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AN OVERVIEW OF ISOLATION IMPROVEMENT TECHNIQUES IN RF SWITCH

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ABSTRACT

In this paper, five techniques to improve isolation of RF switch are reviewed which are material with fabrication process design, circuit design, resonant circuit, transmission line and resonator. Most of these isolation improvement techniques are applied in RF switch designs such as single pole single throw (SPST) and single pole multi throw (SPMT). Several solid-state devices are used for switching element such as PIN diode, MEMS, FET, HBT and HEMT. They are commonly used in satelite communication, radar system, instrumentation and base station applications.

Keywords: RF switch, isolation improvement, single pole multi throw (SPMT), switching element, resonator.

INTRODUCTION

Nowadays, PIN diodes are still desirable for higher power levels used in military, satellite communication or base station applications [1] while the micro-electromechanical-system (MEMS) is currently emerging with existing technology. However, its quality packaging and reliability are always the problems to be solved by the MEMS switch technology. Meanwhile, solid state switches such as PIN diode and FET switches are more reliable and they provide faster switching time and longer lifetime. However, their isolation is always a main issue due to its higher OFF state parasitic capacitance.

Isolation of RF switch is a key performance criterion in order to get better performance of the circuit design. Some of the RF switches encounter a limitation in aspect of low isolation. For instance, FET provides good isolation at low frequency. But, at higher frequency, the isolation of FET is degrading due to the effect of the drain-to-source capacitance [2]. Similarly, PIN diode performance is limited by the parasitic capacitance (which is package capacitance and junction capacitance) at high frequency in the form of isolation roll-off [2]. The junction capacitance becomes constant and dependent only on the geometry of the intrinsic (I) layer at higher frequency [3].

In terms of application of RF switch design, the SPMT switches are the key elements in switch able filter, reconfigurable antenna, transmit/receive circuits and etc. The very essential part of SPMT switches is single-pole-double-throw (SPDT). Recently, there are many designs of SPDT switch are developed. The most common design is a quarter wavelengths placed by two capacitive shunt MEMS switches from the centre of the T-junction [4, 5]. Others are Ku-band SPDT switching circuit based on the toggle switch [6] and two resistive series switches are placed at the end of each output line and a short-end 50 Ω line is connected at the cross junction [7]. Apart of SPDT switches, single pole triple throw is also introduced in [8] where the circuit configuration possesses the three resistive series switches based on fixed beam architecture in coplanar environment. As reported in [9], single-pole-four-throw switching circuit is applied with four series switches and it shows a good matching up to 20 GHz with 50 dB of isolation at 10 GHz. In addition, single-pole-double-throw is reported in [10] where it applies the rotary switch and obtained the isolation of 31 dB at 20 GHz.

In this paper, five methods to improve the isolation in RF switch are reviewed which are material with fabrication process design (in Section I), circuit design (in Section II), resonant circuit (in Section III), transmission line (in Section IV) and resonator (in Section V).

MATERIALS WITH FABRICATION PROCESS DESIGN

In material with fabrication process design, PIN diode is designed for high frequency operation is usually fabricated to have low capacitance because the reactance of the diode in the OFF condition must be large compared to the line impedance [11] in order to get high isolation. As reported in [12] the distance between anode and cathode terminals is optimized so that the PIN diode is able to overcome the limitation of the common SiGe process which do not have customized etching step to remove the N-epi layer to build a high performance vertical PIN diode, where it can get high isolation and low insertion loss. Figure-1 shows PIN diode implemented in a standard 0.18 μm SiGe BiCMOS process. It is similarly reported in [13] where the intrinsic region of PIN diode has increased its depletion region. Hence, PIN diode achieved smaller junction capacitance. The size and fabrication processing steps of the PIN diode have to be carefully selected in order to reduce the junction capacitance and certainly achieves high isolation. In addition, the 6.25 μm @ 5 mA PIN diode is designed using SiGe process to achieve high isolation [14] and it shows isolation larger than 32 dB due to small area and junction capacitance.

