Chip Package Co-design of 5GHz RF Receiver Front-End Using Multichip Module Technology

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ABSTRACT

The transceivers for future technology (third generation cellular, wireless LAN) need to be portable (compact), battery-powered and wireless. The present single-chip solutions for RF front-ends do not yield complete system integration. A system-on-a-package (SoP) approach can solve these problems. High quality components can be integrated in the package. This paper reports a fully integrated single-package RF prototype module for a 5 GHz WLAN receiver front-end, which is intended to demonstrate the concept of SoP integration. The approach that is illustrated here is implemented with a thin film multichip module (MCM-D) interconnect technology. This technology also allows the integration of high quality passive components. With these passives, low-loss filters can be implemented.

Keywords: Low noise amplifier, bandpass filter, chip-package co-design, downconverter, MCM-D, RF front-end, system-on-chip, system-on-package, transceiver.

1 INTRODUCTION

Wireless communication requires better performance, lower cost, and smaller RF front-end size. Although much effort has been devoted to realization of SoC (System-on-Chip) in RF areas using Si based technology, SoC is considered a solution for limited applications, such as Bluetooth. The recent development of materials and processes in packaging makes it possible to bring the concept of System-on-Package (SoP) into the world to meet the stringent needs of wireless communication. RF-SoP provides a complete packaging solution for RF module by integrating embedded passives components and MMIC at the package level. Using SoP approach we can achieve low cost by using embedded passive instead of discrete components, design flexibility for MMIC by using high-Q passives embedded in the package, minimized loss and parasitic effects by reducing the number of interconnections, reduced module size by adopting multilayer packaging, ease of realization of multifunctional RF modules in a single package better high-power handling capability than MMIC chip. RF-SoP is "to provide a complete packaging solution for RF module by integrating embedded passives components and MMIC at the package level" [1], [2].

The System-on-Package approach has emerged as the most effective to provide a realistic integration solution because it is based on multilayer technology using low-cost and high-performance materials [3]-[4]. Multilayer topology high-density hybrid interconnects schemes, as well as various compact passive structures, including inductors, capacitors, and filters, can be directly integrated into the substrate. Thus, a high-performance module can be implemented while simultaneously achieving cost and size reduction [3].

The approach implemented here exploits the concept of Chip package co-design [5], [6]. This approach uses high-quality passive components that are realized in a thin-film MCM (MCM-D) interconnection technology. Passive components such as individual inductors and also complete RF bandpass filters are directly integrated into the MCM substrate (Glass substrate is used having $\varepsilon r = 4.6$). The quality factors 'Q' of the passive components are very high, especially compared to on-chip passive components. The MCM technology features high quality inductances between 1 and 40 nH. The front-end comprises of two bandpass filters, a low noise amplifier (LNA) and a downconversion mixer, as shown in Figure. 1.

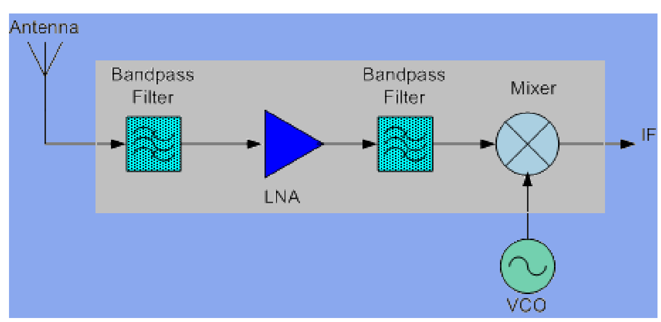

Figure 1 : Block diagram of receiver front-end for 5GHz

The active components are commercially available, "bare die" components [7], [8], which are flip-chip mounted onto the MCM substrate. The MCM module integrates some passives for the active circuits, impedance matching for the LNA and two lumped-element bandpass filters. The two integrated bandpass filters avoid the use of discrete RF filters, which are still required in “single-chip” solutions. This minimizes the number of components to be mounted. The 5.25 GHz RF input signal is downconverted to a fixed intermediate frequency (IF) of 500 MHz. The IF frequency is kept fixed by ranging the local oscillator (LO) frequency depending on which channel is to be received. The measurements are done for an LO frequency around 4.75 GHz. This means that the so called image frequency for the mixer lies around 4.25 GHz, which is the difference of the (variable) LO frequency and the (fixed) IF frequency. Since the downconverter is as sensitive to the RF frequency as to the image frequency, the signal components at the image frequency must be rejected. This is accomplished with one or more bandpass filters, centered on the RF frequency. The largest problem of single-chip integration lies in the integration of the passives for high frequencies. Partitioning a system over a number of chips, which can still be mounted in a single package, also circumvents substrate coupling since the conductive silicon substrate is replaced by a glass substrate that is almost a perfect insulator. In addition, one does not have to stick to one IC-technology. Every component is integrated in the best-fitted technology.

Chip-package co-design optimizes the integration of circuits and systems more effectively than traditional design methods. It is an important concept from the system perspective since the final module’s performance should be optimized, not just the chip or the package. Co-design has several advantages to high frequency circuit design: optimized performance, better design accuracy, and a reduced number of design iterations [6].

