

## **BANDSTOP TO ALLPASS RECONFIGURABLE FILTER TECHNIQUE IN SPDT SWITCH DESIGN**

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**Abstract**—In this paper, a bandstop to allpass reconfigurable filter technique is proposed in Single Pole Double Throw (SPDT) switch design. Proof of concept of the bandstop to allpass reconfigurable filter is presented. It is physically realized using transmission line and radial stub in 3.5 GHz band (3.4 to 3.6 GHz). The isolation, insertion loss and return loss of the SPDT switches are analyzed and to validate this technique the prototypes are fabricated using FR4 substrate with a thickness of 16 mm. A very good agreement is shown between the simulated and measured results. Using this technique, it is able to produce more than 30 dB isolation with minimum number of PIN diodes, thus reducing 42.7% of the total circuit size compared with conventional design. Besides, additional 22.9% of isolation bandwidth can be obtained with the use of radial stub compared with transmission line stub. The potential application of this SPDT switch is Time Division Duplex (TDD) switching for WiMAX and LTE communication system in the 3.5 GHz band.

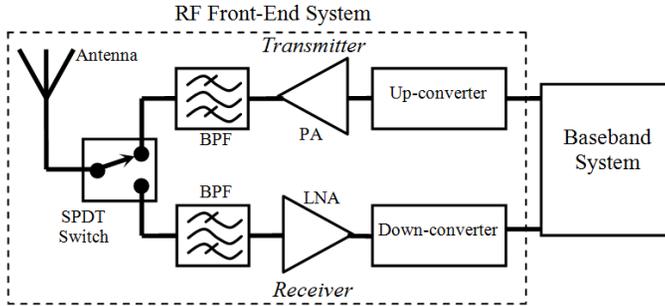
### **1. INTRODUCTION**

In wireless data communications, Single Pole Double Throw (SPDT) switch is used in RF front-end system (Figure 1) to switch between uplink (transmit mode) and downlink (receive mode) transmission such as in WiMAX or LTE [1]. The switch element in SPDT switch can use

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**Figure 1.** An example application of SPDT switch in wireless data communications.

either PIN diodes or FETs [2] that can also be used in reconfigurable antenna design [3]. One of the key parameters in SPDT switch design is the requirement of high isolation between transmitter and receiver [4] in order to minimize any high RF power leakage from transmitter to receiver that could distort receiver's active circuits especially low noise amplifier (LNA).

So far, there are three techniques that widely used to obtain high isolation in SPDT switch design; first, through material and fabrication process of switch element; second, resonated switch element with inductor or capacitor; and third, switch configuration. For the first technique, several examples can be found in [5–7]. Vertical PIN diode cross section was proposed in [5] using SiGe BiCMOS process to improve insertion loss and isolation. The other materials and processes used for better isolation is heterojunction InP/InGaAs PIN diode [6] and heterojunction AlGaAs/GaAs PIN diode [7]. However, these new fabrication processes and materials are sometime complicating the production process and increase the cost. For the second technique, several examples can be found in SPDT switch design for Monolithic Microwave Integrated Circuit (MMIC) [8, 9] or discrete circuit [10]. This technique reduces the parasitic capacitance or inductance in PIN diode or FET near the resonant frequency. Consequently, it increases the isolation performance at that particular frequency. However, this technique is limited for narrowband isolation due to single resonant tank circuit. For the third technique, multiple cascaded shunt configuration [11, 12] and combination of series and shunt configuration [13–15] are the most widely used in switch configuration technique. The multiple cascaded shunt configuration is usually spacing with several quarter wavelengths and suitable for high power

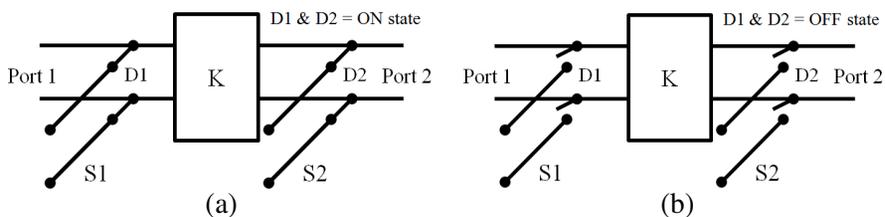
application. However, the major concern of this technique is increasing of total current consumption and overall circuit size.

