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PIT 2025**

# **Composición de Textos y Gráficos con LaTeX**

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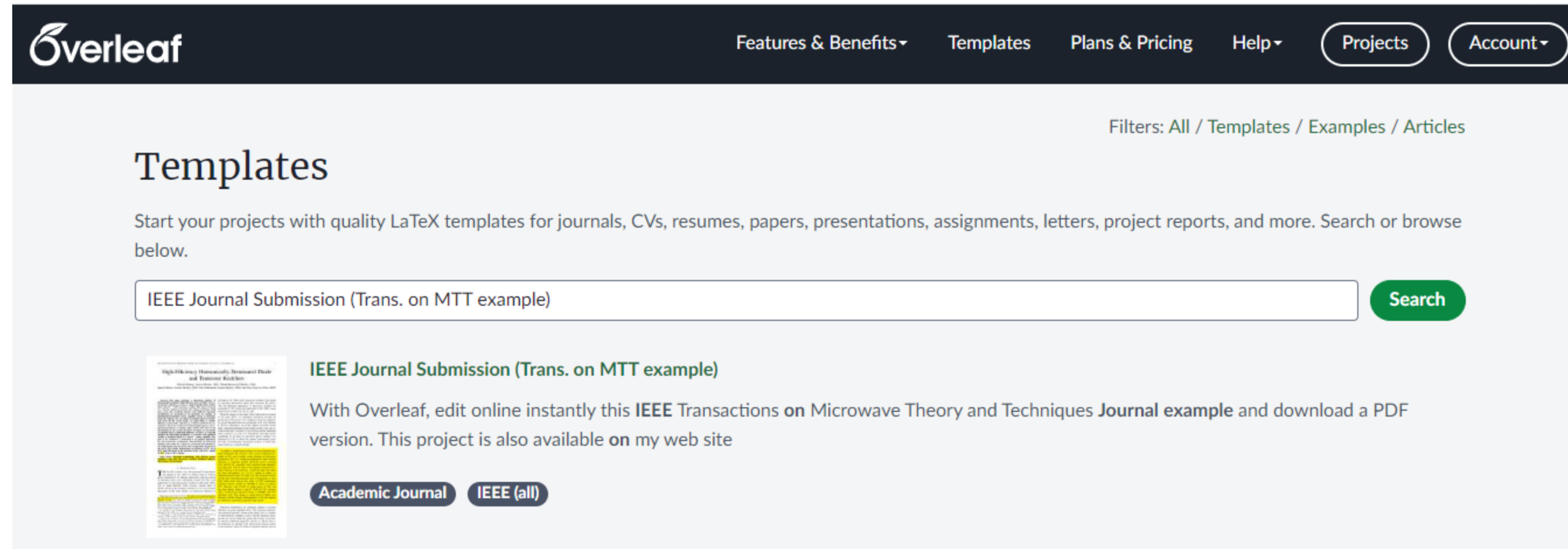
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IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 60, NO. 12, DECEMBER 2012

1

## High-Efficiency Harmonically-Terminated Diode and Transistor Rectifiers

Michael Roberg, *Student Member, IEEE*, Tibault Reveyrand, *Member, IEEE*,  
Ignacio Ramos, *Student Member, IEEE*, Erez Falkenstein, *Student Member, IEEE*, and Zoya Popović, *Fellow, IEEE*

**Abstract**—This paper presents a theoretical analysis of harmonically-terminated high-efficiency power rectifiers and experimental validation on a class-C single Schottky-diode rectifier and a class-F<sup>-1</sup> GaN transistor rectifier. The theory is based on a Fourier analysis of current and voltage waveforms which arise across the rectifying element when different harmonic terminations are presented at its terminals. An analogy to harmonically-terminated power amplifier theory is discussed. From the analysis, one can obtain an optimal value for the DC load given the RF circuit design. An upper limit on rectifier efficiency is derived for each case as a function of the device on-resistance. Measured results from fundamental frequency source-pull measurement of a Schottky diode rectifier with short-circuit terminations at the second and third harmonic are presented. A maximal device rectification efficiency of 72.8% at 2.45 GHz matches the theoretical prediction. A 2.14 GHz GaN pHEMT rectifier is designed based on a class-F<sup>-1</sup> power amplifier. The gate of the transistor is terminated in an optimal impedance for self-synchronous rectification. Measurements of conversion efficiency and output DC voltage for varying gate RF impedance, DC load and gate bias are shown with varying input RF power at the drain. The rectifier demonstrates an efficiency of 85% for a 10 W input RF power at the transistor drain, with a DC voltage of 30 V across a 98  $\Omega$  resistor.