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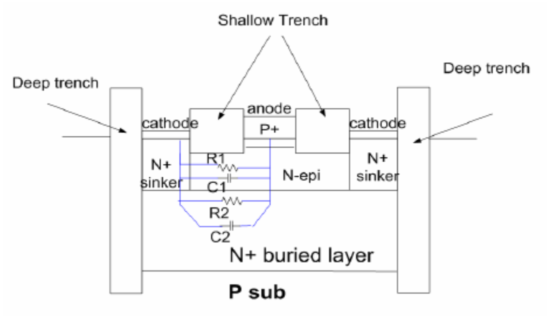


Figure-1. Vertical PIN diode cross section using 0.18 um SiGe BiCMOS process [12].

RF switches compatible with GaAs- (Gallium Arsenide) or InP- (Indium Phosphate) based high frequency electronics is a key element in building up front-end transmitter-receiver modules at microwave frequencies [15]. It is explained that the isolation of single diode switch is limited by the parasitic resistance associated with the side via hole structure used to ground a shunt PIN diode. It is said that the isolation can be improved by using two shunt diodes in each output arm, but this will increase the insertion loss. Hence, the author developed a process which via hole is placed underneath the shunt PIN diode. Microwave frequency on-wafer measurements are used to develop model for this PIN diode show lower parasitic resistance, which lead to the improved isolation in the shunt switch [16].

Another example of RF switch design using GaAs can be found in [17] and [18] where high isolation of the RF switch can be achieved in Double Pole Double Throw (DPDT) switch configuration. As reported in [18] the circuit is designed using a commercial 0.18 µm GaAs pHEMT process, which employs 0.18 µm gate length AlGaAs/InGaAs pHEMT on 100 µm substrate. The simulation result shows the isolation is more than 50 dB. Schematic circuit of DPDT switch is shown in Figure-2. The equivalent circuit of pHEMT for switching device during ON and OFF states can be represented as R_{on} and C_{off}. If the gate width of pHEMT increases R_{on} will decrease, which cause the insertion loss decrease, C_{off} increases which cause the decrease in isolation of switch. Hence the gate width must be chosen carefully to compromise the isolation and insertion loss of the switch.

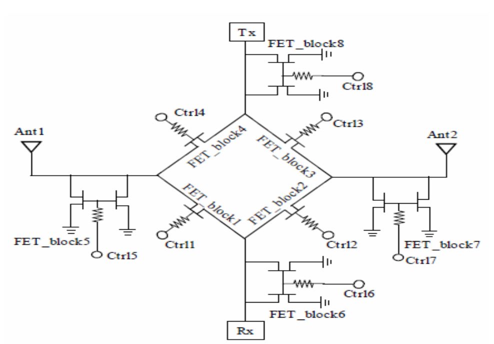


Figure-2. Schematic circuits of DPDT switch [18].

CIRCUIT DESIGN

One of the well-known techniques of isolation improvement in RF switch is circuit design [19] where a high isolation can be achieved by connecting RF switches with multiple shunt PIN diodes separated by λ/4 transmission line as shown in Figure-3. SPDT switch employs series-shunt-shunt topology for wireless data communication [20, 21]. In [22], the author introduces circuit configuration of single series PIN diode and two shunt PIN diode. As explained in [10], 6 dB of isolation on each additional shunt PIN diode can be increased by the two cascaded shunt PIN diode. As reported in [23], the author presented double shunt MMIC switches using MOCVD-grown InGaAs/InP PIN diodes and two most important performances are analyzed; isolation and insertion loss. Two shunt diodes are applied on W-band SPDT switch and it demonstrates isolation excess of 40 dB while maintaining insertion loss at 1.8 dB. Figure-4 shows high isolation SPST switch with two shunt InGaAs PIN diodes.

