Characterizing and Modelling Non-Linear Rectifiers for RF Energy Harvesting

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Abstract

Radio Frequency Energy Harvesting and power transfer, using rectifying antennas, are increasingly seen as an enabling technology of power-autonomous devices. The non-linearity of the rectification element, the diode, adds challenges when experimentally characterizing and comparing the performance of different rectifiers, requiring complex measurement techniques to characterize a diode experimentally, and adds to the challenges of designing a matching network. This paper presents a method for characterizing the power conversion of a mismatched rectifier using a single-port vector network analyzer, omitting the need for impedance tuners and accurately reflecting the non-linearity of the diode. The proposed approach minimizes uncertainty sources in the test setup and shows close agreement with optimized harmonic balance simulation. Finally, harmonic balance simulation is utilized to compare the source and load impedance of the two most common rectifier topologies, a single series and a voltage doubler, acting as a guide for matching network and antenna design.

Introduction

RF energy harvesting and wireless power transfer could enable battery-free electronics in future Internet of Things networks. The power harvester and converter in RFEH is the rectifying antenna (rectenna) consisting of an electromagnetic resonator, an antenna, and an RF to DC converter, a rectifier. The RF-DC efficiency of a system is mainly dependent of the impedance matching between the antenna, the power conversion circuit, and the load. As opposed to a typical RF system where the antenna needs to be matched to 50Ω (the impedance of a typical low noise amplifier or a power amplifier), the rectenna needs to be matched to the varying impedance of the diode, which is highly non-linear and is dependent on the RF power level and frequency.

Characterizing the large-signal behavior of a non-linear system operating at microwave frequencies is a challenging task due to the wide variation in the system's impedance. In Radio Frequency Energy Harvesting (RFEH), while multiple antenna design approaches have been reported, the rectifier and matching network design are the bottleneck of an RFEH system [1]. Measured vector scattering parameters (s-parameters), commercial simulation tools such as harmonic balance, and analytical expressions could be used to calculate the input impedance of a diode [2]. Both simulation and analytical expressions rely on the semiconductor manufacturer's own electrical specification of the diode, which is usually only valid at certain power levels and frequencies, and often ignores the packaging parasitics. While these methods are useful when designing a matching network, evaluating the power conversion efficiency (PCE) without designing a matching network requires complex instrumentation and techniques, such as the source-pull method which utilizes impedance tuners [3], increasing the instrumentation cost and the complexity of the test setup.

This paper presents a new method to characterize a mismatched rectifier and validate the simulation or analytical models through large-signal characterization of the diode using a Vector Network Analyzer (VNA), demonstrating lower complexity compared to source-pull techniques and eliminating the need for impedance tuners. The proposed technique achieves good agreement with optimized harmonic balance simulation, based on the manufacturer's large-signal s-parameters, using commercial tools.

Measurement Setup

In order to connect the diode to the coaxial or waveguide interface (the VNA calibration plane) a microstrip test fixture is required for mounting the packaged diode. The diode-under-test (DUT) is placed on a 50-Ohm microstrip feed, and excited using a single VNA port, while terminated with a resistive load. The measurand in the proposed setup is the magnitude of the reflection coefficient $|S_{11}|$. While VNAs have previously been used to measure the input impedance of the rectifier at certain power levels [4], the power delivered to the DUT is different from the VNA power level due to reflection, which implies measurement inaccuracy. Furthermore, in order to directly measure the impedance of the diode, careful de-embedding of the test fixtures, often involving the design of a bespoke Through Reflect Line (TRL) calibration kit as in [4], is required to eliminate the phase difference inserted by the feed line which was not included in the standard VNA calibration.

The proposed characterisation technique considers the magnitude of the reflected wave to accurately measure the power delivered to the diode. Furthermore, by ignoring the phase component, a standard test fixture can be used without de-embedding. To explain, the S_{11} magnitude is more resilient to change and is only affected by the cable losses which can be measured separately and are included in a standard VNA calibration. Fig. 1 shows the proposed measurement setup using a VNA and the equivalent circuit showing the reflected power measurement.

