

Highly Linear SOI Single-Pole, 4-Throw Switch with an Integrated Dual-band LNA and Bypass Attenuators

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Abstract — An innovative Silicon-On-Insulator (SOI) SP4T T/R switch is presented. The SP4T switch consists of 2 receive paths with an integrated dual-band LNA and bypass attenuators along with 2 high linearity matched transmit paths. Tx paths feature 0.1 dB compression to 34 dBm input power and 0.5-0.8 dB insertion loss from 1 to 6 GHz with > 20 dB return loss and > 25 dB isolation. Receive paths feature 16 dB gain with 2.3 dB NF for 2.4-2.5 GHz and 14 dB gain with 2.4-2.6 dB NF for 4.9-5.9 GHz. The band selectivity exceeds 40 dB. Cascading with a dual-band WLAN PA, a complex dual-band WLAN/MIMO front-end module (FEM) can be easily constructed with low assembly complexity and post PA losses resulting in dual-band transmit linearity >18 dBm with EVM < 3% and < -50 dBm/MHz harmonic emissions within a 4 x 5 mm QFN package.

Index Terms — Dual-Band WLAN/MIMO front-end IC's, switch designs, LNA designs.

I. INTRODUCTION

Wireless local area network (WLAN) applications have been one of fastest growing areas of data communications. WLAN radios were originally designed for computer networking, but have subsequently been widely implemented in consumer products such as cell phones, security monitoring systems, personal data assistants, gaming systems, multi-media personal entertainment devices, and multimedia (video, data, voice) distribution systems [1]. Furthermore, the demand for more bandwidth and higher throughput rates results in the emergence of multiple-input, multiple-output (MIMO) techniques to increase the data rate from the original 54Mbps to a minimum of 108 Mbps.

Most WiFi and MIMO radios operate at the 2.4-2.5 GHz –'b/g' band, with 3 channels for 54Mbps operations. For b/g band MIMO applications, channel bonding techniques result in only 1 or 2 available channels. Therefore, the demand for more bandwidth is inexorable. One may surmise that dual-band WLAN and MIMO radios will be soon adopted to resolve the bandwidth congestion within b/g band WLAN applications. In this context, to achieve small form factors for compact portable computers and electronics, a front-end module (FEM) is the preferred design implementation, especially when MIMO architecture is adopted in portable electronics or other miniature network cards. One advantage of FEM's is that they simplify both circuit and printed circuit board layout for small form-factored WLAN radio solutions.

In this paper, a novel dual-band, single-pole, 4-throw (SP4T) T/R switch with an integrated dual-band LNA and bypass attenuators is presented as shown in Fig. 1. The design is based on SOI technology, which combines both advantages of CMOS for analogue circuitry and low substrate loss RF FET's for T/R switch and LNA. The functional block diagram of the switch-LNA is shown in Fig. 2. The SP4T switch-LNA consists of 4 RF switch paths for both dual-band transmit and receive paths. Each Rx path has an integrated LNA and a bypass attenuator path.

In most WLAN radio designs, T/R switch is the last component prior to the antennas. Therefore, high linearity for the transmit switch path is a must to minimize nonlinear distortions. In this design, each transmit path features low insertion loss (IL) of 0.5-0.8 dB between 1 to 6 GHz with >20 dB return loss combined with 25 dB isolation and less than 0.1 dB input compression up to 34 dBm.

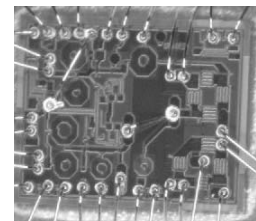


Fig. 1. Die photo for the SP4T T/R switch with dual-band LNA and bypass attenuators. The die size is 1.2x1.6 mm².

In contrast to a conventional FEM architecture shown in Fig. 3 [2], this FEM is based on the proposed switch-LNA IC design and a self-sufficient, dual-band PA presented in [3] can be realized as shown in Fig. 2. The FEM in Fig. 2 has low assembly complexity and low pre-amplifier and post-amplifier losses due to the elimination Tx and Rx diplexers. This leads to improved RF performance including better efficiency, more available linear power, higher gain, and lower noise figure. The proposed FEM can be realized in a 4 x 5 x 0.9mm³ QFN package. Both b/g and a-band transmit paths can provide >18 dBm linear power with EVM < 3% at 54 Mbps and worst-case harmonic emissions less than -50 dBm/MHz up to 20 dBm output power. The Rx path performance of the FEM is dominated by the SP4T switch-LNA design, which has 16 dB gain with 2.3 dB NF between 2.4-2.5 GHz and 14 dB gain with 2.4-2.6 dB NF for 4.9-5.9 GHz band. The band selectivity

exceeds 40 dB. In addition, when a WLAN radio is in proximity to a WLAN access points, the Rx path could be saturated by the associated emissions. In this circumstance, the bypass mode attenuators in the switch-LNA can be activated to provide an 18-dB path attenuation to reduce the impact on the receiver. These unique features ensure easy construction of dual-band WLAN and MIMO radios.

