

Highly Linear 4.9-5.9 GHz WLAN Front-End Module Based on SiGe BiCMOS and SOI

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Abstract — A high linearity 4.9-5.9 GHz T/R FEM is presented. The FEM consists of a SiGe BiCMOS PA and a single-pole double-throw SOI switched LNA in a 3 x 3 x 0.6 mm QFN package. The Tx chain has > 31 dB gain and meets 3% EVM up to 22 dBm with harmonic and out-of-band emissions compliant to regulatory limits. The receive chain features 2 dB NF and 14 dB gain with -3 dBm IP1dB for LNA mode and 4.5 dB attenuation in bypass mode with 10 dBm IP1dB. All these features simplify the front-end circuit designs of complex WLAN/MIMO radios.

Index Terms — WLAN power amplifier, dual-band PA, dual-band front-end module.

I. INTRODUCTION

Recently, applications of Wireless LAN (WLAN) radios have extended beyond traditional computer networking to many other electronic appliances, such as cellular phones, PDA, electronic gaming devices, security and monitoring systems, and multi-media systems [1-2]. A natural evolution of this technology is the use of multiple-input, multiple-output (MIMO) technique to increase the data rate from the 54 Mbps to a minimum of 108 Mbps. Currently, most WiFi and MIMO radios still operate at 2.4 GHz with only 3 channels for 54Mbps operation. For MIMO applications, the channel bonding technique is applied to increase the operational bandwidth and data throughput. Due to the bandwidth congestion in the 2.4 GHz band, dual-band (2.4 and 5 GHz) WLAN and MIMO are increasingly adopted in new WLAN radio designs. Moreover, a commonly used topology for a dual-band WLAN front-end (FE) circuit is seen in Fig. 1, which consists two Tx and Rx paths where the output ports Ant0 and Ant1 can be connected to individual single band antennas.

When using a dual band antenna, the ports Ant0 and Ant1 can be combined with a diplexer or a dual-band single-pole, double throw (SPDT) to increase band selectivity of each band prior to connection to the dual-band antenna. The Dual-band MIMO FE design can be realized by the repetition of the topology shown in Fig. 1. To simplify the radio board design, the FE circuit can be realized with a 3 building blocks as shown in Fig. 1. In addition, the embedded WLAN radios in portable electronic devices may require more compact and integrated designs than a WLAN radio used in computer networking applications. In fact, a front-end module (FEM) is often the preferred design implementation. Specifically in

cases where MIMO is used in portable electronics, FEM's can simplify the design and layout and ultimately reduce the number of components in a multi-channel MIMO configuration.

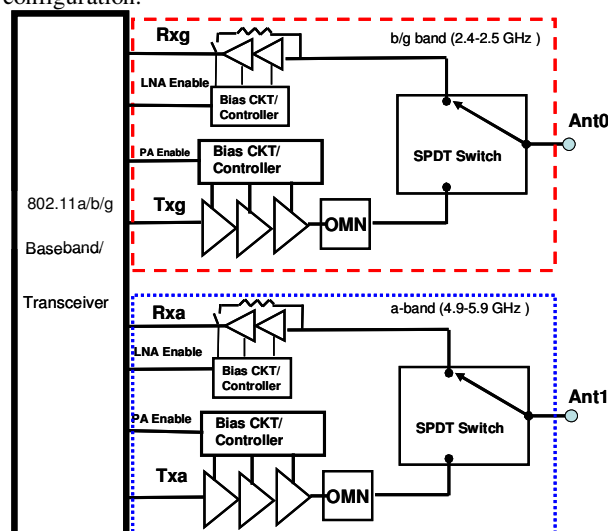


Fig. 1. Block diagram of a dual-band WLAN radio.

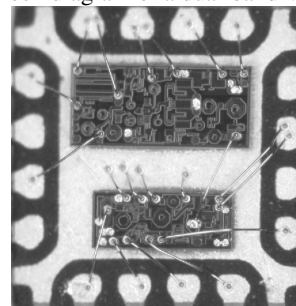


Fig.2. The high linearity 4.9-5.9 GHz FEM in a 3 x 3 mm QFN package.

