A high isolation RF switch designed for amorphous flat air-ground ad-hoc network platform

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Abstract. In this paper, a single-pole, double-throw (SPDT) RF switch is designed for the amorphous flat air-ground ad-hoc network platform, which is used to connect the node, low noise power amplifier and power amplifier. The switch controls the transmission and reception of signals in the node according to the variation of excitation voltage. The simulation results show that the RF switch insertion loss is less than 1.5dB, isolation is more than 40dB and the 0.1 dB compression is 38dBm in the frequency band 2.4GHz to 2.5GHz, which can meet the requirements of the ad-hoc network platform. Networking tests results showed that the topology of ad-hoc networks remains stable within a certain distance and the direction of signal in the node is controlled by the switch.

1. Introduction
Thanks to the rapid development of wireless network technology, we are lived through the age of 4G communication and about to enter the era of 5G communication. Traditional wireless communications such as 4G are usually based on cellular networks, which require infrastructure support, are more suitable for stable environments, and require long-term maintenance. But such wireless communications cannot be established in a short time in some complex and extreme environments, such as disaster relief and battlefield operations. In order to solve various problems existing in the cellular network, amorphous flat air-ground ad-hoc network was proposed.

Amorphous flat air-ground ad-hoc network uses ZigBee module working in 2.4GHz as the network node, introduces air node carried by UAV to eliminate ground interference. Low noise amplifier and power amplifier have also been added to extend the communication distance. Rf switch is a bridge connecting antenna and amplifiers, which controls the flow of RF signals between transmitter and receiver. As the first stage after antenna, the performance of switch has an important influence on the ad-hoc network platform [1]. Switch with low insertion loss, high isolation and high linearity should be
considered. The cost of switch design is also important, which emphasizes the choice of process in the design. Common processes of switch include GaAs pHEMT\[2\], silicon on sapphire (SOS)[3] and silicon on insulating substrate (SOI)CMOS process [4], several of which are costly. With the development of low-cost CMOS technology, the feature size of CMOS devices has been continuously reduced. In recent years, high performance rf switches using CMOS technology have become a trend. [5].

In this paper, a 2.4GHz CMOS SPDT RF switch suitable for the amorphous flat air-ground ad-hoc network platform is proposed. The switch in a series-shunt configuration introduces stack transistor technology and CMOS triple-well design technology to improve its power processing capability [6]. Bandpass filters are added to the transmitter and receiver ports respectively to reduce the interference of other frequency bands [7] and enhance the link stability. The networking tests show that the network topology remains stable within a certain distance after switches are added.

2. Design of RF switch

Key figures of RF switch include insertion loss IL, isolation, linearity, and power handling capability [8]. IL is used to describe the attenuation caused by the signal passing through switch, which is mainly caused by the on-resistance of the transistor $R_{on}$. $R_{on}$ can be expressed as

$$R_{on} = \frac{L[\mu_n C_{OX} W(V_{GS} - V_{TH})]}{\mu_n C_{OX} W(V_{GS} - V_{TH})}$$

$L$ and $W$ are the length and width of the gate, $\mu_n$ is the electron mobility, $C_{OX}$ is the gate oxide capacitance per unit area, $V_{GS}$ is the voltage of the gate-source, and $V_{TH}$ is the threshold voltage of the MOS transistor. IL represents the ratio of the switch input power $P_S$ to the output power $P_L$ when the switch is working

$$IL = \frac{P_S}{P_L} = |S_{21}|^{-2}$$

$$IL(dB) = -20\log |S_{21}|$$

Isolation is used to measure the isolation of the receiver-transmitter port of the switch. It is mainly determined by the parasitic capacitance $C_{off}$ when the transistor is off. $C_{off}$ can be estimated using

$$C_{off} = C_{ds} + \frac{C_{gs} C_{gd}}{C_{gs} + C_{gd}}$$

$C_{ds}$, $C_{gs}$ and $C_{gd}$ are respectively transistor source-drain, source-gate and gate-drain parasitic capacitors. Isolation can be evaluated by

$$Iso(dB) = -20\log \frac{2Z_0}{2Z_0 + (\omega C_{off})^{-1}}$$

Reducing the transistor gate width increases isolation but causes IL to rise, so the size of transistor is a trade-off between IL and isolation.

![Schematic of the SPDT series-shunt switch.](image)

In switch, the series branch serves as the signal path, and the parallel branch grounding the
transmitting and receiving branches [9]. Stack transistor technology is used to improve the power processing capacity, and CMOS triple-well design technology is introduced to improve the linearity [10]. Figure 1 shows the schematic of switch. TX, RX and ANT are transmitting branch, receiving branch and antenna respectively. When the switch is in receiving mode, V2=V4 is connected with positive voltage and V1=V3 is connected with negative voltage. Using the voltage opposite to the receiving mode can make the switch work in the transmitting mode. The transistor gate is connected to a large resistor, which prevents the transistor in the on-branch from being broken down by a large signal. The off-branch gate voltage is bootstrap to signal voltage, which can effectively improve the isolation, and the power processing capacity of each transistor is increased by twice. A large resistor is also connected between the source and drain to ensure the uniform distribution of voltage across each transistor in the off branch.

