Flexible W-Band Rectifiers for 5G-powered IoT Autonomous Modules

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***Abstract*—The new regulatory and technological mm-wave landscape has opened a plethora of opportunities for the powering of flexible and wearable IoT motes, powered by the harvesting of such electromagnetic waves. Nevertheless, the availability and integration of rectifying diodes for such devices are a source of challenges. In this effort, the authors chose a potential candidate of a rectifying element, a W-band Zero-Bias Detector, and analyzed its characteristics, by fine-tuning a set of rectifiers covering all of the aforementioned bands, ranging from 24GHz to 81GHz. The simulated performance of these flexible rectifiers was analyzed and demonstrated their adequate harvesting performance for this application. This study thereby sets the foundation for the development of a new class of low-cost flexible and printable 5G-powered IoT devices and systems.**

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

I. Introduction

The constant increase in data traffic through wireless networks has led to the development of a future generation (5G) of cellular networks using the large bandwidths available above 20 GHz. Currently, a rapid development in the field of mm-wave and IoT technologies is taking place, with billions of IoT devices estimated to be installed in the next couple of years. Accordingly, new ways to achieve power autonomy are required, eliminating the need to constantly charge and replace batteries. Electromagnetic energy harvesting in the 5G bands (above 24GHz) is an attractive technology due to the high transmitted powers recently allowed by the FCC and their non-US homologues. A key component in the design of electromagnetic energy harvesters is the choice of the rectifying element. Schottky diodes have been and still are the component of choice for rectifiers because of their inherently low turn-on voltages—which provides high efficiency—as well as their technological maturity. However, rectification at high frequencies using most commercial Schottky diodes is challenging, due to their high junction capacitance, making rectification above 10GHz extremely difficult [1].

In [2], the authors used a gallium arsenide (GaAs) beam lead Schottky barrier diode from Macom (MA4E2038 model) to design a mm-wave rectifier operating at 24GHz. Another Macom diode, the (MA4E1317) GaAs flip chip Schottky barrier diode was used in [3] for the same purpose. However, the same group later proposed [4] a 94GHz energy harvester using a mm-wave GaAs Schottky diode from Virginia Diodes (VDI ZBD) that demonstrated very good performance.

In this paper the authors propose an approach that leverages the performance of this diode for the powering of IoT nodes and wearable devices by reporting its properties, for use in low-cost printed flexible and wearable IoT systems. The rectifying diode used in this work is a W-band Zero Bias Detector (ZBD) from Virginia diode. The integration of this very small die that is 230µm wide and 580µm long with the packaging substrate was made possible as seen in Fig. 1 through the inkjet-printed-based technique of die attach, dielectric ramp and interconnect lines proposed in [5].

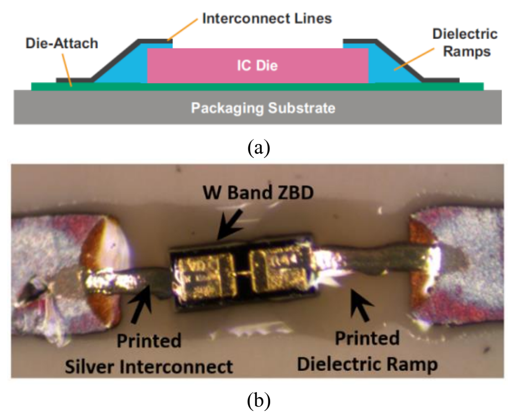

Fig. 1: (a) Cross-section of the inkjet-printed 3D interconnects [5], (b) Integration of the W-band ZBD (230µmx580µm) on a flexible LCP substrate

This work reports the simulated performance of such integrated diodes to enable the harvesting of mm-wave energy in the new and growing mm-wave landscape. A fine tuning in the rectifier's parameters allows rectification to occur in five different frequency bands spanning from 24GHz to 81GHz. The paper is divided as follows: Section II of this paper presents the design of the W-band rectifier. Section III reports the simulated voltage and efficiency results in the considered 5G bands. The paper is then concluded in section IV.

II. Rectifiers Design

The design of a rectifier operating up to 81GHz requires the use of a diode with low series resistance and a low junction capacitance. The W-band Zero Bias Detector (ZBD) from Virginia Diodes offers all the above characteristics and was, therefore, used in this work. Prior to the design, the Shockley diode parameters were recovered using the IV curve and the diode's basic parameters provided on the datasheet along with the model presented in [4] for a Schottky diode from the same company.

