A Highly Integrated Dual-band SiGe Power Amplifier that Enables 256 QAM 802.11ac WLAN Radio Front-End Designs

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***Abstract* — A highly integrated SiGe BiCMOS PA is presented that enables the emerging high throughput 802.11ac WLAN applications. The PA has two stages for the g-band and three stages for the a-band PA, and integrates matching circuitry, out of band rejection filters, power detectors, and bias controls in a 1.5 x 1.6 mm chip. The g-band PA achieves 28 dB gain with 2% EVM at 18 dBm and 3% at 19.5 dBm output power. The a-band PA achieves 32 dB gain with 2% EVM at 18 dBm and 3% EVM at 19 dBm output power. The design is verified meeting not only the regulatory out-of-band emission requirements but also the linearity requirement of the emerging 256 QAM 802.11ac standard.**

***Index Terms* — WLAN 802.11ac high throughput power amplifier, dual-band PA, dual-band front-end module.**

I. INTRODUCTION

Wireless local area network (WLAN) radios have been widely extended from traditional computer networking to many other electronic appliances, such as cellular phones, PDAs, electronic gaming devices, security and monitoring systems, and multi-media systems [1]. In the last decade, there have been three major trends in the evolution of WLAN radios. First, with the increasing demand of higher data rate communications, the multiple-input, multiple-output (MIMO) technique has been widely adopted to increase the data rate from the 54Mbps of a single-input single-output (SISO) operation to a minimum of 108 Mbps dual stream MIMO operation. Second, to avoid the bandwidth congestion of 2.4-2.5 GHz (g-band) having only three channels for 54Mbps operation, dual-band (g-band and a-band) WLAN configuration has been increasingly adopted. The a-band WLAN typically operates from 4.9 to 5.9 GHz, which significantly increases the number of channels. Third, a front-end module (FEM) or front-end integrated circuit (FEIC) is the preferred design implementation for the radio front-end design. FEMs or FEICs not only simplify the RF design of a radio front-end circuitry but also greatly reduce the layout complexity in a compact radio. For the embedded WLAN radios in portable electronic devices and MIMO radios, FEM and FEIC demonstrate the strength of integration for complicate RF circuit designs.

After the successful adoption of MIMO and dual-band WLAN radios, applications of higher bandwidths have been rapidly deployed. To further address the future increasing demand for wider bandwidths and higher data throughput rates, the emerging 802.11ac standard will adopt from traditional 20 MHz up to 160 MHz bandwidth per channel and can provide up to 866.7 Mb/s at each transmit/receive path as shown in Fig. 1 [2] and Table 1. When 802.11ac radios operate in MIMO mode, the data rate can be up to 6 Gbps when the radio is operation with 160 MHz and 8-stream MIMO. As shown in Table 1, the error vector magnitude (EVM) of an 802.11ac radio is -32 dB at the highest data rate, which is 7 dB lower than those for 802.11g radios. Therefore, the linearity requirement for 802.11ac transceivers and power amplifiers are significantly increased compared to those for conventional 802.11 applications.

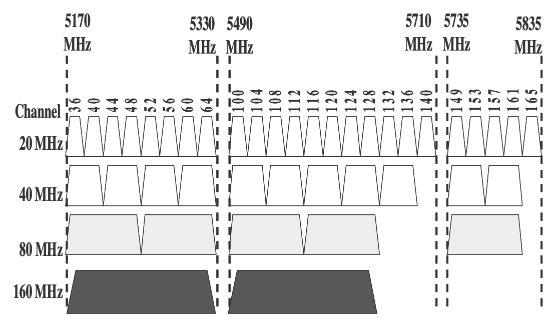

Fig.1 Frequency channels for the emerging 802.11ac WLAN standard [2].

