Indirectly-Non-Reciprocal Load Modulated Balanced Amplifier with Equivalent Operation at Antenna Interface

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***Abstract*—This paper presents, for the first time, a new time-divisional-duplex (TDD) front-end architecture, named Indirectly-Non-Reciprocal Load Modulation Balanced Amplifier (INR-LMBA), for emerging massive MIMO array systems. By transforming the circulator from the PA output to the low power (CA) output, it can relief the power stress on circulator by an order of magnitude, potentially enabling the non-magnetic implementation. Together with the T/R switch, it can be used to offer the same TDD functionality as the conventional front-end, as well as the quasi-isolation to antenna in transmission and low loss in reception. As proof-of-concept for this architecture, a $2-2.5$ GHz INR-LMBA prototype is developed using GaN devices and a commercial circulator. The experimental results exhibit an efficiency of $62-73\%$ for peak output power and $53-57\%$ for 10-dB OBO, respectively. The insensitivity to load mismatch of INR LMBA is also experimentally demonstrated.**

***Keywords*—Load modulation, balanced amplifier, Circulator, power amplifier, high efficiency, wideband, high-PAPR.**

I. Introduction

The evolution of wireless communications systems features ever-increasing user data rate, which calls for spectrally efficient modulation schemes, like orthogonal frequency-division multiplexing (OFDM) and high-order digital modulation (e.g., 1024QAM). This leads to the surge of peak-to-average power ratio (PAPR) of communication signals and necessitates efficiency enhancement of power amplifiers (PAs). To address these challenges, load modulation, like the Doherty PA, has been widely used in many wireless systems. However, the conventional Doherty PA faces limitations in operational bandwidth and a restricted 6-dB dynamic range [1] [2]. Recently proposed load-modulating balanced amplifier (LMBA) have been effective in overcoming these limitations imposed on Doherty PAs with many successful examples [3] [4][5][6][7].

Meanwhile, the emerging 5G/6G systems have started to transform from few-antenna to many-antenna paradigm, also known as massive MIMO. However, the use of large antenna array brings back a classical issue of antenna scan impedance during beam steering, due to the strong mutual coupling between adjacent elements in the array. As the preceding stage to antenna, every PA in the array is typically followed by a circulator to isolate the antenna impedance fluctuation. Since massive-MIMO systems are mostly based on time-division duplex, the circulator is meanwhile used to separate the transmission and reception with the assistance of a T/R switch [8], as shown in Fig. 1(a). It is important to note that the circulators are normally based on magnetic materials, making

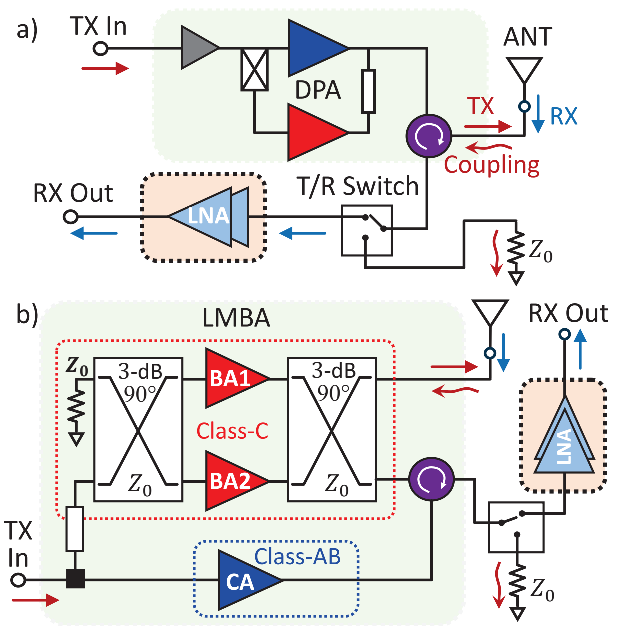

Fig. 1. Conceptual overview of massive MIMO RF front-end: a) conventional solution with magnetic circulator[8], b) proposed INR-LMBA enabling the potential use of non-magnetic circulator.

the resultant devices bulky, expensive, and heavy that are not suitable for large-scale integration and manufacturing. On the other hand, the recently reported non-magnetic circulators are still far from practical application with intrinsic limitations in power handling capability, loss, linearity, etc. [9][10]