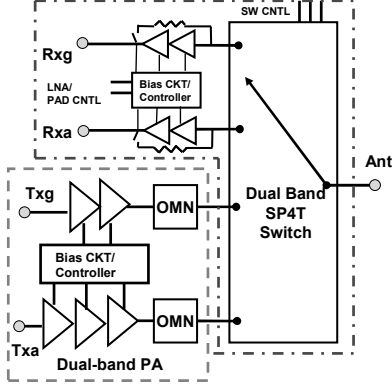


Fig. 2. Architecture for a dual-band WLAN FEM based on the proposed SP4T switch-LNA and a self-sufficient dual-band PA for a/b/g/n radio applications.

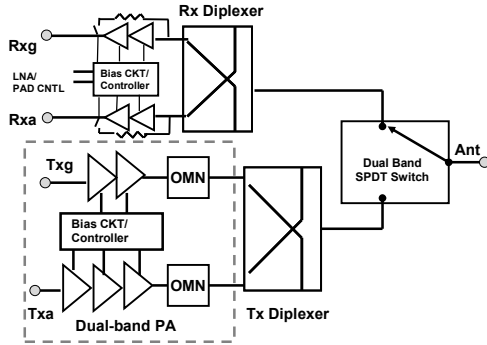


Fig. 3. Traditional architecture used in dual-band FEM in WLAN a/b/g/n radios.

II. DESIGN

A. SP4T Switch-LNA Architecture

As shown in Fig. 2, the proposed SP4T switch-LNA consists of 2 major functional blocks, a dual-band LNA with bypass mode attenuators and a SP4T T/R switch. Using SOI technology, analogue circuitry such as temperature/voltage compensated bias circuits, enable/disable controls, bypass attenuator controllers, and switch logic decoder can be easily integrated onto the same die. In contrast to the traditional FEM architecture shown in Fig. 3, both Tx and Rx diplexers are eliminated. Therefore, the on-chip low and high band LNA's are directly matched to the 2 Rx paths of the SP4T switch. Similarly, the external dual-band PA will be matched to 2 Tx path of the SP4T switch as shown in Fig. 2. Therefore,

Tx switch paths need to support low insertion and mismatch losses and high linearity. In addition, the Tx switch paths feature fast on/off switching time (< 100 ns) to allow the PA enable/disable controls to drive Tx switch controls without degrading the linearity under pulse mode. This feature also reduces the number of external control lines to the FEM.

B. SP4T Switch

The schematic for a switch path of the SP4T switch is shown in Fig. 4. Since the SP4T switch design has 4 symmetrical switch paths, this description of the switch design can focus on a single switch path. 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 power can be calculated by equation (1).

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

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 easily predicted by equation (1).

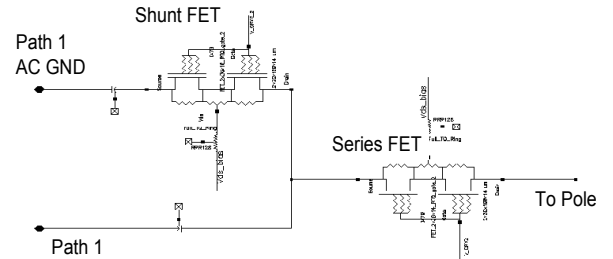


Fig. 4. Schematics of a series-shunt switch path in the SP4T switch.

C. Dual-band LNA with Bypass Attenuators

Unlike the traditional FEM implementation, the proposed dual-band LNA is directly matched to two of the switch paths. Using a diplexer prior to a dual-band LNA will not only degrade the LNA noise figure but also decrease the gain by the path loss. In addition, when a diplexer does not have sufficient out-of-band isolation, the tuning for one

LNA will always detunes the second LNA. The proposed SP4T switch features high isolation to each band, which enables each LNA to operate completely independent of each other.

As a single die implementation, both the low and high band LNA's are based on a similar topology. The 'a-band' LNA schematic 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, an 18-dB bypass attenuator is implemented as shown in Fig. 5. The bypass attenuator has the opposite on/off logic to that of LNA.

