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

Amirul Aizat Zolkefli¹, Badrul Hisham Ahmad², Noor Azwan Shairi³, Adib Othman⁴, Zahriladha Zakaria⁵, Imran Bin Mohd Ibrahim⁶, Huda Bin A. Majid⁷

¹²³⁵⁶Microwave Research Group (MRG), Centre for Telecommunication Research and Innovation (CeTRI), Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), Melaka, Malaysia
⁴Fakulti Teknologi Kejuruteraan Elektrik dan Elektronik (FTKEE), Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia
⁷Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia

Article Info

Article history:
Received Jan 20, 2021
Revised Oct 27, 2021
Accepted Nov 1, 2021

Keywords:
Millimeter wave
SIW resonator
SPDT switch
Substrate integrated waveguide
Switchable resonator

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 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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Corresponding Author:
Badrul Hisham Ahmad
Microwave Research Group (MRG), Centre for Telecommunication Research & Innovation (CeTRI)
Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100, Durian Tunggal, Melaka, Malaysia
Email: badrullisham@utem.edu.my

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]
SPDT discrete switch design using switchable SIW resonators for ... (Amirul Aizat Zolkefli)
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](image)

![Figure 3. Equivalent circuit of allpass (OFF state) and bandstop (ON state) responses](image)

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.

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 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

<table>
<thead>
<tr>
<th>Vbias,1</th>
<th>Transmit Mode</th>
<th>Receive Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>+5 V</td>
<td>+5 V</td>
<td>-5 V</td>
</tr>
<tr>
<td>-5 V</td>
<td>-5 V</td>
<td>+5 V</td>
</tr>
</tbody>
</table>

| 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 |

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.

![Figure 6. Switchable SIW resonator during (a) allpass response and (b) bandstop response](image)

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 discrete switch design using switchable SIW resonators for ... (Amirul Aizat Zolkefli)
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 amplifiers [30], [31] for a complete system design of 5G millimeter wave communications as depicted in Figure 1.

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

![Figure 8. Simulated isolation (S31) results](image)

![Figure 9. Measurement results (proposed design)](image)

<table>
<thead>
<tr>
<th></th>
<th>Return Loss (S11) at 25.875 GHz, dB</th>
<th>Insertion Loss (S21) at 25.875 GHz, dB</th>
<th>Isolation (S31) at 25.875 GHz, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPDT switch with switchable SIW resonators</td>
<td>16 (sim)</td>
<td>1.2 (sim)</td>
<td>42 (sim)</td>
</tr>
<tr>
<td>SIW resonators</td>
<td>11 (meas)</td>
<td>3.4 (meas)</td>
<td>38 (meas)</td>
</tr>
<tr>
<td>Conventional SPDT switch</td>
<td>12 (sim)</td>
<td>1.2 (sim)</td>
<td>17 (sim)</td>
</tr>
</tbody>
</table>

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.

ACKNOWLEDGEMENTS

The authors would like to greatly express their thanks and appreciation to the Centre for Research and Innovation Management (CRIM) and Universiti Teknikal Malaysia Melaka (UTeM) for their encouragement and help to complete this research work. The publication of this paper was funded under the research grant: PJP/2020/FKEKK/H123/S01721.

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**BIOGRAPHIES OF AUTHORS**

**Amirul Aizat Zolkefli** was born in Malaysia in 1996. He is a postgraduate student pursuing his Master’s degree in Electronic Engineering at Universiti Teknikal Malaysia Melaka (UTeM). His research interest is in RF and Microwave Engineering. Currently, he is doing research on SPDT switch by using discrete PIN diode and switchable SIW resonator for 5G millimeter wave communication.

**Badrul Hisham Ahmad** graduated with honours degree in Electronic and Communication Engineering from the University of Leeds, UK in 1998. He received the M.Sc. degree from University Kebangsaan Malaysia in 2003 and Ph.D. degree from University of Leeds, UK for a thesis on the design and development of SIW filters in 2008. He is also an active researcher with a good track record with a number of research projects in RF and Microwave Engineering. He has published more than 200 journals and conference proceedings. Currently he is a Professor of Microwave Engineering in Universiti Teknikal Malaysia Melaka since 2018.
Noor Azwan Shairi was born in Malaysia. He received the Bachelor in Engineering (Electrical–Telecommunication) and the Master in Electrical Engineering from Universiti Teknologi Malaysia (UTM), in 2002 and 2005, respectively. In 2015, he obtained his Ph.D. degrees from Universiti Teknikal Malaysia Melaka (UTeM) in the field of Electronic Engineering (RF and Microwave). He is currently a Senior Lecturer at the Fakulti Kejuruteraan Elektronik dan Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. His research interests are RF switches, switchable/tunable filters, microwave sensors, antennas & resonators.

Adib Othman was born in Malaysia in 1986. He is a PhD Candidate from Universiti Tun Hussein Onn Malaysia. He received the Bachelor of Engineering (Hons) Electrical from Universiti Teknologi MARA in year 2009. In 2015, he obtained his Master of Electrical Engineering in the field of Electromagnetic Compatibility from Universiti Tun Hussein Onn Malaysia. From 2015 to 2020, he was a lecturer at Fakulti Teknologi Kejuruteraan Elektrik dan Elektronik (FTKEE), Universiti Teknikal Malaysia Melaka (UTeM), Malaysia. His research interests are mainly focused on RF and Microwave Engineering.

Zahraida Zakaria was born in Johor, Malaysia. He received the B. Eng. and M. Eng. in Electrical and Electronic Engineering from the Universiti Teknologi Malaysia in 1998 and 2004 respectively, and the PhD degree in Electrical & Electronic Engineering from the Institute of Microwaves and Photonics (IMP), University of Leeds, United Kingdom in 2010. From 1998 to 2002, he was with STMicroelectronics, Malaysia where he worked as Product Engineer. He is currently a Professor at Faculty of Electronic & Computer Engineering, University Teknikal Malaysia Melaka (UTeM).

Imran Bin Mohd Ibrahim is Senior Lecturer at Universiti Teknikal Malaysia Melaka and now serve as Head of Microwave Research Group. He received his bachelor, master and doctoral degree from Universiti Teknologi Malaysia, all in electrical engineering, in 2000, 2005, and 2016, respectively. He served as faculty's first Deputy Dean (Research and Post Graduate Study) and contributed to the early development of research activities at faculty and institution. He has lead several grants from industry, government and university in antenna research and wireless communication. He is also a committee member to draft the Technical Code in 5G Safety Radiation to Malaysia Technical Standard Forum Berhad.

Huda Bin A. Majid received the Ph.D. degree in electrical engineering from the Universiti Teknologi Malaysia (UTM). He worked as a Postdoctoral Fellow with UTM for a period of one year. He is currently a Senior Lecturer with the Faculty Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia. He has published over 100 articles in journals and conference papers. His research interests include planar and flexible antennas, array antennas, reconfigurable antennas, metamaterial, and RF microwave and mm-wave devices.