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Fixed and Selectable Multiband Isolation of Double Pole Double Throw Switch Using Transmission Line Stub Resonators for WiMAX and LTE

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Abstract—A novel selectable multiband isolation of Double Pole Double Throw (DPDT) switch with switchable transmission line stub resonators has been proposed for applications of WiMAX and LTE in 2.3 and 3.5 GHz bands. In this paper, two DPDT switch designs are proposed; the first design is a fixed DPDT switch, and the second is a selectable DPDT switch. The second design allows selecting only one band and unselecting the other or selecting both of them. However, the first design does not allow so. The transmission line stub resonator used in this design is an open stub resonator with quarter wave of the electrical length. By using a simple mathematical model, the theory of the transmission line stub resonator was discussed where it can be cascaded and resonated at center frequencies of 2.3 and 3.5 GHz. Moreover, the cascaded transmission line stub resonators can be reconfigured between allpass and bandstop responses using discrete PIN diodes. The key advantage of the proposed DPDT with switchable transmission line stub resonators is a multiband high isolation with minimum number of PIN diodes. Therefore, the simulated and measured results showed less than 3 dB of insertion loss, greater than 10 dB of return loss and higher than 30 dB of multiband isolation in 2.3 and 3.5 GHz bands.

1. INTRODUCTION

Nowadays, wireless communication switchable/selectable radios designs are highly popular due to their ability to operate with different frequencies using single hardware. For instance, switchable slot antenna has been designed to support the entire UWB operation frequency; at the same time, it created a dual band notch in order to notch the frequency bands of interference between UWB with WLAN, C-band, and WiMAX systems [1]. Furthermore, a dual-band switchable bandpass filter was proposed in [2] with the ability to switch between passbands, low-band and high-band by controlling the bias voltage of PIN diodes. In [3], a frequency switchable T-slot antenna was designed to support diverse applications such as WiMAX, C-band, X-band and fixed satellite communication systems by controlling the PIN diode states (ON and OFF states). Moreover, [4] introduced an SPDT switchable bandpass filter design to operate at narrow-band applications. This design combined SPDT with two filters, and it has the ability to ON one filter and OFF the other by controlling the PIN diodes, switching elements.

In the field of multiband wireless communications, the development of multiband sub-components (e.g., amplifiers, filters, switches and antennas) are highly desired, and they were developed to support several RF front-end systems [5–8]. Meanwhile, Double Pole Double Throw (DPDT) switch (which is a part of RF switches) is ordinarily used in RF front-end system to perform Time Division Duplex (TDD) switching between up-link (Transmitter mode) and down-link (Receiver mode) [9]. It is used to support TDD communication such as in WiMAX and LTE. From the literature, DPDT switches could be

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designed and used in applications such as phase shifter [10, 11], low cost X-band antenna [12], wideband control circuits (attenuators and true time delay elements), Ultra-Wide Band (UWB) applications microwave imaging applications [11], multi-input multi-output (MIMO) system, WLAN [13] and digital cellular handsets [14].

There are several types of configurations to perform DPDT switching function such as SOI-type (allocating the actuators and the waveguides in separate layers of an SOI wafer) [10], absorptive (four parallel- and cross-connected series transistors) [12], bi-directional [11], reflective [13] and ring [14] configurations. Besides, there is a back to back configuration, where two Single Pole Double Throw (SPDT) switches are connected together as a DPDT switch [9]. It is suitable for diversity antennas application as illustrated in Fig. 1. The use of diversity antennas have improved the performance of wireless communication systems as reported in [15–18].

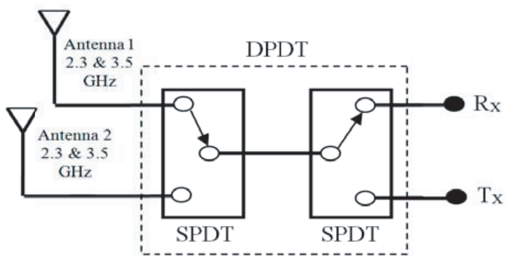

Figure 1. DPDT switch with back to back SPDTs in RF front-end system.

For switching elements in RF switch (including DPDT switch), researchers used either micro-electro-mechanicals (MEMs) [10] or solid state elements such as PIN diode [19] and field effect transistor (FET) [13, 14, 20]. However, MEMs switches are not suitable for high power applications due to their limited power capabilities [21]. Moreover, they have not found wide use in RF and microwave applications since the PIN diode was developed and commercialized [22]. Instead of MEMs, [23] used conductive bridging (CB) due to its low switching time, however, it came out with very low isolation. Additionally, solid state switches, such as PIN diode switch, show more reliability due to faster switching time and accomplish a longer lifetime, if compared to MEMs technology. Consequently, if the fast switching time, long lifetime and high power applications are the key performance requirements, the most popular switching element used is PIN Diode [22, 24].

In DPDT switch design, high isolation plays an important role to prevent unwanted leakage signal [12]. Furthermore, to increase the switch's isolation, researchers have reported different techniques such as layer-wise waveguide/actuator [10], floating body and N-well [12], bi-directional distributed amplifier [11]. These techniques were implemented in integrated circuit RF switches only. On the other hand, for discrete RF switches such as [19, 25], it is quite hard to get high isolation (> 30 dB) if using only discrete PIN diodes and usually multiple cascaded PIN diodes are required for high isolation performance.

Therefore, this paper proposes a multiband isolation of DPDT switch design with switchable transmission line stub resonators for applications of WiMAX and LTE in 2.3 and 3.5 GHz bands. Discrete PIN diodes were used in the proposed DPDT switch due to its advantage of higher power levels used in wireless communication systems. Generally, resonators were used to build up several RF and microwave circuit designs such as antennas [20], amplifier [21], filter [22] and microwave absorber [24]. Thus, by using this technique (resonator) and together with discrete PIN diodes in DPDT switch design, the key advantage is a multiband high isolation with minimum number of PIN diodes as compared to conventional multiple cascaded PIN diodes.

2. SWITCHABLE TRANSMISSION LINE STUB RESONATORS

In this section, we discuss a mathematical modeling for the isolation of multiband DPDT switch with transmission line stub resonator in a simple analyzes form. Fig. 2(a) shows the general diagram of a two-port network, and Fig. 2(b) shows a two-port network of series-shunt PIN diode with transmission

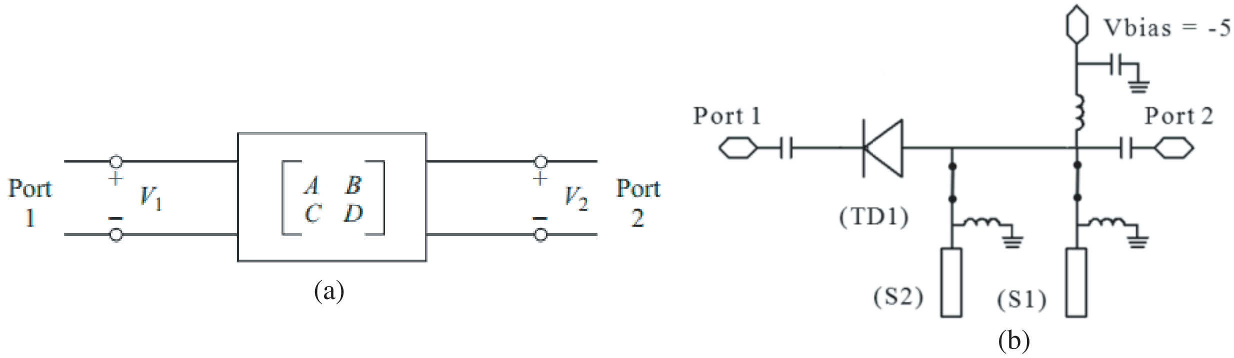

Figure 2. (a) General diagram of Two-port network [30]. (b) Two-port network of series-shunt PIN diode with open stub resonators.

line open stub resonators. From this figure, we analyzed the $ABCD$ matrix of two-port networks taking into account that shunt PIN diodes are switched ON, while series PIN diode is switched OFF.

