RF-Microwave Multi-band Design Solutions for Multilayer Organic System on Package Integrated Passives

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***Abstract* - We present multi-band design solutions for integrated passives using multilayer organic (MLO) process technology for RF and microwave System on Package(SOP) module development. The components developed in this technology include embedded high Q compact inductors and filters designed in three frequency bands: S, C and Ku applicable for Bluetooth, MMDS, IEEE802.11a WLAN and satellite communications. Measured inductor Q factor as high as 182 and Self-Resonant-Frequency(SRF) as high as 20GHz, which represents the highest Q in its frequency range reported to date in a multilayer technology, have been demonstrated. A time domain electromagnetic modeling technique is also use to characterize passive devices.**

I. INTRODUCTION

Emerging applications in the RF/microwave/millimeter wave regimes require miniaturization, portability, cost and performance as key driving forces in this evolution. Multi-band applications are also becoming extremely important within passive development to realize multiple frequency bands for various wireless and optical sub-carrier multiplexing (OSCM) systems. Investigations on System on Package approach for module development [1] have become a primary focus due to the real estate efficiency, cost-saving and performance improvement potentially involved in this integral functionality.

In most of the presently used microwave integrated circuit technologies, it is difficult to integrate the passives efficiently while maintaining the desired performance. Another critical obstacle in efforts to reduce the module size is the design of passive components, which occupy the highest percentage of integrated circuit and circuit board real estate. Design flexibility and optimized integration can be achieved with multilayer substrate technology in which free vertical real-estate is taken advantage of. Various highly integrable multilayer technologies such as multilayer low-temperature co-fired ceramic (LTCC) [2]-[3] and multilayer organic (MLO) [4]- [5] are thus being studied to achieve complete System on Package solutions.

As a next step in the realization of completely integrated wireless communication front-end systems, we demonstrate the capability of embedding passive components, including compact high Q inductors in MLO for RF and microwave applications. In this paper we present compact inductors with high Q for S and C bands. The compact CPW inductor presented demonstrates a measured Q of as high as 182 and Self-Resonant-Frequency(SRF) as high as 20GHz with a 36 mil diameter. This represents the highest reported Q in a multilayer topology including MCM[6], LTCC[7], and organic.[8] The correct characterization of these components require that they be examined over the entire frequency band. It is shown that time domain techniques are well suited for this requirement through the use of Fourier transform. In addition to individual passive device implementation, SOP technology can also be used to integrate complete passive RF front-end functional building blocks, such as filters. Several filters were designed, fabricated and measured. Two low pass filters(LPF) were designed at 750MHz and C bands for 10Gb/s OSCM applications. Two band pass filters (BPF) were designed at C and Ku bands applicable for IEEE802.11a WLAN and satellite communications as well as OSCM front-end applications, respectively. To the best of our knowledge, this work is the first demonstration of integrated filters on multilayer fully organic technology.

II. MULTILAYER INDUCTORS

High Qs at the frequency range of interest can be obtained by designing CPW inductors and HGP [9] series and cascade inductors using multilayer organic technology. The CPW spiral inductor, Fig. 1, avoids via losses, has reduced dielectric losses and increased SRF. The advantage of the HGP implementation includes shunt parasitic capacitance and eddy current reduction resulting in higher Q. The CPW inductor achieves a measured Q of 182, SRF 20GHz, effective inductance (Leff) of 2 nH. The series inductor is designed as one continuous turn; however, the turn on the second layer is offset from the turn on the top layer, Fig. 2a. This offset helps decrease the parasitic capacitance between the turns and improves

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SRF. The top metal and bottom metal of the cascade inductor spiral separately and are connected at the center of the spiral, Fig. 2b. The top and bottom spiral are overlapped and strongly coupled yielding an impressive Q and effective inductance, Leff. The Q, L and SRF of the HGP series and cascade inductors are 122, 2.5nH, 10GHz and 165, 3.4nH, and 11.5GHz, respectively. The measured results of the cpw, series, and cascade inductors can be seen in Fig. 3. Another benefit of the HGP configuration is that the Leff can be adjusted by increasing or decreasing the shunt parasitic capacitance due to the ground plane. This is achieved by decreasing or increasing the hollow ground plane opening, respectively.

