Design and Analysis of Novel Compact Inductor Resonator Filter

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Abstract **– Compact spiral inductor resonators filter using inductor type resonator is proposed. The design is based on the self-resonant frequency of the spiral inductors and electromagnetic coupling between the resonators. The filter is built and measurement results show good agreement with the simulation data. The filter design is flexible. The resonance frequency and bandwidth of the inductor resonator filter can be directly optimized from the physical arrangement of resonators. The compactness of the newly developed bandpass filter makes the design and integration of bandpass filters attractive for further development and applications in SOC and/or SIP.**

I. INTRODUCTION

Recent advances in integration technology and device performance paved the way for higher level of System integration On Chip (SOC) or In Package (SIP). Recent wireless and mobile communication systems use miniature Radio Frequency (RF) module design technologies to satisfy low-cost and compact size requirements. Theses requirements are critical for some specific application such as ISM bandpass filter which occupy large real estate of complete mobile communication system. Planar filters, such as parallel-coupled filters [1], hairpin filters [2], and elliptic function filter [3], would be preferred since they are compatible with printed circuit technology. However, they need large real state area in existing mobile systems. A multilayer filter based on ceramic was introduced as a multilayer LC chip filter to reduce its size. Combline RF bandpass filter integrated into FR4/Epoxy based multilayer substrates has been realized to satisfy low-cost and compact realization [4]. However, this capacitive loaded combine RF bandpass filter uses external capacitor to reduce the filter size. It means that combline RF bandpass filter needs external capacitor to assembly. In addition, the performance of the filter will be changed by the tolerance of external capacitors. Integrated passive components on package substrate provide new chance to achieve compact hybrid-circuit design in a single package. The System-In-Package (SIP) technology not only provides interconnects to both digital and RF circuits, but also includes a unique feature of building integrated passive components. However, RF bandpass filters are not suitable for SIP due to their relatively large size. Most of today embedded filters in SIP are made on Low Temperature Co-fired Ceramics (LTCC) technology, which eliminates Surface Mount Technology (SMT) and reduces the size of the filter [5]. While LTCC filter can reduce the lateral size due to relatively high dielectric constant, it may not represent the most economical solution.

In this paper, we present newly developed ISM bandpass filters using inductor type resonators without any external component. Proposed bandpass filters are designed based on low-cost laminate substrate ($\varepsilon_r = 4.2$, $\tan \delta = 0.009$). Typical design rules for laminate substrate technology are used in the proposed new design for SIP. Design and analysis of the filter performance will be presented.

II. SPIRAL INDUCTOR RESONATORS

Spiral inductor resonators can be used as resonator elements in a filter design. Their self-resonant frequency depends on the physical and material properties of the carrying substrate. Fig. 1 (a) shows typical spiral inductor layout. This inductor is connected to ground at one end using VIAS to reduce the required length for resonators. Fig. 1 (b) presents the effective inductance for inductor resonator from 1 GHz to 4 GHz. This inductor works as an inductor element up to 2.54 GHz. This inductor has self-resonant frequency at 2.54 GHz. The capacitive behavior of the inductor structure is obvious above 2.54 GHz. Then, the spiral inductor structure can be used as a 2.54 GHz resonator. The length of this inductor is less than $\lambda/4$. The

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mutual inductance and parasitics capacitance among the inductor turns enhance the total inductance and capacitance of the resonators.

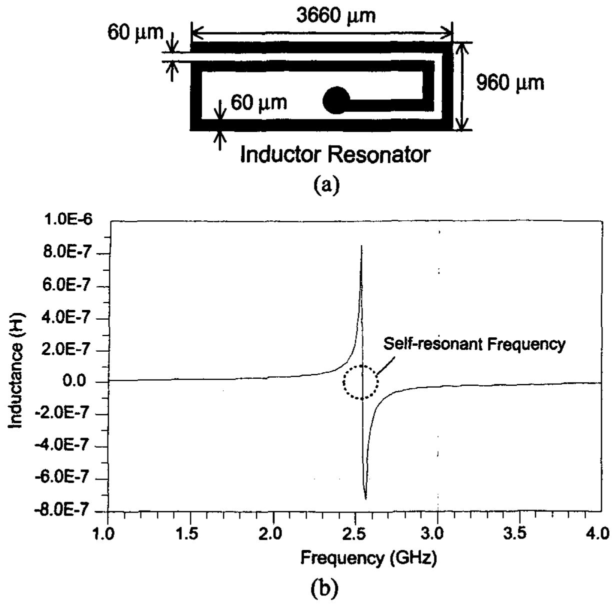


Fig. 1 Inductor resonator layout and self-resonant frequency of inductor resonator