Another consideration for the system is source power. For PC networking application, there are often two different power supply voltages available in the system, 3.3 V and 5.0 V. For embedded application, the power supply can be sourced from the transceiver chip-sets or the battery. Moreover, for battery operation the voltage can vary from 3.0 V to 4.8 V. In this paper, a highly integrated WLAN "a-band" FEM is presented. As shown in Fig. 2, the FEM design consists of two die: a power amplifier (based on SiGe

BiCMOS) and a switched low noise amplifier (based on Silicon-on-Insulator ,SOI). The PA integrates input and output matching network, out-of-band spur rejection filter, harmonic rejection filter, voltage regulator and bias circuits, temperature-compensated power detector, and CMOS compatible enable circuitry. In addition, the PA is controlled by an on-chip temperature and voltage compensated bias control. The PA operates from 4.9 to 5.9 GHz and is able to deliver 32 dB of gain. Measurements between 3.0 V to 5.5V supply show excellent performance and ruggedness up to 10:1 VSWR. Concurrently, with a 54 Mbps signal, the FEM Tx path can deliver > 22 dBm using a 5V supply with current consumption < 300 mA and > 19 dBm using a 3.3V supply with total current consumption <220 mA to meet the linearity requirement of Error Vector Magnitude (EVM) < 3%. This FEM also features a SPDT switched LNA. In the SPDT switch, one of the throws is connected to the PA output forming the Tx path. The Rx path is formed by the other throw and integrated 4.9-5.9 GHz LNA with an integrated bypass attenuator. The transmit path features low insertion loss (IL) of 0.5 dB between 2 to 6 GHz with >20 dB return loss combined with 30 dB isolation and less than 0.1 dB input compression up to 34 dBm. All these features enable us to simplify the dual-band WLAN radio front-end design.

II. DESIGN

The FEM design will be presented in 2 subsections covering first, the PA and then the Switched LNA.

A. PA

As shown in Fig. 1, the PA is a 3-stage amplifier. A major consideration for using a 3 stage 'a' band PA is that many transmitter radios can not deliver sufficient linear input power driving a requirement for relatively high gain in the amplifier. High gain 'a' band PA allows the transmitter to always operate at the linear output levels. In this design, both PA's are controlled by an integrated block providing reference current for current mirrors and on/off control.

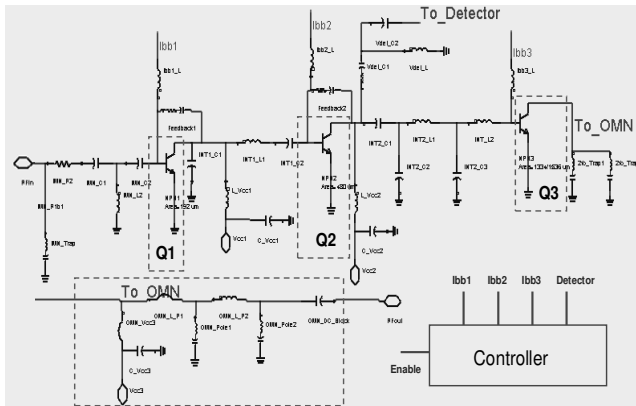


Fig. 3. Conceptual schematic of the 'a-band' PA design.

During WLAN communications, the PA is frequently enabled and disabled to reduce current consumption which introduces the problem of dynamic variation in the amplifier's key figures of merit including linearity and gain. PAs based on GaAs semiconductor technology often suffer in dynamic mode operation due to the poor thermal characteristics of its substrate. In a WLAN radio, a PA is enabled and disabled by a pulsing trigger. The amplitude distortion of the preamble in the first a few micro seconds of the amplified data stream will result in degraded modulation quality. In fact, GaAs-based designs often need external speed-up circuits to improve dynamic mode linearity [3]. The PA design herein employs patent pending methods and circuit techniques to mitigate the thermal difference between PA stages, which results in no degradation in both linearity and gain under dynamic mode operations.