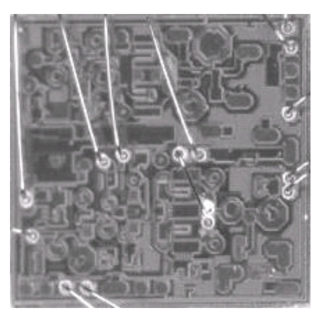

Fig.2 Die photo of the dual-band 802.11ac power amplifier design.

MCS Index	Modulation	Code Rate	Signal Bandwidth				Allowed System EVM	
			20 MHz	40 MHz	80MHz	160MHz		
			Data Rate (Mb/s)	Data Rate (Mb/s)	Data Rate (Mb/s)	Data Rate (Mb/s)	dB	%
0	BPSK	1/2	7.2	15.0	32.5	65.0	-5	56.2
1	QPSK	1/2	14.4	30.0	65.0	130.0	-10	31.6
2	QPSK	3/4	21.7	45.0	97.5	195.0	-13	22.4
3	16-QAM	1/2	28.9	60.0	130.0	260.0	-16	15.8
4	16-QAM	3/4	43.3	90.0	195.0	390.0	-19	11.2
5	64-QAM	2/3	57.8	120.0	260.0	520.0	-22	7.9
6	64-QAM	3/4	65.0	135.0	292.5	585.0	-25	5.6
7	64-QAM	5/6	72.2	150.0	325.0	650.0	-28	4.0
8	256-QAM	3/4	86.7	180.0	390.0	780.0	-30	3.2
9	256-QAM	5/6	N/A	200.0	433.3	866.7	-32	2.5

Table 1 Data rate, modulation scheme, and linearity requirements of various 802.11ac signals.

In this paper, a highly integrated WLAN 802.11ac dual-band power amplifier is presented. As shown in Fig. 2, the PA design is based on SiGe BiCMOS technology with through silicon via and fits in an area of 1.6 x 1.5 mm^2. The power amplifier features a high level of integration, which incorporates all matching networks, out-of-band rejection filters, voltage regulator and bias circuits, temperature compensated power detector, and the enable switch compatible with CMOS logic controls. In addition, the dual-band PA design also features excellent linearity that meets the requirements of the emerging dual-band 802.11ac standards. With 3.3V supply voltage, the g-band PA delivers 28 dB gain and 19.5 dBm linear power with EVM < 3% and total current consumption <170 mA. The a-band PA delivers 32 dB gain and > 19 dBm with EVM < 3% and total current consumption <190 mA. The dual-band design can be also biased at 5.0 V to increase the linear power (see Fig. 8). The design was verified with various 802.11ac signals at the highest data rate, and the variation of linear power was found to be less than 0.5 dB using data bandwidths from 20 to 80 MHz. All these unique features simplify the front-end circuit design of 802.11 a/b/g/n/ac WLAN radios. With a dual-band switch-plexer or switch-LNA [3], a complete dual-band front-end module can be constructed with just two integrated circuit building blocks, the dual-band power amplifier described above, and a dual-band switch-plexer or switch-LNA.

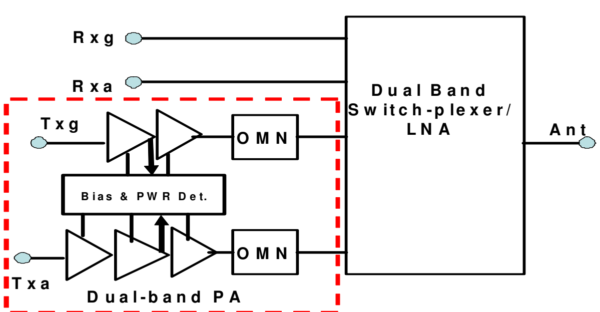

Fig.3 A two-chip dual-band WLAN FEM design for WLAN a/b/g/n/ac radios.