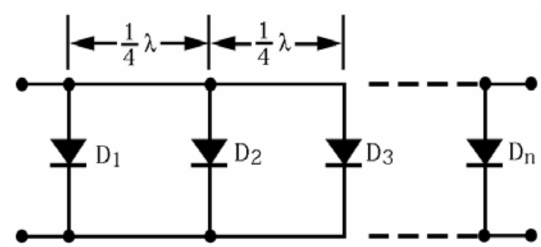


Figure-3. Multiple shunt PIN diodes separated by λ/4 transmission line.

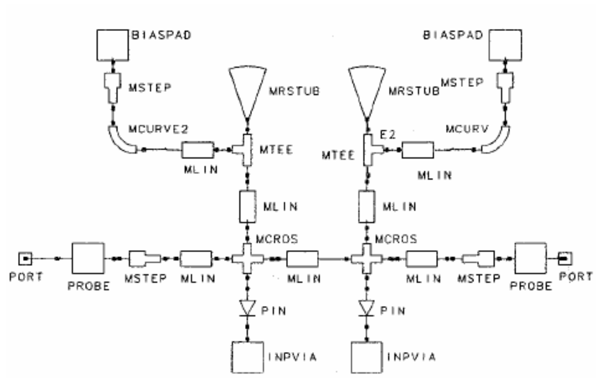


Figure-4. High isolation SPST switch with two shunt InGaAs PIN diodes [23].

RESONANT CIRCUIT

Isolation improvement of RF switch using resonant circuit is another well-known technique. As shown in Figure-5, this inductor will resonate out the parasitic capacitance (C_p and C_j) in a PIN diode and such a circuit is known as a resonant switch and is inherently narrow band [24].

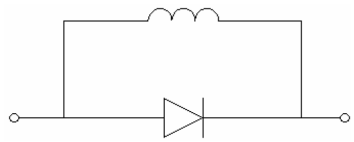


Figure-5. An inductor connected in parallel with PIN diode.

In this technique, lumped elements of inductors are widely used as shown by Avago Technologies in [24, 25]. The HMPP-3865 package [24] has two series PIN diodes in each arm. It is parallel connected with lumped inductor (*L2*) and proposed for SPDT switch design for wireless data communication applications at 1900 MHz and 2.45 GHz as shown in Figure-6. It is claimed that by adjusting the value of the lumped inductor, the RF switch can be tuned for high isolation over a range of 100 MHz typically. Higher values of lumped inductor can be used to move the maximum isolation of RF switch to lower frequencies and lower values can be used to move the maximum isolation to higher frequencies. However, depending on the loaded Q of the parallel resonant circuit, the useful bandwidth is typically limited to 10% of the center frequency or less [25].

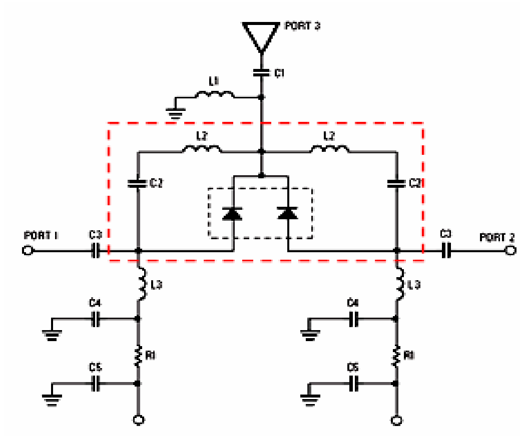


Figure-6. SPDT switch using HMPP-3865 PIN diode [26].

A distributed inductor can also be used to improve isolation where the circuit configuration is the same as the lumped inductor. It has been reported in [26] that high isolation using distributed inductor can be used in SPDT switch operating at 2.4 GHz to 2.6 GHz for TDD WiMAX application. As shown in Figure-7, at the Tx side, the distributed inductor (Z_4, θ_4) is paralleled with a series PIN diode (D_1) to create a resonant circuit during OFF state of the PIN diode (D_1) at the operating frequency, thus improving the isolation between Tx and other ports.

