Harmonic Considerations When Designing with GSM Power Amplifiers

An accurate system design must be implemented to meet ETSI standards.

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Although the cellular handset market has begun to migrate to 2.5G and 3G technologies, the Global System for Mobile Communications (GSM) remains one of the most widely implemented systems in the world. The European Technical Standard Institute (ETSI), which oversees the GSM standard, ensures every handset manufacturer complies with the standard through a type approval process prior to release to the commercial market. The GSM standard allows handsets to transmit in the frequency bands from 880 MHz to 915 MHz for GSM and 1710 MHz to 1785 MHz for Digital Cellular Telecommunications System (DCS). The two bands operate using a modulation scheme known as Gaussian Minimum Shift Keying (GMSK). GMSK operates in a non-continuous pulsed mode with eight different time slots. The maximum output power out of the antenna in each time slot is 33 dBm for power level 5 in the GSM band and 30 dBm for power level 0 in the DCS band. Special consideration is given to GSM 900 harmonics, which are limited to -30 dBm. This article presents the design procedures necessary to meet the harmonics specification of a 50 ohm system by phase matching the power amplifier (PA), coupler, and front-end module (FEM).

Cross-Band Coupling

The non-linear characteristics of a GSM PA generate second harmonics in the range of 1.76 GHz to 1.83 GHz. Because the majority of GSM handsets are designed for dual-band operation, the second harmonic of the GSM band may fall directly in the DCS band. This creates a problem for handset designers because filtering cannot be implemented in the DCS band for the GSM second harmonic (2f(o)). Without filtering, the second harmonic couples onto the DCS band and transmits out of the antenna with very little attenuation.

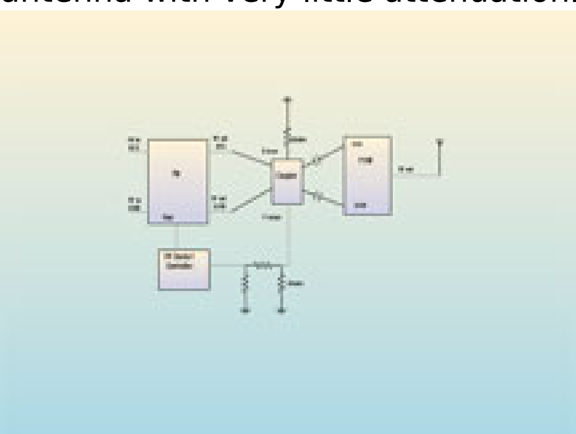

Figure 1. GSM system block diagram

The demand for smaller and lower cost handsets drives designers toward higher integration. Power amplifier vendors have responded to this demand with fully integrated dual-band modules internally matched to 50 ohms, reducing the board space required for external passive components. The close proximity of the high and low band PAs, and the bond wires in a module introduces a significant challenge of cross-band coupling between the two bands. Cross-band coupling occurs when the PA is operated in GSM mode and the second harmonic is coupled onto the DCS output port with very little attenuation.

System Description

A typical GSM transmitter will contain a PA, a coupler and a FEM. The following design example uses the RF3160 PA, the TDK HHM23227-A1 coupler, and the TDK ASM2402 FEM. The GSM system topology selected for this design example is shown in Figure 1.

Power Amplifier The RF3160 is a dual-band power amplifier module internally matched to 50 ohms. The PA is designed to operate in DCS and GSM frequency bands, which are selected by an internal band-select switch. A linear PA is not required for GSM because it uses a constant envelope modulation (GMSK). This allows the PA to be held in deep saturation at maximum power to provide superior efficiency and conserve battery life. The maximum output power out of the PA for the DCS band is 32.5 dBm and for the GSM band it is 35.5 dBm. The efficiencies are approximately 50 percent for DCS and 55 percent for GSM. The measured harmonics in the GSM mode are approximately -12 dBm, and the cross-band coupling is -15 dBm.

TDK Coupler

Following the PA is a dual-band coupler, the TDK HHM 2327-A1. The coupler is used for power control to sample the RF power back to the RF detector. The coupler is terminated with a 56 ohm resistor on the termination pin to provide the proper matching. The power-sense pin is connected to a resistive pad to simulate the control-loop topology. The coupler has an insertion loss of approximately 0.4 dB in both the GSM and the DCS bands.

FEM

Following the coupler is the TDK ASM5417475T-2402 front-end module. The FEM has an integrated diplexer, two low pass filters (LPF) and a TX/RX switch for each band. The diplexer allows simultaneous transmission and reception at different frequencies while maintaining good isolation between the two bands. The low pass filters are used to filter out high order frequencies such as second harmonics, which are attenuated by 30 dB. The TX/RX switches are set to either receive or transmit. The switch provides isolation from the TX input to the antenna. When the isolation is 20 dB for the DCS band, the cross-band coupling is reduced. The FEM has an insertion loss of 1.4 dB for both bands.