2 AN MCM-D SUBSTRATE AS A CARRIER

An MCM-D substrate technology has been employed in this work. The MCM-D technology developed by GEC Plessey Semiconductors has been described in detail elsewhere [9]. One of the constraints on the design of integrated RF systems is the availability of suitable and cost effective components. The system builder is also facing demand for ever greater functional density in RF products, particularly for portable products such as mobile phones and sub notebook computers [10]. MCM-D technology offers many of the necessary components and also gives advantages of size, repeatability and externally component count reduction. The MCM-D technology [Figure 2] allows the integration of different families of ICs together with integrated passive components to produce miniature radio modules and RF functions which offer considerable size and performance advantages over conventional discrete solutions [11], [12]. The benefits are further enhanced by the use of MCM-D passive components to produce structures such as filters which would normally consume significant space and cost in a conventional design [11]. MCM-D processes have been offering 4 to 10 fold reductions in the area of RF functions when compared to the surface mounted equivalent [13]. MCM-D technology as a solution for use in RF systems offers many significant advantages over more traditional technologies. In particular the size reductions and performance improvements possible allow product developers to meet more closely the requirements of the marketplace. The technology then eases many of the design problems in bringing RF systems into production [11].

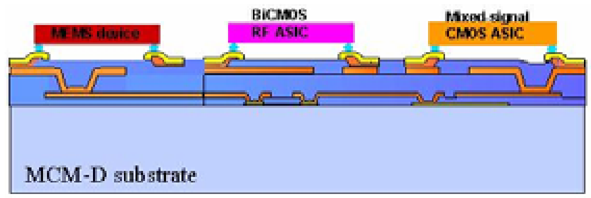

Figure 2 : MCM-D technology.

3 BANDPASS FILTER DESIGN

Filters are essential components in many electrical circuits. For RF and low microwave applications, the filters may be realized by combinations of capacitive and inductive lumped passive components [15]. These passive filters may then be integrated in the MCM-D interconnection substrate, creating a functional interconnection. We have designed embedded MCM, lumped element filters. Since we are looking at the two lower frequency bands only, the passband of interest ranges from 5.15 to 5.35 GHz. Implementing this design in a planar technology such as MCM-D imposes some restrictions. For any device in front of the low noise amplifier (LNA), the insertion loss should be minimized, since the value of the insertion loss (expressed in dB) directly adds to the noise figure of the complete receiver with same amount. A sixth-order filter in MCM-D would have too much insertion loss, due to losses in the passives. Therefore, the RF bandpass filter for the receiver is split into two filters, one second-order filter in front of the low noise amplifier (LNA) and a second one after the LNA. A second-order bandpass filter with lumped elements is realized. The design actually consists of two parallel LC resonators, which are coupled to each other and to their input and output terminals with capacitors. The inductors must have a high quality factor for the filter to have low loss. The quality factor drops with increasing inductance. On the other hand, the inductor cannot be too small. The LC tank determines the center frequency, which needs to be kept constant (at 5.25 GHz). A smaller inductor implies a smaller capacitor, which in turn is related to the required coupling capacitance. The values of the LC-tank components are respectively 1.38nH and 485fF. The capacitor that couples the two resonators has a value of 46fF and the input and output coupling capacitances equal 156fF. In order to select the appropriate bandwidth and center frequency of passband, analysis has been done by considering different design implementations.

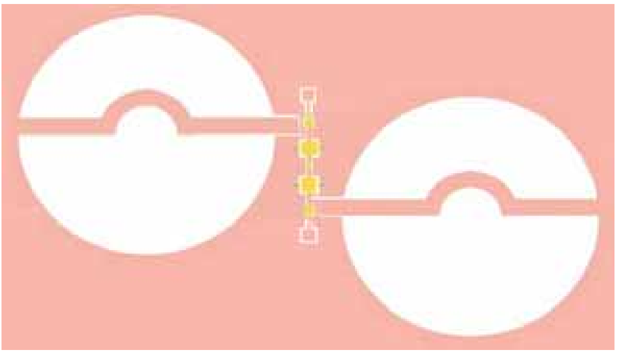

Figure 3 : Bandpass filter layout design.

The Q of the capacitors is not of much concern in this design, as it has been high enough that the designed capacitors have given almost values closer to their ideal models. The layout design of the filter is shown in Figure 3. The measurements [Figure 4] of this filter show an insertion loss of -2.5 dB and bandwidth of 460 MHz. The return loss in this frequency band is better than 13 dB.

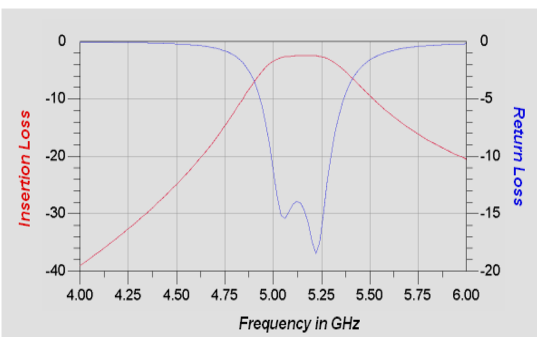

Figure 4 : Insertion loss & return loss.

