A 24-GHz 4-Element Multi-beam Wireless Energy Harvesting Array with Class-F Rectifiers Achieving 51.5 PCE

M. Ghorbanpoor, E. Le Roux, A. M. Ahmadi Najaf Abadi, O. Vorobyov, P. Nussbaum, H. Wang •

This study introduces a compact and efficient Wireless Power Transfer solution for IoT applications, based on a 24GHz 4-element concurrent multi-beam energy harvesting array. Thanks to the utilization of a novel three-line-coupler, the harmonic shaping rectifier achieves the best reported rectifier power conversion efficiency of 51.5%. A 4-port ultra-compact Butler matrix with transformer-based 90° hybrid couplers is utilized for concurrent beamforming.

In the context of the growing Internet of Things (IoT), wireless power transfer (WPT) provides a sustainable alternative to batteries, which are becoming impractical due to their environmental impact and maintenance issues. Most current WPT systems use 2.4/5.8 GHz ISM bands, but these bands have limitations in terms of antenna efficiency, overall Rx size, and reduced system efficiency due to the lack of Tx beamforming. In contrast, millimeter-wave systems offer advantages such as compact antenna sizes and focused beamforming, allowing efficient energy transfer. However, increasing frequency introduces design challenges due to parasitics that degrade the rectifier performance.

The core of the CSEM approach is a cross-coupled Class-F rectifier, which maximizes efficiency by shaping the drain waveform to reduce leakage current. Traditional cross-coupled rectifiers (CCR) suffer from leakage during state transitions, limiting their power conversion efficiency (PCE). By using harmonic termination techniques, the Class-F rectifier achieves a square-shaped drain waveform, minimizing both transition leakage loss by fast transition and conduction loss by limited voltage drop (Figure 1a). The optimal harmonic contents required for Drain and Source terminals are acquired with respect to optimized values in Figure 1b. This rectifier employs a novel three-coupled-line balun design, which achieves wideband operation at both the fundamental frequency (24 GHz) and its third harmonic (72 GHz) (Figure 1c).

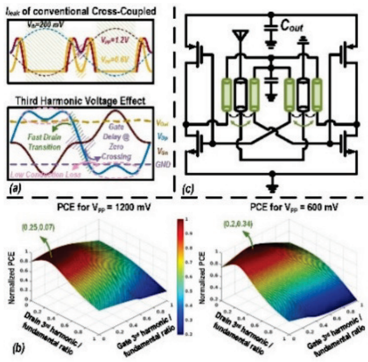

Figure 1: Proposed class-F rectifier. a) 3rd harmonic on S/D signals. b) Optimum PCE point. c) Three-coupled-line class-F rectifier schematic.

A significant novelty in this work is the integration of a 4-port Butler matrix to enable concurrent multi-beam beamforming. This approach is passive, meaning it does not consume additional power, compatible with cold-start, and it allows the system to simultaneously harvest energy from multiple angles, covering the entire field of view (FoV). By performing passive beamforming before rectification, the system enhances the total received power, improving the overall PCE and dynamic range.

In contrast to active beamformers, the passive Butler matrix ensures low-loss and efficient beam steering. This method is particularly useful for WPT applications where the direction of incoming power is not always known maximizing concurrent reception for 4 different directions (Figure 2).

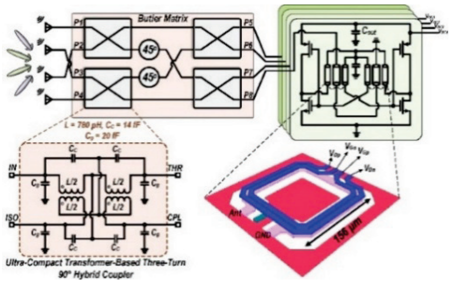

Figure 2: Proposed concurrent multi-beam rectifying array.

The system was fabricated in a 22nm CMOS FD-SOI process with a core area of 0.53 mm². Measurements showed a peak PCE of 51.5% at 22 GHz for a single rectifier, with an optimum DC load of 147Ω. The system achieves a broad 3-dB bandwidth from 17.5 to 28 GHz, maintaining a PCE above 30% across a wide input power range (-5 dBm to 14 dBm).

The Butler matrix demonstrated a low passive loss of 1.21 dB, with a full FoV beam pattern showing a peak-to-null ratio better than 28 dB. The rectifying array's performance showed an output power improvement of 1.49 times compared to non-coherent rectenna arrays, confirming the benefits of the beamforming approach.

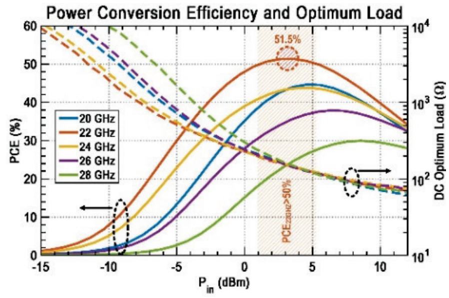

Figure 3: Single rectifier measurement results w/o beamforming.

As shown in Figure 3, this work reports the highest PCE of 51.5% for a millimeter-wave rectifier and demonstrates the effectiveness of combining a Class-F rectifier with a passive beamforming array for efficient wireless power harvesting. The use of a Butler matrix for multi-beam concurrent energy harvesting offers a compact and low-power solution that is particularly well-suited for WPT applications in the IoT era. The system achieves a total efficiency of 30.2% including beamformer, making it a competitive solution for future wireless energy harvesting systems.

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