

Highly Linear and Highly Compact Broadband Load-Modulated Balanced Amplifiers for Next Generation Wireless Communications

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Abstract—This report presents the research outcomes supported by the 2025 IEEE MTT-S Graduate Fellowship Program, focusing on the development of the highly linear and compact load-modulated balanced amplifier (LMBA). By investigating the nonlinearity and efficiency degradation caused by load modulation in LMBA architectures, several power amplifier prototypes are implemented to explore highly linear and efficient LMBA designs in integrated processes for next-generation wireless communication systems.

Index Terms—GaN MMIC, LMBA, efficiency enhancement, power amplifier, RFIC, linearity.

I. INTRODUCTION

TO improve spectrum efficiency, modern wireless communication systems usually use non-constant envelope modulation signals with high peak to average power ratio (PAPR), which imposes stringent requirements on efficiency and linearity for RF power amplifiers (PAs) [1]–[4]. At millimeter-wave (mm-wave) frequencies, these demands are particularly acute: 5G New Radio (NR) frequency range 2 (FR2) deployments require PAs that can handle wide-bandwidth modulated signals with minimal distortion because it is not practical to use digital predistortion (DPD) in dense phased-array architectures. Achieving intrinsic PA linearity alongside high back-off efficiency therefore remains one of the central design challenges in mm-wave transmitter development.

This project aims to develop highly linear and compact broadband load modulated balanced amplifier (LMBA) architectures operating in the mm-wave and FR3 bands for next-generation wireless communication systems. A miniaturized dual-loop (MDL) coupler is first proposed to reduce chip area for monolithic microwave integrated circuit (MMIC) implementation [5]. The linearity and efficiency challenges of LMBA are then addressed through innovative architectures and design methodologies. These approaches incorporate different load-modulation mechanisms and nonlinear cancellation techniques compatible with various fabrication processes and application scenarios, improving the design flexibility of LMBA.

II. PROJECT OUTCOME

A. The Proposed Miniaturized Dual-Loop Coupler

To implement MMIC LMBA in mm-wave and FR3 band, we have proposed an MDL coupler to achieve RF-input LMBA

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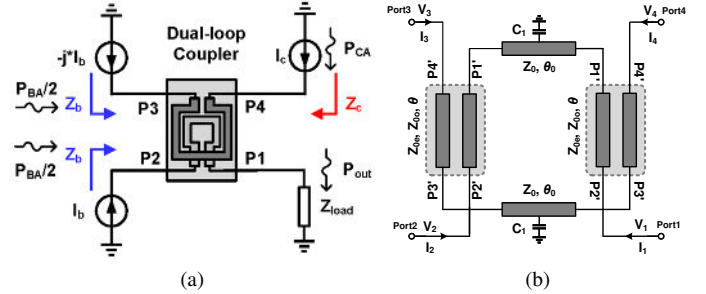


Fig. 1. (a) Simplified model of the LMBA. (b) The equivalent schematic of the proposed coupler.

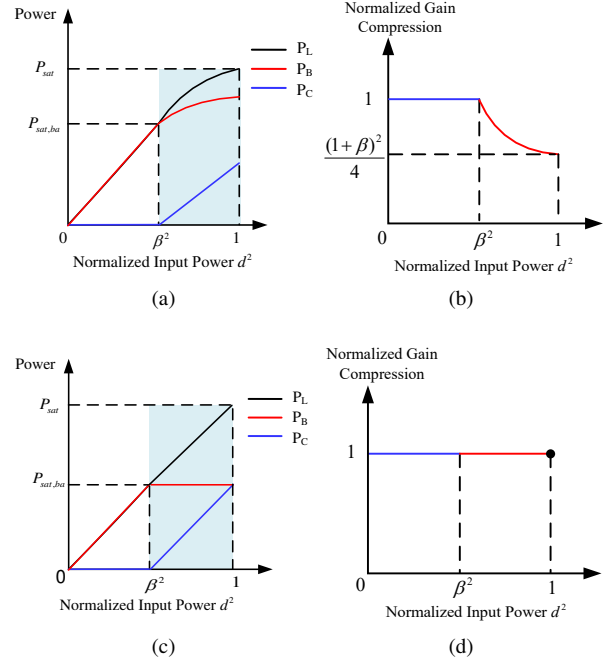


Fig. 2. Conventional LMBA: (a) Power performance, (b) Gain compression. Proposed QL MBA: (a) Power performance, (b) Gain compression.

in GaN MMIC process, as shown in Fig. 1(a), which is dependent on capacitive coupling and inductive coupling to realize coupler operation so that the compact on-chip coupler can be obtained by appropriately adjusting both coupling effects. The proposed dual-loop coupler, shown in Fig. 1(b), which consists of two coupled-line sections with an electrical length of θ and even-/odd- mode characteristic impedance of

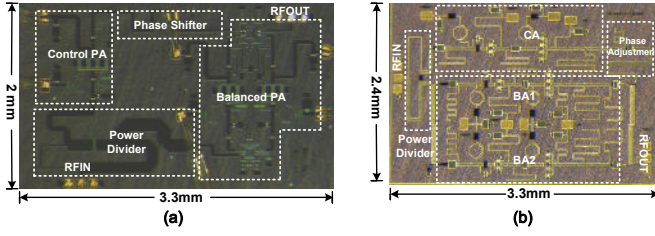


Fig. 3. Photograph of (a) the fabricated MDL-coupler-based LMBA (b) the fabricated QLMBA.

