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Making the Call on 3G: Finding the Right Switch Solution for Complex High-Frequency Bands

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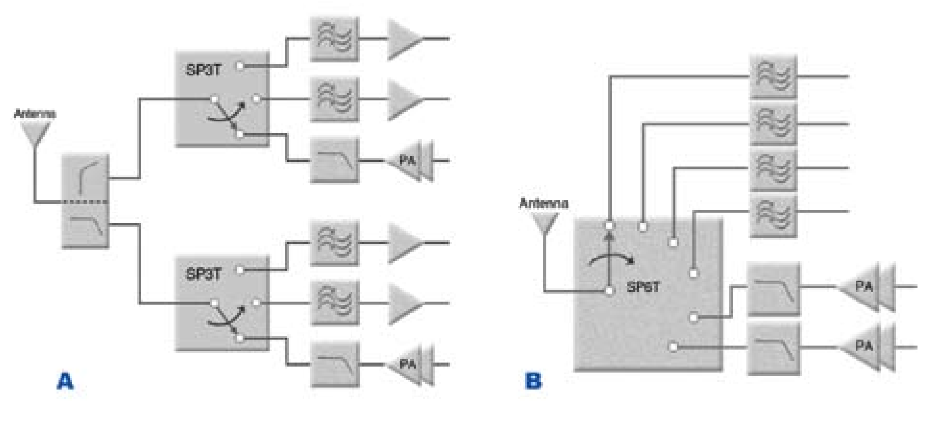

Figure 1A (left) 1B (right): Example front-end architectures for quad-band GSM

Then considered 'high-tech' systems, the first analog cellular handsets were quite basic, though they evolved more quickly as the years went on. Analog systems moved to digital, single-band moved to dual-band, then tri-band, and today the industry is unveiling roadmaps to multi-mode, multi-band complex communications systems with reduced part count and size. To accomplish this, handset OEMs provide well-defined requirements and timelines. Module manufacturers focus their technology roadmaps on modular integration. IC suppliers trend toward higher performance. The result is a host of multi-band cellular phone offerings on an aggressive learning curve.

Traditional RFICs are quickly becoming obsolete as the historic technologies-of-choice no longer support the aggressive performance demanded by the market. New cellular modes such as WCDMA are being integrated with up to 4 additional frequency bands, pushing the limits of performance – especially in the switching function connecting all the frequency paths to the antenna. These design challenges have brought the industry to an inflection point, which can only be solved efficiently with the next generation UltraCMOS™ process and HaRP™ technology.

Quad-Band GSM to WCDMA

Increased functionality requirements for GSM phones from single- to quad-band operation for coverage throughout the world requires up to four transmit and four receive paths. Adding single or dual WCDMA bands requires 1 or 2 additional TRX paths. Given the proximity of the adjacent TX bands, one power amplifier can cover GSM850 plus GSM, while a second power amplifier covers the DCS and PCS bands. Each additional WCDMA path requires a separate and additional power amplifier. Each RX path requires an individual filter, typically a SAW filter, which results in a total of six paths. This configuration requires a single-pole, seven-throw switch for quad band GSM plus a single WCDMA band.

In quad-band phone designs, many different configurations of switches and filters can be combined to implement the single-pole, six-throw function. While the configuration using a diplexer and two SP3Ts (Figure 1A) has some benefits which will be discussed later, it results in higher insertion loss than the implementation with a true SP6T switch (Figure 1B). In adding the WCDMA path the insertion loss of the diplexer adds an even greater negative effect because it is additive to the loss of the duplexer.

While engineers generally design for high isolation to unused paths in order to maintain low insertion loss, the tri- and quad-band GSM systems present a special problem where the GSM TX band overlaps with the GSM850 RX band, and the PCS TX band overlaps with the DCS RX band. During transmit, the RX band-select filters do not provide any attenuation to the transmitted signal that leaks through the switch. To protect the LNAs which follow the RX filters, the switch itself must provide at least 35 dB of isolation.

