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System-in-Package for WLAN/PAN Aids Coexistence with Digital Cellular

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This article looks at the problem of interference, and options for its reduction, between short-range wireless systems and the digital cellular equipment that share both physical and spectrum space.

The common use of cellular phones, laptop computers, cameras, PDAs and various other consumer and commercial products requires the interference-free coexistence of different wireless interconnectivity systems—wireless local area networks (WLAN), personal area networks (PAN) and Digital Cellular—in compact, integrated environments. To facilitate the growth of these markets, these products must concurrently decrease in physical size and weight while continuing to reduce cost, in order meet the end users demands for low cost, high functionality system solutions.

System in Package (SiP) technology is emerging as a strong contender for the module solution that can meet the needs of these market applications. This article examines interference suppression between systems and presents solutions that meet the cost, size, and weight requirements while maximizing system performance. A Bluetooth system is chosen as an example, though the techniques described are also applicable to most 2.4 GHz WLAN and PAN systems.

System Considerations

Digital Cellular systems operate near 900 MHz, 1.8 GHz, 1.9 GHz, and 2.1 GHz while Bluetooth and 802.11b/g systems operate at 2.4 GHz. These are the primary frequencies of consideration for radio coexistence in converged wireless interconnectivity systems. The ideal solution would eliminate interference from a cellular system (both handset and basestation) to the PAN/WLAN system and vice versa. At the same time, it would meet the regulatory requirements of spectrum interference imposed by FCC, ETSI and other spectrum regulatory bodies.

Achieving a practical solution in a SiP or modular solution requires system architecture knowledge and design capability. However, IC interface requirements with the ability to effectively apply high volume materials, substrate design and assembly techniques for optimum size and cost, are equally important. The system architecture must look at the complete RF system chain from transceiver die interconnect to the antenna. Also, considerations for suppression of digital noise must be employed when baseband circuitry is included in the module.

Coexistence Issues

Coexistence of PAN/WLAN systems can occur with any of the digital cellular systems, however, Bluetooth transceivers experience the most hostile environment in the GSM, DCS, and PCS cellular phone market. The GSM and cellular frequency bands are given in Table 1. The interference possibilities can be broken into these scenarios:

1. Bluetooth transmit noise into GSM receiver
2. GSM transmit noise into Bluetooth receiver
3. Bluetooth receiver spurious into GSM receiver
4. GSM receiver spurious into Bluetooth receiver
5. Clock and data spurious into Bluetooth or GSM receiver
6. Base station transmitter into Bluetooth receiver

Region	Type	Portable transmit (MHz)	Base station transmit (MHz)	Subscriber Receiver Sensitivity (dBm)	Subscriber transmit Power (dBm)
Europe	GSM 900	880 - 915	925 - 960	–102	33
	DCS 1800 (GSM)	1710-1785	1805 - 1880	–102	30
	UMTS (W-CDMA)	1920 - 1980	2110 - 2170	–116	24
U.S.	AMPS	824 - 849	869 - 894	–116	34.77
	PCS 1900 (GSM)	1850 - 1910	1930 - 1990	–102	30
Japan	CDMAOne	887 - 901	832 - 846		23
	PDC	940 - 956	810 - 826	–100	Class I = 34.77 Class II = 33 Class III = 29 Class IV = 24.77
		1429 - 1453	1477 - 1501	–100	Class I = 34.77 Class II = 33 Class III = 0.29 Class IV = 24.77
	W-CDMA	1920 - 1980	2110 - 2170	–116	24

Table 1 · Cellular frequency bands of interest in Europe, the U.S. and Japan.

For simplicity, only interference scenarios 1 and 2 will be considered in this article. Scenario 6 depends on the desired protection distance to the base station. The other interference scenarios depend on the Bluetooth and GSM architecture for the L.O. frequency and clock and data spurious. The logic spurious and higher order harmonics of the clock frequencies present noise interference that is difficult to subdue. These factors delay the project due to unanticipated emission from many sources such as wide spread bussing on high impedance traces, resulting in multiple prototypes. However, the main threat for any Bluetooth application is in-band interference from microwave ovens, cordless phones and other WLAN products such as Home RF and 802.11b [1, 2]. In the extreme, it has been suggested to equip microwave ovens with a Bluetooth module [3]. This allows the microwave oven to synchronize its oscillator pulse between Bluetooth hops.

