

# Novel Silicon-on-Insulator SP5T Switch-LNA Front-end IC Enabling Concurrent Dual-band 256-QAM 802.11ac WLAN Radio Operations

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**Abstract** — An innovative SOI SP5T switch-LNA integrated circuit is presented. The switch-LNA consists of a diplexer that provides out-of-band rejection and enables dual-band concurrent operation, a dual-band LNA with bypass attenuators, and three high linearity transmit paths. Tx paths feature 0.1 dB compression at > 33 dBm input power, with > 35 dB Tx to Rx isolation, and 0.8 and 1.2 dB insertion loss for low and high bands respectively. Receive paths feature 12 dB gain with 2.5-2.8 dB NF. Cascading the design with a dual-band WLAN PA, a complex dual-band front-end module can be easily constructed in a 3 x 4 mm package, which demonstrates transmit and receive LNA linearity with EVM < 2% at >16 dBm and > -5 dBm output power respectively and compliant with the linearity requirements of the 802.11ac standard up to of 256-QAM 80 MHz operations.

**Index Terms** — Dual-Band WLAN/MIMO/802.11ac front-end ICs, switch designs, LNA designs, WLAN front-end module.

## I. INTRODUCTION

In the last decade, 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 now WLAN has been widely implemented in many other consumer electronics [1]. The demands of more bandwidth and higher throughput rate result in the developments and applications of multiple-input multiple-output (MIMO) techniques to increase the data rate from the original 54 Mbps of a single-input single-output (SISO) radio to a minimum of 108 Mbps. For further demands of wider bandwidths and higher data throughput, the emerging of 802.11ac standard can provide up to 780 Mbps per transmit /receive path. When 802.11ac radios operate in MIMO modes, the data rate can be up to 6 Gbps. The early generations of WiFi and MIMO radios operate at the 2.4-2.5 GHz b/g band. With the strong demands of bandwidths, the dual-band WLAN radios are widely developed in recent computers and electronic devices. In addition to the b/g band, the “a-band” radio operates at 4.9-5.9 GHz, which provides more frequency channels. For dual-band WLAN radios, concurrent operations are also widely adopted in new generations of radio designs, which allow the low and high band radios simultaneously operate and significantly increase the data throughput.

To design a dual-band WLAN SISO or MIMO radio of a small form factor for compact portable computers and

electronic devices, a front-end module (FEM) is the preferred design method. FEMs simplify both circuit and printed circuit board (PCB) designs. In this paper, an innovative, dual-band, single pole 5 throw (SP5T) switch-LNA is presented (see Figs. 1 and 2). The design is based on SOI technology, which combines both advantages of CMOS FETs for complex, digital circuitry and low substrate loss RF FETs for T/R switch and LNA FETs. The functional block diagram of the switch LNA is shown in Fig. 1. The design consists of an integrated diplexer, a SPDT switch, a SP3T switch, and a dual-band LNA with bypass attenuators. The diplexer combines a SPDT switch and a SP3T switch into a band-selective SP5T switch. Each receive path has an integrated LNA with a bypass attenuator.

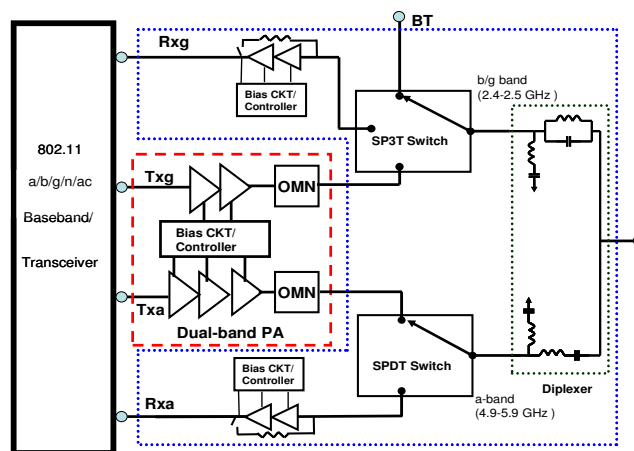


Fig.1. Functional block diagram of proposed SOI SP5T switch-LNA.

