New Materials and Techniques Advance Filter Technology

Filters are some of the most common high frequency circuit elements. Their design is mathematically precise, but their implementation is subject to wide variations. The *Q* and manufacturing tolerance of individual components limits the performance of lumped element filters, Physical limitations of printed circuit board fabrication limits the performance of stripline and microstrip filters. The substrate or encapsulation materials limit the performance of integrated or buried filters in RFICs, MMICs and ceramic technologies like LTCC.

Because of their ubiquity, filters are the object of a great deal of attention, both for their electrical design and their mechanical construction. Today's systems have put pressure on filter designers at both ends of the performance spectrum: highest performance and lowest cost/smallest size. This report covers some of the innovative solutions that have been developed (and continue to be developed) for filters.

High Performance Filters

By "high performance" we mean electrical performance. Some of the performance requirements that may be paramount for a particular filter are:

Minimum loss—Front end filters for instrumentation, space communications and other sensitive systems require low loss to detect of weak signals.

Maximum out-of-band rejection—The spectrum is getting crowded, with many new applications deployed in the past couple decades. This increases the need to separate the desired signals from many others, which may be on nearby frequencies, or be nearby with high signal levels.

Low intermodulation distortion—Co-located and multiplexed transmitters are common in wireless networks. Filters operating in this environment must not create distortion in their components, connectors or assembly hardware.

Flat frequency and delay response—The newest modulation methods are complex, with wide bandwidths and multiple carriers or subcarriers. Filters should be truly "passive" and not degrade the integrity of the signals. At least, they should provide consistent performance that can easily be compensated for elsewhere in the system.

High Performance Technology

To address these requirements, engineers are using new techniques and materials, as well as getting more from existing technologies.

The key to achieving minimum loss is high *Q* inductors or resonators. An important technology in the area is high dielectric constant ceramic materials. With these materials, high *Q* coaxial transmission line elements can be fabricated with sizes much smaller than air or PTFE dielectric lines, and with the reliability of a solid dielectric. Filters using these materials are used to make "good" small filters as well as for making maximum performance filters that previously required large coaxial resonators. The high *Q* also enables engineers to achieve filter with well-controlled passbands.

Low IMD performance is primary achieved by attention to detail in construction and design. Typical contributors to low-level IMD include magnetic materials such as steel and nickel, which are typical avoided, at least in the signal path. Avoiding joints between dissimilar metals also helps. Attention to skin depth when plating a connector, line section or hardware component reduces localized currents that are potential sources of IMD.

One design factor that aids in IMD reduction is maintaining practical intermediate impedances in multi-element filters, avoiding the stresses of high voltages and currents.

Flat frequency and delay response is most important at the circuit and IC level, where modulation, mixing and amplification are applied to low level signals. A major contributor to better filters is more powerful EDA software, particularly 2D and 3D electromagnetic simulation. EM analysis allows the designer to obtain accurate results for stripline, microstrip and waveguide filters. Another powerful feature is visualization of currents in the structure, which literally help the designer see potential problem areas.

The extensive use of SAW filters for IF filtering is a logical choice for controlled response, since this technology is highly flexible, and although well-established, continues to be refined for better performance.

Another significant advantage of today's EDA tools in high performance systems is the ability to deter-

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mine the system-level effects of a single component such as a filter. For example, an engineer can compare different filter options according to their effect on error vector magnitude (EVM) or adjacent channel power ratio (ACPR).

Small, Low Cost Filters

The performance requirements for "commodity" filters are overwhelmingly low cost and small size, while maintaining adequate performance for the application. A few examples of particular requirements are:

Wireless handsets and other handheld devices such as PDAs—While these products won't shrink forever (we still need to hold them in our hands), the RF portion does need to keep shrinking. Additional features like cameras, larger displays, GPS receivers require their own space. The RF circuitry is being subjected to intense pressure to minimize its volume. In some designs, the filters occupy the largest area within the radio footprint.

PC-card WLAN transceivers—This application requires not only low volume, but low height.

Bluetooth personal area network modules—Adding short-range wireless capability to all portable electronics is the aim of some developers. Bluetooth and similar systems provide connectivity in the "personal space" near the user. The manufacturers of these wireless-enabled devices want a pre-assembled module that occupies very little space.

GPS receivers—E911, location-based services, and personal navigation aids use GPS to determine where the user is standing (or driving). Smaller and cheaper are important, but GPS receivers require good performance, too.

Technologies That Address Size and Cost

Currently, the technology of choice for a large number of small, low cost filters (as well as other portions of the circuit) is low temperature co-fired ceramic (LTCC). This technology allows multi-layer printed circuits to be economically manufactured in quantity. A relatively high dielectric constant allows reduced size.

The ability to design in three dimensions is a useful feature of LTCC fabrication. Inductors can be constructed using a series of printed loops and via holes instead of a lower-performance spiral structure. Chip capacitors and even ICs can be embedded within the LTCC structure.

Another choice is on-board filters, including multilayer techniques that embed stripline elements within the circuit board. For many years, creative engineers have been using the interconnections between devices as microstrip circuit elements. The cost of filters implemented in this manner is almost trivial, but the size may not be optimally small.

Low-cost products use FR-4 or similar laminate materials for printed circuits. Although not optimum in RF characteristics, the dielectric constant is high enough to achieve significant size reduction over classic "microwave boards."

A few companies have developed the necessary expertise to combine some of the advantages of LTCC with the lower cost and somewhat simpler fabrication of multi-layer circuit boards. Individual components using these multi-layer building blocks include a wide range of RF devices including filters.

High dielectric constant ceramics are used extensively in low-cost products. For example, 2.4 GHz bandpass filters are small enough to fit on a PC-card. At 5.8 GHz, these filters are even smaller, and maintain good filter performance.

Integrating filters onto RFICs and MMICs has had limited success, because they are limited to spiral inductors with low Q that cannot deliver adequate performance for some applications. However, MEMS (micro electromechanical systems) technology may come to the rescue. MEMS can include inductors suspended in air with enough space between the conductor and substrate to increase the Q to usable levels.

MEMS and the developing BST (barium strontium titanate) technology both support tunable filters. Making filters tunable can save space by eliminating multiple filters, and by allowing optimum-performance filters that may eliminate the requirement for filters elsewhere in the system.

"No Filter" Technology

More than a few engineers will argue that eliminating most filters is the most promising technology. An example of this trend is the rapid adoption of direct-conversion technology, which eliminates intermediate frequency circuits and IF filters.

Direct conversion requires more filtering functions at baseband, in the digital signal processing circuitry. Since DSP is already required for codecs and other baseband functions, this approach is an effective way to save cost and space.

DSP can help in other ways, too. Digital predistortion can be implemented to linearize the power amplifier and reduce the performance requirements of the bandpass filter at the antenna. Polar modulation schemes have been developed that will further improve amplifier linearity, relaxing off-channel filtering requirement even more.

Summary

Filter technology is so important that it gets plenty of attention. The techniques noted here, and others under development, are excellent examples of highest levels of creativity among today's engineers.