

A Compact D-Band Phase-Shifting TRX Front-End for Scalable Phased Arrays

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Abstract—This work presents a compact D-band phase-shifting transmit/receive (TRX) front-end designed for scalable phased-array systems in advanced silicon technology. The proposed architecture integrates bidirectional operation and precise phase control within a highly compact footprint, enabling efficient beam steering for future 6G communication and high-resolution sensing applications. The design focuses on minimizing area and insertion loss while maintaining high phase accuracy and low power consumption, making it well suited for dense phased-array integration.

Index Terms— 6G, transceiver frontend, bi-directional, calibration-free, D-band, millimeter-wave (mmWave), passive, phase shifter, phased array.

I. INTRODUCTION

THE development of compact and efficient transceiver (TRX) front-ends is critical for next-generation wireless communication and sensing systems, especially in the sub-terahertz range. The D-band (110–170 GHz) is a key candidate for 6G and high-resolution radar due to its potential for ultra-high data rates and fine spatial resolution. To support scalable phased-array systems, TRX architectures with shared RF front-ends have been widely adopted to reduce hardware duplication and beamforming complexity. However, practical implementations still suffer from significant integration overhead, routing complexity, and loss introduced by mode-reconfiguration networks, which limit overall area and power efficiency [1], [2]. To address these limitations, a compact phase-shifting TRX front-end with embedded switching and a shared bidirectional phase-shifter-based architecture is presented. By tightly integrating transmit and receive signal paths within a unified front-end, the architecture enables reduced hardware complexity and improved efficiency, making it suitable for highly scalable phased-array systems in future communication and sensing applications.

II. PROPOSED 120 GHz PHASE-SHIFTING TRX FRONT-END

Fig. 1(a) shows a conventional TRX architecture employing a shared phase shifter for TX/RX and separate TX/RX signal paths connected to a common antenna through $\lambda/4$ -based T/R networks implemented with series/shunt switches and transmission lines. At 120 GHz, this approach incurs two key limitations. First, on chip $\lambda/4$ lines consume significant area within a $\lambda/2 \times \lambda/2$ unit cell and complicate RF

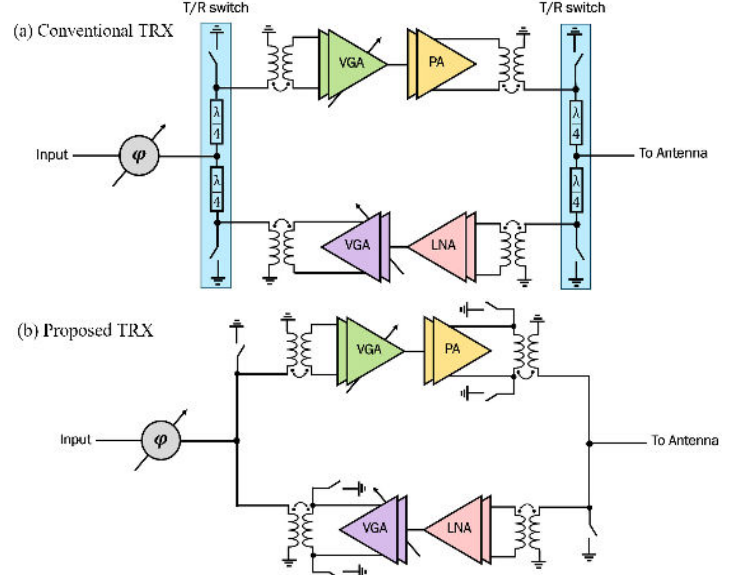


Fig. 1. Block diagram of the (a) conventional and (b) proposed TRX.

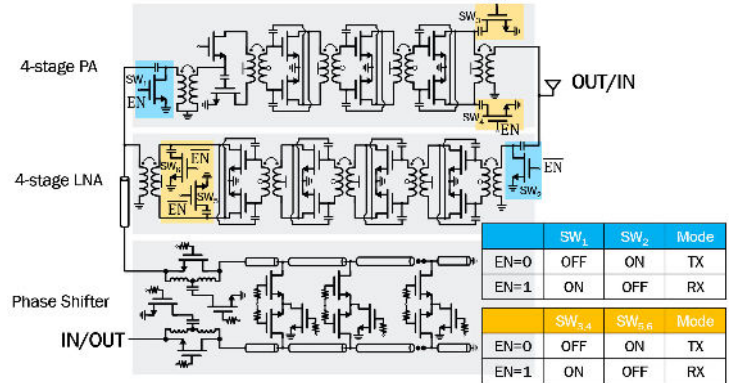


Fig. 2. Schematic illustrating the switching mechanism of the transceiver (TRX) front-end for TX and RX modes.

routing around transformers and bias networks. Second, the $\lambda/4$ T/R networks introduce non-negligible insertion loss in both directions. In RX, this loss precedes the LNA and directly degrades noise figure; in TX, it reduces delivered PA power and EIRP.

