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Electrical and Computer Engineering

Metamaterial-integrated high-gain rectenna for RF sensing and energy harvesting applications

W. Lee , S. Choi , **Hae-In Kim**, S. Hwang, S. Jeon and Yong-Kyu Yoon
Department of Electrical and Computer Engineering

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POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

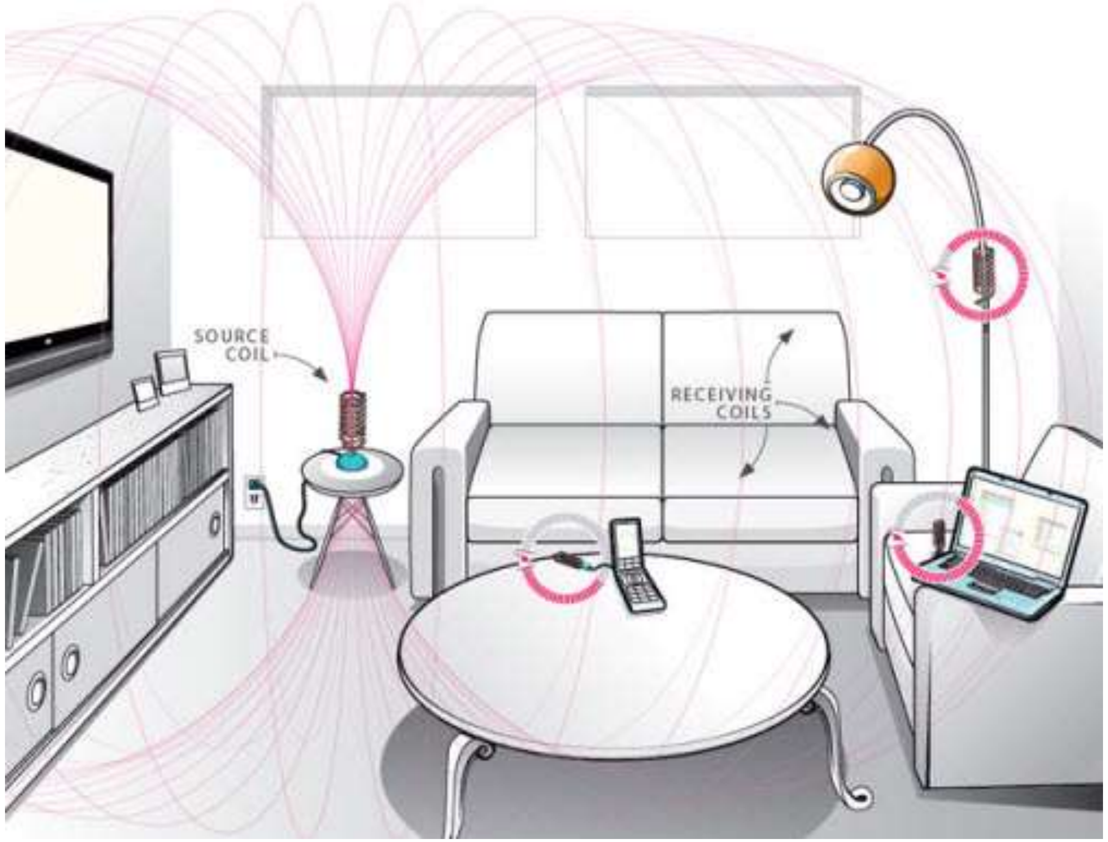
Outline

- Introduction
- 3D integrated high gain rectenna
- Previous work
- Design and analysis
- Fabrication
- Simulated and measured results
- Conclusion

Wireless Power Transfer (WPT)

- **Active research and development of WPT systems**
  - **Recent high demand for wireless power charging** in the modern electronics system

- **WPT technology**
  - **Near-field WPT system**
    - Inductive coupling
    - Magnetic resonant coupling
  - **Far-field WPT system**
    - Radiative WPT



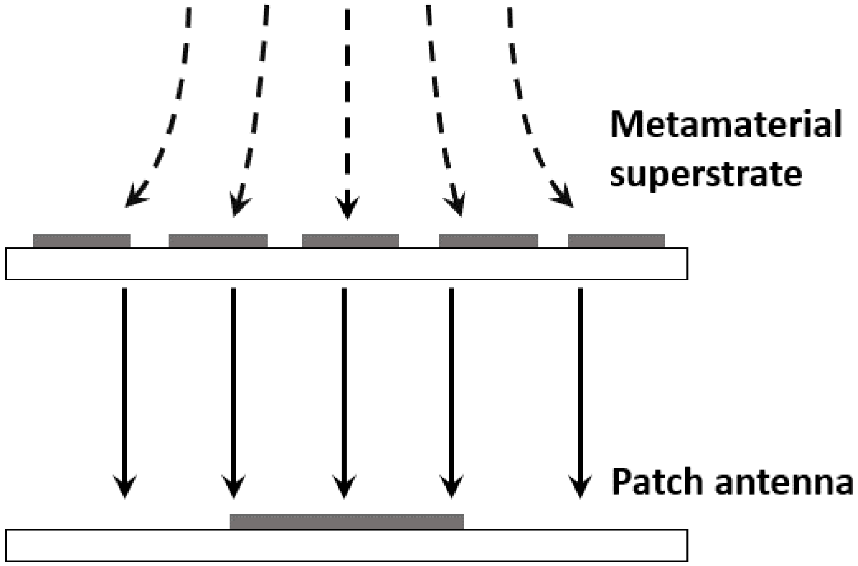
WPT enabled environments

https://www.efxkits.us/overview-wireless-power-transfer-electrical-devices

Metamaterials (MTMs) enhanced rectenna

- **Rectenna (rectifier+antenna) is the core component of the far-field WPT**
  - Provide sufficient power to devices and sensors remotely
  - High gain antenna and high efficiency rectifier are required

- **To enhance the gain of the antenna, MTMs could be utilized [1-3]**
  - **Metamaterials** : artificially engineered materials that have uncommon electromagnetic properties, such as **evanescent wave amplification** and **zero, negative refraction**
  - Enhance the gain of an antenna

