# A Wide Dynamic Range Rectifier Based on HEMT with a Variable Self-Bias Voltage

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***Abstract*— This brief focuses on a highly efficient rectifier based on a high-electron-mobility transistor (HEMT) with a wide dynamic range of input power. Due to the nonlinear characteristics of HEMT, the impedance mismatch at different input power levels is a major challenge in rectifier design. Herein, a variable voltage gate self-bias network is proposed. It can dynamically generate a DC voltage according to the input power level, and continuously provide the optimal bias for the HEMT, thereby improving the RF to DC conversion efficiency in a wide input power range. This design does not require any external sensing or dynamic control circuit. The power needed by the self-bias network is provided using a weak coupling structure placed at the input port, which couples a small amount of the received RF power to operate the self-bias network. It is demonstrated that the proposed rectifier can achieve a dynamic operating power range of 24 dB (from 1 to 25 dBm) for over 60% conversion efficiency, or 16 dB for over 70% conversion efficiency in the measurement.**

***Index Terms*— Wireless power transmission, Rectifiers, HEMTs, Microwave circuits.**

## I. Introduction

WIRELESS Power Transmission (WPT), which can be used for charging automobiles and portable devices, is now an essential technology. In a practical system, due to the difference in the transmission environment and the change of distance, the received power generally cannot remain constant. To achieve a high RF to DC conversion efficiency, rectifiers are usually optimized for specific operating conditions, including the input power level and the output load. The suitable operating range of the input RF power level is very narrow. That is, if the rectifier operates at an input power level outside the desired dynamic range, it will result in a dramatic degradation of the conversion efficiency. Due to the nonlinear characteristics of diodes and transistors used in the rectifier, its impedance mismatch at different input power levels is a major design challenge.

Several types of topologies have been proposed to achieve a high conversion efficiency of the rectifier in a wide dynamic range. The resistance compression network (RCN) [1]-[3] and automatic impedance transformation technology [4] were introduced into the design. It could reduce the impedance variation at the input of the rectifier due to the change of the input power level. In [5]-[7], the input energy was distributed to different sub-rectifiers to achieve the best performance at different input powers. Reference [8] proposed a rectifier with power recycling based on using a branch-line coupler. Two identical sub-rectifiers were connected to the main output ports of the branch-line coupler for high power levels, and the isolated port is connected to a sub-rectifier for low input power.

Most research on RF rectifiers with a wide dynamic range is on diode technology. There is limited research on rectifiers based on high-electron-mobility transistor (HEMT) devices. Thanks to the principle of time-reversal duality, the design method for high-efficiency power amplifiers can also be applied for RF-DC conversion circuit design. Reference [9] proposed a synchronous HEMT rectifier based on a waveform steering solution, which achieved good performance, but the dynamic range was limited, and an external gate bias was required. References [10]-[11] proposed to use a variable gate bias instead of a fixed one to expand the input power range of the synchronous HEMT rectifier. However, complex circuits took up a large space and required careful adjustment.

In this brief, a HEMT rectifier with a wide dynamic range based on a variable voltage gate self-bias network is proposed. This design can provide a suitable gate bias voltage for the HEMT in a wide input power range to improve the overall efficiency. The dynamic range of the proposed rectifier for conversion efficiency over 70% is about 16 dB in the measurement. The maximum measured efficiency is 78% achieved at an input power of 15 dBm. The power needed for the proposed variable voltage gate self-bias network is from the asymmetrical coupling structure at the input port, which can couple a small part (0.1%) of the RF power to this network. No additional bias, sensing or dynamic control is needed.

## II. Operation Mechanism

Fig. 1 shows the conceptual diagram of the proposed rectifier with a variable gate bias voltage. It is mainly composed of three parts: a HEMT based self-synchronous rectifier in the red rectangular box, a three-port coupling structure in the blue box, and a variable voltage gate self-bias network in the green box. The RF power into the proposed rectifier is through a compact asymmetrical three-port structure with weak coupling (coupling coefficient -30 dB). The HEMT-based main rectifier is connected to the transmission port (Port 2), and the self-bias network is connected to the coupling port (Port 3). The output voltage of the self-bias network is variable with the input power to dynamically bias the HEMT.

