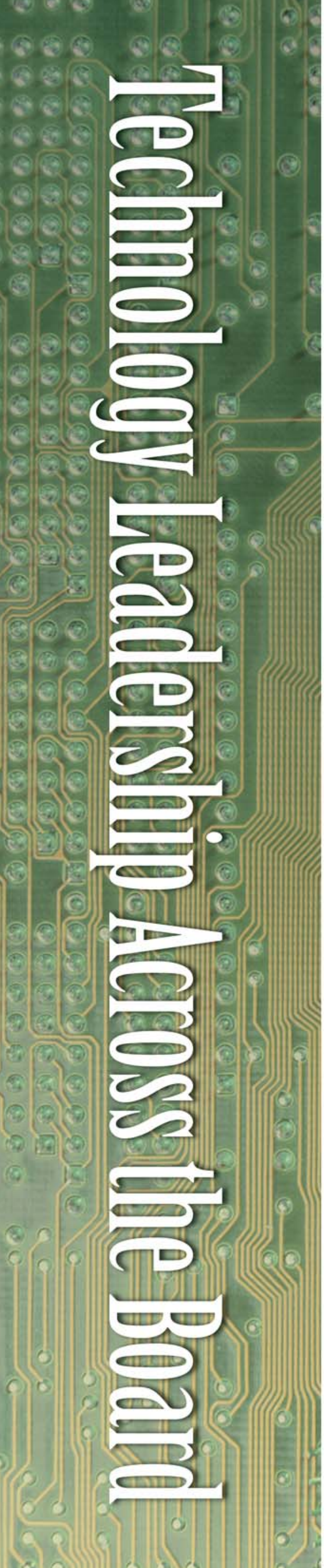

A Review of High Frequency Passive Component Technologies (Thin-Film, Thick-Film, Discretes & PMC) for RF Design Applications

A B S T R A C T :

This article traces the evolution of these technologies and discusses the benefits and trade offs for each. The current level of RF component integration available in existing discrete package sizes is discussed, along with trends to tighter tolerance and ultra-stable parametric performance.

The article concludes with an update on the emergence of higher levels of integration into passive component networks, and how this is now enabling engineers to optimize their RF designs.

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A Review of High Frequency Passive Components Technologies (Thin-Film, Thick-Film, Discretes & PMC) for RF Design Applications

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Radio continues to be one of the most powerful technology drivers in microelectronics with many evolutionary changes taking place in the last few years. Applications, both consumer and mission critical, require solutions that are smaller, increase functionality and reliability, and improve signal clarity, all the time attaining lower power consumption.

To achieve this, almost all modern radios now use digital modulation schemes instead of standard analog. This also fits with the trend to higher frequencies to make use of the wider bandwidth required for these applications. The higher frequency designs also drive to smaller physical layout because the shorter wavelengths can be accommodated in much smaller packages (i.e. the wavelength at 5.8GHz is nearly 6.5 times smaller than at 900MHz).

Although radio design continues to evolve with increasing complexity and need for security, the actual radio block diagram has remained virtually unchanged.

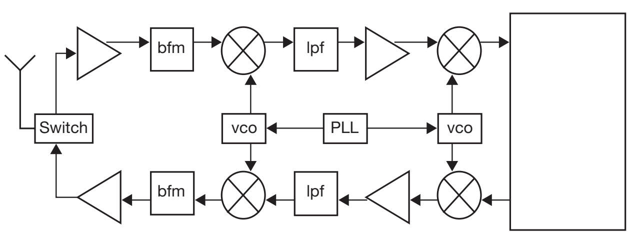


Figure 1. Basic Super Heterodyning Transceiver

Figure 1 is a block diagram of a dual conversion super heterodyning transceiver, one of the most common radio design schemes used today, with the direct conversion receiver (or zero IF- intermediate frequency) gaining momentum for the most widely used. The direct conversion receiver has a single mixing stage that converts the received signal directly to base band and reduces cost considerably, at the expense of performance.

The basic radio consists of several key components and each has a specific job in the chain: Antenna, Switch, LNA (Low Noise Amplifier), Filter, Mixer, Oscillator, Modulator/Demodulator. As the applications have evolved, so has the component technology that has enabled major downsizing of these elements to take place.

Early radio designs were necessarily based on discrete passive components designed for high frequency performance. These use low loss high frequency dielectrics (NP0 ceramic, porcelain or glass), but require precious metal electrode systems which can withstand the high firing temperatures associated with ceramic material processing and still provide good conductivity. These devices remain an ideal solution for high power RF applications, but are nearing the limit of downsizing for microcircuit applications.

LTCC Technology

The next stage of evolution came with LTCC (Low Temperature-Co-fired Ceramic) technology.