Based on the circuit, the derivation equations are as follows:

$$(TD1) = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & Zr \\ 0 & 1 \end{pmatrix} \tag{1}$$

According to [30]:

$$Zr = Rr + j\left[\omega Li - \frac{1}{\omega Cj}\right] \tag{2}$$

where Zr is the reference impedance of the PIN diode, Rr the diode forward resistance, Cj the diode capacitance and Li the diode inductance. Then we find the $ABCD$ matrix for resonators (S1) and (S2);

$$(S1) = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{jZ_{S1}\tan\theta} & 1 \end{pmatrix} \tag{3}$$

$$(S2) = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{jZ_{S2}\tan\theta} & 1 \end{pmatrix} \tag{4}$$

where Z_s is the impedance of the resonator. Then, to determine the isolation at 2.3 GHz;

$$(TD1)\,(S2) = \begin{pmatrix} 1 & Zr \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \dfrac{j\tan\theta}{Z_{S2}} & 1 \end{pmatrix} \tag{5}$$

Substituting the result of $ABCD$ matrix in Eq. (5) into:

$$S_{12} = \frac{2}{A + \dfrac{B}{Z} + CZ + D} \tag{6}$$

where $Z = Z_{S2} = Z_r = 1$. Assume $\theta = \pi/2$ (length of the quarter wave) and convert to decibel. Thus,

$$|S_{12}|^2 = 20\log(0) = \infty\,\text{dB} \tag{7}$$

To determine the isolation at 3.5 GHz;

$$(TD1)\,(S1) = \begin{pmatrix} 1 & Zr \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \dfrac{j\tan\theta}{Z_{S1}} & 1 \end{pmatrix} \tag{8}$$

By substituting the result of $ABCD$ matrix in Eq. (8) into Eq. (6) and converting to decibel, the isolation at 3.5 GHz can be as follows:

$$|S_{12}|^2 = 20\log(0) = \infty\,\text{dB} \tag{9}$$

Theoretically, it is clearly observed that infinite isolation can be achieved, if $Z_S = 1$ and $\theta = \pi/2$. From Eqs. (7) & (9), an ideal infinite attenuation (notch) is produced if the electrical length of the transmission line stub resonator is a quarterwave ($\lambda/4$). This attenuation characteristic was used to produce multiband high isolation in DPDT switch.

Figure 3(a) shows the cascaded switchable transmission line stub resonators connected to discrete PIN diodes. The discrete PIN diodes could be in SOD523, SOD323, SOT23, or SOT323 packages. This configuration is to allow the TDD switching between transmit mode and receive mode operations in DPDT switch. The PIN diodes (D1 and D2) were attached between the microstrip lines and stub resonators, hence the switchable stub resonators could be executed at 2.3 and 3.5 GHz. There are two different conditions of these switchable resonators.

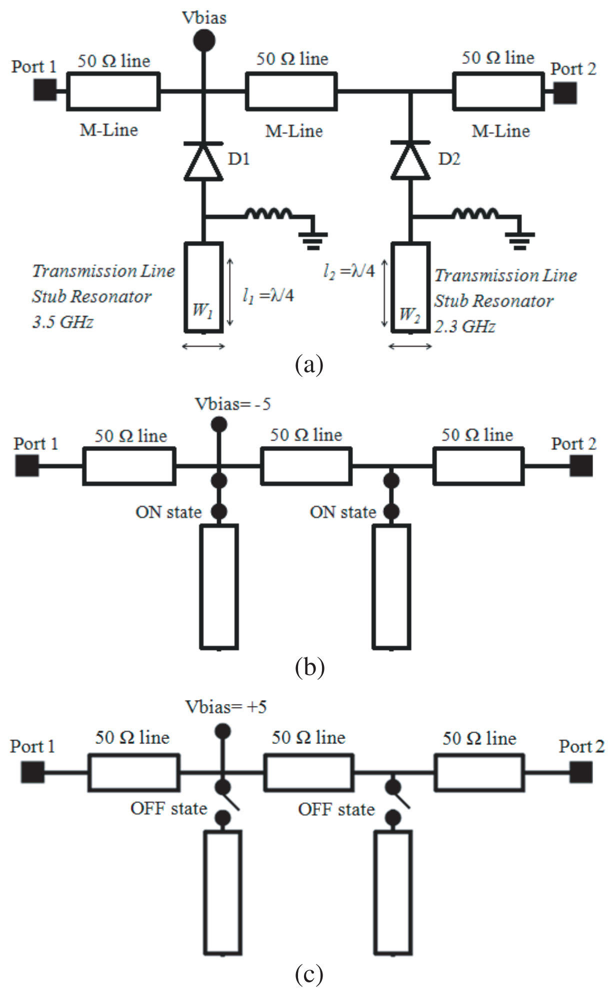

Figure 3. (a) Circuit diagram of cascaded switchable transmission line stub resonator. Circuit operation: (b) bandstop response (ON state) and (c) allpass response (OFF state)

In the first condition, as illustrated in Fig. 3(b), if a negative voltage (−5 V) is applied, the PIN diodes, D1 and D2, will be in the ON state, and the transmission line stub resonators will be connected to the microstrip line. Hence, it operated as a bandstop filter due to the quarter wave ($\lambda/4$) line of the resonator that converting from high impedance to low impedance at the main microstrip line.

In the second condition, as illustrated in Fig. 3(c), if a positive voltage (+5 V) is applied, the PIN diodes, D1 and D2, will be in the OFF state, and the transmission line stub resonators will be disconnected from the microstrip line. Hence, an allpass respond of the resonators can be seen between Port 1 and Port 2.

3. FIXED DPDT SWITCH

As presented in Fig. 4, fixed multiband isolation of DPDT switch with switchable transmission line stub resonators was designed in 2.3 GHz and 3.5 GHz bands. Two SPDT switches had been connected in back to back configuration in order to build up the multiband isolation DPDT switch.