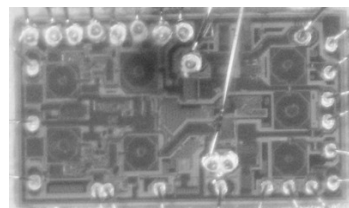


Fig. 2. Die photo of SP5T switched LNA design.

To support concurrent operations, a diplexer is required to combine the dual-band signals at the common port. In addition, the output diplexer provides not only out-of band rejection for both transmit and receive paths to minimize the desensitization of out-of-band interferers, but also

provides harmonic filtering for transmit paths. The three transmit paths are a-band, b/g band, and Bluetooth (BT). Because a T/R switch is often the last component prior to an antenna, the high linearity for the transmit switch path is a must to minimize the post PA nonlinear distortions. In this design, each transmit path features low insertion loss (IL) of 0.4 dB for g-and or BT paths, 0.8 dB for a-band path with >20 dB return loss, >30 dB T/R isolation, and high linearity of input 0.1 dB compression at > 33 dBm. The receive paths feature with > 12 dB gain with 2.5-2.6 dB NF. The LNA has -3dBm input 1 dB compression (IP1dB). The bypass path attenuators provide 4-24 dB variable attenuations up to 15 dBm input drive with high illumination conditions. The uniqueness of the design can enable a two-chip FEM (see Fig. 1) of low assembly complexity in a 3 x 4 mm package for dual-band 802.11 a/b/g/n/ac WLAN applications, which is compliant up to 256-QAM MCS9 80 MHz operations.

## II. DESIGN

### A. Band-selective SP5T Switch

[2] presented a unique SP4T switch-LNA design, which demonstrated low switch path losses and high level of integration. However, to support dual-band concurrent operations and include a BT path, the traditional SP5T switch is not a viable solution. An integrated diplexer ensures the co-existence of the dual-band signals as shown in Fig. 1. Sufficient isolations between low and high band signal is the key for dual-band concurrent operations.

High linearity switch design was illustrated in [2]. The critical design criteria are the choice of FET width and number of FET stacks. The maximum transmit power can be calculated by equation (1) [2],

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

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.

For higher data rate and wider bandwidth operation, the inter-modulation is the key design parameter [3]. To linearize the switch path, the voltage waveforms across each FET in a stack needs to be evenly distributed [2]. In addition, the harmonic terminations by diplexer will also reduce the inter-modulation levels. Careful choices of the bias voltage for a switch FET stack will enhance the linearity [2].

### B. Dual-band LNA with Bypass Attenuators

Both the low and high band LNAs are based on the same topology. To achieve sufficient gain from 4.9 to 5.9 GHz, the cascode topology is used. The integrated diplexer reduces the impacts of out-of-band interferences, so the LNA input matching will be much simplified. In addition, to avoid the high field illuminations saturate the LNA or the receiver, the bypass attenuator can support 4, 12, 24 dB switchable attenuations as shown in Fig. 3. The bypass attenuator provides the gain difference between LNA mode and bypass mode with a more than 20 dB dynamic range, which protects the receiver from being saturated under the high field illuminations.

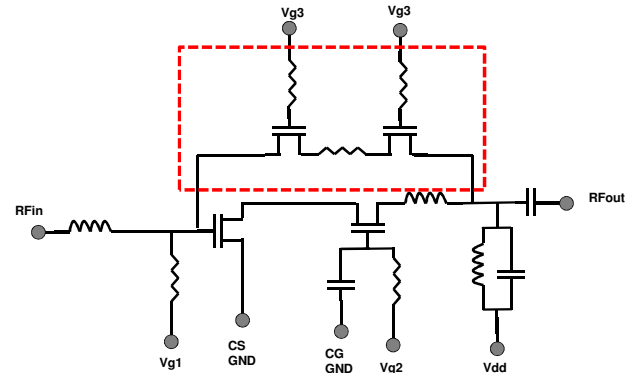


Fig.3. Schematic for the LNA with bypass attenuator.

