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HIGH HARMONIC-REJECTION MATCHING FILTERS FOR QUAD-BAND POWER AMPLIFIERS

In this article, matching filters for GSM amplifiers capable of providing large harmonic rejection are demonstrated using M/A-COM's high Q GaAs MMIC technology. The matching filters are designed for the output of the quad-band (GSM 850/900/1800/1900 MHz) wireless handset amplifier module. Two sets of high harmonic-rejection matching filter circuits are designed and fabricated, one each for the GSM 850/900 MHz and GSM 1800/1900 MHz bands, respectively. For the second harmonic, the amplifier with the matching filter in the plastic-packaged module gave a rejection better than –63 dBc for the GSM 850/900 MHz band at the fundamental output power of 33 dBm and better than –63 dBc for the DCS 1800/1900 MHz band at the output power of 31 dBm. The higher harmonics had a better than –62 dBc rejection. The in-band insertion loss is measured as low as 1.2 dB in the 800/900 MHz band. To the best of the author's knowledge, this is the highest harmonic rejection achieved through a low pass matching filter for GSM handset amplifiers based on a MMIC process.

Recent advances in mobile phone RF modules have been made for the miniaturization and integration of components in such a manner that they can address all of the global standards. The stringent specifications for the different systems have to be met using inexpensive surface-mount plastic modules, which integrate diverse functionality with just a few chips. In addition, the module needs to perform over a wide frequency band in the smallest possible layout space. In the GSM arena, the trend has been towards evolving a GSM mobile phone that supports all the four major GSM frequency bands in a single handset, making it compatible with all the major GSM networks worldwide.[1,2]

Worldwide GSM has four bands: GSM 850 MHz and GSM 1900 MHz (Personal Communication Services, PCS) bands are used in America, while GSM 900 MHz and GSM 1800 MHz (Digital Cellular Services, DCS)

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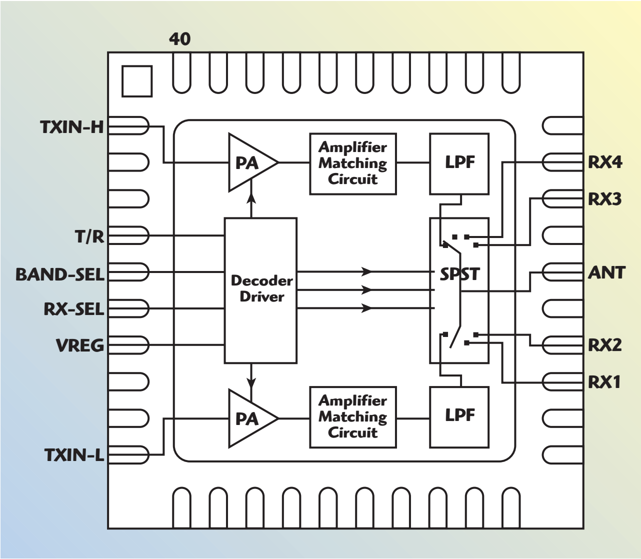
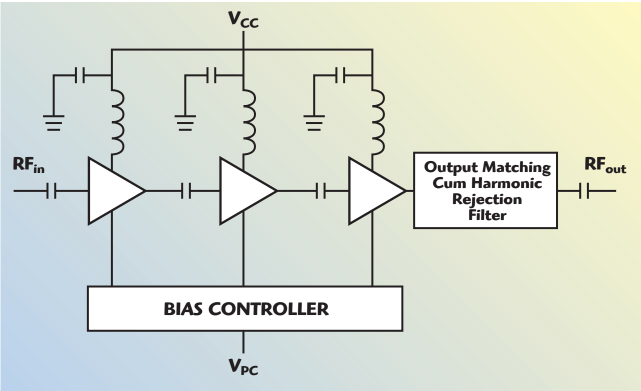