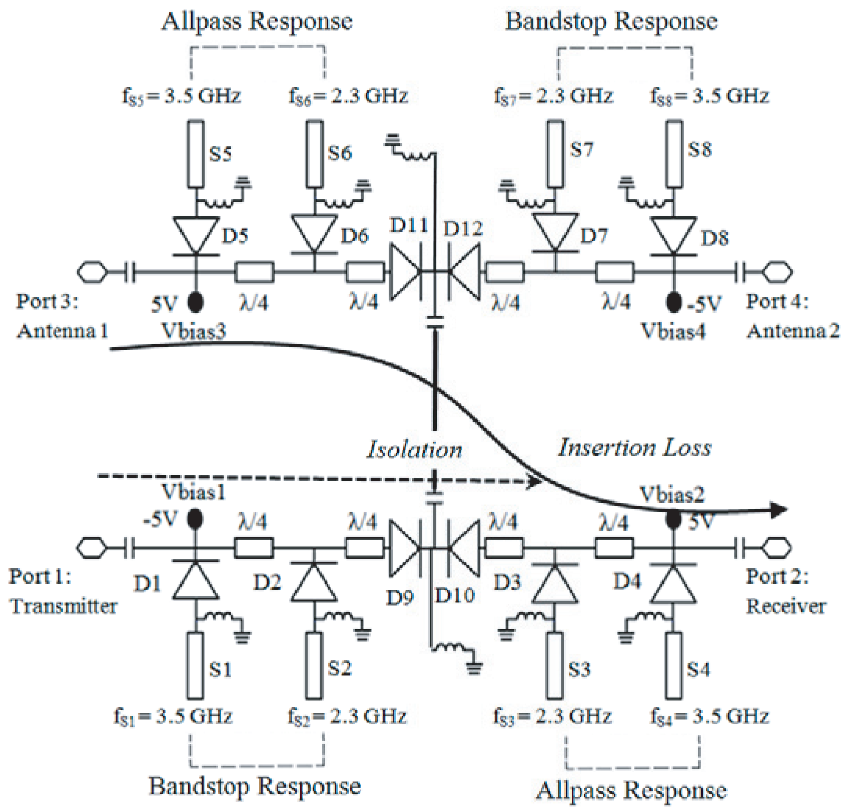

Figure 4. Circuit operation of the fixed DPDT switch during receive mode.

As shown in Fig. 4, in all the arms (Transmitter, Receiver, Antenna 1 and Antenna 2 circuits), the open stub resonators of S1 until S8 were separated with quarter wave ($\lambda/4$) to transform from low impedance of transmission line stub resonator to high impedance in the microstrip line.

Due to the symmetrical construction of the fixed DPDT switch circuit, we discuss the circuit operation during receiver mode only. Therefore, in the receiver mode as depicted in Fig. 4, the series PIN diodes (D9 and D12) were set as OFF state with voltage control of -5 V, while the series PIN diodes (D10 and D11) were set as ON state with voltage control of 5 V.

Further, the PIN diodes (D3–D6) of switchable transmission line stub resonators (S3–S6) were in OFF state with voltage control of 5 V, while the PIN diodes (D1, D2, D7, and D8) of S1, S2, S7 and S8 were in ON state with voltage control of -5 V. In this case, the resonators of S3 until S6 created an allpass response and thus, RF signals propagated from Antenna 1 (Port 3) to Receiver (Port 2) with low insertion loss.

Meanwhile, the isolation between Receiver (Port 2) and Transmitter (Port 1) was obtained from the OFF state of the series PIN diodes (D9) and the two switchable transmission line stub resonators (S1 and S2) in the Transmitter part. In addition, S1 and S2 performed as a bandstop filter creating an additional isolation in the fixed DPDT switch during receive mode operation. Table 1 presents a summary of the circuit operation in both receive and transmit modes of the proposed fixed DPDT switch for WiMAX and LTE in 2.3 and 3.5 GHz bands.

The prototype of the fixed DPDT switch circuit is illustrated in Fig. 5. Advanced Design System (ADS) software was used for DPDT performance simulation and layout design. In order to build up

Table 1. Summary of circuit operation of the proposed fixed DPDT switch with switchable transmission line stub resonators.

Fixed DPDT Switch	Receive Mode	Transmit Mode
Vbias 1* & *Vbias 4	−5 Volt	+5 Volt
Vbias 2* & *Vbias 3	+5 Volt	−5 Volt
Series PIN diode (D9* & *D12)	OFF state	ON state
Series PIN diode (D10* & *D11)	ON state	OFF state
Transmission Line Stub Resonators (S1, S2, S7* & *S8)	Bandstop response	Allpass response
Transmission Line Stub Resonators (S3, S4, S5* & *S6)	Allpass response	Bandstop response

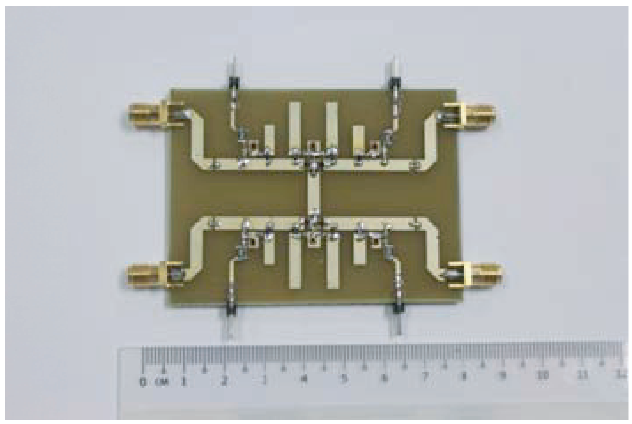

Figure 5. Prototype of the proposed fixed DPDT switch with switchable transmission line stub resonators (dimension: 72 mm × 54 mm).

the switch circuit, microstrip model in ADS was used based on an FR4 substrate with the following parameters; thickness = 1.6 mm and relative dielectric constant, $\varepsilon_r = 4.7$. PIN diodes (part number: BAP64-02) from NXP and the capacitors and inductors from Murata were used in the circuit design.

For the parasitic elements of PIN diode, the parameters such as junction capacitance (C_j) and series inductance (L_s) were considered in the switchable resonator design, through the entire simulation process. Hence, the final dimensions of the resonators were $W_1 = 2.9$ mm and $l_1 = 7.34$ mm for 3.5 GHz; and $W_2 = 2.9$ mm and $l_2 = 13.45$ mm for 2.3 GHz (refer Fig. 3(a)). The entire area of the fixed DPDT switch circuit is 72 mm × 54 mm.

4. SELECTABLE DPDT SWITCH

Figure 6 presents a diagram of the selectable multiband isolation DPDT switch. In fact, this switch is modified based on the previous switch (Fixed DPDT switch). More capacitors and biasing circuits (Vbias 2–5 and 8–11) are added to allow selecting operation frequencies in three different cases; 2.3 GHz only (case 1), 3.5 GHz only (case 2) or both 2.3 GHz and 3.5 GHz (case 3). In selectable DPDT switch, as in the previous switch, eight open stub resonators (S1–S8) are used to achieve high isolation for WiMAX and LTE applications. Resonators (S1, S4, S6 and S7) are assigned to resonate at 3.5 GHz, while (S2, S3, S5 and S8) are assigned to resonate at 2.3 GHz. Quarter wavelength ($\lambda/4$) is placed in between open stub resonators, in order to transform from low impedance of the resonators to high impedance in the microstrip line.

