BRUGES
9-12 SEPTEMBER
ESSERC 2024

GreEnergy
Power from optical antennas

2nd GreEnergy Workshop
Wideband Optical Antennae for Use in Energy Harvesting Applications

Energy Harvesters: Challenges in Circuit Design

Mesut Inac, IHP Microelectronics GmbH

Outline

- Introduction
- Simulation environment
- Rectenna as a circuit model
- Possible matching configurations
- Circuit Design in GreEnergy
- Conclusion

Outline

- Introduction
  - IHP Microelectronics
  - Circuit-Design Department
  - Rectification
  - Matching
- Simulation environment
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Introduction | IHP Microelectronics

Ca. **350** employees

Third-party funds (2020, without FMD): € 17. 3 million

Institutional funding (2020): €33.5 million (of which €21 million operating budget, €12.5 million investment funds)

Vertical research concept from materials research and technology to circuits and systems

Unique selling point of a **200 mm pilot line** for state-of-the-art BiCMOS technologies, operated under **industry-oriented conditions**, **24/7**, for the provision of prototypes and small batches

Bridging the gap between basic research and application through close cooperation with universities and industry

Qualified technological platform with direct access for science and industry

Introduction | IHP Microelectronics

- Vertical Approach
- 5 Scientific Departments
  - Materials Research
  - Technology
  - Circuit Design
  - System Architectures
  - Wireless Systems

Cleanroom Area
- ~ 1.000 m² class 1

Technology
- RF SiGe BiCMOS

Wafer Diameter
- 200 mm

Capacity
- 100 Wafer Starts/Week

Technology Level
- 0.25 µm & 0.13 µm

Operation Mode
- 24 h, 7 Days/Week

SiGe BiCMOS Preparation Time
- ≥ 1.7 Days/Level

Introduction | Circuit Design @ IHP

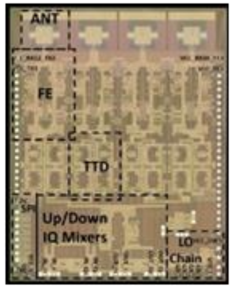
- Circuit-Design Department: 4 Research Groups

High Data-Rate Communication Circuits
- Wireless data communications
- Broadband circuits for optical fiber communications
- Monolithic-integrated EPIC

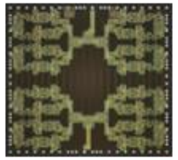
Millimeter-Wave & THz Sensor Circuits
- mm-Wave wireless communication
- Sensing systems for mm-wave to sub-THz frequency range
- RF to millimeter-wave biosensors
- Hetero-integrated SiGe-InP

Converters & High-Speed Logic Circuits
- ADC and DAC in GHz sampling range
- High-speed logic
- Serializer and de-serializer ICs
- Neuromorphic computing

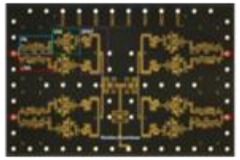
Energy-Efficient Wireless & Analog Circuits
- Wake-up receiver
- Impulse-Radio Ultra-Wide Band (UWB)
- Sensor readout circuits
- Radiation-hard RF circuits
- Applications at cryogenic temperatures



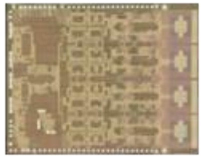
D-Band 200Gbps Transceiver



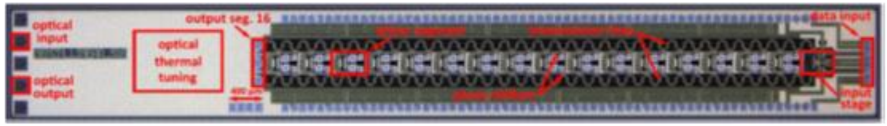
Ka Band (5G)



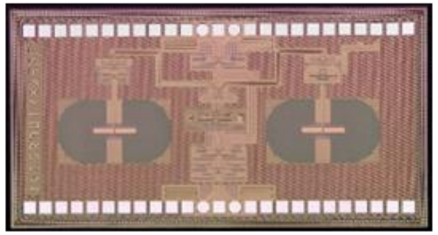
V Band



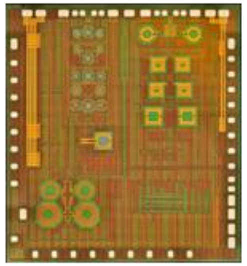
D Band (6G)



Segmented MZ-Modulator Driver



240GHz Radar Transceiver



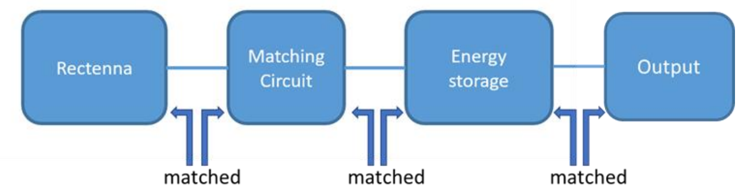
UWB Transceiver

Introduction

- Energy harvester architecture and operation

- Efficiency
  - Reflections
  - Impedance matching
  - Power transfer

- Regulated supply
  - Stable
  - Adaptable
  - Consumes power (!!!)



