X-Band Wireless Power Transfer with Two-Stage High-Efficiency GaN PA / Rectifier

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***Abstract*—A 2-stage X-band GaN MMIC operating as a power amplifier and rectifier is measured in a wireless power transfer link. The PA operates at 9.9 GHz in class-AB and achieves 10 W of output power and >20 dB of gain. As a rectifier, the MMIC achieves over 52% RF-DC conversion efficiency at a power level of >8 W. In a wireless powering link at a distance of 5 cm, the system achieves 10% DC-DC efficiency. The applications are bi-directional high power directional wireless power transfer (WPT).**

***Index Terms*—high-efficiency power amplifiers (PAs), load-pull, microwave rectifiers, MMIC, wireless power conversion, x-band**

I. Introduction

Wireless near-field and far-field power transfer is becoming more popular for remotely powering devices which are not easily accessible [1], [2]. The use of diodes for RF and microwave rectification has an established well documented history [3], [4], [5]. Multi-watt level wireless power transmission and rectification has been demonstrated with solid-state power amplifiers and diodes fabricated in wide-bandgap semiconductors [1] or silicon by means of power division at the rectifier/rectenna [6]. Recently, it was shown theoretically with the time reversal duality principle that power amplifiers can operate as rectifiers [7]. Single-stage rectifiers operated in this way were demonstrated experimentally in [8], [9], [10] in the 2 and 10 GHz range with over 80% and 60% efficiency and 12 and 3 W respectively. High-efficiency self-synchronous rectifiers are obtained by applying RF power to the drain and terminating the gate in a optimal load as shown in Fig. 1.

In this work we investigate the performance of a two-stage class-AB X-band MMIC for use in a wireless link, as shown in Fig. 2. The performance of the MMIC as a rectifier was investigated in [11]. Two MMICs are used as PAs at one time to achieve high-efficiency rectification for one MMIC. The transmitter/rectifier MMICs are switched in an out of the network as necessary for rectification on the right (solid lines) or left (dashed lines). In addition, DC loads are connected at the drain bias lines of each stage and an isolator terminates the rectifier MMIC gate of the driver stage. X-band was chosen with far-field power beaming in mind since it allows for physically smaller antenna arrays with high directivity and effective area on the transmit and receive sides, respectively. In addition, mid-field applications such as powering through walls, would allow for smaller transmit-receive modules and antennas while delivering watt-level power. Compared to lower-frequency PAs and rectifiers, X-band is expected to have lower efficiency, and it is the goal of this paper to show that high efficiency with compact integrated circuits are still possible. As a PA, the MMIC utilizes two 8x50 μm devices for the driver stage and four power-combined 10x90 μm devices for the output stage (see [11]). Since the amplifier RF output becomes the RF input of the rectifier, the output stage is referred to as Stage 1 and the driver stage as Stage 2 as shown in Fig. 2.

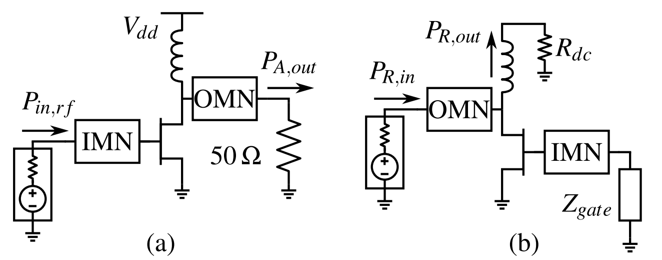


Fig. 1: (a) Block diagram of PA with a FET transistor. (b) Block diagram of PA used as a rectifier.

TABLE I: Performance of MMIC as PA at 9.9 GHz

P_{in} (dBm)	P_{out} (dBm)	PAE (%)	Gain (dB)
15	38.6	45.4	23.6
17.5	39.8	50.0	22.3
20	40.3	49.8	20.3

TABLE II: Performance of Rectifier at $P_{in,rf}$=8 W with RF Gate Load

Z_{RF} (Ω)	P_{S1} (W)	P_{S2} (W)	RF-DC (%)
69-0.4j	4.11	0.040	52.2
47.3+2j	4.10	0.040	52.1

II. PA, Rectifier, and Wireless Link Measurements

The MMIC characterized as an amplifier has an output power, gain, and PAE shown in Table I. Peak power is achieved at an input power of 20 dBm with a resulting output power of 40 dBm and a PAE of 49.8%. Following the time reversal duality, a RF rectifier using this amplifier should be able to rectify 10 W of RF power with an approximate 50% conversion efficiency, close to the peak PAE.