III. SPIRAL RESONATORS FILTER DESIGN

The layout and structure of the new compact inductor resonators filter is shown in Fig. 2. This edge-coupled inductor filter is designed on two-metal layers low-cost laminate substrate using typical package laminate substrate layers and materials, as shown in Table 1. Metal layers are assumed perfect conductor material, which is PEC for simplicity. All filter resonators are designed on the first metal layer. Although the filter is designed on laminate substrate, it can be extended to other materials, as GaAs, LTCC substrate or PCB, which may reduce its size progressively.

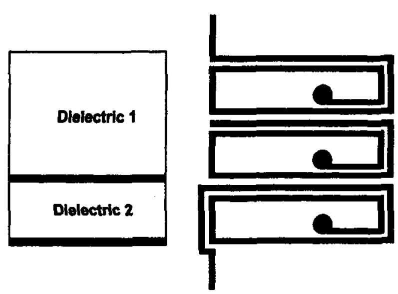


Fig. 2 Cross-section of edge-coupled inductor resonator filter

Table 1. Physical dimensions of laminate-based substrate

Structure parameter	Dimensions	Material
Dielectric 1 (Molding)	900 μm	$\varepsilon_r = 4.3$
Layer 1	27 μm	PEC
Dielectric 2 (Core)	200 μm	$\varepsilon_r = 4.2$, $\tan\delta = 0.009$
Layer 2	27 μm	PEC

The filter consists of three typical spiral inductance resonators. Each resonator is designed and optimized to achieve 2.8 GHz resonance frequency. The dimension of each resonator equals to 3660 μm x 960 μm. Electromagnetic coupling among resonators is achieved by edge-coupled lines to obtain the bandpass filter behavior. The resulted bandpass filter using inductor resonators has the following geometrical characteristics: area of 3660 μm by 3120 μm, line width of 60 μm, and spacing of 60 μm. We also considered the molding effect to consider more realistic structure in a package. The electrical and physical material characteristics of the filter structure are listed in Table 1. The newly designed inductor resonator filter was simulated using Ansoft 3-D full wave electromagnetic software HFSS [6], the simulated characteristics of the filter is shown in Fig. 3. The insertion loss in the passband and return loss of the new inductor resonator filter equal to 1 dB and 20 dB, respectively. The target center frequency of the passband equals to 2.4 GHz and 3-dB bandwidth is 95 MHz, as specified.

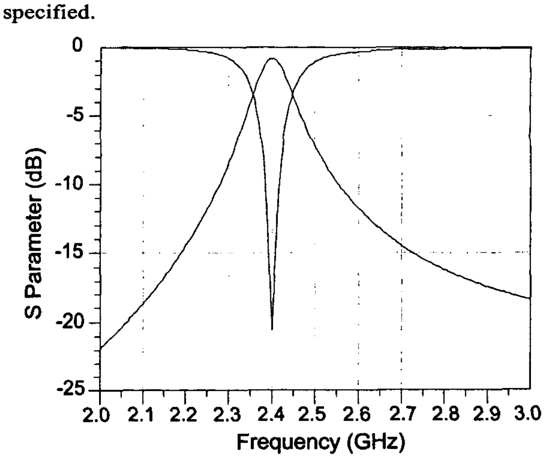
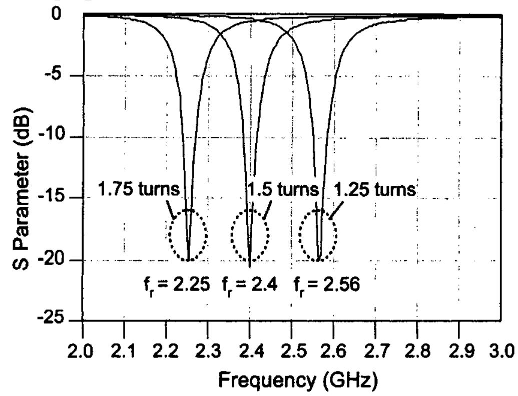