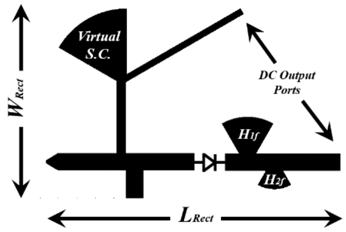

Fig. 2: Layout of W-band rectifier with *Lrect = 5mm* and *Wrect = 3mm*

The rectifier is designed and simulated with the Agilent Advanced Design System (ADS) software, using large signal S-parameters (LSSP) and harmonic balance (HB) simulations. The via-less layout presented in Fig. 2, consists 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 H_{1f} and H_{2f} 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. Minimal tuning in the design's parameters such as matching network and radial stubs, allowed the operation to be moved from one band to another within the 5G licensed and unlicensed/shared bands. The simulated rectifiers are designed to operate at 28GHz, 38GHz, 60GHz, 68GHz and 79GHz, falling within 24-29GHz, 37-40GHz, 57-64GHz, 64-71GHz and 76-81GHz bands respectively. An ultrabroadband operation of the rectifier, covering several bands at a time, is also possible by combining multiple matching networks or implementing tapering techniques [6]. The average active area of the designed rectifier on LCP substrate (h = 0.18mm and ε_r = 3.02) is 5mm x 3mm.

III. Rectifiers' Simulated Performance

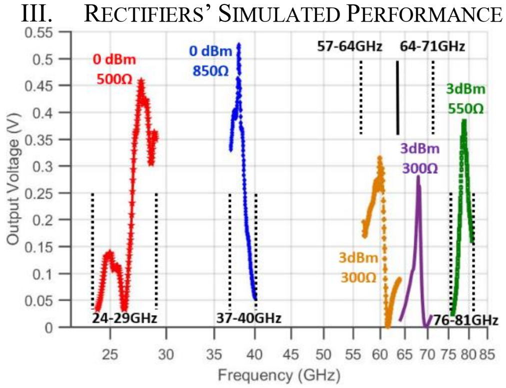

Fig. 3: Simulated output voltages versus frequency for the five considered 5G bands at their optimal loads and input powers

The output voltage of every designed rectifier was tested over its respective band at their optimal loads and input powers, as shown in Fig. 3. This graph presents the five plots falling within the considered licensed and unlicensed 5G bands. The diode is able to provide rectification over most of the targeted bands with an optimal performance at the design frequency. For example, the simulated rectifier at 38GHz outputs a DC voltage over the whole band from 37 to 40GHz while reaching a peak performance (at 38GHz) of 0.53V at 0dBm input power and a load of 850Ω. Their power conversion efficiency (PCE) was also evaluated, as shown in Fig. 4 at the design frequencies, and still with optimal loads, with respect to input power spanning from -30dBm—the lowest power and maximum sensitivity achieved by the diode—to 5dBm. The simulated data shows that the rectifier can achieve a maximum efficiency of 43%, 45%, 16%, 13% and 15% with the W-band at 28GHz, 38GHz, 60GHz, 68GHz and 79GHz, respectively. The diode is, therefore, demonstrated to potentially enable mm-wave harvesting for flexible, printable and wearable devices operation in any of these new frequency bands.

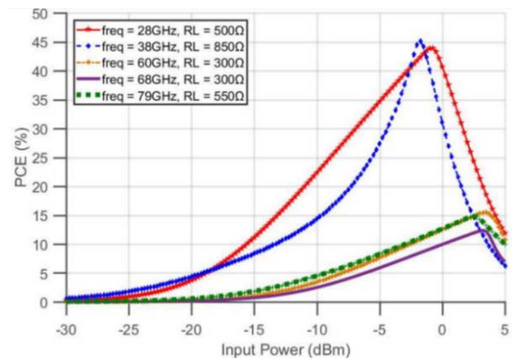

Fig. 4: Simulated efficiency results for the five designed rectifiers versus input power at their optimal loads

IV. Conclusion

The simulations presented in this study demonstrates the ability for the studied diode to provide at least 10% PCE if used in any of the open mm-wave bands from 24GHz to 81GHz. This result provides the groundwork for the exploration of mm-wave harvesting and its implementation for the powering of low-cost additively-manufactured flexible and wearable 5G and mm-wave-powered motes for the IoT. The integration of a fully-additively-manufactured ultra-broadband W-band harvester for IoT modules will soon be reported.

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