MINIATURIZATION OF FIXED AND TUNABLE FILTERS – WHERE AND WHEN TO USE INTEGRATED PASSIVE DEVICES

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ABSTRACT

RF and microwave filters are a major building block in the design of Software Defined Radios (SDR). These filters are used to reduce cosite interference, reduce transmitter spurious emissions, attenuate strong out-of-band signals and reduce transmitter broadband noise. In software defined radios, filters may also be necessary to reduce DAC images and spurs as well as attenuate unwanted received signals that could cause aliasing.

As the need to reduce filter size and cost becomes more prevalent, there are several implementation tradeoffs that must be examined. These tradeoffs will lead to the most appropriate design for the intended application based on filter size, cost and performance. The circuit technologies that will be compared in this paper are discrete components, microstrip and Integrated Passive Devices (IPD).

This paper will present an overview of Integrated Passive Device technology and present examples of fixed and tunable filters that range in frequencies from 30 MHz to 6 GHz. These filters have achieved size reductions of approximately 80%. We will also describe design and performance tradeoffs for IPD filters implemented on different types of substrate materials.

1. INTRODUCTION

Software Defined Radios involve the integration of many different functions into a single package. The continued demand for increased functionality and smaller size has required more components to be confined in a smaller area than previously realized. A recent survey of common consumer devices showed ratios of up to 30:1 for passive to active components [1]. This paper will focus on the integration of capacitors, resistors and inductors for use in filter miniaturization. By increasing the passive components increasingly complex filters and radios can be produced in a smaller footprint. At high rates of production, using very small IPD die can also significantly reduce filter cost

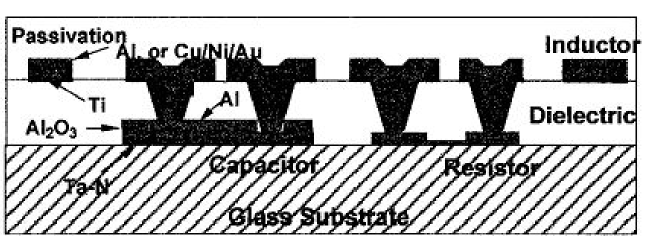


Figure 1: Cross section of typical IPD[2]

2. IPD 101

The term Integrated Passive Device (IPD) can be used to refer to the integration of any passive component. Capacitors, resistors and inductors have all been implemented in IPDs. Integration can produce a large number of passive components within a small area. This will lower the cost of the components, reduce the overall complexity at the board level and reduce manufacturing and packaging demands. Using IPDs in SDR products will help designers achieve optimization in terms of performance, size and cost. A typical cross section is shown in Figure 1.

IPD resistors are made by depositing resistive material onto the layers of the substrate. Very tight tolerances can easily be achieved with values ranging from 0.01Ω to tens of MΩ's. Commonly used materials are TaN and CrSi.

Integrating capacitors and inductors involves many tradeoffs regarding size, Q factor, and component values. Integrated capacitors are typically MIM capacitors or interdigitated capacitors with substrate layers between the conductive plates. The size and Q of an integrated capacitor depend on the dielectric constant (K) and dissipation factor (DF) of the substrate. Depending on the substrate material used, capacitor values can range from less than 1 picofarad to several hundred nanofarads. Figure 2 shows the wide variety of tradeoffs in capacitor IPD construction.

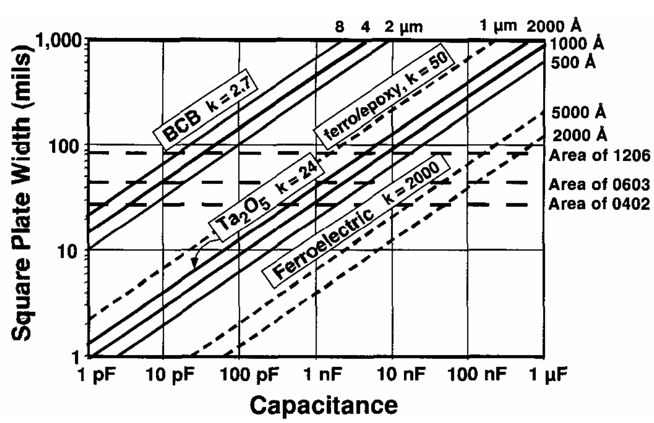


Figure 2:Capacitor tradeoff tables[3]