In general, this switch circuit has been built to switch between transmitter (Tx) mode and receiver

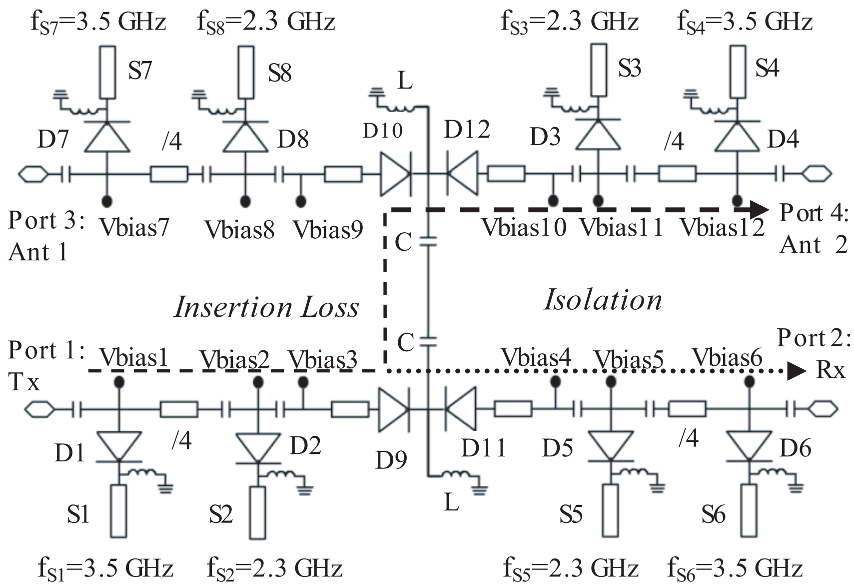

Figure 6. Circuit operation of the selectable DPDT switch during transmitter mode.

(Rx) mode. To do so, series PIN diodes (D9–D12) and shunt PIN diodes (D1–D8) has been used. These PIN diodes are controlled by biasing circuits (Vbias 1–Vbias 12). For the DC block, C, the chosen value is 10 pF in order to achieve highpass response. For the RF choke, L, the chosen value is 10 nH to block RF signals at 2.3 GHz and 3.5 GHz. Due to the symmetrical construction of the selectable DPDT switch circuit, we discuss the circuit operation during transmitter (Tx) mode only.

During transmitter mode process, RF signals propagate from transmitter (Tx) to antenna (Ant 2), as can be seen in Fig. 6. We have mentioned that in selectable DPDT switch there are three different cases.

In the first case (selecting 2.3 GHz band only), Vbias 1, 6, 7 and 12 must be deactivated. Then, series PIN diodes, D9 and D12 are turned ON, while shunt PIN diodes (D2 and D3) are turned OFF with voltage control, 5 V. So, transmission line open stub resonators, S2 and S3, create allpass response. In contrast, in receiver (Rx) and antenna (Ant 1) arms, series PIN diodes, D10 and D11 are turned OFF, while shunt PIN diodes, D5 and D8, are turned ON with voltage control, −5 V. So, transmission line open stub resonators, S5 and S8, create bandstop response.

In the second case (selecting 3.5 GHz band only), Vbias 2, 5, 8 and 11 must be deactivated. Then, in transmitter (Tx) and antenna (Ant 2) arms, series PIN diodes, D9 and D12 are turned ON, while shunt PIN diodes (D1 and D4) are turned OFF with voltage control, 5 V. So, transmission line open stub resonators, S1 and S4, create allpass response. In contrast, in receiver (Rx) and antenna (Ant 1) arms, series PIN diodes, D10 and D11 are turned OFF, while shunt PIN diodes, D6 and D7, are turned ON with voltage control, −5 V. So, transmission line open stub resonators, S6 and S7, create bandstop response.

In the third case (selecting both 2.3 GHz 3.5 GHz bands), all biasing circuits must be activated. Then, in transmitter (Tx) and antenna (Ant 2) arms, series PIN diodes, D9 and D12 are turned ON, while shunt PIN diodes (D1–D4) are turned OFF with voltage control, 5 V. So, transmission line open stub resonators (S1–S4) create allpass response. On the other hand, in receiver (Rx) and antenna (Ant 1) arms, series PIN diodes, D10 and D11 are turned OFF, while shunt PIN diodes (D5–D8) are turned ON with voltage control, −5 V. So, transmission line open stub resonators (S5–S8) create bandstop response. Obviously, in all cases, the created bandstop response in the receiver (Rx) arm is the most responsible of the isolation between transmitter (Tx) and receiver (Rx). Table 2 presents a summary of the process in the receiver and transmitter modes of selectable multiband isolation DPDT switch using transmission line open stub resonators for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz bands.

Table 2. Summarization of the process in receiver and transmitter modes of selectable multiband isolation DPDT switch using transmission line open stub resonators for WiMAX and LTE applications.

Selectable DPDT Switch		Receive Mode	Transmit Mode
Case 1 (selecting 2.3 GHz band)	***PIN diode (D9 & D12)***	ON state	OFF state
	PIN diode (D10 & D11)	OFF state	ON state
	Resonator (S1 & S4)	No response	No response
	Resonator (S2 & S3)	Allpass response	Bandstop response
	Resonator (S5 & S8)	Bandstop response	Allpass response
	Resonator (S6 & S7)	No response	No response
Case2 (selecting 3.5 GHz band)	***PIN diode (D9 & D12)***	ON state	OFF state
	PIN diode (D10 & D11)	OFF state	ON state
	Resonator (S1 & S4)	Allpass response	Bandstop response
	Resonator (S2 & S3)	No response	No response
	Resonator (S5 & S8)	No response	No response
	Resonator (S6 & S7)	Bandstop response	Allpass response
Case3 (selecting 2.3 GHz and 3.5 GHz bands)	***PIN diode (D9 & D12)***	ON state	OFF state
	PIN diode (D10 & D11)	OFF state	ON state
	Resonator (S1 & S4)	Allpass response	Bandstop response
	Resonator (S2 & S3)	Allpass response	Bandstop response
	Resonator (S5 & S8)	Bandstop response	Allpass response
	Resonator (S6 & S7)	Bandstop response	Allpass response

Table 3. Summary of performance of multiband isolation of fixed DPDT switch for WiMAX and LTE in 2.3 GHz and 3.5 GHz bands.

Fixed DPDT Switch		Isolation (dB)	Insertion Loss (dB)	Return Loss (dB)
2.3 GHz Band	***Simulation***	45.60	1.12	34.60
	Measurement	33.00	1.17	23.52
3.5 GHz Band	***Simulation***	42.69	1.57	25.15
	Measurement	33.20	2.99	12.02

5. SIMULATION AND MEASUREMENT RESULTS FOR FIXED DPDT SWITCH

Figure 7 presents the simulation and measurement results of the proposed fixed DPDT switch with switchable transmission line stub resonators in 2.3 GHz and 3.5 GHz bands. The simulated and measured results were compared to each other for the following parameters; insertion loss, return loss and isolation. It can be clearly seen that the isolation performance (S_{12}) of the DPDT switch achieved more than 30 dB in both simulated and measured results at 2.3 and 3.5 GHz as indicated in Fig. 7(a). The difference between simulated and measured isolation, as shown in Fig. 7(a) and detailed in Table 3, was due to parasitic capacitance and inductance of package materials (PIN diodes), and additional resistance during soldering stage [31, 32]. Moreover, it is found that more than 30 dB of isolation was obtained with only three discrete PIN diodes in each arm. By having more than 30 dB isolation, the fixed DPDT switch can isolate more than 1 Watt/10 Watt of power leakage in the RF front-end system.