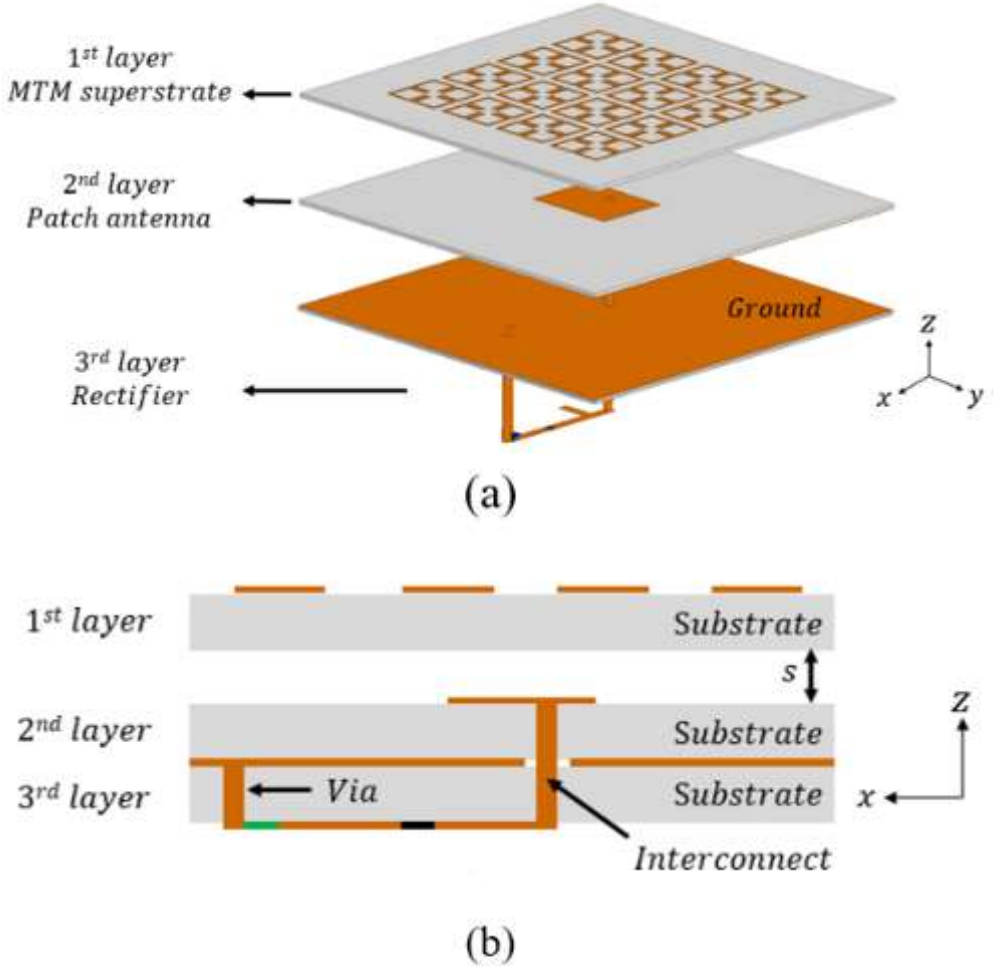


Conceptual principle of gain improvement in a patch antenna using an MTM

1. C. Kim et al., *IEEE ECTC 2012*, 2012
2. A.K Singh et al., *IEEE AWPL*, 2017
3. W. Lee et al., *IEEE ECTC 2020*, 2020

3D integrated high gain rectenna

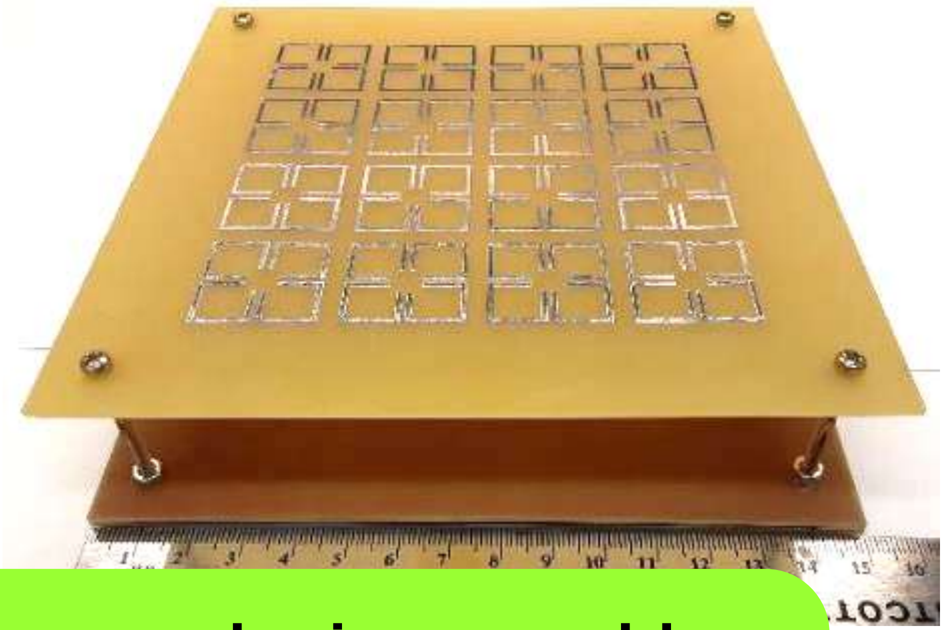
- **Integrated 3-layer high gain rectenna using MTM superstrates is demonstrated**
- **Advantages**
  - By integrating the MTM superstrate,
    - **Enhanced antenna gain**
    - Increase of the incident RF power at the rectifier input
    - High output DC power and high end-to-end efficiency
  - By integrating a rectifier circuit on the bottom of the antenna,
    - **System footprint remains the same**
    - Cross coupling between MTM superstrates and rectifier is suppressed



Schematic of a 3D integrated rectenna: (a) perspective view, (b) side view

Previous work

- **3D integrated high gain rectenna was demonstrated on FR4 substrate[4]**
  - Antenna gain is enhanced by **5.8 dB**
  - Improvement of RF-DC conversion efficiency by integrating MTM superstrate (when input power = 4.7 dBm)
    - 5
    - 1



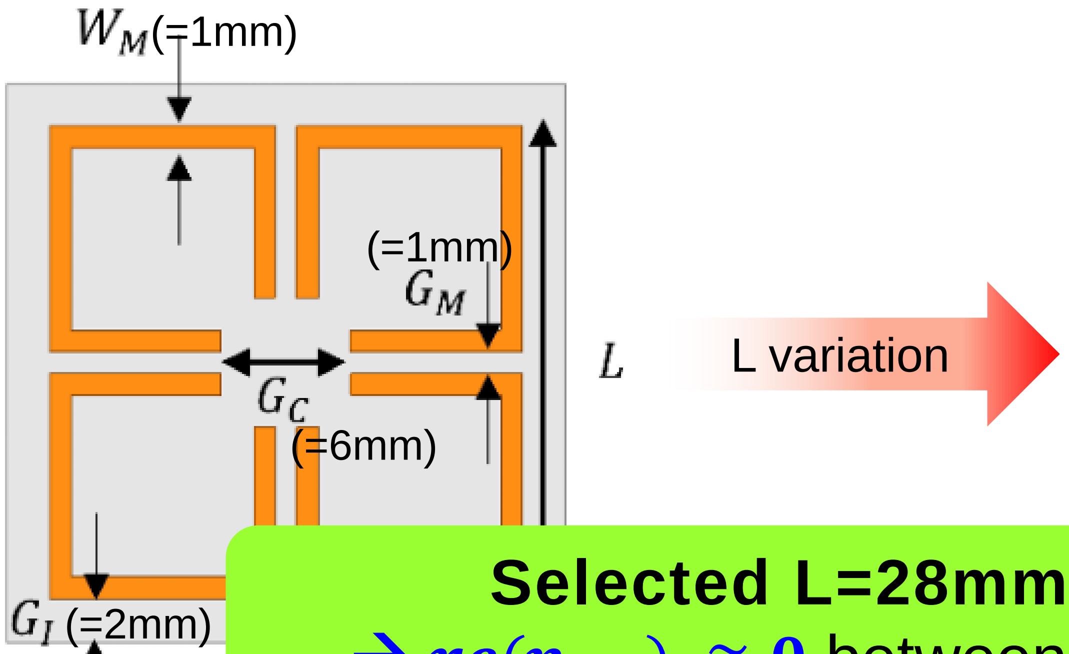
Gain and RF-DC conversion efficiency can be improved by

