Selectable Multiband Isolation of Single Pole Double Throw Switch Using Transmission Line Stub Resonator for WiMAX and LTE Applications

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Abstract: This paper presents a selectable multiband isolation of Single Pole Double Throw (SPDT) switch with switchable transmission line stub resonators for applications of WiMAX and LTE in 2.3 and 3.5 GHz bands. Two SPDT switches are presented. (Design 2) either allows selecting only one band while unselecting the other or selecting both of them. However, (Design 1) 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 all-pass and band-stop responses using discrete PIN diodes. The key advantage of the proposed SPDT with switchable transmission line stub resonators is a multiband high isolation with a minimum number of PIN diodes. Therefore, the simulated and measured results showed the followings: 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

The rapid development in wireless communication systems led to switchable/selectable radio designs which are highly popular due to its ability to operate with different frequencies using single hardware. For instance, switchable slot antenna has been designed to support the entire UWB operation frequency, and 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 band-pass filter was proposed in [2] with the ability to switch between passband, 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 SPDT switchable band-pass 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.

For 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]–[7]. Meanwhile, Single Pole Double Throw (SPDT) switch (which is a part of

RF switches) is ordinarily used in RF front-end system to switch between up-link (Transmitter mode) and down-link (Receiver mode) [8]–[11] or, in general, to switch between two different signal paths [12]. From the literature, SPDT switches could be designed and used in applications such as Time Division Duplex (e.g. WiMAX and LTE) [13], [14], X- band applications [15], low frequency applications [10], communication and radar applications [9], millimeter-wave applications and high power applications [11] such as base statins which is the target for the proposed design.

SPDT switch topologies can be divided into two main topologies: asymmetrical [8], [16]–[18] and symmetrical [10], [11]. Both are used to perform switching for high power applications [11], [18] but the latter produces higher isolation than the former. On the other hand, there are three popular configurations for SPDTs: series [19], shunt [11] and series-shunt configurations [10]. However, the third configuration is the best choice when high isolation and high power applications of wireless communication such as base stations (BS), military and satellite communication are targeted, as reported in [20], [21].

RF switch (such as SPDT switch) elements can be categorized as micro-electro-mechanicals (MEMs) [22] or solid state elements such as PIN diode [9], [11] and field effect transistor (FET) [10], [23]. However, MEMs switches are not suitable for high power applications due to their limited power capabilities [24]. Moreover, they have not been widely used in RF and microwave applications since the PIN diode was developed and commercialized [20]. Additionally, solid state switches, such as PIN diode switch, show more reliability due to faster switching time and they accomplish a longer lifetime in comparison 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 [20], [25].

In SPDT switch design, high isolation plays an important role in preventing unwanted leakage signal [26]. Furthermore, to increase the switch's isolation, researchers have reported different techniques such as series PIN diode with compensation parasitic capacitance [27], a lumped λ/4 transformer [8], hollow waveguide [12], resistive bias network [10], and other techniques reported in [28]. However, for the solution of discrete circuit design using standard discrete PIN diode packages, there are trade-offs in these high isolation techniques such as increasing the overall circuit size, a higher number of PIN diodes, and a limited choice of lumped component values. On the other hand, for discrete RF switches such as [11], it is quite hard to get high isolation (> 30 dB) when using only discrete PIN diodes and usually multiple cascaded PIN diodes are required for high isolation performance.

Therefore, this paper proposes a selectable multiband isolation of SPDT 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 SPDT 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], switch [32] and microwave absorber [24]. Thus, by using this technique (resonator) and together with discrete PIN diodes in SPDT 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 mathematical modelling for the isolation of multiband SPDT switch with transmission line stub resonator in a simple analysis form. Fig. 1 shows two-port network of series-shunt PIN diode with transmission line open stub resonators. From this figure (Fig. 1), we analysed the ABCD matrix of two port network, thus taking into account that shunt PIN diodes are switched ON, while series PIN diode is switched OFF. Thus,

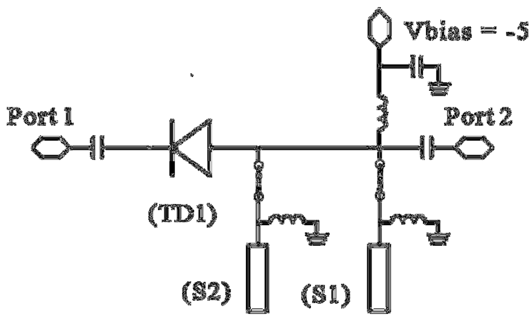

Fig. 1.*Two-port network of series-shunt PIN diode with open stub resonators*

$$(TD1) = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & Z \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & Rr + jXr \\ 0 & 1 \end{pmatrix} \quad (1)$$

Where $Z = Rr + jXr$ is known as the reference impedance of the PIN diode. Then we find the ABCD matrix for resonators (S1) and (S2);

$$(S1) = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{jZo\tan\theta} & 1 \end{pmatrix} \quad (2)$$

$$(S2) = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{jZo\tan\theta} & 1 \end{pmatrix} \quad (3)$$