Inductors are the easiest component to fabricate. IPD inductors are typically designed as spiral inductors with a single layer of metal resting on top of an insulating substrate. The Q of an integrated inductor is primarily dependant upon the conductivity of the metal conductor and the conductivity and loss tangent of the substrate material. There are other secondary factors that can also influence Q. These factors are discussed in a later section. Integrated inductors can range in value from 0.5 to 80 nH with Q values greater than 120 in certain frequency ranges.

There are many different processes and materials to choose from when designing an IPD. Successful IPD implementation requires good device models for accurate simulation and a close relationship with foundries and suppliers. This will ensure that the appropriate materials and processes are used to optimize performance.

There are many reasons for integrating the passive components used for implementing filters. Some of these reasons are [4]:

- The weight and volume of the filter circuitry is reduced because several components are integrated into a small die.
- Electrical performance is improved because layout and component parasitics are significantly reduced. Layout parasitics are reduced due to the elimination of solder pads and interconnecting traces. Component parasitics are reduced because package inductance and capacitance are gone.
- Design flexibility is increased because the designer is not restricted to using catalog values for components.
- Circuit reliability is improved because an IPD filter has fewer solder joints than a discrete, lumped element filter.
- Unit cost is reduced because several discrete components are replaced by one integrated component. Depending on production volume and the number of passives integrated into the IPD, part cost, manufacturing cost and test cost can all be reduced.

3. 30 – 88 MHZ TUNABLE FILTER

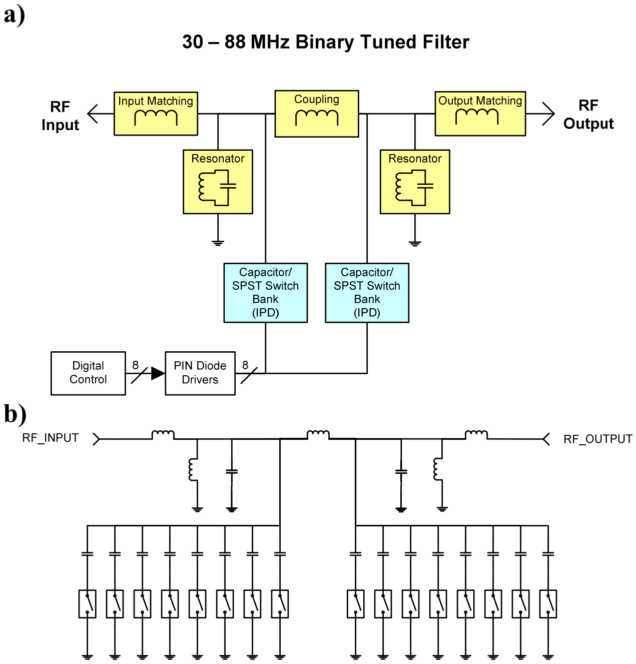
To demonstrate the application of Integrated Passive Devices in a miniaturized tunable filter design, consider an 8-bit, binary tuned filter (BTF) that covers the 30 to 88 MHz frequency band. The design to be examined is a lumped element, coupled resonator filter that changes center frequency in 256 discrete steps. This filter is a second order, inductively coupled filter. It uses a single inductor matching network to transform the resonator's nodal impedance to 50 ohms at the input and output of the filter.

This filter uses parallel LC (inductor/capacitor) resonators. Each resonator has a bank of parallel capacitors that are used to tune the filter. Changing the number of parallel capacitors that are switched in to each resonator tunes the filter's center frequency. To tune the filter to a lower center frequency, additional capacitors are switched into the resonator. This increases the resonator's nodal capacitance and lowers the resonant frequency. To tune to a higher center frequency, capacitors are switched out of the resonator. This reduces the nodal capacitance that is in parallel with the inductor and raises the resonant frequency of the resonator.