Impedance matching:

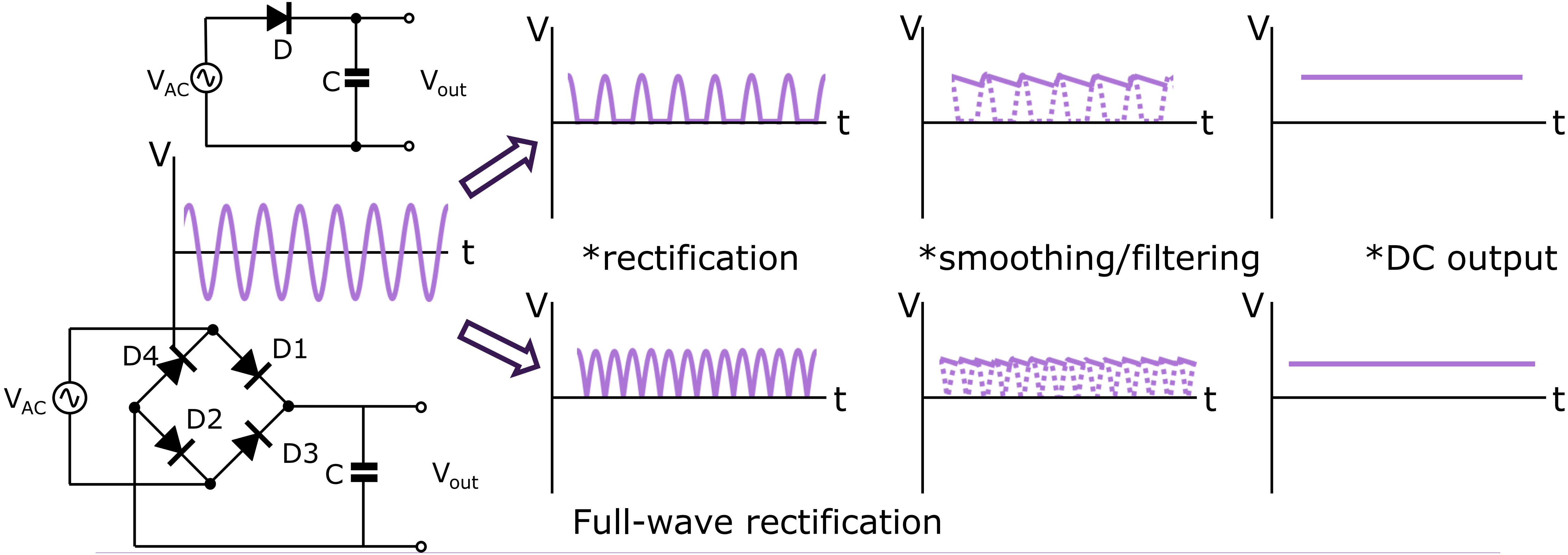
$$Z_{load} = Z^{*}_{source}$$

$$R_{load} = R_{source} \qquad X_{load} = -X_{source}$$

Regulated and unregulated under different loads

Introduction | Rectification

- Rectification
  - AC → DC



Introduction

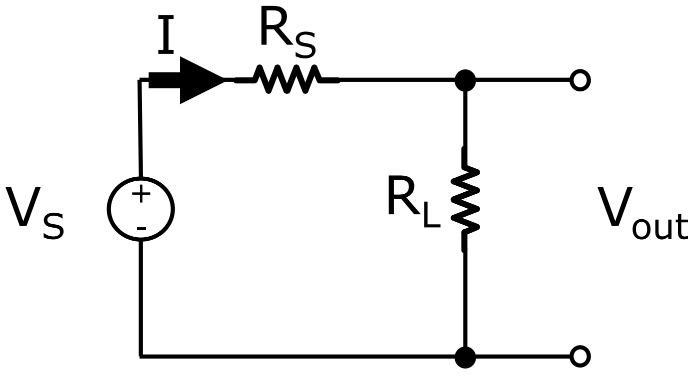
- Impedance matching
  - Maximum power transfer
  - Maximum efficiency
- Power delivered to load:

$$P_L = I^2 R_L = \left(\frac{V_S}{R_S + R_L}\right)^2 R_L = \frac{V_S^2}{\frac{R_S^2}{R_L} + 2R_S + R_L}$$

Minimize denominator to maximize P_L

$$\frac{d}{dR_L}\left(\frac{R_S^2}{R_L} + 2R_S + R_L\right) = 0 \qquad \frac{R_S^2}{R_L^2} = 1$$

$$R_L = \pm R_S \qquad Z_L = Z_S^*$$



Efficiency perspective:

$$\eta = \frac{P_L}{P_{Total}} = \frac{I^2 R_L}{I^2 (R_L + R_S)} = \frac{R_L}{R_L + R_S} = \frac{1}{1 + {R_S}/{R_L}}$$

$$\boxed{I \neq 0}$$

$$R_L \to \infty; I \to 0$$

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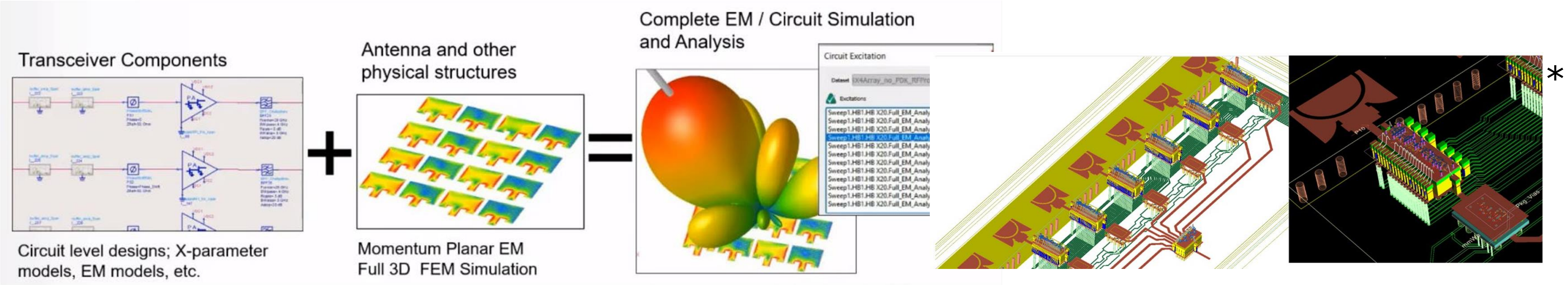
Simulation Environment