Where Z_O is known as the impedance of the resonator. Then, to determine the isolation at 2.3 GHz, we replace Z_O by Z_{S2}. Thus

$$(TD1)(S2)=\begin{pmatrix}1 & Rr+jXr\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ \dfrac{j\tan\theta}{Z_{S2}} & 1\end{pmatrix} \tag{4}$$

$$(TD1)(S2)=\begin{pmatrix}1+\dfrac{j\left[Rr+jXr\right]\tan\theta}{Z_{S2}} & Rr+jXr\\ \dfrac{j\tan\theta}{Z_{S2}} & 1\end{pmatrix} \tag{5}$$

$$S_{21}=\frac{2}{A+\dfrac{B}{Z_O}+CZ_O+D} \tag{6}$$

Assume θ=π/2 (length of the quarter wave), Z_{S2}= Z_O=1. Therefore,

$$S_{21}=\frac{2}{2+\infty+Rr+jXr+\infty}\cong 0 \tag{7}$$

Convert to decibel;

$$\left|S_{21}\right|^2=20\log(0)=\infty dB \tag{8}$$

To determine the isolation at 3.5 GHz, we replace Z_O by Z_{S1}. Thus

$$(TD1)(S1)=\begin{pmatrix}1 & Rr+jXr\\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\ \dfrac{j\tan\theta}{Z_{S1}} & 1\end{pmatrix} \tag{9}$$

$$S_{21}=\frac{2}{A+\dfrac{B}{Z_{S1}}+CZ_{S1}+D} \tag{10}$$

Assume θ=π/2 (length of the quarter wave), Z_{S1} = 1.Therefore,

$$S_{21}=\frac{2}{2+\infty+Rr+jXr+\infty}\cong 0 \tag{11}$$

Convert to decibel;

$$\left|S_{21}\right|^2=20\log(0)=\infty dB \tag{12}$$

Theoretically, it is clearly observed that infinite isolationS_{21} can be achieved if Z_S=1 and θ=π/2. From (8 and 12), an ideal infinite attenuation (notch) was produced if the electrical length of the transmission line stub was a quarter wave (λ/4). This attenuation characteristic was used to produce multiband high isolation in SPDT switch.

3. Fixed SPDT Switch Design (Design 1)

Fig. 2 shows the diagram of multiband isolation fixed SPDT switch. Actually, four open stub resonators (S1, S2, S3 and S4) are used to achieve high isolation for WiMAX and LTE applications. Resonators S1 and S4 are assigned to resonate at 3.5 GHz, while S2 and S3 are assigned to resonate at 2.3 GHz. Quarter wavelength (λ/4) is placed in between S1 and S2 as well as between S3 and S4, in order to transform from low impedance of the resonators to high impedance in the microstrip line.

Generally, this circuit has been built to switch between the transmitter (Tx) mode and receiver (Rx) mode. To do so, series PIN diodes (D5 and D6) and shunt PIN diodes (D1-D4) are used. These PIN diodes are controlled by biasing circuits (Vbias 1 and Vbias 2).

In this section, we will discuss the circuit operation during the transmitter (Tx) mode only, due to the symmetrically construction of the SPDT switch circuit. Therefore, during the transmitter (Tx) mode process, as illustrated in Fig. 2, RF signals propagate from transmitter (Tx) to Antenna. In this case, series PIN diode D5 is turned ON, while shunt PIN diodes, in the transmitter (Tx) arm, D1 and D2 are turned OFF with voltage control, 5 V. So, transmission line open stub resonators S1 and S2 create all-pass response. On the other hand, series PIN diode D6 is turned OFF, while shunt PIN diodes, in receiver (Rx) arm, D3 and D4 are turned ON with voltage control, -5 V. So, transmission line open stub resonators S3 and S4 create band stop response. Obviously, in this process, the created band stop response in the receiver (Rx) arm is the most responsible of the isolation between transmitter (Tx) and receiver (Rx). Table 1 presents a summary of the process in receiver (Rx) and transmitter (Tx) modes of fixed multiband isolation SPDT switch using transmission line open stub resonators for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz bands.

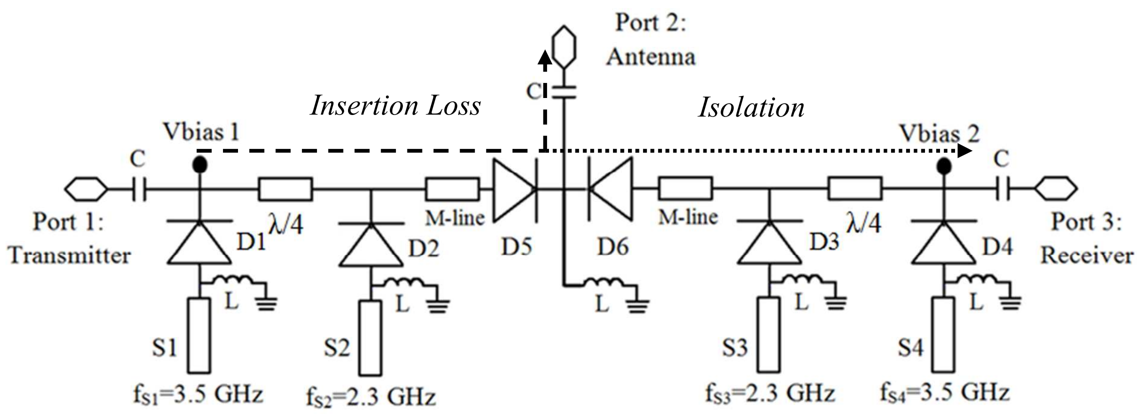

Fig. 2.*Circuit diagram of fixed multiband isolation SPDT switch, Design 1 (Transmitter mode)*

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Table 1 Summarization of the process in receiver and transmitter modes of fixed multiband isolation SPDT switch

	Receiver mode	Transmitter mode
Vbias1	-5 Volt	+5 Volt
Vbias2	+5 Volt	-5 Volt
Series PIN diode (D5)	OFF state	ON state
Series PIN diode (D6)	ON state	OFF state
Transmission Line Stub Resonators (S1, S2)	Band-stop response	All-pass response
Transmission Line Stub Resonators (S3, S4)	All-pass response	Band-stop response

4. Selectable SPDT Switch (Design 2)

Fig. 3 presents the diagram of selectable multiband isolation SPDT switch. In fact, this design is modified based on the previous design (Design 1). More capacitors and biasing circuits (Vbias 2, 3, 4 and 5) 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 general, this switch circuit is built to switch between the transmitter (Tx) mode and receiver (Rx) mode. To do so, series PIN diodes (D5 and D6) and shunt PIN diodes (D1-D4) are used. These PIN diodes are controlled by biasing circuits (Vbias 1 - Vbias 6). For the DC block, C, the chosen value is 10 pF in order to achieve high-pass response.