The capacitor banks contain eight different capacitors that can be switched in and out of the resonators. The switching function is performed by a bank of Single Pole Single Throw (SPST) PIN diode switches. The bias to each PIN diode switch is provided by a PIN diode driver. There are eight PIN diode drivers, one for each switch in the resonator. Although the filter has two resonators, only one set of PIN diode drivers is used to tune both resonators. The block diagram and partial schematic for this filter are given in Figure 3.

To reduce the size of this filter, an MCM-L design approach was taken. The PIN diode drivers were implemented using surface mount technology (SMT) parts for the passives and chip and wire for the active devices. To achieve further size reduction, the capacitor bank and the SPST switches from the filter are implemented in an IPD. Surface mount parts were used for the filter inductors. These inductors were not integrated into the IPD because of the large inductance and Q values that are required to meets performance goals.

a)



b)

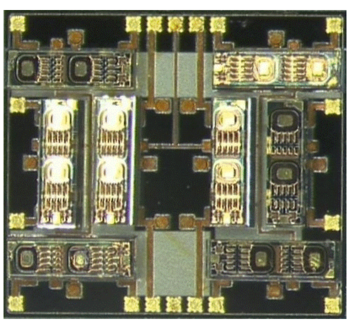
Figure 3: 30-88 MHz Binary Tuned Filter: a) Block Diagram, b) Schematic

This original design of this filter was a board level design using discrete SMT parts. The circuit card area required for the filter and PIN diode driver circuitry was approximately 3 square inches. Although this is a fairly compact design, it is too large for most wireless and handheld devices.

The IPD for this design was implemented by the AVX Passive Micro Components (PMC) Group. This device contains the capacitors in the capacitor bank and the passive components in the SPST switch circuitry. Due to material and process differences, the PIN diodes in the SPST switch can not be integrated into the IPD substrate. As an alternative to integration, small chip-scale package PIN diodes were used. The chip-scale package allows the diodes to be soldered directly onto the top of the IPD die making it into a chip-on-chip PMC module. By using this stacked-die technique, the PIN diodes can be added without increasing the size of the footprint. The IPD contains 8 capacitors that range in values from 3 pF to 107 pF, 24 resistors that range in value from 120 ohms to 2 Mohms, 16 PIN diodes and 18 I/O's. The size of the PMC module is 2.6 x 2.9mm with a total height of 0.58mm max. The PMC module is shown in Figure 4.

As stated above, the inductors in the filter were not integrated into the IPD. This is because there are many tradeoffs to be considered when designing passives into an IPD. For example, there are tradeoffs between the size and cost of an IPD inductor versus an equivalent SMT component. If an IPD inductor is larger than an equivalent SMT inductor, an SMT inductor should be used if the main design objective is to minimize size. It is important to find a balance between IPD and SMT component size [5]. The size of an inductor versus its inductance value will vary depending on the IPD substrate that is used. In addition, there are tradeoffs regarding inductor performance that must be considered. When large inductance values or high Q values are needed, high quality SMT inductors will most likely be preferred. AVX's PMC processes can produce inductors with inductance values up to 40 nH and Q values up to 80. In the case of this design, a combination of SMT and IPDs was preferred based on size and performance.

a)



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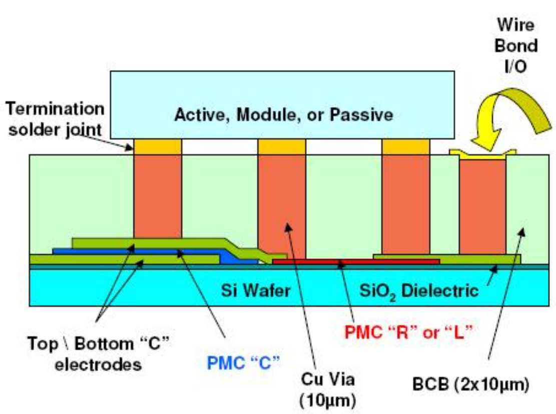