To illustrate the PA topology, the 3-stage PA is shown in Fig. 3. Perhaps the most challenging part of SiGe RF amplifier design is the on-chip matching. The use of measurement based transistor models and large-scale electromagnetic based models can enhance the chances of having first pass design success. The out-of-band rejection filtering is well integrated in the input matching network and 1st and 2nd stage inter-stage matching networks. A typical design consideration is to use a 2nd harmonic short as shown in Fig. 3 to not only enhance the linearity but also effectively force the 2nd harmonic to ground. It may be appreciated that the 3rd harmonic emissions are typically much lower in magnitude. Therefore, the L-C networks of a dual-pole matching network will effectively reduce the 3rd harmonic emission.

B. Switched LNA

As shown in Fig. 1, the switched LNA consists of a SPDT switch and a LNA with a bypass mode attenuator. To support high linearity and low loss switch, the schematic for a switch path of the SPDT switch is shown in Fig. 4. In Fig. 4, two multi-gate SOI switch FET's are used to construct both series and shunt paths in a switch path to minimize insertion loss and maximize high isolation at high frequency. The linearity of a series-shunt switch path is usually constrained by that of the shunt path FET's [4]. Consequently, the maximum transmit can be calculated by equation (1).

$$P_{\max} (dBm) = 10 \log_{10} \left(\frac{[n(V_{gs} + V_{th}) \times 2]^2}{0.001 \times 2 \times Z_o} \right) \quad (1)$$

where Z_o is the characteristic impedance of the measurement system, V_{gs} is the control voltage difference between the gate and source (or drain), V_{th} is the threshold voltage of the switch FET, and n is the number of cascaded switch FET. When the parasitic capacitance of multiple stacked FET's in a shunt path is well designed and balanced, the RF voltage swing will be evenly distributed across each drain-source junction in the stacked FET's [4]. Therefore, the maximum transmission power can be predicted using equation (1).

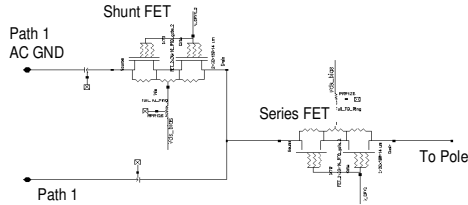


Fig. 4. Schematics of a series-shunt switch path in the SPDT switch design.

As shown in Fig. 1, the Rx path consists of a switch path and a LNA. A conceptual schematic of the LNA is illustrated in Fig. 5. To achieve sufficient gain between 4.9 to 5.9 GHz, the cascode topology is used. To reduce the impact of out-of-band interference, two out-of-band traps were implemented to ensure sufficient out-of-band rejections as shown in Fig. 5. In addition, to avoid saturation of the LNA, a 5-dB bypass attenuator is implemented. Not surprisingly, the bypass attenuator has the opposite on/off logic to that of LNA.

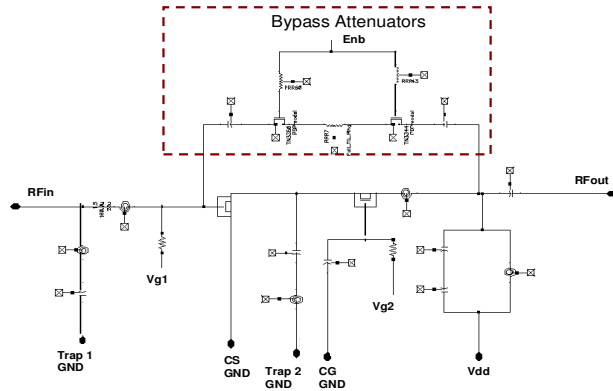


Fig. 5. Conceptual schematic of the a-band LNA design.