This work was supported in part by the Royal Society under Grant IEC\NSFC\181364 and in part by EPSRC IAA with project ID 179631). (Corresponding author: J. Zhou).

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This article has been accepted for publication in IEEE Transactions on Circuits and Systems--II: Express Briefs. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TCSII.2023.3313879



The design procedure of the proposed rectifier is as follows:

1. Design a HEMT-based self-synchronous rectifier.
2. Determine the optimal gate bias voltages required for the rectifier to achieve the highest efficiency under different input powers. The voltage values can be obtained through either simulation or measurement.
3. Design the self-bias network, a suitable coupling structure is needed to take a small amount of power (typically less than 1%) from the RF input to operate the self-bias network.
4. Choose an appropriate output resistor for the self-bias network, so that it can automatically generate the desired bias voltage for the HEMT according to the input power.

The challenge of this design is how to make the bias voltages produced by the bias network as close to the optimal ones as possible to achieve the high efficiency over a wide dynamic range of input power. The design of the HEMT-based self-synchronous rectifier and the self-bias network will be explained in detail as follows.

### *A. HEMT-based Self-synchronous Rectifier*

The HEMT-based self-synchronous rectifier is shown in the red box in Fig. 1. The DC output of the rectifier is on the load resistor $R_L$. To realize a HEMT-based rectifier that can operate completely independently without external control and power supply, a gate drive signal is required to make the HEMT self-synchronizing. The method used in most previous works was to place a sampler incorporated with a phase shifting circuit to provide a gate signal for the rectifier. This increases the complexity of the circuit design and the size of the overall circuit. Thanks to the drain-gate feedback capacitance $C_{gd}$ of the HEMT, the RF signal can be directly fed into the gate. The rectifier can be self-synchronous without any feedback loop. However, a gate control circuit is required for tuning the signal phase at the gate. Commonly used microstrip line-based gate control circuit occupies a larger circuit area [9],[11]. The proposed self-synchronous rectifier uses lumped components to replace microstrip lines for minimizing the board size.

A HEMT of ATF54143 from Avago was chosen as the rectifying element, which has a small positive threshold voltage $V_{th}$ of 0.3 V. Therefore, the transistor has good performance in the low power range under the condition of zero bias. For the successful self-synchronous operation of the HEMT, a gate matching network was added at the gate to optimise the phase of the signal at the gate. Another impedance matching network was added at the drain of the HEMT to transform the 50 Ω system impedance to the optimum drain impedance $Z_{d\_opt}$, which was obtained by source-pull simulation when the input power level is 10 dBm with zero bias.

### *B. Variable Voltage Gate Self-Bias Network*

One very useful characteristic of HEMT based rectifiers is that the input power level to achieve the highest conversion efficiency can be controlled by adjusting the gate bias voltage. Simulation results of the RF to DC conversion efficiency versus gate bias voltage of an ideal HEMT rectifier at different input power levels are shown in Fig. 2. This rectifier can achieve a maximum efficiency of 80% at an input power of 10 dBm under zero bias, as shown by the red line. As shown by the blue, green, and purple curves, as the input power level increases, the bias voltage required to obtain the maximum efficiency gradually decreases. For example, when the input power is 15 dBm, the optimal gate bias voltage is -0.3 V; when the input power is 20 dBm, the optimal voltage is -0.7 V. When the bias voltage is higher or lower than the optimum value, the efficiency will drop. This phenomenon is especially obvious at low input power levels. When the input power is high, if the bias voltage is slightly lower than the optimal value, the efficiency change is much slower than the case when the bias voltage is slightly higher than the optimal value. In other words, the bias voltage is set at a value slightly lower than the best one to accommodate for simulation and fabrication errors.

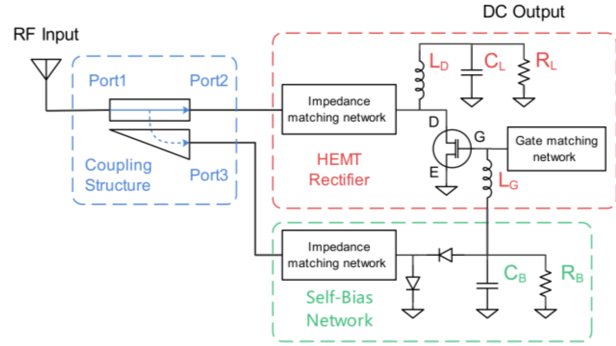



Fig. 1. Block diagram of the proposed rectifier.