Figure 4: a) AVX PMC Module, b) Cross Section

The main factor affecting the size of an inductor is the inductance value. Inductors also require keep-away distances from other signal traces and ground planes so that their magnetic fields are unimpeded. Inductors that are located too close to these structures are susceptible to undesired coupling and interference. Also, depending on the IPD design, the required Q can affect the inductors size. When IPD technology was first developed, inductors were rarely integrated because of the large physical area that was required to obtain practical inductance values. Additionally, substrate and metal losses made it very difficult to fabricate inductors with Q's that were high enough for realizing filter designs. Today, better substrate and metal materials are being used that enable the integration of smaller, higher quality inductors.

The Q of integrated inductors is a function of the loss in the substrate material used to fabricate the IPD and the loss in the metal layers [6]. The losses in the substrate are caused by the conversion of electromagnetic energy into heat in the volume of the substrate. The three main loss mechanisms within the substrate are displacement currents flowing through the substrate to ground, induced current flow in the substrate due to magnetic fields within the substrate, and radiation losses. In general, the higher the conductivity of the substrate material, the greater the loss will be. For high Q inductors, as few conductive layers as possible should appear under or near the inductor.

The loss in the metal layers of an inductor is the other factor that plays a role in determining the Q. The resistance of the metal has an affect at all frequencies. At higher frequencies, the current distribution changes due to eddy currents and skin effect. As the effective cross-sectional area of a conductor decreases, the current density increases, increasing the loss.

The resistance of the metal layers can also increase due to proximity effects of other conductors and ground planes. The magnetic field in these areas is the sum of two terms, the self magnetic field and the neighboring magnetic field. If these other conductors enhance the magnetic field of the inductor, the AC resistance will increase, further increasing the loss and decreasing the Q.

3.1 Design Tradeoffs

Two different filter designs were evaluated for size tradeoffs. The first design was an LC coupled resonator filter design using discrete SMT components. The second design used a combination of IPDs and SMT components. For higher frequency designs, a combline filter and tunable hairpin filter designs could also be considered, but these topologies are very large at 30 MHz.

When size is a critical parameter, there are two drawbacks to designing filters with discrete components. First, many of the discrete components will be significantly larger than equivalent values of integrated passives. Additionally, 0201 and 0402 package size SMT capacitors and inductors typically have very low Q's and low breakdown voltages. If higher Q's and breakdown voltages are required the designer may be forced to user larger components. The other drawback to using discrete SMT components is that the designer is limited to catalog values. In cases where the filter response is critical, the designer may be forced to use series and parallel combinations of catalog parts in order to achieve the desired filter response. These additional parts will increase the size of the filter. With integrated passives, the designer is not restricted to using catalog values. This gives the designer greater flexibility when designing the filter and allows for better filter optimization.

Another advantage of an IPD filter is that depending on the substrate material used for the IPD, smaller capacitors can be implemented that have higher breakdown voltages than are available using 0201 size components.

The required inductance and Q values needed for this design made it impractical to integrate the entire filter into an IPD. The AVX PMC process can produce inductors with inductance values up to 40 nH and Q values up to 80. This filter design required larger values of both inductance and Q. Additionally, some of the bypass capacitor values were too large to be implemented into the IPD. For these reasons, the filter design was implemented using a combination of SMT and IPD components. When this combined SMT and IPD filter was implemented into a Laminate Multi-Chip Module, further size reduction was achieved because the MCM-L allowed for bare die to be used in the PIN diode driver circuitry. The final module size is 1.220" x 0.546" (0.666 in^2). A picture of the filter MCM-L and simulation results of the filter response as it is tuned from 30-88 MHz are shown in Figure 5.

