SPDT discrete switch design using switchable SIW resonators for millimeter wave MIMO transceiver

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ABSTRACT

A single pole double throw (SPDT) discrete switch design using switchable substrate integrated waveguide (SIW) resonators is proposed in this paper. It was designed for the millimeter wave multiple input multiple output (MIMO) transceiver. An example application is for 5G communication in 26 GHz band. High isolation between transmitter and receiver (in the transceiver) is needed in SPDT switch design to minimize any high radio frequency (RF) power leakage in the receiver. Therefore, the use of switchable SIW resonators can achieve higher isolation if compared to the conventional series SPDT switch, where the isolation of the proposed SPDT is depend on the bandstop response of the SIW resonators. The switchable SIW resonators can be switched between allpass and bandstop responses to allow the operation between transmit and receive modes. As a result, the simulation and measurement showed that the proposed SPDT switch produced an isolation higher than 25 dB from 24.25 to 27.5 GHz compared to the conventional design.

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1. INTRODUCTION

In a front-end system of wireless communication, the single pole double throw (SPDT) switch is used to switch between transmit and receive modes in time division duplex (TDD) communication. As depicted in Figure 1, it is an example use of the SPDT in millimeter wave multiple input multiple output (MIMO) transceiver architecture [1]. This architecture is proposed for 5G millimeter wave communications where the SPDT switches need to be connected to 5G MIMO antennas [2], [3]. Therefore, the need for high isolation between transmitter and receiver is one of the key parameters in SPDT switch design to minimize any high radio frequency (RF) power leakage from transmitter to receiver that could distort the active circuits of the receiver, particularly low noise amplifier (LNA).

There are three techniques from literature that are mostly used to achieve high isolation in the design of SPDT switches; first, through configuration of the switch [4], [5]; second, switch element material and manufacturing process [6], [7]; and third, resonated switch element with inductance or capacitance elements [8], [9]. The first technique is widely used either by configuring it in the multiple cascaded shunt [4] or the combination of series and shunt elements [5], [10]. The multiple cascaded shunt SPDT is usually spaced with quarter wavelength of transmission lines and ideally used for high-power application. The key concern of this technique, however, is increasing the SPDT circuit size and consuming more current to turn-on the switch elements (eg. PIN diodes). For the second technique, an example can be found in [7], where high isolation of the SPDT switch is based on GaN high-electron mobility transistor (HEMT) technology with MOCVD-grown AlGaN/GaN heterostructure on 100-mm semi-insulating SiC substrates. These materials and modern manufacturing process, however, often complicate the process of fabrication and would increase the costs. Then, for the third technique, an example can be found in SPDT switch design for the improved isolation by using a section of transmission line (equivalent to capacitance) in series with a single shunt PIN diode [9]. This technique reduces the parasitic inductance in the PIN diode near the resonant frequency. As a result, at that specific frequency, it improves the isolation performance. This technique, however, limiting the isolation bandwidth because of the single resonant tank circuit of inductance and capacitance.

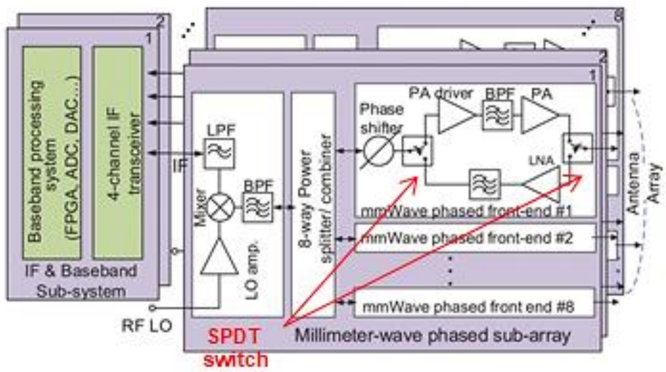


Figure 1. SPDT switch in a millimeter wave MIMO transceiver architecture [1]