The specified GSM, DCS, and PCS receiver sensitivity is –102 dBm. Typically, most receivers achieve –108 dBm in practice. The channel bandwidth is 170 kHz. Over this bandwidth the noise must be less than:

$$-102 \text{ dBm} - 10\log(170{,}000) = -154.3 \text{ dBm/Hz}.$$

This assumes that the noise is flat across the channel bandwidth. A noise floor of –154.3 dBm/Hz would result in a noise power equal to the receiver sensitivity. An additional 10 dB margin is added to reduce the noise level significantly below the receiver sensitivity level. However, a Signal-to-Noise ratio of 6 dB is also required. This brings the total noise floor requirement to:

$$-154.2 \text{ dBm/Hz} -10 - 6 = -170 \text{ dBm/Hz}.$$

This limit is only 4 dB above the physical thermal noise limit of –174 dBm/Hz. The noise in good transmitter architecture designs is determined by the local oscillator phase noise. The 400 MHz Bluetooth to PCS band separation places the phase noise in the noise floor beyond the 1/f, $1/f^2$, etc., factors. A good 0 dBm VCO will have a noise floor at or better than –150 dBm/Hz. However, Bluetooth is meant to be low cost and, for that reason, typically utilizes CMOS. A good CMOS VCO may only achieve a –125 dBm/Hz noise floor. This would require 45 dB of selectivity to protect a Bluetooth transmitter directly coupled into a GSM receiver. Careful circuit layout can provide this isolation, however, both systems require antennas. A gain plot for a Bluetooth module with an integrated antenna is depicted in Figure 1. This antenna provides 5 dB of protection to the PCS band and 20 dB to the GSM band. These protection figures ignore polarization, and require the PCS antenna to be directly coupled to the Bluetooth antenna with no spatial separation. Therefore, a highly conservative estimate of the Bluetooth noise in the PCS band at the PCS antenna is:

$$-125 \text{ dBm/Hz} - 5 \text{ dB} = -130 \text{ dBm/Hz}.$$

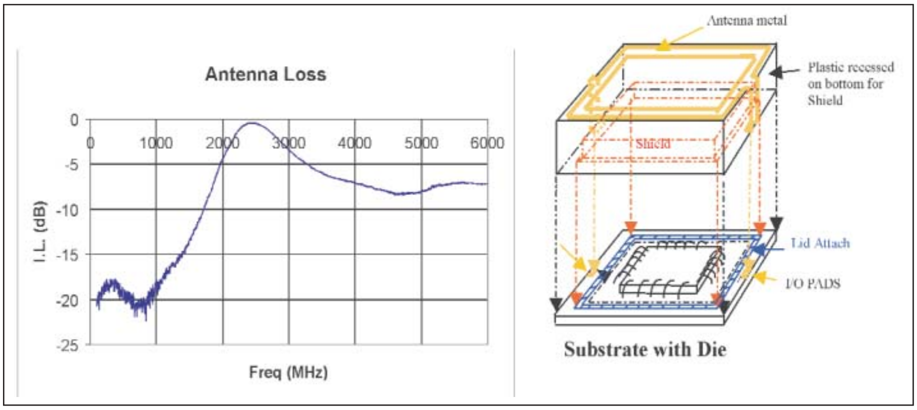

Figure 1 · Integrated antenna module and antenna response.