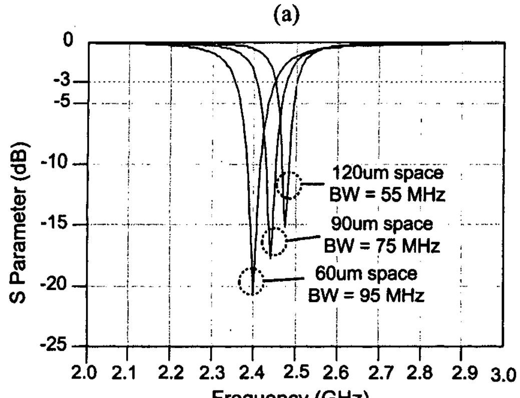
Fig. 3 Return loss and Insertion loss of bandpass filter using inductor resonator

IV. SPIRAL RESONATORS FILTER OPTIMIZATION

The spiral resonators filter design optimization is one of the major aspects in filter design. The resonance frequency and the bandwidth should be adjusted to meet the target specification. Fig. 4 (a) depicts center frequency variations versus number of turn for inductor resonator. The center frequency in the filter passband is determined by changing the number of resonators turns. It can be easily tuned by changing the number of resonator turns, which determines the self-resonant frequency of each inductor type resonators. The self-resonant frequency of inductor depends on the inductance of the spiral inductor, and the parasitics capacitance among the spiral inductance turns as well as between the inductor structure and ground plane. Therefore, self-resonant frequency of the inductor resonators can be optimized by changing the spiral inductor geometry. Fig. 4 (b) shows bandwidth variations with distance between resonators. The bandwidth of proposed inductor resonator filter can be optimized by changing the distance between resonators.



(a)



(b)

Fig. 4 Center frequency (a) and bandwidth (b) variations versus number of turns and resonators distance, respectively.

The 60 μm space inductor resonator filter has wider bandwidth compared to 90 μm and 120 μm space inductor resonator filters. This is due to the strong electromagnetic coupling between resonators.

The target performance of the filter can be easily achieved by optimizing the filter structure. The center frequency and bandwidth of the filter, can be adjusted by the resonator number of turns and distance between resonators, respectively.

V. SIMULATION AND MEASURED RESULTS

Fig. 5 shows the fabricated inductor resonator bandpass filter on four layers laminate substrate. The filter is located on metal layer # 2. The ground on layer #3 is 200 μm apart from the resonators filter. The filter is connected to layer #1 using VIAS. Probing pads are included for 2-ports microwave measurement. The bandpass filer is built on typical package laminate substrates dimension and materials, which was available at the time of the design. The characteristics of the materials are as follows, core layer height of 200 μm, ε_r of 4.2, and substrate loss of tan $\delta = 0.009$, dielectric layer 1 height of 65 μm, ε_r of 3.4, and substrate loss of tan $\delta = 0.015$, and molding layer height of 900 μm and ε_r of 4.3. The newly developed bandpass filter occupies an area of 3660 μm by 3120 μm. Metal line has width of 60 μm, thickness of 27 μm, and space of 60 μm.

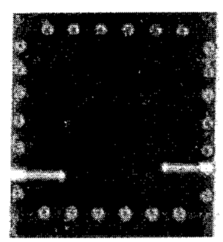


Fig. 5 Layout of the fabricated inductor resonator filter

The center of each spiral inductors is connected to ground through VIAS to decrease the required length of the resonators as previously explained. The filter is measured in microstrip line configuration using HP 8510C Network Analyzer and Universal Test fixture (UTF). Standard short, open, thru are fabricated on the laminate substrate. A standard TRL-method, using the load from the UTF calibration kit, is performed.

