mm-Wave Tunnel Diode-Based Rectifier for Perpetual IoT

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***Abstract*—In this effort, the authors propose, for the first time, a tunnel diode-based rectifier for 5G/mm-wave energy harvesting. The tunnel diode, a unique semiconductor device with a negative resistance region, is often used in oscillator and amplifier circuits. However, this work exploits one new property for tunnel diodes, that sets a strong foundation for 5G long-range self-powered IoT nodes. This property is verified by the high sensitivity/low turn-on power and self-voltage-regulating behavior of the tunnel diode-based rectifier over a large range of load variations. Compared to a Schottky diode-based rectifier at 28GHz, the tunnel diode counterpart demonstrates a superior compatibility with the ambient mm-wave energy harvesting challenges and needs.**

Keywords—Flexible electronics, W-band, PCE, 5G, RF energy harvesting, IoT, wireless power transfer.

I. Introduction

The current era is witnessing a huge interest in the capabilities of the new generation (5G) of cellular networks that uses large bandwidths above 20GHz necessary for the continuous increase in data traffic. Billions of IoT devices are estimated to be installed in the next couple of years, serving a wide range of applications such as wearables, smart agriculture and smart cities. Power autonomy is becoming a necessity, especially with the emergence of green technologies and the need to eliminate batteries and chemical waste. Electromagnetic energy harvesting is a very attractive technology because it relies on scavenging power from thin air and converting it to dc power. At 5G bands (above 24GHz), the amount of allowable transmitted power—according to FCC regulations—reaches 75dBm, a valuable parameter that enables long-range harvesting. However, the choice of the rectifier element at mm-wave frequencies becomes trickier compared to its lower frequency counterpart, since the package parasitics effect becomes more significant. Schottky diodes are the number one choice when it comes to designing rectifiers for electromagnetic harvesting because of their inherently low turn-on voltages—which provide high efficiency—as well as their technological maturity. However, with the increase in frequency, their high junction capacitance makes the rectification above 10GHz more challenging, especially for input powers below 0dBm.

An example illustrating the use of Schottky diodes for harvesting at mm-wave frequencies was presented in [1], where the authors used a gallium arsenide (GaAs) beam lead Schottky barrier diode from Macom (MA4E2038 model) to design a mm-wave rectifier operating at 28GHz. The system was able to turn on at a power of around -10dBm, that outperforms other systems available in the literature using similar commercial Schottky diodes. A 15dB improvement in the sensitivity of the Schottky diode-based rectifier was observed in [2] where the authors used a W-band zero bias diode from Virginia diodes. However, due to its extremely small dimensions (230µmx580µm), the integration of this diode in a die form was more challenging.

In this paper, the authors propose a new approach for the design of a self-voltage-regulating, load-independent and high-sensitivity (down to -30dBm) rectifier that relies on a commercial tunnel diode for the powering of IoT nodes and wearable devices. A rectifier at 28GHz was designed, fabricated and measured, resulting in a performance that competes with available Schottky diodes similarly packaged for input powers below 0dBm, enabling by that a greater efficiency in realistic ambient harvesting conditions.

II. Tunnel Diode IV Curve

A tunnel diode is a type of semiconductor device heavily used in oscillator circuits up to mm-wave frequencies because they are not limited by transit-time effects. A tunnel diode's behavior is governed by the quantum tunneling effect that results in a unique IV curve portraying a negative differential resistance region, a very desirable feature for amplification purposes. The tunnel diode offers a wide range of functions depending on the region where it is being operated. In this work, the MBD2057-E28X tunnel diode from Aeroflex was used. Its IV curve is presented in Fig. 1.

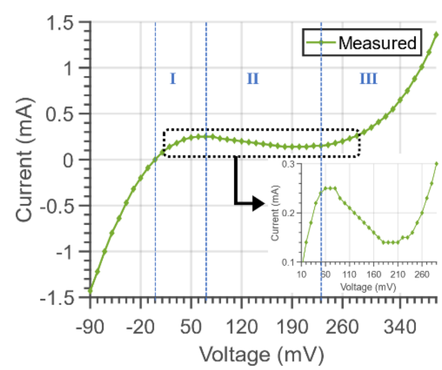


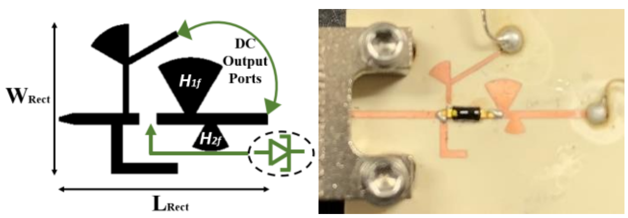
Fig. 1: IV curve of the MBD2057-E28X tunnel diode.