The MMIC is tested as a rectifier as shown in Fig. 1b. To investigate and determine the optimal mode of operation for rectification, the DC power of each stage is measured

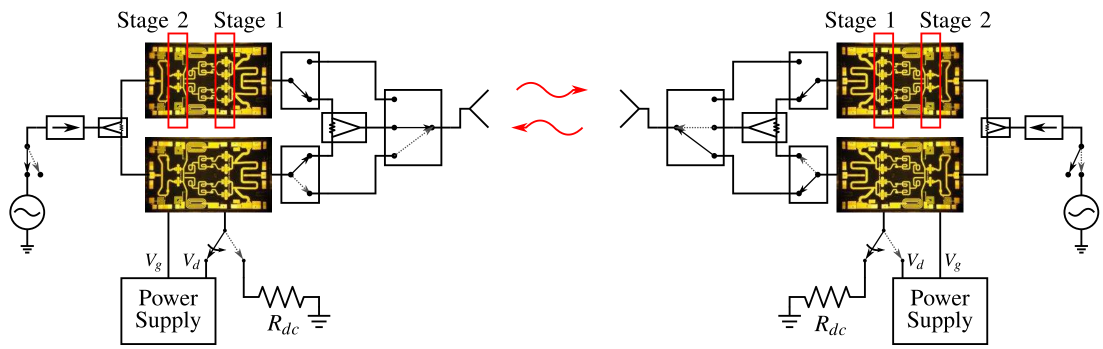
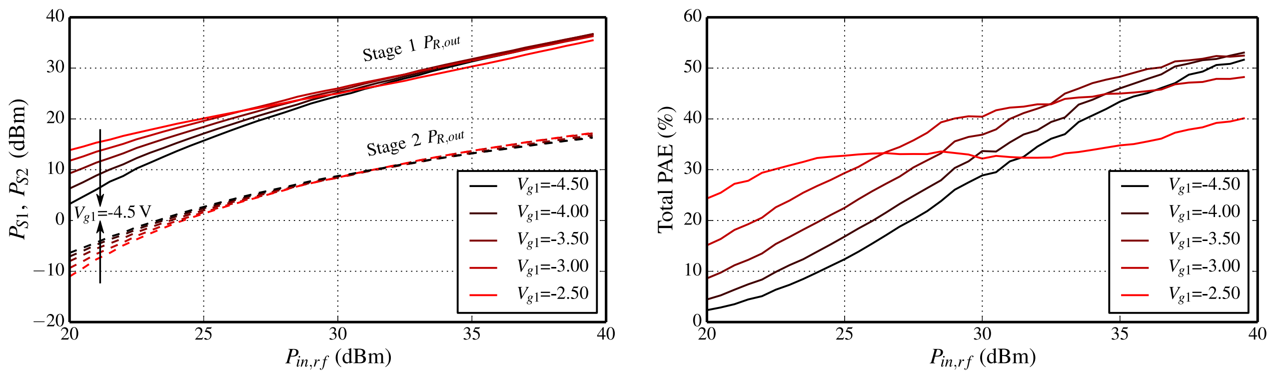


Fig. 2: Envisioned application of wireless power transfer. MMIC can be uses as transmitter and receiver in the same system by switching in DC loads for the drain supply and changing the gate bias voltages. Solid arrows indicate power transmission from left to right while dashed arrows transmits power from right to left. Transmission uses two MMICs to achieve high-efficiency at the rectifier (one MMIC).



(a) (b)

Fig. 3: (a) Stage 1 and Stage 2 rectified power as a function RF input power at various Stage 1 gate bias voltages (V_{G1}). (b) Total RF-DC conversion efficiency. The optimal bias point depends on input power. For high input power, a lower gate bias for Stage 1 and a higher gate bias for Stage 2 gives maximum output power for each stage respectively. The measurement is performed at 9.9 GHz with $R_{DC1} = R_{DC2} = 30\,\Omega$.

separately and the gate voltages, V_{G1} and V_{G2}, RF gate load, Z_{RF}, and R_{DC} for both stages are varied. For Stage 1, the gate voltage was varied from -4.5 V to -2.5 V, with the optimal V_{G1}=-3.5 V. The devices in this process are pHEMTs and are effectively cutoff at -4 V. Measured rectified power for both stages is shown in Fig. 3a. The optimal gate bias for Stage 2 was -3.0 V, used in the remainder of this paper.

After the optimal Stage 1 gate bias was determined, Z_{RF} is varied using a Focus impedance tuner. The rectifier performance from the loadpull is listed in Table II. At 8 W RF input power, the maximum RF efficiency is observed at 69-0.4j Ω with a peak DC power of 4.11 W. However, there is very low sensitivity to the load and 50 Ω gives nearly identical performance because Stage 2 is a buffer between Stage 1 and the RF gate load. The power contribution from Stage 1 accounts for 98% of the total rectified power. The overall conversion efficiency as a function of the RF input power and gate bias is shown in Fig. 3b with a maximum measured value of 52.2% with 8 W input power.