Figure 7(b) shows that the insertion loss (S_{23}) was less than 3 dB in both simulation and measurement at 2.3 and 3.5 GHz bands. During measurement, an unwanted and unknown resonant

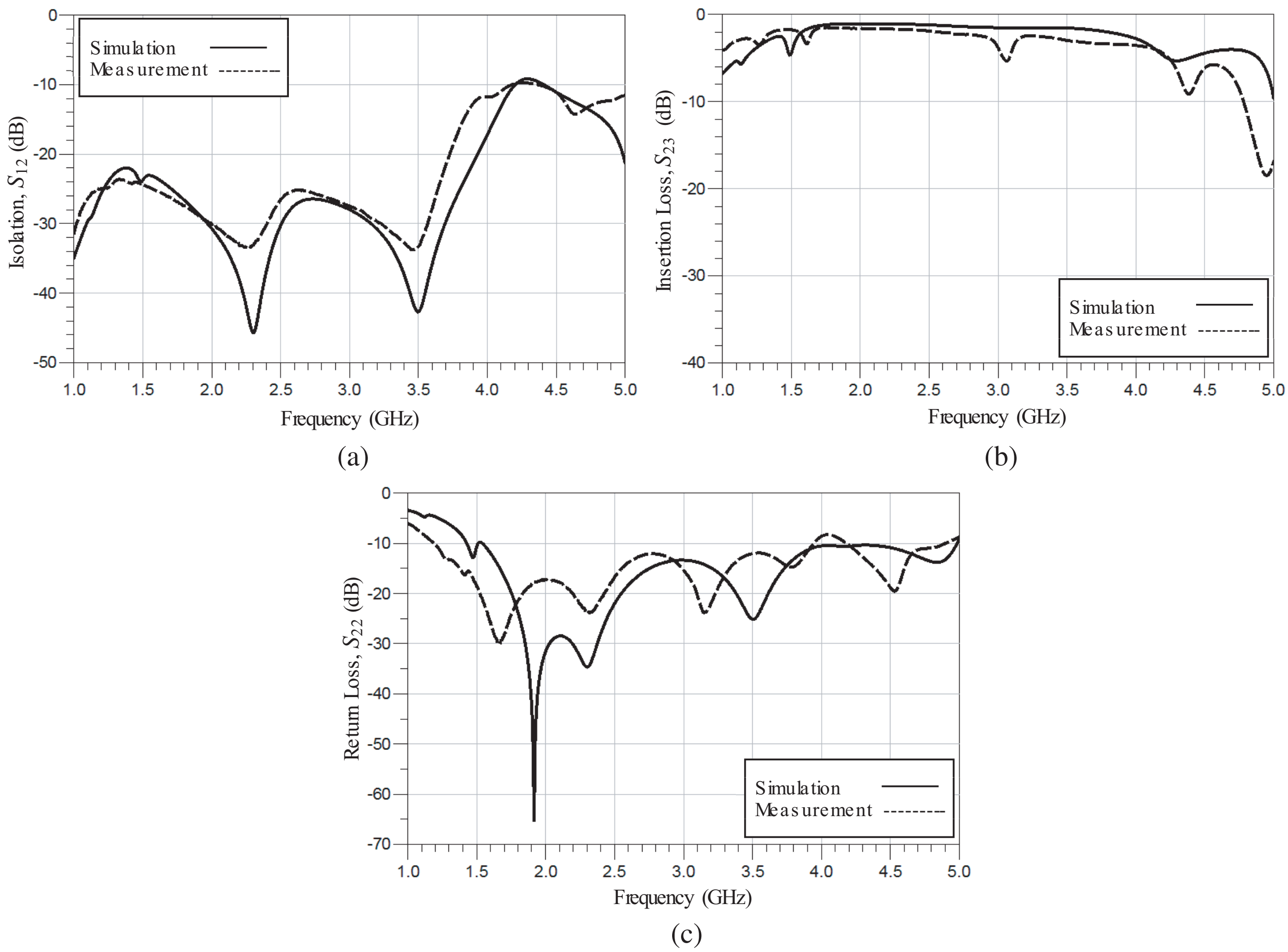

Figure 7. Simulation and measurement results of fixed DPDT switch, (a) isolation (S_{12}), (b) insertion loss (S_{23}) and (c) return loss (S_{22}).

was created in the insertion loss response at around 3 GHz frequency, but it was outside the frequency operation bands (2.3 and 3.5 GHz). Meanwhile, in Fig. 7(c), the measured return loss (S_{22}) was higher than 10 dB but it was slightly shifted to low frequency due to fabrication process.

The performance of the proposed fixed multiband isolation of DPDT switch with switchable transmission line stub resonators is summarized in Table 3. It summarizes the performance in terms of isolation, return loss and insertion loss that were discussed in the previous paragraphs.

6. SIMULATION AND MEASUREMENT RESULTS FOR SELECTABLE DPDT SWITCH

The proposed selectable multiband isolation DPDT switch with transmission line stub resonators has been designed for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz bands. The prototype of the switch is shown in Fig. 8. The switch circuit was built using microstrip model in Advance Design System (ADS) software. Then, it was fabricated using FR4 substrate with thickness of 1.6 mm and relative dielectric constant, εr of 4.7. PIN diodes (part number: BAP64-02) from NXP and the capacitors and inductors from Murata were used in the circuit design. The parasitic capacitance (Cj) and inductance (Ls) of PIN diodes were considered through the entire simulation process. Hence, the optimized dimensions of the resonators (S1, S2, S3 and S4) were as follows: $W = 2.9$ mm and $l = 7.35$ mm for 3.5 GHz; and $W = 2.9$ mm and $l = 13.5$ mm for 2.3 GHz. The width for all resonators

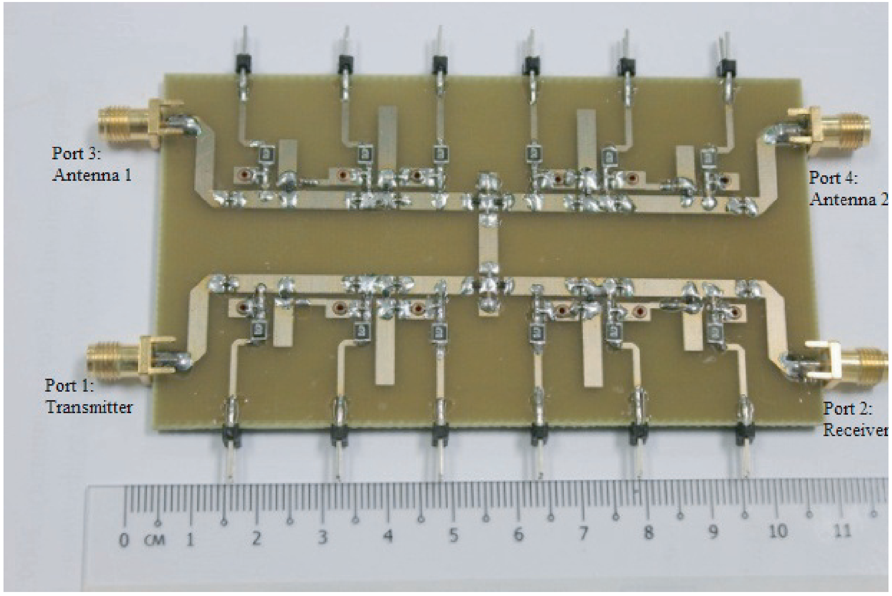

Figure 8. Prototype of the proposed selectable DPDT switch with switchable transmission line stub resonators, (dimension: 104 mm × 54 mm).

was equal (2.9 mm) for 50 Ω characteristic impedance. The overall area of the switch design equals to 55 mm × 104 mm. The value of the resistors at the biasing circuit was 47 Ω, so the total current was limited to 87.0 mA during simulation and 80.0 mA during measurement.