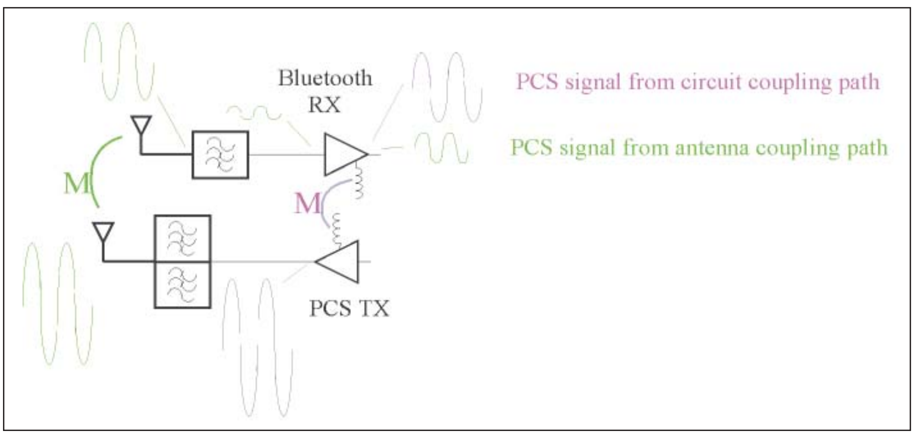

Figure 2 · Circuit coupling greater than antenna coupling.

This requires 40 dB of selectivity to meet the –170 dBm/Hz requirement derived above. Less selectivity is required with better antenna isolation, however, this selectivity may be required if the antennas share the same feed network. This network may produce strong coupling between the antennas.

The other concern is PCS transmitter noise degrading the Bluetooth receiver. The Bluetooth receiver sensitivity specification is –70 dBm, with typical receiver performance at a sensitivity of –80 dBm. Although the GSM 900 MHz transmitter power is 3 dB higher than PCS, the PCS band is closer in frequency. The lower antenna isolation makes PCS a larger threat than GSM to the Bluetooth receiver. A conservative SNR for Bluetooth FSK modulation is 20 dB. This brings the noise to a required:

80+20+10log1 MHz =
–160 dBm/Hz.

This is not an issue for PCS phones using more expensive better performing VCO components in the –150 dBm/Hz range. Duplexer filtering and antenna selectivity will reduce the noise to the required –160 dBm/Hz in the Bluetooth band. However, circuit isolation is required to maintain this noise level. A signal can couple in the circuit board after the Bluetooth front end filter as shown in Figure 2. This may cause a larger noise level into the Bluetooth LNA than an interferer that is external to the product. Circuit coupling may also affect the PCS receiver. This may be a direct coupling as depicted in Figure 2, or it may couple later in the receiver chain. It may enable AGC if it is within the AGC bandwidth. The AGC bandwidth is typically larger than the IF bandwidth. This could enact 30 dB of AGC in the receiver degrading the receiver sensitivity. Care must be taken during the circuit layout to avoid coupling.

In addition to these direct coupling mechanisms, the Bluetooth and PCS transceivers must coexist with each other's clock and spurious products. Effects of these emissions are not easily predicted. Shielding at the package level can contend with these requirements as well as meeting the regulatory requirements imposed on the system. Shielding is typically accomplished at the product level, however, package level shielding can provide a cost reduction for many product developers by eliminating expensive and logistic manufacturing provisions. One alternate solution is shown in Figure 3, where the shield is encapsulated with the die. The module can be incorporated with multiple shields to protect against baseband and radio interferers or transmitter and receiver circuitry.

Filter Construction

Today's PAN/WLAN systems are typically configured using a discrete ceramic bandpass filter. This filter has a physical height of 1 mm or more and occupies 8 mm [2] or more of board space, to provide this func-

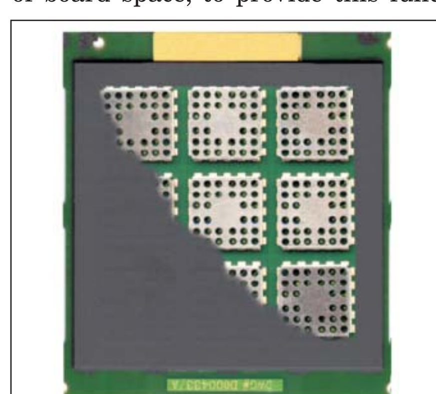

Figure 3 · Integrated module shielding, encapsulated with the die.