During the transmitter mode process, RF signals propagate from transmitter (Tx) to Antenna, as can be seen in Fig. 3. We have mentioned that in this design there are three different cases. In the first case (selecting 2.3 GHz band only), Vbias 1 and Vbias 6 must be deactivated. Then, in transmitter (Tx) arm, series PIN diode, D5 is turned ON, while shunt PIN diode, D2 is turned OFF with voltage control, 5 V. So, the transmission line open stub resonator S2 creates an all-pass response. On the other hand, in receiver (Rx) arm, series PIN diode D6 is turned OFF, while shunt PIN diode, D3 is turned ON with voltage control, -5 V. So, the transmission line open stub resonator S3 creates a band-stop response.

In the second case (selecting 3.5 GHz band only), Vbias2 and Vbias5 must be deactivated. Then, in the transmitter (Tx) arm, series PIN diode, D5 is turned ON, while shunt PIN diode, D1 is turned OFF with voltage control, 5 V. So, the transmission line open stub resonator S1 creates an all-pass response. In contrast, in receiver (Rx) arm, series PIN diode D6 is turned OFF, while shunt PIN diode, D4 is turned ON with voltage control, -5 V. So, the transmission line open stub resonator S4 creates a band-stop response.

In the third case (selecting both 2.3 GHz 3.5 GHz bands), all biasing circuits must be activated. Then, in the transmitter (Tx) arm, series PIN diode, D5 is turned ON, while shunt PIN diodes, D1 and D2 are turned OFF with voltage control, 5 V. So, transmission line open stub resonators, S1 and S2 create an allpass response. On the other hand, in the receiver (Rx) arm, series PIN diode D6 is turned OFF, while shunt PIN diodes, D3 and D4 are turned ON with voltage control, -5 V. So, transmission line open stub resonators S3 and S4 create a band-stop response. Obviously, in all cases, the created band-stop response in the receiver (Rx) arm is most responsible for the isolation between the transmitter (Tx) and the receiver (Rx). Table 2 presents a summary of the process in the receiver and transmitter modes of selectable multiband isolation SPDT switch using transmission line open stub resonators for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz bands.

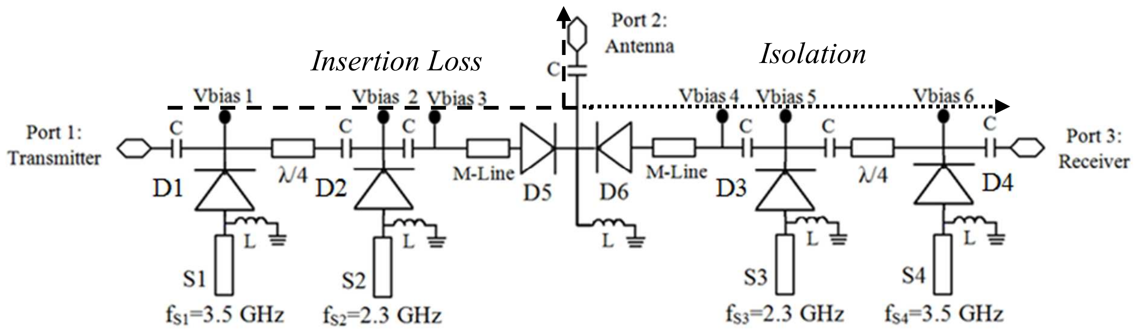

Fig. 3. *Circuit diagram of selectable multiband isolation SPDT, Design 2 (Transmitter mode)*

Table 2 Summarization of the process in receiver and transmitter modes of selectable multiband isolation SPDT switch

		Receiver mode	Transmitter mode
Case 1 (select 2.3 GHz band)	Vbias1	Deactivated	Deactivated
	Vbias2	-5 Volt	+5 Volt
	Vbias3	-5 Volt	+5 Volt
	Vbias4	+5 Volt	-5 Volt
	Vbias5	+5 Volt	-5 Volt
	Vbias6	Deactivated	Deactivated
	PIN diode (D5)	OFF state	ON state
	PIN diode (D6)	ON state	OFF state
	Resonator (S1)	No response	No response
	Resonator (S2)	Band-stop response	All-pass response
	Resonator (S3)	All-pass response	Band-stop response
	Resonator (S4)	No response	No response
Case 2 (select 3.5 GHz band)	Vbias1	-5 Volt	+5 Volt
	Vbias2	Deactivated	Deactivated
	Vbias3	-5 Volt	+5 Volt
	Vbias4	+5 Volt	-5 Volt
	Vbias5	Deactivated	Deactivated
	Vbias6	+5 Volt	-5 Volt
	PIN diode (D5)	OFF state	ON state
	PIN diode (D6)	ON state	OFF state
	Resonator (S1)	Band-stop response	All-pass response
	Resonator (S2)	No response	No response
	Resonator (S3)	No response	No response
	Resonator (S4)	All-pass response	Band-stop response

