Switchable Radial Stub Resonator for Isolation Improvement of SPDT Switch

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***Abstract*—This paper proposes switchable radial stub resonator for isolation improvement of Single Pole Double Throw (SPDT) discrete switch for Time Division Duplex (TDD) switching of wireless communications. A commercialized discrete PIN diode is used to switch the radial stub resonator between bandstop to allpass response where an analytical modeling of the switchable resonator is presented and analyzed. In this analysis, correlation between inner radial and angle radial stub with the characteristic impedance and attenuation pole is determined. Isolation improvement is analyzed with two-port network of single shunt PIN diode with switchable radial stub resonator where it is found that an additional isolation can be obtained with the switchable radial stub resonator. In measurement result, the SPDT switch with switchable radial stub resonator has shown more than 30 dB of transmit-receive (Tx-Rx) isolation at centre frequency of 3.5 GHz giving better isolation compared to conventional SPDT switch design. The potential application of this SPDT switch is TDD switching for WiMAX and LTE communication system.**

Keyword-RF switch, SPDT, resonator, radial stub, switchable resonator

I. Introduction

In wireless data communications using Time Division Duplex (TDD), Single Pole Double Throw (SPDT) switch is commonly used in RF front-end system [1] to switch between transmitter and receiver. As illustrated in Fig. 1, the SPDT switch is part of other subcomponents such as antenna [2]-[3], filter [4], amplifier [5] and mixer (up-converter or down-converter) [6]. Until now, the switching elements in the SPDT switch can use either PIN diodes or FETs where discrete PIN diodes are still desirable for higher power levels used in military, satellite communication or base station applications [7].

One of the key parameters in SPDT switch design is the requirement of high isolation between transmitter and receiver port. However, it is difficult to get isolation of SPDT switch higher than 20 dB (for applications above 3 GHz) if using single low performance PIN diodes. The PIN diodes are usually in standard packaging such as SOT23, SOT323, SOD323 or SOD523.

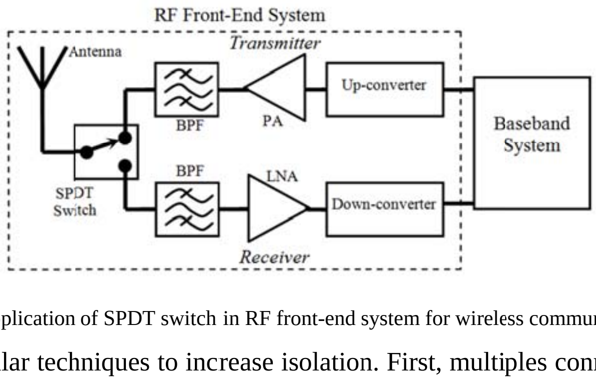


Fig. 1. Application of SPDT switch in RF front-end system for wireless communications.

There are two most popular techniques to increase isolation. First, multiples connection of PIN diodes either in series, shunt or combination of series-shunt [8]. However, using multiples PIN diodes, it will increase current consumption of the circuit. Second, the parallel resonant of inductor with PIN diode [9]; but it has a limitation of discrete inductance values.

Recently, there is a technique using switchable resonator for isolation improvement of SPDT switch as reported in [10] and [11]. The key advantage of this technique is reduction of circuit size with minimum usage of switching elements (PIN diode or FET) compared to the technique using multiples connection of PIN diodes. As suggested in [11], to cater for wireless broadband application, wider isolation bandwidth can be obtained by widening the width of open stub resonator. However, the gap between transmission line and the input port of the open stub resonator contributes to RF coupling. Such RF coupling effect has been reported in [12] where the series capacitance of the gap increases as the gap spacing decreases, thus allowing RF coupling.

In order to improve isolation of SPDT switch with minimum RF coupling effect, radial stub resonator is a good candidate. Furthermore, the radial stub of angle 90° or greater is more broad-banded than a conventional quarter wavelength open stub of straight microstrip line of similar resonance frequency, in the sense that its dispersion is smaller [13]. Thus, wider isolation bandwidth can be achieved by adjusting the angle of the radial stub while maintaining the same width at the input port of the stub. It is found that radial stub was still popular until today and used for the design such as antenna [14], filter [15], amplifier [16] and phase shifter [17]. The only application of radial stub in switch design is biasing circuit as reported in [18] and [19].

