Three-Stage Bandpass Filters Implemented in Silicon IPD Technology Using Magnetic Coupling between Resonators

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Abstract — **Thin-film technologies most commonly use capacitors or inductors to couple resonator stages for the implementation of band-pass filters. The use of mutual inductance (referred to as magnetically coupled, to distinguish it from conventional inductive coupling) has some inherent advantages, especially for ESD robustness and DC isolation. Furthermore, this method is naturally suited for the implementation of balanced filters. This paper describes the design and characterization of some example bandpass filters for wireless LAN applications in silicon IPD technology using capacitively-loaded ring resonators coupled by mutual inductance.**

Index terms – **Bandpass filters, circuit topology, passive circuits.**

I. INTRODUCTION

The synthesis of filter designs was originally developed for lumped-element components. The direct correspondence between networks of reactive components and functions of a complex variable gave rise to a well-developed methodology for filter synthesis based on analytical optimization [1]. These methods are very effective for lower frequencies at which lumped components approximate their ideal behavior.

As electronic applications have progressed to higher frequencies, however, the traditional methods of filter synthesis have encountered some difficulty. Lumped components exhibit distributed effects, deviating from their ideal behavior. Furthermore, parasitic effects that are negligible at lower frequencies may significantly alter the characteristics of lumped components at GHz frequencies. In this case, the simple correspondence between the characteristics of lumped components and the analytical methods of circuit synthesis ceases to exist, and alternative approaches are required.

This problem led to the extension of filter synthesis methods to distributed circuit elements, particularly transmission lines. There is a well-developed and growing body of knowledge related to the design of planar transmission-line filters [2]. Filters based on this approach are used extensively, especially in microwave radar and telecommunications applications.

Filters based on distributed elements generally rely on quarter-wave or half-wave resonant sections of transmission line. As consumer products, particularly for telecommunications and wireless data communications, have advanced to GHz frequencies, pressures on size and cost have favored alternative technologies, particularly multilayer ceramics [3] and, more recently, integrated passive devices (IPDs) based on silicon fabrication methods [4]. These technologies rely on design methodologies that are more closely related to lumped circuit design than to distributed. The analytical methods of traditional filter synthesis are less applicable because of the non-ideal component behavior, but these problems can be overcome by the use of simulation and optimization tools [5].

Filter circuits developed for multilayer ceramics and silicon IPDs are architecturally similar, but show significant differences in detail because of constraints in the technologies. In comparison, ceramic technologies have lower capacitance density than silicon (and related thin-film technologies) because of their thicker dielectrics. On the other hand, they can obtain higher inductance density through the use of multiple layers of conductor. Consequently, the resonators in multilayer ceramic filters tend to have larger inductors and smaller capacitors (i.e. higher internal impedance) than those used in silicon IPDs.

Another key difference between ceramic and silicon technologies is their robustness to electrostatic discharge (ESD) failure. The dielectric layers in silicon IPD technology are about 50 times thinner than those in multilayer ceramics. This leads to much higher capacitance density, but also makes the capacitors much more prone to breakdown. This is an important consideration in many applications of bandpass filters, which are often used in receiver front-ends directly connected or close to the antenna.

This paper describes the design and implementation of bandpass filters in silicon IPD technology using an arrangement of compact, capacitively-loaded ring resonators that are coupled by mutual inductance. We refer to these as being "magnetically coupled," to distinguish them from inductively coupled circuits using lumped inductors. The resulting circuits show greatly enhanced ESD performance compared with more conventional designs.

II. CIRCUIT DESCRIPTION

The top diagram in Fig. 1 shows a general representation of a three-stage top-coupled LC resonator filter. The three LC resonators in this configuration share a common ground reference, and are coupled by reactive admittances. In general, these coupling admittances can be either inductors or capaci-

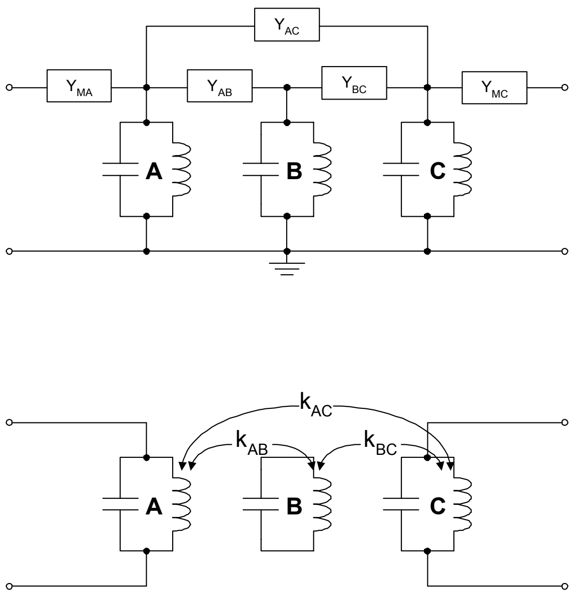


Figure 1: Top: general circuit configuration for a three-stage top-coupled bandpass filter. Bottom: an alternative configuration in which the coupling is by mutual inductance.