From literature, several bandstop to allpass reconfigurable filters were reported in [16–18] where the targeted application is for filter of cellular base station [16], electronic warfare receiver [17] and cognitive radio [18]. Recently, new designs of bandstop to allpass reconfigurable filters were investigated and reported in [19–22]. This includes a potential bandstop to allpass reconfigurable filter using stepped impedance dual mode resonator [18, 23].

Therefore, this paper proposes bandstop to allpass reconfigurable filter technique in SPDT switch design where its isolation depends on the bandstop response of the reconfigurable filter. The reconfigurable filter is realized using transmission line stub and radial stub. Discrete PIN diodes are chosen to switch between bandstop and allpass response which is also controlling the transmit and receive mode in the SPDT switch circuit. This paper is organized as follows. Section 2 discusses the proof of concept of bandstop to allpass reconfigurable filter, while Section 3 presents the implementation of the reconfigurable filter in SPDT switch design. Then, followed by the experimental result of the proposed SPDT switch in Section 4. Finally, the work is concluded in Section 5.

## 2. PROOF OF CONCEPT OF BANDSTOP TO ALLPASS RECONFIGURABLE FILTER

A circuit of bandstop to allpass reconfigurable filter is illustrated in Figure 2 which has two quarter wave ( $\lambda/4$ ) open stub resonators ( $S1$  and  $S2$ ). The  $S1$  and  $S2$  are resonated at two different frequencies and separated with impedance inverter. This circuit can be switched between bandstop to allpass response by using PIN diodes ( $D1$  and  $D2$ ). As shown in Figure 2(a), if a positive voltage is applied,  $D1$



**Figure 2.** Equivalent circuit of bandstop to allpass reconfigurable filter. (a) Bandstop response during ON state of PIN diodes and (b) allpass response during OFF state of PIN diodes.

and  $D2$  will be ON state. In this condition,  $S1$  and  $S2$  operate as a bandstop due to the  $\lambda/4$  open stub resonator. If a negative voltage is applied (Figure 2(b)),  $D1$  and  $D2$  will be OFF state. In this condition,  $S1$  and  $S2$  are disconnected from the transmission line. Thus, it responses as allpass.

The bandstop response of the circuit in Figure 2(a) can be modeled using transmission matrix ( $ABCD$  matrix) [24] as

$$[T] = [T_{S1}][T_K][T_{S2}]|_{ON\ state} \tag{1}$$

where  $T_{S1}$  and  $T_{S2}$  are transmission matrix of  $\lambda/4$  open stub resonators and  $T_K$  is transmission matrix of  $K$  inverter. Therefore, we have

$$[T] = \begin{bmatrix} 1 & 0 \\ \frac{j \tan \theta_1}{Z_{S1}} & 1 \end{bmatrix} \begin{bmatrix} 0 & jK \\ \frac{1}{jK} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{j \tan \theta_2}{Z_{S2}} & 1 \end{bmatrix} \tag{2}$$

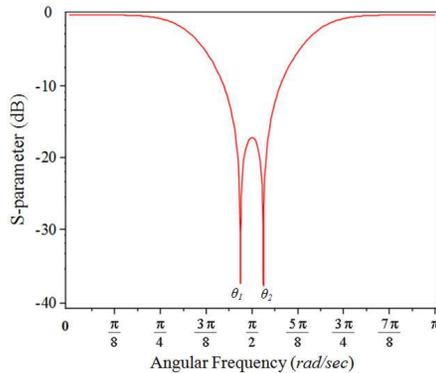
$$[T] = \begin{bmatrix} -\frac{K \tan \theta_2}{Z_{S2}} & jK \\ \frac{j}{K} - \frac{jK \tan \theta_1 \tan \theta_2}{Z_{S1} Z_{S2}} & -\frac{K \tan \theta_1}{Z_{S1}} \end{bmatrix} \tag{3}$$

where  $\theta_1$  and  $\theta_2$  are angular frequency of resonators,  $Z_{S1}$  and  $Z_{S2}$  are impedance of resonators; and  $j$  is the imaginary unit.

From (3), by using conversion between  $ABCD$  to  $S$ -parameter [24], the  $S_{21}$  is expressed as

$$S_{21} = \frac{2}{\frac{jK}{Z_0} + \left( \frac{j}{K} - \frac{jK \tan \theta_1 \tan \theta_2}{Z_{S1} Z_{S2}} \right) Z_0 - \frac{K \tan \theta_1}{Z_{S1}} - \frac{K \tan \theta_2}{Z_{S2}}} \tag{4}$$

where  $Z_0$  is characteristic impedance. By selecting  $K=1$  and  $Z_0 = 1$  (normalize impedance) and assuming  $Z_{S1} = Z_{S2} = 1 \Omega$ , a graphical representation of (4) is shown in Figure 3. It can be seen that a bandstop response is produced by two transmission zeros which are



**Figure 3.** Graphical representation of bandstop response.

closely spaced by  $\theta_1$  and  $\theta_2$ . This is to provide wide isolation in SPDT switch design.

