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MMIC Filters: Revolutionizing RF Systems with Compact Design and High Performance

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As next-generation technologies push towards higher frequencies, technologies are capitalizing on wider available bandwidths and higher channel densities, enabling increased data throughput. Consequently, RF market trends for filters are starting to prioritize higher frequency capabilities and size, weight and power (SWaP) and scalability. In contrast to competing filter technologies, Monolithic Microwave Integrated Circuit, or MMIC, planar filters are uniquely suited to meet the demands of next-generation systems.

RF/microwave filters are electronic circuits that selectively permit specific frequencies to pass through a system while rejecting undesired signals outside of a filter's passband. In system designs, filters are crucial for band selection and for cleaning up unexpected spurious tones. Filters are present at multiple points throughout the RF signal chain, commonly placed at the output of multiplier and amplifier blocks to knock down unwanted harmonics or following the frequency conversion block to reject spurious tones, improving system dynamic range.

Filters are often custom designs due to applications having unique frequency bands in which they can operate. For this reason, filters are often designed in-house. While filter designs are ideally planned for during the initial design phase, the need for filters often arise towards the end of a project when issues such as unexpected spurious tones arise. For this reason, it is important that modern filter development is quick and accurate as to not cause project delays and to ensure functionality of an RF system.

Many different filter technologies are in use today, each with their own trade-offs:

- **Acoustic Wave Filters** provide excellent out-of-band rejection in a small form factor but feature low power handling and are frequency limited to below 8 GHz.
- **Cavity Filters** utilize higher filter orders relative to other filters and are best suited for frequencies from 1 to 20 GHz. They feature excellent out-of-band rejection, high power handling and low loss but require manual tuning and are physically large.
- **Lumped Element Filters** are low cost per design, have high yield and feature high Q, but have limited performance and are suited for frequencies below 6 GHz.
- **Planar Filters** (e.g., MMIC, Thin Film, Laminate) offer a balance between size, performance, cost, and development time, making them suitable for modern applications.

When considering a filter for a particular application, designers will generally look for a filter that has a high Q factor, indicating a narrowband and highly selective filter due to a sharp resonant peak at the center frequency, low center frequency insertion loss, high out of band rejection with steep transitions between the passband and stopband, and sufficient return losses. Additionally, a balance between filter order and size is considered as higher order filters will have steeper rejection slopes at the expense of a larger filter design.

Filters currently consume a large portion of a system's overall footprint, however, as next-generation systems have started to prioritize smaller form factors, filter specifications have been impacted as there is a natural trade-off in Q factor and the max filter order employable as size of the filter decreases. In Marki Microwave's experience over the past year, designers have proven to be willing to trade Q factor as long as they can achieve substantial size reduction while still meeting their passband insertion loss and out of band rejection requirements. This, in addition to reasons that will be discussed further, has allowed MMIC filters to emerge as the ideal filter solution for new systems.

Performance Metrics and Design Considerations for MMIC Filters

Size Reduction

As mentioned, each filter technology in use today has its own trade-off space and the same is true for MMIC filters. The increasing channel count and bandwidth demands of next-generation systems are met by MMIC technology as MMIC filters are unmatched in terms of the size reduction achievable and the high frequency capability. MMIC's precision lithography and small lumped element capacitors and inductors enable innovative circuit designs that allow smaller filter circuits to be realized. High frequency MMIC filters can be as small as 1.5 x 1.5 mm and integrate with other MMIC blocks or packaging methods to reduce system footprint. One of the differences between GaAs MMIC and thin film technologies is the higher dielectric constant, Dk, of GaAs (12.9) compared to thin film (9.8), which allows for smaller designs that can be realized in QFN packages that are 10 times smaller than equivalent thin film filters. MMIC is the only technology that can get to die-level size.

High Frequency Capability

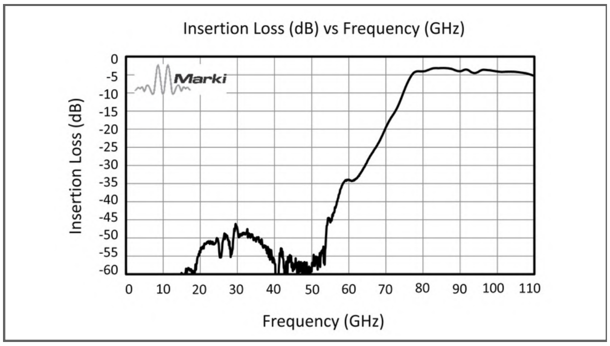

Figure 1. 78 GHz – 110 GHz MMIC Bandpass Filter Response

Utilizing the fine line widths available through MMIC lithography in addition to the use of thin substrates enable high frequency filter designs that were previously unattainable with competing technologies. Standard frequency capability for MMICs has been demonstrated up to 110 GHz thus far. This is crucial as next-generation systems move into E band, W band and beyond to enable higher data rates. Competing planar technologies are capable up to 40 GHz but are typically best suited to 20 GHz or below.