1) *Using a low loss substrate*
2) *Optimizing the design parameters*
3) *Studying the effects of the number of MTM unit cells*

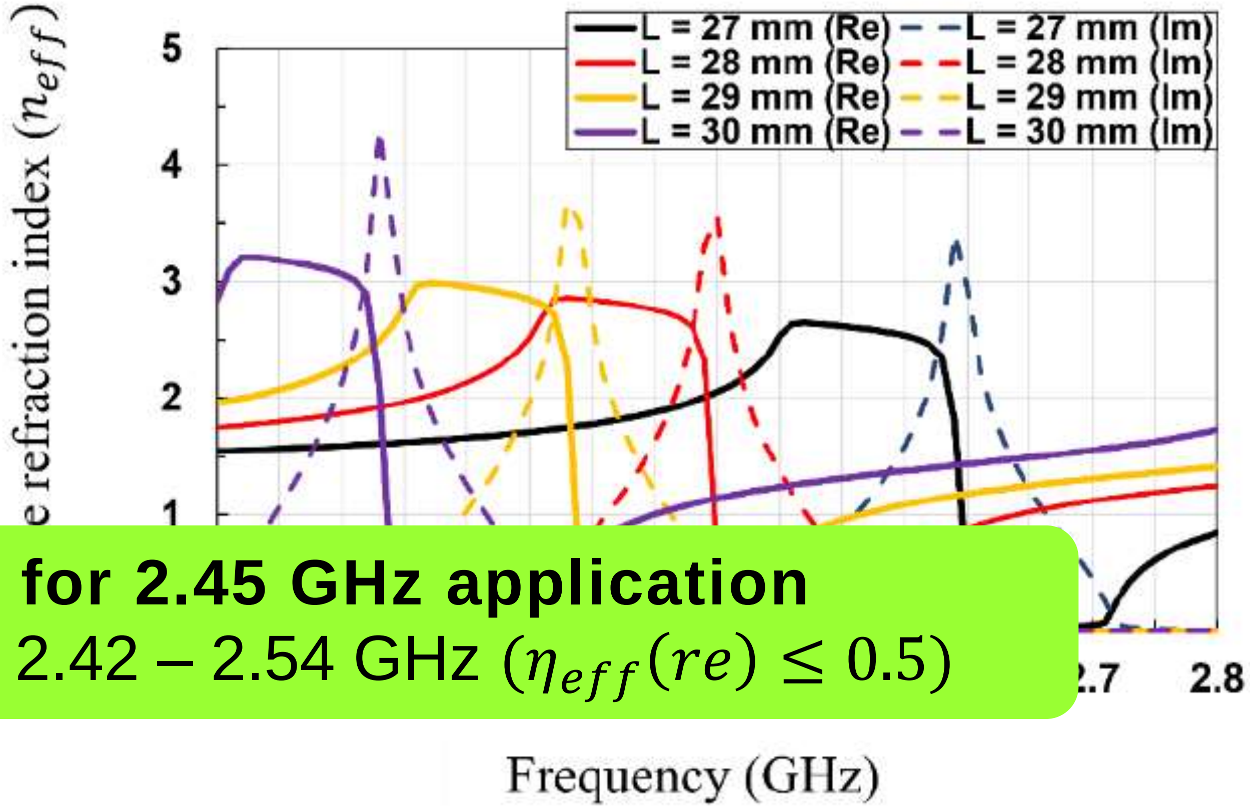
4. W. Lee et al., *IEEE ECTC 2021*, 2021

Design of the MTM unit cell

- **Designed four-clover shaped MTM unit cell on Rogers RT5880**
  - thickness = 1.57mm ε = 2.2, δ=0.0009
- **Performed parametric study to have a zero refractive index at 2.45 GHz**