## III. RESULTS

Measurement validation for the proposed design is presented in this section. As shown in Fig. 4, the transmit switch paths have the insertion loss of 0.8 dB for g-band as well as the BT path and 1.2 dB for a-band path. In Fig. 4, the harmonic rejection of g-band Tx path is more than 15 dB, which enhances harmonic rejection for a dual-band FEM. All three switch paths have >20 dB return loss, providing a good impedance matching condition for the PA. The Tx path linearity of the SP5T switch was validated at 5.66 GHz. As shown in Fig. 5, the 0.1 dB compression was found at >33 dBm input power and harmonic emission < -50 dBm up to 25 dBm input power. These features ensure the transmit path linearity for the entire range of operations.

As shown in Fig. 6, the Rx paths have two operation modes: the 12 dB gain LNA mode and the 12 dB bypass attenuation mode. The noise figures are 2.5-2.6 dB for low band and 2.6-3.0 dB for high band. The Rx LNA enhances the receiver sensitivity, and the bypass attenuator reduces the impairments caused by high field illumination. The input 1 dB compression of the LNA was measured around -4 dBm. The current consumption for the LNA is 10 mA.

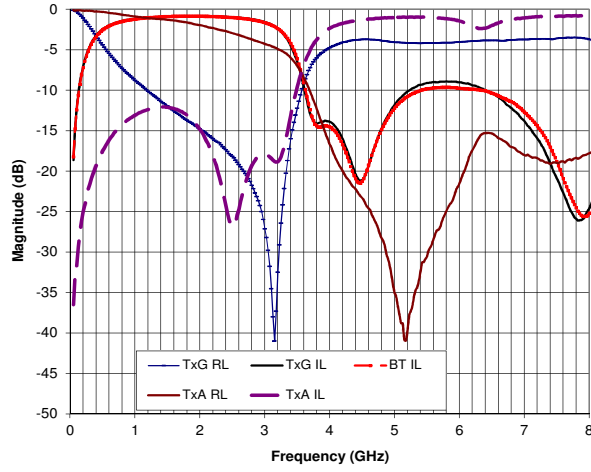


Fig. 4. Measured S-Parameters of Transmit and Bluetooth paths.

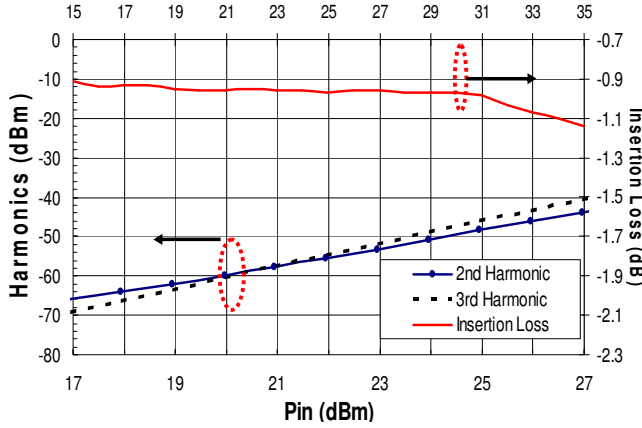


Fig. 5. Measured 0.1 dB compression and harmonic emission of a-band transmit path at 5.66 GHz.

To support concurrent operations, the a-band receive path needs to reject the low band signals. The blocker limit of a-band LNA was validated with a g-band test signal, and the results showed no desensitization up to  $> +5$  dBm g-band interferer. This feature ensures the concurrent operations of a dual-band radio front-end design.