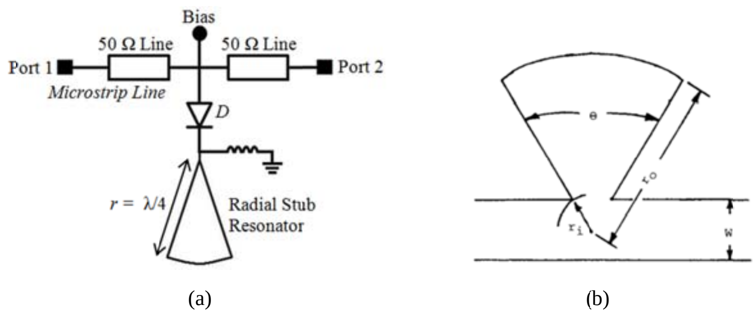
Therefore, this paper proposes switchable radial stub resonator for isolation improvement of SPDT discrete switch. An analytical modeling of the switchable resonator is presented and analyzed for isolation improvement. The SPDT switch with switchable radial stub resonator is demonstrated at 3.5 GHz where the PIN diodes are based on commercialize PIN diode (BAP64-02) in SOD523 package from NXP Semiconductors. This paper is organized as follows. The circuit design and analysis of the proposed switchable radial stub resonator and its application in SPDT switch design are presented in section II. The analysis of isolation improvement is focused more in this section. Then, simulation and measurement result of SPDT switch with the proposed switchable radial stub resonator are discussed in section III. Concluding remarks are given in section IV.

II. Circuit Design and Analysis

In this section, the concept and operation of switchable radial stub resonator are explained. The correlation between radial stub parameters and attenuation pole are analyzed with mathematical modeling. Next, analysis of isolation improvement performance is performed with a two-port network of single shunt PIN diode with switchable radial stub resonator.

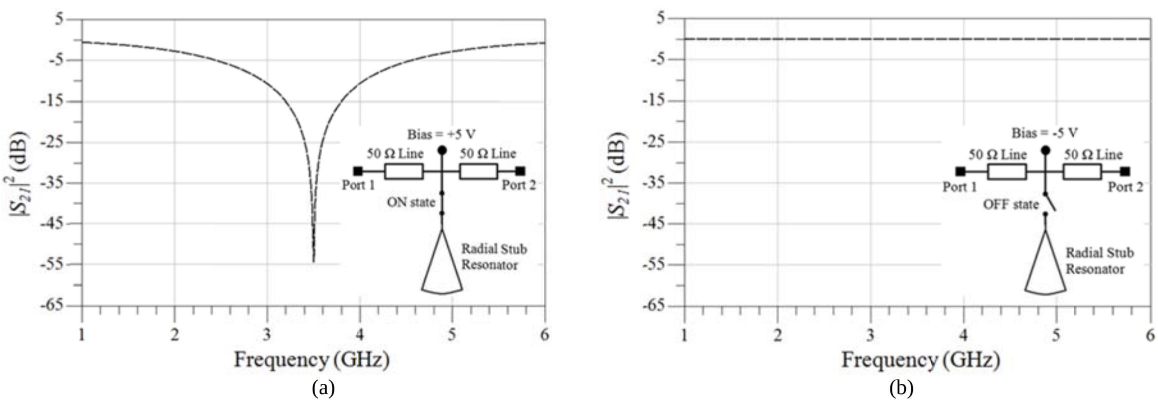
A. Switchable Radial Stub Resonator

A simple structure as illustrated in Fig. 2 (a) is a switchable radial stub resonator which is based on the geometry of radial stub in Fig. 2 (b) [20]. It is connected in shunt to 50 Ω transmission lines. The proposed switchable radial stub resonator can be reconfigured between bandstop and allpass response which is the same concept applied in [21]-[23]. The operation between bandstop and allpass response is controlled by PIN diode which is connected in series with the radial stub.



(a) (b)

Fig. 2. (a) The proposed switchable radial stub using PIN diode and (b) geometric of radial stub [20].



(a) (b)

Fig. 3. (a) Bandstop response during PIN diode in ON state and (b) allpass response during PIN diode in OFF state.

In ON state condition of the PIN diode (Fig. 3 (a)), the RF signal in 50 Ω microstrip line will be short circuited because of low impedance at the input shunt PIN diode due to λ/4 impedance transformation of radial stub (from high to low impedance). The radial stub is equivalent to series inductance and capacitance having a bandstop response between Port 1 and Port 2. In OFF state condition of the PIN diode (Fig. 3 (b)), the radial stub resonator is disconnected from 50 Ω microstrip line having allpass response between input and output port.