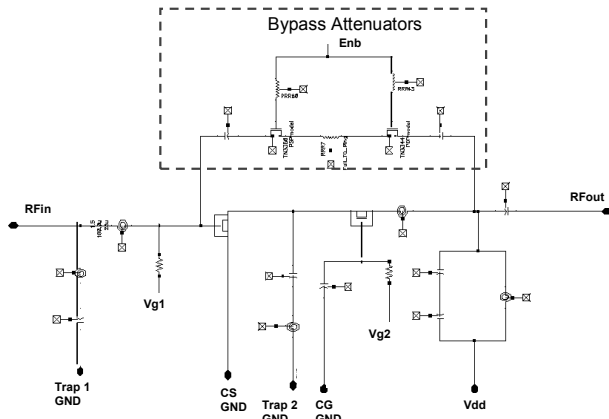


Fig. 5. The schematic for the integrated, low noise amplifier with bypass mode attenuator

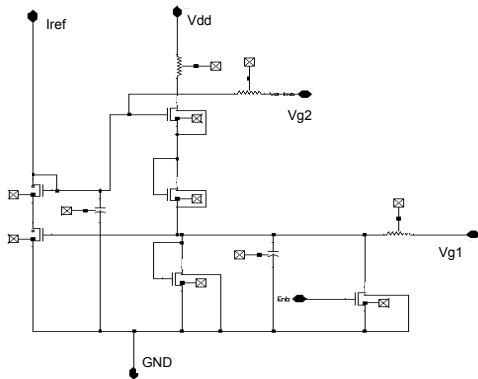


Fig. 6. The schematic for the bias circuit for the LNA.

The bias circuitry is also an important design consideration to ensure the gain response and noise figure of an LNA. The bias circuit for the cascode LNA is shown in Fig. 6. The reference FET devices are chosen to be matched to RF FET's to ensure the proper current scaling. Vg1 and Vg2 are providing the bias currents for both LNA FET's as shown in Figs. 5 and 6. In addition, when the SP4T switch is under transmit mode, the shunt FET at Vg1

will pull down the gate voltages of the cascode LNA to avoid having the LNA unintentionally turn on.

III. PERFORMANCE

Measured results for the design are presented in this section. The Tx path linearity of the SP4T switch-LNA was validated with a high power PA operating at 2.5 GHz. As shown in Fig. 7, the 0.1 dB compression point was found above 34.0 dBm input power with harmonic emission < -50 dBm up to 25 dBm input power.

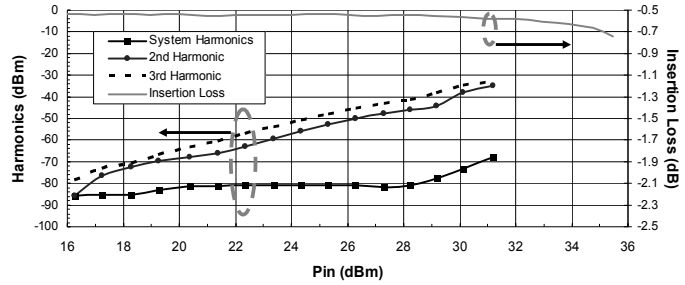


Fig. 7. Transmit characteristic of the SP4T switch-LNA at 2.5 GHz.

The s-parameters of the SP4T switch-LNA are shown in Fig. 8. The transmit switch paths have IL between 0.5-0.85 dB from 1 to 6 GHz. In addition, the return loss for each Tx path is typically >20 dB, providing a good impedance matching condition for the PA. As shown in Figs. 8 and 9, the Rx paths have 16 dB with NF < 2.3 dB between 2.4 to 2.5 GHz and 14 dB gain with NF < 2.6 dB between 4.9 and 5.9 GHz. The band selectivity is measured to be > 40 dB. The bypass attenuators were also measured and shown in Fig 8. The input 1 dB compression of the LNA was measured to be around -5 dBm With current consumption at 15 mA.

In addition to the characterization of the standalone SP4T switch-LNA, the switch-LNA design is also cascaded with a dual-band PA presented in [3] to demonstrate its performance in a FEM configuration as shown in Fig. 2. Since the SP4T switch-LNA is the last component in the FEM design, the Rx path performance remains the same as that previously reported. The s-parameters for the transmit paths of the FEM are shown in Fig. 10. Both Tx paths can provide ~28 dB gain with +/- 0.5 dB and +/- 1 dB flatness for b/g and a-band, respectively, along with 8-10 dB of input return loss. Transceiver spurious rejection at 1.6 GHz, 3.2 GHz, and 3.88 GHz are also addressed with the on-chip PA matching networks.

The modulation quality was tested with OFDM signal at 54 Mbps, having more than 10 dB peak to average ratio, the measured EVM of the FEM is shown in Fig. 11. The linear power is defined as the peak average power with EVM measurement at less than 3%. The power level

achieved was roughly 18 dBm in both bands. The EVM at mid power range is less than 2.0%. The quiescent currents for both band is 110 and 140 mA for b/g and a-band PA respectively. The current at peak linear power are approximately 180 and 220 mA with worst-case harmonic emissions below -50 dBm/MHz up to 20 dBm output power. These performance attributes can be partly attributed to the usage of the SOI technology platform for this design. Consequently, a high linearity dual-band FEM can be housed within a 4x5 mm compact package addressing the requirements of dual-band WiFi and MIMO applications.