II. DESIGN

SiGe BiCMOS is a proven technology for g-band PA design [1]. Several major design challenges for realizing an amplifier with high gain and linearity at 6 GHz in silicon germanium technology were well addressed in [4]. The challenge of producing high power at high frequency with acceptable efficiency trends inversely due to the low breakdown voltage of silicon transistors. In [4], it reported the first dual-band SiGe PA in volume production. The advantage of using SiGe BiCMOS process is the easy integration of RF core and analogue circuits. As shown in Figs. 2 and 3, the RF core is based on SiGe transistors, and the analog circuits such as the bias band-gap circuits, PA enable switches, and the temperature compensated power detectors are designed with CMOS devices. For embedded applications used in portable electronic devices, the current consumption is a key parameter in system designs. Accurate power detection can enhance the performance of the closed loop power control. Adaptively adjusting the output power can reduce the unnecessary waste of current at near range data communications by reducing the transmitting power.

As shown in Fig.3, the dual-band PA consists of a 2 stage amplifier for g-band and a 3-stage amplifier for a-band. The major consideration for 2 stage b/g band PA is the PA driver in today's transceivers can deliver more linear power, so the requirements of high gain for g-band PAs has been reduced. Both PAs are controlled by a CMOS controller providing the reference currents for current mirrors. During WLAN data communications, the PAs are frequently enabled and disabled to reduce current consumption. Typically, GaAs PA linearity can suffer in dynamic mode operation due to the poor thermal characteristics of the GaAs substrate. GaAs PA designs typically need external circuits to improve dynamic mode linearity [5]. The presented PA design implements more advanced bias circuitry to resolve the thermal difference between PA stages, which results in no degradation in both linearity and gain under dynamic mode operation, while reducing the overall current requirements to operate with low EVM floors required for 802.11ac operation.

To illustrate the PA topology, the 3-stage a-band PA is shown in Fig. 4. Due to the commonality between g and a-band PA, the discussion will be focused on a-band PA design. The out-of-band rejection is also achieved in the input matching network and inter-stage matching networks. The output matching network not only provides optimal matching for in-band but also provides the harmonic termination.

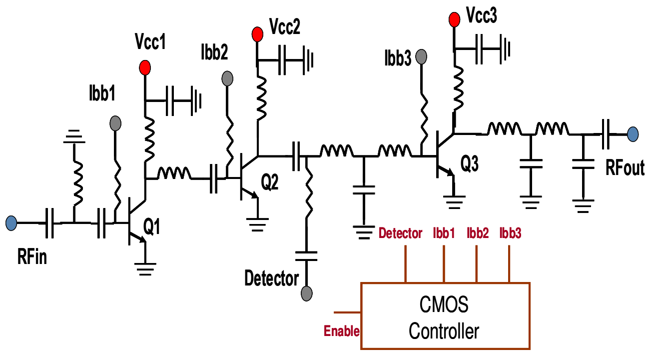

Fig.4 Conceptual schematic of the a-band PA design.

An accurate power detector always requires a directional coupler to isolate and reduce the impact from reflected signals. Instead of using a directional coupler, which is large and requires high directivity, an in-house proprietary design [6] was re-used. The power detector is realized at the inter-stage matching circuit between the driver and output stage. When the last inter-stage matching network is well designed, the gain flatness is naturally ensured. The isolation from the 3rd stage device and the inter-stage matching network will provide sufficient isolation, similar to using an active directional coupler.

III. PERFORMANCE

Measurement validation for the dual-band WLAN 802.11ac PA design is presented in this section. Fig. 5 shows the S-parameters of g-band and a-band PA. The gain variation is within 0.5 dB for g-band PA and 1.0 dB for a-band PA. As shown in Table 1, the 802.11ac standard has much higher linearity requirements than those of conventional 802.11 applications. Although the system EVM requirement at the highest data rate is defined as -32 dB or 2.5%, the EVM for either a PA or a FEM should be less than -35 dB or 2% to tolerate the -36.5 dB or 1.5% EVM from a transmitter. Due to the lack of 160 MHz test signal and vector network analyzer, the linearity of the design was validated with the modulation quality with various OFDM 802.11ac test signals of 20, 40, and 80 MHz. All tests were done under dynamic mode of pulsing PA enable [5]. As shown in Figs. 6 and 7, with 3.3V supply voltage, the g-band PA can achieve 2% dynamic mode EVM (DEVM) at 18 dBm and 3% DEVM at 19.5 dBm output power with both 20 and 40 MHz 802.11ac signals. The current consumption is 160 mA at 18 dBm and 170 at 19.5 dBm. The a-band PA achieves 2% DEVM at 18 dBm and 3% DEVM at 19 dBm output power with 20 and 40MHz test signals. When using 80 MHz, the linearity has 0.2-0.3 dB degradation in linear power. The current consumption is 180 mA at 18 dBm and 195 mA at 19 dBm.