As shown in Fig 3 (a), the bandstop response of the radial stub resonator can be modeled using transmission matrix.

$$[T\ ] = \ [T_1][T_s][T_2]|_{V=+5\ V} \tag{1}$$

where T_s is transmission matrix of radial stub resonator, T_1 is transmission matrix of Microstrip Line at Port 1 and T_2 is transmission matrix of Microstrip Line at Port 2.

Therefore, we have

$$[T] = \begin{bmatrix} \cos\theta_1 & jZ_1\sin\theta_1 \\ jY_1\sin\theta_1 & \cos\theta_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_s\tan\theta_s & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & jZ_2\sin\theta_2 \\ jY_2\sin\theta_2 & \cos\theta_2 \end{bmatrix} \tag{2}$$

Since the impedance of the microstrip lines are 50 Ω, thus they are fully matched with the characteristic impedance of 50 Ω and exhibit very minimum power losses. Therefore T_1 and T_2 can be ignored in order to simplify the following equation where S parameter of the radial stub resonator can be obtained by converting the transmission matrix in (2) as

$$S_{21}|_{V=+5V} \ = \frac{2}{2+jZ_0Y_s\tan\theta}\ . \tag{3}$$

where Z_o is characteristic impedance of microstrip line and Y_s is characteristic admittance of radial stub.

The characteristic impedance of radial stub can be obtained as [20]

$$Z_s = \frac{1}{Y_s} = \frac{120\pi d}{r_i\theta\sqrt{\epsilon_e}} \tag{4}$$

where d is thickness of substrate, r_i is inner radial of radial stub and ϵ_e is effective dielectric constant.

The effective dielectric constant of microstrip, ϵ_e can be calculated from [24]

$$\epsilon_e = \frac{\epsilon_r+1}{2} + \left(\frac{\epsilon_r-1}{2}\right)\left(\frac{1}{\sqrt{1+12d/W}}\right) \tag{6}$$

where ϵ_r is relative dielectric constant of substrate. As suggested in [20] for radial stub, W in (6) is calculated as

$$W = (r_i + r_o)\sin\left(\frac{\theta}{2}\right) \tag{7}$$

Then, rearrange (3) with (4), we get

$$S_{21}|_{V=+5V} \ = \frac{240\pi d}{240\pi d + j\tan(\theta) Z_o r_i \theta\sqrt{\epsilon_e}}\ . \tag{8}$$

To calculate length of radial stub resonator, we know

$$\theta = \beta r_o = \ \sqrt{\epsilon_e}k_0 r_o \tag{9}$$

where

$$k_0 = \frac{2\pi f}{c}.$$

Therefore, rearrange (9) and by substituting $r_o = \frac{\pi}{2}$, the λ/4 length of the radial stub resonator can be determined as

$$r_o = \frac{\frac{\pi}{2}}{\sqrt{\epsilon_e}\left(\frac{2\pi f}{c}\right)} \tag{10}$$

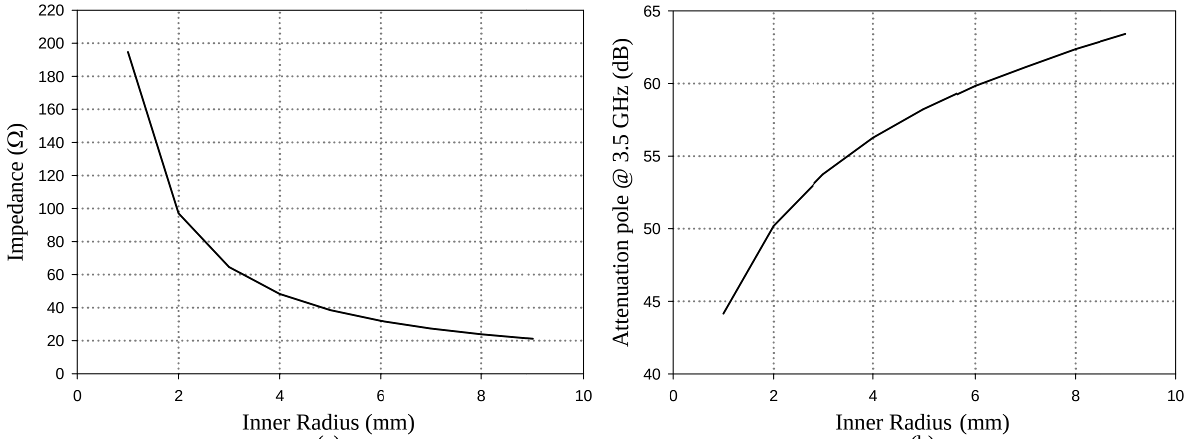
where c is speed of light and f is resonant frequency.