III. PERFORMANCE

Measurements of the FEM are presented in this section. Fig. 6 shows the S-parameters of transmit and receive paths. The in-band gain variation is within 2 dB for the transmit path and within 1 dB for the receive path with 30 dB and 13 dB of gain, respectively. Linearity of the transmit path is validated using an OFDM signal at 54 Mbps and under dynamic mode of pulsing PA enable instead of providing a constant voltage at the PA enable. As shown in Fig. 7 and Fig. 8, with 3.3V supply, the transmit chain delivers 18.5 dBm at 3% dynamic mode EVM (DEVM) with 210 mA current consumption. With a 5V supply, the transmit path can deliver 22 dBm at 3% DEVM with 300 mA current consumption.

The harmonic emissions were also validated and are shown in Fig. 8. Harmonic emission levels of all channels under test are below -45 dBm/MHz up to the maximum linear output powers. Therefore, the PA can be used in a FEM design without using external harmonic filters. In addition, based on the FCC requirement of -41.2 dBm/MHz, the FEM provides sufficient

margin for the radio designs using a high gain antenna. Spurious emissions under load mismatch were also verified. The PA stability was confirmed to a VSWR 10:1 (load mismatch) while the input was overdriven up to +10dBm and 5.5 V without any spurious emissions and ruggedness weakness.

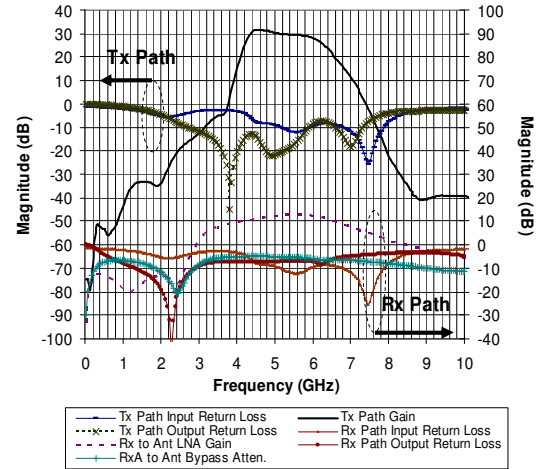


Fig. 6. Measured S-parameters of the WLAN a-band F

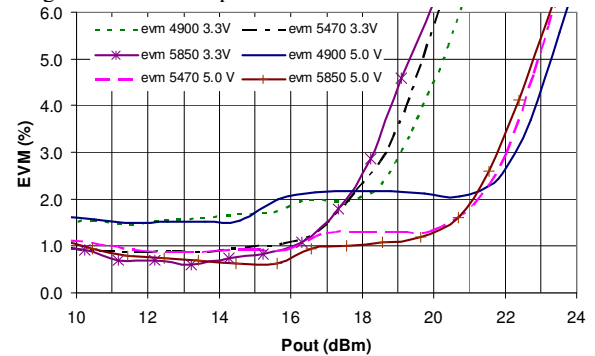


Fig. 7. Measured dynamic mode EVM at 54 Mbps for Tx path of the a-band FEM.

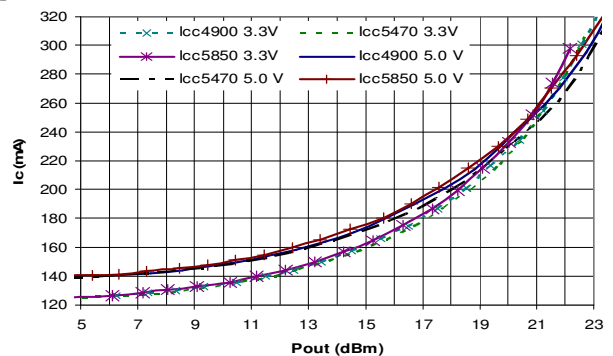


Fig. 8. Current consumptions for the FEM design at 5.0V and 3.3V supply voltage.

As shown in Fig. 10, the linearity for the SPDT switch Tx path was validated with a high power PA operating at 5.5 GHz. The 0.1 dB compression point was found to be above 34.0

dBm input power with harmonic emission < -50 dBm up to 25 dBm input power.