▲ *Fig. 1 Block diagram of the quad-band transit module.*

bands are used in Europe and elsewhere in the world. The quad-band GSM mobile handset requires power amplifiers that meet stringent harmonic rejection at the specified output power with the maximum power-added efficiency (PAE) possible. The FCC's harmonic rejection specifications require that the output power level at harmonics be less than –30 dBm for all nf_0, where $n \geq 2$ and f_0 is the fundamental frequency of transmission. At the low GSM band (GSM 800/950 MHz), the specified output power is 33 dBm, thus requiring better than –63 dBc rejection, while at the high GSM band (GSM 1800/1900 MHz), the specified power is 31 dBm, requiring better than –61 dBc rejection. Traditionally, the harmonic rejection is achieved by employing an output impedance matching circuit followed by a harmonic-rejection filter. SAW filters are being used since they are small, with low insertion loss, and can provide the required rejection. However, SAW filters are expensive and not easy to incorporate in the module. Using high Q passive substrates, the best figures reported are –40 to –49 dBc for second- and third-harmonic filters.[3,4] The disadvantages of using independent circuits for matching and filtering are two-fold: greater insertion loss due to a larger number of elements and thus the requirement for larger chip area. However, to design an optimal low pass circuit with the highest possible harmonic rejection is a theoretically challenging problem.[5] It becomes more challenging if there are implementation constraints such as layout size, which is driven by today's cost requirements. The design challenges are further aggravated by the impedance matching transformation ratio (of the order of 20 to 50) required to match high power amplifiers to a 50 Ω load.

In this article, the design of a smaller footprint, single passive circuit, providing a high impedance matching transformation ratio and a very high harmonic rejection, is demonstrated. The designed impedance matching and harmonic-rejection filters (also called matching filters) are integrated in a quad-band module comprised of GSM power amplifiers (PA), an antenna-diversity switch and a digital controller. This single module provides a commercially viable method of integration at reduced cost and low form-factor in a more reproducible manner.



▲ *Fig. 2 Block diagram of the three-stage power amplifier followed by the harmonic rejection filter.*

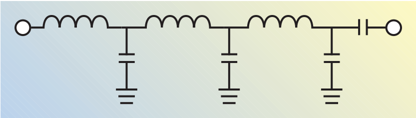
DESIGN DETAILS

Power Amplifier

Figure 1 shows the schematic representation of the blocks inside the quad-band transmit module. The quad-band transmit module consists of two sets of power amplifiers and matching filter circuits, one antenna-diversity switch and a CMOS controller in an FQFP-N plastic package. One set of power amplifiers and their matching filter circuit operates in the 824 to 915 MHz frequency band (GSM low band), while the other operates in the 1710 to 1910 MHz frequency band (GSM high band). The power amplifiers are made by a 4-mil standard iHBT GaAs process, the antenna switch by a pHEMT process and the matching filter by a high Q GaAs MMIC process. Both amplifiers have three stages, as shown in ***Figure 2***. The amplifiers provide a gain greater than 30 dB. The loss through the pHEMT switch is approximately 0.5 dB in the low band and 0.7 dB in the high band.[6] The amplifiers were measured separately on PC boards, using the traditional methods of matching for efficiency.[8] The optimum output powers of the amplifiers, at low and high GSM bands, were measured to be 35 and 33 dBm, with PAEs of 55 and 45 percent, respectively. The measured harmonics were –5 and –15 dBm, respectively. Clearly, from these measurements, including the switch loss alone, the expected composite PAE for low and high bands would be less than 49 and 38 percent, respectively. A theoretical analysis, with two transmission zeros (TRZ) at $2f_o$ with a Q of 30, predicts a composite PAE of 39 and 31 percent for the low and high band, respectively. The FQFP-N package was modeled in two parts. The lead frames were modeled using libraries in ADS, whereas the ground current paths in the paddle were accurately simulated using Sonnet's *Em*™. An isolation of approximately 50 dB was observed through the package at the low band requiring design layouts based on EM results to achieve greater than 60 dB of harmonic rejections.

Impedance Matching Filter

For the quad-band module, a matching filter is designed for each GSM low band and GSM high band. The starting point for the design is a low pass matching filter with a three-stage L-C impedance-transforming network configuration, as shown in