Considering fixed value of d and ϵ_e of printed circuit board (PCB) in (4) and (8), we found that angle, θ and inner radius, r_i of radial stub are significantly influence Z_s and S_{21}. Further analysis is carried out using (4) and (8) by considering resonant frequency at 3.5 GHz and a FR4 substrate having thickness of 1.6 mm and dielectric constant, ϵ_r of 4.7.

As shown in Fig. 4, angle, θ is fixed at 90° and inner radius, r_i is varied in order to observe the correlation with Z_s and S_{21}. It is found that as the r_i is increased it will produce lower Z_s and higher attenuation pole of S_{21}.

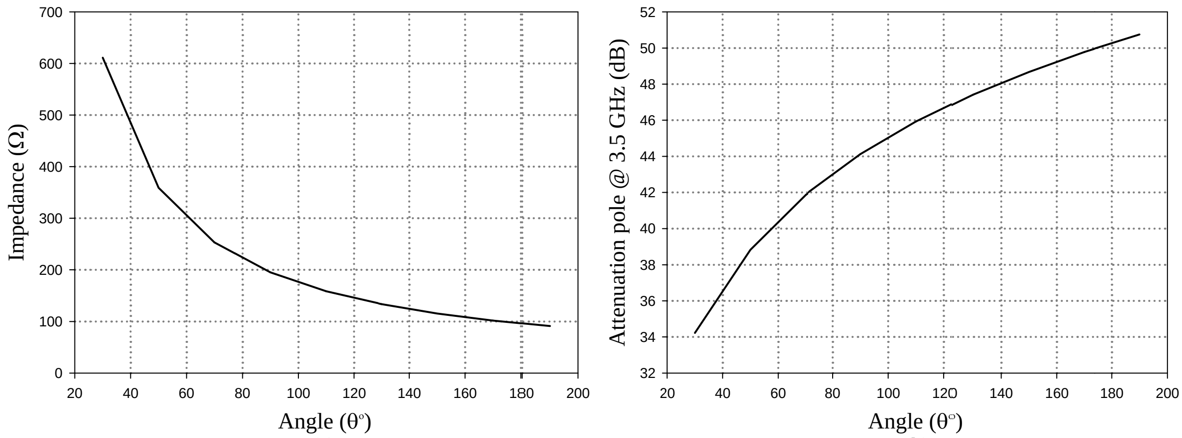
Fig. 5 shows the correlation of angle, θ with Z_s and attenuation pole of S_{21}. In this calculation, inner radius, r_i is fixed at 1 mm and angle, θ is varied. It is observed that as the θ is increased it will produce lower Z_s and higher attenuation pole of S_{21}.

Therefore, we can conclude that higher attenuation pole of S_{21} will be obtained if angle, θ and inner radius, r_i are increased. This result has a potential to improve the isolation of SPDT switch design.



(a) (b)

Fig. 4. Inner radius, r_i versus (a) charateristic impedance, Z_s and (b) attenuation pole of S_{21}.

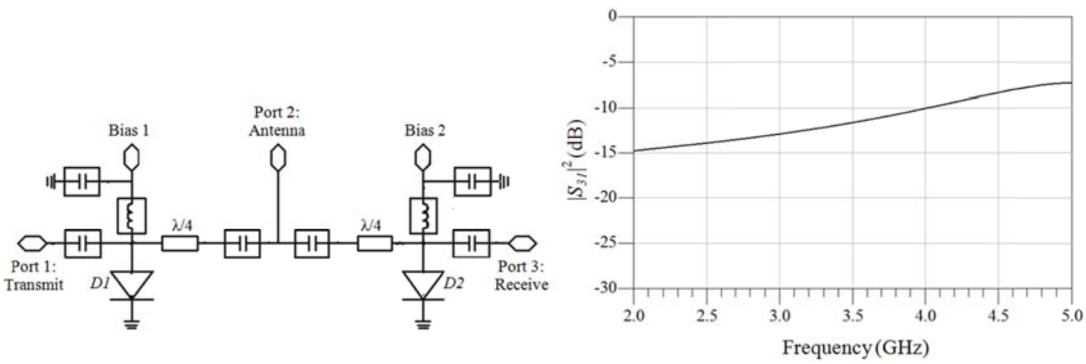


(a) (b)

Fig. 5. Angle, θ versus (a) charateristic impedance, Z_s and (b) attenuation pole of S_{21}.