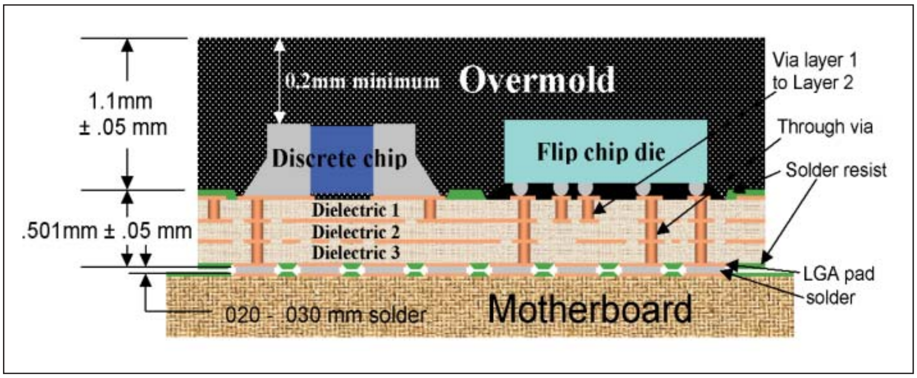

Figure 4 · Four layer laminate Amkor standard construction.

tion. The height of the component drives cost by requiring nonstandard High Volume Manufacturing (HVM) processes or tools to achieve reliability requirements in the protection of die. For cost efficiency, the entire top surface of the SiP is encased in a plastic overmold to protect the die, provide high levels of reliability along with a marking and handling surface. While the ceramic BPF provides typical rejection of 50 dB up to 2 GHz, system requirements do not demand this level of rejection. The size and cost of the component itself then become opportunities for cost reduction when utilized with a high pass filter approach.

High Pass Filtering as an Alternative to Bandpass Filtering

An alternative solution to the BPF is the use of a high pass filter since the primary issue is the suppression of 1.9 GHz. The highpass filter protects the receiver from PCS/DCS and cellular. It also provides some attenuation to the harmonics of the transmitter and systems such as 802.11a operating in the 5 GHz range. The amount of filtering depends on the desired protection level, distance and dynamic range of the receiver, and the compression point of the LNA. However, the compression point is tightly correlated with the current drain of the LNA. Filtering cannot provide protection to in-band interferers like 2.4 GHz wireless phones and leaky microwave ovens. LNA compression is the only protection to in-band interferers. Filtering can provide pro-

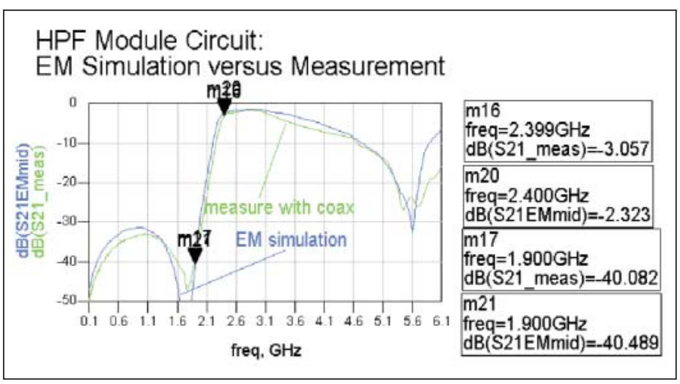

Figure 5 · Embedded 40 dB typical from 1.7 GHz to 1.9 GHz rejection filter.