6.1. Case 1: Select 2.3 GHz Band Only

The simulation and measurement results of the isolation between transmitter and receiver are compared to each other, in Fig. 9(a), presenting good agreement where the isolation performance reached higher than 30 dB for the selected frequency, 3.5 GHz. However, the slight difference between measurement and simulation is probably because of substrate tolerance, fabrication and soldering processes. To analyze the switch circuit performances for WiMAX and LTE applications, the simulation and measurement results of the isolation, S_{12} (at 2.3 GHz) reached 41 dB and 33 dB respectively, whereas the isolation at 3.5 GHz is only 19 dB (in simulation) and 21 dB (in measurement). It is observed that there is a large difference between simulated and measured result. This, as mentioned in the previous section, was due to the additional parasitic capacitance and inductance of PIN diodes, and additional resistance during the soldering [31, 32]. However, both, the simulated and measured isolation are still greater than 30 dB which results in the ability of the selectable DPDT switch to isolate more than 1 Watt/10 Watt of power leakage in the RF front-end system.

The simulation and measurement results of return loss S_{11} for WiMAX and LTE applications

Table 4. Performance summary of selectable DPDT switch with transmission line stub resonators (case 1).

Selectable DPDT Switch		**Isolation (dB)**	**Return Loss (dB)**	**Insertion Loss (dB)**
2.3 GHz Band	***Simulation***	41.46	15.73	1.74
	Measurement	33.46	19.56	2.65
3.5 GHz Band	***Simulation***	19.10	17.19	2.36
	Measurement	21.32	13.10	3.90

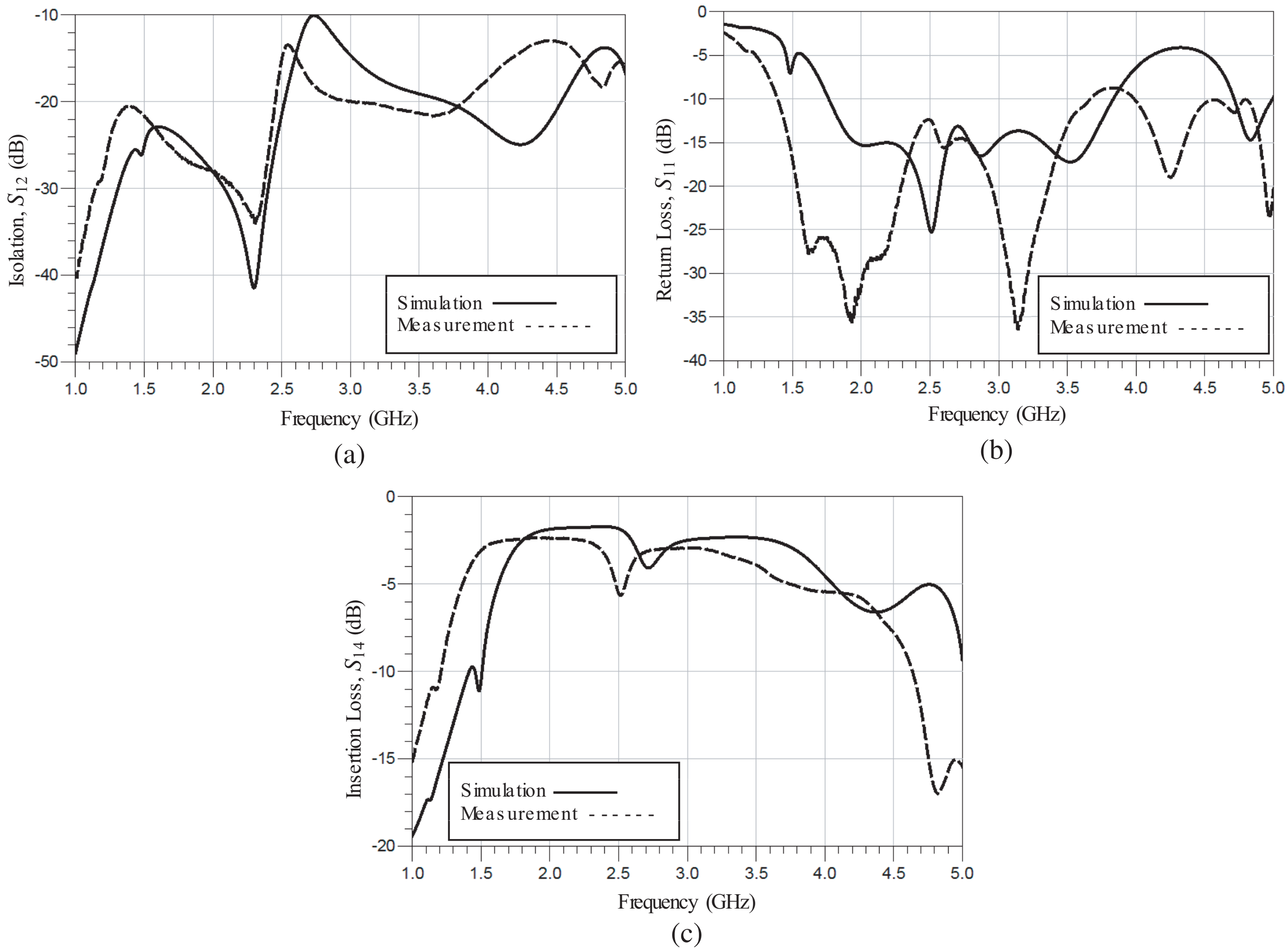

Figure 9. Simulation and measurement results of selectable multiband isolation DPDT switch (case 1), (a) isolation (S_{12}), (b) return loss (S_{11}), (c) insertion loss (S_{14}).

at 2.3 GHz and 3.5 GHz are compared to each other and shown in Fig. 9(b). For 2.3 GHz band, the simulated and measured return losses S_{11} are 15 dB and 19 dB, respectively. Whereas, for 3.5 GHz, the simulated return loss S_{11} achieves 17 dB, and the measured S_{11} achieves 13 dB. On the other hand, the result of insertion loss S_{14} for the applications and operation frequencies, mentioned above, is illustrated in Fig. 9(c). For 2.3 GHz band, the simulated insertion loss S_{14} is 1.7 dB while the measured one is 2.6 dB. For 3.5 GHz band, the simulated insertion loss S_{14} is 2.3 dB while the measured one is 3.9 dB. Table 4 summarizes all the simulation and measurement results of selectable multiband isolation DPDT switch with transmission line stub resonators (case 1).

6.2. Case 2: Select 3.5 GHz Band Only

The simulated and measured results of the isolation between transmitter and receiver are compared to each other, in Fig. 10(a), presenting good agreement where the isolation performance reaches higher than 30 dB for the selected frequency, 3.5 GHz. However, the slight difference between measurement and simulation is probably due to substrate tolerance, fabrication and soldering processes. To analyze the switch circuit performances for WiMAX and LTE applications, the simulation and measurement results of the isolation, S_{12} (at 3.5 GHz) reached 42 dB and 30 dB respectively, whereas the isolation at 2.3 GHz is only 15 dB (in simulation) and 17 dB (in measurement).

