Compact System-on-Package (SOP) Architectures for low cost RF Front-end modules

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Abstract **- This paper presents the development of RF System-on-Package (SOP) architectures for compact and low cost wireless radio front-end systems. We present multi-layer Ceramic-based module development such as a 2.4 GHz SiGe HBT power amplifier module with a harmonic suppression filter implemented in LTCC substrate and a via-fed stacked cavity-backed patch antenna designed to fully cover the required band (5.725-5.825 GHz). Multi-layer organic packaging development for SOP is reported. A C-band up-converter MMIC integrated with a square patch resonator band pass filter and an Intelligent Network Communicator (INC) RF block are presented as example of the high performances of multi-layer organic package.**

I. INTRODUCTION

The current drawbacks of most commercially available microwave, millimeter wave, and high-speed optoelectronics transceiver front-ends include the relatively large size and heavy weight primarily caused by discrete components and separately located modules. Multi-layer ceramic and organic-based SOP implementation is capable of overcoming this limitation by integrating components that would have otherwise been required in discrete form, and MMICs in a single package, hence the term System-on-Package (SOP). On-package components not only miniaturize the module, but also eliminate or minimize the need for discrete components and thereby reduce the assembly time and cost as well. In addition, less discrete components improves reliability because of the reduced solder joint failures. In this paper, we present highly miniaturized LTCC and fully-organic-based radio front-end packaging development for compact low cost wireless front end systems.

In particular, we present a 2.4 GHz SiGe HBT power amplifier module with a harmonic suppression filter implemented in LTCC substrate [1]. Also, a via-fed stacked cavity-backed patch antenna has been designed (based on a 10 layers LTCC process) for IEEE 802.11a band [2]. The input impedance characteristic of the stacked-patch antenna and 10-dB return-loss bandwidth of the antenna is about 4%, meet the specification of the required band (5.725-5.825 GHz).

Finally, the multi-layer organic packaging development is reported such as a fully integrated multilayer organic (MLO)-based transmitter module that incorporates a single MMIC for WLAN applications [3] as well as an Intelligent Network Communicator (INC) [4], a Universal Information System that integrates digital, optical, analog and RF functions.

II. MULTI-LAYER CERAMIC BASED MODULE DEVELOPMENT.

A. 2.4 GHz SiGe HBT power amplifier module development.

The power amplifier is designed in IBM's commercial SiGe HBT process. A high breakdown device available in the process with a unit cell area of 20 um^2 is used in this design. The schematic of the designed power amplifier is shown in Fig. 1. It consists of three stages: two driver stages and a power stage; interstage, input and output match networks, and bias circuits for the three stages. The power amplifier is packaged in an 8-pin SOIC package. Package parasitics, lead and bond wire inductances are included in the design of the power amplifier. Interstage matching is compact and is achieved using only on-chip capacitors, bond wire and package lead inductances that also serve as RF chokes for the first two stages. Variations in these inductances from the estimated values due to variation in bond wire length can be compensated by using small lengths of external microstrip lines. The output match network and harmonic filter are off-chip and implemented in LTCC. Emitter ballasting is used to prevent thermal runaway.

The harmonic suppression filter and the output matching network are designed in Kyocera's 10 metal layers LTCC process. The filter consists of a transmission line in parallel with a capacitor C, and is designed to give deep suppression of the second and third harmonics. A $\lambda/4$ length RF-shorted stub is used to achieve a short at the second harmonic. The output matching network, tuned in conjunction with the harmonic suppression filter presents nearly a short at the second harmonic and nearly an open at the third harmonic. The harmonic suppression performance of the filter is shown in Fig. 2. As can be seen, the suppression of the second and third harmonics is better than 45 dB. The filter exhibits a loss of about 1dB at the fundamental frequency (2.4 GHz).The output power and efficiency of the power amplifier with the LTCC harmonic suppression filter is shown in Fig. 3. The power amplifier achieves an output power of 27 dBm at 0 dBm input with a PAE of 45% at 2.4GHz and Vcc=3.3 V. At 5 dBm input, the output power is 27.5 dBm with a PAE of 47%. The linear gain of the power amplifier is 35dB. The second and third harmonics are –44 dBc and –49 dBc respectively at 0 dBm input. The power amplifier thus exhibits high efficiency with more than 0.5W output power. This represents the first reported high power, high efficiency power amplifier in SiGe HBT in the 2.4 GHz band with performance comparable to that seen with GaAs MESFET/HBT.

