Design and analysis of a dual function of switchable resonator for RF switch

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Abstract. This paper presents the design and analysis of a dual function of a switchable resonator for Radio Frequency (RF) switch. The most common configuration of RF switch is Single Pole Double Throw (SPDT) switch that widely used in the wireless communication system. In order to achieve the dual function between isolation improvement and band-stop filter in SPDT switch, two switchable resonators were used that resonated at 2.3 and 5.2 GHz bands. PIN diodes were used as switching elements in the SPDT switch. The main advantages of the dual function of the switchable resonator are minimum usage of switching elements for isolation and integrated band-stop filter in a single device of SPDT switch. As a result, the design showed almost 40 dB of isolation at 2.3 GHz and 39 dB of the notch response of the band-stop filter at 5.2 GHz.

1. Introduction

In general, RF switches such as SPDT switches are used for signal routing between transmitter and receiver. There are 2 main switching elements can be used in RF switches which are micro-electromechanicals (MEMs) and solid-state electronic devices. Examples of solid-state electronic devices are PIN diode and field-effect transistor (FET) [1].

RF switch is commonly used to route signals and transmit RF signals from the antennas to the transmitter (Tx) and receiver (Rx) in wireless data communications. There are several types of configurations of RF switch such as single pole single throw switch (SPST) switch [2], double pole single throw switch (DPST) switch, single pole double throw switch (SPDT) switch and double pole double throw (DPDT) switch [3]. Nowadays, RF switches such as SPDT switch and DPDT switch are mostly used in the civilian wireless communication system. Examples of civilian wireless communication systems for data exchange in different standards are Time Division Synchronous Code Division Multiple-Access (TD-SCDMA), Wireless Fidelity (WiFi), Worldwide Interoperability for Microwave Access (WiMAX), and other applications [4]. Generally, SPDT switch will operate at either transmitter (Tx) port or receiver (Rx) port, and it will produce an insertion loss at that path. Meanwhile,
the isolation will occur at another port [5]. DPDT switch is used to operate between two inputs and two outputs [6] for multiple antennas.

**Figure 1.** SPDT switch in wireless data communications [7].

One of the most significant parameters in the RF switch is isolation [8]. Isolation is the key feature to achieve a good performance of the circuit design. High isolation can minimize any leakage of high RF power transmitted from transmitter to receiver that might alter the active circuits of the receiver, for example, low noise amplifier (LNA) [9]. From previous research, there are several ways or techniques to improve the isolation performance in RF switch such as the circuit design, material with the fabrication process, resonator, resonant circuit, transmission line [10].

So far in wireless data communications, the existing application switch does not have a dual function between isolation improvement and band-stop filter in SPDT switch because the main target of RF switch design is focusing on isolation performance. There are several ways to improve the isolation performance, such as the configurations of multiple connections of PIN diodes are either connect in series, shunt or series-shunt. However, using multiple PIN diodes, the size of the circuit will increase. Therefore, this paper proposes a dual function of the switchable resonator as isolation improvement and band-stop filter in SPDT switch that offered a circuit simplicity and size reduction. On the other hand, it is known that there is a requirement in a wireless communication system to attenuate unwanted unlicensed band in 5.2 GHz applications. Thus, band-stop filter in the RF switch design is an additional feature that needs to be added in the circuit.

From the literature, as reported in [11]–[13], transmission line stub resonators were used in SPDT switch design in order to achieve high isolation. Although it presented very good isolation, they have no integrated band-stop filter in the SPDT switch. Therefore, this paper presents a dual function of switchable resonators for SPDT switch that produced isolation improvement and band-stop filter in a single circuit of the resonator.

2. Circuit design and analysis

In this section, the design and operation of a dual function of the switchable resonator in SPDT are explained. Besides, a mathematical analysis of transmission line stub resonator is also explained and discussed as well, prior to SPDT switch design.

