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DESIGN OF SPDT SWITCH WITH TRANSMISSION LINE STUB RESONATOR FOR WIMAX AND LTE IN 3.5 GHZ BAND

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ABSTRACT

A Single Pole Double Throw (SPDT) switch design with transmission line stub resonator for application of WiMAX and LTE in 3.5 GHz band is proposed in this paper. The transmission line stub resonator is an open stub with quarter wave of the electrical length. A PIN diode was used in the resonator to reconfigure the resonator between bandstop and allpass responses. The implementation of the transmission line stub resonators in SPDT switch design was discussed together with the circuit operation. The result showed that the isolation of SPDT switch with transmission line stub resonator was higher than 30 dB in the 3.5 GHz band compared to the conventional design and it was verified with measurement results.

Keywords: RF switch, SPDT, resonator, transmission line stub, switchable resonator, bandstop to allpass.

INTRODUCTION

In Time Division Duplex (TDD) communication systems such as WiMAX [1] and LTE [2], Single Pole Double Throw (SPDT) switch is commonly used in RF front-end system to switch between transmitter [3] and receiver [4]. This allows a switching between uplink (transmit mode) and downlink (receive mode) for data transmissions. As illustrated in Figure-1, in the RF front-end system, the SPDT switch is a part of other subcomponents such as amplifier [5], [6] , low noise amplifier (LNA) [7] and antenna [8].

To minimize any RF power leakage between the transmitter and receiver, high isolation (especially for high power application) is the key parameter in SPDT switch design. Therefore, discrete PIN diodes are still desirable for this higher power application used in military, satellite communication or base station applications [9].

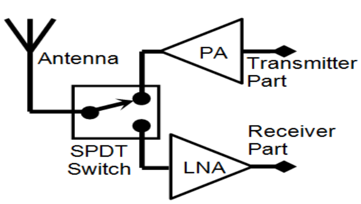

Figure-1. SPDT switch in RF front-end system.

For low frequencies application especially in L-band (1 - 2 GHz) and S-band (2 - 4 GHz) [10], the discrete PIN diodes are usually in standard packaging such as SOT23, SOT323, SOD323 or SOD523 [11], [12]. However, it is difficult to get isolation higher than 25 dB (for applications above 3 GHz) if using only single discrete PIN diodes in SPDT switch design.

On the other hand, there are several techniques of isolation improvements such as material with fabrication process design, circuit design, resonant circuit, transmission line and resonator [13]. Most of these techniques were applied in SPST and Single Pole Multi Throw (SPMT) switches. In general, resonators can be used in several circuit designs such as filter [14], [15], microwave absorber [16], amplifier [5] and antenna [17], [18].

In this paper, a transmission line stub resonator is proposed in SPDT switch design for application of WiMAX and LTE in 3.5 GHz band. By using this resonator, high isolation was obtained compared to conventional single shunt SPDT switch.

Transmission line stub resonator

Figure-2 is a general diagram of transmission line stub resonator, whereby it was connected in shunt with a 50 Ω transmission line.

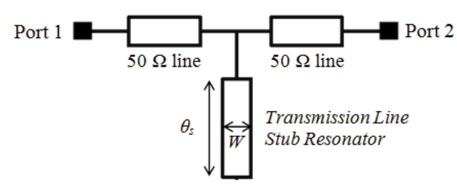

Figure-2. Transmission line stub resonator.

The transmission line stub resonator is an open stub resonator. Hence, the input impedance of the resonator was mathematically modeled as

$$Z_{in} = \frac{Z_s}{j \tan \theta_s} \tag{1}$$

where Z_s is characteristic impedance of resonator and θ_s is electrical length in degree. From (1), the *ABCD* matrix of the resonator was given by

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$$[T_s] = \begin{bmatrix} 1 & 0 \\ Y_{in} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \left(\frac{j \tan \theta_s}{Z_s}\right) & 1 \end{bmatrix}. \quad (2)$$

The transmission line stub resonator is a reciprocal and symmetrical network, whereby $S_{12} = S_{21}$. Therefore, the S_{12} and the S_{21} of the resonator were obtained by converting the *ABCD* matrix in (2) to *S*-parameter. Hence,

$$S_{12} = S_{21} = \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D} = \frac{2}{2 + \left(\frac{j \tan\theta_s}{Z_s}\right) Z_0}. \quad (3)$$

Consider a normalized characteristic of impedance where $Z_0 = 1$ and impedance of resonator, $Z_s = Z_0 = 1$. In order to produce attenuation or notch response of the resonator, the electrical length was $\theta_s = 90°$ (or $\pi/2$ radian). Hence, the *S*-parameter of (3) becomes,