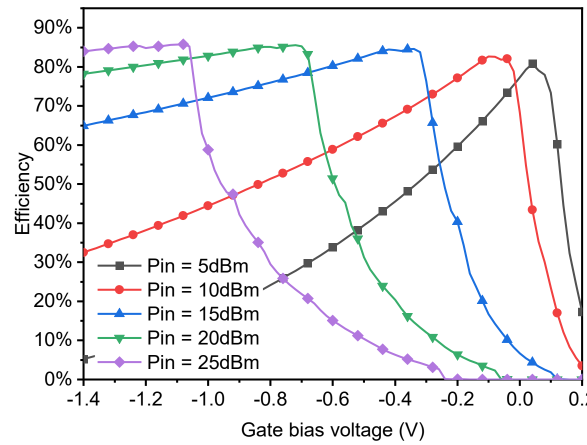



Fig. 2. Performance of the HEMT rectifier with different gate bias voltages

In order to enable the rectifier to achieve high efficiency in a wide input power range, the rectifier should work with different bias voltages under different input power levels. For a low input power level, the rectifier should work with zero bias. For a high input power, the rectifier should work under a negative bias voltage, and the bias voltage should gradually decrease as the input power increases. If the self-bias network can provide different bias voltages for the HEMT gate at different input power levels dynamically, that is, if the bias voltage gradually decreases as the input power increases, the efficiency can always be maintained at the maximum value.

To realize such a variable bias voltage, a compact asymmetrical three-port coupling structure with a weak coupling coefficient of -30 dB is designed to power the self-bias network. The coupling coefficient is determined by the length of the microstrip line and the width of the microstrip gap. For achieving the desired coupling coefficient, a structure with a length of 5 mm and a width of 0.5 mm was selected, as shown in Fig. 3. A high-impedance area is formed on the opposite side of the coupling port (Port 3), so the coupled energy will be reflected and concentrated on the well-matched coupling port. This is evident in the current distribution in Fig. 3 which is obtained from electromagnetic (EM) simulation using Advance Design System (ADS). Since the coupling coefficient of the coupling structure is only -30 dB, only a very small part (0.1%) of power will be taken from the input. The power consumption is very low and can be ignored in the overall conversion efficiency calculation. Compared with a traditional coupler using quarter-wavelength transmission lines, the proposed coupling structure has a very small size. Because of its short length, the insertion loss is further reduced. The measured performance of the coupling structure is depicted in Fig. 4 (a). The structure has a coupling coefficient ($S_{31}$) of -30.4 dB and a low insertion loss ($S_{21}$) of -0.1 dB at 0.95 GHz.

The self-bias network is based on two Schottky diodes in a reversed voltage doubler configuration. That is, its diodes are arranged in a way to produce a negative output DC voltage. The negative DC voltage gradually decreases as the input power increases. This voltage is used to provide a dynamic bias at the gate of the HEMT. An input matching network was added between the coupling port and the two diodes to improve the rectification efficiency of the self-bias network. Schottky diodes SMS7630 with an ultralow threshold voltage from Skyworks were chosen, which had high sensitivity at low input power levels.

Fig. 4 (b) shows how the output voltage of the self-bias network changes as a function of the input power. Since the power coupled to Port 3 is 30 dB below the input power, when the input RF power is lower than –10 dBm, the voltage across the Schottky diodes in the self-bias network is lower than the threshold voltage $V_{th}$. The output voltage from the self-bias network is approximately zero. Thus, no bias voltage is supplied to the HEMT. The synchronous rectifier works in the zero-bias mode.