Since the front-end switch is connected directly to the antenna, the switch must have onerously high ESD tolerance. Handset designs must survive +/- 8 kV contact discharge and +/- 16 kV air discharge per the IEC 1000-4-2 specification. This ESD model has a series 330 ohm resistor and 150 pF capacitor, making it significantly more damaging than the human-body model. The switch must withstand this stress, or additional protection components must be included.

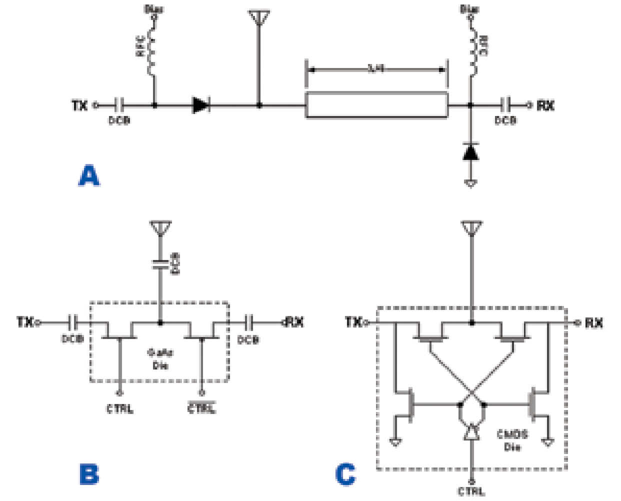

Figure 2: SP2T switches built with a) PIN diodes, b) a GaAs IC, and c) an RF CMOS IC

Once all of the technical requirements have been addressed, there are additional constraints on size and cost of the front-end switching solution. Both area and height are restricted, with height requirements now dropping below 1.4 mm. As the front-end switch is usually integrated into multilayer substrates such as LTCC, industry-standard form factors have been established to provide a roadmap of size reduction. Technologies which shrink these antenna switch modules (ASMs) are highly prized by phone manufacturers, as the ASMs are generally the tallest package in the radio section. LTCC offers high quality-factor passive integration capability in the substrate, but adding passives requires additional LTCC layers which increase the thickness of the module. PA harmonic filters are integrated in the substrate, but frequently blocking capacitors and ESD protection are left outside of the module to reduce size and layer count. Some ASMs also place SAW filters on the surface of the LTCC.

There are several different switching technologies that can meet the technical requirements of GSM and WCDMA handsets. Each has its own set of advantages and disadvantages.

Solid-State Switching

The solid-state switching industry was founded in the 1970s with PIN diode switches. Still the dominating technology in ASMs, PIN diodes achieve very low insertion loss and very low harmonic distortion. However, PIN diodes by themselves cannot complete an ASM. To bias the diodes, the module must include blocking capacitors and feed inductors. To build a multi-throw switch, series and shunt diodes are combined by quarter-wave transmission lines (Figure 2A). As a quarter-wavelength in LTCC at 900 MHz is several centimeters, these transmission lines drive the size of the diode-based ASMs.

GaAs pHEMT switches (Figure 2B) have emerged as a viable replacement to PIN diodes by reducing the size and complexity of ASMs. Although PIN diode ASMs generally offer lower insertion loss, a market opportunity has opened for FET switches as they greatly reduce size and hence cost of ASMs.

GaAs switches use multiple FETs per switching path and require one control line per path. Unlike PINs, pHEMT FETs cannot intrinsically tolerate the 17.8 Vpk GSM signal. By placing multiple FETs in series, the voltage can be divided across the devices to meet the power handling requirement. Shunt FETs can be added to improve isolation and increase immunity to load pulling from the isolated ports, but will double the number of control signals from six to twelve. To meet the GSM isolation requirement of 35 dB, shunt FETs or cascaded switches must be used.