4. 900 – 1450 MHZ FILTER

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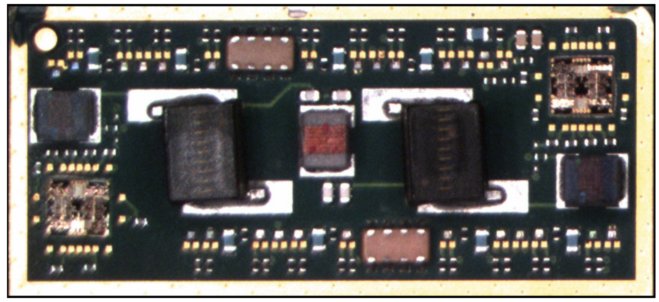

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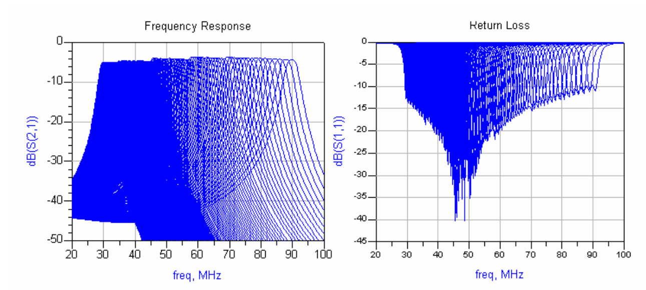

Figure 5: a) Filter Module, b) Simulated Filter Response

As another example of the tradeoffs between using an IPD filter versus other filter technologies, consider the design of a seventh order BPF with a passband ranging from 900 – 1450 MHz. The frequency of this filter falls in a range where either a discrete component design or a transmission line design could be used to implement the filter. To identify the best implementation in regards to size, we will examine the tradeoffs between discrete component, microstrip and IPD filter designs.

4.1. Discrete Component Design

The schematic of this filter design is shown in Figure 6. As mentioned earlier, a major drawback to using discrete components is that the designer is restricted to using catalog values. At higher frequencies, this becomes even more of an issue because the combination of additional series and parallel components will increase layout parasitics and can severely degrade the filter response. When this happens it may be necessary to add short transmission lines or stubs between the components, requiring considerable optimization. The parasitics and self resonant frequencies of the SMT components will also affect the filter response. This, in combination with the layout parasitics can make circuit optimization very difficult.

The board area required for this filter is approximately one half inch square. This is assuming that 0201 capacitors

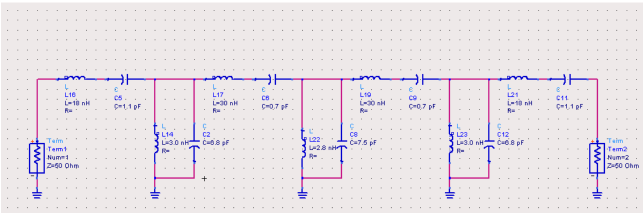

Figure 6: 900-1450 MHz Lumped Element Filter

and 0402 inductors are being used. This board area can vary depending on the size of the components used. Depending on the design requirements, larger capacitors and inductors could be necessary if higher power levels are present at the input of the filter.

4.2. Microstrip Design

There are several different microstrip filter topologies that can be used to implement this filter. Some of the typical, compact microstrip filter topologies are interdigital, combline and hairpin filters. These filters use quarter wavelength microstrip resonators whose coupling depends on their spacing.

The combline filter has many advantages over other quarter wave microstrip filters. For example, the size of a combline filter can be reduced by shortening the length of the resonators and capacitively loading their ends. The more the resonator is loaded, the shorter it can be made. The drawback is that when the resonator is shortened, its Q is reduced. Another advantage of the combline filter is its reentrance characteristic. A normal quarter wave resonator filter exhibits a reentrance (repeated passband) at approximately three times its center frequency. For example, an interdigital filter with a center frequency of 1100 MHz would have a second passband centered at 3300 MHz. This reentrance also causes a significant reduction in stopband attenuation at frequencies between the responses. With combline filters, the reentrances can be moved higher in frequency by shortening the resonators with capacitive loading. Therefore, combline filters are not only smaller than other quarter wave resonator filters, but they can also be designed with the reentrance moved to a frequency that is high enough to not cause system problems. This, of course, is done at the expense of reduced resonator Q and increased insertion loss.