The simulation and measurement results of return loss S_{11} for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz are also compared to each other and shown in Fig. 10(b). For 2.3 GHz band, the simulated and measured return losses S_{11} are 14 dB and 25 dB, respectively. However, for 3.5 GHz, the simulated return loss S_{11} achieves 15 dB and the measured S_{11} achieves 13 dB. In contrast, the result of insertion loss S_{14} for the applications and operation frequencies, mentioned above, is illustrated in Fig. 10(c). For 2.3 GHz band, the simulated insertion loss S_{14} is 2.1 dB while the measured one is 2.6 dB. For 3.5 GHz band, the simulated insertion loss S_{14} is 2.2 dB while the measured one is 4.2 dB. Table 5 summarizes all simulation and measurement results of selectable multiband isolation DPDT switch with transmission line stub resonators (case 2).

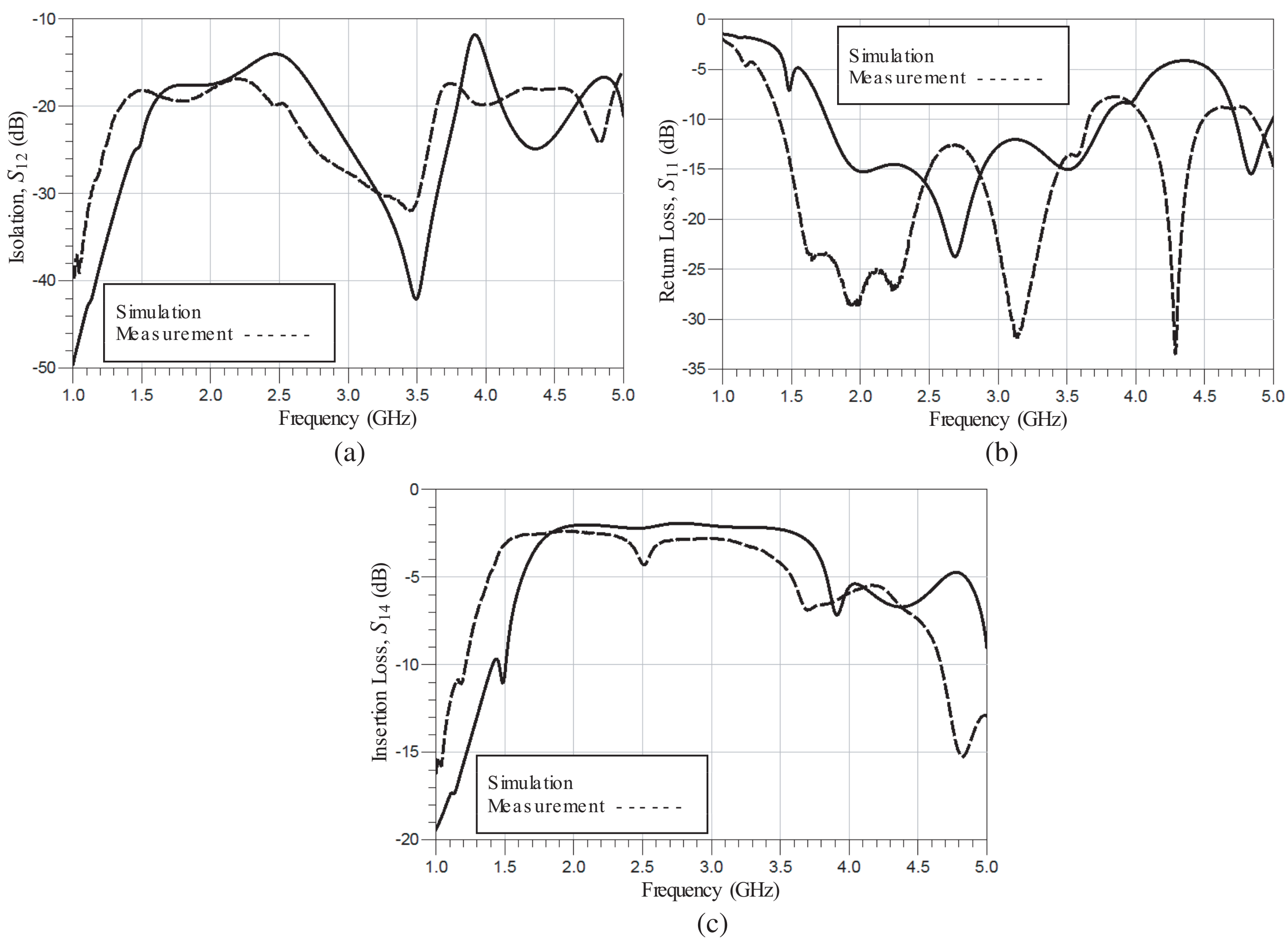

Figure 10. Simulation and measurement results of selectable multiband isolation DPDT switch (case 2), (a) isolation (S_{12}), (b) return loss (S_{11}), (c) insertion loss (S_{14}).

Table 5. Performance summary of selectable multiband isolation DPDT switch with transmission line stub resonators (case 2).

Selectable DPDT Switch		**Isolation (dB)**	**Return Loss (dB)**	**Insertion Loss (dB)**
2.3 GHz Band	***Simulation***	15.17	14.62	2.13
	Measurement	17.34	25.93	2.65
3.5 GHz Band	***Simulation***	42.02	15.02	2.29
	Measurement	30.85	13.67	4.21