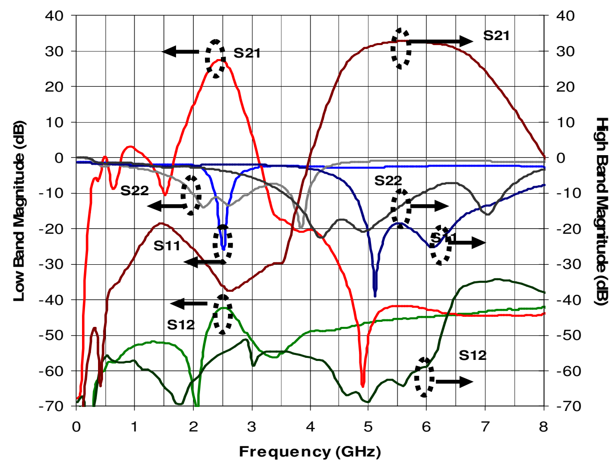

Fig.5 Measure S-Parameters of the WLAN dual-band PA.

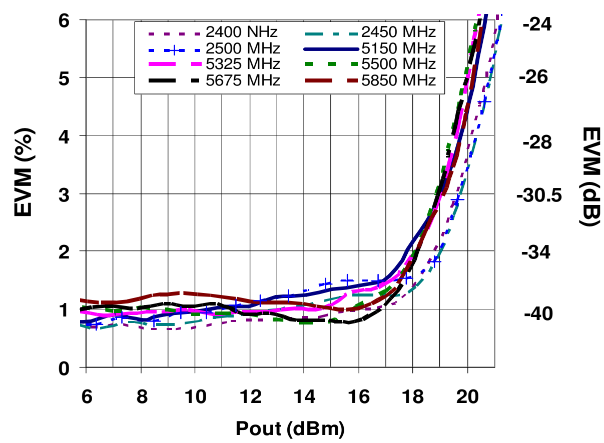

Fig.6 Measured dynamic mode EVM at 54 Mbps of the presented SiGe dual-band WLAN 802.11ac PA.

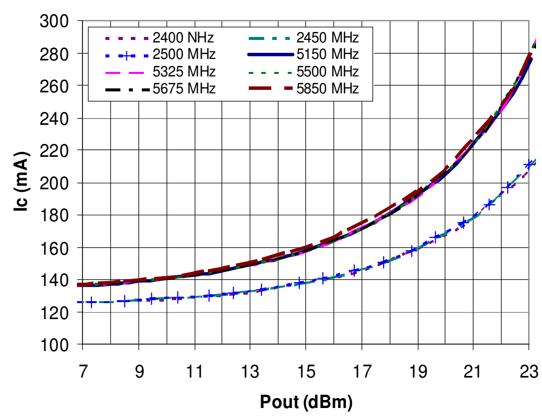

Fig.7 Measured total current consumption for the presented SiGe dual-band WLAN PA with a 3.3 V supply voltage.

The harmonic emissions were validated versus output power. The worst cases were found at the harmonics of 21 dBm output at 1Mbps for the g-band PA and 20 dBm at 6

Mbps for the a-band PA. Harmonic emission levels of most channels under test are below -50 dBm/MHz up to the maximum linear output power, which exceed the FCC requirement of -41.2dBm/MHz.