Q Factor

MMIC technology does not offer the same high Q factor achievable through competing technologies, however, the use of unique architectures and topologies provides more levers to pull than just Q factor and filter order to achieve high-performance designs. While the Q factor might not be as high as for laminate, thin film or other filter technologies, Marki Microwave has found that the selectivity and loss of MMIC filters has been more than agreeable from the standpoint of system designers.

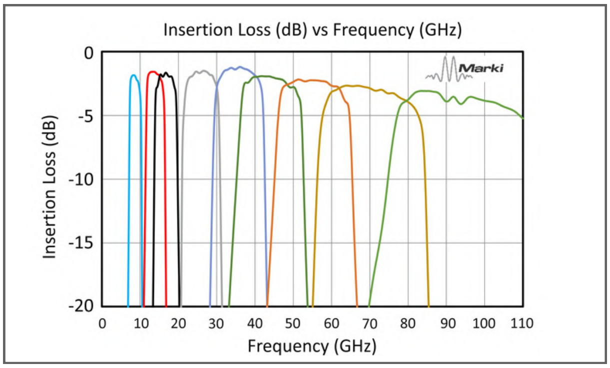

Figure 2. Passband Insertion Loss Vs Frequency for 9 Selected Filters

Q factor is directly related to the filter insertion loss, specifically the center frequency loss. As Q increases, the loss improves. Loss also improves with increasing percent bandwidths but decreases with increasing filter order as higher order filters trade-off size for improved rejection steepness. Typical passband losses for MMIC designs range from 1 to 5 dB, with lower frequency designs exhibiting superior losses. These insertion losses may be higher in comparison to competing planar technologies at lower frequencies; however, these insertion losses have been demonstrated as capable of meeting most system specifications. As previously noted, the move to higher frequencies and smaller filter sizes does impact Q and insertion loss, but MMIC filters outperform laminate and thin film technologies in insertion loss above 40 GHz.

Filter Order and Rejection

In terms of filter order, whereas thin film and laminate filters can use up to 11th and 15th order designs respectively, MMIC can typically employ 9th order circuits and below while keeping sizes small. However, a system designer will be more concerned with the resulting out of band rejection rather than the filter order employed to achieve it. Marki Microwave has found that filter orders between 4 and 8 have been sufficient to develop MMIC filters with acceptable rejections, rejection slopes and passband insertion losses. So far, MMIC filters have been demonstrated to achieve a 40 dBc minimum stopband rejection at 10% from the band edge for designs below 40 GHz, with typical values being much higher.

Return Loss

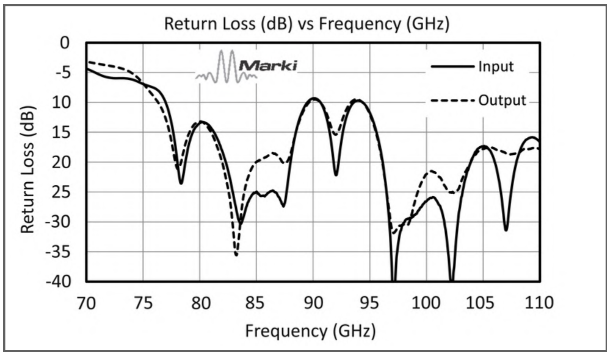

Figure 3. 78 GHz – 110 GHz MMIC Bandpass Filter Return Loss

For reflective filters, MMICs have demonstrated typical passband return losses better than 15 dB for designs below 40 GHz, while at mmWave frequencies, return losses have been measured around 10 dB. A high (negative) return loss indicates efficient signal transfer with minimal reflections. In addition to reflective designs, reflectionless designs have also been developed with excellent return losses both in the passband and stopband, making these designs excellent for eliminating unwanted spurs present in the system.

Integration

MMIC technology offers versatile integration capabilities. MMIC components can be seamlessly integrated with other MMIC blocks or co-packaged into surface mount packages or multi-chip modules. This flexibility allows for the consolidation of various RF and microwave functions into a single, compact package, reducing system footprint and complexity. MMIC integration capabilities are highly valuable in applications where SWaP constraints are critical.

Filter Response Types

The choice of filter response type depends on the specific needs of the RF system, including the desired frequency range, bandwidth, insertion loss, and out-of-band rejection requirements. MMIC technology offers flexibility in designing and implementing these various filter response types:

- **Lowpass Filters:** These filters allow frequencies below a certain cutoff frequency to pass through while attenuating higher frequencies. Lowpass filters are useful for applications where filtering out unwanted harmonics or noise is necessary.

- **Highpass Filters:** Highpass filters permit frequencies above a specified cutoff frequency to pass while attenuating lower frequencies. They are employed to remove DC offset or filter out undesired low-frequency signals.