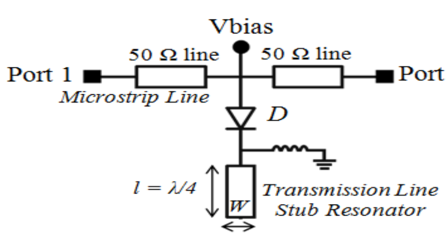
$$S_{12} = S_{21} \approx 0 \quad (4)$$

or in decibel

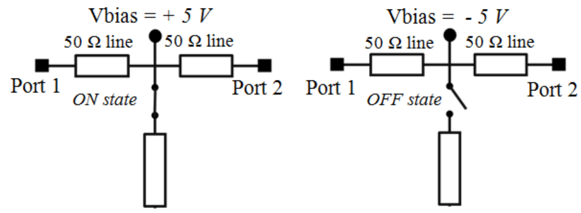
$$|S_{12}|^2 \text{dB} = |S_{21}|^2 \text{dB} = 20 \log_{10}(0) = \infty \text{ dB}. \quad (5)$$

From (5), an ideal infinite attenuation or notch were obtained when the electrical length of the open stub resonator was a quarter wave ($\lambda/4$). In degree and radian, they were 90° and $\pi/2$ radian respectively. These attenuation characteristics were used to produce high isolation of SPDT switch.

To allow transmit and receive mode switching operation in SPDT switch, the transmission line stub resonator was attached with a PIN diode as illustrated in Figure-3(a). The PIN diode was connected in between the microstrip line and stub resonator, hence the switchable stub resonator could be performed by giving a different biasing voltage. As depicted in Figure-3(b), if a positive voltage was applied (+5 V), the PIN diode, *D* would be in the ON state and the transmission line stub resonator would be connected to the microstrip line. In this condition, it operated as a bandstop filter due to the quarter wave ($\lambda/4$) line of the open stub resonator, converting from an open to short circuit to the main microstrip transmission line. If a negative voltage (-5 V) was applied (as shown in Figure-3(c)), *D* would be in the OFF state and the transmission line stub resonator would be disconnected from the microstrip line. In this condition, the transmission line stub resonator responded as an allpass between Port 2 and Port 1.



(a)



(b) (c)

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

SPDT Switch design

Conventional single shunt SPDT switches was designed (as shown in Figure-4(a)) for isolation performance comparison to the proposed SPDT switch with transmission line stub resonator. A quarter wavelength of transmission line ($\lambda/4$) was used in order to transform the short circuit (created by the ON state of shunt PIN diode) to an open circuit at transmit and receive transmission line junctions. For example, during transmit mode, the transmitted RF signals from Port 1 to Port 2 would see high impedance at this transmission line junction. Hence, there would be almost no RF leakage from Port 1 to Port 3.

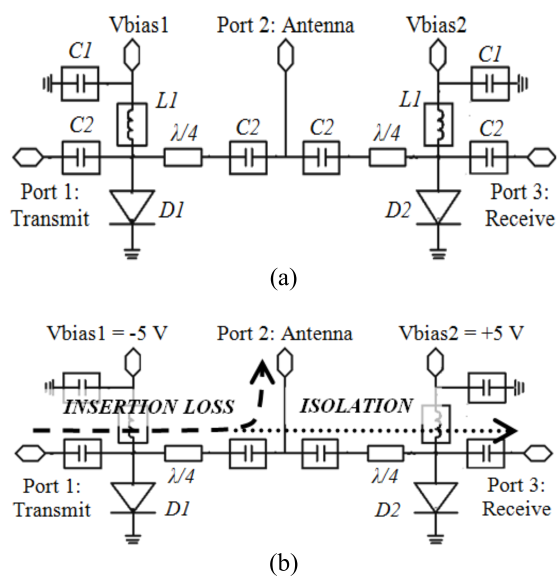


Figure-4. (a) Circuit diagram of conventional shunt SPDT switch; and (b) Circuit operation during transmit mode.

Figure-4(b) is the circuit operation of single shunt SPDT discreet switch. Since the circuit of SPDT switch is symmetrical, this paper discusses the operation in transmit mode only. Hence, during transmit mode operation, *D1* must be turned OFF and *D2* must be turned ON with Vbias1 = - 5 V and Vbias2 = + 5 V. In this condition, the RF signals propagated from Port 1 (Transmit) to Port 2 (Antenna) that was measured as insertion loss. The

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transmit arm should produce very low RF signal losses. The isolation between Port 3 (Receive) and Port 1 (Transmit) was obtained from the ON state of PIN diode (*D2)* in the receive arm.

Figure-5 shows SPDT switch with transmission line stub resonator. In each arm (transmit and receive circuits), the switchable transmission line stub resonators (*S1* and *S2*) were cascaded with conventional single shunt SPDT switch. They were spaced with quarter wave ($\lambda/4$) line to convert from low impedance of transmission line stub resonator to high impedance in the microstrip line.