Using the same analytical modeling steps in bandstop response, the transmission matrix of allpass response in Figure 2(b) is

$$[T] = [T_k]|_{OFF\ state} \tag{5}$$

where  $T_{S1}$  and  $T_{S2}$  are disconnected from transmission line. Therefore, from (5), we have

$$[T] = \begin{bmatrix} 0 & jK \\ \frac{1}{jK} & 0 \end{bmatrix}. \tag{6}$$

Then, the  $S_{21}$  is expressed as

$$S_{21} = \frac{2}{\frac{jK}{Z_0} + \frac{jZ_0}{K}}. \tag{7}$$

By selecting  $K = 1$  and  $Z_0 = 1$  (normalize impedance), the absolute value of (7) can be obtained as

$$|S_{21}| = \left| \frac{2}{\frac{jK}{Z_0} + \frac{jZ_0}{K}} \right| = 1 = 0\text{ dB} \tag{8}$$

where zero loss is produced during OFF state of the PIN diodes, thus having an allpass response in the circuit.

Therefore, from the analytical modeling of the bandstop and allpass reconfigurable filter, it is shown that the bandstop and allpass response can be controlled by PIN diodes in the resonators. The next section will show the implementation of this circuit in SPDT switch design.

### 3. SPDT SWITCH DESIGN, OPERATION AND ANALYSIS

A conventional multiple cascaded shunt configuration in SPDT switch design is constructed (Figure 4) in order to compare with the proposed

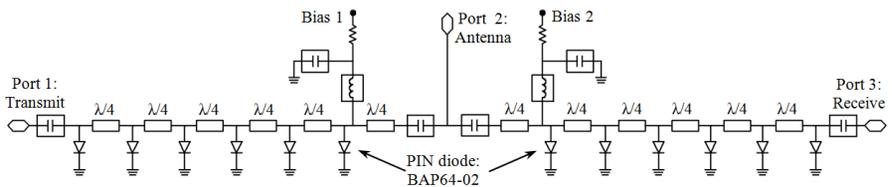
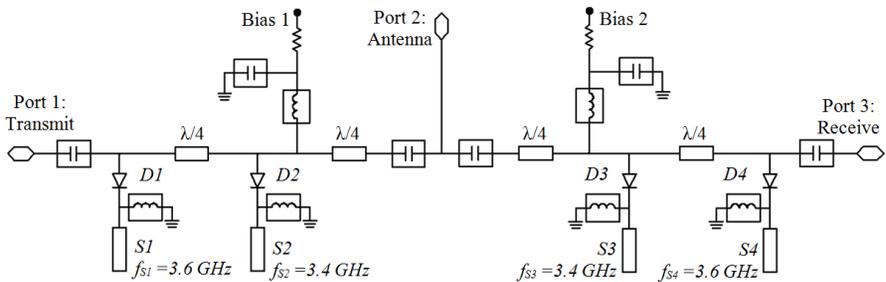


Figure 4. Conventional SPDT switch design.

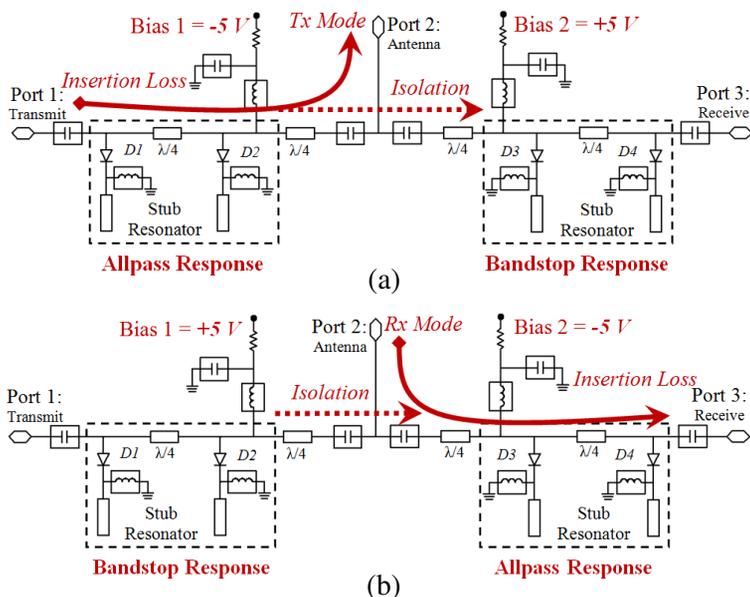
SPDT switch in term of circuit performance, circuit size and the number of PIN diodes needed. As shown in Figure 4, each arm (transmit and receive circuit) requires six PIN diodes (BAP64-02 from NXP Semiconductors) in order to get more than 30 dB isolation (between Port 3 and Port 1) at frequency between 3.4 to 3.6 GHz. All shunt PIN diodes are spacing with quarter wave ( $\lambda/4$ ) lines. During ON state of shunt PIN diodes, the  $\lambda/4$  lines will transform the short circuit (due to shunt PIN diode) into open circuit, thus isolating any RF signal between Port 3 and Port 1.