This technology enables integration of passive components within compact modules and can provide a platform for actives. This integrated technology does yield small size, but requires careful design discipline to achieve repeatable characteristics. LTCC is essentially a “wet” or tape process technology – material is screened in place, building up the device layers, while the lower temperature manufacturing process enables the use of more standard conductive metals such as copper, for internal electrodes and contacts. Plated-through vias are used for inter-layer interconnection and the electrical conductors can be configured in plates (capacitors) or spirals (to make efficient inductors). Different low temperature ceramic materials with a variety of characteristics are available, including high capacitance density dielectrics, but these yield high dielectric constant at the expense of tighter temperature and voltage coefficients that characterize the high temperature ceramic types.

This type of lay-down process also has wider process tolerances (from the capability of the wet system to the variability of post-firing shrinkage) with interconnect (line) widths limited to ~ 150 microns. Table 1 gives comparative data for key characteristics. The technology is applicable to the passive and active modules such as PAs (power amplifiers), RF switches, and RF front-ends by integrated capacitors, resistors, and inductors in a very small area. The process results in a mechanically strong and compact structure but does limit the materials available for RF component design.

One challenge facing designers working with LTCC is the ability to characterize the RF properties of the complex internal structures that lack electrical models. Most embedded components, especially spiral inductors and parallel plate capacitors, suffer from significant parasitic coupling due to their large area and proximity to other structures or to ground planes.

It follows that LTCC modules are more suited to application specific designs in high volume platforms, as varying the design for different configurations becomes more problematic as their complexity increases. This technology also benefits from economies of scale – once upfront costs for custom design and characterization have been met, the process itself can support low cost manufacturing - but it also limits any future revisions and changes without a module redesign.

Because LTCC technology, in itself, is not always the optimum performance solution, there has been an increased interest in new integrated devices that have evolved from discrete solutions based on thin-film technology.

Thin-Film Solutions

Thin-film technology, as a first step, goes back to a discrete format. The key difference with this technology is that it is based on photolithography and PECVD (Plasma Enhanced Chemical Vapor Deposition) processing. The photolith gives extremely precise geometry while the low temperature PECVD process combines the benefits of high conductivity conductors with the use of highly stable dielectrics (e.g. SiO_2) deposited on a stable alumina base. The technology also allows downsizing to 0201 size and further integration. The most basic element is the thin-film capacitor as shown below:

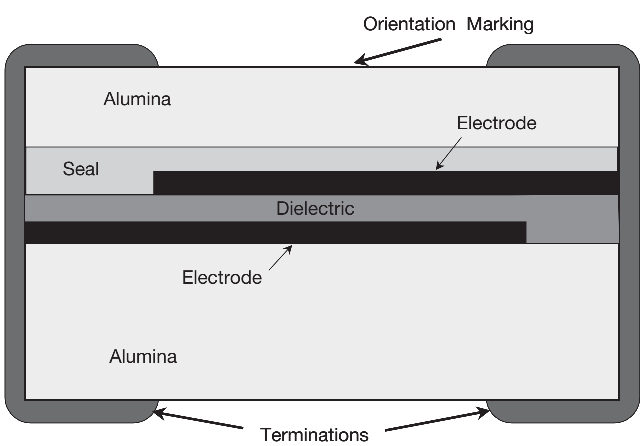


Figure 2. Thin-Film Capacitor Structure

The system above is characterized by extremely stable dielectric, single layer construction (which eliminates harmonics), is readily modeled and extremely reproducible – designs breadboarded on the bench will be precisely reproduced in mass production at the CEM, month to month and year to year. Because the parts are discrete circuit elements, there are no up-front design costs and full design flexibility is maintained throughout the program lifetime. Ultra-Stable dielectrics usually have trade-off – low dielectric constant. But thin-film is capable of far thinner dielectric films (~1m) compared to LTCC (50m – 250m) which results in a higher cap yield / mm². The conductors used for the electrodes also have lower resistivity (~ 1mW / mm²) than their LTCC counterparts (10 – 20 mW / mm²) giving greater RF power handling capability. Because of their precision, these devices can be used in conjunction with LTCC packages – while any given LTCC module will have limited design flexibility, the small size and termination compatibility of discrete thin-film devices means that they can be used to fine tune an application or modification, or even for last minute tuning for FCC compliance, etc.