B. SPDT Switch with Switchable Radial Stub Resonator

A conventional single shunt PIN diode in SPDT switch [25] is constructed (Fig. 6) for a performance comparison with the proposed shunt SPDT switch. By assuming the SPDT switch in transmit mode, *D1* must be turned OFF and *D2* must be turned ON . In this condition the isolation between Port 1 and Port 2 (or Tx-Rx isolation) is obtained solely due to ON state of *D2* in the receive arm.



(a) (b)

Fig. 6. Conventional SPDT switch. (a) Circuit design and (b) isolation between Port 1 and Port 3.

The ON state of a single shunt PIN diode is equivalent to forward resistance (R_f) and series inductance (L_s) [24]. Thus, a simplified transfer matrix of the SPDT switch for isolation analysis is given by

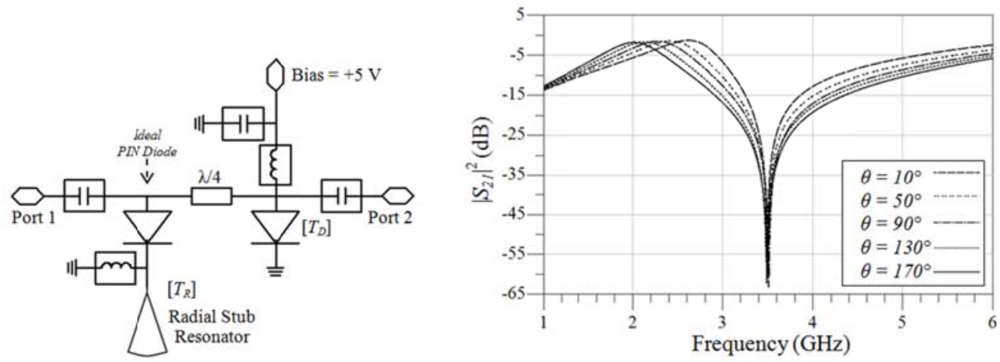
$$[T] = \begin{bmatrix} 1 & 0 \\ \left(\frac{1}{R_f + j\omega L_s}\right) & 1 \end{bmatrix}. \tag{11}$$

Then the isolation between Port 1 and Port 3 (S_{31}) can be obtained by converting the transfer matrix in (11) to S-parameter. Hence,

$$S_{31} = \frac{2}{2 + \frac{1}{R_f + j\omega L_s}}. \tag{12}$$

From (12), we know that isolation is obtained solely due to R_f and L_s of the ON state of shunt PIN diode. It can be shown that difficult to achieve more than 20 dB of isolation between Port 1 and Port 3 if using single shunt discrete PIN Diode in standard package (e.g. SOD523). This can be seen in Fig. 6 (b) where the simulated single shunt PIN diode (BAP64-02 from NXP Semiconductors) in SOD523 package shows very low isolation performance between 2 to 5 GHz.

As proposed in this paper, radial stub is used to improve isolation of the single shunt PIN diode in SPDT switch design. The radial stub resonator is cascaded in shunt with the existing PIN diode. This can be analyzed by considering a two-port network consist of a shunt PIN diode and a switchable radial stub resonator as shown in Fig. 7 (a). A voltage supply of +5 V is used to turn ON the PIN diode and the radial stub resonator. The resonator will then produce an additional isolation between Port 1 and Port 2.



(a) (b)

Fig. 7. Two-port network of shunt PIN diode with switchable resonator. (a) Circuit diagram and (b) isolation between Port 1 and Port 2 with different angle of radial stub.