By comparing this filter with [14], it has good result even though in this design aluminum metal is used than copper in [14]. There has been acceptable compromise on bandwidth and insertion loss because in order to further improve the design the size of the filter has been increasing beyond the acceptable values

4 RECEIVER FRONT-END BLOCKS

The presented integration demonstrator contains two bandpass filters, an LNA and a downconversion mixer. The prototype module is intended to demonstrate the concept of SoP. A lot of optimization work on the different blocks, especially on the LNA, is still possible. Figure 5 shows S-parameters of LNA.

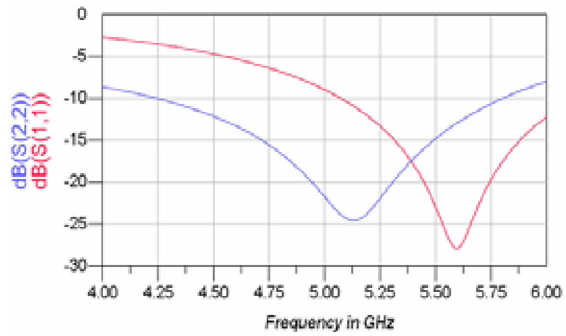

Figure 5 : S(1,1) and S(2,2) of LNA.

An on-package integrated multilayer filter offers a more attractive implementation than on-chip and discrete filters [3]. There is possibility to improve the filter design by making multilayer inductors by having the freedom of equal thickness of metal layers. The size of the inductors influences much on the quality factor. The quality factor improves by increasing the conductor coil width, inner diameter. However, increase in inductance occurs by increasing the number of turns but at the same time if the inductor is drawn on one layer, this causes the decrease in quality factor which in turn increases the insertion loss of the filters. This problem can be solved by designing multilayer inductors explained. All components are matched for 50Ω , which is not necessarily an optimum, but is often a requirement when using of-the-shelf components or when measurement of the separate functions is mandatory. It consists of a single class A stage. The transistor is available as bare die and is mounted on the MCM-D substrate with the flip-chip technique. All the passives are integrated in the MCM.

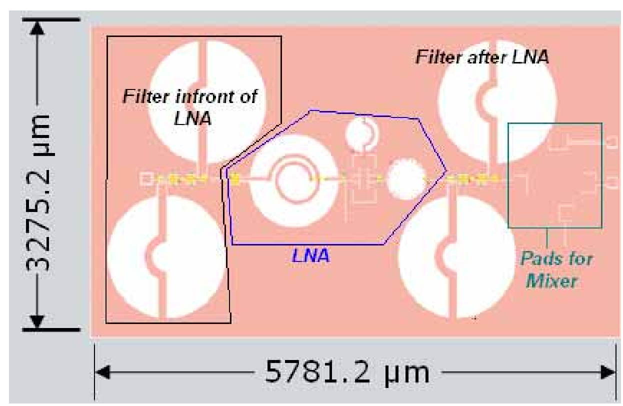

Figure 6 : Receiver front-end layout.

The low noise amplifier is built around a GaAs high electron mobility transistor [7]. Amplifier is designed to be unconditionally stable, which means that the amplifier is stable for every possible source and load impedance.

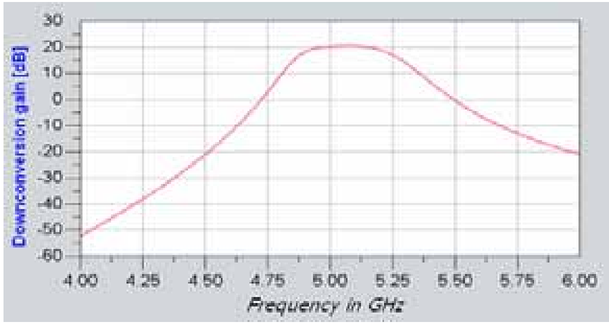

Figure 7 : Downconversion Gain.

The amplifier consumes 10 mA for a 2 V power supply [7]. The downconverter is a GaAs MMIC [8]. The device has a minimum specified gain of 12 dB. The complete receiver front-end layout design is shown in Figure 6 and has a measured conversion gain of 20 dB shown in Figure 7. The whole structure measures 3.3mm by 5.8mm. The conversion gain is with in the acceptable range, it can be further improved by making the filters with more improved performance i.e., with low insertion loss.

5 CONCLUSIONS

In this document, we have shown the advantages of SoP over single-chip solutions. Single-chip solutions do not provide complete system integration. A SoP approach using an MCM-D technology is a more complete solution that is compact and that is more flexible than a single-chip approach. Moreover, we have demonstrated that high-quality passive components can be embedded on an MCM-D substrate. These passives can be used together with mounted active components as well as for the design of integrated RF bandpass filters and matching networks. We have built prototype SoP-integrated RF modules of a receiver front-end with commercial bare-die components to demonstrate this concept. This receiver has a measured gain of 20 dB, making it suitable to serve as a part of a 5 GHz Wireless LAN system. A single-package approach is neither limited to one certain technology, nor to the availability or limits of commercial components, thus creating more degrees of freedom for design.

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