- Requirements for a simulation environment:
  - Schematic simulations
  - Electromagnetic solver
  - Packaging and interconnects

Keysight ADS®



*Keysight RF-pro website

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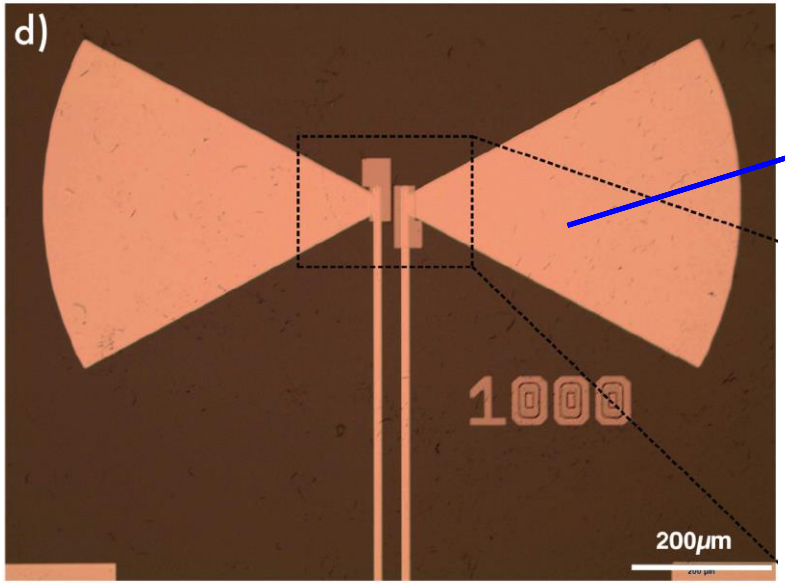
Rectenna as a Circuit Model

- Many possible models exist
- Starting from simple template
- Fitting with the measurements



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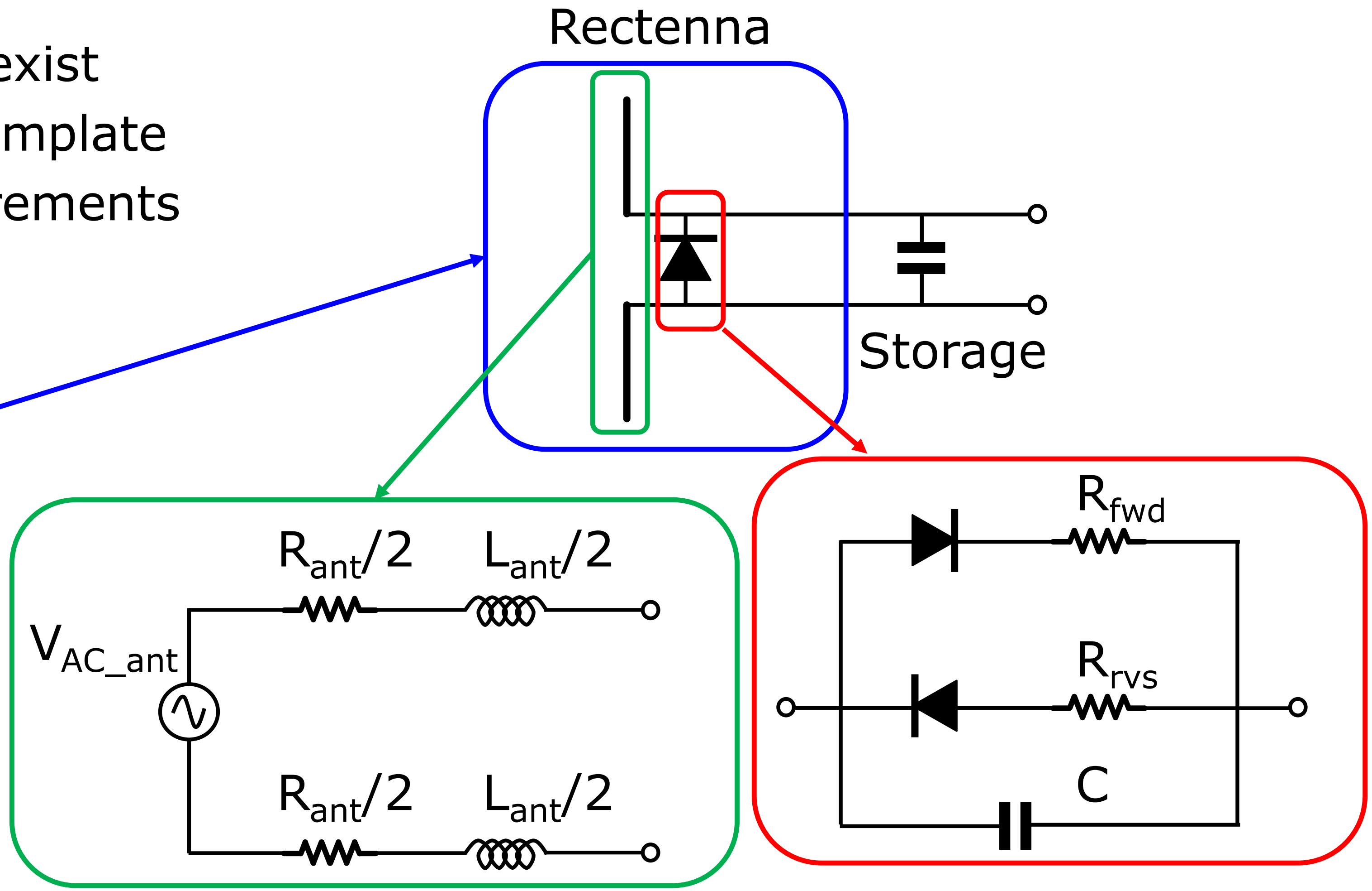

*Hemmetter, et.al. 2021, Terahertz Rectennas on Flexible Substrates Based on One-Dimensional Metal-Insulator-Graphene Diodes