Besides the traditional continuous wave (CW) characterizations of the LNAs, the modulation quality of the LNA is also evaluated with 256-QAM test signals. The low band LNA is tested with 256-QAM MCS9 40 MHz test signal under pulse mode. Because the low band has  $< 100$  MHz bandwidth, the maximum bandwidth of a channel is limited to 40 MHz for 802.11ac applications. The dynamic EVM (DEVM) [4] of the low band LNA is  $< 2\%$  ( $-34$  dB), up to  $> -5$  dBm output power as shown in Fig. 7. Similarly, with MCS9 80 MHz test signal, the high band LNA has DEVM  $< 2\%$  up to  $-4$  dBm output power as

shown in Fig. 7. The modulation qualities of both LNAs for 256-QAM 802.11ac applications were proven.

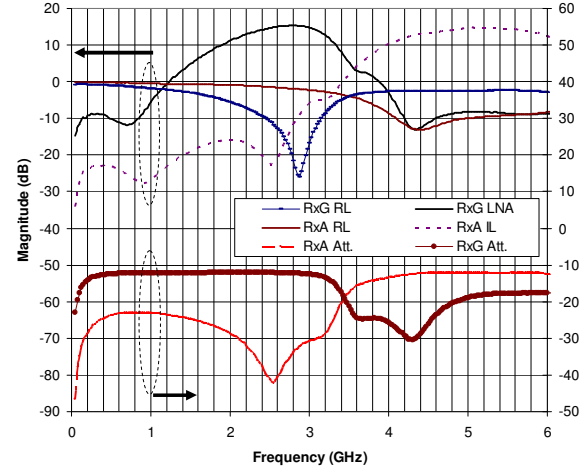


Fig. 6. Measured S-Parameters of receive path in LNA mode and bypass attenuation mode at 3.3 V.

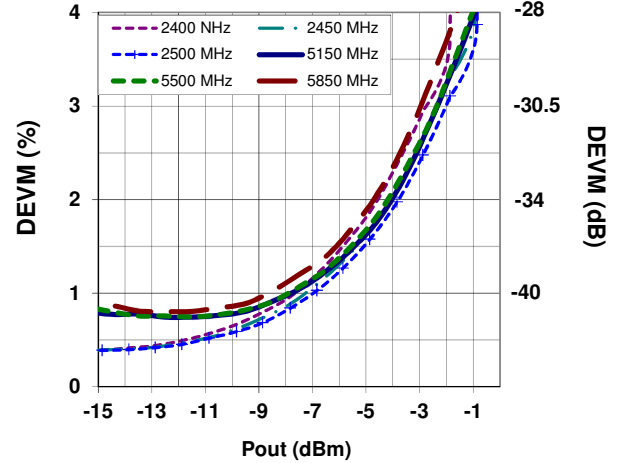


Fig. 7. Measured dynamic EVM of the LNAs at 3.3 V with 256-QAM MCS9 test signals.

In addition to the characterizations of the standalone SP5T switch-LNA, the design is also cascaded with a dual-band PA [5] to demonstrate its performance in a FEM configuration as shown in Fig. 1 in a  $3 \times 4$  mm package. Since the SP5T switch-LNA is the last component in the FEM design, the receive path performance remains the same as that reported in the previous paragraph. The modulation quality of the transmit paths was tested with a 256-QAM MCS9 OFDM signal. For 802.11ac standards, the DEVM requirements are more stringent than those of 802.11a/b/g/n. For 2% dynamic EVM with a 3.3 V supply, the linear power levels achieved were roughly  $> 16$  dBm

for a-band and  $>17$  dBm for g-band (see Fig. 8). The data throughput of the a-band Tx path is 390 Mbps. The worst case harmonic emissions are  $< -50$  dBm/MHz up to 23 dBm output power. Similarly, the g-band transmit path can deliver 1 dB higher linear output power with the MCS9 40 MHz test signal. The current consumption of the FEM is shown in Fig. 9. The gains of the Tx paths are 27 dB for the low band and 30-31 dB for the high band. The receive paths performance reported in the previous sections were evaluated in the FEM, so the receive path performance of the FEM can be found in the previous sections.