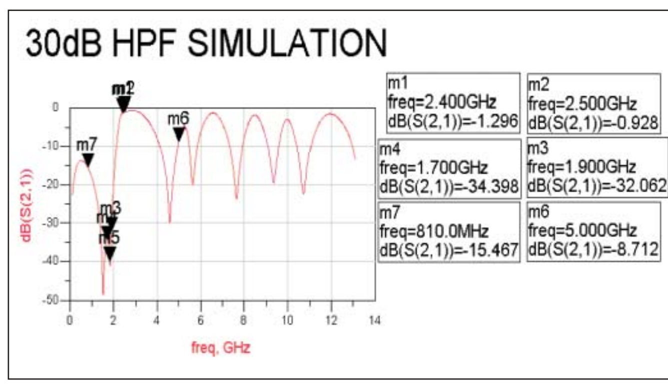

Figure 6 · Embedded 30 dB typical from 1.7 GHz to 1.9 GHz rejection filter.

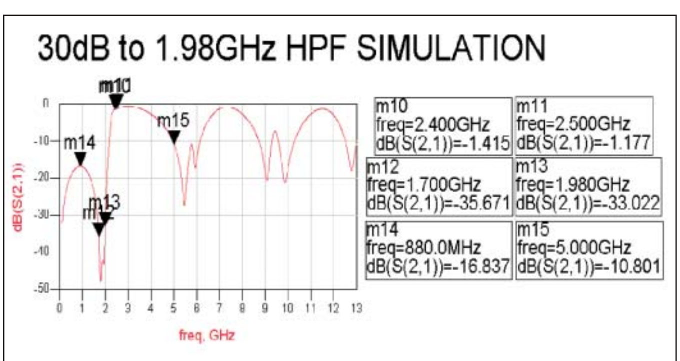

Figure 7 · Embedded 30 dB typical from 1.7 GHz to 1.98 GHz rejection filter.

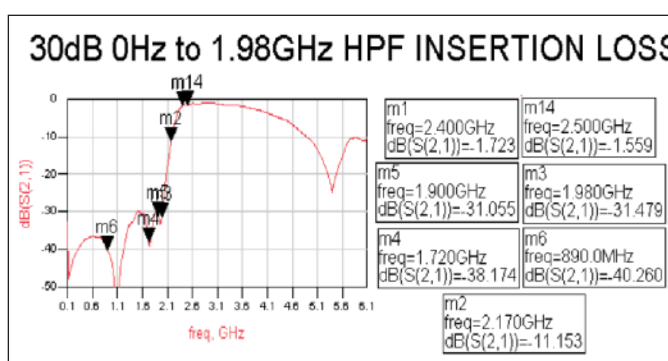

Figure 8 · Embedded 30 dB typical from 0 Hz to 1.98 GHz rejection filter.

tection to out-of band interferers. There is still a balance with the LNA compression and filter selectivity. Adequate filtering may not be achievable for a low P_{1dB} LNA without higher insertion loss. However, the insertion loss will impact the overall receiver noise figure since it is in front of the LNA. This higher filter insertion loss may require an unachievable LNA noise figure to met the overall receiver sensitivity. The opportunity to embed the filter in the substrate arises from using a high pass filter instead of the traditional BPF. The benefits include eliminating the component and the space required as well as a cost reduction for the filter and allowing the use of a lower cost standard moldcap.

Example Implementations

Three quasi-standard filters have been developed to combat interferers. The filters are designed to primarily deal with selectivity in the DCS and PCS band though they give some harmonic selectivity. The filters were realized in low cost, double core construction utilizing low loss laminates (typical loss tangent =. 01). One such construction is shown in Figure 4 where a flip chip die is shown, however, wirebond and stacked die are also possible.

Filter 1

The first filter discussed was designed to meet the typical worst case 40 dB requirement discussed above. This would allow cohabitation of a Bluetooth module in proximity to DCS/PCS circuitry with no isolation between antennas. The measured results include extra insertion loss due to two coaxial probes and transmission line and via interconnect; see Figure 5.

Filter 2

This filter could also be used within a Bluetooth module that is in proximity to DCS/PCS circuitry. Electromagnetic simulation results are depicted in Figure 6. It requires 10 dB or more isolation between the Bluetooth and DCS/PCS antennas, which is easily achieved with separate antennas. It may be difficult to achieve with a dual-band antenna system.