To reduce the interface complexity with the pHEMT ASM, a CMOS decoder chip is typically included in the ASM. While there are some pHEMT processes under development which include both enhancement and depletion mode devices, static digital logic still cannot be implemented because there is no complementary device in GaAs pHEMT. The additional CMOS chip adds area and routing complexity. Considering there is typically nine or more control lines wire-bonded from the CMOS chip to the switch, care must be taken in the layout to prevent RF coupling to the control signals.

GaAs switches generally have low ESD tolerance, 250 to 500 V HBM, and require additional protection. This requirement in conjunction with difficulties in making a true SP6T has driven many ASM designers to use two SP3Ts combined with a diplexer. The diplexer provides ESD protection , but adds approximately 0.4 dB insertion loss to the design. An alternative implementation offered by several GaAs vendors is an SP4T switch cascaded with an SP3T on a single IC. The outputs of the SP4T are routed to the RX ports resulting in two switches in series between RX and TX. This provides adequate isolation to protect the LNAs in the band overlap region, but increases insertion loss and therefore noise figure.

GaAs switches are built with depletion-mode FETs which are on at 0 VGS, and must have a negative VGS lower than the pinch-off voltage to turn the device off. To work with positive control signals from CMOS logic, the FETs are DC blocked and the source and drains are biased up to VDD of the CMOS supply. This allows for 0 to VDD signals to control the GaAs switch. The LTCC can integrate the blocking capacitors, although the capacitors add area and layers to the LTCC substrate.

Recently RF CMOS has made inroads into front-end switching (Figure 2C). Traditionally, RF CMOS has been relegated to only low voltage applications, but breakthroughs in device and circuit technologies have resulted in RF CMOS switches which meet all of the GSM requirements.

UltraCMOS™ Process Technology and Switch Solutions

An ideal example of leading edge RF CMOS technology is UltraCMOS™ – a process based on standard CMOS processing, although as opposed to building devices on silicon, a semiconducting substrate, UltraCMOS-based devices are developed directly on top of a sapphire. The perfectly insulating, single crystal alumina properties of sapphire give UltraCMOS™ its performance edge. Specifically, UltraCMOS maintains all the positive attributes of bulk CMOS including the low power operation, manufacturability, repeatability, scaling properties and IP block re-use, yet delivers RF performance similar to GaAs.

Examples of SP6T and SP7T handset switches – the PE42660 and PE42672 from Peregrine implemented in UltraCMOS -- are shown in Figure 3. The RF switches are developed in a series-shunt configuration to improve insertion loss and isolation. No additional control signals are required as the decoder is integrated into the chips. No blocking capacitors are required as the switches integrate a negative voltage generator to provide the negative bias to turn the 0 VTH FETs off. The shunt devices are directly connected to ground. This provides a path for ESD current and the low isolated-state impedance makes the switches immune to load pulling on isolated ports. Also integrated are ESD protection circuits on the digital control lines. The HBM tolerance of the chip is 1500 V and is limited by the digital control lines. The antenna node tolerates 4000 V HBM.

The sapphire substrate in the UltraCMOS process allows for unique flip-chip packaging capability. As sapphire is a ceramic, its coefficient of thermal expansion is well matched to LTCC. Sapphire is also the hardest substance after diamond, making it very tolerant of mechanical stress. Switches with these properties can easily be flip-chip mounted to an LTCC substrate without underfill, eliminating the area that had been required for wirebonding. True wafer-level chip-scale packaging is under development and will produce switches which can be handled like a standard surface mount package.

Low insertion loss and high isolation can be achieved in UltraCMOS (Figure 4). The SP6T and SP7T architecture eliminates the diplexer requirement, significantly reducing the total insertion loss. To meet the IEC 61000-4-2 ESD requirement, a shunt 27 nH inductor followed by a series 33 pF capacitor at the antenna are sufficient. These values can be integrated into LTCC and contribute less than 0.1 dB to insertion loss.

The most difficult aspect of GSM switch design, particularly in a low voltage process, is meeting the linearity requirement. While arbitrarily high power handling can be realized by stacking as many devices as necessary, the stack should optimized to minimize die size while meeting the specification. This example switch has been designed to have P0.1 dB of +38.5 dBm and a P1dB compression point of +41 dBm.