Figure 2. Cross-sectional view of NMOS transistor in triple-well CMOS technology.

Due to the weak performance of CMOS transistor in processing high-power signals, CMOS triple-well processing technology was proposed. Figure 2 shows the cross section of the NMOS transistor in the triple-well structure. The deep-N-well separates the body from the P substrate, so the voltage offset at the body and the gate can be easily biased by using a large resistor. But the introduction of DNW also introduces two new diodes. When the transistor body is suspended by a large resistor, the voltage of the P-well is bootstrap to the signal voltage, ensuring that the source-body diode and drain-body diode are not turned on by the large signal. However, the high voltage at the P-well may cause the diode between the P-well and the DNW to open, resulting in a decrease in linearity. To overcome this, the design uses a large resistor to suspend the DNW so that both the P-well and the DNW are both RF floating and the diode between them will not be turned on. The diodes between DNW and P substrates are also at risk of being turned on by large signals. But the voltage bootstrap is decreasing, so P substrate needs not be protected.

The influence of other frequency band signals on ad-hoc network should be minimized, so the transmitter and receiver ports are cascaded with bandpass filters. The filters use coupled microstrip line structure with central frequency of 2.45GHz, relative bandwidth of 5%, loss<0.6dB and a ripple<0.5dB. According to the equation

\[ Z_{\text{out}}|_{i,i+1} = Z_0[1 - Z_0 J_{i,i+1} + (Z_0 J_{i,i+1})^2] \]  
\[ Z_{\text{in}}|_{i,i+1} = Z_0[1 + Z_0 J_{i,i+1} + (Z_0 J_{i,i+1})^2] \]  
\[ J_{0,1} = \frac{1}{Z_0} \left( \frac{\pi BW}{2 \theta \beta (\theta \beta)} \right)^{1/2} \]  
\[ J_{i,i+1} = \frac{1}{Z_0} \left( \frac{\pi BW}{2 \theta \beta (\theta \beta)} \right)^{1/2} \]  
\[ J_{N,N+1} = \frac{1}{Z_0} \left( \frac{\pi BW}{2 \theta \beta (\theta \beta)} \right)^{1/2} \]  

Filter parameters are calculated, as shown in Table 1.
Table 1. Bandpass filter parameters.

| Section | $Z_0$(Ohm) | $Z_F$(Ohm) |
|---------|------------|------------|
| 1       | 62.11      | 41.95      |
| 2       | 52.57      | 46.67      |
| 3       | 52.57      | 47.67      |
| 4       | 62.11      | 41.95      |

3. Simulation of switch

According to the requirements of long communication distance and high link stability of amorphous flat air-ground ad-hoc network, the switch with filtering function should meet the following requirements within the frequency band of 2.4GHz-2.5GHz: $IL<1.5$dB, isolation$>40$dB, $P_{0.1dB}>32$dBm.

3.1 RF switch simulation

The transmitter and receiver branches of RF switch are symmetrical. Port 1 is selected as input, port 2 as on branch output, and port 3 as off branch output. The simulation curves of IL and isolation of the switch are shown in Figure 3. the insertion loss and isolation of the switch at 2.4GHz were 0.809dB and 41.218dB respectively.

Figure 4 describes the linearity of the switch transmission state. At 2.4GHz, the compression point of 0.1dB output power is 38dBm, which is higher than the maximum output power of 31dBm of the ad-hoc network platform node, meeting the working requirements.
3.2 Filter simulation
The S parameters simulation results of filter are shown in Figure 5. Simulation shows that the insertion loss of the filter in the frequency band of 2.4GHz - 2.5GHz is less than 0.6dB, the maximum ripple is 0.095dB, the return loss is less than 20dB, and the attenuation at 300MHz out of the band is more than 30dB.

3.3 Joint simulation
Figure 6 shows the insertion loss and isolation simulation of the filter switch. The simulation of 0.1dB compression point is shown in Figure 7. The maximum insertion loss of the filter switch is 1.443dB, the minimum isolation is 41.534dB, and the compression point of 0.1dB is still 38dBm. The simulation results of switch satisfy the ad-hoc performance. Chapter 4 will present the results of the switch networking experiment.
4. Networking experiment result of filter switch

Figure 8 is the schematic of networking test. The transmitter ports of the switches are connected to PA, and the receiver ports are connected to LNA. The two switches are connected to the node and the antenna respectively. Figure 9 shows the circuit of the networking experiment. It can be seen that the node separated the transmitting and receiving branches after the switches were added.

The network topology of the three nodes with switches is shown in Figure 10, and the thick green lines indicate that the topology is very stable. The test proves that the switch can control the direction of the signal in the node and make the topology stable within a certain distance.
5. Conclusion
A single-pole double-throw CMOS RF switch is proposed in this paper, and stack transistor technology, triple-well design technology and bulk suspension technology are used in design. Insertion loss was less than 1.5dB, the isolation was more than 40dB, and the 0.1dB compression point reached 38dBm of the switch at 2.4GHz. Bandpass filters are added to the switch to avoid interference and enhance the stability of network links. The experiment shows that the switch can effectively control the signal direction of the nodes in amorphous flat air-ground ad-hoc network platform, and the network topology remains stable within a certain distance with switches.

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