Figure 3 shows how these components are typically configured in a standard radio application:

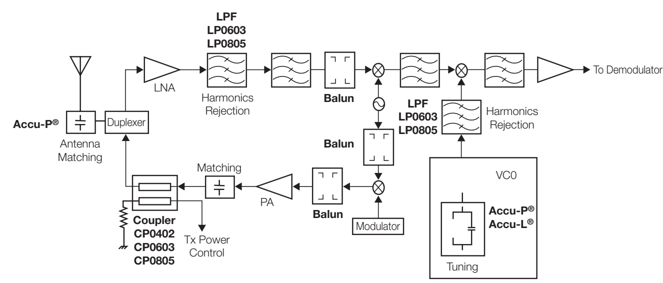
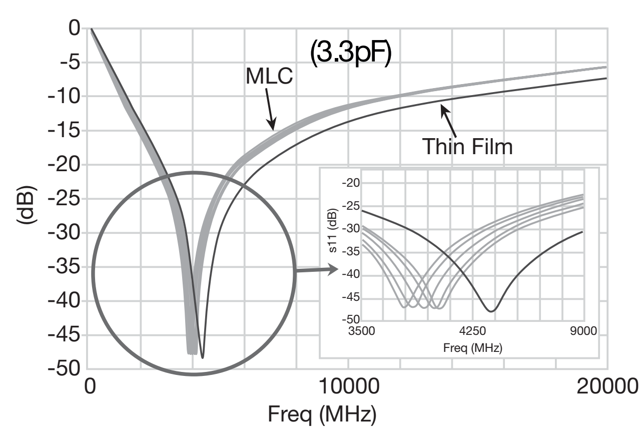


Figure 3. Thin-Film Capacitor Structure

The LNA (Low Noise Amplifier) is one of the more critical sections in the receiver circuitry and to maximize the performance, it is essential to have stable biasing and accurate impedance matching. Thin-Film provides discrete capacitors and inductors with are High Q, low ESR, and very accurate capacitance values (±.01pf) and inductance values (±.1nH).

By using this technology, an LNA can have a more accurate match over temperature and greater repeatability from board to board compared to both traditional discrete devices and wider tolerance LTCC:



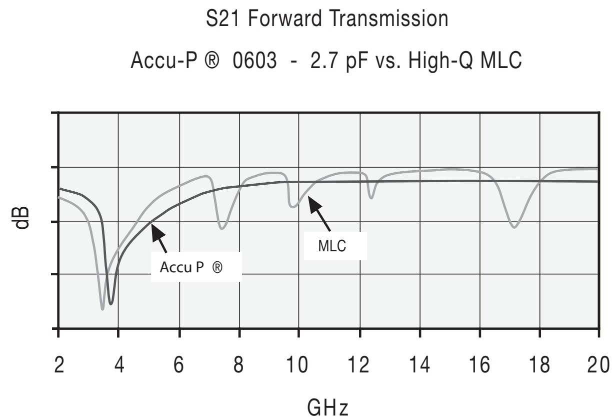


Figure 4a & 4b. Thin-Film vs NP0 MLC Ceramic

Figure 4a shows the deviation in S11 when comparing MLC NP0 Ceramics vs. Thin-Film capacitors. Notice that the thin-film capacitor response tracks with no variation between parts. This demonstrates exactly how precise the thin-film process can be from capacitor to capacitor and from batch to batch. This can not only improve the quality of the LNA, it can actually improve the yield in manufacturing by eliminating the fine tuning of circuits in production. Figure 4b shows the response at higher frequencies; being single layer devices, thin-film show no harmonic resonances.

The same components can be used to accomplish the critical matching of the input and output of a power amplifier. By using low loss thin-film capacitors and inductors, more power can be sent to the amplifier transferred to the antenna. This results in improved performance and increased efficiency of the power amplifier, as well as improving temperature performance.

Antenna matching itself is also a critical design issue. The available real estate for the antenna is continually decreasing which generally leads to a non-ideal form factor design. This situation will almost always require an impedance matching circuit for the antenna. Thin-film capacitors and inductors are ideal for this application, providing an accurate match of impedance to the antenna to maximize energy transfer under all conditions to minimize losses from the PA or to the LNA.

Beyond high accuracy microminiature capacitors and inductors, thin-film PECVD technology also lends itself to integration. By combining both a capacitor and inductor element on the substrate, an LC Low Pass Filter (LPF) can be formed, as shown in Figure 4 below. These can be made in the same small form factors (0402 and up) and so use very little board space while saving cost through component count reduction. These thin-film filters provide high out of band attenuation (>30dB) while maintaining the lowest insertion loss available to the RF designer (<.3dB). They can also be used to isolate the frequency of interest on the output of the mixer after conversion. The filters are internally matched to 50_ so no external matching is necessary, and the conductor materials used make them capable of handling up to 3W continuous power.