Harmonic Calculation

Using the components' measured values, the harmonics can be calculated through both bands to find an estimate of the harmonic levels at the antenna. Consider the following calculations:

GSM harmonic at the antenna = GSM
2f(o) + LPF attenuation at 2f(o)   (1)
-12 dBm + -30 dB = -42 dBm

Coupled harmonic at the antenna =
Coupled 2f(o) + Switch isolation (2)
-15 dBm + -20 dB = -35 dBm

Two signals will be present at the antenna, one at -35 dBm and the other at -42 dBm. The maximum value will occur when the two sinusoids are equal in phase thus adding the two magnitudes, which gives:

Pmain := -35
PmW : = $10^{(\text{Pmain}_{10})}$
Converts dBm to mW (3)

PmW = 3.162 &#215 10^{-4}
Pcoupled := -42

PcmW := $10^{(\text{Pcoupled}_{10})}$
PcmW = 6.31 &#215 10^{-5}
Max_mW := PmW + PcmW (4)
Max_mW = 3.793 &#215 10^{-4}
Total 2f(o) in mW

Max_dbm := 10log(Max_mW)
Max_dbm = -34.21
Max 2f(o) in dbm (5)

From these calculations, the system will meet GSM harmonic specification with some margin. Next, carefully measure and calculate the impedances to ensure a solid system that yields the same calculated results.

Characterizing the GSM Band

The first step in characterizing the GSM band is to determine the effect the coupler and the switch will have on the performance of the PA. This is accomplished by load pulling the RF3160's GSM output port with a randomly chosen voltage standing wave radio (VSWR) while transmitting at full power. The second harmonic is best suppressed when the impedance is 47 - 19j ohms at the 2f(o) and 52.8 +j 16 at the fundamental. The optimal phase angle that attenuates the 2f(o) provides the worst match to the PA at the second harmonic. The impedance presented at the 2f(o) gives the engineer the optimum phase angle in which to design to.

Designing for the Optimum Load (GSM Band)

The next step is to characterize the devices that follow the PA. The coupler and the switch are analyzed using s-parameter files to simulate their impedances. The s-parameters of the coupler are measured with a 56 ohm resistor on the termination pin. The resistor provides the appropriate match for the coupler. The FEM's s-parameters are determined while in the GSM transmit mode. The RF out, DCS/RX and GSM/RX ports are all terminated with 50 ohms. The simulation is performed using measured s-parameter files and a 33 pF DC blocking capacitor located between the two data blocks. The blocking cap is placed in the system to isolate the DC current from the switch. At this point, no transmission line is added to the simulation. The results of the simulation reveal that the impedance of the coupler and the switch at the second harmonic is 12.4 + j2.08 and the fundamental impedance is 36.2 + j9.6. The coupler and switch impedances are not optimal for the power amplifier. In order to rotate the input impedances to the optimal load impedance for the PA, a phase shifting network must be used. Since the simulation was designed without transmission lines, the length of the lines can be calculated now to rotate the phase to the desired impedances. Using the smith chart one can see that the impedance needs to be shifted by 0.55 wavelengths to achieve the correct values. The length of trace required can be calculated using the wavelengths. Consider the following equations:

c := 3 &#149 10^{10}
Speed of light in cm/s
f := 1.76 &#149 10^{9}
Frequency of operation

λcm := c/f (6)

λcm = 17.045
in := 2.45 cm
Conversion from cm to inches

The design requires a phase shift of 0.55 wave lengths in phase

λ := λin &#149 0.55
λ = 3.691

The total distance in phase

Eff := 4.5
Dielectric Constant for FR-4

λg := λ
(square rootEff)

To calculate λ when the wave enters the dielectric (7)

λg = 1.74
Trace := λg/2

To calculate the actual distance in trace length requires a division by 2.

Trace = 0.87
Actual length of transmission line needed

According to the calculations from equation 6, a 0.870 inch length of trace is required between the PA and the FEM. After adding the 0.870 inch trace, the measured S11 of the system from the output of the PA to the FEM was 121 - j88.15 at the 2f(o) and 56.8 + j 24.73 at the fundamental. The impedance is now shifted to the correct phase angle.