When the input RF power increases, the HEMT needs a negative bias voltage to achieve high conversion efficiency as shown in Fig. 2. When the input power is greater than -10 dBm (or the coupled power is greater than -40 dBm), the power coupled to the self-bias network will be able to operate the diodes. When the input power further increases, the negative output voltage of the self-bias network will decrease (or its absolute value will increase). The decreasing rate can be controlled by adjusting the load resistance $R_B$ of the self-bias network. By choosing a proper value of $R_B$, the output voltage of the self-bias network can follow the trend of the

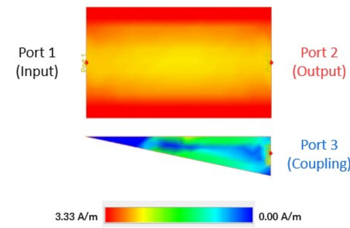
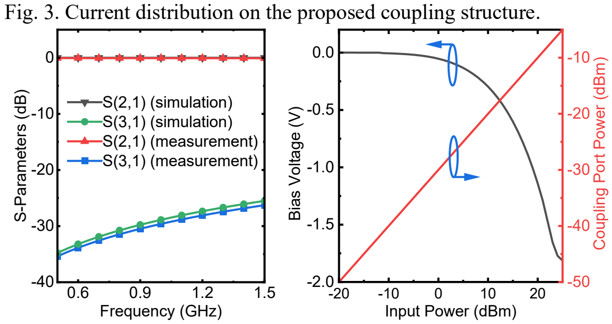



Fig. 3. Current distribution on the proposed coupling structure.




(a) (b)

Fig. 4. (a) The S-parameters of the proposed coupling structure in simulation and measurement. (b) Bias voltage and coupling port power versus input power

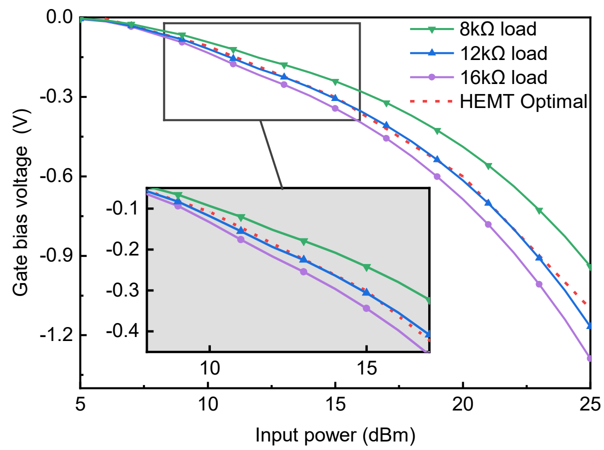



Fig. 5. The output voltage of the self-bias network with different load values as a function of the input power in measurement, compared with the optimal bias voltage for the HEMT obtained from simulation. The load value of the self-bias network can be chosen so that the network can always generate the optimal voltage for the HEMT.

optimal gate bias voltage of the HEMT. The rectifier can constantly maintain a high conversion efficiency.

Fig. 5 shows the output voltage of the self-bias network versus input power with different values of $R_B$ in measurement. The red dotted line shows the optimal bias voltage for the HEMT as a function of the input power level, which is obtained from the bias voltage required to achieve the highest efficiency at each input power as shown in Fig. 2. As discussed at first paragraph of this chapter, at low input power levels, the efficiency is more sensitive to the bias voltage than at high power levels. In this design, the value of $R_B$ is selected to be 12 kΩ, and the output voltage is shown as the blue line in Fig. 5. The output voltage from the self-bias network fits the optimal voltage curve very well in the low power range and is slightly lower than the optimum voltage in the high power range. Based on this bias voltage curve, the HEMT rectifier can achieve high efficiency over

TABLE II
COMPARISON OF THE PROPOSED RECTIFIER

| Ref. (year) | Components | Type | Frequency $f_0$ | Input power range for efficiency over 70% | Peak efficiency | Board size $\lambda_0$ |
|---|---|---|---|---|---|---|
| [7] (2018) | FET & Two diodes | Reconfigurable network | 1 GHz | 6 dBm to 18 dBm (12 dB) | 80% (17 dBm) | 0.193×0.047 |
| [9] (2019) | High power HEMT | Fixed gate bias | 2.8 GHz | 35 dBm to 50 dBm (5 dB) | 71% (39 dBm) | 1.120×0.560 |
| [11] (2021) | Two HEMTs | Variable gate bias | 2.35 GHz | 9 dBm to 24 dBm (15 dB) | 73% (19 dBm) | 0.329×0.164 |
| **This Work** | **HEMT & Two diodes** | **Variable self-bias** | **0.95 GHz** | **7 dBm to 23 dBm (16 dB)** | **78% (15 dBm)** | **0.054×0.044** |