As depicted in Figure 5, the bandstop to allpass reconfigurable filter (Figure 2) is implemented as SPDT switch where it is placed in transmit and receive arm. The  $\lambda/4$  open stub resonators are implemented using transmission line resonator where the resonator impedance is the same with characteristic impedance,  $Z_0$ . In order to produce high and wider isolation between 3.4 to 3.6 GHz, the resonator  $S1$  and  $S4$  are resonated at 3.6 GHz and resonator  $S2$  and  $S3$  are resonated at 3.4 GHz. The  $K$ -inverter (Figure 2) is implemented as quarter wave transformer line. The  $D1$ ,  $D2$ ,  $D3$  and  $D4$  are the same PIN diode manufacturer used in conventional circuit in Figure 4.



**Figure 5.** The proposed SPDT switch design using bandstop to allpass reconfigurable filter.

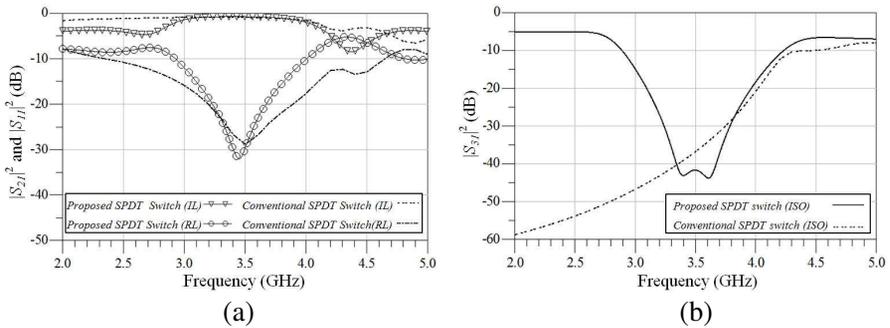
A circuit operation of the proposed SPDT switch is shown in Figure 6. As mentioned earlier, either in transmit mode or receive mode, any SPDT switch design should be able to isolation high power transmit signal from entering into receiver circuit. In transmit mode (Figure 6(a)),  $D1$  and  $D2$  are turned OFF and  $D3$  and  $D4$  are turned ON with  $-5$  V and  $+5$  V of voltage supply respectively. In this mode, the circuit in transmit arm produces allpass response and the circuit in receive arm produces bandstop response. The insertion loss between Port 2 and Port 1 is depend on allpass response in the transmit arm while the isolation between Port 3 and Port 1 is depend on bandstop response in the receive arm.



**Figure 6.** Circuit operation during (a) transmit mode, (b) receive mode.

The same circuit operation can be obtained in receive mode (Figure 6(b)) when  $D1$  and  $D2$  are turned ON and  $D3$  and  $D4$  are turned OFF with  $-5\text{ V}$  and  $+5\text{ V}$  of voltage supply respectively. In this mode, the circuit in transmit arm produces bandstop response and the circuit in receive arm produces allpass response. The insertion loss between Port 3 and Port 2 is depend on allpass response in the receive arm while the isolation between Port 3 and Port 1 is depend on bandstop response in the transmit arm.