DCS Load Considerations
After the GSM band is completed, the DCS path is analyzed to minimize cross-band coupling. The DCS switch input impedance is measured while in the GSM transmit mode configuration. The DCS band is set in the receive mode providing 20 dB of isolation between the coupled second harmonic and the antenna. While the switch is in this configuration, a typical 6:1 VSWR is presented to the DCS output port of the PA. To fully understand the effect of the mismatch, the PA's DCS band must be characterized.
PA Characterization (DCS Band)
The PA is designed to operate at full power in the GSM mode. The GSM port is terminated into 50 ohms to provide the appropriate output match. While operating at full power in the GSM mode, the PA's DCS band is load pulled with a 6:1 VSWR to determine the effect of the mismatch. As the phase changes on this port, the fundamental power remains the same, but the cross-band coupling will vary from 10 to 15 dB. The highest cross-band coupling occurs when an impedance of 7.8 - j 3 is presented to the DCS output port. Once the non-optimum impedance of the PA is determined, it is possible to design the system around this impedance. The optimum impedance will be λ/2 wavelengths away from this point.
Designing for the Optimum
Load (DCS Band)
Through simulation, the coupler and switch s-parameter files are used to determine the impedances presented to the PA in the DCS band. The simulation consists of the coupler, a 12 pF blocking capacitor and the switch. This will provide the impedance presented to the PA without transmission lines. The simulated impedance is 14.4 + j 53. Even without the inclusion of transmission lines the resulting impedance is close to the target. The length of transmission line can now be calculated by rotating the phase to the optimum impedance. The calculation is made by using wavelengths to determine the correct length of trace between the PA and the input of the switch. Again, the smith chart is utilized to determine that the phase needs to be shifted. Equation 6 shows:

The design requires a phase shift of 0.2 wave lengths
λ := λin &#149 0.2
λ = 1.342
The total distance in phase

Eff := 4.5
Dielectric Constant for FR-4

λg := λ/ (square rootEff)
To calculate λ when the wave enters a dielectric

λg = 0.633
Trace := λg/2

To calculate the actual distance in trace length requires a division by 2.
Trace = 0.316
Actual length of transmission line needed.
This is the total length of trace required from the output of the PA to the input of the

FEM (resulting s11 shown in Figure 2).

Figure 2. Simulated impedance with correct transmission line lengths.

The next step is to examine the receive ports of the switch. The switch provides 20 dB of isolation, which is directly related to the Rx port's termination. Since the switch is in Rx mode, the impedance presented to this port will vary the isolation from the DCS input port to the antenna. The TDK DCS/RX port (internally matched to 50 ohms) is terminated into 50 ohms. The DCS/RX ports are then pulled through different phases to determine the correct transmission line lengths to achieve the best possible isolation. In this design example, the RX ports do not offer any significant change in isolation when tested. This will vary between different FEM vendors and should be measured in every design.

Table 1. Final Measured Data

Pin	F0	Vcc	Vapc	Pout (dBm)	Efficiency (%)	2nd Harmonic dBm
6	880	3.2	1.8	33.4	35.8	-40.8987
6	885	3.2	1.8	33.1	33.7	-36.5386
6	890	3.2	1.8	33.2	33.8	-40.7548
6	895	3.2	1.8	33.3	34.6	-38.8021
6	900	3.2	1.8	33.1	33.1	-38.7757
6	905	3.2	1.8	33.3	35.3	-37.2808
6	910	3.2	1.8	33.2	34.7	-35.2985
6	915	3.2	1.8	33.1	34	-38.8778

Measured Performance

The final step in the design process is to create a layout using the calculated line lengths. The measured results of the board manufactured from this design example are provided in Figure 3 and Table 1.

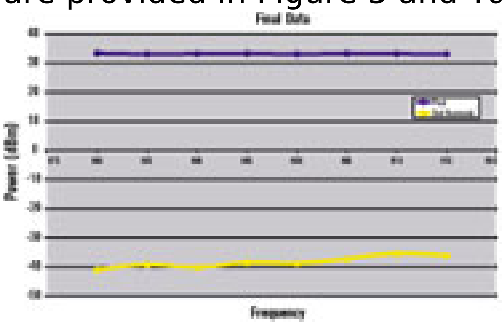

Figure 3. Final Measured Data

As the table shows, the design meets the second harmonic specification (-30 dBm) with plenty of margin. Recall from earlier that that calculated harmonic values could be as high as -34 dBm if the two signals added in phase at the antenna. The data reveals that the design has 5 dB of margin. With this margin the design engineer has some degree of flexibility in the layout. In a small compact design, for example, the trace lengths could be shortened to save space while still meeting specifications, but with less margin. Conclusion

In conclusion, an accurate system design must be implemented to meet ETSI standards. For dual-band GSM handsets, the second harmonic specification can pose a significant challenge. Factors like PA non-linearity, mismatch conditions, frequency band locations and board space reduction must be considered for successful handset design. This design example has proven that with the correct optimization of the GSM and DCS impedances, these challenges can be overcome.

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