2.1. Mathematical analysis

The transmission line open stub resonator is mathematically expressed by

\[ Z_{in} = -jZ_0 \cos \theta \]  \hspace{1cm} (1)

Then, the input impedance of the resonator can be rewritten as
where $Z_s$ is the characteristic impedance of the resonator and $\theta_s$ is the electrical length in degree form. From (2), the ABCD matrix of the resonator is found by

$$
T_s = \begin{bmatrix}
1 & 0 \\
Y_{in} & 1
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
\frac{j \tan \theta_s}{Z_s} & 1
\end{bmatrix}
$$

(3)

$S_{12}$ and $S_{21}$ of the resonator can be found when transforming the ABCD matrix in (3) to S-parameter. Thus,

$$
S_{12} = S_{21} = \frac{2}{A + \frac{B}{Z_0} + C(Z_0) + D}
$$

(4)

$$
S_{12} = S_{21} = \frac{2}{2 + \frac{[\frac{j \tan \theta_s}{Z_s}] Z_0}{Z_0}}
$$

(5)

The transmission line stub resonator is then executed using a microstrip line based on FR4 board material. Therefore, the impedance of the resonator, $Z_s$ is replaced with the following equation in order to analyse the attenuation ($S_{21}$) of the resonator.

$$
Z_s = Z_0 = \frac{120\pi}{\sqrt{\epsilon_e \left(\frac{w}{d} \right) + 1.393 + 0.667 \ln \left(\frac{w}{d} \right) + 1.444}}
$$

(6)

by given thickness for FR4 substrate, $d = 1.6$ mm, $\epsilon_e$ is the effective dielectric constant, and $w = 2.9$ mm for the width of microstrip line for (2 GHz - 4 GHz). Therefore, Equation (5) has been rearranged with Equation (6)

$$
S_{21} = \frac{2}{2 + \frac{[\frac{jZ_0 \tan \theta_s \sqrt{\epsilon_e \left(\frac{w}{d} \right) + 1.393 + 0.667 \ln \left(\frac{w}{d} \right) + 1.444}]}{120\pi}}}
$$

(7)

Then, the following equation can be used to calculate the physical length (in meter) of $\lambda/4$ (or 90°) of the transmission line open stub resonator [14]:

$$
\theta_S = \beta l = \sqrt{\epsilon_e} \ k_0 \ l
$$

(8)

where,

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

Therefore, Equation (8) was rearranged and replaced by $\beta l = \frac{\pi}{2}$, while the $\lambda/4$ length of the transmission line open stub resonator was found to be

$$
l = \frac{\pi}{\sqrt{\epsilon_e \left(\frac{2\pi f}{c} \right)}} \text{ meter}
$$

(9)
where \( c \) is the speed of light and \( f \) is the resonant frequency. Based on these derivatives, the appropriate length and width of the open stub transmission line resonator associated with the resonant frequency and attenuation or notch (\( S_{21} \)) of the resonator were determined, and these are related to the isolation improvement and band-stop filter in SPDT switch design.

2.2. Dual function of a switchable resonator

RF signals are propagating between transmitter and receiver. Therefore, the SPDT circuit is used to switch between transmit mode and receive mode in a wireless communication system where PIN diodes are controlled by biasing voltage for the switching modes (transmit and receive). When a positive voltage is applied, then the PIN diode will be in ON state. Meanwhile, if a negative voltage is applied, then the PIN diode will be in OFF state.

Figure 2 shows the circuit for a dual function switchable resonator for SPDT switch during transmit mode. During the transmit mode, the signal is propagating from the transmitter (Port 1) to the antenna (Port 2). D1 is turned ON when the biasing voltage (Vbias1) is +5V whereas D2 is turned OFF with biasing voltage (Vbias2) of -5V. Resonator S2 is controlled by D2. When D2 is turned OFF, the signal cannot flow through the diode of D2. Therefore, resonator S2 is disconnected and S1 creates band-stop response at 5.2 GHz. For the isolation, D3 is turned OFF when the biasing voltage (Vbias3) is -5V whereas D4 is turned ON with biasing voltage (Vbias4) of +5V. Resonator S4 is controlled by D4. When D4 is turned ON, the signal flows through the diode of D4. Therefore, resonator S3 and S4 are connected and produce isolation at 2.3 GHz.

Meanwhile, Figure 3 shows the circuit for a dual function switchable resonator for SPDT switch during the receive mode. It is the same operation for the circuit as explained for transmit mode but in the opposite voltage control as summarized in Table 1.