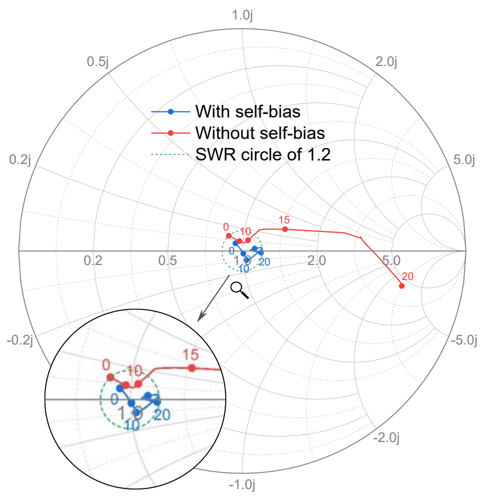



Fig. 6. The input impedance of the proposed rectifier in the Smith chart as a function of the input power with a sweeping range of 0 dBm to 20 dBm (1 dBm steps).

a wide input power range.

The input impedance of the HEMT rectifier obtained using large-signal S-parameter simulations in ADS as a function of power is shown in Fig. 6. The red solid line shows the input impedance of the HEMT without the gate bias by sweeping the input power in a range of 0 dBm to 20 dBm (1 dBm steps). The input impedance value varies in a large range. This is because when the input power increases, the power coupled to the gate through $C_{dg}$ (the feedback capacitance) also increases, causing the gate voltage to rise rapidly. Since the gate voltage controls the drain current, a rapidly growing gate voltage causes abrupt changes in the drain current and thus abrupt changes in the drain input impedance. The increased negative gate bias voltage limits the gate peak voltage so that the drain current controlled by it does not change abruptly. This ensures a relatively stable input impedance of the drain, which largely determines the input impedance of the rectifier. The input impedance of the HEMT with the dynamic gate bias is shown by the blue solid line in Fig. 6. All points are within the constant VSWR circle of 1.2. It can be seen that the applied bias voltage can mitigate the input impedance mismatch at high power levels, resulting in high efficiency over a wide dynamic range.

## III. EXPERIMENTAL VALIDATION

To verify the design method, a self-synchronous rectifier with the proposed self-bias network working at 0.95 GHz is designed. The rectifier can be used for wireless power transmission systems, such as sensor network tags, at the industrial, scientific and medical (ISM) band. As shown in Fig. 7, a lumped-element π-network consisting of two

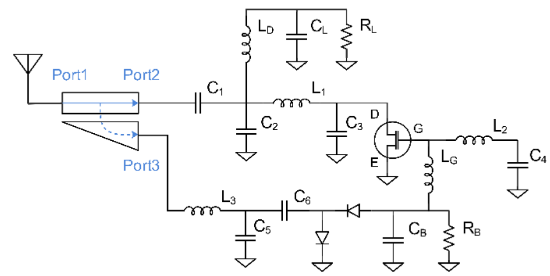



Fig. 7. Schematic of the proposed rectifier.

TABLE I
KEY COMPONENTS OF THE PROPOSED RECTIFIER

| Name | $L_1$ | $L_2$ | $L_3$ | $L_D$ | $L_G$ |
|---|---|---|---|---|---|
| Value | 30 nH | 16 nH | 27 nH | 22 nH | 22 nH |
| Name | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
| Value | 100 pF | 3.3 pF | 0.5 pF | 2.3 pF | 0.5 pF |
| Name | $C_6$ | $C_B$ | $C_L$ | $R_B$ | $R_L$ |
| Value | 100 pF | 100 pF | 100 nF | 12 kΩ | 1.2 kΩ |