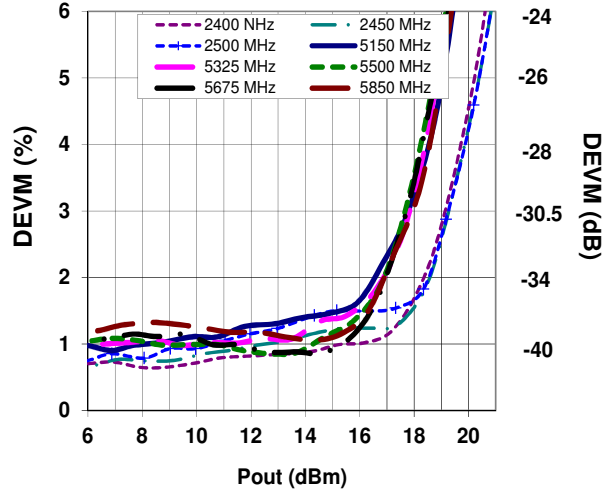


Fig. 8. Measured dynamic EVM of the transmit paths at 3.3 V of the proposed 2-chip FEM.

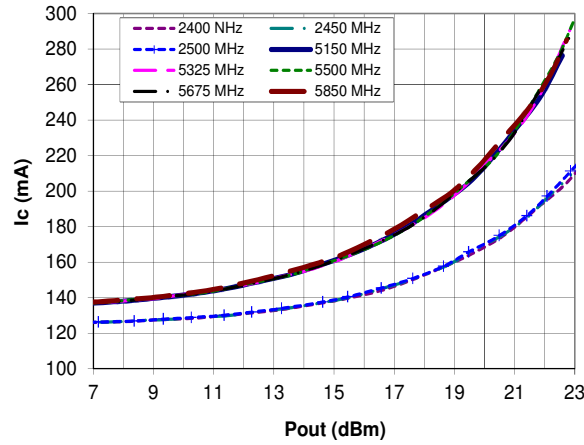


Fig. 9. Measured current consumptions of the transmit paths at 3.3 V of the proposed 2-chip FEM.

#### IV. CONCLUSION

A novel SOI SP5T switch-LNA that enables dual-band 256-QAM concurrent operations is presented. The design consists of two receive and three transmit paths. The integrated diplexer combines SPDT and SP3T switches into a band-selective SP5T switch, which provides the required out-of-band rejections for dual-band concurrent transmit/receive operations. In addition, the integrated diplexer provides not only the enhancements on harmonic rejections for Tx paths but also the out-of-band rejections which allow LNA to sustain a 5 dBm interferer at the antenna port.

Each receive path feature an integrated LNA with switchable integrated bypass attenuators. Receive path LNA features 12 dB gain with 2.5-2.6 dB NF. The bypass attenuator can provide 4, 12, and 24 dB switchable attenuations and remains linear up to 15 dB input drive. The Tx paths feature 0.1 dB compression at  $> 33$  dBm, the insertion loss of 0.8 dB for g-band as well as BT paths, and 1.2 dB for a-band path with  $> 20$  dB return loss and  $> 30$  dB Tx to Rx isolation.

Pairing the proposed switch-LNA with a dual-band WLAN PA [5], an innovative 2-die dual-band FEM can be realized in a 3 x 4 mm compact package. Both dual-band Tx and Rx paths demonstrate both Tx and Rx paths compliant to the linearity requirements of 802.11ac standard up to 256-QAM MCS9 80 MHz applications. All these unique features of the proposed design enable a dual-band concurrent FEM design addressing the linearity requirements of dual-band WiFi, MIMO, and the emerging 802.11ac 256-QAM applications.

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