tors. If Y_{AB} and Y_{BC} are inductors, this introduces transmission zeros at infinity, and the tails of the response (plotted on a logarithmic scale) will fall off more steeply above the passband than below. Alternatively, the use of capacitors for these coupling elements introduces transmission zeros at zero frequency, and the response will fall off more steeply below the passband. Finite admittance for the element Y_{AC} in this circuit introduces transmission zeros at finite frequency. In addition to the coupling admittances, top-coupled bandpass filter circuits often include impedance matching reactive elements, denoted by Y_{MA} and Y_{MC}. These elements make it possible to accommodate a wide range of resonator impedances in this circuit.

For thin-film technologies, the most common implementation of this circuit is to use identical inductors in the three resonators. Since capacitors are generally much smaller than the inductors, the coupling and matching components are usually capacitors. Inductor coils dominate the physical size of thin-film IPDs, so the number of inductors is usually kept to a minimum.

The lower diagram in Fig. 1 shows an alternative circuit in which the coupling between the resonator stages is by mutual inductance. In this circuit, the couplings k_{AB}, k_{BC} and k_{AC} play the same role as the corresponding admittances in the upper figure. The shape of the filter response in the case of magnetic coupling is the same as in the case in which the coupling admittances are inductors – i.e. the magnetic coupling introduces transmission zeros at infinity. In effect, magnetic coupling is an alternative form of inductive coupling requiring no explicit inductor.

In general, this alternative could include series impedance matching admittances at the input and output, but in the example discussed below it is preferable to omit these elements.

For silicon IPD technology, the use of magnetic coupling has some advantages over the use of lumped admittance components. It typically results in more compact layout, especially in comparison to circuits using lumped inductors, since these large components are eliminated from the layout. Furthermore, note that in comparison to the conventional top-coupled circuit, the input and output do not need to share a common ground reference. This is very useful in devices that need to withstand large DC offsets or in balanced filters.

If the impedance matching elements Y_{MA} and Y_{MC} are not used, then the circuit will only work for specific values of resonator impedance, particularly at the input and output stages. The port impedances (typically 50) load these resonators, and if their loaded Q is too low, the filter bandwidth will be too large. For bandpass filters in wireless LAN applications (802.11a or b) with 50 ports, suitable inductance values for the resonators tend to be in the range of 0.3 to 0.6nH. These values are at the low end of the practical range for IPD inductors. Physically, they are best implemented as a single-turn ring.

III. IMPLEMENTATION

The physical design of the bandpass filters is similar in many respects to planar filters with microstrip ring resonators. However, because the IPD filters use capacitive loading, the inductor rings are much smaller than quarter-wavelength. Consequently, it is more difficult to obtain adequate coupling by simply placing adjacent rings in proximity to each other. Fig. 2 shows two alternative physical arrangements for a three-stage filter using single-turn inductors. Typical values of the desired coupling coefficients, k_{AB} and k_{AC} are in the range

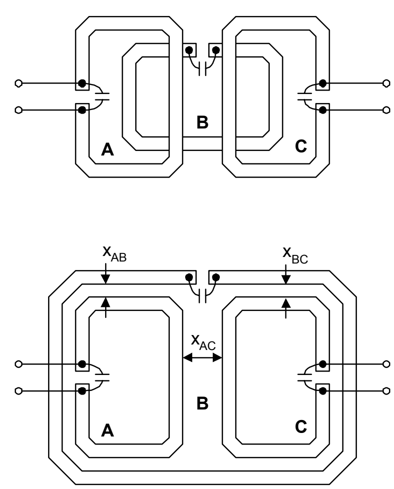


Figure 2: Physical implementations. The upper diagram shows the arrangement with three identical inductor rings, the lower with a larger middle stage.

of 0.1 to 0.2, depending on filter bandwidth. For single-turn inductor coils, it is usually necessary to overlap the coils, as shown in the upper diagram, to achieve such values. Most IPD technologies have only a single low-resistance layer of metal, so schemes like this one are not well-suited to the technology.

