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FABRICATION AND TESTING OF DOUBLE-POLE FOUR-THROW SWITCH WITH N-MOSFETS

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Abstract

In this research work, a Double-Pole Four-Throw (DP4T) switch has been fabricated using *n*-MOSFET. This switch is beneficial in terms of the MIMO system and reduces the size, power, and hardware structure. This designed DP4T switch operates within the widely used frequency band up to 10 GHz applications. This makes the RF switch accomplished of selecting data streams to/from the two antennas for transmitting/receiving processes simultaneously. The simulated result gives the return loss 15.90 dB, insertion loss 1.68 dB, and off-isolation loss 39.34 dB, and for measured (after fabrication) these values are 11.96 dB, 2.53 dB, and 30.72 dB, respectively. It uses the MOSFETs, hence, it is also suitable for low power devices and nanotechnology devices.

Keywords: DP4T switch, Low power device, Microelectronics, MOSFET, MIMO system, Switch, VLSI.

1. Introduction

Numerous antenna systems have been utilized to update the transmission capacity and unwavering quality of the communication system [1-3]. For such communication system, antenna selection and switch instrument are very important to avoid RF chain, related to the different reception systems. The popular switching system has basic and eases structures, which combines all the enhancement of Multiple-Input Multiple-Output (MIMO) system [4, 5]. The MIMO wireless systems have multiple antennas at Transmitter and Receiver (T/R). These antennas are used to improve the transmission capability and reliability of the communication systems [6].

Sanayei and Nosratinia [7] have presented a review for the antenna selection in the MIMO systems. It reviewed the classic results on selection diversity and discussions of the antenna selection algorithms at transmitting and receiving sides. Certain modifications to the conventional electronic switch design facilitate the high-speed switching, rapid switching times between ON and OFF states, low ON-resistance, and high-density configuration of multiple switches, etc. [8, 9]. In view of problems that arise in MIMO systems, the DP4T RF switch with n-type MOSFET is proposed as part of the solution. This proposed RF switch is able to select data bits to/from various antennas for transmitting/receiving processes. Mekanand et al. [10] have designed a switch, which is operating at 2.4 GHz and 5.0 GHz for the MIMO system. These designed switches alleviate the attenuation of passing signals and show high isolation to avoid the distortion of received signals.

For a MOSFET (as for a switch), if the gate to source voltage (V_{gs}) < threshold voltage (V_{th}), the MOSFET behaves as an open circuit (between drain and source), in this case, acts as an open switch. However, $V_{gs} > V_{th}$, then a small resistance (or ON-resistance, R_{on}) between the source and drain terminal exist. If this R_{on} is zero, then MOSFET behaves as a closed ideal switch. However, generally, R_{on} is not zero, so it behaves as closed non-ideal switch [11].

Various parameters have been experiential in this design of DP4T switch with MOSFET [12]. The designed DP4T switch with MOSFET has better and improved parameters. The improvement of the design of DP4T switch with MOSFET device and its capabilities have been tested. DP4T RF switches with MOSFET as the better switch has been designed with improved parameters. At an instance, Srivastava et al. [13, 14] have analysed the Double-Gate (DG) CMOS for DP4T switch (at 45-nm technology). Lee et al. [15, 16] have designed a novel transmit/receive switch architectures for MIMO applications. Khan et al. [17] have demonstrated the implementation of D-band single-pole double-throw (SPDT) switch at 32 nm CMOS SOI technology. This switch demonstrates better performance with an insertion loss of 2.6 dB at 140 GHz. Kim and Min [18] have designed a silicon-on-insulation CMOS T/R and single-pole-four-throw (SP4T) switches with high-power handling capability. This switch operates up to 18 GHz and has insertion loss and isolation less than 2.4 and greater than 19.5 dB, respectively, with the return loss less than - 9.3 dB. Dey and Koul [19] have done a reliability analysis of Ku-band 5-bit phase shifters using micro-electro-mechanical systems (MEMS) SP4T and SPDT switches. Ilkhechi et al. [20] have designed SPDT RF MEMS switch for ultra-broadband applications. It has insertion loss below -0.73 dB up to 90 GHz, return loss below -16.43 dB and isolation below -23.91 dB.

In this present research work, DP4T switch has been designed using the MOSFET technology and then it has been fabricated. This design can achieve antenna diversity since it can operate at 2.4 GHz, 5 GHz, and 10 GHz. In addition, this design uses basic principles of MOSFET as a switch. Therefore, this switch is different from the existing DP4T switch. This work has been organized as follows and shown in Fig. 1: Section 2 explains the circuit model of the switch. Section 3 describes the fabrication process. Section 4 has the testing of transmission between the transceivers. Section 5 has the result and analysis for this fabricated switch. Finally, Section 6 concludes the work and recommends future works.