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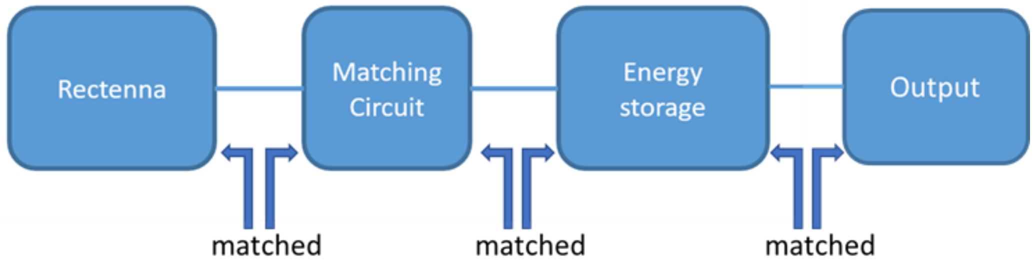
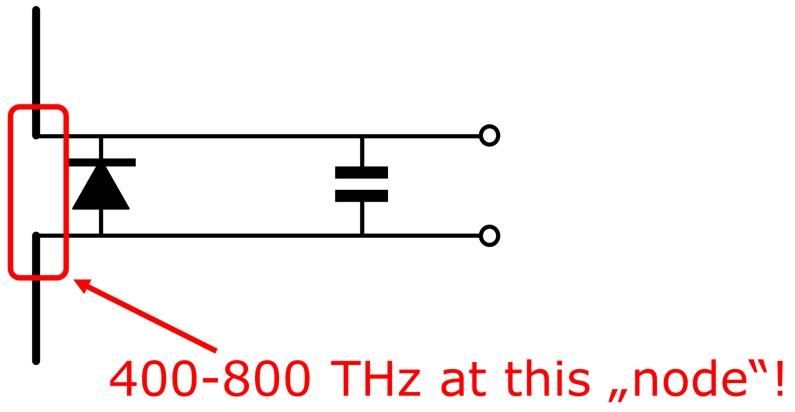
Possible Matching Configurations

- Matching aspects
  - DC matching
    - After AC→DC conversion
  - High frequency matching
    - Antenna load
  - Constructing arrays
    - Collecting more currents



- Integration
  - On board: low frequency to quasi DC
  - On chip: high frequency portions of the system (if any in this case)



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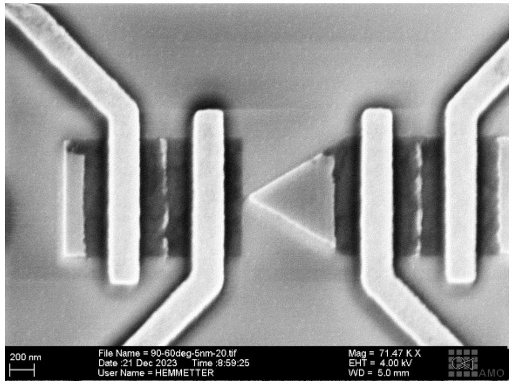
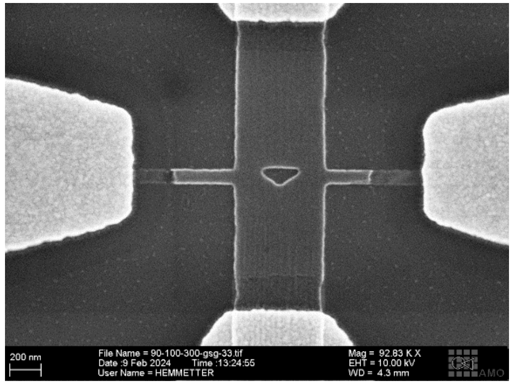
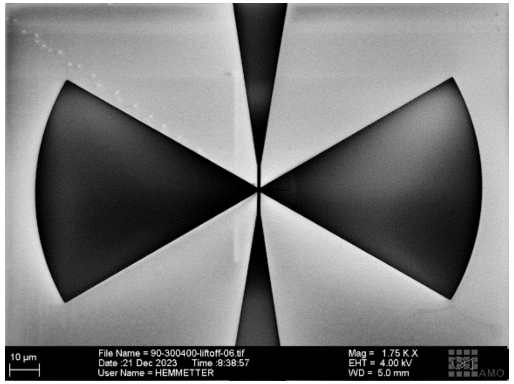
Circuit Design in GreEnergy

- Devices
  - Nanoantenna
  - Geometric diode
  - Ballistic diode
  - Supercapacitor





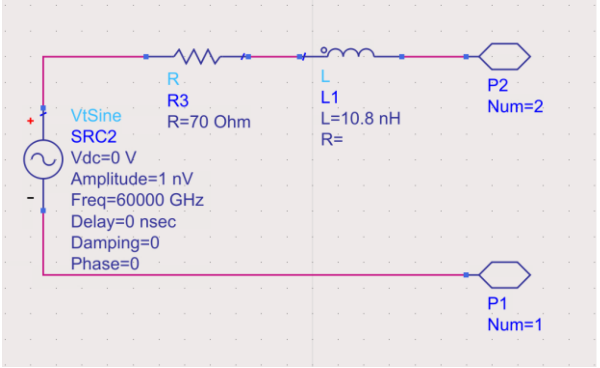


- Models
  - Extracted from measurement results
  - Library in the simulation environment
  - Enable the design and optimization of circuit blocks and systems