Filter 3

This filter provides 30 dB protection to the base station transmitter as well as the mobile DCS and PCS transmitters. The electromagnetic simulation results are depicted in Figure 7. The 30 dB protection level is maintained below 1.7 GHz with the addition of a few discrete components, as depicted in Figure 8.

Filter 4

Some Bluetooth applications do not need as much selectivity as the

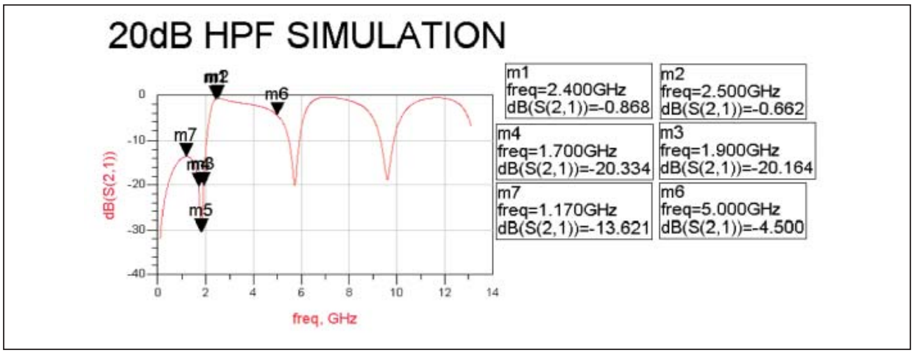

Figure 9 · Embedded 20 dB typical from 1.7 GHz to 1.9 GHz rejection filter.

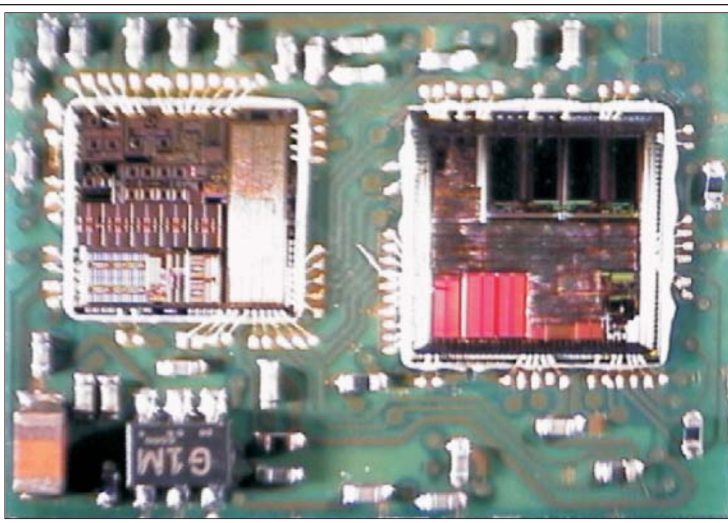

Figure 10 · Laminate Bluetooth transceiver measuring 10 x 14 x 1.7 mm including substrate embedded balun and filter.