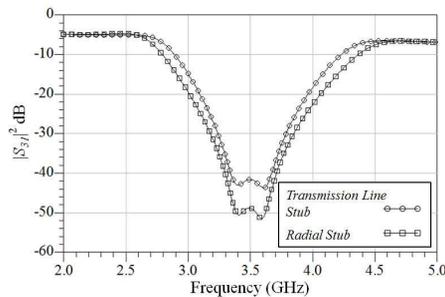
Since the SPDT switch circuits are symmetrical between transmit and receive arm, this paper analyzes the circuits performance in transmit mode only. In Figure 7, the proposed SPDT switch and conventional SPDT switch are designed using microstrip line and simulated in Advanced Design System (ADS) software. The FR4 substrate is considered in the simulation with a thickness of 16 mm and dielectric constant of 4.7. The simulation results are compared in term of isolation ( $ISO$ ), insertion loss ( $IL$ ) and return loss ( $RL$ ). Generally, it can be seen that the isolation for both circuits is higher than 30 dB from 3.4 to 3.6 GHz. However, we found that the two resonant frequencies at 3.4 and 3.6 GHz of the proposed SPDT switch produce better isolation across the frequency band compared with conventional SPDT switch.



**Figure 7.** Comparison of circuit performance between conventional and the proposed SPDT switch (a) simulated insertion loss ( $IL$ ) and return loss ( $RL$ ), (b) simulated isolation ( $ISO$ ).

Furthermore, the proposed SPDT switch is only use two PIN diodes in each arm (Figure 4) to produce more than 30 dB isolation at frequency between 3.4 to 3.6 GHz. Both circuits also show a good performance of insertion loss and return loss between 3.4 to 3.6 GHz.

The isolation bandwidth of the proposed SPDT switch in Figure 7(b) can be widened by using radial stub. Thus, Figure 8 depicts the comparison of isolation bandwidth between transmission line stub and radial stub where the isolation bandwidth at 30 dB isolation is 545 MHz for transmission line stub and 670 MHz for radial stub. Thus additional 22.9% of bandwidth was produced with the use of radial stub. Besides, it can be seen that radial stub produces higher isolation compared to transmission line stub. This is due to impedance of radial stub which is lower than the impedance of transmission line stub.

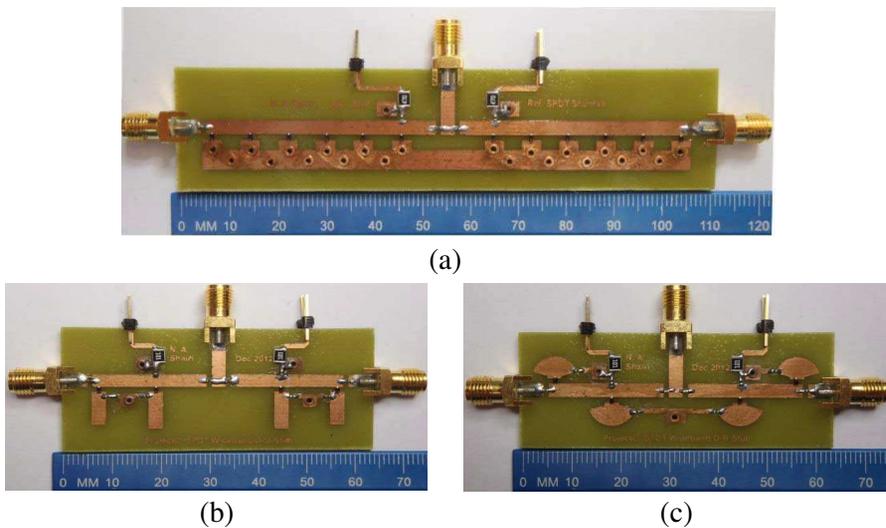


**Figure 8.** Comparison of simulated isolation performance of the proposed SPDT switch between transmission line stub and radial stub.

Referring to (4), lower impedance of stub resonator will yield higher attenuation in the bandstop resonator.