Note, however, that the loading imposed by the port impedance mainly affects the outer stages of the filter. The center stage is less affected by loading, and can be designed to substantially higher impedance. This permits the use of an arrangement like the one shown in the lower part of Fig. 2. Here, the inductor ring for resonator B wraps around the outside edges of the other two stages.

In tuning the physical design of this arrangement, the inductor size was first chosen to obtain the desired value of inductance for each stage. The values of coupling coefficient between each of the stages were adjusted by changing the separation between each of the rings, as indicated in the figure. Because the inductor for the middle stage of the filter surrounds the outer stages on three sides, sufficient mutual coupling can be achieved with reasonable gaps between the inductors. After adjusting the physical design of the coils, the capacitors values were determined by optimization, using the method described in [5].

Fig. 3 shows micrographs of two example filters fabricated in silicon IPD technology using this approach. These filters are designed for wire-bond attachment. The 802.11a filter is 0.8 X 1.4 X 0.25mm and the 802.11b is 1.0 X 1.5 X 0.25mm. Similar filters were also designed and fabricated for flip-chip attachment, with similar characteristics.

IV. EXPERIMENTAL RESULTS

Fig. 4 and Fig. 5 show simulated and measured characteristics of the two example filters shown above. In addition to the basic bandpass characteristics, both of these designs show a transmission zero below the passband. This arises from the coupling, k_{AC}, between the input and output stages of the filter. In design, its location can be adjusted by changing the separation between the two resonators. In addition, there is another transmission zero above the passband. This arises from mutual capacitance between the stages, and is also determined in part by the inductance of the wire bonds.

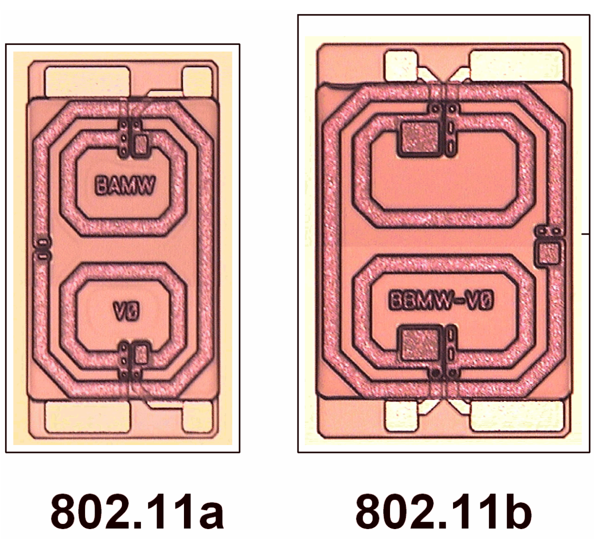


Figure 3: Micrographs of two example bandpass filters.

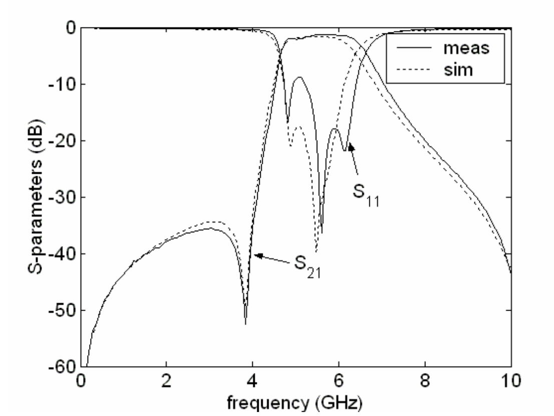


Figure 5: Measured and simulated characteristics for the 802.11a bandpass filter shown in Fig. 3.

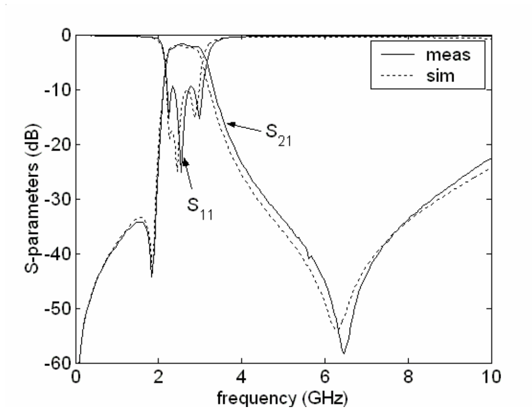


Figure 5: Measured and simulated characteristics for the 802.11b bandpass filter shown in Fig. 3.