▲ *Fig. 3 Basic architecture of the three-stage low pass filter.*

Figure 3. The number of stages is based on a careful trade-off between size, rejection and performance. The impedance transformation ratio is selected based on the effect of the impedance ratio on the efficiency of L-C networks.[7] Since inductors are the primary power dissipation element, the intermediate impedance ratios were selected so that the inductors were of optimum size. For a given area, there is an inductor value that provides the best Q and optimum loss.[8] The matching circuit was designed to be able to achieve optimum Q for a given area. The lumped L-C network circuit component parameters were obtained for an impedance transformation of 2 Ω (nominal) to 50 Ω for the GSM 850/900 MHz band and 2.5 Ω (nominal) to 50 Ω for the GSM 1800/1900 MHz band. Multiple transmission zeros (TRZ) were then judiciously added to provide adequate harmonic rejections. In addition, the frequency band for a quad-band module is much larger than that of a single-band module, which in turn increases the harmonic-rejection bandwidth and thus the design complexity. The most challenging part is to provide more than 65 dB rejection at the second harmonic and at the same time provide minimum loss in the fundamental band whose bandwidths are 90 MHz for the GSM low band and 200 MHz for the GSM high band. The increased rejection was achieved through a combination of shunt capacitor split resonance (patent pending) and series inductor split resonance techniques (patent pending) shown in the schematic of ***Figure 4***. Here, the shunt arm capacitor is split into two parallel arms labeled 2 and 3. The series inductor is split into two additive series arms, 6 and 7. The shunt capacitances are designed for series resonance with an inductor, whereas the series inductances are parallel resonated with capacitors. Both of these give extra transmission zeros to achieve high out-of-band rejection. The component values of series L-C resonances are determined by the following equations

$$C_{eff} = \frac{C}{1-\omega_0^2 LC} \tag{1}$$

$$\left(n\omega_0\right)^2 = \left(LC\right)^{-1} \tag{2}$$

where

C_{eff} = effective capacitance at the fundamental frequency obtained through impedance transformation for maximum in-band efficiency

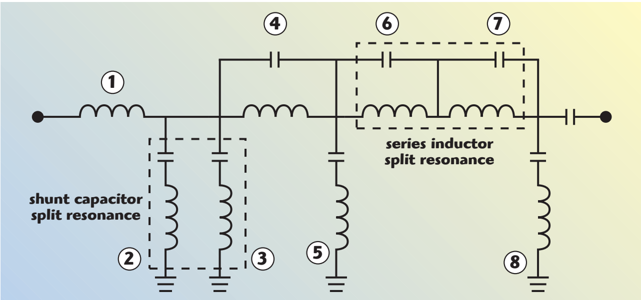
n = harmonic number

ω_0 = geometric mean of the lower frequency ω_L and the higher frequency ω_H

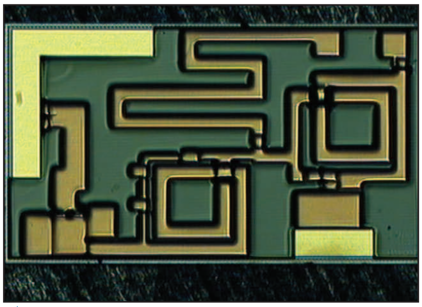
$$\omega_0 = \sqrt{\omega_L \omega_H} \tag{3}$$

The multiple TRZs are designed at $2f_o$, $3f_o$, $4f_o$ and $5f_o$. Three transmission zeros are provided at $2f_o$ for the GSM low and high band. For the optimum band rejection at $2f_o$, one of the $2f_o$ resonances is provided with the highest possible capacitance for a small resonator physical size and a high unloaded Q. Two other $2f_o$ resonances are provided at shunt arms 5 and 8 and are detuned by small amounts from $2f_o$. This makes the net transmission null broader to suppress the second harmonics for the whole fundamental band.

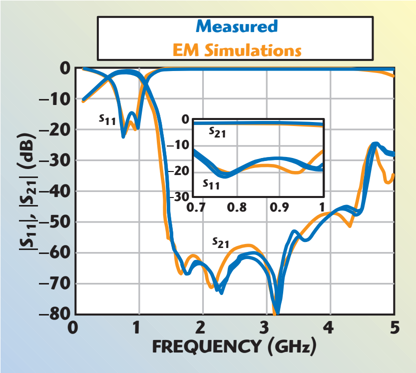
Another consideration is the choice of TRZ at the first split shunt resonance, legs 2 and 3. Leg 2 was chosen to have a resonance at $2f_o$ and leg 3 to have a resonance at $4f_o$. Another possible choice is for leg 3 to have a resonance at $3f_o$. This would result in peaking of the harmonic level at the higher edge of $2f_o$ due to a reactance pole between $2f_o$ and $3f_o$, thus compromising the $2f_o$ rejection. By selecting $4f_o$ as the companion resonance with $2f_o$, the pole could be placed farther from $2f_o$. The effect of the pole is suppressed by another arm of the filter, arm 4. The design of the series elements would be similar. Also, for high efficiency, the inductance at arm 1 is designed so that the second and higher harmonics see a high inductive load through inductance peaking techniques.[9] The initial circuit was designed in Agilent's ADS software, using idealized elements but with realistic loss factors (Q). The circuit was then laid out in Sonnet's *Em* simulator. The space constraint of 2.2 × 1.38 mm made the modeling of coupling critical and therefore required EM-based optimization and design. The critical sections were simulated in Sonnet *Em* to accurately model the coupling between nearest neighbors. For certain other elements, scalable models using circuit parameter lookup tables were used. Equivalent-circuit models of the inductors of different dimensions and turns were extracted and libraries created to provide Q as a function of the geometry of the inductors.[8] This method of modeling and design provides a quick insight into the performance of the whole matching filter chip in the presence of nearest neighbor electromagnetic interactions. However, it did not include long distance coupling. Therefore, EM-based optimization in Sonnet *Em* was needed to achieve the best performance accounting for long distance coupling. Since a full circuit optimization requires a huge amount of computer memory and time, smaller subsets of a large circuit can be simulated. Dividing the circuit in an EM-coupled environment is not always obvious but, by careful study of the layout and EM coupling, the circuit can be optimized. ***Figure 5*** provides a photograph of the



