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SP10T Switch Routes 2G/3G/4G Signals

This antenna switch module is compact enough for next-generation mobile communications applications, with outstanding electrical performance as a result of intelligent design choices.

Nuttapong Srirattana | January 2011

Smart phones owe some of their multimode, multiband capabilities to multithrow antenna switches. As mobile handsets evolve, a single antenna switch may handle as many as 10 transmit (Tx) and/or receive (Rx) ports. The challenges facing multithrow antenna switches for these applications are not trivial but, fortunately, solutions exist for managing high throw counts while still maintaining excellent RF performance in next-generation mobile handsets.

An antenna switch directs transmit signals from a wireless communications system's power amplifier (PA) to the antenna and routes received signals from the antenna to the system's receiver block. It must be capable of handling high power transmission from power amplifiers and be extremely linear without generating harmonics and intermodulation distortion (IMD) that would reduce signal integrity and receiver sensitivity, or create interference to other nearby communication devices.

With the increased number of wireless communications standards in use around the world, demand is growing for antenna switches for multimode and multiband applications. Such switches must be capable of as many as nine or ten connections, in the form of single-pole, nine-throw (SP9T) and singlepole, 10-throw (SP10T) switches. An increase in the number of connections greatly impacts the performance of the switch. The number of switch arms and their associated parasitic capacitances present one of the limiting factors for insertion loss, isolation, harmonic performance, and linearity. In pseudomorphic highelectron- mobility-transistor (pHEMT) antenna switches, the size of the field-effect transistor (FET) used as the active switching device, the number of stacking devices (the number of devices connected in series), and the switch architecture must be carefully chosen to achieve good performance in both low- and high-power operation. What follows is a review of the challenges in designing a high-count multimode, multiband antenna switch with respect to various key RF parameters, including insertion loss, isolation, second- and third-harmonic performance, and third-order intermodulationdistortion (IMD3) performance.

For any multithrow antenna switch, the insertion loss is generally a function of the on-resistance and off-capacitance of the switch arms, especially as frequency increases. It can also be impacted by other factors, such as the parasitic capacitance and inductance of the interconnections and bond wires. Deleterious effect of the parasitic capacitance due to package encapsulant can be negated by using bondwire inductance as part of the design. However, the addition of more switch ports degrades the insertion loss, which can be explained using Eq. 1[1]:

Insertion loss = $10\log_{10}\{(1 + R_{on}/2Z_0)^2 + [(Z_0 + R_{on})/2X_C]^2\}$ (1)

where

$X_C = 1/(2\pi f C_{off})$ (2)

when

R_{on} = the on-resistance of the on arm, C_{off} = the off-capacitance in total of the off-arms, and Z_0 = the characteristic impedance of the system (typically 50 Ω).

Figure 1 shows how insertion loss is affected by the increased shunt capacitance due to the increased number of switch off-arms. The increase of C_{off} in this case represents all switch arms biased into their high-isolation states and connected directly to the common port or antenna. It is clear that the insertion loss increases greatly when all the switch arms are connected directly to the antenna port as a result of additional C_{off}. The impact of Coff on insertion loss can be lessened by a matching network at a frequency band of interest to resonate out the impedance mismatch. Nevertheless, C_{off} is still a major contributing factor to linearity and harmonic generation. Furthermore, it is not always desirable to have all the arms connected directly to the antenna as Coff will be too high, resulting in degraded performance.

There are several ways to reduce the impact of C_{off}. Different switch architectures have been developed for this purpose. By separating some of the off-arms using an “enable” switch, the effect of C_{off} can be alleviated for the arms located outside the enable switch, although there will be additional insertion loss for switch arms placed inside the enable switch. This technique is often used for switch arms that can tolerate more insertion loss such as those at receiver ports.

The isolation between ports of a multithrow antenna switch is typically determined by the on-resistance and off-capacitance of the FETs comprising the switch. In many multithrow switch designs, the switches are designed with a series-shunt device configuration to improve isolation. This can be explained by Eq. 3:

Isolation = $10\log_{10}[(1 + Z_0/2R_S)^2 + (X_C/2Z_0)2(1 + Z_0/R_S)^2]$ (3)

where in this case,

X_c = the reactance from off-capacitance of the arm to be isolated and

R_s = the resistance of the associated shunt arm used to improve the isolation.