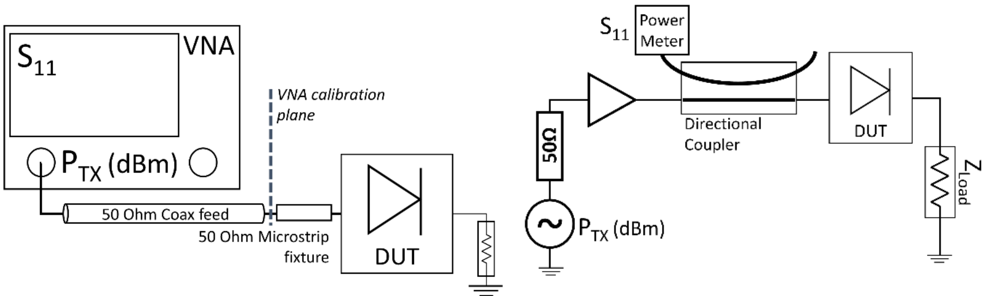

Fig. 1. Proposed broadband diode characterisation setup (left) and the equivalent schematic (right).

Equation (1) [3], commonly used to calculate the efficiency of a rectifier, can be modified to use the net received power, based on the reflection coefficient measured at different power levels, to calculate the power conversion efficiency (PCE) assuming no power is reflected from the diode.

$$PCE_{end-end} = \frac{P_{DC}}{P_{RF}} = \eta_{matching}\eta_{diode}\eta_{DC\ load} \quad (1)$$

$$PCE_{mismatched} = \frac{P_{DC}}{(1-|\Gamma|^2)P_{TX}} = \eta_{diode}\eta_{DC\ load} \quad (2)$$

A commercial Schottky diode (Skyworks SMS7630-079) is used in this experiment due to the availability of complete SPICE parameters from the manufacturer, which enables comparison of the proposed technique to harmonic balance simulation. The VNA used in this experiment, Rohde and Schwarz ZVB4 (capable of outputting up to 13 dBm), has been calibrated using a standard Through, Open, Short, Transmission (TOSM) calibration kit and used to characterize the diode. Should higher power levels than a VNA's capabilities be required, the setup shown in the equivalent schematic, Fig. 1, can be realized using discrete components with attenuators at the power monitor for instrument protection.

The power reflection coefficient $|S_{11}|^2$ has been measured at different power levels at 2.2 GHz. The frequency was chosen as a representative of LTE ambient cellular harvesting and license-free 2.4 GHz wireless power transfer. Fig. 2 shows the measured and simulated power reflection coefficients, with their close agreement demonstrating the potential of the S_{11} acting as an accurate indicator of the diode's performance. The higher accepted power is due to the variation in the input impedance discussed in the next section.

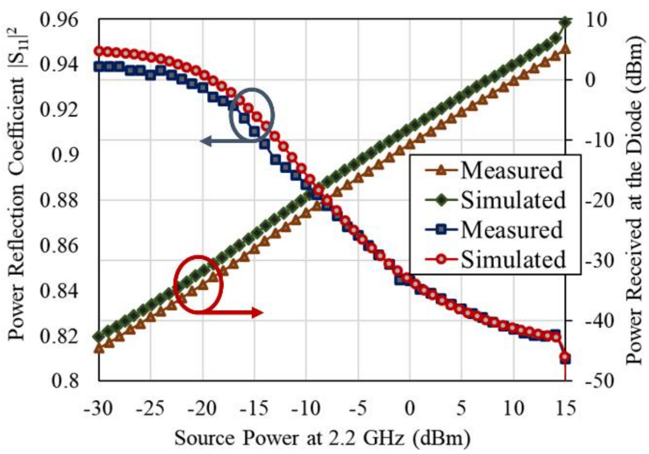

Fig. 2. Measured and simulated (ADS harmonic balance) power reflection coefficient and received power at the diode's input, showing close agreement. Hence, validating the approach of relying on S_{11} to measure effective power at the diode.