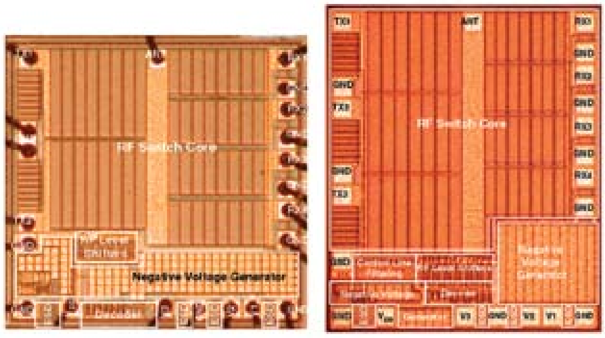

Figure 3: Die microphotograph of Peregrine Semiconductor's PE42660 (SP6T) and PE42672 (SP7T) WCDMA / GSM switches built in UltraCMOS process

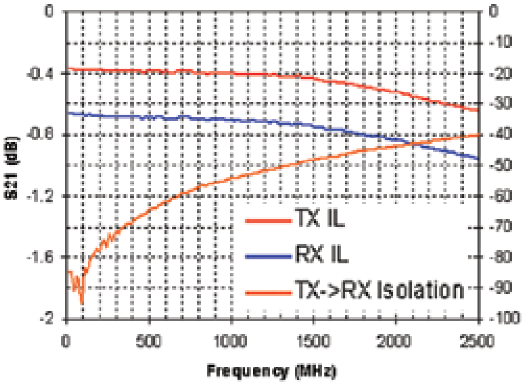

Figure 4: Insertion loss and isolation performance of SP6T switch

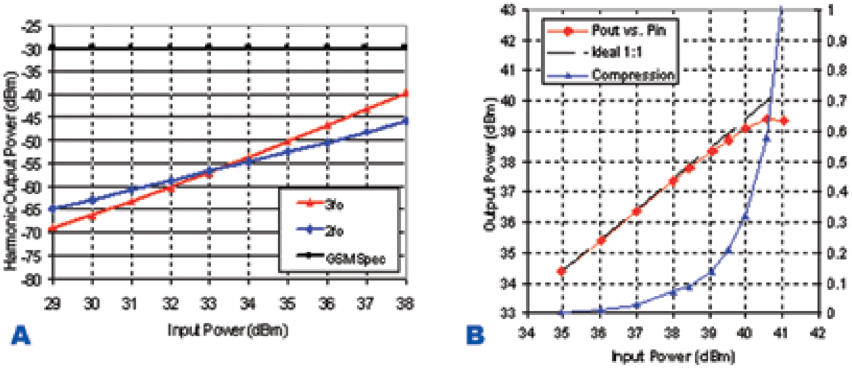

Figure 5A (left) & 5B (right): GSM linearity performance is shown by a) output harmonic powers versus input power and b) the compression behavior

The harmonics versus input power as well compression behavior are shown (Figure 5a and 5b) with a supply voltage of 2.4 V.

At the maximum operating power of +35 dBm, the UltraCMOS switch

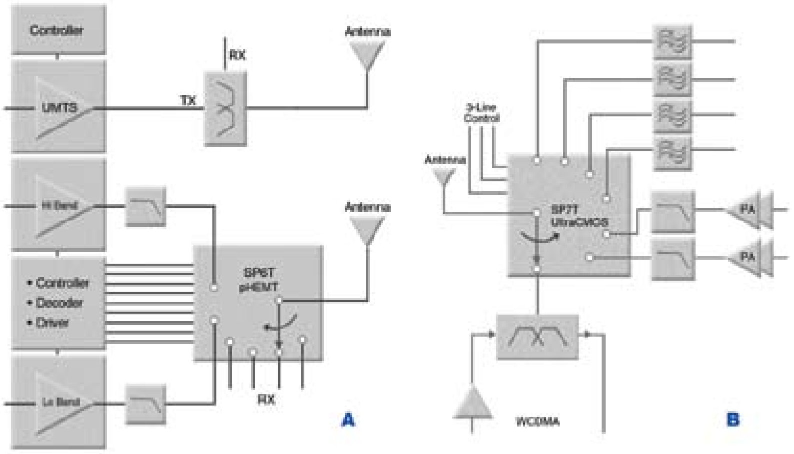

Figure 6A (left) 6B (right): Front-end options for WCDMA handset a) separate and b) integrated architectures.