Fig. 1(b) shows the proposed TRX architecture, which retains a shared bidirectional phase shifter [3], [4] and antenna but replaces $\lambda/4$ T/R networks with compact embedded switches and co-designed PA/LNA interface transformers. The transformers remain in the signal path in both modes and are jointly optimized to provide mode-dependent impedance transformation. In TX mode, the LNA is power-gated while its associated transformers remain passive and, together with the PA-side transformers, synthesize the load-pull-derived optimum load impedance to maximize output power and

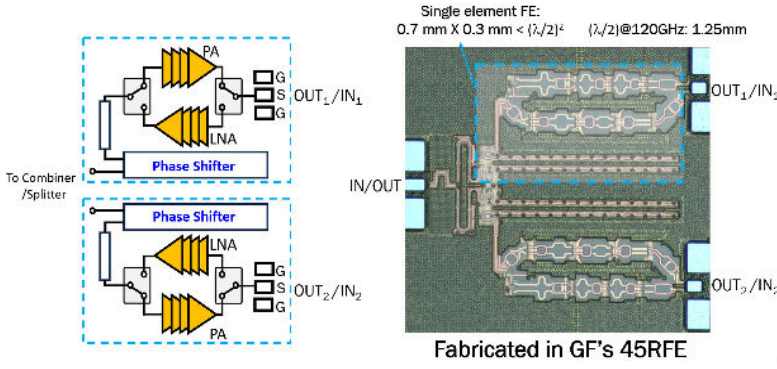


Fig. 3. Chip photo of the 2-element TRX, with the core area of one element highlighted (0.7mm x 0.3 mm).

EIRP. In RX mode, the PA is power-gated and its transformers are reused with the LNA-side network to present the optimum noise-matched source impedance, minimizing receiver noise figure. Unlike conventional $\lambda/4$ -based isolation networks, the proposed topology reuses passive transformer structures as functional matching elements across modes. This removes quarter-wave lines, reducing area and insertion loss, while enabling simultaneous load-pull-optimal TX matching and noise-optimal RX matching within a compact $\lambda/2 \times \lambda/2$ unit cell. Fig. 2 shows the six switches (SW₁–SW₆) used to configure TX and RX operation. SW₁ and SW₂ are the primary embedded switches, controlled by EN and $\overline{\text{EN}}$, respectively. In TX mode (EN = 0, $\overline{\text{EN}}$ = 1), SW₁ is off, routing the signal to the PA, while SW₂ is on, grounding the LNA output capacitor as part of the PA output matching network for optimum load impedance.

In RX mode (EN = 1, $\overline{\text{EN}}$ = 0), SW₁ is on, adding a shunt capacitor to the phase shifter matching network, while SW₂ is off, allowing the antenna signal to propagate to the LNA. The PA and LNA interface transformers are also reused across modes. In RX mode, SW₃ and SW₄ ground the PA-side balun, enabling it to function as part of the LNA input matching network. Similarly, in TX mode, SW₅ and SW₆ ground the LNA-side balun, allowing it to participate in the matching network between the phase shifter and PA. Additional bias switches, omitted in Fig. 2 for simplicity, selectively power down the inactive PA or LNA during TX/RX operation.

III. MEASUREMENT RESULTS

Fig. 3 shows the chip photo of the 2-element TRX, with the core area of one element highlighted. The dimensions of this core area are 0.7 mm by 0.3 mm, showcasing the small size of each element within the TRX. At a frequency of 120 GHz, the $\lambda/2$ is 1.25 mm, underscoring the compact nature of the design. This is a key feature, as it demonstrates how efficiently the system utilizes space to achieve high-performance operation at millimeter-wave frequencies. The chip is fabricated using the GlobalFoundries (GF) 45RFE process. The measured results demonstrate consistent and robust performance of the proposed TRX front-end across both TX and RX modes.

In TX operation, the measured gain across all phase states exhibits a bandwidth of 14 GHz. The gain varies between 13 and 15 dB, with the peak response occurring at 110 GHz. Compared to simulation, where the peak was centered at 120

GHz, a slight leftward shift in the peak frequency is observed. The measured phase response confirms full 360-degree phase coverage at 110 GHz across all phase states. The TX RMS phase error remains low across the operating frequency range, reaching 1.7° at 110 GHz, indicating accurate phase control and minimal phase deviation, which is essential for precise beam steering in phased-array systems. The corresponding RMS gain error is measured to be 0.6 dB at 110 GHz, demonstrating strong gain uniformity and stable amplitude behavior across all phase states. Overall, both phase and gain errors remain within acceptable limits, confirming reliable TX performance.

In RX mode, the measured gain across all phase states shows a bandwidth of 9 GHz. The gain varies from 16 to 18 dB, with the peak response occurring at 113 GHz. The RX phase response also confirms full 360-degree phase coverage at 110 GHz across all phase states. The RX RMS phase error is measured to be 1.7° at 110 GHz, demonstrating accurate phase control and consistent behavior across frequency. The RX RMS gain error is 0.6 dB at 110 GHz, indicating excellent gain stability across all phase states.

Collectively, the measurement results for both TX and RX modes confirm that the proposed design achieves stable gain, accurate phase control, and reliable wideband operation, making it suitable for high-frequency phased-array and sensing applications.

IV. FELLOWSHIP IMPACT AND NEXT CAREER PLANS

The MTT-S Fellowship has been a valuable recognition of my work and has further motivated me to contribute to the microwave and millimeter-wave community. It has also strengthened my engagement with the RF/microwave research community and reinforced my commitment to this field. Attending IMS provided an opportunity to interact with leading researchers and industry experts and gain insight into the latest advancements and emerging trends in RF and millimeter-wave technologies.

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