- **Bandpass Filters:** Bandpass filters allow a specific range of frequencies to pass through, while attenuating frequencies both below and above this range. They are crucial for selecting a particular frequency band of interest. MMIC bandpass filters can be realized with traditional bandpass structures as seen on thin-film and microstrip designs, however in a more compact form factor design. Bandpass filters can also be realized as a cascade of lowpass and highpass filters to provide a broadband response.

- **Bandstop Filters:** Bandstop filters, also known as notch filters, attenuate a specific range of frequencies while allowing all others to pass. Essentially the opposite of a bandpass filter.

- **Diplexers:** Diplexers are specialized filters used to separate or combine multiple frequency bands within a single system. They are commonly employed in RF systems that require signal routing and frequency management.

- **Balanced Reflectionless Filters:** These filters use two identical bandpass filters terminated with quadrature hybrids at both the inputs and outputs. Reflected out-of-band signals are coupled into on-chip 50Ω terminations such that no reflections reach the input or output ports, thus providing excellent return losses both in the passband and stopband.

- **Switched Filters:** As mentioned, due to the integration capability of MMICs, some MMIC filters can incorporate switching mechanisms that allow dynamic selection of different frequency responses. These are valuable in applications requiring reconfigurable filtering or where size is a premium.

Repeatability, Scalability and Simulation

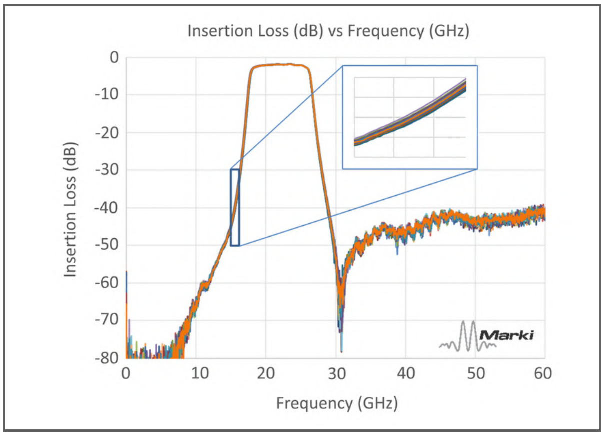

Figure 4. Repeatability of 24 randomly selected MMIC filters from a lot of over 8000 units

GaAs fabrication yields high-volume, repeatable single crystals for MMIC filter production, scalable from thousands to millions of units, meaning that at volume, MMIC filter are cost competitive solutions. Precise lithography optimizes features like transmission zeros, closely matching simulations for quick design success. Tighter tolerances enhance repeatability across units and wafers, outperforming other technologies. MMIC's etching tolerance (0.25 um) surpasses laminate filters (25 um), minimizing detuning issues and improving yield. Thin-film processes, less controlled than ICs, result in lot-to-lot variability. Additionally, the development of an iterative filter design tool is enabling designers to quickly determine whether filter designs are feasible. The tolerances of lithography ensure high accuracy between the initial simulated filter design and the final realized filter, allowing designers to proceed with their projects through accurate simulation files while said filters are being fabricated.

Impedance Matching

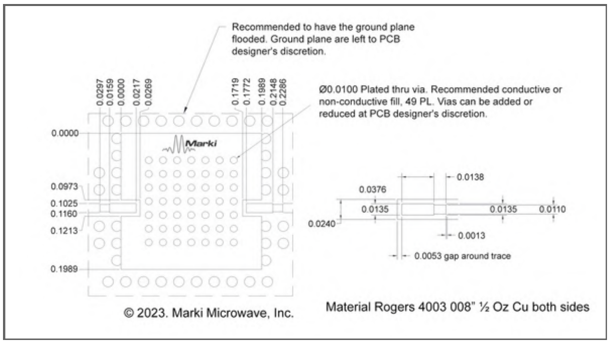

Figure 5. Optimized Landing Pattern for a QFN Filter Featuring an Inductive Taper

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Impedance Matching

Filter performance relies on precise impedance matching to ensure that these components don’t detune due to parasitic capacitance and inductance from packaging components such as leads and wirebonds, particularly at frequencies above 40 GHz. This issue is solved by co-designing packages with the die to ensure a well-matched 50Ω transition to optimize the filter return loss. Using optimized landing patterns with inductive tapers is essential to tune the transmission line leading to the filter package.

In conclusion, next-generation technologies are driving the RF market towards higher frequencies, increased bandwidths, and greater scalability. MMIC planar filters are uniquely positioned to meet these evolving demands. RF filters play a crucial role in system design, and MMIC technology offers a compelling solution by combining size reduction, high-frequency capabilities, and versatile integration. These advantages together with a right first-pass design process when shared across multiple designs make MMIC filters a cost-effective and performance-driven choice, revolutionizing their role in custom filter development for modern applications.