By measuring the DC voltage across the load resistor, the PCE of the diode can be calculated using the modified PCE formula (2). Fig. 3 shows the measured and simulated PCEs, using equations 1 (standard) and 2 (proposed), showing a close agreement and giving a good prediction of the diode's PCE when in real operation allowing rapid comparison of different diodes without designing matching networks. The x-axis values were calculated using the reflection coefficient, as opposed to relying on the source power controlled using the VNA.

$$P_{effective} = (1 - |\Gamma|^2)P_{TX} \qquad (3)$$

While the simulated and measured PCE show a close agreement when utilizing (2), a key limitation of the proposed method in predicting the PCE of the diode is that the ideal maximum achievable PCE is obtained using a 50Ω source. To explain, in real operation the diode will be fed using a high impedance source, either a high impedance inductive antenna as in [1] or a 50Ω antenna with an impedance transformer. As a result, the practical rectenna PCE will be different from that in Fig. 3, hence, this method is only valid as a mean of validating a simulation or an analytical model which can then be used to calculate the PCE of the diode when excited using a 50Ω source.

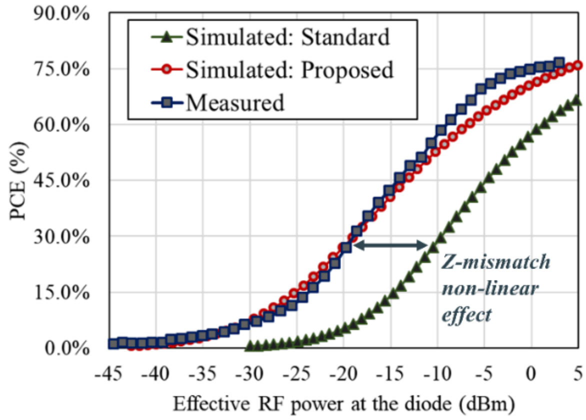

Fig. 3. Measured and simulated power conversion efficiency of a SMS7630s single-series diode at 2.2 GHz, Z_{load}=1.5 kOhm, showing improved accuracy over the standard approach using the effective RF power.

Rectifier Impedance Analysis and Topologies Comparison

The harmonic balance model constructed in Keysight ADS uses the SPICE parameters provided by the manufacturer and is optimized based on the measured S_{11}. Fig. 4 shows the diode's equivalent circuit and the simulation power monitors used to imitate the operation of the VNA and the DC voltage probe in the previous section.

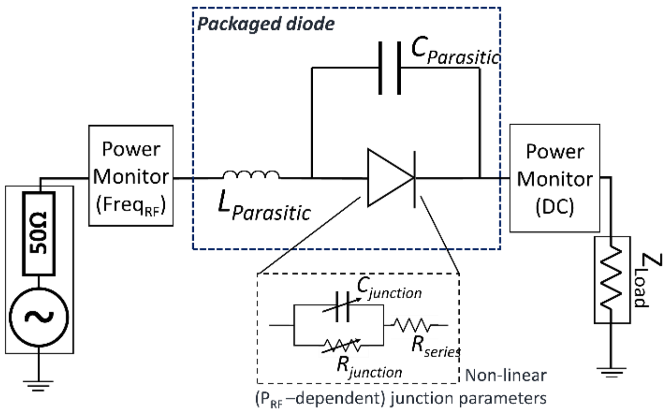

Fig. 4. Rectifier model simulated using harmonic balance, showing the packaging parasitic and the non-linear junction parameters.

Two rectifiers based on the SMS7630, a single-series and a voltage-doubler, have been modelled with the aim of demonstrating the effect of the rectifier's topology on the input and output impedance. While the input impedance of an ideal diode is high (approaching open-circuit impedance), the parasitic inductance and capacitance act as an impedance transformer resulting in frequency-dependent variation of the impedance, and a highly capacitive imaginary component especially at lower frequencies. On the other hand, at frequencies approaching the diode's cut-off frequency, the impedance of the diode approaches 50Ω (matched impedance) and result in the RF signal propagating to the output without rectification, therefore yielding low to zero DC power output. The Smith chart shown in Fig. 5 demonstrates the variation in impedance over frequency, and the usable range of frequencies where the diode is capable of rejecting harmonics and rectifying the input signal.