This is illustrated in **Fig. 2**. The challenge in multithrow switch design comes when switch arms are being designed in a small, limited-die-size allocation, and there are significant couplings between bond wires. The illustration of bond wire coupling is shown in **Fig. 3**. It can be difficult to decrease bond-wire coupling because of the limitations imposed by package pin out and die placement. The best way to predict and estimate the impact of bond-wire coupling on the isolation performance is through a co-simulation of the pHEMT switch circuit and electromagnetic (EM) simulation of the bond wires as well as package parasitic structures.

Harmonics can be generated from both the on and off arms of a switch net work. For a pHEMT switch, the switch is biased in the triode (linear) region where the operating range is limited by drainsource current Idss. In theory, Idss and the periphery of the arm should be scaled such that:

$I_{dss} = (2P_{in}/ZL)^{0.5}$ (4)

where

P_{in} = the input power and

Z_L = the load impedance.

Current I_{dss} is a function of the on-arm FET size. Proper sizing of the on-arm FET can minimize harmonic generation, as well as IMD, created by the device operating in a nonlinear R_{on} region. Harmonics and IMD generated from the off-arms are more critical for multithrow switches than with simpler switch configurations. Because of the high number of off-arms, the off-arms are the main contributors of harmonics and IMD. The off-device must be biased to ensure a pinch-off condition. This can be explained by the following set of Eqs. 5-7[2]:

$V_{gs} = V_{RF}/2n – V_{GS}$ (5)

$V_{GS} = V_L – (V_H – V_F)$ (6)

$V_{RF} = (2P_{max}Z_L)0.5$ (7)

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The device will remain in the off-condition as long as V_{gs} is still in pinch-off mode, or $V_{gs} < V_p$ (where V_p is normally around -0.8 to -1.1 V depending on pHEMT processing and doping profile) as illustrated in **Fig. 5**. Voltage V_{gs} is the voltage across the gate and source junctions and is a function of n, the number of FETs in series, V_H, the control voltage (high setting), and V_L, the control voltage (low setting). Voltage V_{RF} is the peak voltage of the RF signal at the load impedance, Z_L. Voltage V_F is the forward voltage of the gate-source Schottky junction (approximately 0.3 V to 0.45 V), while Pmax is the maximum RF power (in W) for an off-device to remain pinched off, without being selfbiased into conduction. In practice, V_{gs} must be lower than V_p with some margin because of the nonlinear characteristic of C_{gs} near pinch-off conditions.

To reduce the distortion produced by a multithrow switch's off-arms, increasing the number of FET devices in series in each arm can ensure a true off condition under high-power operation. However, it is important to note that there will be an additional on-resistance from adding the series FET and the FET device size may need to be readjusted to maintain acceptable insertion loss. The sizing of the FET device has a great impact on the onresistance as well as the off-capacitance. A large FET has lower R_{on} and higher C_{off}. On the other hand, an excessively small FET can degrade on-harmonic distortion, insertion loss, and limit power-handling capability.

Stacking FETs or increasing FET periphery to maintain the same on-resistance is sometimes not desirable as they both produce increases in die area. An alternative is to use a charge-pump circuit to increase the available bias voltage to ensure proper operation of the off-arms, especially at elevated power or mismatch condition. However, the addition of a charge-pump circuit will consume more current and die area at a greater cost. The charge-pump architecture must be carefully selected and optimized to meet the supply voltage and current requirements.