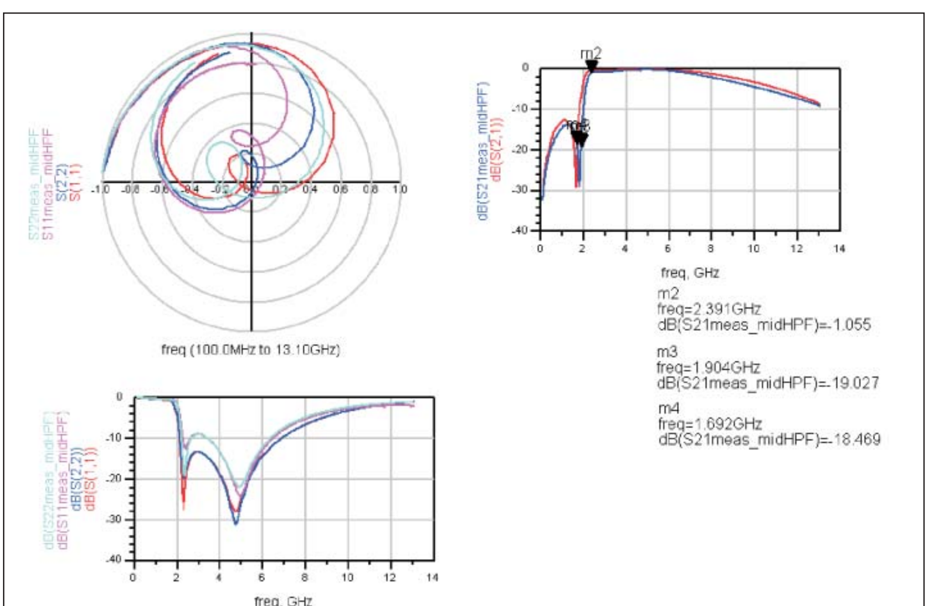

Figure 11 · Highpass filter response for Module 2.

preceding filters, although these applications require some selectivity to deal with phones that may be operating in the vicinity. The antenna isolation will be greater due to the separation, which diminishes the filter selectivity requirements. Electromagnetic simulation results for a filter with typical 20 dB rejection in the DCS/PCS band is given in Figure 9.

Module 1

The filter in Figure 5 was implemented in a 10.00 × 14.00 × 1.67 mm Bluetooth transceiver module. The module contains a digital die approximately 5 × 5 mm and an RF die approximately 4.25 × 4.5mm as well as a BALUN, filter, 30 discrete components, and an antenna switch. A reference signal and an antenna are required for a complete Bluetooth solution. This module is depicted in Figure 10.

Module 2

Another Bluetooth module included the antenna. The module depiction and an antenna response are given in Figure 1 above. The module measured 15 × 15 × 6.5 mm. A highpass filter was mated to a lowpass filter and a BALUN. This module only required a reference to complete the Bluetooth transceiver. Its applications did not include operation in proximity to DCS/PCS circuitry. The system's analysis indicated that the LNA could withstand interferes with only 7 dB of filtering outside the Bluetooth band. This was increased to 15 dB attenuation between 1.7 GHz and 1.9 GHz with greater than 10 dB attenuation below 1.7 GHz. This provided some cushioning without taking a detrimental hit on insertion loss. The insertion loss was the driving factor for this design. The measured and simulated highpass filter response is given in Figure 11.

To obtain the results shown, a prototype substrate was fabricated which had increased nickel and gold

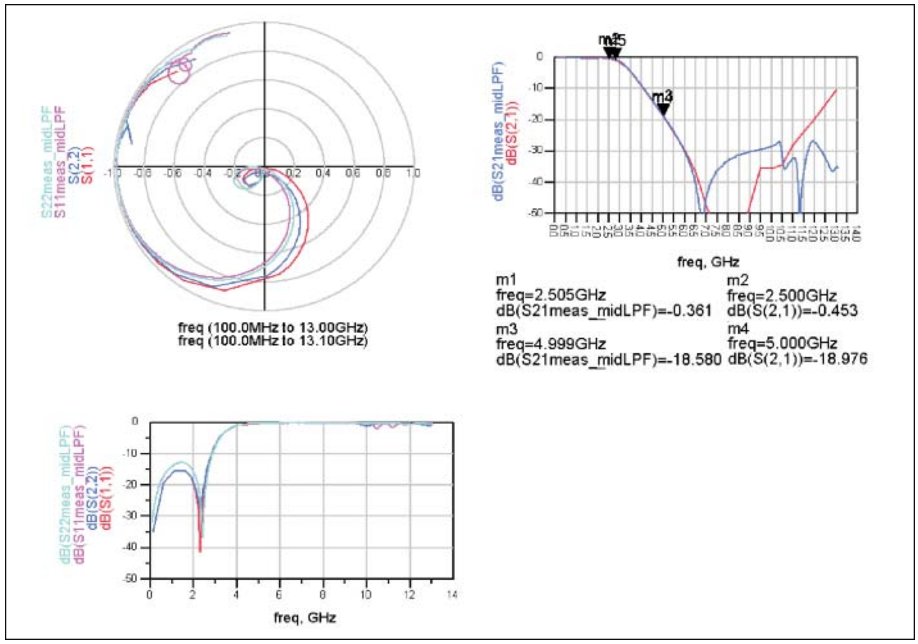

Figure 12 · Lowpass filter response for Module 2.