Top view of the MTM unit cell

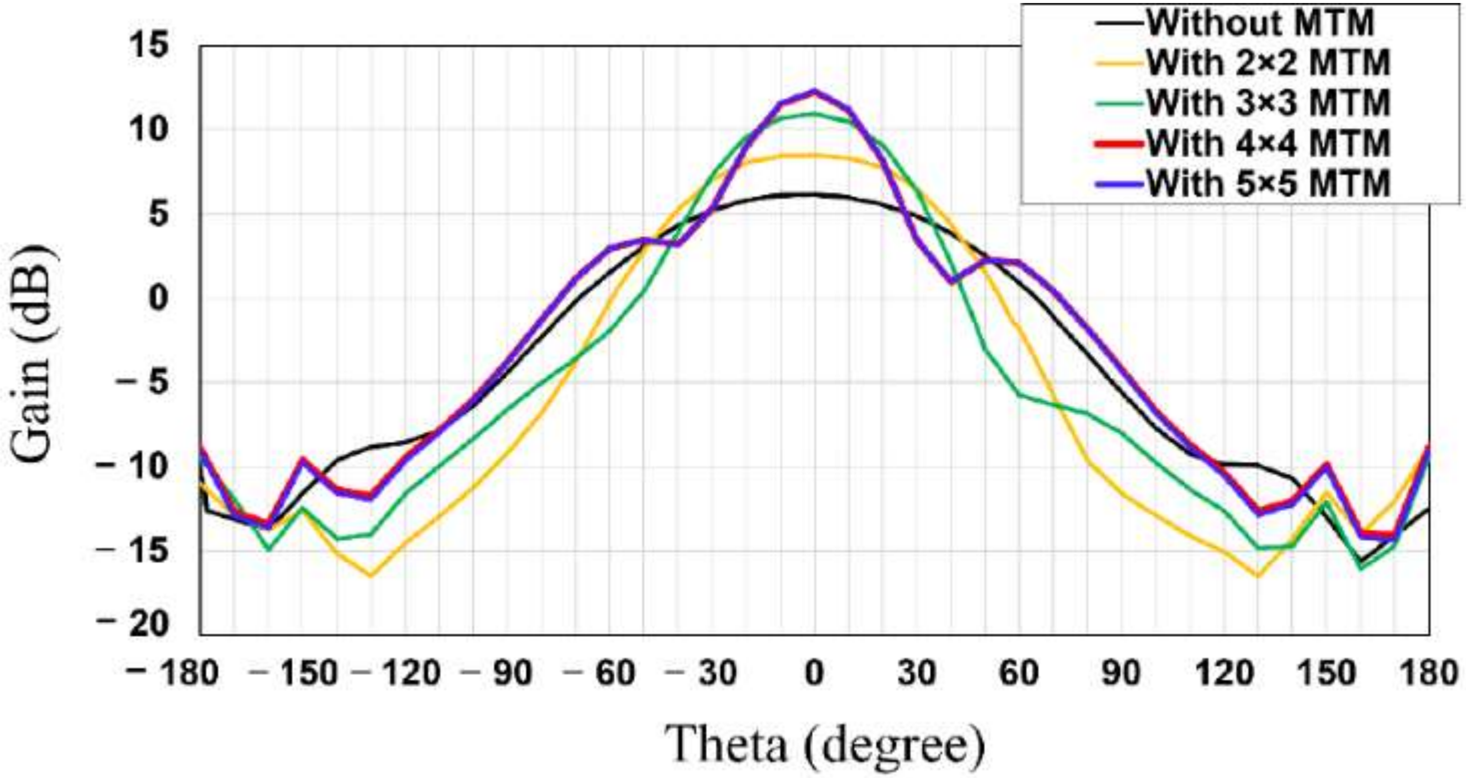


Selected L=28mm for 2.45 GHz application
→ $re(\eta_{eff}) \cong 0$ between 2.42 – 2.54 GHz ($\eta_{eff}(re) \leq 0.5$)

Simulated effective refraction index

Study on the number of MTM unit cell

- 2.45 GHz patch antenna is designed (47.8 x 39.9 mm)
- MTM superstrate is integrated with the antenna



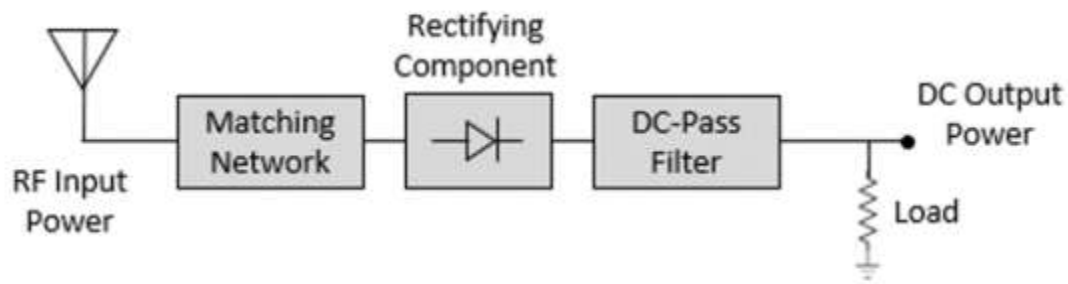
Simulated radiation patterns of the antenna with/without an MTM superstrate

Simulation results

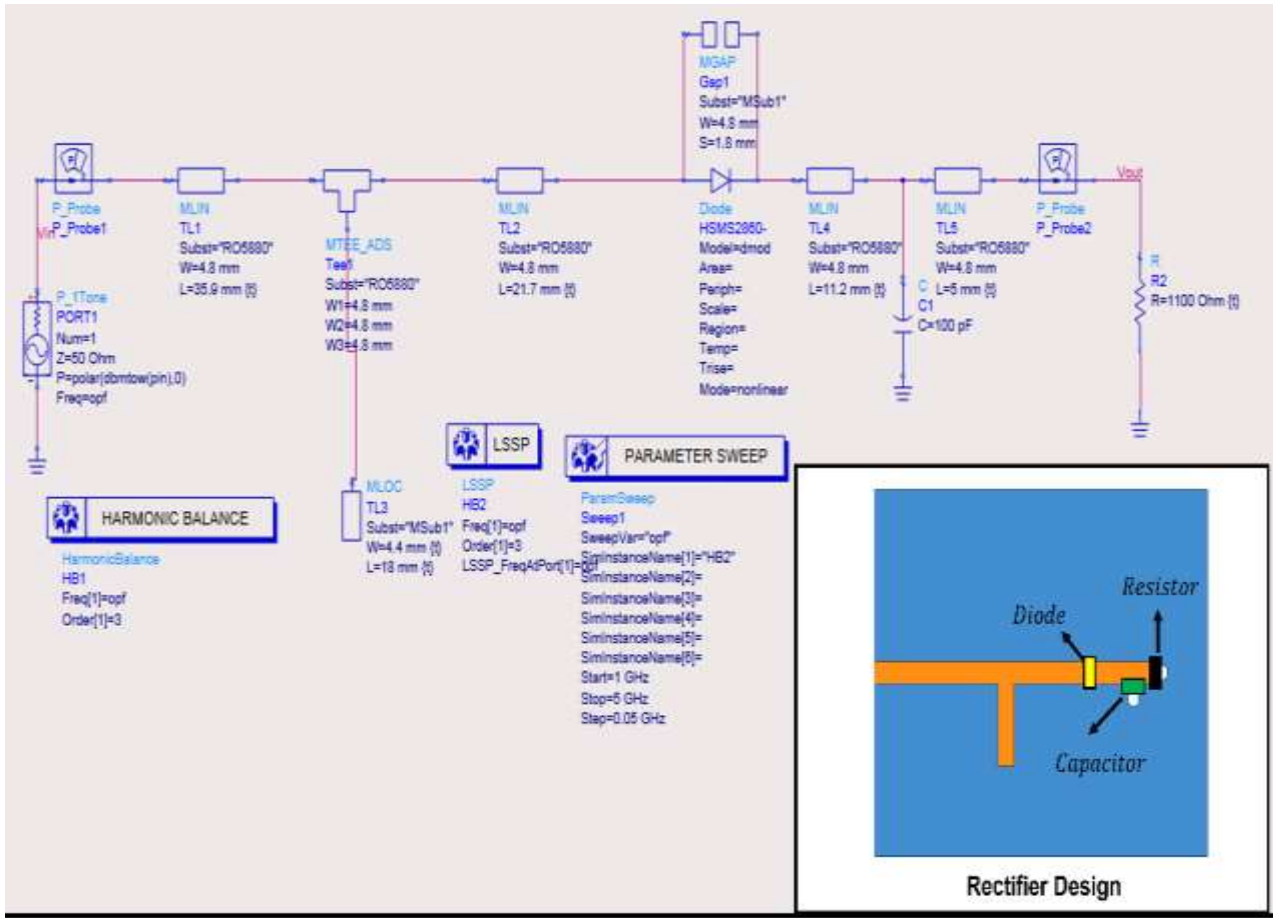
# of MTM	Peak Gain (dBi)	
Antenna only	6.15	
2 X 2	8.44	+2.3 dB
3 X 3	10.93	+4.8 dB
4 X 4	12.30	+6.15 dB
5 X 5	12.25	+6.10 dB