A SP10T pHEMT antenna switch module (ASM) that can support as many as four linear transmit-receive (TRx) ports and has integrated harmonic filtering on GSM transmit (Tx) ports to reduce harmonic levels from PAs was designed and evaluated. **Figure 6** shows a block diagram of the switch, which is housed in a 3.0 x 3.8 x 0.75 mm 26-lead QFN package (**Fig. 7**), with a brief summary of RF performance given in the table. The insertion loss of each port was measured and plotted in **Figure 8** and **Figure 9**, where the insertion loss of Tx1 and Tx2 are the insertion loss of switch and filter combined. Isolation is plotted in **Figure 10** and **Figure 11** along with its limit over different frequency bands. The low loss and high isolation validate the optimal FET periphery as well as the routing of bond wires within the module. Harmonic attenuation of the Tx1 and Tx2 signals is accomplished with integrated filtering (**Fig. 12**). Tx1 and Tx2 harmonics are measured over a broad temperature range (-30 to +90°C) and shown in **Fig. 13**. Both second and third harmonics at room temperature measure better than -80 and -78 dBc for low and high bands, respectively, well within system specification of -67 dBc.

The SP10T ASM requires only four input ports for use with an integrated 4-to- 10-b charge-pump decoder. The negative charge-pump scheme eliminates the need for blocking capacitors on the RF ports while maintaining good RF performance over the supply voltage range, with process variations, and with temperature variations. The negative charge-pump decoder has been successfully implemented in this design with the supply current of less than 400 µA.

Harmonic measurements were also performed at power levels of +35 dBm in the low band and +33 dBm in the high band under mismatched conditions to ensure that radiated harmonics are controlled within the maximum limit of -30 dBm required by the

Federal Communications Commission (FCC). Some margin below this limit is desirable, since harmonic performance can be degraded by harmonics generated by the PA. The second- and third-harmonic levels of the SP10T ASM were found to be better than -35 dBm even with a mismatch equal to a 5.0:1 VSWR (**Fig. 14**), using a harmonic test setup (**Fig. 15**). Third-order- intermodulation (IMD3) measurements were performed across all phases of fundamental and blocker signals using the test setup of **Fig. 16**. Because the levels of intermodulation products can vary depending on the phase of the two mixing signals, an IMD3 test over a range of phase variations was necessary to guarantee adequate performance under worst-case conditions.3 The SP10T ASM was tested for the worst-case phase IMD3 and the results are plotted in **Fig. 17**, with worst-case performance found to be -105 dBm at room temperature.

At room temperature, the SP10 ASM achieved typical insertion-loss performance of 1.05 dB in the GSM Tx1 band from 824 to 915 MHz and typically 1.0 dB in the GSM Tx2 band from 1710 to 2179 MHz. It should be noted that these GSM transmitter-band insertion loss measurements involved the use of a harmonic filter, which also contributed some loss to the measurement setup. The insertion loss in the UMTS band from 1710 to 2170 MHz was typically 0.75 dB, while the insertion loss in the GSM receive band from 1805 to 1990 MHz was typically 1.00 dB. The SP10T switch module achieved typically more than 30 dB isolation from the Tx1 port to all other ports, from 824 to 915 MHz, and better than 32 dB isolation from the Tx2 port to all other ports, from 1710 to 1910 MHz. The transmit/receiver- port-to-transmit/receive-port (TRxto-TRx-port) isolation from 1710 to 1980 MHz was typically better than 25 dB.

The compact SP10 antenna switch module exhibited GSM transmit-band harmonic levels of typically -80 dBc from 824 to 915 MHz when tested under 50-O conditions with a +35-dBm test tone. Using a +33-dBm test tone at 50-O conditions, the GSM transmit-band harmonics were typically -78 dBc from 1710 to 1910 MHz.

The miniature switch module was also evaluated for third-order intermodulation distortion (IMD3) at UMTS frequencies, using a +20-dBm fundamental-frequency test tone and a -15-dBm blocker signal under worst-case phase conditions, where in-phase signals would lead to the highest-possible interference conditions experienced during normal operation. The UMTS IMD3 performance was measured as typically -105 dBm at room temperature

In short, the SP10T switch module is compact but meets the performance requirements of multimode, multi-band 2G/3G/4G mobile communications systems, with outstanding insertion-loss performance and very high port-to-port isolation. It leverages pHEMT device technology, intelligent use of bond wires, integrated dual lowpass filters, and a negative charge-pump decoder to minimize insertion loss, provide high isolation, achieve good linearity, and deliver excellent harmonic suppression in a package measuring only 3.0 x 3.8 x 0.75 mm.

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