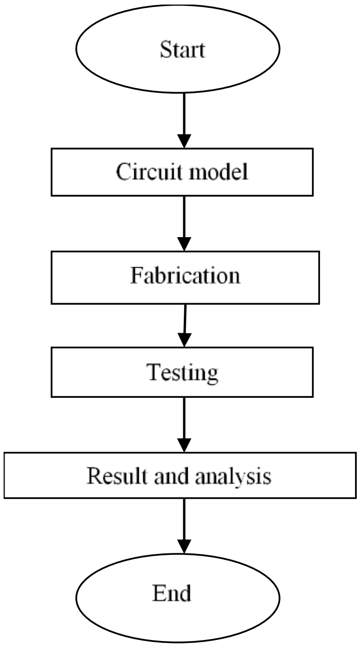


Fig. 1. Flow chart of working process.

2. Circuit Modelling

The proposed switch (Fig. 2) is designed to improve the various parameters compared to the existing RF switches and it will show the advantages in applications [12]. It consumes low power and low distortion with able to transmit data on the MIMO system. It can operate around a frequency of 2.4 GHz, 5.0 GHz, and 10 GHz with decreased current consumption. In addition, it saves energy and useful for portable devices.

The proposed DP4T switch consists of two antennas, which are connected on the dual sections of the switch. The transmitter could be connected on the transmit section, it applies to the receiver, which is connected to the receive section [21-24]. This DP4T switch consists of the dual sections, which gives it an advantage of multiple-input multiple-output. The connected antennas communicate with each other for data transmission. The DP4T switch is made up by simply pairing the SPDT switch, which makes DP4T switch to have improved parameters compared to other existing radio frequency switches.

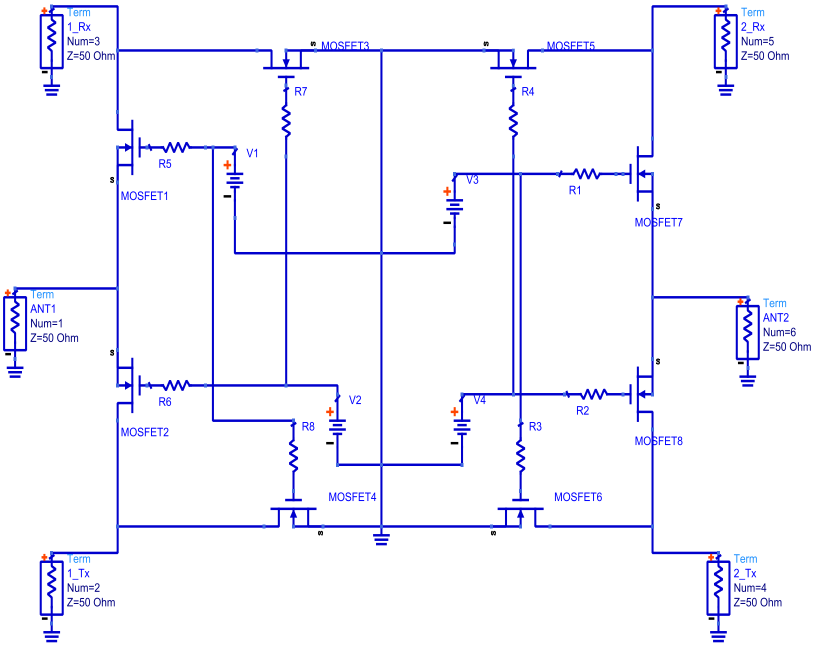


Fig. 2. DP4T RF switch circuit with *n*-MOSFET [12].