Design of rectifier

- **Rectifier circuit is designed**
  - Matching network, Schottky diode (HSMS2860), low-pass filter (100 pF shunt capacitor), resistive load (1.1k ohms)



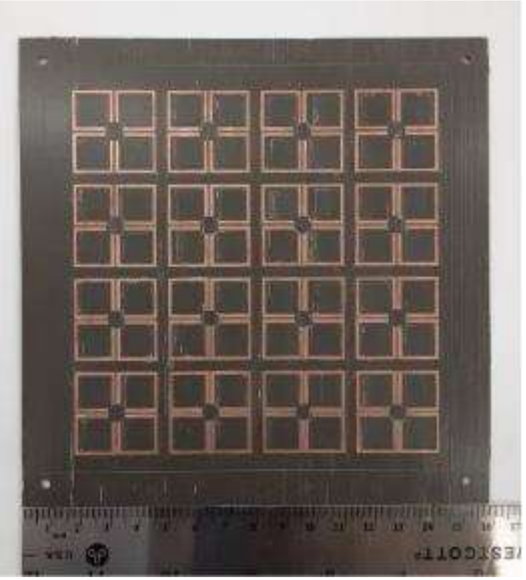
Block diagram of rectifier



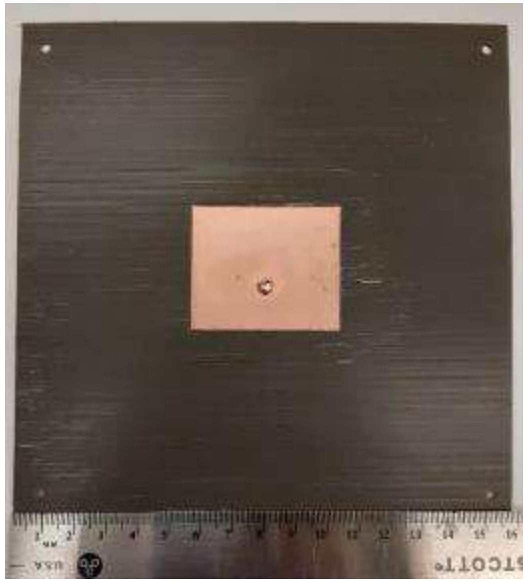
Advanced design system (ADS) schematic of the rectifier design

Fabricated 3D integrated high gain rectenna

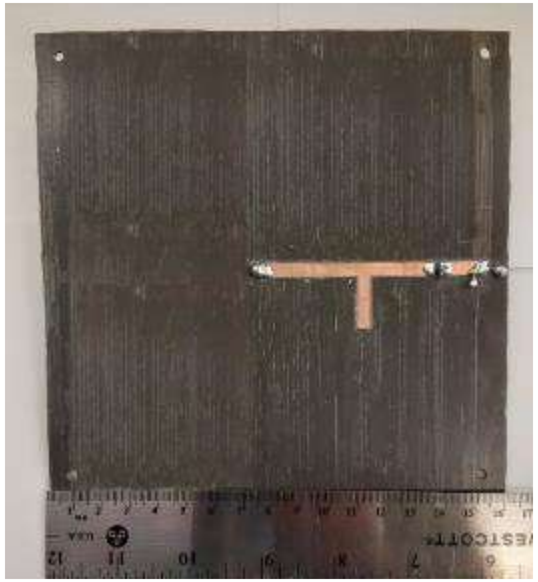
- Milling machine is utilized to fabricate each unit cell