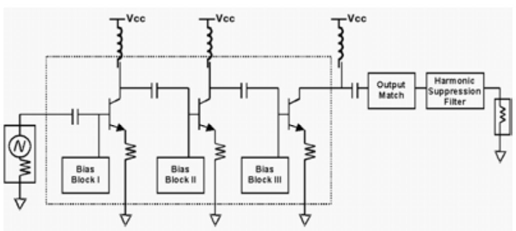

Fig. 1. Schematic of the SiGe HBT power amplifier

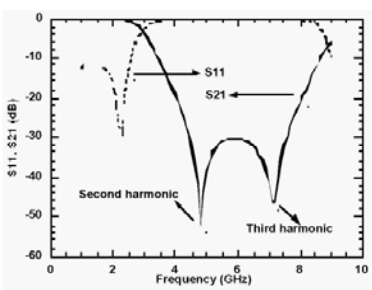

Fig. 2. Performance of the harmonic suppression filter

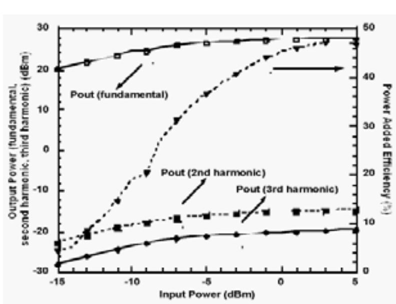

Fig. 3. Performance of the power amplifier module.

B. LTCC Antenna development.

A via-fed stacked cavity-backed patch antenna has been designed (based on a 10 layers LTCC process) for IEEE 802.11a 5.8 GHz band as shown in Figure 4. The heights of the lower and upper patches (400 mils × 400 mils) are respectively 8 mils (2 LTCC layers) and 32 mils. The input impedance characteristic of the stacked-patch antenna is shown in Figure 5. The 10-dB return-loss bandwidth of the antenna is about 4%, fully covering the required band (5.725-5.825 GHz). The radiation pattern at 5.8 GHz is plotted in Figure 6. This antenna has a desirable gain (near 6 dBi) and very low cross-polarization (less than –35 dBi).

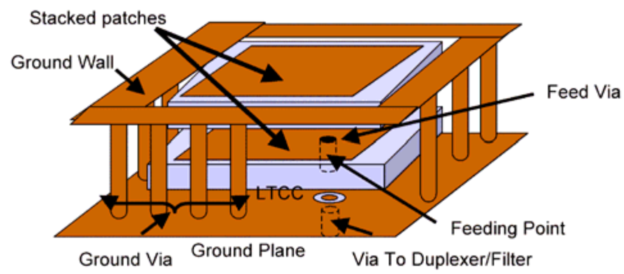

Fig. 4. Double patch cavity backed antenna for 5.725-5.825 GHz applications.

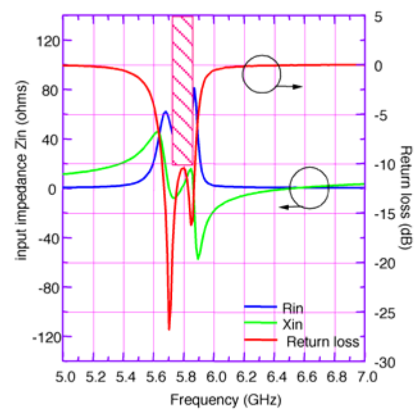

Fig. 5. Input impedance characteristic of the stacked patch antenna.