**Index Terms**—harmonic terminations, high efficiency power amplifiers, load pull, microwave rectifiers, nonlinear analysis, time-domain measurements

### I. INTRODUCTION

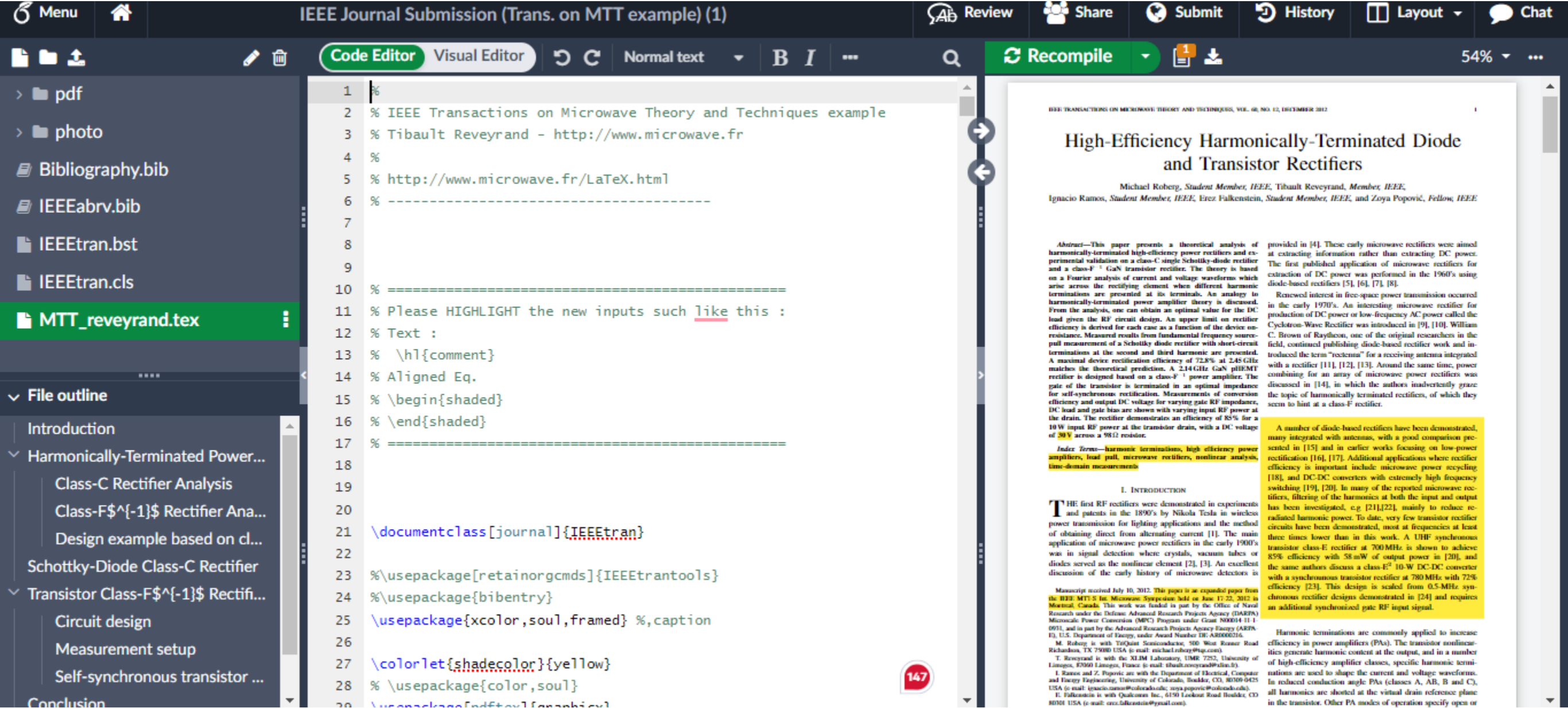
THE first RF rectifiers were demonstrated in experiments and patents in the 1890's by Nikola Tesla in wireless power transmission for lighting applications and the method of obtaining direct from alternating current [1]. The main application of microwave power rectifiers in the early 1900's was in signal detection where crystals, vacuum tubes or diodes served as the nonlinear element [2], [3]. An excellent

provided in [4]. These early microwave rectifiers were aimed at extracting information rather than extracting DC power. The first published application of microwave rectifiers for extraction of DC power was performed in the 1960's using diode-based rectifiers [5], [6], [7], [8].

Renewed interest in free-space power transmission occurred in the early 1970's. An interesting microwave rectifier for production of DC power or low-frequency AC power called the Cyclotron-Wave Rectifier was introduced in [9], [10]. William C. Brown of Raytheon, one of the original researchers in the field, continued publishing diode-based rectifier work and introduced the term "rectenna" for a receiving antenna integrated with a rectifier [11], [12], [13]. Around the same time, power combining for an array of microwave power rectifiers was discussed in [14], in which the authors inadvertently graze the topic of harmonically terminated rectifiers, of which they seem to hint at a class-F rectifier.

A number of diode-based rectifiers have been demonstrated, many integrated with antennas, with a good comparison presented in [15] and in earlier works focusing on low-power rectification [16], [17]. Additional applications where rectifier efficiency is important include microwave power recycling [18], and DC-DC converters with extremely high frequency switching [19], [20]. In many of the reported microwave rectifiers, filtering of the harmonics at both the input and output has been investigated, e.g. [21], [22], mainly to reduce re-radiated harmonic power. To date, very few transistor rectifier circuits have been demonstrated, most at frequencies at least three times lower than in this work. A UHF synchronous transistor class-E rectifier at 700 MHz is shown to achieve 85% efficiency with 58 mW of output power in [20], and the same authors discuss a class-F<sup>2</sup> 10-W DC-DC converter

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