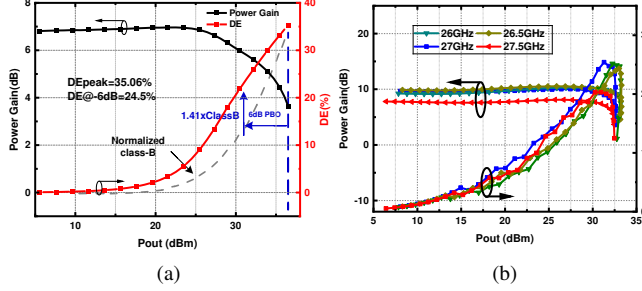


Fig. 4. Measured PAE and power gain versus output power: (a) MDL-based LMBA, (b) QLMBA.

Z_{0e} and Z_{0o} , and two capacitors C_1 at the middle of TL with the electrical length θ_0 and characteristic impedance Z_0 . By introducing shunt capacitors C_1 , the flexibility of coupler design is increased, which allows the utilization of coupled lines of shorter electrical lengths, and thus, reduce the chip area in MMIC process.

B. Highly Linear and Efficient PA architecture

LMBA offers compelling efficiency advantages over broad frequency ranges, but their inherent gain compression in the power back-off region poses a significant linearity challenge for modern 5G mm-wave applications where digital predistortion (DPD) is difficult to deploy [6], [7]. Therefore, we have proposed a quadrature-phase LMBA (QLMBA) that addresses this limitation through a quadrature-phase control signal injection technique. By establishing a 90° phase offset between the balanced amplifier (BA) and control amplifier (CA), the proposed architecture isolates BA and CA power contributions, suppressing the nonlinear gain compression inherent to conventional LMBA designs. Fig. 2 demonstrates the power performance and normalized gain compression compared with the conventional LMBA. It can be seen that gain compression can be fully eliminated with a properly selected CA to BA drive ratio.

C. Implemented PA Prototypes

To validate the proposed theory and architecture, we implemented two PA prototype circuits in a $0.12\text{-}\mu\text{m}$ GaN-HEMT process. As shown in Fig. 3(a), we presents a 26-GHz LMBA using the proposed MDL couplers with a coupler footprint of $265 \times 240 \mu\text{m}^2$. The measured gain and DE versus output power is shown in Fig. 4(a). As can be seen, the DE of

35.06%/24.5% is obtained at peak power/6-dB back-off. The fabricated LMBA provides over 36-dBm output power and 1.41 times DE enhancement over an ideal Class-B PA at 6-dB PBO level.

As illustrated in Fig. 4(b), we also performed a 26–28-GHz RF-input QLMBA with quadrature load modulation to eliminate the inherent gain compression. The fabricated chip achieves a saturated output power of 32.3 dBm, a peak drain efficiency of 29.3%, and a peak PAE of 24.5%. At 6-dB power back-off, drain efficiency of 20.71% and PAE of 16.7% are obtained, representing approximately 1.2 times efficiency enhancement over an ideal class-B PA at the same back-off level. These results are consistent across the full 26–28 GHz band, with saturated output power exceeding 32 dBm at all measured frequencies. Critically, the measured power gain curves in Fig. 4(b) remain flat across the full output power range at all measured frequencies, with a gain compression factor of 0.98, within 1 dB of the small-signal gain up to saturation. This near-unity gain compression factor directly validates the feasibility and practicality of the proposed QLMBA architecture.

III. CAREER PLAN AND IMPACT STATEMENT

I am deeply honored to receive the 2025 MTT-S Graduate Fellowship Award. This recognition has greatly encouraged me to continue my research in RF PA design and in the development of next-generation wireless communication systems. The fellowship program also supported my participation in the 2024 IEEE International Microwave Symposium (IMS), where discussions with researchers and exposure to state-of-the-art microwave technologies greatly enriched my research perspective.

Through this fellowship, I have gained valuable knowledge, research experience, and broader perspectives that will support my future work in RF and microwave circuit design in both academia and industry. In the future, I will continue to remain active engagement with the MTT-S community and closely following emerging developments in both academia and industry.

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