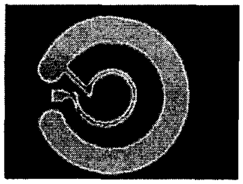
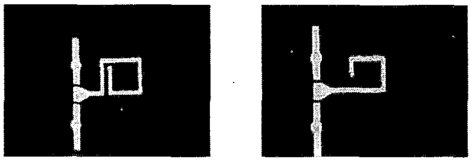


Fig. 1. Photograph of CPW inductor



a) b)

Fig. 2. Photographs of a series inductor(a) and cascade inductor(b)

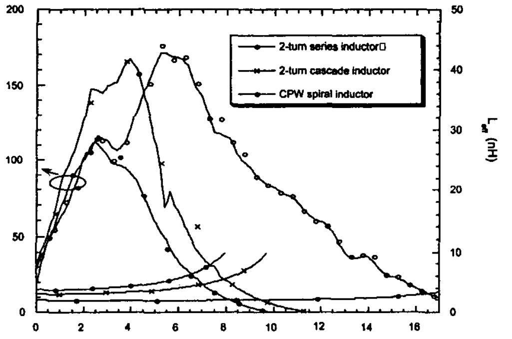


Fig. 3. Measured Q and Leff of high Q inductors

III. MULTILAYER INDUCTOR MODELING

A simple 2-turn inductor is used to test a finite-difference time-domain (FDTD) method, which is a time domain electromagnetic modeling method, which can be used to predict the Q. The FDTD code used to simulate the inductor uses both variable grid and parrallelization optimizations. A 3D rendering of the structure is presented in Fig. 4. The results for both Q in both the simulation and measurement are very similar, Fig. 5. The Q value found from simulation is not an exact match, which is expected because the simulation does not include metal loss.

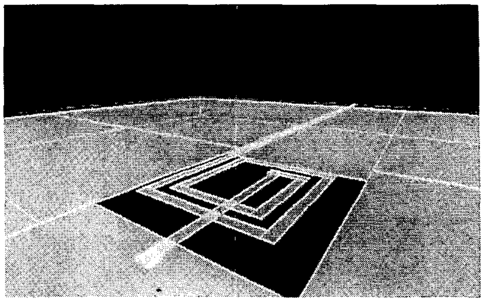


Fig. 4. Diagram rendering of modeled structure

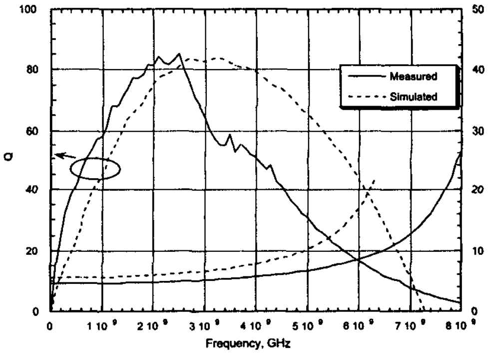


Fig. 5. Q and Leff of simple 2-turn inductor

IV. EMBEDDED FILTERS

Several front-end RF filters were designed in various topologies. Two LPF were designed for 750MHz and C band, respectively; two BPF were designed for C and Ku bands, respectively. For RF and low microwave applications, the first LPF can be implemented by combinations of capacitive and inductive lumped passive components. Fig. 6 shows the 2nd order Bessel lumped element lowpass filter with cutoff frequency at 750MHz. The simulated and measured return loss and insertion loss are shown in Fig, 7. It is used to filter 1Gb/s header data stream in a 10Gb/s OSCM system operating at 14GHz. A stepped impedance LPF was designed with cutoff frequency at 7GHz, Fig. 8. It is used to filter 10Gb/s data stream in a 14GHz OSCM transmitter as well. The series inductors represent the high impedance sections(94Ω) and the shunt capacitance represents the low impedance sections(7.2Ω). The simulated and measured return and insertion loss are shown in Fig. 9.