In microwave and millimeter wave spectrums, substrate integrated waveguide (SIW) is found to be a suitable choice for designing and developing the components such as power divider [11], filter [12] and antenna [13]: because it has compact dimensions, low insertion loss, high-quality factor (QF), and can easily integrate with planar RF components [14]. On the other hand, there are several switchable designs for millimeter wave MIMO such as switchable diplexer [15], switchable low noise amplifier (LNA) [16] and switchable antenna [17]. Besides, our previous works proposed the use of switchable microstrip resonator in RF switch design (SPDT and DPDT) for isolation improvement [18], [19] and multiband isolation [20], [21].

Therefore, in the application of millimeter wave MIMO transceiver [1], this paper proposes a SPDT discrete switch design using switchable SIW resonators. The switchable SIW resonators can be switched between allpass and bandstop responses where the isolation of the SPDT depends on the bandstop response of the SIW resonators. The proposed SPDT switch is operated in 26 GHz band and targeted for millimeter wave MIMO transceiver for 5G communication. Besides that, a conventional series SPDT was designed and simulated as a reference to the proposed SPDT switch for isolation performance comparison.

2. CIRCUIT DESIGN

2.1. Switchable SIW resonator

The switching of the SIW resonator in Figure 2 is performed by using discrete PIN diode to allow the switching between bandstop and allpass responses. The bandstop of the resonator is operated due to the resonant frequency of quarter wavelength ($\lambda/4$) of the open stub SIW transmission line. The PIN diode is operated by two distinct states which are ON state (+5 V) and OFF state (- 5 V). The PIN diode of the SIW resonator is supplied with +5 V, which allows allpass response and is supplied with -5 V for switching to a bandstop response (for isolation performance).

In the SIW design, via holes form a major part of the SIW to realize the bilateral edge walls. Via holes are the most important discontinuities in multilayered circuits. Therefore, in designing via holes of the SIW resonator, the equations in [22] were used. The via hole dimension must follow the calculation of the diameter (d) of the via and the pitch (p) between the via. The calculated dimension is to ensure that the radiation leakage will be maintained at a very low amount and with that SIW can be designed almost similar to the conventional rectangular waveguide with the appropriate dimension of p and d.

For millimeter wave MIMO transceiver in 26 GHz band, four switchable SIW resonators as illustrated in Figure 3 that based on the design in [23]. These resonators (S1, S2, S3 and S4) are resonated at 24.25, 25.33, 26.42 and 27.5 GHz respectively. These resonant frequencies are expected to cover for 5G communication in 26 GHz band [24]. Each resonator is separated by an impedance inverter (k-inverter) which uses a quarter wavelength (λ/4) of microstrip lines (K1, K2 and K3). This circuit can be switched between bandstop and allpass responses by using PIN diodes (D1, D2, D3 and D4). The detailed operation of this circuit is reported and discussed in [23].

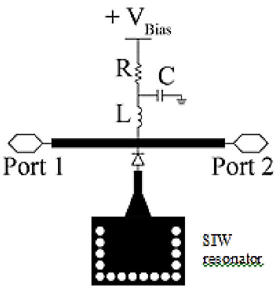


Figure 2. The proposed switchable SIW resonator

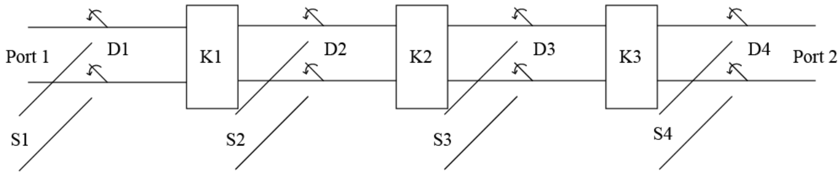


Figure 3. Equivalent circuit of allpass (OFF state) and bandstop (ON state) responses

2.2. SPDT switch design

The conventional series SPDT switch and the proposed SPDT switch are shown in Figure 4(a) and Figure 4(b) respectively. The conventional series SPDT was designed and simulated as a reference to the proposed SPDT switch for isolation performance comparison. As shown in Figure 4(a), during transmit mode (RF signals propagate from port 1 to port 2), the isolation of the series SPDT switch is totally depend on the OFF state of the series PIN diode in receive arm.