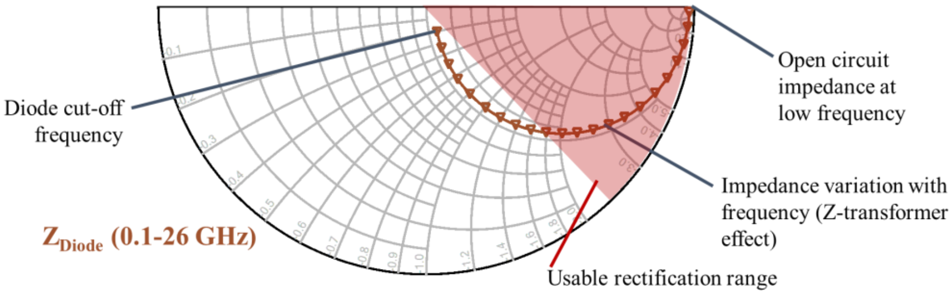

Fig. 5. Smith chart of the simulated input impedance of the rectifier (computed from the vector S_{11}), showing the range of frequencies where the diode is useful for rectification, and the impedance variation over frequency.

The rectifier topology and the input power level play a significant role in varying the input impedance, with the variation increasing in the forward bias region of the diode's IV curve as seen in Fig. 6. Moreover, external components such as the series capacitor in a voltage doubler reduce the observed real-input impedance

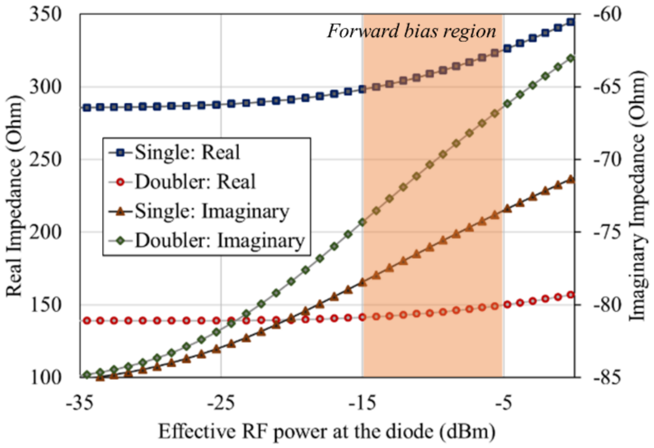

Fig. 6. Simulated input impedance at 2.2 GHz, Z_{load}=1.5 kΩ of the single series and the voltage doubler rectifiers based on the SMS7630.

The final stage in the impedance matching chain of a rectenna is the load impedance, where the RF section of the rectenna can be modelled as a Thevenin voltage source with a series resistance, usually in the order of 1-10 kΩ depending on the source impedance and the rectifier topology. As in Fig. 7 a voltage doubler, and subsequently a higher-order multiplier result in a higher optimal load impedance which increases the DC voltage output of the system.

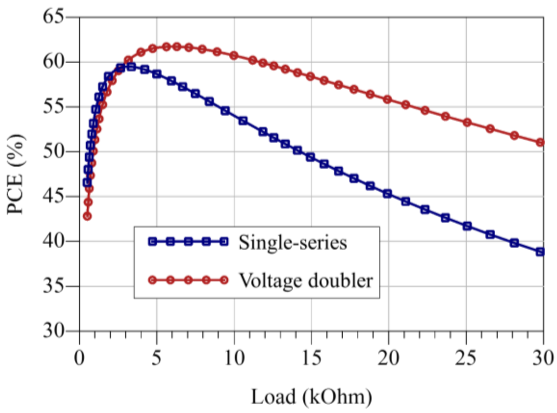

Fig. 7. Optimal load impedance of a single-series and a voltage-doubler rectenna, excited using a 50 Ohm source.

Conclusion

This paper has presented a new simple and accurate method of characterizing non-linear rectifiers using a single-port VNA, enabling a standardized rapid comparison of different diodes as well as optimizing and evaluating the validity of simulation and analytical models. The optimized simulation model has been utilized to study a RFEH system from an impedance matching perspective, analyzing the rectifier's impedance under different operation conditions.

References

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