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Case 3 (select 2.3 and 3.5 GHz bands)	Vbias1	-5 Volt	+5 Volt
	Vbias2	-5 Volt	+5 Volt
	Vbias3	-5 Volt	+5 Volt
	Vbias4	+5 Volt	-5 Volt
	Vbias5	+5 Volt	-5 Volt
	Vbias6	+5 Volt	-5 Volt
	PIN diode (D5)	OFF state	ON state
	PIN diode (D6)	ON state	OFF state
	Resonator (S1)	Band-stop response	All-pass response
	Resonator (S2)	Bands-top response	All-pass response
	Resonator (S3)	All-pass response	Band-stop response
	Resonator (S4)	All-pass response	Band-stop response

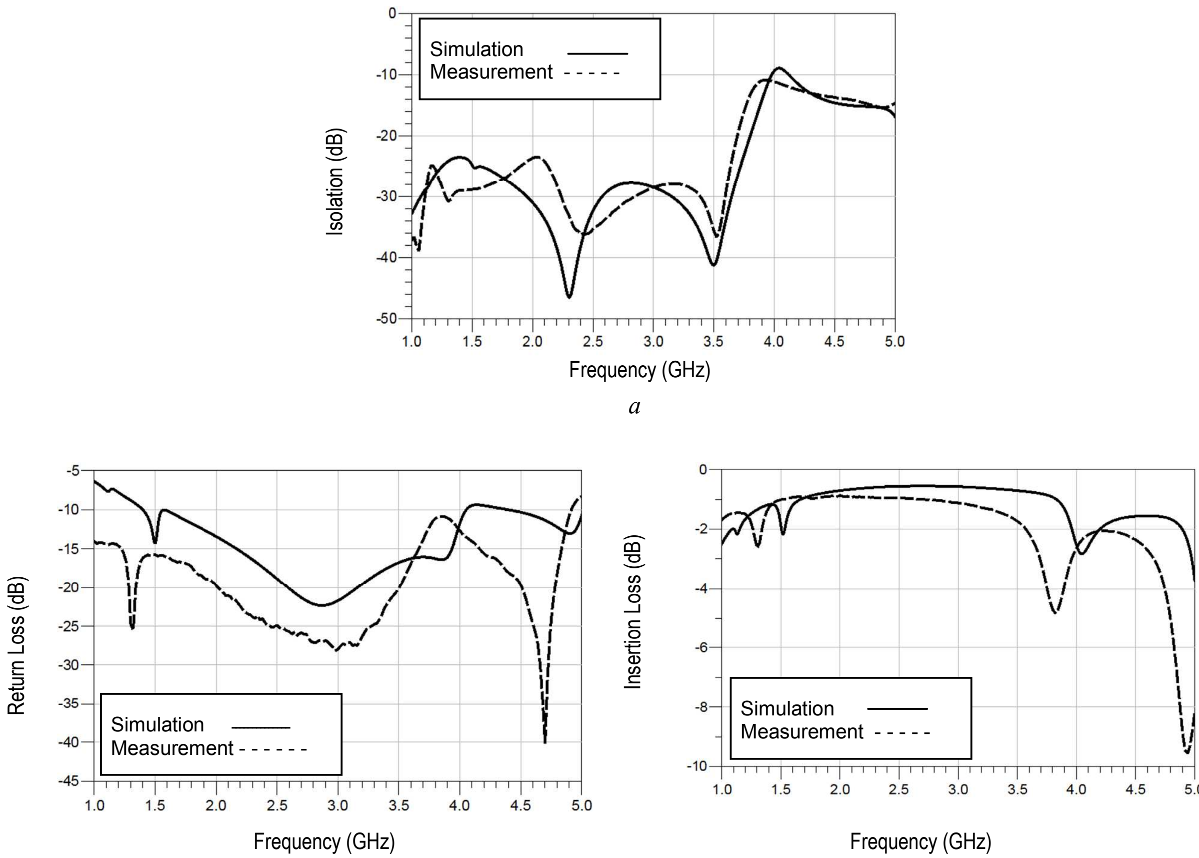
Advanced Design System (ADS) software was used for SPDTs, Design 1 and Design 2, performance simulation and layout design. In order to build up the switch circuit, a microstrip model in ADS was used based on FR4 substrate with the following parameters; thickness = 1.6 mm and relative dielectric constant, εr = 4.7. PIN diodes (part number: BAP64-02) from NXP and the capacitors and inductors from Murata were used in the circuit design as well. For the DC block, C, the chosen value is 10 pF in order to achieve a high pass response. For the RF choke, L, the chosen value is 10 nH to block RF signals at 2.3 GHz and 3.5 GHz.

5. Simulation and Measurement Results for SPDT Switch (Design 1)

Fig. 8(a) shows the prototype of fixed multiband isolation SPDT switch for WiMAX and LTE at 2.3 GHz and 3.5 GHz. The layout's total area of the switch design is 29 mm x 52 mm. The dimensions of the transmission line stub resonators (S1, S2, S3 and S4) were as follows. ForS1and S4, the final dimension were W = 2.9 mm and l = 7 mm (at 3.5 GHz). However, for S2 and S3, the final dimension where W = 2.9 mm and l = 13.45 mm (at 2.3 GHz). During the simulation process, these final dimensions were determined together with the parasitic effect of the PIN diodes such as the effect of junction capacitance and series inductance.