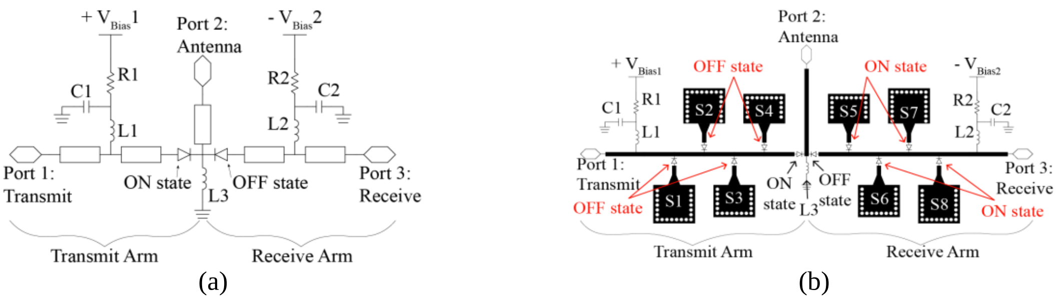


Figure 4. The (a) conventional series SPDT switch and (b) proposed SPDT switch

Meanwhile, during transmit mode operation of the proposed SPDT switch (Figure 4(b)), in the transmit arm, all PIN diodes on SIW resonators are turned OFF. Then, all the resonators in transmit arm become an allpass response. In the receive arm, all PIN diodes on SIW resonators are turned ON. Then, all the resonators in receive arm become a bandstop response. In this transmit mode, the isolation between port 3 and port 1 (S31) depends on the bandstop response and also the OFF state of the series PIN diode in the receive arm.

During receive mode operation of the proposed SPDT switch, RF signals propagate from port 2 to port 3. Therefore, in receive arm, all PIN diodes in SIW resonators are turned OFF. Then, all the resonators in receive arm become an allpass response. While in transmit arm, all PIN diodes in SIW resonators are turned ON. Then, all the resonators in transmit arm become a bandstop response. In this receive mode, the isolation between port 1 and port 3 (S31) depends on the bandstop response and also the OFF state of the series PIN diode in the transmit arm. These operations, for transmit and receive modes are summarized in Table 1.

The proposed SPDT switch circuit in Figure 4(b) was constructed in computer simulation technology (CST) software. All the parameters of Roger RT/duroid 5880 substrate such as thickness of 0.254 mm and relative dielectric constant of 2.2 were included in the microstrip line and the SIW model of the circuit design. The circuit was simulated in terms of insertion loss, return loss and isolation. For the actual fabrication and measurement, the commercial PIN diodes (MADP 000907-14020W) were used to control between transmit and receive modes. The fabricated of the proposed design is shown in Figure 5. The total layout area is 77×33 mm.

Table 1. Transmit and receive modes operation in the proposed SPDT switch

	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
SIW Resonators (transmit arm)	Allpass response	Bandstop response
SIW Resonators (receive arm)	Bandstop response	Allpass response