Table 1: Performance comparison of SP6T implemented with different switch technologies.

Parameter	Frequency (MHz)	D-Mode[1] pHEMT	UltraCMOS™	Units
RX Insertion Loss	1900 900	1.0 0.8	1.0 0.8	dB dB
TX Insertion Loss	1900 900	0.65 0.55	0.65 0.55	dB dB
TX - RX Isolation	1900 900	– 40	37 45	dB dB
Harmonics	$2f_0$ $3f_0$	-32 -32	-54 -50	dBm dBm
Linearity	IP3	58	70	dBm
Supply Voltage		2.5 - 5.0	2.65 - 2.85	V
Current Drain		80 per ctrl	20	uA
Integrated Decoder		no	yes	
Antenna ESD Tolerance (HBM)		0.5	4	kV

Note 1: GaAs SP6T is implemented as SP3T + SP4T

has 20 dB of margin to the GSM specification of -30 dBm. The second harmonic is intrinsically low in UltraCMOS technology because distortion is symmetric on positive and negative voltage swings.

Harmonic performance of the RF switch is extremely important to the designer of the ASM. Typical switch technologies such as PIN diode and GaAs pHEMT provide only 6 dB of margin and designers may need up to 3 or 4 design spins to match the LTCC to the switch before hitting the specification. The 20 dB of margin provided by UltraCMOS virtually eradicates this concern and provides for first pass success resulting in shorter design cycles and time to market. The very low even order distortion for the second harmonic is desirable in the GSM system as the second harmonic of the GSM transmit band lands in the DCS receive band.

The greater than 50 dBm 2fo performance allows for less noise transmitted in the DCS band and increased system capacity for the carrier.

Another key performance characteristic is based on the recent introduction of HaRP™ technology – a key development in the advancement of high throw count switch linearity which dramatically improves harmonic performance. Switches built on HaRP-enhanced UltraCMOS have IP3 specifications that are greater than 70 dBm. The importance of this is valued when applied to the 3GPP standards body intermodulation specification for WCDMA handsets. This specification requires the switch to have an IP3 greater than 65 dBm and today only UltraCMOS switches can meet this stringent requirement.

Figure 6 looks at the impact HaRP™ will have on the front end of a WCDMA handset. Figure 6a identifies the architecture of a WCDMA radio today, which virtually bolts a WCDMA radio with separate antenna inside a GSM phone. Future requirements demand that the radios be integrated and share a single architecture. According to the 3GPP standards body specification, if the switch which shares the antenna as shown in Figure 6b does not have an IP3 of 65 dBm or greater, a condition can occur due to ambient blocking signals that will drop the user's call. This condition is unacceptable to all service providers and consumers alike.

The PE42660 UltraCMOS SP6T switch has small signal performance similar to pHEMT switches, however delivers superior large signal, ESD tolerance (See Table 1). The pHEMT switch performance shown is for a SP6T implemented as an SP3T followed by an SP4T for the RX paths. The PIN diode data is for the case where the switch is built with series and shunt diodes combined by quarter-wave transmission lines.

UltraCMOS eliminates the decoder, blocking capacitors, and the diplexer. Combined with chip-scale packaging technology, UltraCMOS can dramatically reduce the size and thickness of LTCC ASMs. High inherent ESD tolerance and a three-control line interface simplify implementation and use. The high yield of UltraCMOS processes and scalability to additional switch throws provides a roadmap to higher levels of integration in the next generation of handsets.

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