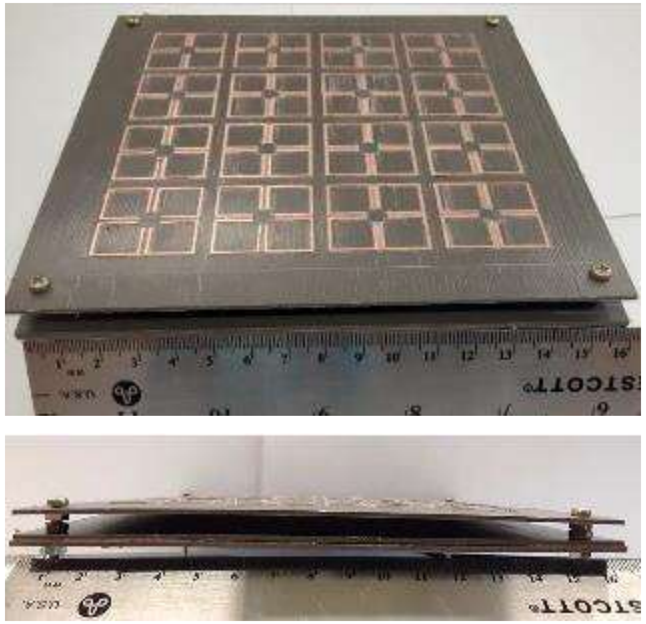
Fabricated MTM superstrate



Fabricated patch antenna

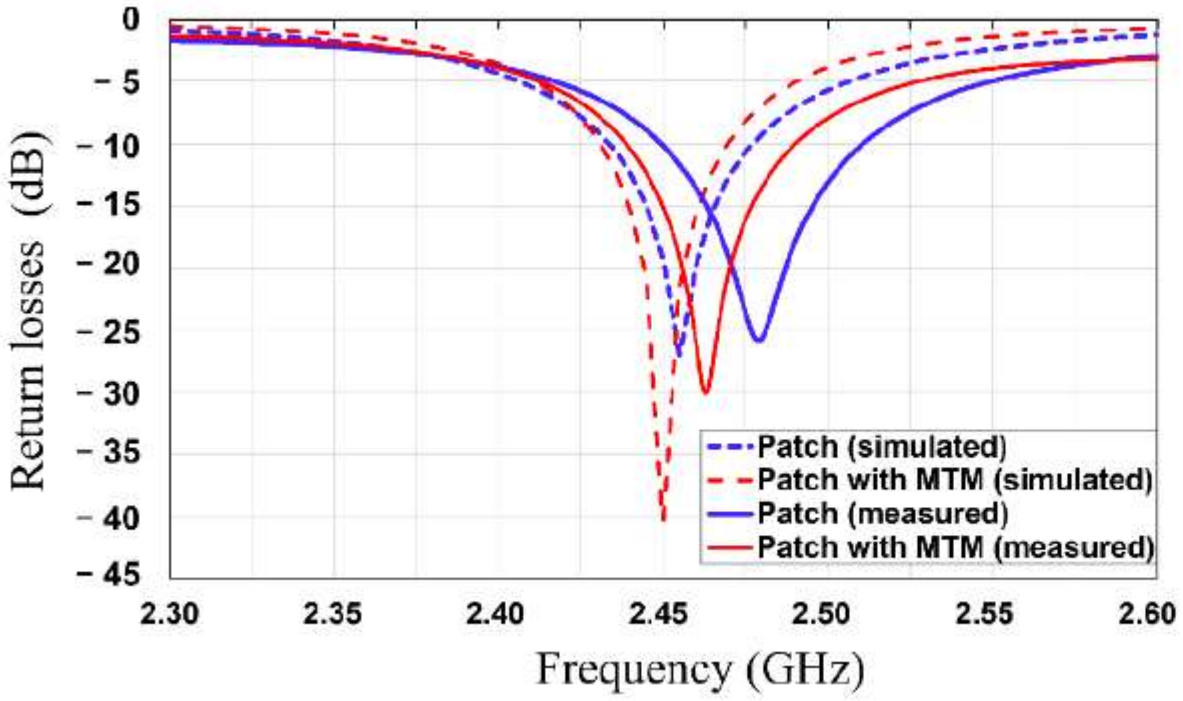


Fabricated rectifier

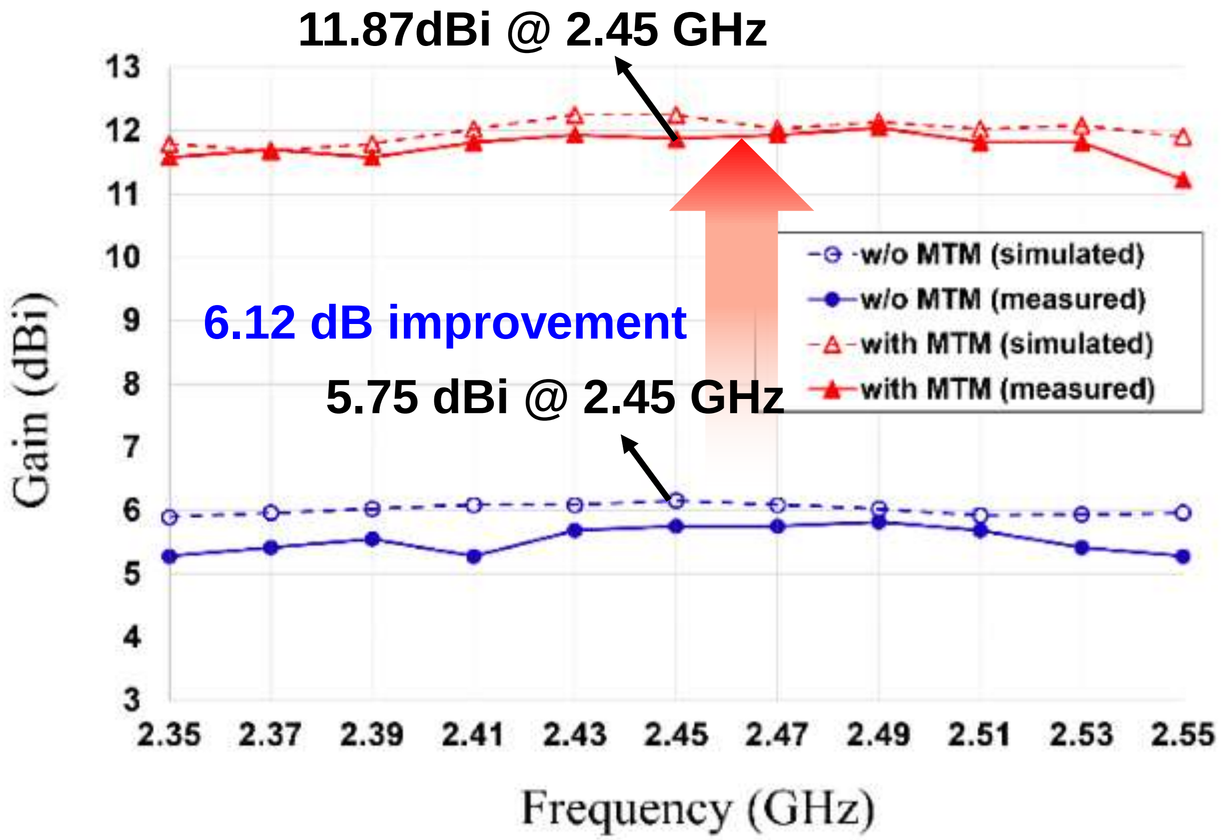


Fabricated 3D integrated rectenna

Simulated and measured results of the patch antenna with/without MTM