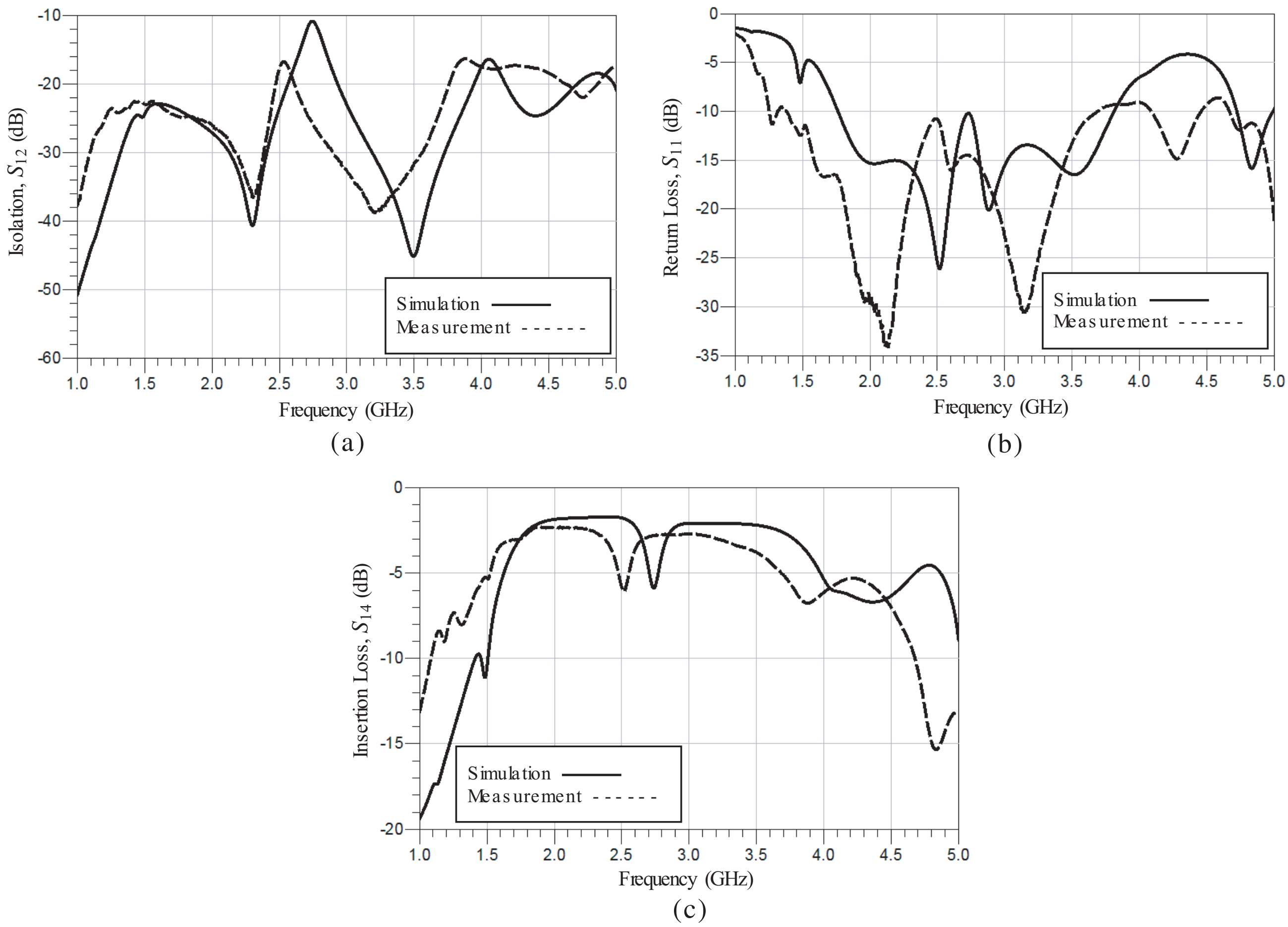

Figure 11. Simulation and measurement results of selectable multiband isolation DPDT switch (case 3), (a) isolation (S_{12}), (b) return loss (S_{11}), (c) insertion loss (S_{14}).

6.3. Case 3: Select 2.3 GHz and 3.5 GHz Bands

The simulated and measured results of the isolation are compared to each other, in Fig. 11(a), presenting good agreement where the isolation performance reached higher than 30 dB for the selected frequencies, 2.3 GHz and 3.5 GHz. However, the slight difference between measurement and simulation is probably because of substrate tolerance, fabrication and soldering processes. To analyze the switch circuit performances for WiMAX and LTE applications, the simulation and measurement results of the isolation, S_{12} (at 2.3 GHz) reached 40 dB and 36 dB, respectively whereas, the isolation at 3.5 GHz is 45 dB (in simulation) and 31 dB (in measurement).

The simulation and measurement results of return loss S_{11} for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz are compared to each other and shown in Fig. 11(b), respectively. For 2.3 GHz band, the simulated and measured return losses S_{11} are 15 dB and 18 dB, respectively. Whereas, for 3.5 GHz, the simulated return loss S_{11} achieves 16 dB and the measured S_{11} achieves 13 dB. On the other hand, the result of insertion loss S_{14} for the applications and operation frequencies, mentioned above, is illustrated in Fig. 11(c). For 2.3 GHz band, the simulated insertion loss S_{14} is 1.7 dB while the measured one is 2.6 dB. For 3.5 GHz band, the simulated insertion loss S_{14} is 2.2 dB while the measured one is 3.8 dB. Table 6 summarizes all simulation and measurement results of selectable multiband isolation DPDT switch (case 3).

It was found that for the fixed DPDT switch, the measured isolation reached greater than 33 dB for the two bands, 2.3 GHz band and 3.5 GHz band, while for the selectable DPDT switch, the isolation results were higher for 2.3 GHz (36 dB) and lower for 3.5 GHz (31 dB). However, the selectable DPDT

Table 6. Performance summary of selectable multiband isolation DPDT switch with transmission line stub resonators (case 3).

Selectable DPDT Switch		**Isolation (dB)**	**Return Loss (dB)**	**Insertion Loss (dB)**
2.3 GHz Band	***Simulation***	40.73	15.73	1.74
	Measurement	36.70	18.14	2.61
3.5 GHz Band	***Simulation***	45.16	16.44	2.21
	Measurement	31.54	13.26	3.80

Table 7. A comparison between the previous research works and this work.

	This Work	[12]	[11]	[10]
Technique	Switchable open stub resonator	Floating body and N-well	Bi-directional distributed amplifier	Layer-wise waveguide /actuator
Element	PIN diode	FET CMOS	SiGe HBT	MEMs
Application	WiMAX & LTE	General applications	UWB & Imaging	Active phased array antenna (APAA)
Isolation	36 dB	25 dB	30 dB	30 dB
Frequency	2.3 & 3.5 GHz	8.5–10.5 GHz	2–22 GHz	12 GHz
Size (Length $\times$Width) mm^2	72×54	2.06×0.58	1.07×0.98	2×4
DC Power	5 V	2.4 V	2.5 V	4 V
Selectable?	Yes	No	No	No

switch allows selecting only one band and unselecting the other or selecting both of them, while the fixed DPDT switch does not. In addition, by having more than 30 dB of isolation, these two switches can be appropriate for high power of wireless communication and can isolate more than 1 Watt/10 Watt of power leakage in the RF front-end systems.

7. COMPARISON BETWEEN THE PREVIOUS RESEARCH WORKS AND THIS WORK

As evident from Table 7, in comparison to previous researches [10–12], the results of the current study are in the highest isolation between transmitter and receiver (36 dB). In addition, it is the only selectable RF switch that is able to operate with different frequencies using single hardware and thus, overcoming the interference issue. As a matter of fact, results of previous studies are also in a good isolation performance ($>$ 25 dB). Yet, they are not appropriate to be utilized for high power applications due to their nature as (integrated circuits) [21], while the current research suits such application.

8. CONCLUSION

In this paper, we present a novel DPDT switch with switchable transmission line stub resonators for WiMAX and LTE in 2.3 and 3.5 GHz bands. Two DPDT switches are presented. The results indicate that while the selectable DPDT switch allows selecting only one band and unselecting the other or selecting both of them, the fixed DPDT switch does not allow this. The circuit operation of the cascaded switchable transmission line stub resonators was discussed where it could be reconfigured between allpass and bandstop responses at 2.3 and 3.5 GHz. Then, it was applied in a multiband isolation of DPDT switch design where it was connected in back to back SPDT switches configuration. The proposed DPDT switches were successfully simulated in ADS software and fabricated on an FR4 board. As a result, the DPDT switches showed more than 30 dB isolation, less than 3 dB insertion loss and greater than 10 dB return loss in 2.3 and 3.5 GHz bands. Moreover, more than 30 dB of multiband isolation, in both fixed and selectable DPDT switches, was obtained with only three discrete PIN diodes in each arm. These switches can be appropriate for high power of wireless communication and can isolate more than 1 Watt/10 Watt of power leakage in the RF front-end systems.

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