#### 4. EXPERIMENTAL RESULT AND DISCUSSION

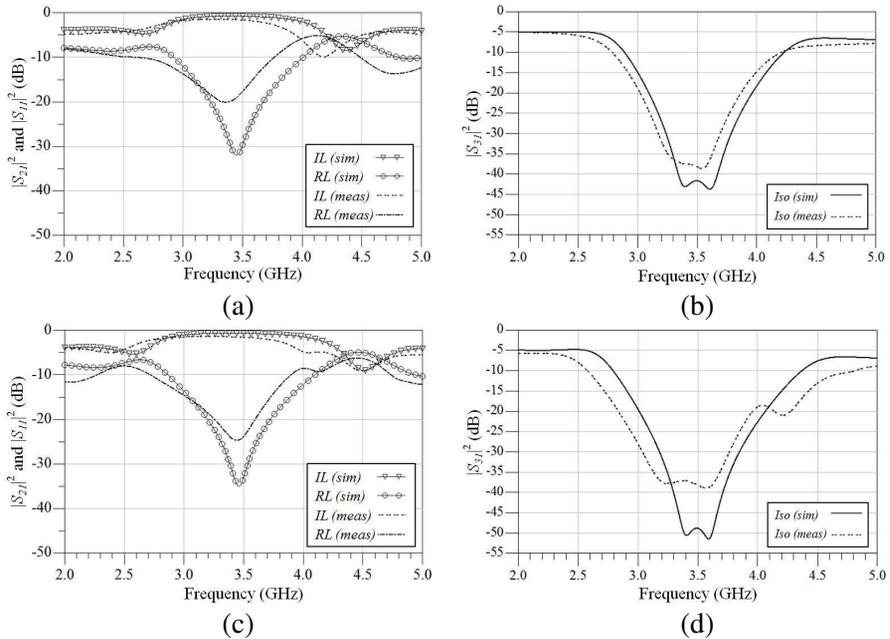
Figure 9 shows the photographs of conventional and proposed SPDT switch design in microstrip technology. All the prototypes were fabricated on FR4 substrate. The dimension of the conventional circuit (Figure 9(a)) is  $110\text{ mm} \times 20\text{ mm}$  and the proposed circuit (Figures 9(b) and 9(c)) is  $63\text{ mm} \times 20\text{ mm}$ . It shows that the proposed SPDT switch circuits are smaller than the conventional SPDT switch. In term of percentage, 42.7% of size reduction is achieved with this technique.



**Figure 9.** Fabricated prototype of (a) conventional SPDT switch, (b) proposed SPDT switch with transmission line stub and (c) proposed SPDT switch with radial stub.

The simulated and measured result of the proposed SPDT switches are depicted in Figure 10 and summarized in Table 1. In general, the result of insertion loss, return loss and isolation are comparable between simulation and measurement. Both designs have low insertion loss (less than 2 dB loss in measured result) and return loss is higher than 10 dB in 3.5 GHz band. Generally, it is successfully demonstrated that the proposed SPDT switches can achieve high isolation which is higher than 30 dB in 3.5 GHz band.

Although the measured isolation shifted to lower frequencies but



**Figure 10.** Simulated and measured result of proposed SPDT switch with (a) transmission line stub resonator and (b) radial stub resonator.

**Table 1.** Performance comparison in 3.5 GHz band (from 3400 MHz to 3600 MHz).

|   |             | Insertion Loss (dB) | Return Loss (dB) | Isolation (dB) |
|---|-------------|---------------------|------------------|----------------|
| SPDT switch with transmission line stub resonator | Simulation  | 0.74–0.82           | 29.9–23.2        | 43.1–43.7      |
|   | Measurement | 1.5–1.9             | 19.9–14.5        | 37.5–36.9      |
| SPDT switch with radial stub resonator            | Simulation  | 0.66–0.71           | 31.3–25.5        | 50.6–51.3      |
|   | Measurement | 1.4–1.7             | 24.3–19.8        | 37.1–38.7      |

it is still within 3.4 to 3.6 GHz. The measured isolation bandwidth of the proposed SPDT switch with radial stub has proven that it is wider than the transmission line stub. However, the measured isolation of the radial stub has degraded about 10 to 15 dB compared to the simulated result. Main factor that contribute to the frequency shifting and isolation degradation is due to the parasitic inductance and capacitance associated with the package leads, bond wires and package material [25]

and combined with the different amount of solder connections on the discrete PIN diode leads. Other factor of frequency shifting is the board fabrication process that causes the resonant frequency variation on the transmission line stub and radial stub.

## 5. CONCLUSION

The bandstop to allpass reconfigurable filter technique in SPDT switch design has been proposed in this paper. The conceptual and circuit operation of the reconfigurable between bandstop and allpass have been proven analytically. It is then implemented in SPDT switch design in 3.5 GHz band where the bandstop to allpass response is controlled by PIN diodes. The fabricated prototypes show excellent agreement with theory and simulated results. The proposed SPDT switches have produced isolation higher than 30 dB with minimum number of PIN diodes and 42.7% of size reduction has been achieved compared with conventional one. Besides, the radial stub has given wider isolation compared with transmission line stub. Potential future works include verification of the proposed SPDT switch for WiMAX or LTE application in 3.5 GHz band and the implementation on MMIC technology for smaller scale of SPDT switch design.

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