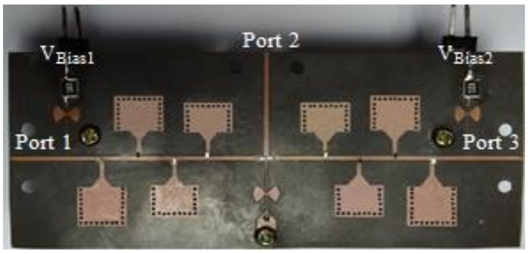
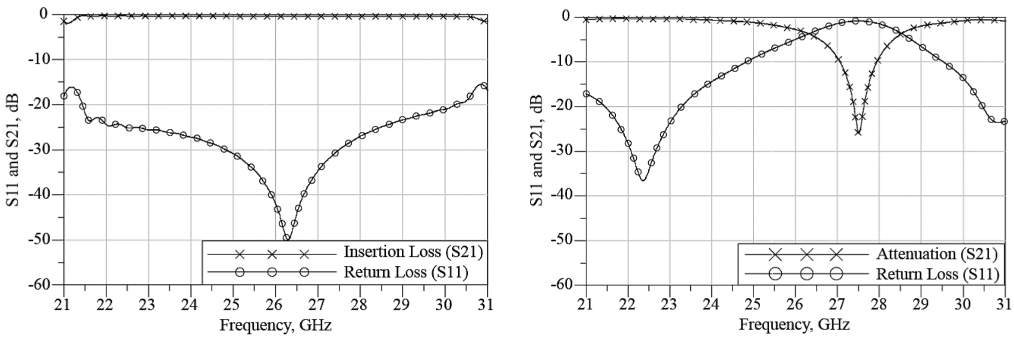


Figure 5. Prototype of the proposed SPDT switch with the total area of 77×33 mm

3. RESULTS AND DISCUSSION

3.1. Switchable SIW resonator

For better understanding of the characteristic of the switchable SIW resonator structure, the analysis was done with a single SIW resonator (Figure 2). The circuit configuration was simulated with a length of SIW resonator, *l*=4.8 mm (resonated at 27.5 GHz), the diameter of the via, *d*=0.75 mm and the pitch between the via, *p*=1.0 mm. Figures 6(a) and (b) show the allpass and bandstop responses at 27.5 GHz of the switchable SIW resonator. In Figure 6(a) (allpass), the return loss (S11) was more than 20 dB at 27.5 GHz 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 25 dB and the bandstop bandwidth of the resonator was around 2 GHz (at -3 dB). This bandstop response was used as an isolation performance in SPDT switch. Thus, higher isolation of SPDT switch could be achieved by properly design the structure of the SIW resonator.



(a) (b)

Figure 6. Switchable SIW resonator during (a) allpass response and (b) bandstop response

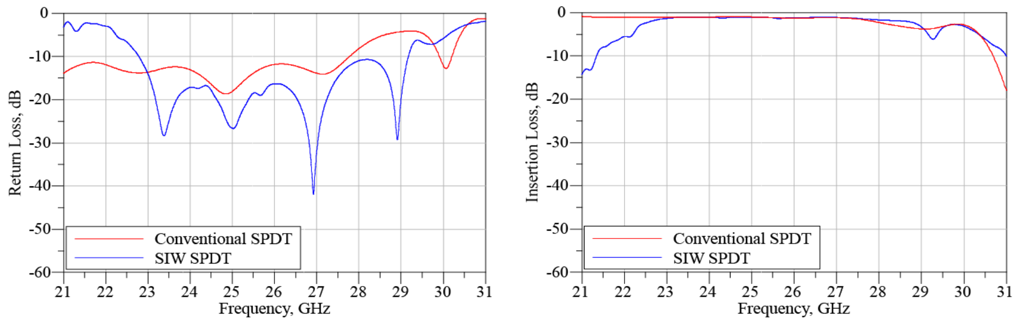
3.2. SPDT switch

Figures 7 and 8 are the simulated results of the conventional SPDT switch and the proposed SPDT switch for the return loss (S11), insertion loss (S21) and isolation (S31) respectively. The switch circuit is symmetrical between transmit arm and receive arm, hence only the performance results in transmit mode are discussed in this paper. Figure 7(a) shows the return loss (S11) for both SPDT switches in the transmit arm. The simulated results of return loss in the conventional SPDT switch and the proposed SPDT switch are more than 12 dB and 14 dB respectively from 24.25 to 27.5 GHz frequency. This showed that the proposed

SPDT switch exhibited better return loss performance compared to the conventional SPDT switch. As shown in Figure 7(b), the simulated results of insertion loss (S21) for the conventional SPDT switch and the proposed SPDT switch are almost the same response. For maximum power from transmit port to antenna port, it should have low insertion loss with an acceptable return loss. Thus, it can be seen that the SPDT switches managed to achieve less than 1.5 dB of insertion loss from 24.25 to 27.5 GHz frequency.