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**Figure 2.** Circuit diagram for switchable resonator for SPDT switch during Transmit mode.

**Figure 3.** Circuit diagram for switchable resonator for SPDT switch during Receive mode.
Table 1. Circuit operation between transmit mode and receive mode.

|          | Transmit mode | Receive mode                  |
|----------|---------------|-------------------------------|
| $V_{bias}$ 1 | +5 V          | -5 V                         |
| $V_{bias}$ 2 | -5 V          | +5 V                         |
| $V_{bias}$ 3 | -5 V          | +5 V                         |
| $V_{bias}$ 4 | +5 V          | -5 V                         |
| PIN Diode (D1) | ON state   | OFF state                    |
| PIN Diode (D2) | OFF state   | ON state                     |
| PIN Diode (D3) | OFF state   | ON state                     |
| PIN Diode (D4) | ON state   | OFF state                    |
| Resonator (S1) | Band-stop response $\leq 5.2$ GHz | Connected each other and produces Isolation at 2.3 GHz |
| Resonator (S2) | Disconnected |                               |
| Resonator (S3) | Connected each other and produces Isolation | Band-stop response $\leq 5.2$ GHz |
| Resonator (S4) | at 2.3 GHz   | Disconnected                  |

Figure 4 shows the prototype of a dual function of switchable resonator for the RF switch. The total area of the prototype is 48 mm x 43 mm. The dimensions of the resonators were as follows. The dimensions of resonator S1 and S3 are 5.8mm x 2.9mm. Whereas the dimensions for S2 and S4 is 8.4mm x 2.9mm.

3. Results, analysis and discussion
This section analyzes and discusses the result of return loss, insertion loss (as well as band-stop response) and isolation obtained from the simulation and measurement of the proposed SPDT switch design.

Figure 5, 6 and 7 show the results of simulation and measurement for the dual function SPDT switch with the switchable resonator. All the simulated and measured results are compared to each other for analyses and discussion. Figure 5 shows the simulated and measured results for return loss ($S_{11}$). The return loss ($S_{12}$) at 2.3 GHz for simulation result is 14.15 dB whereas for measurement result is 8.09 dB. The simulated and measured results for insertion loss (IL) as shown in Figure 6 are less than 3 dB at 2.3 GHz. In the same figure, the band-stop filter (BSF) response can be seen at 5.2 GHz where the attenuation at the resonant frequency is 39 dB (in the simulation result) and higher than 20 dB (in the measurement). Meanwhile, Figure 7 shows the simulated and measured results for the isolation performance ($S_{13}$). In these results, they are clearly can be seen that the isolation performance for both simulated and measured results are higher than 30 dB. However, it is noticed that all the measured results in Figure 5, 6 and 7 have been shifted around 1 GHz. This could be due to the additional inductance caused by fabrication and soldering process (for PIN diodes).
**Figure 5.** Comparison of simulated and measurement for Return Loss ($S_{11}$).

**Figure 6.** Comparison of simulated and measurement for Insertion Loss at 2.3 GHz and Band-stop at 5.2 GHz ($S_{12}$).

**Figure 7.** Comparison of simulated and measurement for Isolation ($S_{13}$) at 2.3 GHz.
4. Conclusion
A dual function of the switchable resonator between isolation improvement and band-stop filter for SPDT switch was proposed. The main advantages of the dual function of the switchable resonator are minimum usage of switching elements for isolation and integrated band-stop filter in a single device of SPDT switch. The switchable resonator for SPDT switch has successfully designed to improve the isolation performance which was more than 30 dB of isolation at 2.3 GHz band and produced a band-stop response at 5.2 GHz with 39 dB attenuation. The band-stop filter can attenuate unwanted unlicensed band of 5.2 GHz applications. The designed circuit was then fabricated to validate the result. Although the simulation and measurement results are comparable to each other, it was found that the resonant frequency (in measurement) was shifted around 1 GHz to lower frequency. This was due to the additional inductance from the fabrication and soldering process. In this paper, the proposed switchable resonator between isolation improvement and the band-stop filter is suitably used in the RF switch and could be used in the wireless communication system.

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