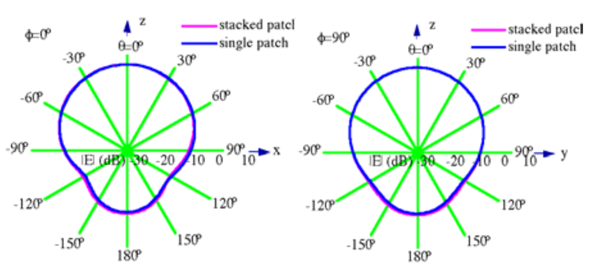

Fig. 6. Radiation pattern of the stacked patch antenna.

III. MULTI-LAYER ORGANIC BASED PACKAGE

A multi-layer packaging process using an organic material developed by Georgia Institute of Technology's Packaging Research Center offers the potential as the next generation technology of choice for SOP for RF-wireless, high speed digital and RF-optical applications. Indeed, 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 toward complete System on Package solutions (SOP). The current SOP configuration incorporates low cost materials and processes consisting of a core substrate (FR-4 for example) laminated with two thin organic layers. The thickness of the core substrate is 40 mils while the thickness of the laminate layers are 2.46 mils each.

A. Multi-Layer Organic transmitter module .

We developed the first reported fully integrated multi-layer organic (MLO)-based transmitter module incorporating a single MMIC for WLAN applications. We present the design and measurement of a C-band upconverter MMIC with excellent LO and image rejection as well as wideband operation fabricated in a commercial GaAs MESFET process. This development of a complete module also includes a miniaturized integrated square patch resonator band pass filter (BPF) with inset feed lines fabricated in MLO packaging technology (Fig.6.). The upconverter MMIC consists of a double balanced diode ring mixer (DBM), a wide tuning range (20%) voltage controlled oscillator (VCO), an LO buffer amplifier, an IF amplifier, and a RF amplifier. The upconverter MMIC integrated with a VCO exhibits a measured up-conversion gain of 14 dB and an IIP3 of 15 dBm as well as LO-to-RF rejection of 45dB and image rejection of 11dBc without any band pass filtering. These isolation performances are comparable to, or better than, the best reported results of balanced upconverter implemented in GaAs-based technologies. In addition, a second harmonic suppression of more than 22 dB is obtained. The IF amplifier and RF amplifier were designed to compensate for the conversion loss of the mixer and to provide a better input/output matching of the DBM as shown in Fig. 7 and Fig. 8. An integrated square patch resonator band pass filter (BPF) with inset feed lines was developed in MLO technology and incorporated with the upconverter MMIC to reject the spurious signals generated by the mixer. This realizes a compact and highly integrated transmitter module suitable for the low cost network interface card (NIC), IEEE 802.11a WLAN applications in 5-6 GHz frequency band. This is the first C-band module built on fully organic and to the best of our knowledge this is the highest frequency fully organic system-on-package (SOP) technology ever used to build a functional transmitter.

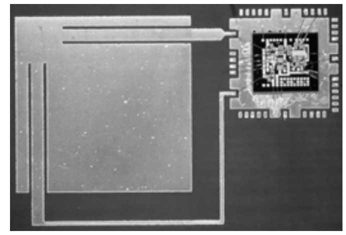

Fig. 6. Photograph of the implemented up-converter MMIC and the MLO-based band-pass filter for 5.8 GHz.