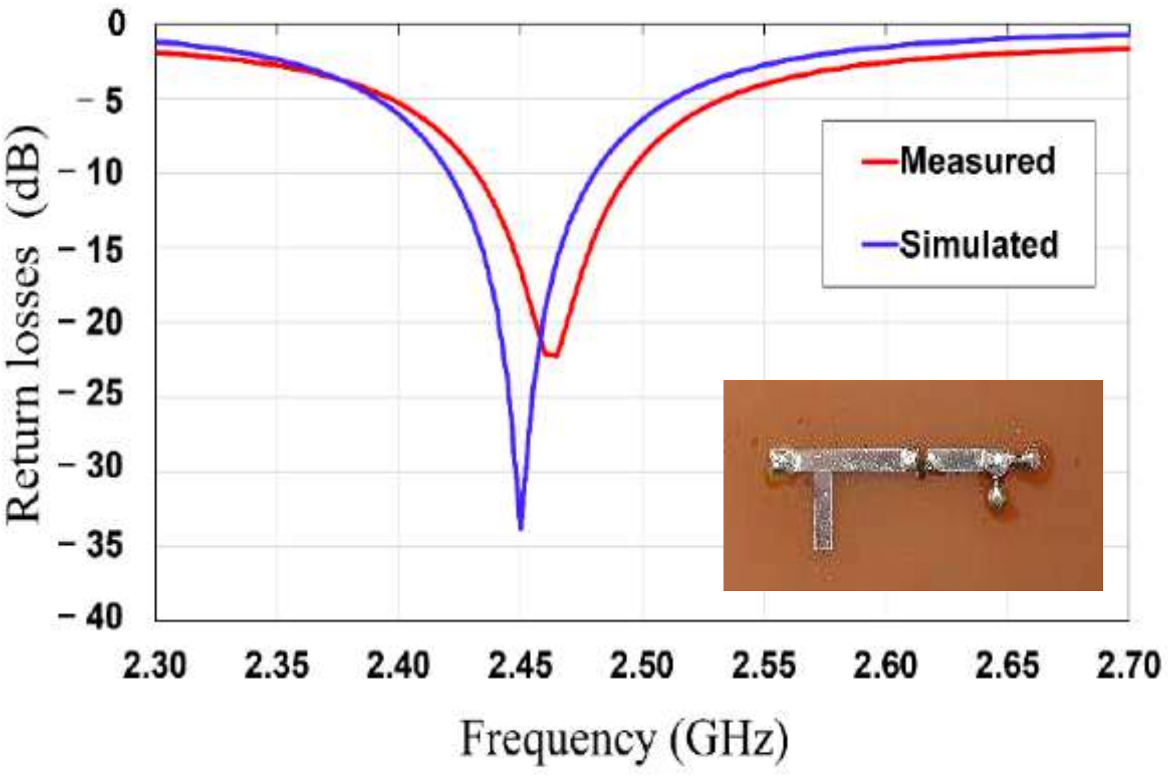


Simulated and measured return loss results

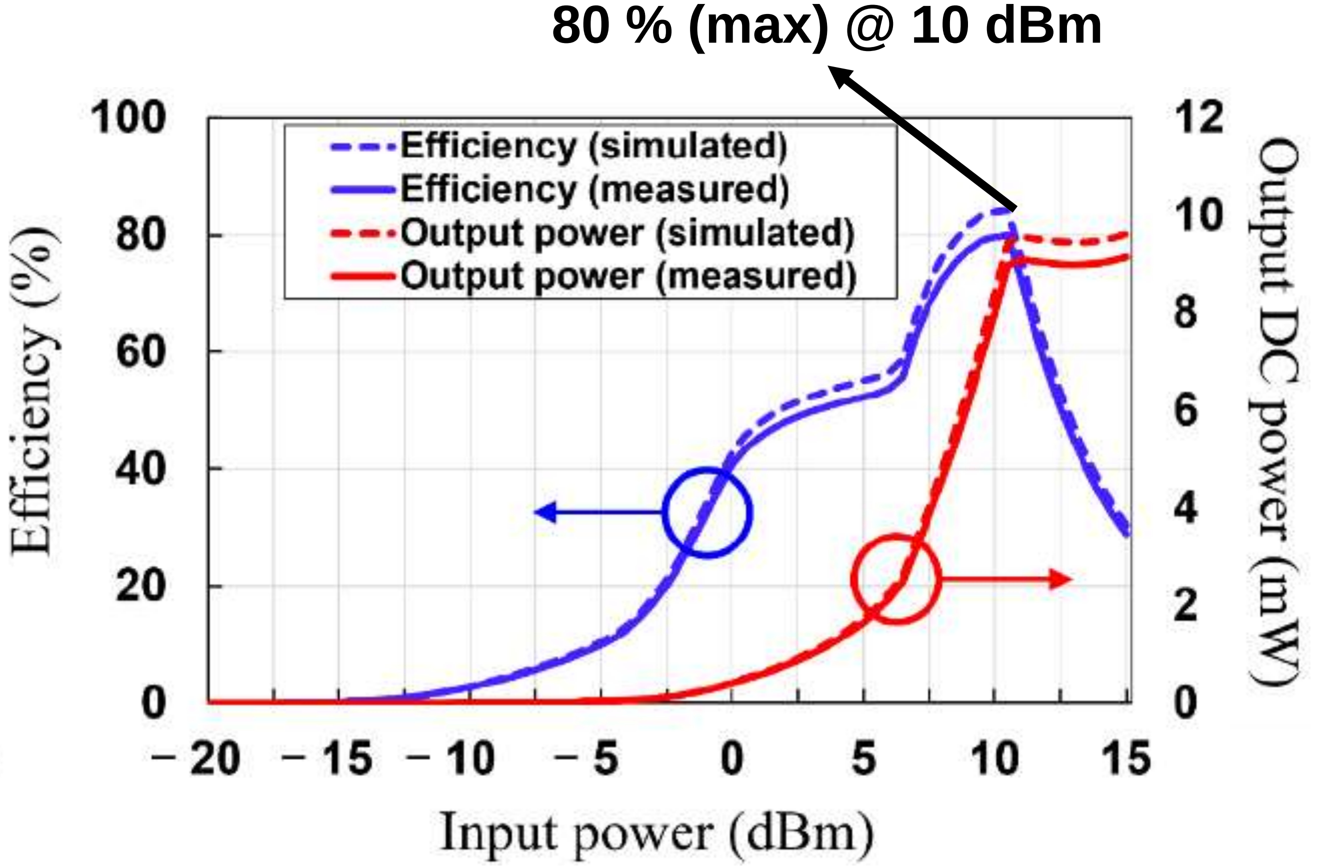


Simulated and measured peak gain results

Simulated and measured results of rectifier



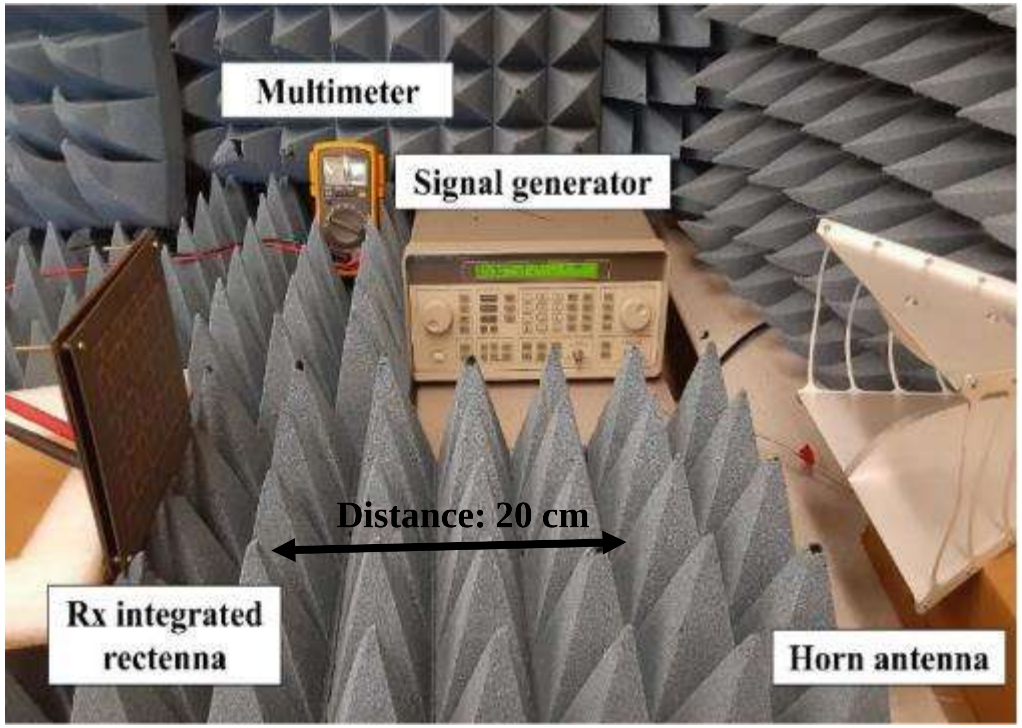
Simulated and measured return loss results