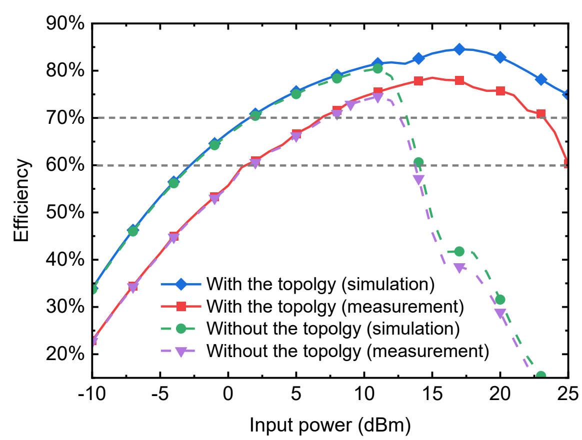



Fig. 8. The RF-DC conversion efficiency versus input power of the proposed rectifier with or with out the added self-bias network.

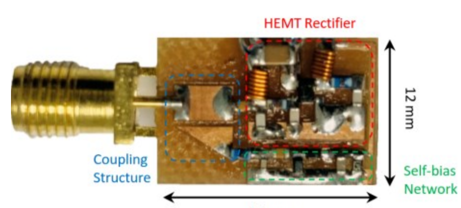



Fig. 9. Layout and photograph of the proposed rectifier.

capacitors $C_2$, $C_3$ and one inductor $L_1$ was designed to match 50 Ω to $Z_{d\_opt}$ which is obtained by the source-pull simulation. The gate matching network was composed of one inductor $L_2$ and one capacitor $C_4$ for tuning the signal phase at the gate. An inductor $L_D$ and a filtering capacitor $C_L$ were used for suppressing the ripple of the DC output voltage across the load resistor $R_L$. The rectifying circuit in the self-bias network consisted of two capacitors $C_6$ and $C_B$ and the rectifying elements $D_1$ and $D_2$ to form a voltage doubler. An inductor $L_3$ and a capacitor $C_5$ formed a basic L-network for the input impedance matching of the voltage doubler. A filtering capacitor $C_B$ was connected in parallel with resistor $R_B$ to provide a low-ripple DC bias for the HEMT gate. As discussed in Section II, the value of the load resistance $R_B$ in the self-bias network was selected to be 12 kΩ to match the optimal gate bias voltage. $L_G$ is an RF choke for connecting the bias voltage to the gate of the HEMT. The values of the circuit components are given in Table I. Harmonic balance simulation was carried out using ADS based on the Curtice nonlinear model from Avago. Fig. 8 shows the simulated RF to DC conversion efficiency of the self-synchronous rectifier with and without the proposed self-bias network. The input power range of the proposed rectifier with a conversion efficiency over 60% is from -3 to 25 dBm, while the range of the rectifier without the self-bias network is from -3 to 14 dBm, featuring 11 dB dynamic range improvement.

A prototype was fabricated on an FR4 substrate with a permittivity of 4.3 and a thickness of 1.52 mm. The size of the active area is only 17 mm long and 12 mm wide as shown in of Fig. 9. In the measurement, the proposed rectifier can achieve a wide operating power range of 24 dB from 1 dBm to 25 dBm for over 60% conversion efficiency, or 16 dB for over 70% conversion efficiency. The measured results differ slightly from the simulated results, but the trends remain consistent. This discrepancy is attributed to the omission of additional loss of components and possible impedance mismatch caused by the FR4 substrate in the fabrication. Table II compares the design of the proposed rectifier with previous works. For conversion efficiency over 70%, the proposed design by this paper achieves the widest dynamic range of 16 dB. The peak efficiency is 78% at a lower input power of 15 dBm. The circuit size of the proposed rectifier is the smallest compared to previous designs that achieve a wide dynamic range.

## IV. Conclusion

This brief has proposed a highly efficient HEMT-based rectifier with a wide dynamic range of input power. Thanks to the introduced self-bias network, a variable voltage can be generated to dynamically bias the HEMT. No external power supply or controller is needed. The rectifier can achieve high conversion efficiency in a wide operating power range. The proposed rectifier has achieved a dynamic input power range of 24 dB for over 60% conversion efficiency or 16 dB for over 70% conversion efficiency in the measurement. The proposed method has high adaptability and flexibility in complex application scenarios.

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