The rectified power in a WPT setup as a function of antenna separation and Stage 1 DC load, R_{DC1}, is shown in Fig. 4. The antenna is a standard gain horn with the far field calculated

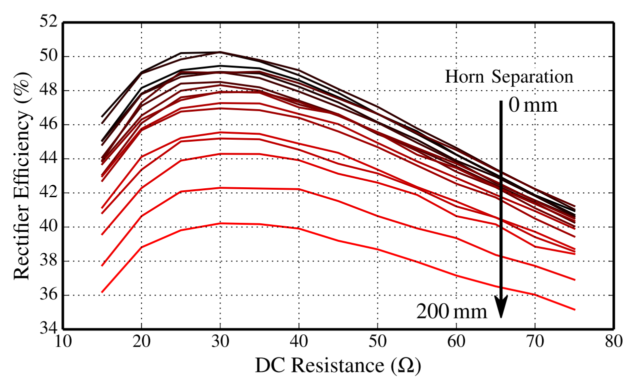


Fig. 4: Stage 1 DC rectified efficiency (RF to DC) versus DC load and increasing horn separation. The optimum DC load resistance is approximately 30 Ω regardless of the input power. The input power versus horn separation is shown in Fig. 6a.

at $\approx$50 cm. The optimal DC load is approximately 50 Ω regardless of input power to the rectifier. This DC load was also used for Stage 2. With the optimal gate voltage and DC rectifier load found, and RF load set to 50 Ω for convenience,

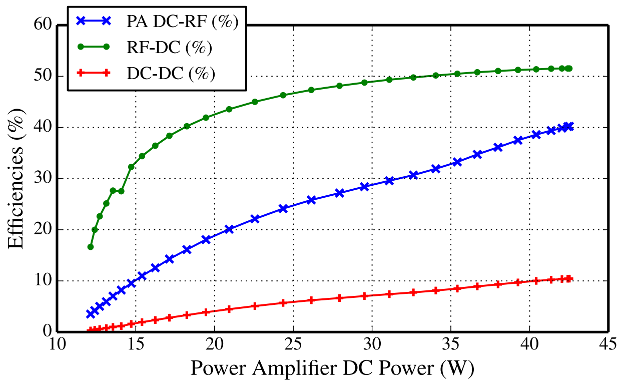


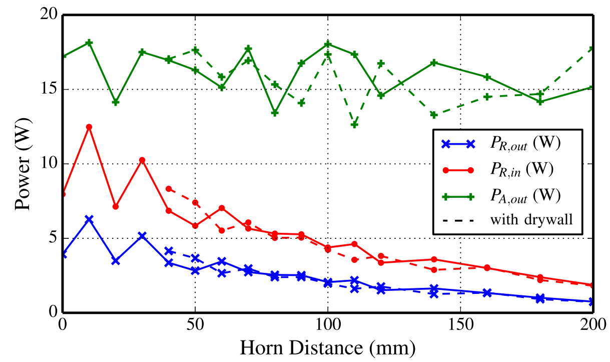
Fig. 5: Wireless link efficiencies of the power amplifier, rectifier, and total system efficiency versus total DC power consumed in watts. Peak system efficiency of >10% is achieved with the highest DC power consumed by the PA.

a wireless power transfer measurement was performed similar to that shown in Fig. 2. Two combined PAs are necessary for high-efficiency rectifier operation. The power amplifier DC to RF, rectifier RF to DC, and total system DC to DC efficiencies for a horn separation of 50 mm are shown in Fig. 5 and versus horn separation shown in Fig. 6. Above 40 mm, the system was tested with (dashed lines) and without (solid lines) a 1.27 cm thick gypsum board (drywall) section inserted between the horn antennas. A system DC to DC efficiency of 10% is achieved with the power amplifiers having the largest effect on the system efficiency. The power amplifier efficiency is lower than expected due to imbalances in the power combining and reflections from the rectifier. Large reflections causing load modulating can be seen in the output power of the amplifiers, $P_{A,out}$, in Fig. 6a. Higher PA efficiency could be achieved by phase matching the power amplifiers and using a low loss amplitude and phase matched power combiner.

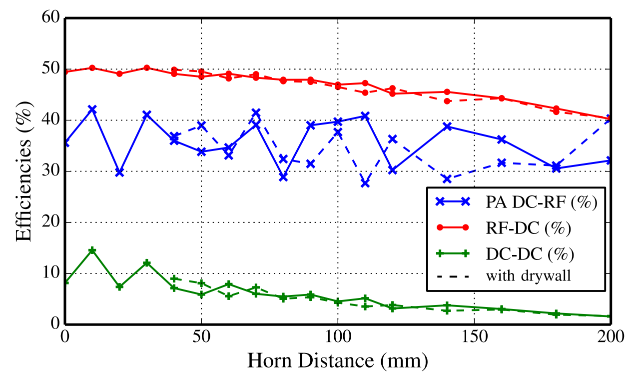
III. Conclusion

This paper has demonstrated that high efficiency and high power RF rectifiers can be realized with MMICs designed as two-stage power combined PAs. In a WPT link for a Fresnel-zone distance of 5 cm, a total DC-DC system efficiency of 10% was achieved with a rectification efficiency of >50% and combined PA efficiency of 40%. This range allows for applications such as powering through a wall, which is shown not to affect the efficiency.

This work demonstrates that high power multistage MMIC amplifier/rectifier pairs, designed using traditional PA techniques, can be applied to bi-directional high efficiency wireless power transfer systems. Additionally, power combining, as demonstrated in both the PA and rectifier modes by the same MMIC, is scalable on either transmitter or receiver side with additional MMIC modules.



(a)



(b)

Fig. 6: (a) Power and (b) efficiencies of wireless power transfer system with (dashed) and without (solid) a 1.27 cm section of drywall equidistant between the horn antennas.

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