The simulation and measurement results were compared to each other in terms of the return loss, insertion loss and isolation, as shown in Fig. 4. As illustrated in Fig. 4 (a), the isolation performance (S_{13}) of the fixed multiband isolation SPDT switch reached more than 30 dB at 2.3 GHz and 3.5 GHz in simulation results as well as in the measurement result. In addition, it was found that more than 30 dB of isolation was obtained with only three PIN diodes in each arm; transmit arm and receive arm. By having more than 30 dB of isolation, the fixed SPDT switch can isolate more than 1 Watt/10 Watt of power leakage in the RF front-end system. However, the resonant frequency of isolation, 2.3 GHz (in measurement) shifted to a higher frequency (2.42 GHz) due to the passive/active component, tolerance of substrate as well as the fabrication process. Generally, the simulated isolation for WiMaX and LTE applications at 2.3 GHz and 3.5 GHz were 46.5 dB and 41.2 dB, respectively. While the measured isolation for 2.3 GHz and 3.5 GHz were 33.1 dB and 35.7 dB, respectively.

The simulation result and measurement result for the return loss (S_{11}) and insertion loss (S_{12}) for WiMAX application and LTE application are displayed in Fig. 4 (b) and Fig. 4 (c), respectively. As seen in Fig. 4 (b), for 2.3 GHz, the return loss (S_{11}) achieved 16.4 dB (in simulation) and 23.8 dB (in measurement). For 3.5 GHz, the return loss (S_{11}) achieved 16.7 dB and 20.0 dB in simulation and in measurement, respectively. As indicated in Fig. 4 (c), the simulated insertion loss (S_{12}) was 0.6 dB for 2.3 GHz and 0.7 dB for 3.5 GHz, while the measured insertion loss (S_{12}) was 0.9 dB for 2.3 GHz and 1.7 dB for 3.5 GHz. 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. Table 3 summarizes all the measured and simulated results of the fixed multiband isolation SPDT switch with transmission line stub resonators.



a

b *c*

Fig. 4.*Simulation and measurement results of SPDT switch (Design 1)*
a Isolation (S_{13})
b Return loss (S_{11})
c Insertion loss (S_{12})

Table 3 Performance summary of fixed multiband isolation SPDT switch with transmission line stub resonator (design 1)

Fixed SPDT Switch		Isolation (dB)	Insertion Loss (dB)	Return Loss (dB)
2.3 GHz band	Simulation	46.52	0.60	16.40
	Measurement	33.14	0.94	23.83
3.5 GHz band	Simulation	41.25	0.71	16.76
	Measurement	35.72	1.73	20.09

6. Simulation and Measurement Results for Selectable SPDT Switch (Design 2)

The selectable multiband isolation SPDT switch for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz was fabricated and its isolation, return loss and insertion loss were validated experimentally using the Agilent Network Analyzer (N5242A). Fig. 8(b) shows the prototype of the selectable multiband isolation SPDT switch. A parametric study was conducted and the optimized dimensions of the resonators (S1, S2, S3 and S4) were as follows: $W1= W4=$ 2.9 mm, $l1= l4=$ 7.35 mm, $W2= W3=$ 2.9 and $l2= l3=$ 13.6 mm. The total area of the prototype is 29 mm x 84 mm. The selectable multiband isolation SPDT switch can switch between transmitter mode and receiver mode in three different cases; case 1 is to select 2.3 GHz only, case 2 is to select 3.5 GHz only and case 3 is to select both 2.3 GHz and 3.5 GHz. The resistors value at the biasing circuit was 47 **Ω**. Therefore, 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

As seen in Fig. 5, the simulation and measurement results show a good agreement. In case 1, only 2.3 GHz band was selected (by voltage control) which can be applicable for WiMAX and LTE applications. To explain the results in details, both the measured and simulated isolation (S_{13}) are higher than 30 dB which can isolate more than 1 Watt/10 Watt of power leakage in the RF front-end system. The measured isolation between the transmitter and the receiver modes (S_{13}) is 44.65 dB, while the simulated isolation is 44.50 dB, as presented in Fig. 5(a).

Fig. 5(b) and Fig. 5(c) compare the simulation and measurement results of the return loss (S_{11}) and the insertion loss (S_{12}), respectively. As can be indicated in Fig. 5(b), the measurement result and simulation result of the return loss (S_{11}) at 2.3 GHz (for WiMAX and LTE applications) both reach higher than 10 dB, which is the minimum specification of the return loss. As can be seen in Fig. 5(c), the simulated insertion loss (S_{12}) is 1.1 dB, while the measured insertion loss (S_{12}) is 1.2 dB. However, the slight difference between the simulation and measurement results is probably attributed to substrate tolerances, active or passive components and fabrication process. Table 4 summarizes all simulation and measurement results of the multiband isolation SPDT switch with transmission line stub resonators (case 1).