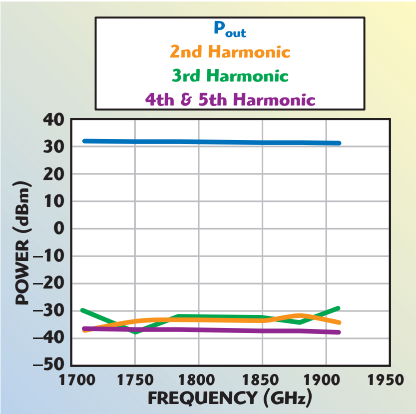
▲ *Fig. 4 Matching filter with split-shunt and split-series arms.*



▲ *Fig. 5 The matching filter chip for the 1800/1900 MHz GSM band.*



▲ *Fig. 6 Simulated and measured S-parameters of the 850/900 GSM filter with Z_{in} = 2Ω and Z_{out} = 50Ω.*



▲ *Fig. 7 Fundamental and harmonic output power levels for the GSM 1800/1900 MHz band.*

designed GSM matching circuit for the high band.

PERFORMANCE

To demonstrate the overview and efficacy of the concept, two sets of measured data are presented. First, the S-parameters of the matching filters were measured in a 50 Ω environment with an on-chip measurement setup for the GSM 850/900 MHz band. Second, a power measurement of the entire quad-band module with a novel matching filter was taken for the GSM 1800/1900 MHz band. The S-parameters for the GSM low band are measured in a 50 Ω environment and later renormalized to the input port impedance of 2 Ω and output port impedance of 50 Ω. This is done to estimate the harmonic-rejection level seen by the amplifier. ***Figure 6*** shows the very close agreement between simulated and measured S-parameters of the matching filter for the GSM 850/900 MHz band. A 100 MHz shift at $2f_0$ between simulated and measured data was expected due to a variety of factors including non-inclusion of metal thickness in Sonnet *Em* and process variations. The measured insertion loss is 1.2 to 1.4 dB across the 90 MHz wide GSM low band and is within 0.1 dB of the predictions. The output power and composite PAE of the amplifier, matching filter and switch were measured for the quad-band module. The data were taken at 5 dBm input power with supply voltages of 3.5 V and a control voltage of 2.7 V. An output power of 32 to 33 dBm was measured across the 90 MHz GSM low band with a composite PAE up to 38 percent. Excellent rejections of –63 to –67 dBc are obtained for the second harmonic across the band. The rejection of the higher harmonics is greater than 62 dBc. For the GSM 1800/1900 MHz band, the output power of the quad-band module chain is 31 to 32 dBm across the 200 MHz band with harmonic rejections of the order of –64 to –67 dBc. The measured results are shown in ***Figure 7***. The composite PAE for the GSM high band exceeds 30 percent.

CONCLUSION

State-of-the-art impedance matching filters using MMIC technology with excellent harmonic rejection have been demonstrated within a small footprint for quad-band amplifiers. The FQFP-N-packaged quad-band amplifier module, based on the MMIC matching filters, shows the feasibility of further miniaturization and part count reduction, thereby allowing a higher level of chip integration and minimizing of on-board components for more efficient commercial handset manufacture. ■

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