As depicted in Figure 8, it can be observed that the proposed SPDT switch managed to get better isolation (S31); more than 25 dB between port 3 to port 1 as compared to the conventional SPDT switch where the isolation was just around 15 to 18 dB from 24.25 to 27.5 GHz. As reported in [25], more than 25 dB isolation of SPDT switch is required for high power application to weaken any high RF power leakage between transmit and receive arms. Figure 9 shows the measurement results for the proposed SPDT switch. In the 26 GHz band (24.25 to 27.5 GHz), it managed to achieve more than 11 dB, less than 3.9 dB and more than 30 dB for return loss, insertion loss and isolation respectively. This shows that the measurement results were in good agreement with simulation results.

The circuit performance comparison between the proposed SPDT switch and conventional SPDT switch; and the comparison between simulation and measurement results for the proposed SPDT switch are listed in Table 2. The comparison was made at the center frequency of 25.875 GHz in the 26 GHz band for 5G millimeter wave communications. Therefore, the proposed SPDT switch design could be integrated with other millimeter wave sub-components such as antenna array [26], [27], bandpass filters [28], [29] and power amplifers [30], [31] for a complete system design of 5G millimeter wave communications as depicted in Figure 1.



(a) (b)

Figure 7. The (a) simulated return loss (S11) and (b) insertion loss (S21) results

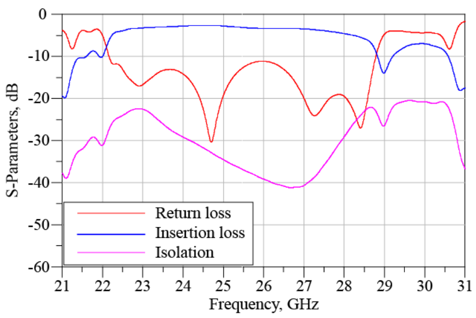


Figure 8. Simulated isolation (S31) results

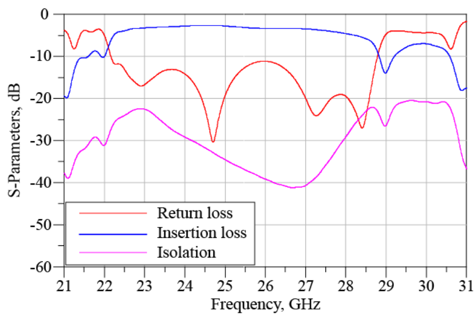


Figure 9. Measurement results (proposed design)

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

	Return Loss (S11) at 25.875 GHz, dB	Insertion Loss (S21) at 25.875 GHz, dB	Isolation (S31) at 25.875 GHz, dB
SPDT switch with switchable	16 (sim)	1.2 (sim)	42 (sim)
SIW resonators	11 (meas)	3.4 (meas)	38 (meas)
Conventional SPDT switch	12 (sim)	1.2 (sim)	17 (sim)

4. CONCLUSION

The SPDT discrete switch design using switchable SIW resonators was successfully designed and simulated in CST software. The isolation of the proposed SPDT switch and the conventional SPDT switch was compared where the different isolation performance between these two SPDT switch designs are very significant. The proposed SPDT switch was then fabricated for verification. It was successfully demonstrated that the proposed design produced isolation, higher than 25 dB in 26 GHz band (from 24.25 to 27.5 GHz) as compared to the conventional design.

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