A simple transfer matrix of two-port network of the circuit in Fig. 7 (a) is analyzed by considering an ideal PIN diode in the switchable resonator. Hence,

$$[T] = [T_R][T_D] = \begin{bmatrix} 1 & 0 \\ \left(\frac{j\tan\theta}{Z_s}\right) & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \left(\frac{1}{R_f + j\omega L_s}\right) & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \left(\frac{1}{R_f + j\omega L_s} + \frac{j\tan\theta}{Z_s}\right) & 1 \end{bmatrix}. \tag{13}$$

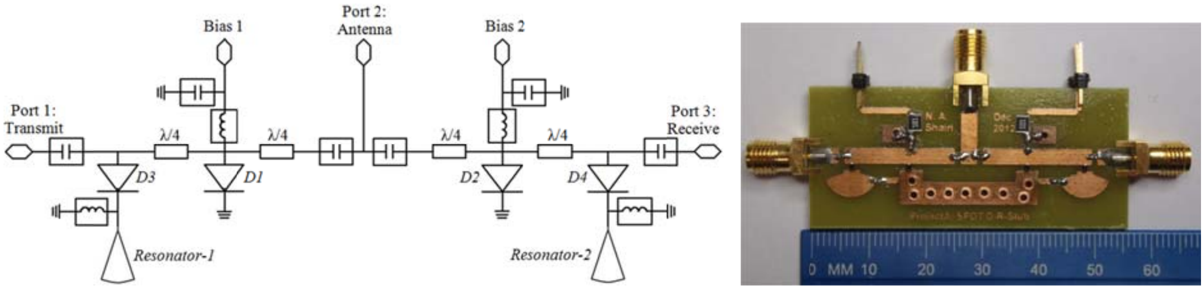
Converting the transfer matrix in (13) to S-parameter, we get

$$S_{21} = \frac{2}{2 + \left(\frac{1}{R_f + j\omega L_s} + \frac{j\tan\theta}{Z_s}\right)Z_0}. \tag{14}$$

High isolation can be obtained if $\theta = \frac{\pi}{2}$ and $Z_s \approx 0$ in the radial stub resonator where the total isolation in (14) is a cumulative of isolation of shunt PIN diode and isolation of the radial stub resonator. This can be observed in Fig. 7 (b) where different isolation performance is simulated with different angle of radial stub. In this simulation, the inner radius, r_i is fixed at 1.5 mm in order to minimize any RF coupling effect between microstrip line and the input of radial stub resonator. Besides, it is observed that larger angle of radial stub produces wider isolation bandwidth in spite of high attenuation pole.

A circuit diagram and prototype of SPDT switch with switchable radial stub resonator are depicted in Fig. 8. As a trade-off between radial stub size and its attenuation pole performance, the angle of radial, $\theta = 145°$ is chosen and r_i is fixed at 1.5 mm. All the PIN diodes are supplied with +5 V (ON state) and -5 V (OFF state) control voltage.

In transmit mode (RF signals from Port 1 to Port 2), the *D1* and *Resonator-1* are turned OFF. Then, the *Resonator-1* becomes allpass response. The *D2* and *Resonator-2* are turned ON. Then, the *Resonator-2* becomes a bandstop response in the receive arm producing additional isolation (between Port 1 and Port 3). The same operation and response can be obtained in the receive mode (RF signals from Port 2 to Port 3) when *D1* and *Resonator-1* are turned ON; and *D2* and *Resonator-2* are turned OFF.

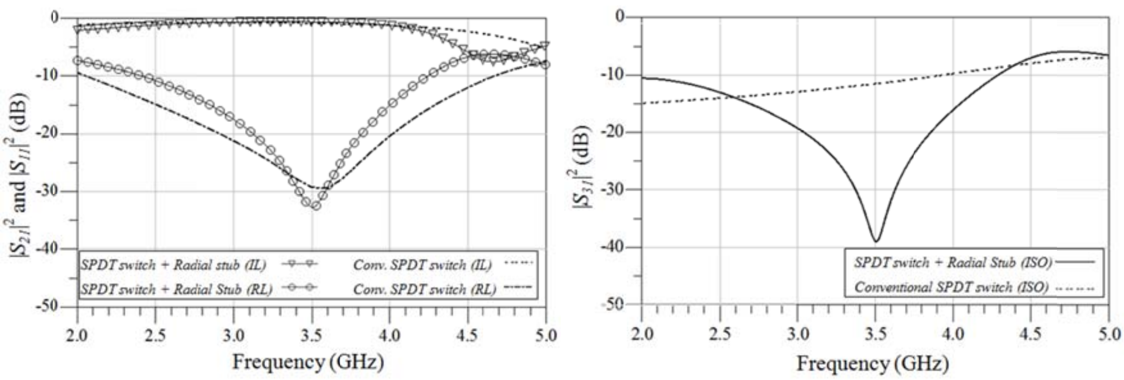


(a) (b)

Fig. 8. SPDT switch with switchable radial stub resonator (a) circuit diagram (b) circuit prototype.