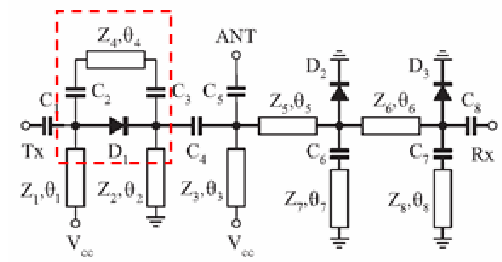


Figure-7. Distributed inductor (Z_4, θ_4) in parallel with series PIN diode [27].

Punch Hole Structure (PHS) has similar characteristics of resonant circuit for isolation improvement where a SPDT switch employing PHS is reported in [28]. The PHS is realized by making periodic holes of a certain size in the microstrip line, dielectric layer, and ground layer and by connecting wires with certain size of diameter over the punched holes. Figure-8 shows the proposed PHS. Due to the additional L-C parameters introduced by punched holes, isolation performance of SPDT switch can be improved. Increase of about 20 dB isolation of SPDT switch is obtained when the radius of punched holes is same to the width of microstrip line, 0.03 λ_c(λ_c: wavelength of 2.7 GHz).

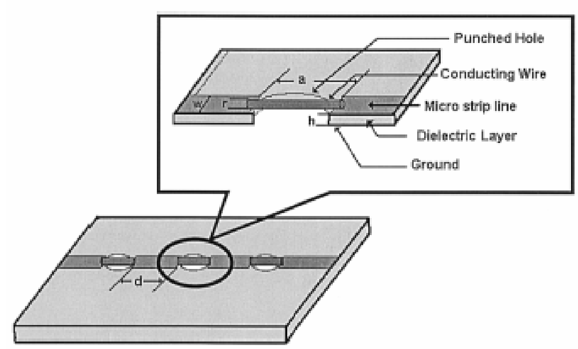
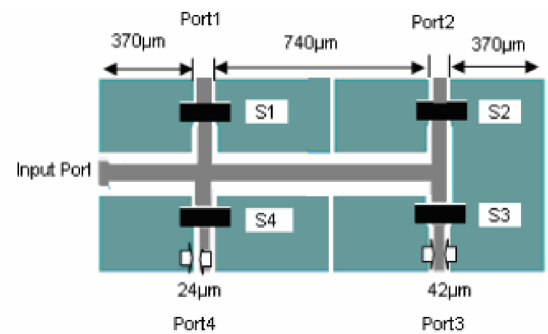


Figure-8. The proposed PHS [28].

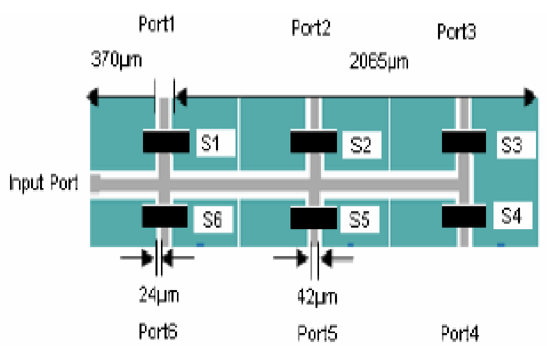
In RF switch using MEMS, several disadvantages such as slow switching speed, high voltage of actuation and hot switching in high RF power have been tolerated in high isolation telecommunication radar and switches [27]. As reported in [29], the resistor-capacitor-inductor (RCL) model of the MEMS switch is used to design the tuned high-isolation switches. It increases the isolation during the OFF state of the switch. The measurement result shows isolation better than -30 dB from 11 to 13 GHz. As reported in [30], a circuit configuration consisting of three shunt and one series transistors has been adopted in SPDT switch. In order to increase isolation in SPDT switch, an inductor has been employed [31] to isolate at the upper side of desired frequency band during OFF state (of transistor) as it acts as a large resistor in parallel with a large capacitance; the isolation at high frequency is reduced by the parasitic capacitance. However, as the frequency increases, the isolation of series PIN diode decreases due to the increasing of junction capacitance (parasitic capacitance). Thus, the isolation performance at high frequency is improved by connecting in parallel the series resistor and inductor with series PIN diode. During OFF state, the inductance resonates with the parasitic capacitance of the PIN diode. At the resonant frequency, the capacitive effect has been decreased by this resonance and effectively increases the isolation performance. This method has been similarly reported in [32].