This paper proposes, for the first time, a new RF front-end architecture based on indirect integration of circulator with the load-modulation circuitry, named indirectly-non-reciprocal (INR) LMBA depicted in Fig. 1(b). By moving the circulator from the high-power antenna node to an inner low-power node at the CA (carrier) output, it only needs to sustain a fraction of the transmitted power, e.g., $1/10$ for 10-dB-OBO pseudo-Doherty LMBA (PD-LMBA). This transformation holds a promising potential to enable the use non-magnetic circulator (with watt-level power handling reported in [10]) in such a high-power circuit with the equivalent non-reciprocal functionality in terms of 1) TX/RX separation for TDD operation, 2) isolation of antenna impedance mismatch in TX mode, and 3) low path loss in RX mode. Theoretical analysis is first introduced to explain the operation of the proposed INR LMBA, which is further validated by a developed prototype circuit in both simulation and experiment.

II. Indirectly Non-Reciprocal LMBA Theory

The indirectly non-reciprocal (INR) LMBA is configured by transforming the circulator from the PA output to the low-power CA (carrier) output. Together with the T/R switch, it can be used to offer the same TDD functionality as the conventional front-end, as illustrated in Fig. 1. In this section, a mathematical model is established in Fig. 2 to verify the transmission (TX) mode of INR LMBA which is able to isolate the large back reflection from the strong mutual coupling in antenna array. The reception (RX) mode can be considered as equivalent to the carrier path in low-power mode with the peaking amplifier turned off.

A. Transmission Mode of INR PD-LMBA

Based on the equivalent circuit illustrated in Fig. 2, the impedance of the CA and BA are calculated for the general case that the load is terminated by an arbitrary impedance of Z_{L} at the antenna port, which mimics the coupling from adjacent antenna elements in the array. The BA and CA stages are modeled as the ideal current sources of magnitudes I_b and I_c, and the phase offset between BA and CA (θ) is assumed to be 0° as for the ideal PD-LMBA condition. From the theoretical mode with combined Z matrix of quadrature coupler and Y matrix of the isolator, the BA load modulation behavior under random load is derived as

$$Z_{\mathrm{BA1}} = Z_0[(1+\frac{\sqrt{2}I_c}{I_b}) + \Gamma_{\mathrm{L}}(2+\frac{\sqrt{2}I_c}{I_b})]; \quad (1)$$

$$Z_{\mathrm{BA2}} = Z_0[(1+\frac{\sqrt{2}I_c}{I_b}) - \Gamma_{\mathrm{L}}(2+\frac{\sqrt{2}I_c}{I_b})]; \quad (2)$$

$$Z_{\mathrm{CA}} = Z_0. \quad (3)$$

It is interesting to note that Z_{BA1} and Z_{BA2} still complement each other during load modulation like the standard BA. The CA sees a constant load impedance regardless of Z_{L} due to the isolator. The operation of INR LMBA is analyzed in different load conditions.

- **Matched Load ($Z_{\mathrm{L}} = Z_0$):** In this condition, when the load is matched to Z_0, the operation of the proposed INR LMBA based on the Eq. (3) is equivalent to the standard PD-LMBA, as $\Gamma_{\mathrm{L}} = 0$. The BA stage is turned off at the lower power region until the CA reaches saturation at the pre-determined back-off range. In this high power region, the impedance of the BA can be seen to be modulated by the factor proportional to the amplitude of CA current being driven in. The impedance of the CA in standard PD-LMBA remains constant of Z_0 throughout the entire power range, so that the addition of isolator does not change the operational condition.
- **Mismatched Load ($Z_{\mathrm{L}} \neq Z_0$):** In this condition, we examine the load dependence of CA and BA individually. First, the CA is fully isolated from the load by the isolator. Second, the BA, despite being modulated, maintains its resilience to load mismatch according to Eq.(3), which indicates that the load modulation behaviors of two sub-amplifiers present a mutually complementary trend, thus effectively cancelling the load-pulling effect. As a result, the overall INR LMBA is intrinsically insensitive to the load mismatch.