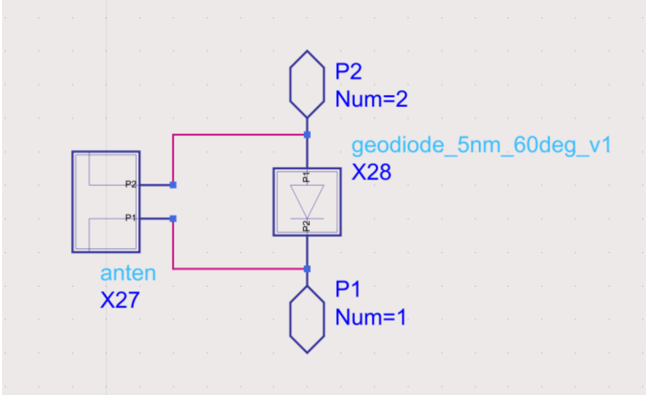
- Common test-bench to simulate and compare variants of the system

Library of Device Models

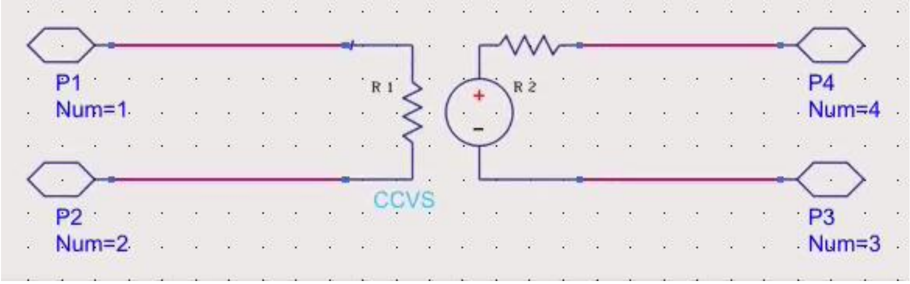
Antenna model from simulations



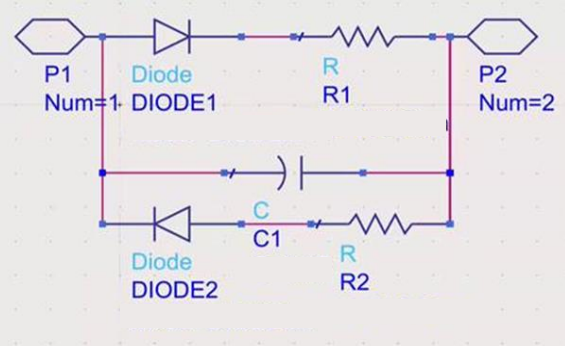