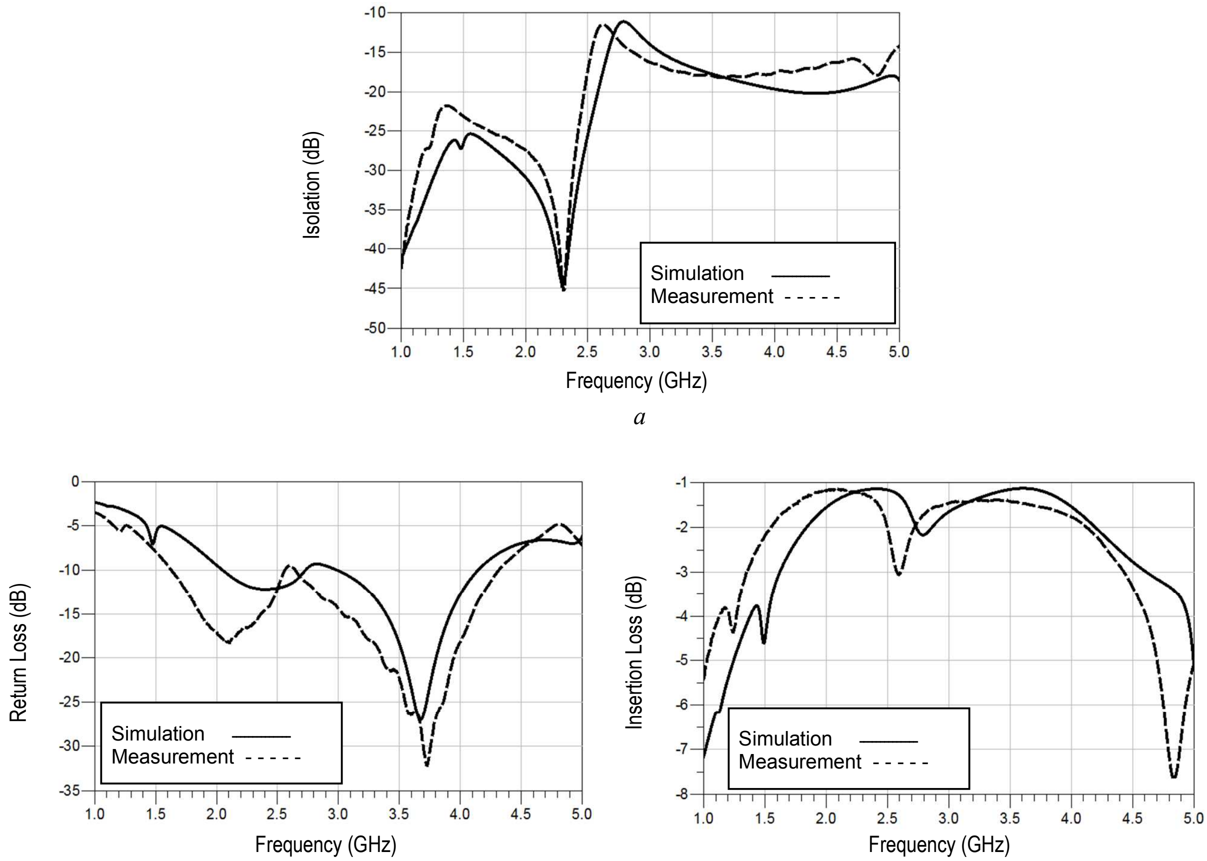


Fig. 5.*Simulation and measurement results of selectable multiband isolation SPDT switch (case 1)*
a Isolation (S_{13})
b Return loss (S_{11})
c Insertion loss (S_{12})

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

Selectable SPDT Switch		Isolation (dB)	Return Loss (dB)	Insertion Loss (dB)
2.3 GHz band	Simulation	44.50	12.00	1.16
	Measurement	44.65	16.06	1.24
3.5 GHz band	Simulation	17.77	18.37	1.15
	Measurement	18.00	22.28	1.41

6.2. Case 2: Select 3.5 GHz Band Only

The simulated and measurement results of the isolation between the transmitter and receiver were also compared to each other. As shown in Fig. 6(a), there is a 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 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_{13} (at 3.5 GHz) reached 43 dB and 35 dB, respectively whereas, the isolation at 2.3 GHz is only 17 dB (in simulation) and 14 dB (in measurement).

The simulation and measurement results of the return loss, S_{11} for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz were compared to each other as shown in Fig. 6(b). For 2.3 GHz band, the simulated and measured return loss, S_{11} are 11 dB and 14 dB, respectively, whereas, for 3.5 GHz, the simulated return loss, S_{11} achieved 19 dB and the measured S_{11} achieved 18 dB. On the other hand, the result of the insertion loss $S_{12}$for the applications and operation frequencies, mentioned above, is illustrated in Fig. 6(c). For 2.3 GHz band, the simulated insertion loss, S_{12} is 1.3 dB, while the measured is 1.4 dB. For 3.5 GHz band, the simulated insertion loss, S_{12} is 1.0 dB, whereas the measured is 1.4 dB. Table 5 summarizes all simulation and measurement results of the multiband isolation SPDT switch with transmission line stub resonators (case 2).