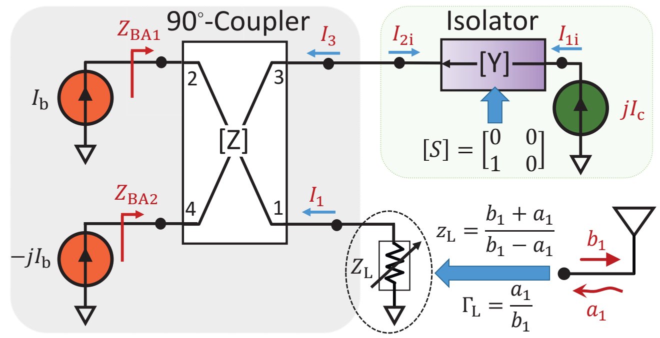

Fig. 2. Equivalent circuit modeling for the transmission mode of INR LMBA based on Z-matrix of quadrature coupler and Y-matrix of isolator (circulator with the third port terminated by Z_0).

B. Reception Mode with Low Path Loss

As illustrated in the Fig. 1, The INR-LMBA is designed architecturally to function as an RF front-end that can support both transmission and reception. Envisioned for TDD, the TX and RX modes of the INR-LMBA are operated at distinct time slots. Hence, in the RX mode of operation, there is no power transmitted in the TX-path of the amplifier stages. In other words, the peaking branch of BA sub-amplifier duo is turned off, and thus, the RX signal received from the antenna should be quadrature split and completely reflected by BA1 and BA2 [11] [12]. The reflected signals, by virtue of quadrature coupler, are due for subsequent quadrature combination at the isolated port, leading to a full reconstruction of the RX-signal. It is important to note that the RX path is technically reciprocal to the CA signal path at low-power region with BA turned off, which means the path loss should be low by design so as to maximize the first efficiency peak at designated back-off.

III. Design of Broadband INR-LMBA

Following the INR-LMBA theory and the ideal schematic in Fig. 1, the physical circuits of the CA and BA in the broadband INR-LMBA are constructed using 10-W GaN transistor (Wolfspeed CG2H40010F). In order to accommodate the high PAPR of emerging 4G/5G signals, the target OBO is set to 10 dB, and the operational band of the design is chosen from 2 to 2.5 GHz. The realized circuit schematic is shown in Fig. 3(a). In order to realize the broadband BA, a two-section impedance transforming hybrid (5:1) is designed as the output coupler together with a high-impedance bias line to provide the inductive reactance for BA loadline. This impedance transformation eases out the requirement for an additional matching network design at the output and minimizes the phase dispersion for load modulation. At the input, a broadband commercial quadrature Hybrid coupler (IPP-7118) is deployed[13]. The input matching networks of CA and BA are designed using multi-stage low-pass matching techniques implemented with transmission lines [14].

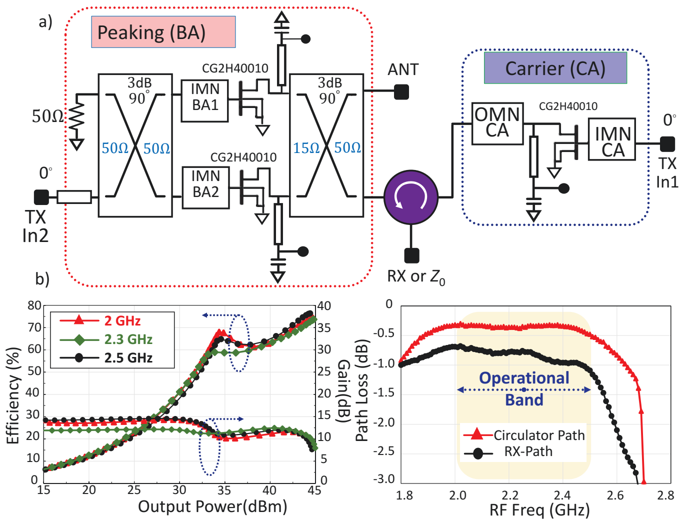

Fig. 3. (a) Practical design schematic of the proposed broadband INR-LMBA using impedance-transformer coupler and GaN transistor; (b) Simulated efficiency and gain measurements at various frequencies; (c) Simulated path loss for the receiver and circulator standalone.