Fig. 6 compares the simulated and measured results of the inductor resonator filter characteristics, insertion loss and return loss. The measured and simulated center frequency equals to 2.495 GHz and 2.485 GHz, with return loss of 8.062 dB and 8.314 dB, respectively. The difference between the measured and simulated data, 10 MHz for the center frequency and 0.3 dB for the return loss at the center frequency, is due to the difference in the drawn and built dimensions of the inductor resonator filter. The relatively high insertion loss of the measured filter is a result of weak electromagnetic edge-coupled resonators coupling, that are 60 μm apart, and the losses associated with metal conductivity, which was not considered in the initial design. The measured bandpass filter was fabricated based on the available laminate substrate technology at the time of the design. These results show that spiral inductor resonators can be used to implement compact filter even on relatively low dielectric constant material.

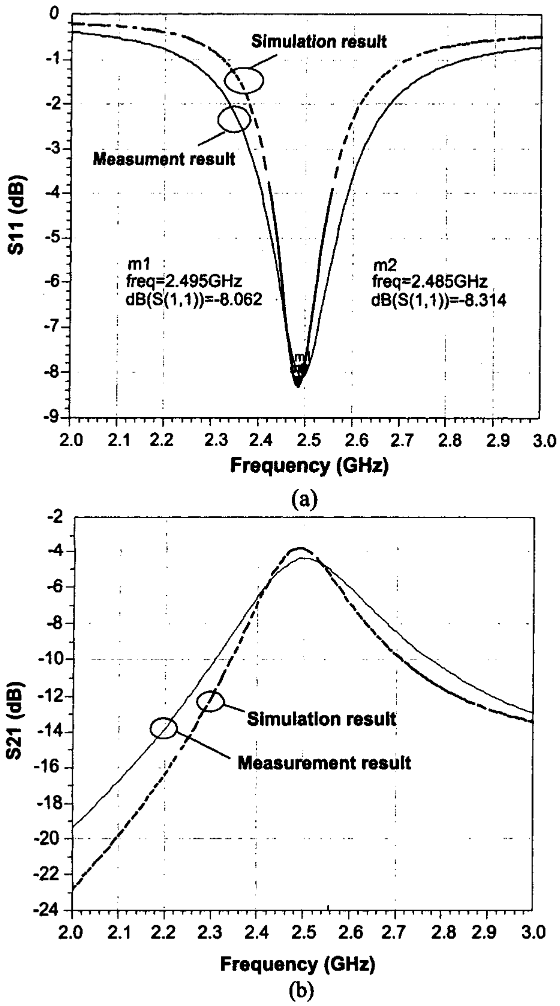


Fig. 6 (a) Return loss and (b) Insertion loss of measured and simulated bandpass filter.

VI. CONCLUSION

A novel inductor resonators filter structure is presented. The design can achieve compact filter structure, even on low cost relatively low dielectric constant material. The design is based on the self-resonant frequency of the spiral inductors and electromagnetic coupling effects between resonators. The measured results show good agreement with simulation result. The compactness of newly developed bandpass filter makes the design and integration of bandpass filters attractive for further development and applications in SOC or SIP.

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REFERENCES

[1] S. B. Cohn, "Parallel-coupled transmission-line resonator filters," *IRE Trans. Microwave Theory Tech.*, vol. MTT-6, pp. 223 – 231, Apr. 1958.

[2] E. G. Cristal and S. Frankel, "Hairpin-line and hybrid hairpin-line/harlf-wave parallel-coupled-line filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 719-728, Nov. 1972

[3] Zen-Tsai Kuo, Ming-Jyh Maa, and Ping-Han Lu, "A Microstrip Elliptic Function Filter with Compact Miniaturized Hairpin Resonators," *IEEE Microwave and Guided Wave Letters*, vol. 10, No. 3, March 2000.

[4] Mi-Hyun Son, Sung-Soo Lee, Young-Jin Kim, "Low-Cost Realization of ISM Band Pass Filters Using Integrated Combline Structure," *IEEE Asia-Pacific Microwave Conference*, pp. 1294 – 1297, December 2000.

[5] Kwang Lim Choi and Madhavan Swaminathan, "Development of Model Libraries for Embedded Passives Using Network Synthesis," *IEEE Transactions on Circuits and Systems – II.: Analog and Digital Signal Processing*, vol. 47, No. 4, April 2000.

[6] *HFSS Software User's Manual*, Version 7, Ansoft Inc.