The added transmission zero below the passband is very useful in wireless LAN applications. In 802.11b filters it enhances the attenuation in the cellular bands, which may act as strong blockers in LAN front ends. Similarly, in 802.11a filters, the zero enhances the attenuation for 802.11a.

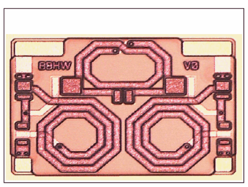
One advantage of this circuit, as mentioned above, is that the input and output are not required to share a common DC reference. It is also the case that they can operate in different modes. So, for example, the input can be single-ended and the output can be differential, or vice-versa. This eliminates the need for a separate balun transformer in applications requiring balanced-to-unbalanced conversion. The characteristics in the case of mixed-mode operation are almost the same as those shown above, but the zero above the passband is suppressed.

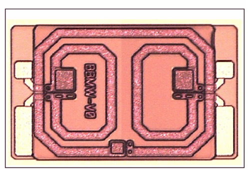
V. ESD COMPARISON

One of the motivations for the development of this type of bandpass filter was to improve the ESD performance of the filters. Thin-film technologies typically achieve high levels of miniaturization through the use of thin dielectrics. This greatly increases the capacitance density, but is accompanied by a corresponding reduction in the capacitor breakdown voltage. In bandpass filter circuits like the one shown in the top part of Fig. 1, using series capacitors for impedance matching poses a problem for ESD performance.

High levels of ESD robustness in thin-film passive technologies can be obtained by using inductive shunt protection across vulnerable capacitors. Most of the energy in an ESD event is concentrated at low frequency, for which inductors in the nano-Henry range are effectively short circuits. In the magnetically-coupled circuit, each capacitor is protected by a low-value inductor in shunt with it. This increases the circuit's robustness to ESD.

TABLE I
ESD FAILURE VOLTAGE
(HUMAN BODY DISCHARGE MODEL)





TEST	Capacitive coupling	Mutual inductive coupling
Input to ground	400	>3000
Output to ground	550	>3000
Input to output	400	>3000

To test this, the ESD failure voltage of the 802.11b magnetically-coupled IPD filter was measured, and compared with the characteristics of a capacitively-coupled filter with similar performance characteristics [4]. The test procedure consisted of applying voltage pulses simulating Human Body Discharge in increasing increments of 50V, and determining the voltage at which irreversible damage first occurred. 10 samples of each device were measured to verify consistency. The results of the comparison are listed in Table I.

As Table 1 shows, the inductive shunt in parallel with the capacitors in the magnetic circuit very effectively protects the device from ESD damage. (3000V was the upper limit of the test system used in the measurement.)

VI. CONCLUSIONS

We have demonstrated a bandpass filter design using a magnetically-coupled circuit architecture. By using higher resonator impedance for the middle stage in a three-stage design, a practical layout can be achieved for typical wireless LAN bandpass filters. The design of the filters is accomplished by adjusting the separation between capacitively loaded inductive rings to tune the coupling. The resulting filter characteristics are similar to those of more conventional circuits using lumped capacitive or inductive coupling elements.

Key advantages of the magnetically coupled circuit are compact footprint, DC isolation between input and output, natural application to the implementation and high ESD robustness. Comparison with more conventional designs shows at least seven-fold improvement in ESD failure voltage.

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REFERENCES

[1] A. I. Zverev, *Handbook of Filter Synthesis* , John Wiley and Sons, ISBN 0-471-98680-01(1967).
[2] J. S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, John Wiley and Sons, ISBN 0-471-38877-7 (2001).
[3] C. Q. Scrantom and J. C. Lawson, "LTCC technology: Where we are and where we're going. II," Proc IEEE/MTT-S International Microwave Symposium, pp.193-200, Feb. 1999.
[4] R. C Frye, K. Liu, G. Badakere and Y. Lin, "A Hybrid Coupled-Resonator Bandpass Filter Topology Implemented on Lossy Semiconductor Substrates," Proc IEEE/MTT-S International Microwave Symposium, pp.1757-1760, June 3-8, 2007.
[5] K. Liu and R. C. Frye, "Full-Circuit Design Optimization of a RF Silicon Integrated Passive Device," Proc 15th IEEE Topical Meeting on Electrical Performance of Electronic Packaging, pp.327-330, Oct. 23-25, 2006.