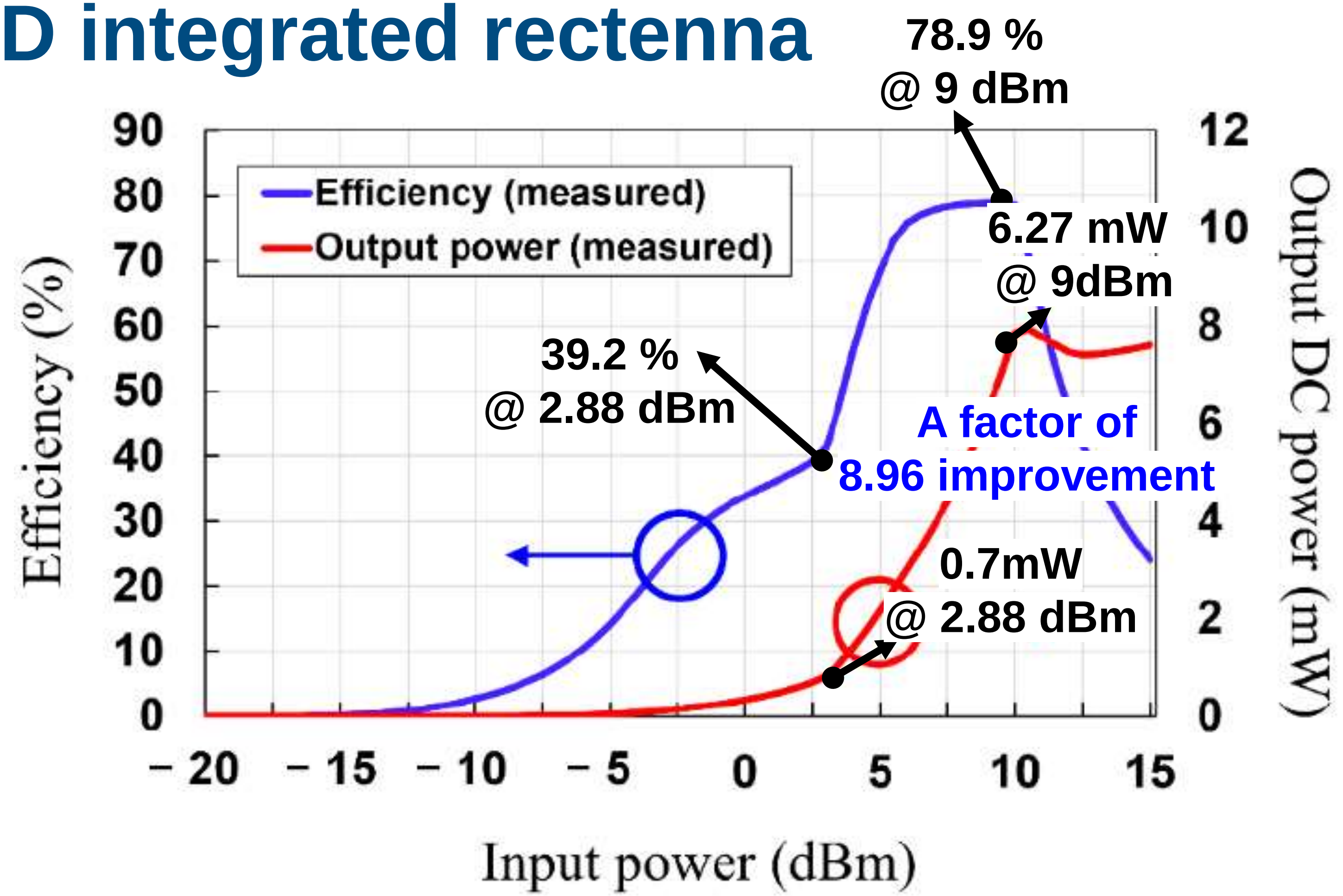
Simulated and measured RF-DC conversion efficiency

$$* \ \eta_{RF-DC} = \frac{P_{out}}{P_{in}} \times 100\ (\%) = \frac{{V_{DC}}^2}{P_{in} R_L} \times 100\ (\%)$$

Measured results of the 3D integrated rectenna



Measurement setup



Measured RF-DC conversion efficiency of the 3D integrated rectenna

* $\eta_{rectenna} = \frac{V_L^2}{P_r R_L} \times 100\ (\%)$
* $P_r = \left(\frac{\lambda}{4\pi r}\right)^2 G_t G_r P_t$

Comparison

Parameters	ECTC 2021[4]	This work[5]
Substrate	FR4 (ε = 4.4, δ=0.03)	RT5880 (ε = 2.2, δ=0.0009)
Dimensions (mm3)	150 X 150 X 14.71 ($0.18\lambda^3$)	158 X 158 X 14.71 ($0.19\lambda^3$)
Peak gain w/o MTM	4.78 dBi	5.75 dBi
Peak gain with MTM	10.7 dBi	11.87 dBi
Improved gain	5.92 dB	**6.12 dB**
RF-DC conversion efficiency	56.8 to 63.5 %	**39.2% to 78.9 %**
Output DC power improvement	1.6 mW to 6.35 mW (factor of 4)	**0.7 mW to 6.27 mW (factor of 9)**

4. W. Lee et al., *IEEE ECTC 2021*, 2021
5. W. Lee et al., Sensors, 2021

Conclusion

- **3D integrated high gain rectenna is demonstrated**
  - Antenna gain is enhanced by 6.12 dB
  - The measured RF-DC conversion efficiency
    - 2.67 % (-10 dBm), 33.84 % (0 dBm), and 78.63 % (10 dBm)
  - Improvement of RF-DC conversion efficiency by integrating MTM superstrate (when input power = 2.88 dBm)
    - 39.2 % to 78.9 %
    - 0.7 mW to 6.27 mW (a factor of 9 improvement)
- It is highly envisioned that the demonstrated **3D integrated high gain rectenna will open new possibilities** for practical energy harvesting applications with improved antenna gain and efficiency in various IoT environments.

Acknowledgement

- RF experiment/characterization have been performed at the University of Florida
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Reference

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2. A. K. Singh, M. P. Abegaonkar and S. K. Koul, "High-Gain and High-Aperture-Efficiency Cavity Resonator Antenna Using Metamaterial Superstrate," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2388-2391, 2017.
3. W. Lee, H. Kim and Y. Yoon, "Metamaterial-inspired dual-function loop antenna for wireless power transfer and wireless communications," 2020 IEEE 70th Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, pp. 1351-1357, 2020.
4. W. Lee, H. Kim, S. Hwang, S. Jeon, H. Cho and Y. -K. Yoon, "3D integrated high gain rectenna in package with metamaterial superstrates for high efficiency wireless power transfer applications," 2021 IEEE 71st Electronic Components and Technology Conference (ECTC), San Diego, CA, USA, 2021, pp. 1317-1322, doi: 10.1109/ECTC32696.2021.00213.
5. W Lee, S Choi, H Kim, S Hwang, S Jeon, YK Yoon, “Metamaterial-Integrated High-Gain Rectenna for RF Sensing and Energy Harvesting Applications”, Sensors, 2021

Thank you

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