TRANSMISSION LINES

SPMT RF switches are easily integrated with other module so they are able to improve RF switch performance in term of isolation. Two of the SPMT switches which are SP4T switches [33] and SP6T switches [34] have been reported employing transmission line to improve the isolation of the switches. As reported in [35], SP4T and SP6T switches are designed with CPW transmission line to carry out significant improvement in insertion loss and isolation without changing any RF parameters. Figure-9 shows the SP4T and SP6T switches with CPW transmission line.



(a)



(b)

Figure-9. Layout view of CPW with RF MEMS (a) SP4T and (b) SP6T switch [31].

For the design of the SP4T CPW switch, it requires integration of four optimized SPST switches [36]. The switches are placed symmetrically around with transmission line and the input port is 50 Ω CPW lines. In SP6T CPW switch, it is designed with single input port and six output ports all interconnected by 50 Ω CPW lines. Both SP4T and SP6T RF MEMS switches are integrated with ohmic contact SPST switch. The SPST switch is placed in a CPW transmission line configuration. During ON state, the transmission line and the switch make ohmic contact and suspended at height of 3 μm above it during OFF state. The simulated isolation for both SP4T and SP6T are better than 53 dB and 57.2 dB respectively.

Similar method is also reported in [15] where SPST switch is designed using high impedance quarter-wave transmission line sections ($Z_o = 95\ \Omega$) in order to obtain higher isolation. As the transmission line impedance, Z_o is increased, the ON state PIN diode impedance, Z_{on} is less significant, and the diode looks more like an ideal short accordingly to (1).

$$Isolation(SPST - 1diode) = 20 \cdot log_{10}\left(1 + \frac{Z_o}{2R_{on}}\right) \text{ (dB)} \quad (1)$$

$$Isolation(SPST - 1diode) = 10 \cdot log_{10}\left(1 + (\pi f C_{off} Z)^2\right) \text{ (dB)} \quad (2)$$

The isolation improvement is resulted in insertion loss accordingly to (2), where the diode OFF state capacitance, C_{off} is more noticeable as the transmission line impedance, Z_o increases. As the impedance increases, the transmission line will become narrower and less capacitive, and then the diode is like ideal open.

RESONATOR

Resonator is one of the techniques which can improve isolation in RF switch. Recently, several switchable resonator designs have been implemented in switches as reported in [37- 42]. In [37], the authors have successfully improved isolation in SPDT MMIC switch by employing the shunt pHEMT resonator, which reduced ON state resistance of FET for OFF state of the switch. This technique has been applied to develop V-band SPDT MMIC switch. Figure-10 shows a circuit diagram of the proposed V-Band SPDT switch. During ON state, the resonator operates as the ON state matching circuit like an open stub due to the high impedance of the shunt FET as shown in Figure-11(a). During OFF state, the resonator acts as the lossy circuit due to the low impedance of the shunt FET as shown in Figure-11(b) and improves the isolation. Experimental result shows the isolation greater than 45 dB.