3. Fabrication Procedure

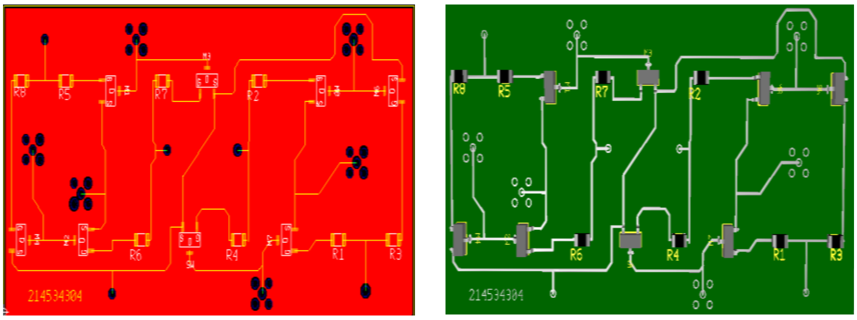
This Printed Circuit Board (PCB) has been designed using a surface mount technique to achieve the working for high frequencies up to 10 GHz. The circuit is designed and simulated using electronic design software, where the circuit has been optimized to achieve the improved parameter performance [25-28]. The PCB part has been constructed in Ultiboard where the surface mount components were easily available and helped the design engineer to able to get the clear picture of the fabricated SMD PCB. It has been shown in Fig. 3.

The line tracks of the PCB are designed carefully and ensure proper routing of high-frequency signals. This circuit has been designed with continuous RF ground plane that comes with a variety of benefits, that is why the red colour, in this case, is called bottom copper, the top copper is where there are line tracks and components as well. The single drills holes are for connecting the top circuit with ground plane and for applying voltage to the circuit (will not relate to ground plane, will be separated carefully). The drills with five holes those drills indicate the RF signal connector (SMA connectors) that will be used to connect the antenna to the DP4T circuit, for transmitting and receive the signal that will be going into/out the circuit.

The reason Ultiboard became more reasonable for DP4T RF switch Surface Mount Device (SMD) PCB because of its visualization in 3D perspective to have a clear picture of the design with components [29-33]. Srivastava et al [34] has suggested that it canalso be designed using high dielectric material. Since this design has been completed through surface mount technique to achieve the RF switch to be able to operate at 2.4 GHz, 5 GHz and 10 GHz the line track of the circuit was designed carefully to contribute to the successful implementation when soldering the surface mount components. This circuit has a ground plane.

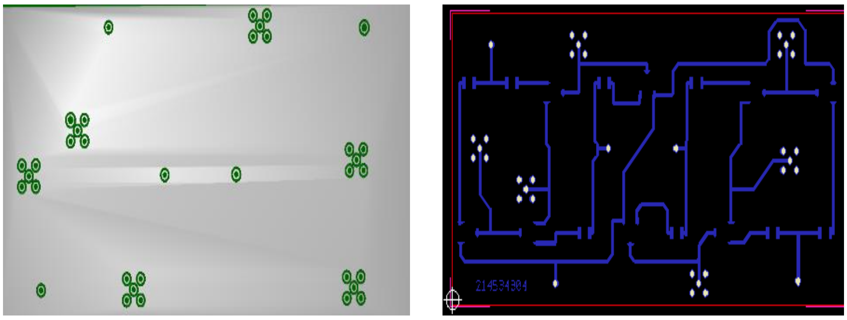
Noise is a great concern in communication systems since this DP4T RF switch with *n*-MOSFET forms a major part of MIMO systems. The noise part in this design is also addressed in terms of making the layout bottom copper be the ground plane. Thus, revealing a special technique utilized by the engineer when designing the DP4T RF switch, the benefits of the ground plane in this design is to provide a low-impedance ground connection, this is important since the ground is how different components relate to each other. Secondly, it will act as an EMI shield. This ground plane will make a difference in reducing noise.

The design of DP4T RF switch with *n*-MOSFETs was simulated with electronic design simulator, which allows the designer to explore the S-parameter characterization of this design, leading to a successful simulation of all the performance parameter of the DP4T RF switch, such as return loss, insertion loss and isolation loss. Thereafter, the completed circuit design with optimized parameters transferred into the layout. The layout is a bit tricky since the design required surface mount technique, of which, in layout, the components were not surface mount. This challenge was solved by using Ultiboard to create the surface mount PCB. Figure 4 shows the final surface mount PCB.



(a) With SMD PCB designed hardware. **(b) With *n*-MOSFETs layout.**

Fig. 3. DP4T RF switch.



(a) Back view of 3D view of designed DP4T circuit. **(b) DP4T RF switch with *n*-MOSFET PCB view.**

Fig. 4. Surface mount PCB for the designed switch.

Figures 5 and 6 consist of the final surface mount printed circuit board design for DP4T RF switch design with MOSFET. The signal line tracks are designed carefully to be able to route high-frequency signals like 2.4 GHz and 5 GHz. The ground plane as the bottom layer will be used to this design advantage when it comes to implementation.