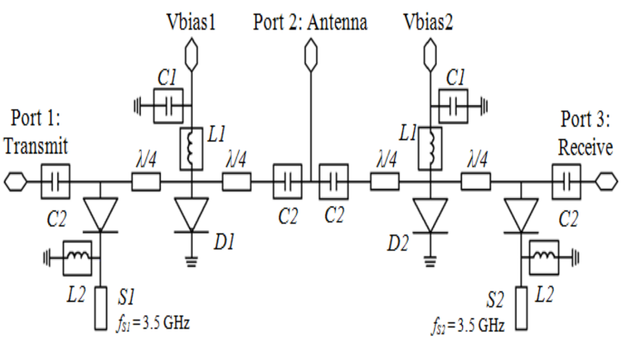


Figure-5. Circuit diagram of SPDT switch with transmission line stub resonator.

During transmit mode operation, the *D2* and PIN diode of *S2* were turned ON with voltage control of +5 V, and *D1* and PIN diode of *S1* were turned OFF with voltage control of -5 V. In this condition, the *S1* produced an allpass response and RF signals with low insertion loss propagated from Port 1 (Transmit) to Port 2 (Antenna). The switchable transmission line stub resonator (*S2)* in receive arm (Port 3) acted as a bandstop filter, hence produced an additional isolation in the SPDT switch.

Table-1 summarizes the circuit operation during transmit and receive modes of SPDT switch with transmission line stub resonator for WiMAX and LTE in 3.5 GHz band.

Table-1. Summary of circuit operation of SPDT switch with switchable transmission line stub resonator.

	Transmit Mode	Receive Mode
Vbias1	-5 Volt	+5 Volt
Vbias2	+5 Volt	-5 Volt
Shunt PIN diode (*D1*)	OFF state	ON state
Shunt PIN diode (*D2*)	ON state	OFF state
Transmission Line Stub Resonator 1 (*S1*)	Allpass response	Bandstop response
Transmission Line Stub Resonator 2 (*S2*)	Bandstop response	Allpass response

The SPDT switch with transmission line stub resonator circuit in Figure-5 was constructed in Advanced Design System (ADS) software for performance simulation and layout design. Using microstrip model in ADS, all the FR4 substrate parameters were included in the circuit design having thickness of 1.6 mm and relative dielectric constant, ε_r of 4.7. The commercial PIN diodes (part number: BAP64-02) from NXP were used in the circuit design. Through a simulation process, the final dimensions of transmission line stub in the SPDT discrete switch design were determined together with the parasitic effect of the PIN diode model. This means that the parameters of PIN diode such as junction capacitance (C_j) and series inductance (L_s) were taken into account in the resonator design. Therefore, the final dimensions of the resonator were W = 7 mm and l = 5.25 mm. The prototype of the SPDT switch circuit is shown in Figure-6. The total area of the circuit was 57 mm x 20 mm.

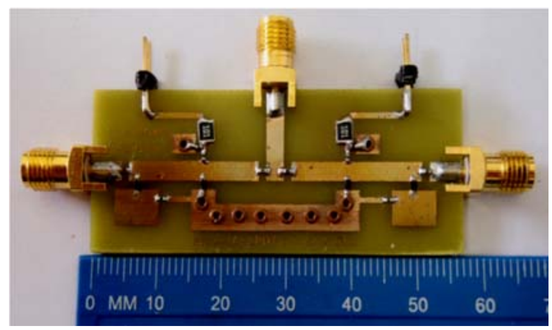
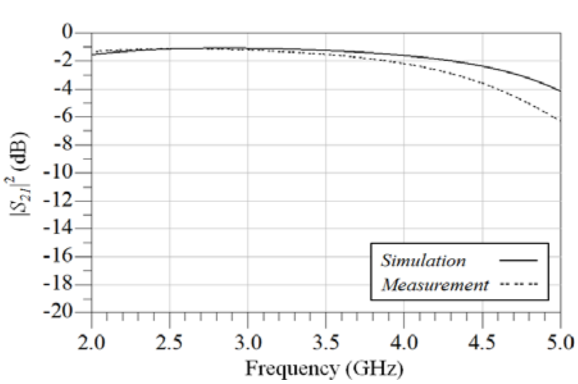


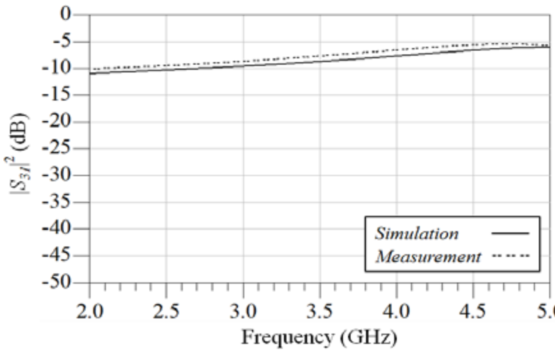
Figure-6. Prototype of SPDT switch with switchable transmission line stub resonator.