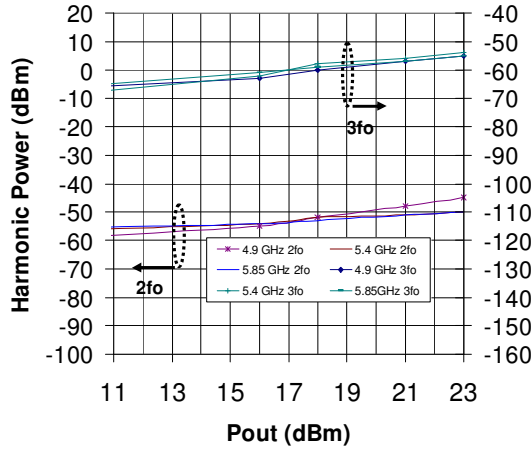


Fig. 9. Harmonic emission for the FEM design at 5V.

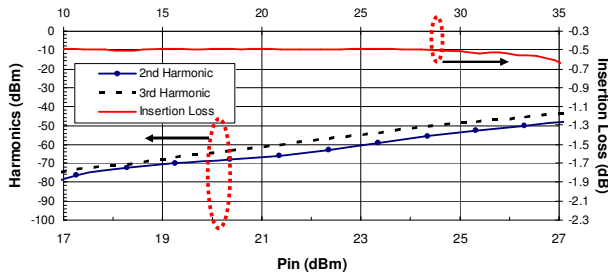


Fig. 10. Transmit characteristic of the SP4T switch-LNA at 2.5 GHz.

As shown in Figs. 10 and 11, the Rx paths has 14 dB gain with NF < 2.0 dB at the current consumption of 15 mA. Due to the on-chip, out-of-band rejection filter, the band selectivity between b/g band and 'a' band is measured to be > 25 dB. This attractive feature provides the immunity from a b/g band jamming signal level up to 10 dBm without any degradations of in-band NF. The input 1 dB compression is measured at -4 dBm for the LNA mode while the bypass attenuator was measured and shown in Fig 10. The path attenuation is 4.5 dB with the current consumption of 15 uA. The input 1 dB compression of the bypass attenuator is 10 dBm whereas the LNA was measured to be approximately -5 dBm.

These advantages encompass both the traditional RF figures of merit (such as dynamic linearity) and other control features that are attractive to the system integrator in a variety of WLAN applications.

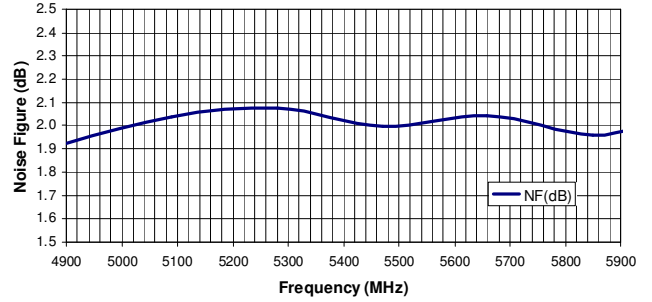


Fig. 11. Measured NF of the Rx paths of the a-band FEM.

IV. CONCLUSIONS

In this paper, a high linearity 4.9-5.9 GHz WLAN FEM is described and realized in a 3 x 3 x 0.6 mm QFN package. The PA is based on SiGe BiCMOS process and the switch LNA is based on SOI process. Notwithstanding the technology trade-offs inherent to modern design of RF components, the technology selection enables us to incorporate a variety of control features into the block functionality whilst preserving the RF performance required by the application. Consequently, the FEM features advanced integration complexity and functionality, which provides a turn-key solution for WLAN FE designs. With a 3.3 V supply, the transmit path at 3.3 V achieves 30 dB gain with 19.0 dBm output power at 3% dynamic mode EVM, while consuming 220 mA of current. With a 5 V supply, the FEM achieves >31 dB gain with 3% dynamic mode EVM power of 22 dBm with 320 mA of current. The receive path has an integrated 14 dB LNA with 2.0 dB NF and a 5-dB bypass attenuator. This FEM greatly simplifies dual-band radio FE designs and enables the reduction of the radio board form factor and consequently results in simple constructions of complex dual-band MIMO radios for 802.11n applications.

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