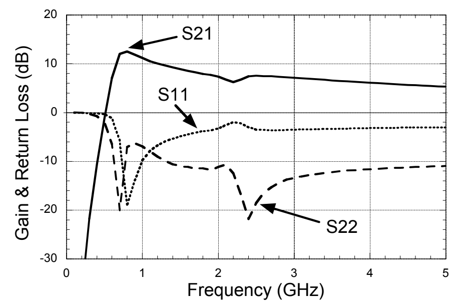

Fig. 7.Measured IF amplifier performances

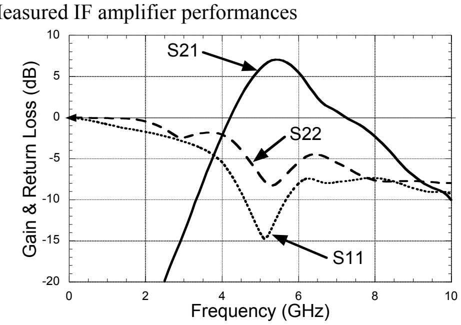

Fig. 8.Measured RF amplifier performances

B. Intelligent Network Communicator (INC).

Short distance hybrid digital/RF fiber optic link system (HDROS) is promising because it transmits baseband Ethernet signal and RF signal for GSM/PCS//IMT-2000/WLAN data traffic simultaneously via pre-installed multi-mode fibers. For the implementation of the HDROS, a device, which can combine the digital baseband signal and RF signal with reliable insertion loss and isolation in both band is essential. We developed, in the Multi-Layer Organic (MLO) process, a novel combiner that was optimized for the HDROS and where a 7Gb/s digital baseband signal is simultaneously transmitted with IEEE802.11b WLAN signals up-converted to around 14GHz. Fig 9 shows the basic block of the HDROS.

To overcome the weak coupling at base band and the bandwidth limitation of conventional combiner, we modified the conventional coupled line coupler as vertical coupling structure as shown in Fig 10. The output port of the coupled line coupler is used as the input port for the RF signal and the isolation port is shorted to the ground. Also we designed 9th order Bessel LPF at the input port for the base band, which performs as band stop filter for the 14GHz RF signal and reflects the RF signal at the output of the LPF. We optimized the 14GHz RF signal in-phase to obtain a constructive effect at the output port of the combiner by adjusting the embedded microstrip line which interconnects the LPF with vertical coupling structure. The design was finalized with the 3D method of momentum electromagnetic simulation software.

We used the HP8510 Vector Network Analyzer (VNA) to measure the frequency characteristic of the combiner. The insertion loss of the RF signal at the output port of the combiner was measured as 1.9dB. The isolation between port 1 and port 2 of the combiner was greater than 10dB in base band and 38dB at 14GHz. These results satisfy the requirement for the proposed HDROS. 3dB bandwidth of 7GHz is achieved between port 1 and port 3. Fig. 11 shows the measured frequency spectrum at the output of the combiner when 7Gb/s PRBS with 14GHz sinusoidal wave are sent. Fig. 11 also shows the measured eye opening of the 7Gb/s PRBS at the output port.

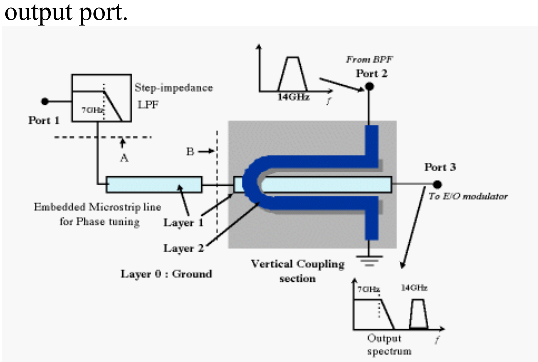

Fig. 9 Schematic configuration of INC.

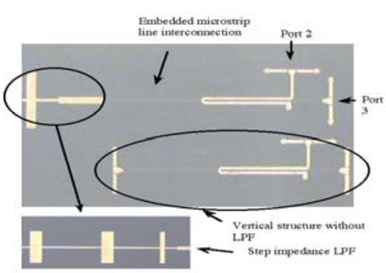

Fig. 10 Picture of fabricated combiner in MLO process

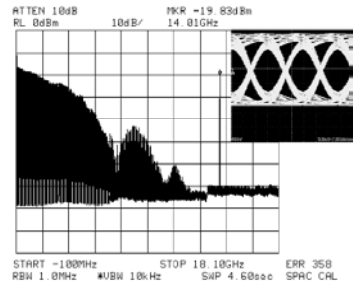

Fig. 11 Frequency spectrum at the output port of the combiner and eye diagram

VI. CONCLUSION

We have presented a 2.4 GHz SiGe HBT power amplifier module with a harmonic suppression filter and a via-fed stacked cavity-backed patch antenna has been designed and implemented in multilayer LTCC substrate. Multi-layer organic packaging developed for SOP has also been reported. A C-band up-converter MMIC integrated with a square patch resonator band pass filter, and an Intelligent Network Communicator (INC) RF block have been presented as examples of the high performances of multi-layer organic package.

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