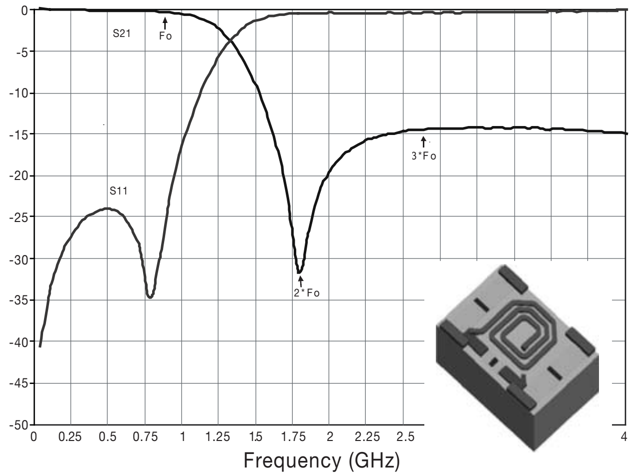


Figure 5. Thin-Film Low Pass Filter and Response for 915MHz LPF

A directional coupler is a device that samples an RF/Microwave signal while minimizing loss to the signal. Thin-film devices, based on back-to-back inductors, produce very high directivity (Isolation – Coupling), low insertion loss directional couplers. These couplers offer the highest amount of directivity found on the market today, in small package sizes down to 0402. In the diagram in figure 3, the coupler is being used to sample the output and send the sample to a gain control circuit for the power amplifier. As with the LPF, the couplers are also capable of handling up to 3W continuous power.

Directional couplers work from the principal of field coupling. The electric field produced by a transmission line in series with the signal is coupled onto an adjacent conductor through the air or dielectric medium. Coupler elements can be included within LTCC modules; the technology allows lumped elements, rather than coupled lines, to produce directional couplers to 10dB. However, thin-film technology has a number of advantages in this area; the finer line widths maximize the coupling coefficient, making available hybrid couplers to 3dB in 0603 size.

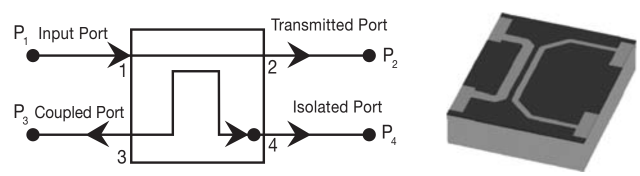


Figure 6. Directional Coupler

This coupler, with port configuration shown in Figure 6 above, is designed to couple 3dB of power (half) to another channel, with the addition of a 90o phase shift to the signal. This can be very useful in designs utilizing an I-Q architecture where the channels are 90 degrees out of phase. By using a hybrid coupler on the output of the oscillator, the LO (Local Oscillator) can be generated for both I and Q sections. It can also be instrumental when using two amplifiers to improve the linearity by splitting the power between the two circuits and then recombining after amplification. This reduces harmonic emissions, improves efficiency and increases gain from an amplifier.

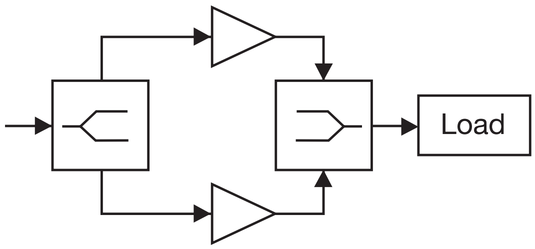


Figure 7. Hybrid Coupler Used to Improve Linearity

The latest stage in evolution is PMC (Passive Micro circuits). This goes to the next level of passive integration; its key advantages are that it retains the minimum line width capability and line width precision of thin-film, but increases the maximum stacking layers capability. This can be used for increased capacitor and resistor density per mm^2 and added turn capability in inductor elements. Table 1 below gives the prime characteristics for these materials.The PMC process is ideal for integration of the passive content of the RF circuit to optimize PA or LNA performance for a given application. As with all integration, the higher the complexity, the more single application specific the device.

Property	Perovskite	SiON	SiO_2	BCB
Range	2.2pF-400nF	0.47-150pF	1-500pF	1-50pF
pF/mm^2 Typical	8800	55	35	25
Stability	X7R -55 to +125 ±15%	NP0 ±30ppm/ºC	NP0 ±30ppm/ºC	NP0 ±60ppm/ºC
Rated	2-4	≤≤ 100	≤ 100	≤ 25
BDV (v/µm)	100	600	1000	300
DF	≤ 8%	≤ 0.1%	≤ 0.1%	≤ 0.1%
Voltage Stability	Less 1.25%/volt	Independent	Independent	Independent
Frequency Range	≤ 10 GHz	≤ 40 GHz	≤ 40 GHz	≤ 75 GHz

Table 1: PMC Material Capabilities

Summary

In summary, designers have choices at the outset of the product cycle to choose from full integrated systems to full discrete solutions with their associated pro and cons. Both thin-film and PMC are rapidly developing technologies and there are guaranteed to be a number of new devices emerging during the next few quarters – watch this space…..

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