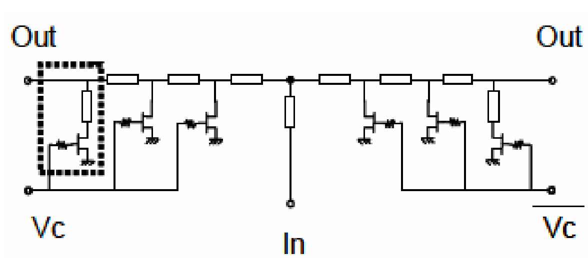


Figure-10. A circuit diagram of the proposed V-Band SPDT MMIC switch [36].

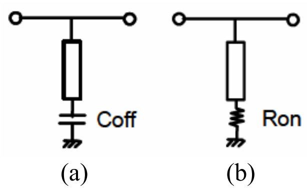


Figure-11. Equivalent circuit of resonator during (a) ON state and (b) OFF states of switch [36].

As reported in [38], A MEMS reconfigurable defected-ground-structure (DGS) resonator using two-dimensional (2-D) periodic DGS for RF MEMS series-resistive switches is presented. The MEMS reconfigurable DGS resonator has been designed on a high-resistivity silicon substrate in CPW environment that is suitable for monolithic integration in the context of a standard planar microwave process. It consists of five cells of 2-D periodic DGS in CPW environment and eight RF MEMS series resistive switched based on fixed-fixed beam to cover the whole K-band for automotive applications and transceivers. Under the simulation process, isolation more than 25 dB is obtained of this RF MEMS switches.

The author in 40] has proposed single switchable open stub resonator to improve isolation in SPDT discrete PIN diode switch as shown in Figure-12. It is known that the discrete PIN diode is applicable up to 3 GHz but it finds difficulty to reach more than 15 dB of isolation due to its single low performance of discrete PIN diode. In transmit mode (Tx Port to Antenna Port), the D2 and D4 are turned ON while D1 and D3 are turned OFF. In this mode, the open stub resonator will operate at receive arm (Rx Port) in which it acts as a band stop in the receive arm. Thus, additional isolation (S_{31}) can be achieved due to the λ/4 open stub resonator where it converts from high impedance to low impedance. The same operation can be realized in the receive mode (Rx Port to Antenna Port) when D1 and D3 are turned ON and D2 and D4 are turned OFF. This concept has been similarly reported in [41-43].

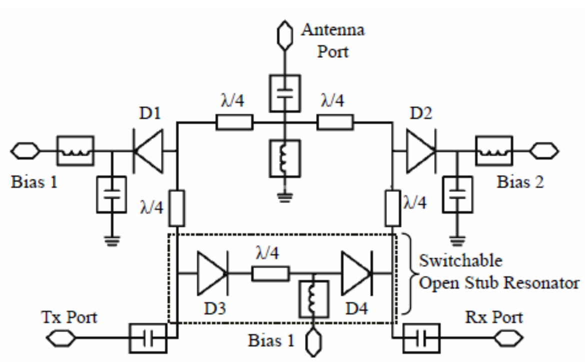


Figure-12. Equivalent circuit of resonator during (a) ON state and (b) OFF states of switch [37].

CONCLUSIONS

In this article, the techniques to improve isolation of RF switch are discussed. Isolation is a crucial key performance parameter in RF switch design. It has been discussed that isolation of RF switch can be improved by using method of material with fabrication process design, circuit design, resonant circuit, transmission line and resonator. In fabrication process design, the improvement of isolation is focused on PIN diode with fabrication processes such as SiGe BiCMOS, GaAs pHEMT and AlGaAs/InGaAs pHEMT. In circuit configuration, RF switch is designed in shunt with cascaded of multiple PIN diode to achieve high isolation. In resonant circuit, it can contribute to high isolation performance of RF switch by employing inductor and capacitor. Distributed inductor is one of elements which is also can create the resonance in RF switch. Resonator and transmission line that integrated with RF switches are other techniques which absolutely can improve isolation in RF switches. This high isolation of RF switches can absolutely be applied in satelite communication, radar and micowave engineering system, instrumentation or base station applications.

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