For most computer and access point applications, 5 V is available to the front-end module. The PA is also verified at 5 V and with more than 3 dB increase of linear power as the theoretical analysis (3.5 dB). With 5V supply voltage, the modulation quality of the a-band PA was validated with 20, 40, and 80 MHz test signals at the highest data rate. As shown in Fig. 8, there is 0.5 dB degradation of linear power when using 80 MHz test signal, which reporting 20 dBm at 2% DEVM.

The PA is also validated under a wide temperature variation of -30 to 85°C, and excellent temperature stability and tight performance variation versus temperature was found due to the on-chip temperature compensation circuitry. The performance is similar to that reported in [4] due to the similarity in design architectures. The power detectors were also validated under the temperature variation, power supply voltage, and load mismatch. The variations for temperature and voltage were found 0.6 dB or +/-0.3 dB and 0.5 dB or +/- 0.25 dB respectively. The detector variation under the load mismatch up to VSWR 3:1 mismatch was found within +/-1 dB. All these unique characteristics can enhance the closed loop power control design within the entire linear power operation rage, which can help the radio adaptively adjust the output power to reduce un-required current consumption at near range data communications.

IV. Conclusions

In this paper, a 1.6 x 1.5 mm^2 SiGe BiCMOS dual-band 802.11ac WLAN power amplifier is presented. The PA features high integration level, which provides a turn-key solution for complicated 802.11ac WLAN front-end designs. The g-band PA achieves 28 dB gain and 2% DEVM at 18 dBm output power with 160 mA and 3% DEVM at 19.5 dBm output power with 170mA. The a-band PA achieves >32 dB gain with 2% DEVM at 18 dBm with 180 mA and 3% DEVM at 19.0 dBm with 195mA. The modulation quality was also tested under the highest data rate of various signal bandwidths. When the test signal has 80 MHz bandwidth, the degradation of the linear power is within 0.5 dB. The integrated temperature and voltage compensated bias circuit ensure the minimum variation of performance under extreme temperature and supply voltage change. The PA is designed to deliver linear power proportional to the supply voltage. The application of higher supply voltage demonstrated the boost of linear power. In addition, the unique power detector was validated to be insensitive to load mismatch up to VSWR of 3:1, temperature, and supply voltage variations, which can construct an accurate closed loop control within the entire linear output power operation.

Based on these unique features, the presented PA can be used as a key building block that simplifies the construction of a dual-band front-end circuit designs. The PA can be used as a discrete component in the radio front-end circuit designs or as a building block for a dual-band FEM. With a dual-band switch-plexer or switch-LNA similar to the design presented in [3], a dual-band 802.11ac FEM can be easily realized in a 2-chip design as shown in Fig. 3. All the uniqueness of the presented dual-band PA design not only fulfills the high linearity requirements of the emerging 802.11ac WLAN standard, but also greatly reduces the complexity of 802.11ac front-end circuit designs.

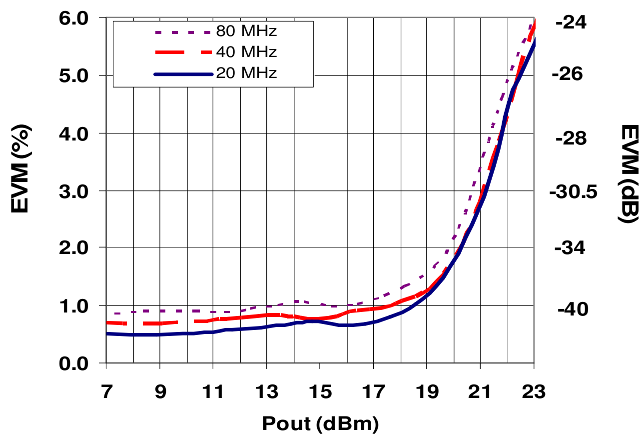

Fig.8 Measured Dynamic EVM at 5.0 V with 802.11ac test signals of various bandwidths.

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