At zero-bias in region I, the diode can be used for harvesting applications. In the negative differential resistance region represented as region II, the diode can be used as an oscillator or a reflection amplifier. For large biases (region III), the tunnel diode behaves like a Schottky diode and can be implemented in mixer applications. This diode was characterized in [3] and its parameters were extracted for two different packages: MBD2057-C18 (die form) and MBD 2057-E28X (traditional diode package).

III. Tunnel Diode-Based Rectifier

A. Rectifier's Design and Fabrication

The rectifier is designed and simulated at 28GHz with the Agilent Advanced Design System (ADS) software, using large signal S-parameters (LSSP) and harmonic balance (HB) simulations. The via-less layout along with the fabricated prototype are presented in Fig. 2, consisting of a 50Ω feed line followed by an L-matching network at the input of the diode. At its output, a virtual short-circuit for the fundamental and second harmonic frequencies is achieved through two quarter-wave radial stubs. In the upper side of the design, a quarter wave radial stub is providing a virtual short-circuit (S.C.) used to isolate a DC port on this side of the rectifying diode; the other DC port is located after the diode. The active area of the designed rectifier on LCP substrate (h = 0.18mm and ε_r = 3.02) is 9mm x 7mm. The circuit was printed using inkjet-printed masking technique followed by etching.



(a) (b)

Fig. 2: (a) Layout of the active area of the designed 28GHz tunnel diode-based rectifier: L_{Rect} = 9mm and W_{Rect} = 7mm, (b) photo of the fabricated rectifier on LCP substrate.

B. Rectifier's Measured Performance

The output voltages of the fabricated tunnel diode-based rectifier were measured and plotted in Fig. 3 with respect to input powers for different load values. The rectifier was able to turn on at a power as low as -30dBm and displayed a voltage saturation at around 4dBm with a unique plateau starting at 0dBm. This behavior gives the diode a self-voltage-regulating property at higher power levels, where the output voltage stops increasing with the increase of the power at the input of the rectifier. Another distinctive observation is the extremely low dependence of the output voltage on the load attached to the rectifier. The plots presented in Fig. 3 cover low loads values such as 1kΩ up to an almost open load of 1MΩ and highlight the ability of the diode in preserving an almost constant regulated output voltage under large changes in the load values. The output voltage of the tunnel diode-based rectifier was also compared to a Schottky diode-based rectifier previously designed in [1] at 28GHz using the Macom MA4E2038 diode. Fig 4 compares the two rectifiers with respect to the power received at their inputs. This result demonstrates the superiority of the tunnel diode at lower power levels (less than 0dBm) and that of the Schottky diode for power levels exceeding 1dBm. The observed performance demonstrates that the tunnel diode is equipped with a higher sensitivity and highlights its ability to turn ON and rectify at extremely low power levels, enabling by that a greater efficiency in realistic ambient harvesting conditions.

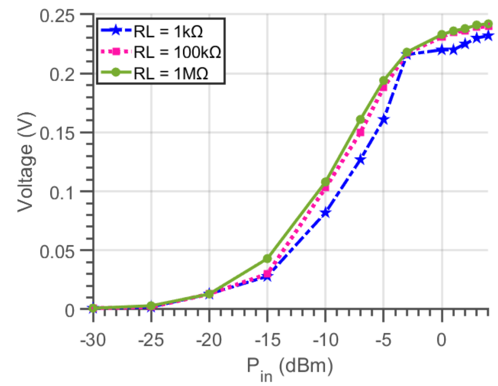


Fig. 3: Measured voltage results of the tunnel diode-based rectifier vs input powers for different load values.

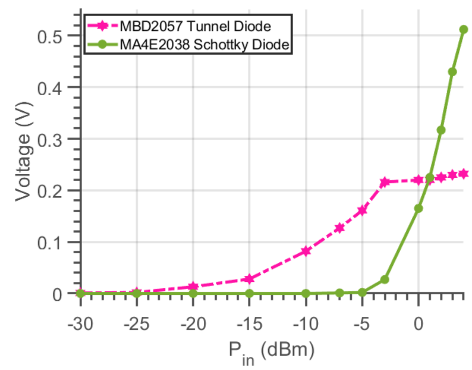


Fig. 4: Comparison between the measured voltages of a tunnel diode-based rectifier and a Schottky diode based-rectifier vs input powers for R_L = 1kΩ.

IV. Conclusion

This work presented the design, fabrication and measurement of a tunnel diode-based rectifier at 28GHz. The circuit demonstrated an unprecedented independence on the load values variations and a self-voltage-regulating behavior outlined by the plateau observed around 0dBm. This rectifier equipped with a very high sensitivity/low turn-on power may trigger the emergence of 5G-power IoT nodes.

References

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