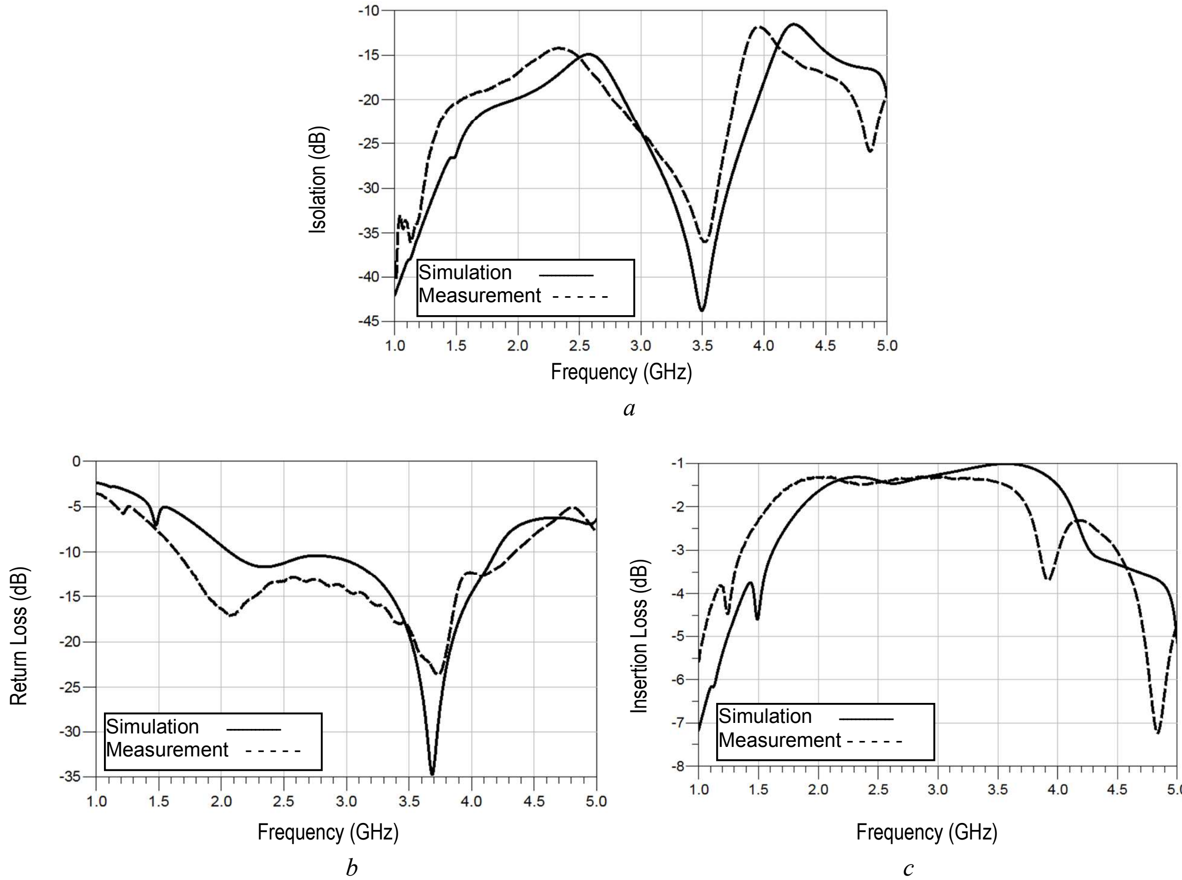


Fig. 6.*Simulation and measurement results of selectable multiband isolation SPDT switch (case 2)*
a Isolation (S_{13})
b Return loss (S_{11})
c Insertion loss (S_{12})

Table 5 Performance summary of selectable SPDT switch with transmission line stub resonators (case 2)

Selectable SPDT Switch		Isolation (dB)	Return Loss (dB)	Insertion Loss (dB)
2.3 GHz band	Simulation	17.49	11.60	1.31
	Measurement	14.27	14.59	1.4
3.5 GHz band	Simulation	43.77	19.17	1.01
	Measurement	35.80	18.44	1.43

6.3. Case 3: Select 2.3 and 3.5 GHz Bands

The simulated and measurement results of isolation were compared to each other. In Fig. 7(a), there is a good agreement where the isolation performance reached higher than 30 dB for 3.5 GHz band. However, the slight difference between measurement and simulation, shown in Fig. 7, is probably because of substrate tolerance, fabrication and soldering processes. For analysing the switch circuit performances for WiMAX and LTE applications, the simulation result of isolation, $S_{13}$is 43 dB (for 2.3 GHz) and 45 dB (for 3.5 GHz), while the measurement result is 42 dB (for 2.3 GHz) and 40 dB (for 3.5 GHz).

The simulation and measurement results of the return loss, S_{11} for WiMAX and LTE applications at 2.3 GHz and 3.5 GHz were also compared to each other as shown in Fig. 7(b). For 2.3 GHz band, the simulated and measured return loss, S_{11} are 12 dB and 16 dB, respectively. However, for 3.5 GHz, the simulated return loss, S_{11} achieved 19 dB and the measured S_{11} achieved 21dB. In contrast, the result of insertion loss S_{12} for the applications and operation frequencies, mentioned above, is illustrated in Fig. 7(c). For 2.3 GHz band, the simulated insertion loss, S_{12} is 1.1 dB, while the measured is 1.3dB. For 3.5 GHz band, the simulated insertion loss, S_{12} is 1.0 dB, while the measured is 1.3dB. Table 6 summarizes all simulation and measurement results of the selectable multiband isolation SPDT switch with transmission line stub resonators (case 3).