III. Simulation and Measurement Result

Fig. 9 shows the simulated results of insertion loss (IL), return loss (RL) and isolation (ISO) of conventional SPDT switch and SPDT switch with switchable radial stub resonator. The simulated IL and RL of the proposed SPDT switch are comparable with the conventional SPDT switch. The simulated ISO of the proposed SPDT switch shows a significant improvement of isolation which is higher than 20 dB between 3.05 to 3.85 GHz compared with the conventional SPDT switch.



(a) (b)

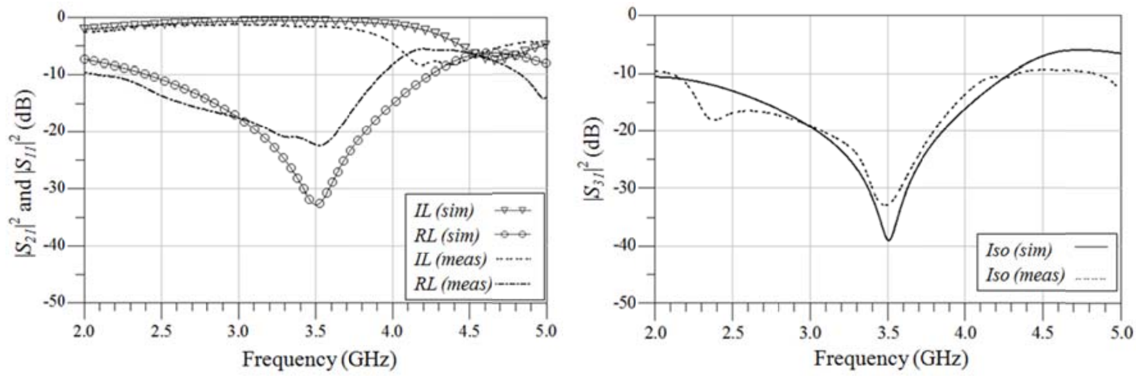
Fig. 9. Simulated (a) insertion loss, return loss and (b) isolation between single shunt SPDT switch (conventional) and SPDT switch with switchable radial stub resonator.

The performance comparison at 3.5 GHz between the conventional SPDT switch and the SPDT switch with switchable radial stub resonator are listed in Table I. The performance is compared between insertion loss, return loss and isolation.

TABLE I
Performance comparison at 3.5 GHz

	Insertion Loss	***Return Loss***	***Tx-Rx Isolation***
Conventional shunt SPDT switch	0.88 dB	29 dB	11.5 dB
Shunt SPDT switch with switchable radial stub resonator	0.65 dB	32.7 dB	39 dB

Fig. 10 shows the simulated and measured result of SPDT switch with switchable radial stub resonator. It is successfully demonstrate an isolation higher than 20 dB at 3.5 GHz compared with the conventional circuit. Both simulation and measurement show a comparable insertion loss and isolation result but the measured return loss is slightly lower compared with simulated ones. However, it is still higher than 10 dB which is a minimum specification of return loss.



(a) (b)

Fig. 10. Simulation and measurement result of SPDT swith (a) double switchable radial stub resonator and (b) single switchable radial stub resonator.

IV. Conclusion

A switchable radial stub resonator is proposed in SPDT discrete switch at 3.5 GHz for isolation improvement. The potential application is TDD switching for WiMAX and LTE communication system. The characteristic of the switchable radial stub was analyzed in term of characteristic impedance and attenuation pole using mathematical modeling. Then, the isolation improvement was analyzed with two-port network of single shunt PIN diode with switchable radial stub resonator. There is a correlation between inner radial and angle radial stub with the characteristic impedance and attenuation pole, thus provide an additional isolation in SPDT switch design. Finally, we successfully fabricated the SPDT switch with switchable radial stub resonator to validate the simulation result which shows an isolation improvement higher than 20 dB between 3.05 to 3.85 GHz.

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