This hardware requires standard surface mount kit, surface mount resistors (10 kΩ), surface mount *n*-MOSFET and SMA RF connector for creating ports in this circuit for integrating with external equipment like signal generator and oscilloscope were used in the final implementation. The surface mount components are too small and that required a magnifier glass for clear visual of the circuit at the time of soldering of each component.

Figure 7 shows the implemented circuit with the magnifying glass. Each component was held with tweezers since it is too small, before putting on top of the PCB for soldering, the liquid flux was applied on the board because it removes the oxidation that prevents solder from bonding to metals. Test points were created in the circuit for applying required control logic for properly routing the signal. The bottom layer (in Fig. 8) is a ground plane and is used to advantage when looking at the fact that the top layer consists of the actual circuitry design tracks with components. The Sub-Miniature version A (SMA) RF connector was integrated in a smart way with the design circuit since the outer part of SMA connector is ground and the inner part is where the signal is drive into the circuit. The position of the SMA RF connectors are soldered in this circuit really gives a clear perspective of the designer expertise and understanding the circuit in and out, so this is the best position for optimization and accurate results.

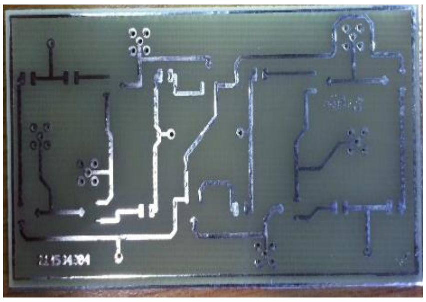


Fig. 5. SMD PCB top view of DP4T RF switch.

Fig. 6. SMD PCB bottom view of DP4T RF switch.

Fig. 7. Final DP4T RF switch soldered PCB (view from lens).

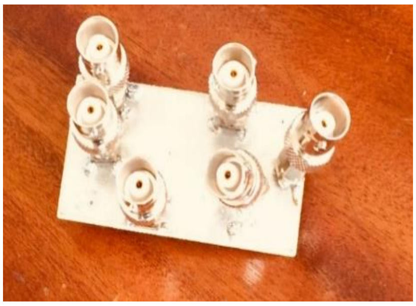


Fig. 8. Bottom view of DP4T RF switch with ground plane.

4. Testing of transmission between transceivers

Since the DP4T RF switch with MOSFET consist of two transceivers, to test the RF switch of this nature, two 1 GHz oscilloscopes, two 0.1 GHz signal generators and 5 V power supply have been used.

The two 1 GHz signal generator were used to provide a signal of 4.121 Vp-p into each antenna (ANT1 and ANT2) of the two transceivers. Thereafter, the two 0.1 GHz oscilloscopes were used to connect each transmitter antenna and the receiver antenna of each transceiver and the 5 V power supply was used to provide the required control logic in a mode that the RF switch will be required to operate for a simultaneous receiver and transmit data. This show that the RF switch will be compatible with the MIMO systems.

Figure 9 shows the signal that will be driven inside ANT1 and ANT2, as well as the signal properties that will be used for calculations. Figure 10 shows the pre-test connections for each transceiver as well as how the connections are set for testing.

Figure 11 shows the output signals when the switch is only operated for transmitting and in this case, the receiver is not in use but there is small signal noticeable that will be taken to account when calculating the isolation loss between TX and RX ports. The pre-testing of the two transceivers became successful as the DP4T RF switch was capable of routing signals for TX and RX.

Figure 12 represents the transmitted signal from the input signal that went through the RF switch. The RF switch was operated with 5 V control logic to route signals properly for different modes and the RF switch also manage to be capable of port isolation and that one of the important specifications of the RF switch to make sure that no stray signal, but all signal should be routed according to the control logic applied.

In Fig. 12, ANT1 is connected to the transmit antenna and ANT2 is connected to the receive antenna and the control logic are applied to suit these conditions. While this is happening, each transceiver consists of three ports namely main Antenna (ANT1 or ANT2), transmit antenna and receiver antenna.

In this case, while ANT1 is transmitting data at 0.1 GHz only, receiving port sense some small signal that leads to the calculations of performance parameters of this RF switch namely, insertion loss, isolation between the transmit and receive port. ANT2 is receiving data at 0.1 GHz and the transmit antenna port can sense some small signal and this is caused by imperfection that exists in RF components.

Figure 12 shows the results of the switch performance for transmitting and receiving data at the same time. The switch can switch with the required control logic to enable simultaneous data transmission.