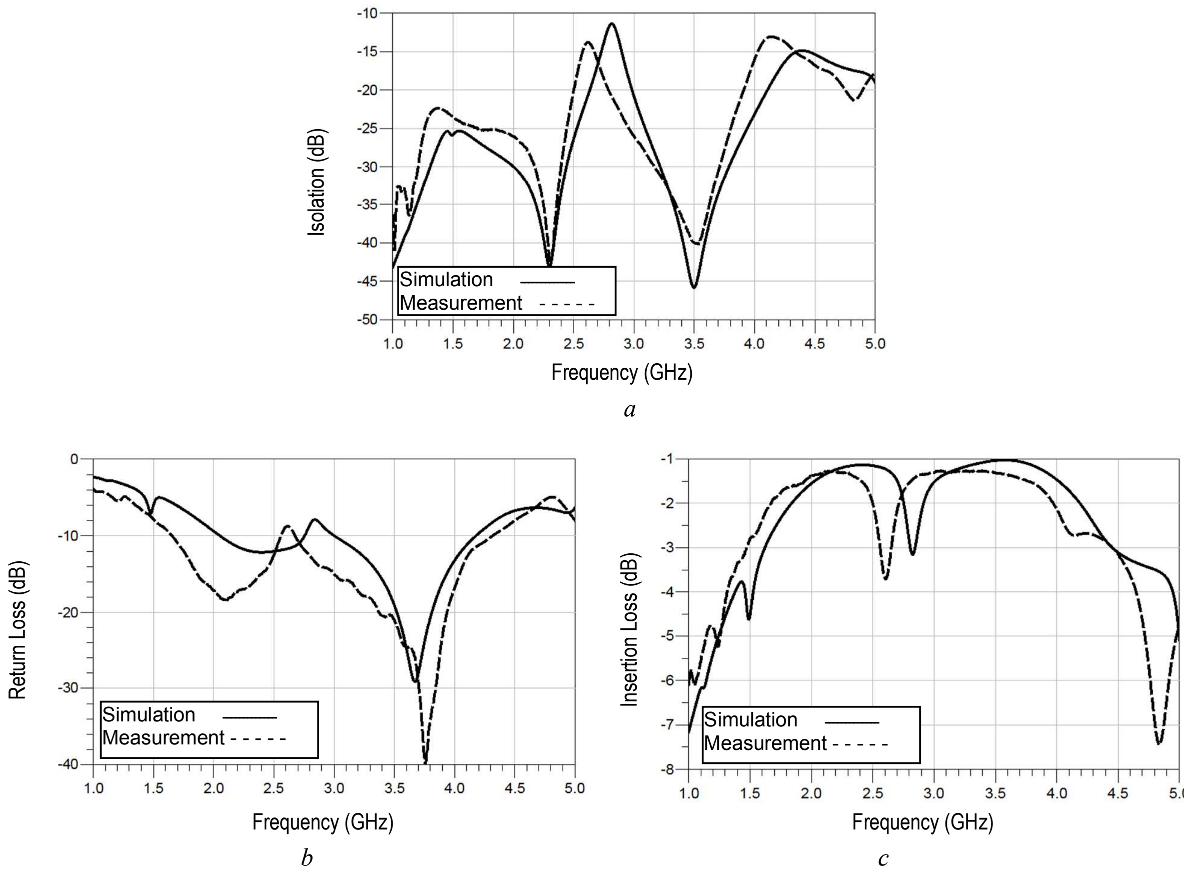
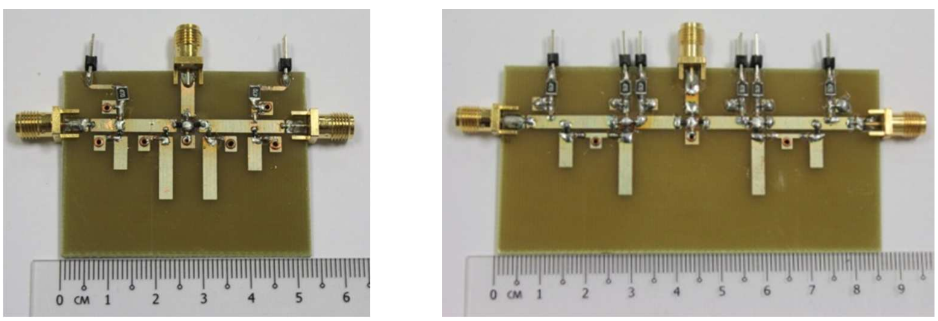


Fig. 7.*Simulation and measurement results of selectable multiband isolation SPDT switch (case 3)*
a Isolation (S_{13})
b Return loss (S_{11})
c Insertion loss (S_{12})

Table 6 Performance summary of selectable SPDT switch with transmission line stub resonators (case 3)

Selectable SPDT Switch		Isolation (dB)	Return Loss (dB)	Insertion Loss (dB)
2.3 GHz band	Simulation	43.07	12.00	1.16
	Measurement	42.00	16.44	1.32
3.5 GHz band	Simulation	45.79	19.09	1.03
	Measurement	40.04	21.04	1.31

It was found that, in (Design 1), the isolation reached around 33 dB for 2.3 GHz and 35 dB for 3.5 GHz while, in (Design 2), the isolation results were higher as they reached 42 dB for 2.3 GHz and 40 dB for 3.5 GHz. These were the measurement results, as the designs were fabricated in order to validate the simulation results. Only six PIN diodes were enough for each switch to get the mentioned high isolation performance due to the use of the transmission line stub resonators. However, (Design 2) allows selecting only one band and unselecting the other or selecting both of them, while (Design 1) does not do so. By having more than 30 dB of isolation, these two designs 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. Table 7 presents a comparison between the previous research works and this work.



a *b*

Fig. 8.*The prototype of selectable and fixed multiband isolation*
a Design 1
b Design 2

Table 7 Comparison between the previous research works and this work

Works	Technique	Element	App	S13(dB)	Selectable
This Work	Switchable open stub resonator	PIN Diode	WiMAX / LTE	44.6	Yes
[8]	lumped λ/4transformer	PIN diode	T/R	26	No
[11]	Switchable open stub resonator	PIN Diode	WiMAX / LTE	37	No
[15]	Resonator	PIN Diode	X-band	15-31	No
[27]	Series PIN diode with compensation parasitic capacitance	PIN diode	Radar (S-band)	19	No
[12]	Hollow waveguide	-	W-band	16	No
[34]	HMSIW units	-	-	28.5	No

7. Conclusion

A new SPDT switch with switchable transmission line stub resonators was successfully designed and validated at 2.3 and 3.5 GHz bands. Two SPDT switches were proposed. The results indicate that while (Design 2) allows selecting only one band and unselecting the other or selecting both of them, (Design 1) does not allow this. The circuit operation of the cascaded switchable transmission line stub resonators was discussed where it could be reconfigured between all-pass and band-stop responses at 2.3 and 3.5 GHz. Then, it was applied in a multiband isolation of SPDT switch design where it was designed using series-shunt configuration. The two SPDT switches, Design 1 and Design 2, were successfully simulated in ADS software and fabricated on the FR4 board. As a result, the designs 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 designs, was obtained with only three discrete PIN diodes in each arm. This type of design is a suitable for multiband RF front-end application such as in WiMAX and LTE.

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