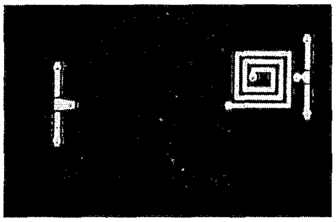


Fig. 6. Photograph of the organic-based lumped element filter

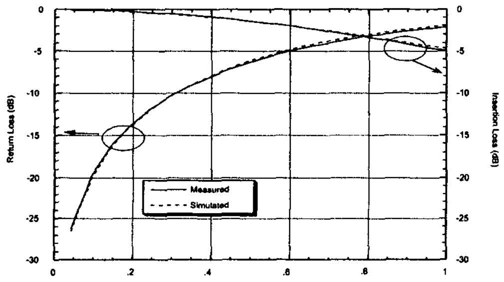


Fig. 7. Return and insertion loss of lumped element LPF

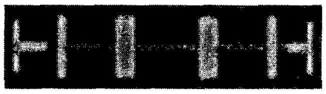


Fig. 8. Photograph of the organic-based stepped impedance LPF

The first bandpass filter design for C band applications consists of a square patch resonator[10] with inset feed lines, Fig. 10. The inset gaps act as small capacitors and cause the filter to have a pseudo-elliptic response with transmission zeros on either side of the passband. This structure also has a tunable bandwidth. The length of the insets and the distance between them are the main controlling factors, effectively setting the size of the mode-splitting perturbation in the field of the resonator. The length of the feed lines is determined by the input and output matching requirements. Fig 11 shows a center frequency of 5.8 GHz, bandwidth of 1.5 GHz and a minimum insertion loss of 3 dB.

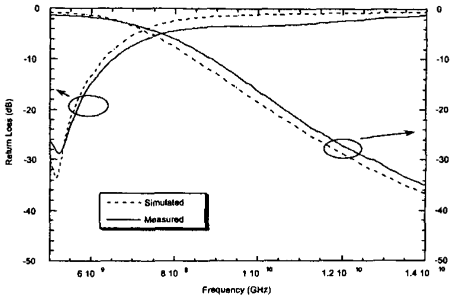


Fig. 9. Return and insertion loss of stepped impedance LPF

The second BPF design for Ku band applications uses a broadside-coupled microstrip dual-mode square ring resonator[11]. This consists of a microstrip ring resonator that is perturbed by inserting a small metal polygon at one corner, Fig. 12. The outputs are taken symmetrically with respect to this perturbation, which causes the resonator modes to split into two degenerate coupled modes, giving a second-order bandpass filter response. The advantages of this design are compactness and controllability of the bandwidth by varying the size of the perturbed polygon that causes mode splitting. Larger perturbations cause more mode splitting and result in a larger bandwidth. The strength of the coupling gap affects the insertion loss and resonant frequency. Fig. 13 shows a measured center frequency of 14.5GHz, bandwidth of 1 GHz and an insertion loss of 4 dB.

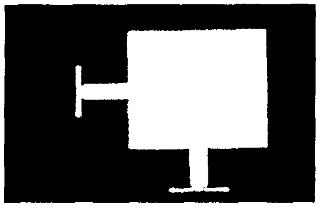


Fig. 10 Photograph of the organic-based C-band BPF

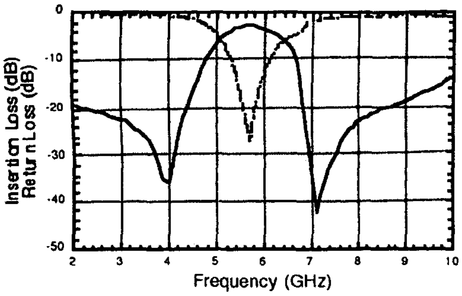


Fig. 11. Return and insertion loss of C band BPF

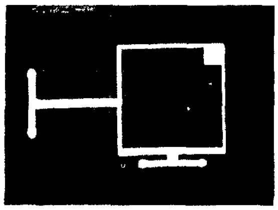


Fig. 12. Photograph of organic-based Ku band BPF

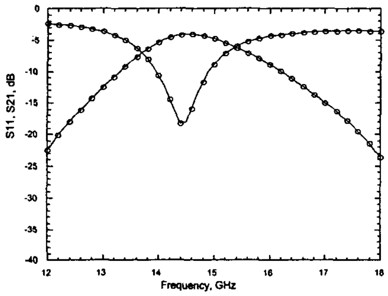


Fig. 13. Return and insertion loss of Ku band BPF

V. CONCLUSION

In this paper we have reported embedded passive inductor and filter designs and measurements for C, S, and Ku bands implemented in a multilayer organic-based packaging environment. A compact inductor with a measured Q of as high as 182 and SRF as high as 20GHz is presented. The filters demonstrate potential for compact designs in multiple filter bands. It is also shown that FDTD analysis can be used to simulate and accurately characterize devices that are traditionally difficult to model.

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