The DP4T switch is connected for simultaneous data transmission, ANT1 is connected to the transmitting antenna and ANT2 is connected to the receiver antenna, with appropriated control logic. Control logic can be applied according to the specific needs are represented in Table 1 for DP4T switch working principle.

This proposed DP4T switch design with *n*-MOSFET captures all the MIMO systems advantages.

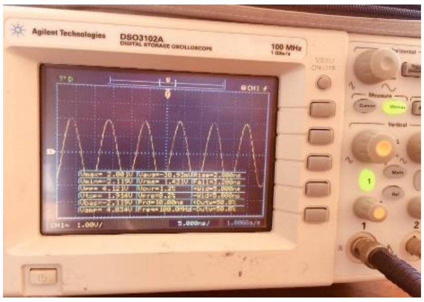


Fig. 9. ANT1 and ANT2 signal and properties.

Fig. 10. DP4T RF switch pre-testing each transceiver.

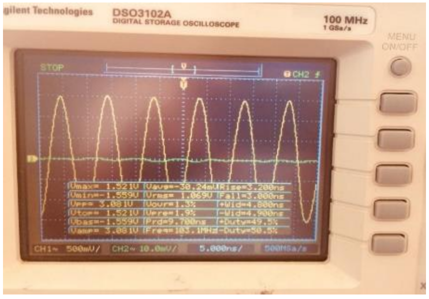


Fig. 11. Testing of transceivers.

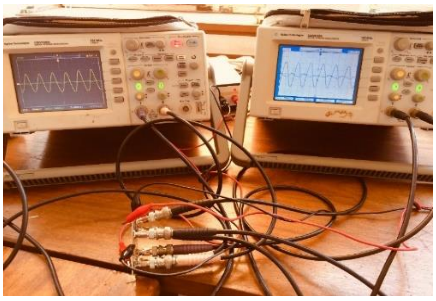


Fig. 12. Simultaneous signal routing between two transceivers.

Table 1. Working process of DP4T switch.

Supply				Transceiver 1				Transceiver 2				ANT-1	ANT-2
V_1	V_2	V_3	V_4	M-1	M-2	M-3	M-4	M-5	M-6	M-7	M-8		
L	*L*	*L*	*L*	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	*NC*	*NC*
H	*L*	*L*	*L*	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF	1_*Rx*	*NC*
L	*H*	*L*	*L*	OFF	ON	ON	OFF	OFF	OFF	OFF	OFF	1_*Tx*	*NC*
L	*L*	*H*	*L*	OFF	OFF	OFF	OFF	OFF	ON	ON	OFF	*NC*	2_*Rx*
L	*L*	*L*	*H*	OFF	OFF	OFF	OFF	ON	OFF	OFF	ON	*NC*	2_*Tx*
L	*L*	*H*	*H*	OFF	OFF	OFF	OFF	ON	ON	ON	ON	*NC*	2_*Tx* and 2_*Rx*
L	*H*	*L*	*H*	OFF	ON	ON	OFF	ON	OFF	OFF	ON	1_*Tx*	2_*Tx*
L	*H*	*H*	*L*	OFF	ON	ON	OFF	OFF	ON	ON	OFF	1_*Tx*	2_*Rx*
L	*H*	*H*	*H*	OFF	ON	ON	OFF	ON	ON	ON	ON	1_*Tx*	2_*Tx* and 2_*Rx*
H	*L*	*L*	*H*	ON	OFF	OFF	ON	ON	OFF	OFF	ON	1_*Rx*	2_*Tx*
H	*L*	*H*	*L*	ON	OFF	OFF	ON	OFF	ON	ON	OFF	1_*Rx*	2_*Rx*
H	*L*	*H*	*H*	ON	OFF	OFF	ON	ON	ON	ON	ON	1_*Rx*	2_*Tx* and 2_*Rx*
H	*H*	*L*	*L*	ON	ON	ON	ON	OFF	OFF	OFF	OFF	1_*Tx* and 1_*Rx*	*NC*
H	*H*	*L*	*H*	ON	ON	ON	ON	ON	OFF	OFF	ON	1_*Tx* and 1_*Rx*	2_*Tx*
H	*H*	*H*	*L*	ON	ON	ON	ON	OFF	ON	ON	OFF	1_*Tx* and 1_*Rx*	2_*Rx*
H	*H*	*H*	*H*	ON	ON	ON	ON	ON	ON	ON	ON	1_*Tx* and 1_*Rx*	2_*Tx* and 2_*Rx*

**NC*-Not connected, *H*-High, *L*-Low, *Tx*-Transmitter, *Rx*-Receiver.

4. Results and Analysis

The signal that was driven into the main antenna (ANT1 and ANT2) ports were 4.121 Vp-p sine wave at 0.1 GHz, also called an incident wave. When transceiver 1 is operated to transmit data only through transmitter ANT1 and transceiver 2 is operated to receive data only through receiver ANT2, at this instance, it has been observed that the portion of the signal that was successfully transmitted and received was 3.081 Vp-p sine wave signal at 0.1 GHz.