A combline filter has some disadvantages also. Although this type of filter is smaller than other classical quarter wave filters, there are limited to a maximum fractional bandwidth of approximately 30%. For designs needing a larger fractional bandwidth, other filter topologies should be considered. An interdigital filter was used to implement the filter for this design. The circuit board area required for this filter was approximately 1.6 x 0.5 inches.

There are several other topologies that can be used to create "miniaturized" microwave filters [7]. A few of these topologies are meander open loop resonator filters, folded hairpin resonator filters, slow-wave resonator filters and dual-mode resonator filters. These filter topologies can significantly reduce the filter size over conventional combline filters, but they will likely be larger than an IPD filter. The tradeoff with these filters is in power handling vs. size. Although IPD filters can be smaller, they can only handle low to moderate power levels (depending on the substrate material used). The miniaturized microwave filters can handle larger power levels at the cost of having larger volume and weight.

4.3. IPD Design

The IPD implementation of this filter is a lumped element filter design using spiral inductors and parallel plate capacitors. The dimensions of the IPD are approximately 2.0 x 2.0 mm. This is significantly smaller than the discrete component and the microstrip implementations. Unlike the 30-88 MHz filter, all components in this filter, including the inductors, can be integrated. The inductance and Q values needed for this design easily fall within the allowable range of many IPD processes.

In addition to reduced size, the IPD design has many other advantages over the discrete component design and the microstrip design. As stated earlier, the IPD implementation of this design will have much smaller component and layout parasitics than those that are present in the discrete component design. Also, with an IPD design the circuit designer is not limited to catalog values. This additional design flexibility allows for improved optimization in both size and performance.

The IPD filter also has several advantages over the microstrip implementation. As can be seen, this design offers and incredible savings in size over the microstrip filter design. This is accomplished without the increase in insertion loss that is associated with reducing the size of combline filter resonators. Likewise, the IPD filter does not have reentrances and therefore its stopband performance is superior to a microstrip filter. Finally, the maximum bandwidth restriction that is associated with the combline filter design is not present with an IPD filter.

An instance where the IPD design would not be acceptable is when the power levels that are incident on the filter are expected to be large enough that the voltage and temperature ratings of the device are exceeded. In this cases, it would be recommended to use one of the "miniaturized" microwave filter topologies that were briefly discussed in the previous section.

5. SUBSTRATES

Substrate selection is a critical step in the filter design process. The substrate chosen impacts cost, yield and performance. Tradeoffs must be evaluated to optimize performance based on the components to be integrated. Two of the most common substrates types are ceramic and silicon based substrates although GaAs substrates are becoming more common.

Silicon based IPDs are manufactured using existing high-volume wafer production techniques which provides tight tolerances and low cost in high volume. Ceramic based substrates benefit from a lower loss tangent than silicon based substrates and benefit high frequency applications. There are many varieties of materials which allow for flexibility in the design process. For example, Alumina based substrates are commonly used in applications that require high power levels because it provides better thermal characteristics than traditional ceramic substrates.

Typical parameters for evaluating substrates are conductivity, dielectric constant, and voltage rating. Higher quality inductors can be fabricated on substrates with a lower conductivity. The dielectric allows for larger capacitor values to be integrated into smaller areas, and higher voltage ratings allows IPDs to be used in higher power applications.

6. CONCLUSIONS

Prior to beginning any filter design it is essential that the designer survey substrates and processing techniques suited for their particular application. New advances in materials are allowing higher Q values and higher K substrates to be developed. These advances are allowing IPDs to achieve performance levels previously unobtainable.

IPDs provide the potential to increase functionality, reduce cost, and decrease the size and weight. These improvements are particularly beneficial for devices using circuits where there are a significant number of passive components. To take full advantage of this technology, the properties of the resistors, capacitors, inductors, and substrate must be properly integrated together.

7. REFERENCES

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