Simulation and measurement results

Figure-7 shows the simulated and measured results of conventional single shunt SPDT switch in 3.5 GHz band (3.4 to 3.6 GHz). In general, both simulated and measured results were comparable to each other. As shown in Figure-7(a), the insertion loss, S_{21} was from 0.76 to 0.77 dB in simulation and from 1.28 to 1.29 dB in measurement. Meanwhile, the simulated isolation, S_{31} as shown in Figure 7(b) was from 8.9 to 8.5 dB while the measured isolation was from 7.8 to 7.4 dB. It showed that the isolation of single shunt PIN diode (in discrete packaged form) was very low and insufficient to isolate high RF power leakage between transmitter and receiver in the RF front-end system.



(a)



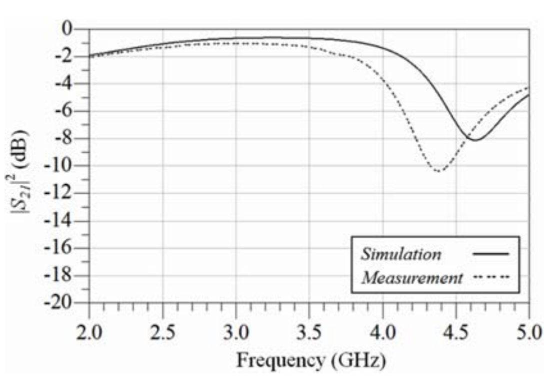
(b)

Figure-7. Simulated and measured results of conventional SPDT switch, (a) insertion loss (S_{21}), (b) isolation (S_{31}).

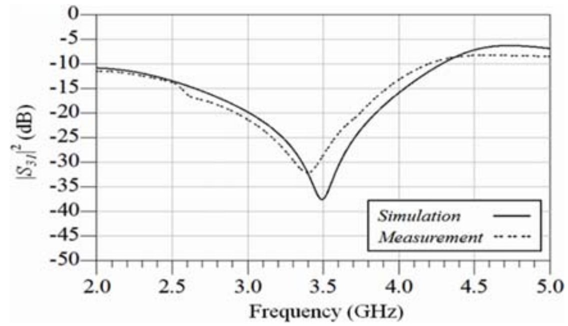
Figure-8 shows the simulated and measured results of SPDT switch with transmission line stub resonator in 3.5 GHz band (3.4 to 3.6 GHz). As shown in Figure-8(a), the insertion loss, S_{21} was from 0.64 to 0.71 dB in simulation and from 1.20 to 1.55 dB in measurement.

As shown in Figure-8(b), the isolation performance of SPDT switch with transmission line stub resonator was more than 25 dB at 3.5 GHz. However, the resonant frequency of the isolation, 3.5 GHz (in simulation) had shifted 3.14 % to lower frequency, which was 3.39 GHz (in measurement). The simulated and measured isolations at resonant frequency were 37.5 dB (at 3.5 GHz) and 32.2 dB (at 3.39 GHz) respectively. This was due to tolerances of substrate, passive/active device and fabrication process in the prototyping stage. Then, by analyzing the circuit performances for WiMAX and LTE applications from 3.4 - 3.6 GHz, the simulated isolation, S_{31} was from 32.5 to 30.8 dB while the measured isolation was from 32.2 to 24.2 dB. Therefore, it was found that a high isolation of SPDT discreet switch was obtained by cascading a single shunt PIN diode (in conventional design) with transmission line stub resonator.

The isolation performance comparison in 3.5 GHz band (3.4 to 3.6 GHz) is summarized in Table-2. The comparison is made between the conventional single shunt SPDT switch and the SPDT switch with transmission line stub resonator.



(a)



(b)

Figure-8. Simulated and measured results of SPDT switch with transmission line stub resonator, (a) insertion loss (S_{21}), (b) isolation (S_{31})

Table-2. Summary and comparison of isolation performance of SPDT switches for WiMAX and LTE from 3.4 to 3.6 GHz.

SPDT Switch		Isolation (dB)
Single Shunt	Simulation	8.9 - 8.5
	Measurement	7.8 - 7.4
Single Shunt with Resonator	Simulation	32.5 - 30.8
	Measurement	32.2 - 24.2

CONCLUSIONS

The SPDT switch with switchable transmission line stub resonator was designed in 3.5 GHz band. The application is TDD switching of WiMAX and LTE communication systems. The theory and circuit operation of the transmission line stub resonator were derived and explained where it can be reconfigured between bandstop and allpass responses. It was then implemented in SPDT switch design and was successfully fabricated to validate the measured results with simulated results. It showed that more than 30 dB isolation in the 3.5 GHz band can be achieved compared to the conventional single shunt SPDT switch.

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