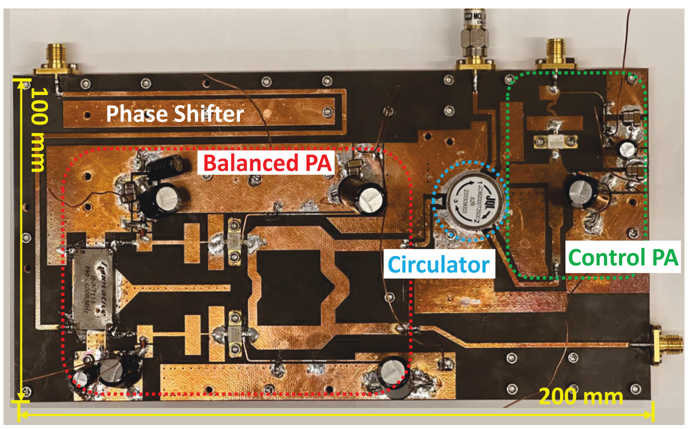

Fig. 4. Fabricated INR-LMBA prototype with two inputs connected to external splitter (A magnetic circulator is used just for experimentally demonstrating the concept in real circuit architecture).

Due to the lack of commercial non-magnetic circulator, a commercially available surface mount magnetic circulator (JCM2000T2500S2R, JQL Technologies) is selected for demonstrating the proposed theory and circuit architecture, as shown in Fig. 3(a). Compared to the standard PD-LMBA, the circulator in CA path involves introduces an extra phase. It is important to note that the circulator's phase dispersion is also linearly proportional to frequency, which can be compensated for by introducing the same phase delay at the BA input added to the original phase-offset line for PD-LMBA, in order to maintain its wide bandwidth. The simulated efficiency and gain versus output power are presented in Fig. 3(b), indicating the desired load modulation behavior across the entire band. The RX loss is simulated with no TX input, as shown in Fig. 3(c). Compared to the standalone circulator, the added loss, due to the passive quadrature coupler and finite Q of BA off-state, is less than 0.4 dB in band.

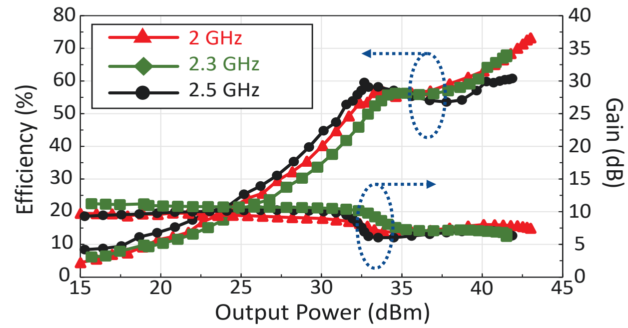

Fig. 5. (a) Power-swept measurement of efficiency and gain of the proposed INR-LMBA architecture at various frequencies.

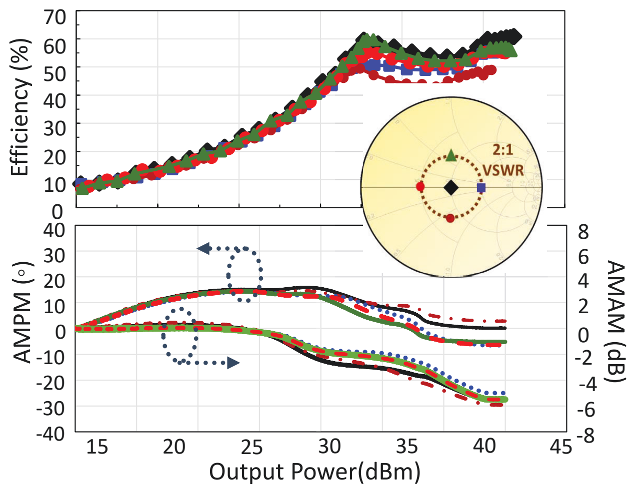

Fig. 6. The mismatch efficiency and the measured AM-AM, AM-PM results of the INR-LMBA Architecture.