Rectenna model



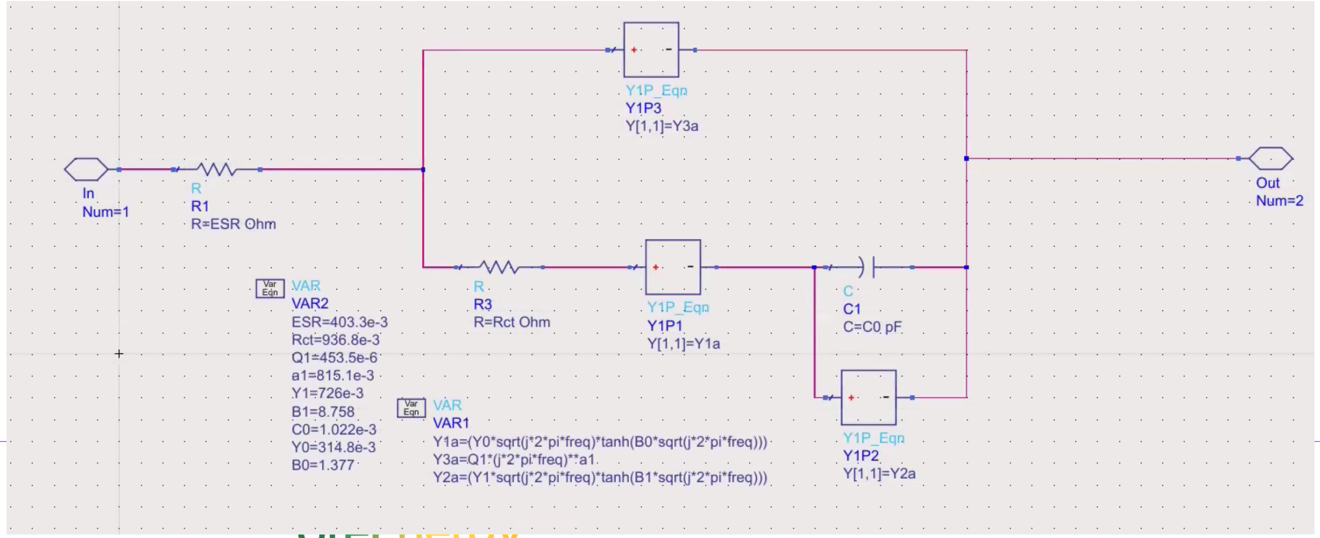
Ballistic diode model



Geometric diode model

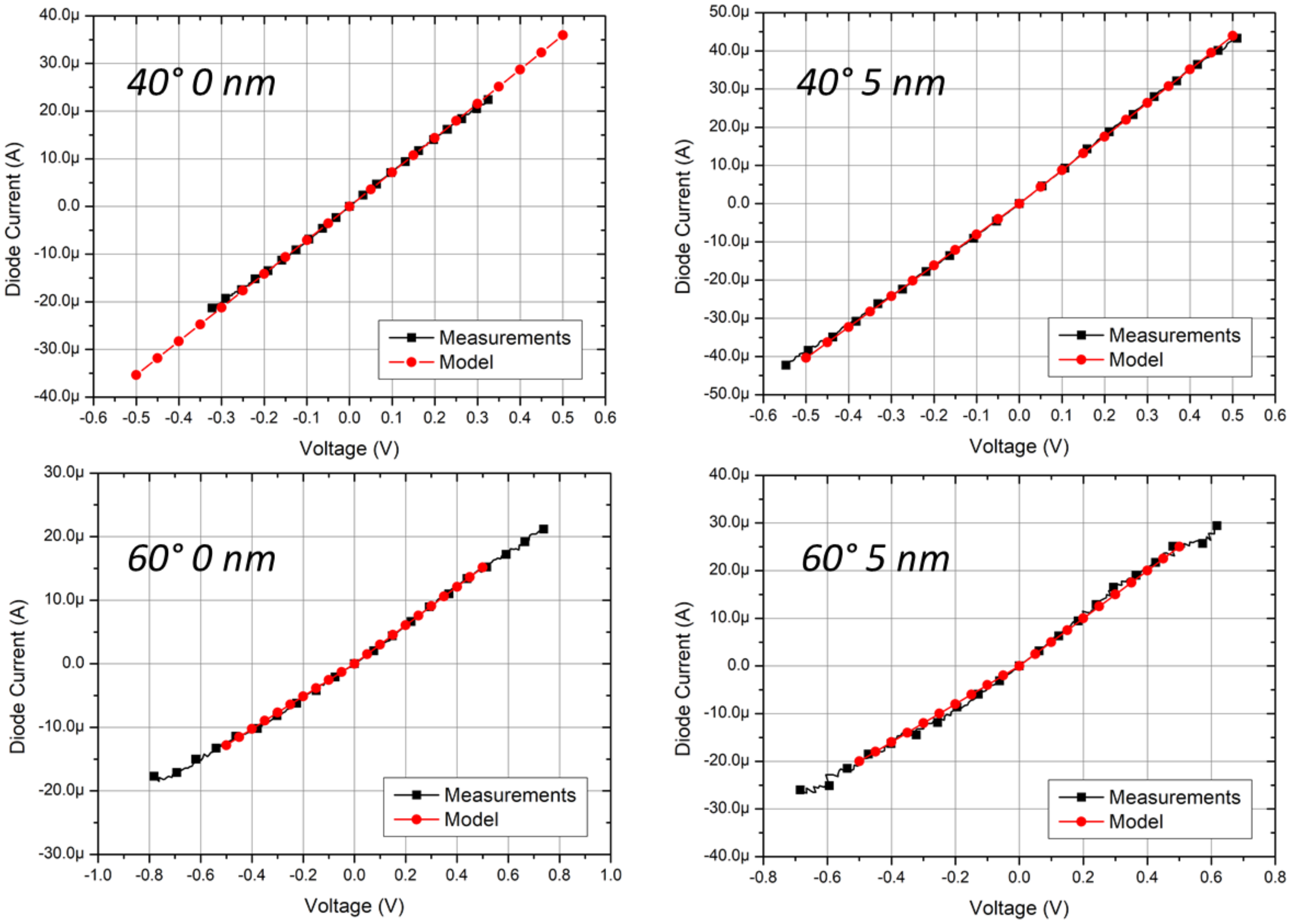


Supercapacitor model



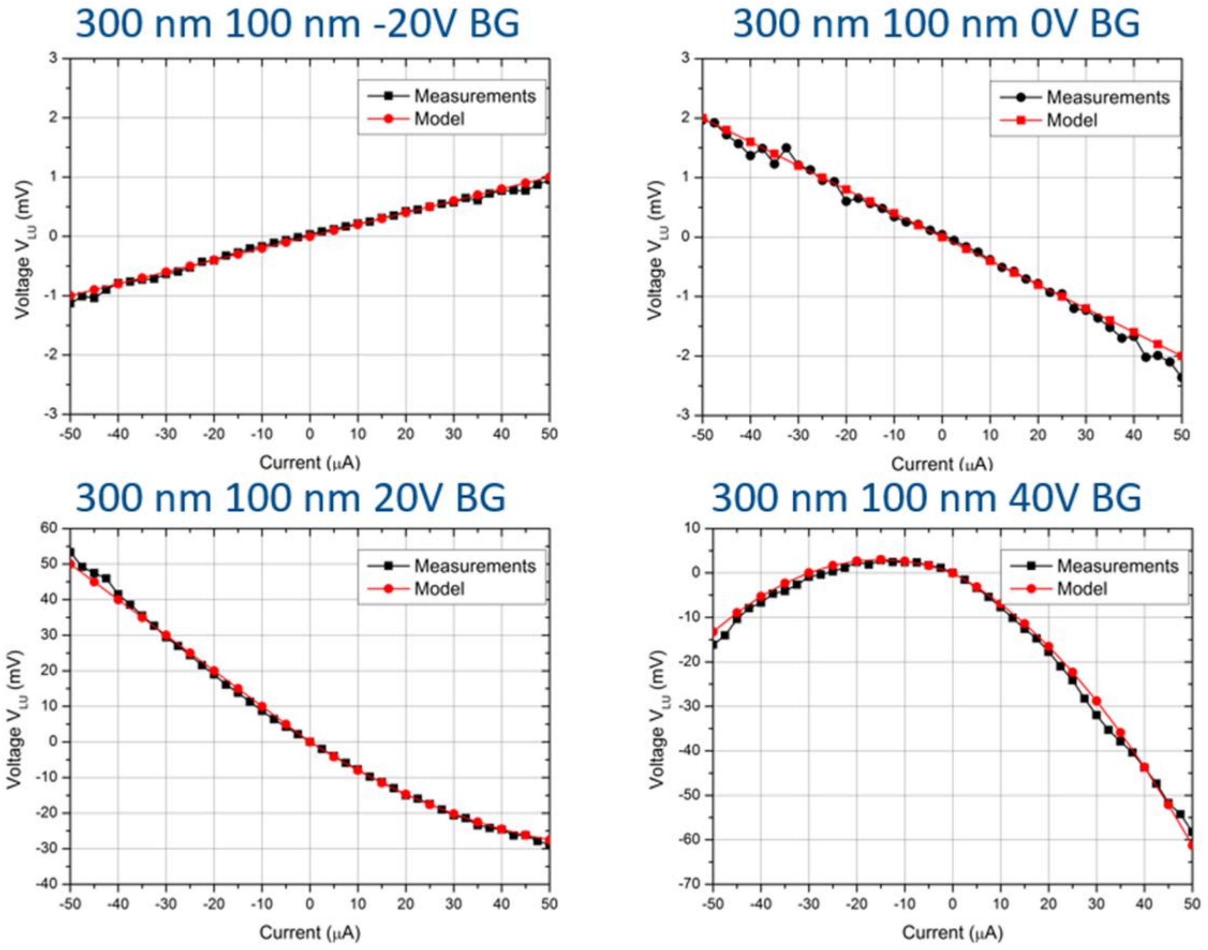
Library of Device Models

- ☐ Geometric diode:



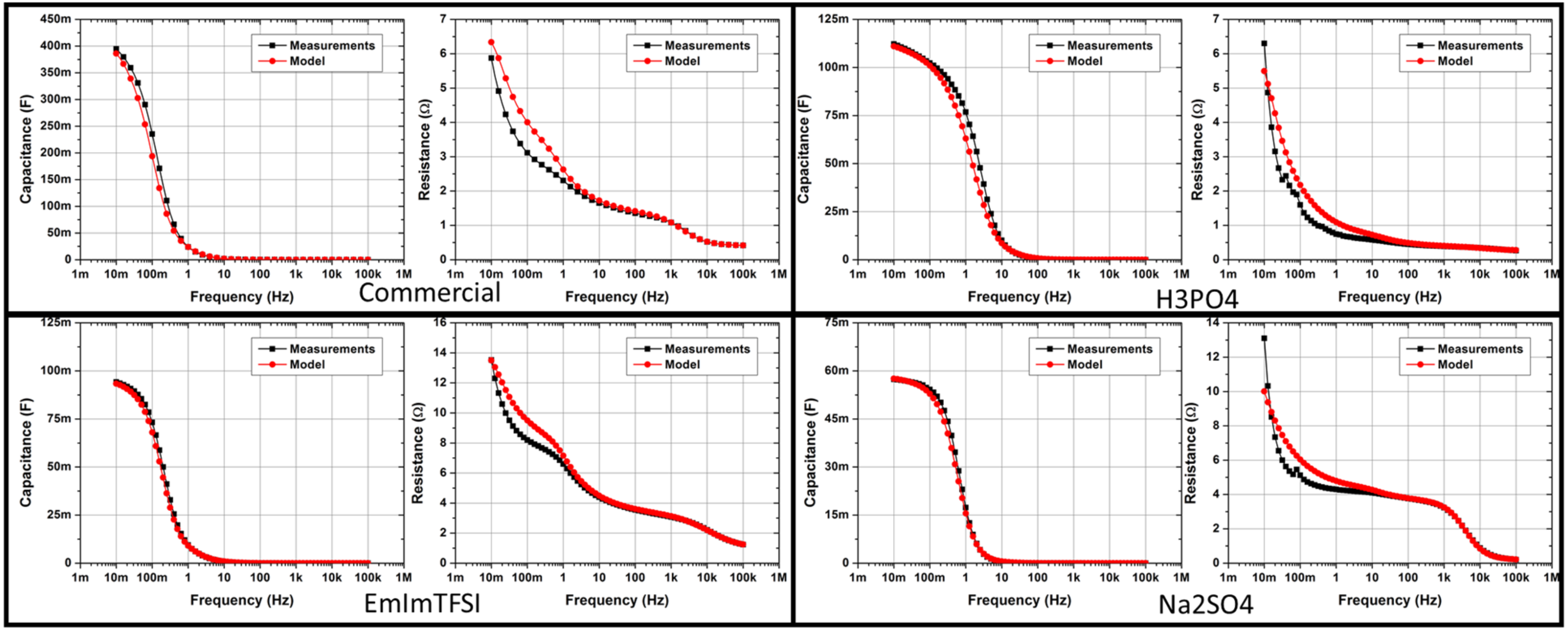
Library of Device Models

- Ballistic diode:



Library of Device Models

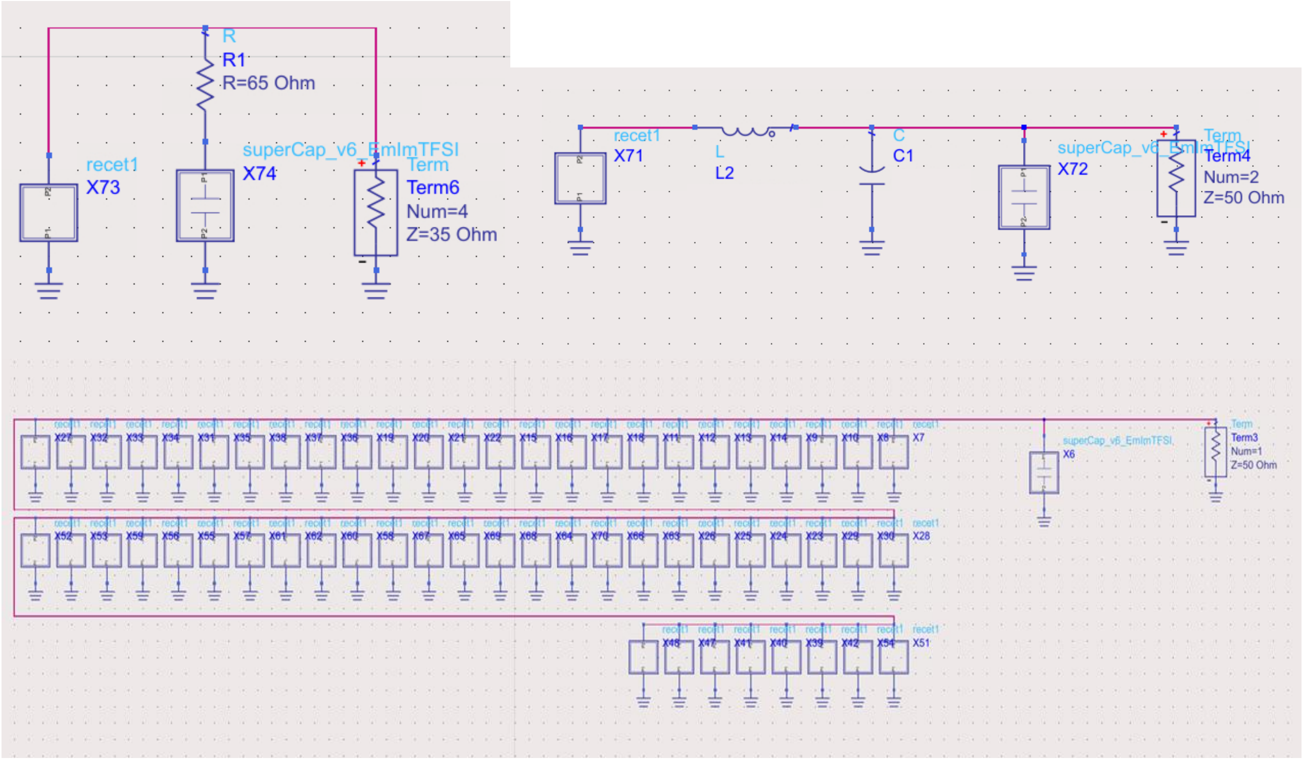
- Supercapacitor:



Circuit Design in GreEnergy

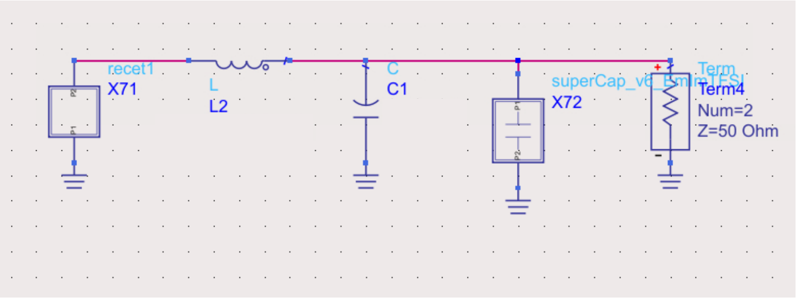
- Test bench for the simulation of:
  - Time-domain behavior
  - Frequency-domain behavior
  - Rectification efficiency

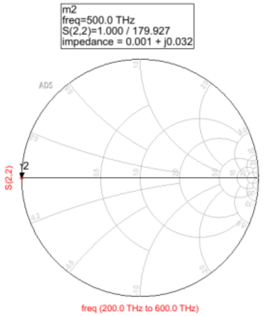
- Target
  - Higher rectification
  - Lower reflections
  - Better matching

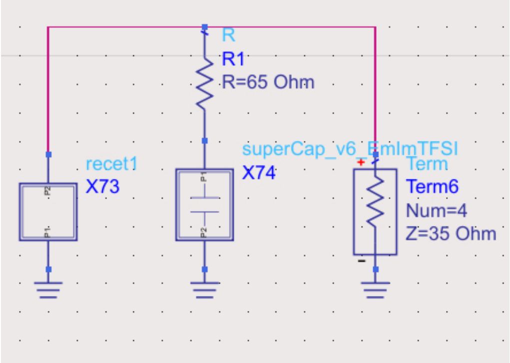


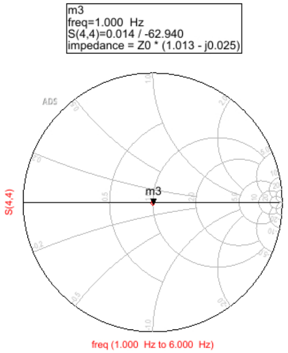
Circuit Design in GreEnergy

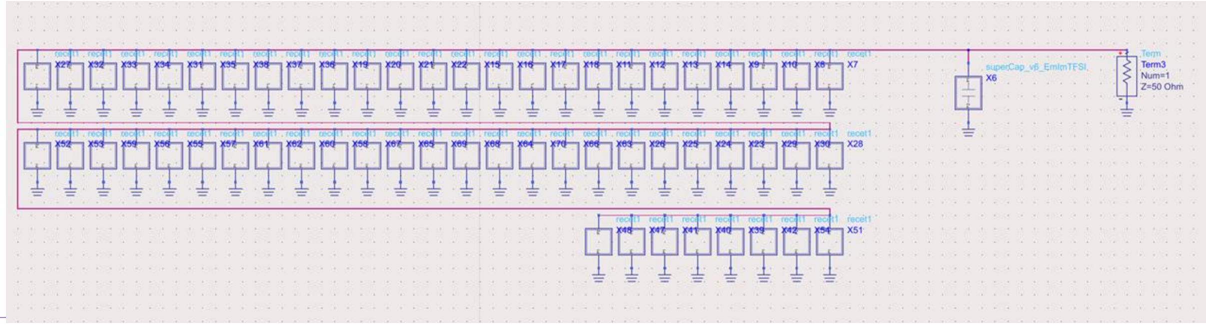
- Matching examples

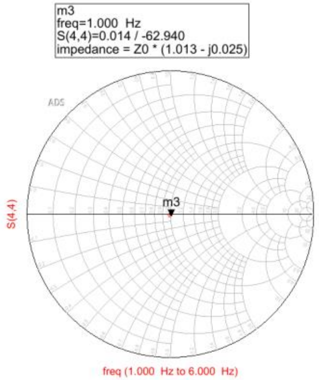












GreEnergy

Overview

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Conclusion

- Established suitable simulation environment
- Enabled software tools for e.g. maximization of energy transfer
- Established approach to build models
- Fitted models to available measurements
- Test simulations of different configurations
- Best configurations will need to be studied once measurements and models of functional devices will be available

Thank you for your attention!

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