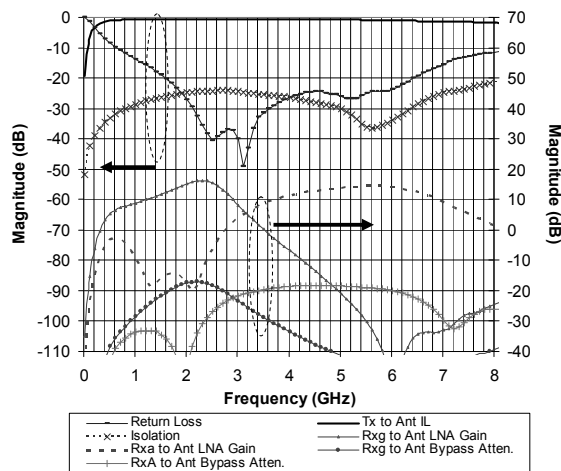


Fig. 8. s-parameters for the SP4T switch-LNA.

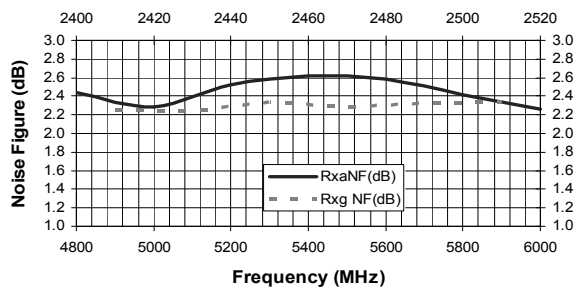


Fig. 9. Measured NF of the Rx paths in the SP4T switch-LNA.

VII. Conclusion

A novel SOI-based SP4T T/R switch with an integrated dual-band LNA and bypass attenuators is presented. The design consists of 2 receive and 2 transmit paths. Each Rx path has an integrated LNA and an 18-dB bypass attenuator. The Tx paths features 0.1 dB compression point above 34 dBm and 0.5-0.8 dB insertion loss between 1 to 6 GHz with > 20 dB return loss and > 25 dB isolation. Receive paths feature 16 dB gain with < 2.3 dB NF for b/g band path and 14 dB gain with 2.4-2.6 dB NF for 'a-band' path. Pairing the switch-LNA with a self-sufficient dual-band WLAN PA, an innovative 2-die dual-band FEM can be realized as shown in Fig. 2 in a 4 x 5 mm compact

package. Moreover, as a result of the low post PA losses, the dual-band transmit linearity at >18 dBm with EVM < 3% and < -50 dBm/MHz harmonic emissions were achieved. The proposed SP4T switch-LNA front-end IC greatly simplifies dual-band FEM designs and enables the reduction of the FEM form factor, which leads to simple constructions of complex dual-band MIMO radios for 802.11n applications.

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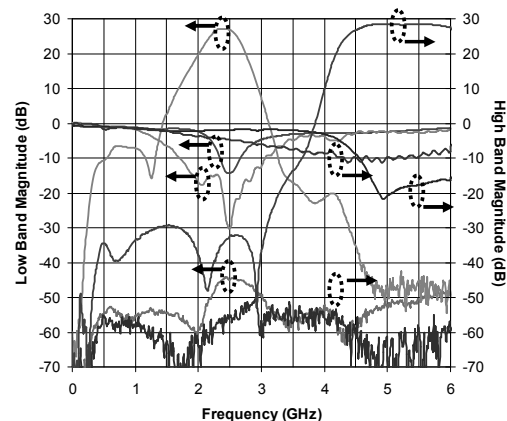


Fig. 10. Transmit characteristics for the proposed FEM.

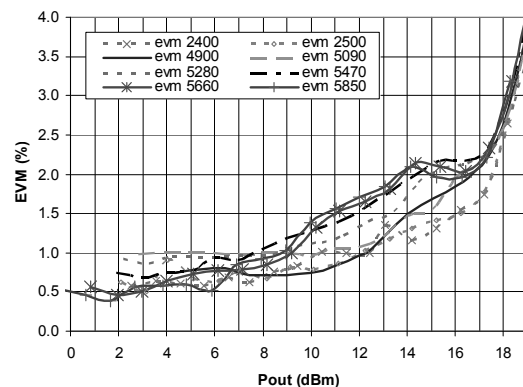


Fig. 11. Measured EVM at 54 Mbps for Tx to antenna path of the proposed 4 x 5 mm FEM.