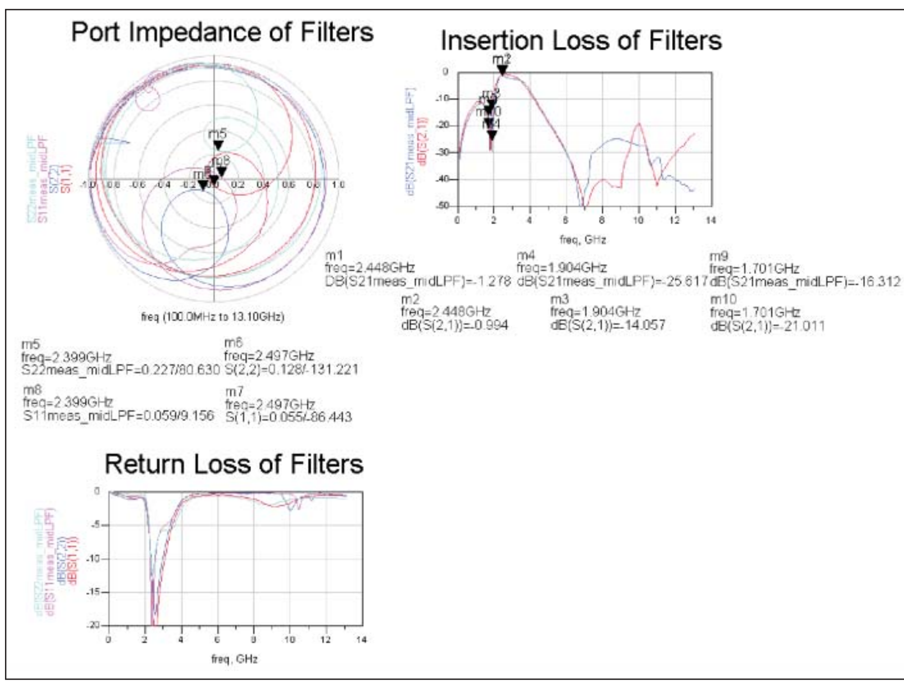

Figure 13 · Combined filter response for Module 2.

plating beyond what a standard, high volume substrate would have. The additional thickness increased the insertion loss of the microstrip high-pass filter by 0.3 dB. The effect on selectivity is negligible.

The LPF data is shown in Figure 12. The gold plating does not effect this buried stripline filter. Data for the mated HPF and LPF is depicted in Figure 13.

Conclusion

These filter architectures have

been designed into many Bluetooth modules. Two small full transceiver module examples were provided. The filters presented lead to more functionality within the module at a lower cost.

By modification of the system architecture, the original ceramic block filter and BALUN were eliminated and replaced with embedded substrate functions. This provided significant cost savings. In addition, the ceramic block filters physical height was a manufacturing limitation. It would have incurred additional cost through either new tooling or alternative, higher cost, encapsulation methods. These filters allow Bluetooth and WLAN to co-exist with digital cellular circuitry. They minimize the impact to the end user with a nearly complete "plug and play" module solution. The end user is required to provide a reference signal only for one module. The other module examined only requires a reference signal and an antenna. In either case the end users implementation is made easier by eliminating the need for the customer to provide filtering, balun or supply bypassing interface circuitry.

The design of the system was a collaborative co-design effort with the IC manufacturer and Amkor RF system, RF circuit design, and process engineers. Early involvement of the packaging developers during the system architecture definition phase is key to achieving the desired cost, size and performance of any RF-based module system.

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