Obviously, there was noticeable small-signal leakage of 120 mVp-p for transmitter and receiver port isolation. In this case, it is acceptable since the transmitted or received signal was not distorted. From this data, it becomes easier to derive the reflected signal from the variation of the incident signal to the transmitted signal.

Table 2 shows the performance of the DP4T RF switch results when operated for a different mode of transmitting and receiving data as per MIMO systems requirement. The indicator (symbol *x*) inside Table 2 represents the included data to calculate the required parameter.

The DP4T RF switch design with MOSFET has been simulated in advanced electronic software, with a model of *n*-MOSFETs based on existing ones. The simulated results have been achieved after some number of iterations, which resulted in an optimized width and a channel length of *n*-MOSFETs [12]. This was performed to achieve small insertion loss and high OFF-isolation loss.

The comparison of the simulated and measured results shows similarity though testing equipment was the great constraint undoubtedly, the designed DP4T RF switch measured results showed impressive improvements close to simulated results.

The comparisons in Table 3 justify the successful implementation of the DP4T RF switch. However, Table 4 has the performance comparison of the proposed DP4T switch with *n*-MOSFET with the various existing RF switches.

Table 2. DP4T RF switch hardware performance results.

RF parameters	Incident signal (4.121 V_{p-p})	Transmitted signal (3.081 V_{p-p})	Reflected signal (1.040 V_{p-p})	OFF Isolated *Tx* or *Rx* signal (120 mV_{p-p})	Parametric value (dB)
Return loss	*x*		*x*		11.96
Insertion loss	*x*	*x*			2.53
OFF-isolation	*x*			*x*	30.72

Table 3. Simulated and measured results.

Parameters	Simulated results (dB) [12]	Measured results (dB)
Return loss	15.90	11.96
Insertion loss	1.68	2.53
OFF-isolation loss	39.34	30.72

Table 4. Proposed DP4T switch compared with existing switches.

Reference	Frequency (GHz)	Insertion loss (dB)	Isolation (dB)
[10]	2.4	0.75	*x*
[10]	5.0	0.86	*x*
[15]	2.4	1.2	25-53
[15]	5.24	1.7	23-37
[16]	5.8	1.8	23-37
This work	2.4	1.68	39.34
This work	5.0	1.70	33.02
This work	10.0	1.78	27.10

5. Conclusions

In this research work, Double Pole Four-Throw (DP4T) switch has been fabricated, which uses the n-type MOSFETs. The optimization of the width and length of the *n*-MOSFET has been considered. In this design, high isolation loss is achieved with better return loss. The design objectives are met for the entire performance parameters analysed. The simulated result gives the return loss 15.90 dB, insertion loss 1.68 dB, and off-isolation loss 39.34 dB, and for measured (after fabrication) these values are 11.96 dB, 2.53 dB, and 30.72 dB, respectively. The fabricated tested results and simulated realized results are similar

In future, this DP4T switch fabrication can be extended with a high dielectric material, in which, it uses the silicon-based MOSFET. In addition, radiation patterns with respect to near and far-field regions can be realized using this switch with any particular antenna.

Nomenclatures

IL	Insertion loss, dB
RL	Return loss, dB
R_{ox}	On-resistance, Ω
V_{gs}	Gate to source voltage, V
V_{p-p}	Voltage peak-to-peak, V
V_{th}	Threshold voltage, V

Abbreviations

3D	Three-Dimensional
ANT	Antenna
CMOS	Complementary Metal Oxide Semiconductor
DG	Double Gate
DP4T	Double-Pole Four-Through
EMI	Electro-Magnetic Interference
GaAs	Gallium Arsenide
H or L	High or Low
HEMT	High Electron Mobility Transistor
MEMS	Micro-Electro-Mechanical Systems
MIMO	Multiple in Multiple Out
NC	Not Connected

PCB	Printed Circuit Board
RF	Radio Frequency
SMA	Sub-Miniature version A
SMD	Surface Mount Device
SPDT	Single Pole Double Through
Tx	Transmitter

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