IV. Implementation and Experimental Results

The INR LMBA prototype designed above is fabricated on a 20-mil thick Rogers Duroid-5880 PCB board with a dielectric constant of 2.2. A photo of the fabricated PA is shown in Fig. 4. The CA and BA are biased in Class-AB and Class-C, respectively, with $V_{\mathrm{DD,CA}}$ around 12 V and $V_{\mathrm{DS,BA}}$ of 28 V. The gate bias voltages is fine-tuned at different frequencies to perfect the overall LMBA performance. The measurement is primarily conducted for the TX mode (large-sginal) of INR LMBA with both continuous-wave (CW) and modulated stimulation signals. The experimental performance of RX is very close to simulation.

A. Continuous-Wave Measurement

A single-tone CW signal is generated to evaluate the overall performance of developed prototype for the matched load condition from 2 to 2.5 GHz at swept power levels. Fig. 5 captures the frequency response of the INR LMBA under matched-load conditions. A peak output power of $41.5-43.3$ dBm is measured across the entire bandwidth, together with $8-11.5$ dB gain at different OBO levels. The corresponding measured efficiency at peak power is $62-73\%$. The efficiencies at 10-dB OBOs are in the range of and $53-57\%$, respectively. The power-dependent gain and efficiency profiles are shown in Fig. 5 at different frequencies. A desired

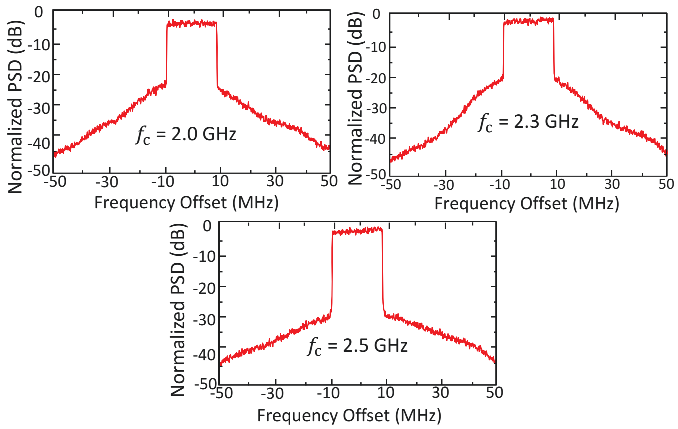

Fig. 7. Measured normalized power spectral density for 20-MHz 4G-LTE sitimulus with 9.5dB PAPR at various frequencies.

load-modulation behavior similar to standalone PD-LMBA is observed at the matched load condition.

The proposed INR LMBA architecture features mismatch resilience as a key attribute. Mismatch evaluation is conducted at 2.3 GHz by connecting the PA output to variable loads covering the 2:: 1 VSWR circle on the Smith chart. The phase is swept at four distinct points to simulate the impedance scan of an antenna array. The drain efficiency, ranging from 49 to 56% in mismatched conditions (slightly degraded from the 60% in matched conditions), is depicted in Fig. 6. Additionally, the overall AM-AM and AM-PM responses, measured using a VNA, are experimentally sustained across mismatch ranges.

B. *Modulated Measurements*

In order to validate the effectiveness of the INR LMBA in realistic communications, a 20-MHz-bandwidth LTE signal with a PAPR of 9.5 dB is generated for stimulation using a Keysight PXIe vector transceiver (VXT M9421), which is also used to analyze the output signal of prototype. For an average output power of 33 dBm, the measured output spectrum at 2, 2.3 and 2.5 GHz are shown in Fig. 7, with 53%, 51.6% and 54% average efficiency, respectively.

V. Conclusion

This paper introduces a novel RF front-end architecture, termed indirectly-non-reciprocal (INR) LMBA, which integrates the circulator with the load-modulation circuitry. By relocating the circulator to a lower-power node at the carrier output, the proposed architecture effectively reduces the power handling requirements, allowing for the potential use of non-magnetic circulators with watt-level power handling capabilities. The proposed technique is experimentally validated by a hardware prototype, demonstrating the capability of efficiently amplifying signals with 10-dB PAPR. The proposed architecture achieves distinctive back-off efficiency enhancements across the band of its intended design with a decent linearity. The simulation and experimental results validated the broadband and high-efficiency performance of the proposed INR-LMBA architecture.

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