS (receive arm)	Bandstop response	Allpass response

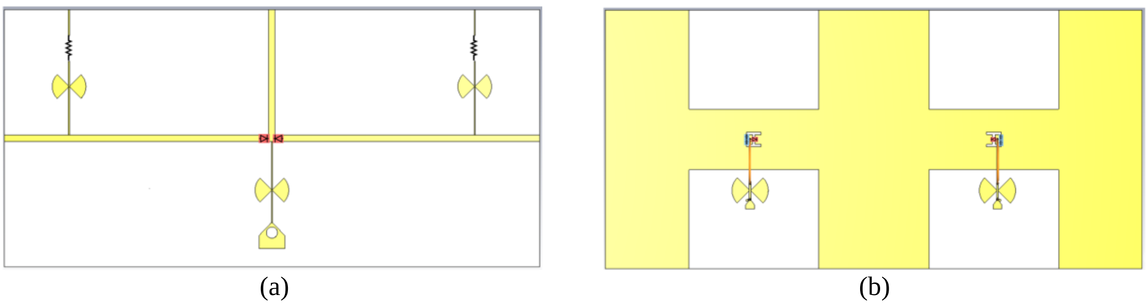


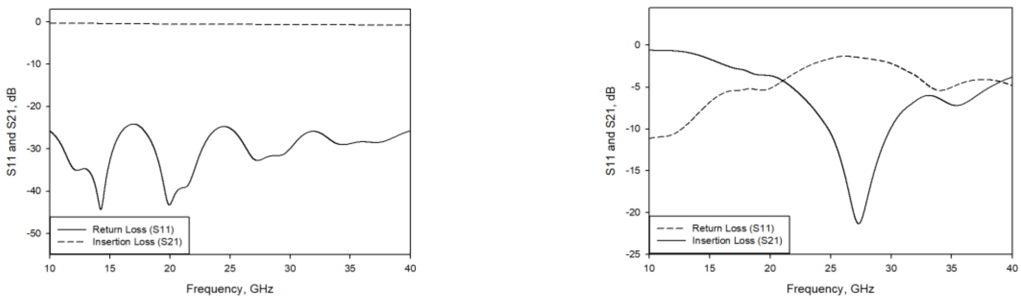
Figure 5. Final layout of the proposed SPDT switch, (a) top view and (b) bottom view

3. RESULTS AND DISCUSSION

Simulation results of the switchable dumbbell-shaped DGS were analyzed and discussed for the bandstop and allpass responses for verification with the mathematical analysis. Then followed by the analysis and discussion on the simulation results for the conventional versus proposed SPDT switches in terms of return loss, insertion loss and isolation.

3.1. Switchable dumbbell-shaped defected ground structure

By referring to the mathematical analysis in subsection 2.1, a simulation verification was done with the switchable dumbbell-shaped DGS (Figure 3). Thus, Figures 6(a) and (b) show the allpass and bandstop responses at 27.3 GHz. In Figure 6(a), the return loss (S11) was more than 20 dB and the insertion loss (S21) was less than 1 dB. While in bandstop response in Figure 6(b), the return loss (S11) was less than 1 dB and the attenuation (S21) was more than 15 dB in the 28 GHz band. This bandstop response was used as an isolation performance in SPDT switch.



(a) (b)

Figure 6. Switchable dumbbell-shaped DGS during; (a) allpass response and (b) bandstop response

3.2. Single pole double throw switch

In Malaysia, the 28 GHz band is in the range of 26.5 to 28.1 GHz. Thus, the performance results of the proposed SPDT switch are analyzed and discussed in this frequency range. Besides, in this paper, the performance results in transmit mode were discussed since the proposed SPDT circuit is symmetrical between transmit arm and receive arm.

As depicted in Figure 7, the simulated results of return loss in the conventional SPDT switch and the proposed SPDT switch were more than 10 dB from 26.5 to 28.1 GHz frequency. This showed that the proposed SPDT switch has the same return loss performance as the conventional SPDT switch. Meanwhile, as depicted in Figure 8, the simulated results of insertion loss (S21) for the proposed SPDT switch were slightly lower than the conventional SPDT switch with the difference around 0.9 dB. This is due to an additional circuit element of DGS in the SPDT switch circuit. By referring to Figure 9, it was found that the proposed SPDT switch produced better isolation (S31) which was more than 30 dB between port 3 to port 1 as compared to the conventional SPDT switch where the isolation was around 22 dB from 26.5 to 28.1 GHz. Take note that more than 25 dB isolation of SPDT switch was required to weaken any high RF power leakage between transmit and receive arms [30].

As shown in Table 2, the circuit performances of return loss, insertion loss and isolation between the proposed SPDT switch and conventional SPDT switch were compared. The comparison was made at the center frequency of 27.3 GHz in the 28 GHz band for 5G millimeter wave communications. For the isolation performance, there was 63% isolation improvement by using switchable dumbbell-shaped DGS as compared to the conventional SPDT switch.

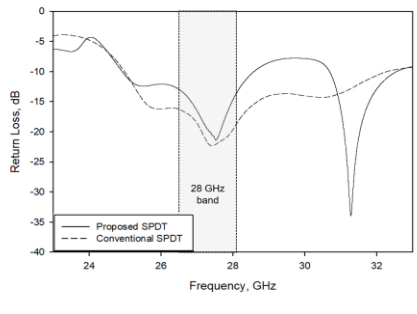


Figure 7. Simulated return loss (S11) result

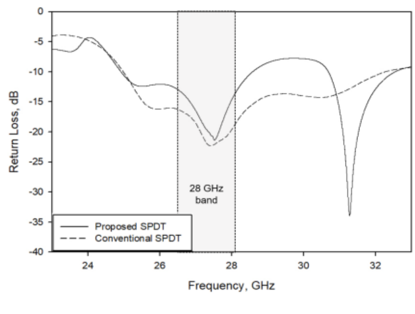


Figure 8. Simulated insertion loss (S21) result

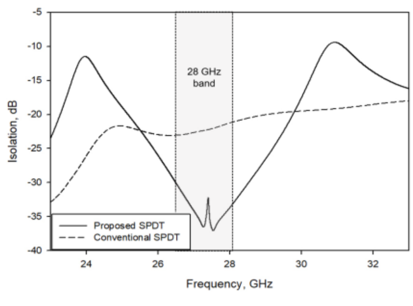


Figure 9. Simulated isolation (S31) result

Table 2. Circuit performance comparison for the proposed and conventional SPDT switch

	Return loss (S11) at 27.3 GHz, dB	Insertion loss (S21) at 27.3 GHz, dB	Isolation (S31) at 27.3 GHz, dB
SPDT switch with switchable dumbbell-shaped DGS	19.61	1.89	36.36
Conventional SPDT switch	21.76	0.95	22.31

4. CONCLUSION

The proposed SPDT PIN diode switch using switchable dumbbell-shaped DGS was designed and a simple mathematical analysis was discussed for the bandstop and allpass responses. The switchable dumbbell-shaped DGS was completely designed with biasing line for the PIN diode control between ON and OFF states. Then, the switchable dumbbell-shaped DGS was implemented in the SPDT switch circuit by considering the actual PCB using Roger RT/duroid 5880 and the PIN diode model of MA4AGBLP912 by MACOM. Simulated result showed that the proposed SPDT PIN diode switch using switchable dumbbell-shaped DGS produce high isolation as compared to the conventional SPDT switch (single series PIN diode).

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