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ADVANCEMENT IN CIRCUIT TECHNOLOGIES FOR ENERGY HARVESTING SYSTEMS

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Abstract

Fractional Open-Circuit Voltage (FOCV) - Maximum Power Point Tracking (MPPT) technology is a novel approach for optimizing energy harvesting in low-powered systems operating at 220 GHz, a challenging frequency range. This paper introduces FOCV as an efficient MPPT technique, utilizing fractional voltage measurements to determine the optimal operating point for energy extraction in 220 GHz multi solid-state circuits. By employing FOCV, the proposed energy harvesting system achieves enhanced power efficiency, making it suitable for applications with strict power constraints. Additionally, this paper addresses the electromagnetic interference (EMI) challenges associated with operating at such high frequencies, presenting mitigation strategies to ensure reliable and interference-free operation of the FOCV-based energy harvesting system in the 220 GHz multi solid-state circuits. The results demonstrate the effectiveness of the FOCV - MPPT technology in improving energy harvesting efficiency while minimizing EMI-induced performance degradation.

Keywords:

Millimeter-Wave Frequencies, 220 GHz Circuits, Electromagnetic Interference, Interference-Free Operation

1. INTRODUCTION

Energy harvesting, the process of capturing and converting ambient energy into electrical power, has gained significant attention in recent years due to the increasing demand for self-sustaining and low-powered electronic devices. This technology has the potential to revolutionize various industries, including wireless sensor networks, Internet of Things (IoT) devices, biomedical implants, and wearable electronics. The key advantage of energy harvesting lies in its ability to extend the lifetime of battery-powered devices or even eliminate the need for batteries altogether, reducing maintenance costs and environmental waste [1].

One of the most promising frontiers in energy harvesting research is the exploration of millimeter-wave frequencies, specifically in the 220 GHz range. The millimeter-wave spectrum offers a wealth of untapped energy sources, such as ambient radiofrequency signals from broadcasting and communication systems, as well as infrared radiation from the surrounding environment [2]. These abundant energy sources present unique opportunities for capturing energy and powering electronic devices in various scenarios, including urban environments, industrial settings, and even remote locations. However, the design and implementation of energy harvesting systems at 220 GHz pose significant challenges [3]. Operating at such high frequencies demands cutting-edge circuit design techniques and highly efficient solid-state circuits to achieve desirable power harvesting levels. Moreover, energy harvesting systems must operate with strict power constraints, ensuring that the energy extracted from the environment is efficiently converted and stored [4]. Researchers and engineers have been exploring innovative circuit architectures and tracking techniques to optimize energy harvesting efficiency [5]. One promising approach is the Fractional Open-Circuit Voltage (FOCV) - Maximum Power Point Tracking (MPPT) technology. FOCV-MPPT is a novel method that uses fractional voltage measurements to determine the optimal operating point for energy extraction [6]. This technology promises to improve energy harvesting efficiency and adaptability in low-powered systems, making it particularly suitable for applications with varying energy sources and power requirements [7]. Despite the potential benefits of FOCV-MPPT, challenges remain, especially concerning electromagnetic interference (EMI) [8]. Operating at such high frequencies increases the susceptibility to EMI, which can degrade the performance of energy harvesting circuits and overall system reliability. Hence, effective EMI mitigation strategies are essential to ensure interference-free operation and optimal energy harvesting performance [9].

To overcome these challenges, researchers have been exploring innovative circuit architectures and tracking techniques to optimize energy extraction in the millimeter-wave range. One such promising technology is the FOCV - MPPT approach. FOCV-MPPT offers a unique solution to improve energy harvesting efficiency in low-powered systems operating at 220 GHz, leveraging fractional voltage measurements to determine the optimal operating point.

This paper aims to introduce the concept of FOCV-MPPT and its application in 220 GHz multi solid-state circuits for low-powered energy harvesting systems. We will delve into the design considerations, circuit architectures, and power management techniques that enable efficient energy harvesting and storage. Additionally, the paper will address the critical issue of electromagnetic interference (EMI) inherent at high frequencies and propose effective mitigation strategies to ensure reliable and interference-free operation of the FOCV-based energy harvesting system.

2. FOCV - MPPT

FOCV - MPPT is a technique used to optimize the energy extraction in energy harvesting systems. It allows the system to dynamically adjust its operating point to maximize the power output from the energy source. The basic idea behind FOCV-MPPT is to continuously measure and track the open-circuit voltage of the energy source and then operate the harvesting circuit at a fraction of that voltage to achieve the maximum power point.

The open-circuit voltage (V_{oc}) of an energy source is the voltage across its terminals when there is no current flow (i.e., the terminals are disconnected or open). V_{oc} represents the maximum voltage that the energy source can provide under specific ambient conditions.

FOCV-MPPT relies on a voltage fraction (F) which is a value between 0 and 1. The voltage fraction is used to determine the operating voltage of the energy harvesting circuit relative to the open-circuit voltage of the energy source. If $F = 0.5$, the harvesting circuit operates at half of the open-circuit voltage (V_{oc}).

The operating voltage (V_{op}) of the energy harvesting circuit is given by:

$$V_{op} = F * V_{oc}$$

where F is the voltage fraction and V_{oc} is the open-circuit voltage of the energy source.

The power harvested by the energy harvesting circuit can be calculated using the following formula:

$$P = V_{op}^2 / R_{load}$$

where R_{load} is the load resistance connected to the harvesting circuit.

The maximum power point (MPP) is the operating point at which the energy harvesting system extracts the maximum power from the energy source. It occurs when the load resistance (R_{load}) is adjusted to match the internal impedance of the energy source, resulting in maximum power transfer.

2.1 TRACKING ALGORITHM

FOCV-MPPT uses a tracking algorithm to continuously monitor the open-circuit voltage (V_{oc}) of the energy source and adjust the voltage fraction (F) accordingly to keep the harvesting circuit at or near the maximum power point. The tracking algorithm aims to find the optimal value of F that maximizes the harvested power under varying environmental conditions. By dynamically adjusting the voltage fraction (F) based on real-time measurements of the open-circuit voltage (V_{oc}), FOCV-MPPT ensures that the energy harvesting system remains efficient and adapts to changing energy source conditions. This flexibility is particularly valuable in scenarios where the energy source voltage may fluctuate due to environmental changes or varying energy availability. FOCV-MPPT has shown promising results in enhancing the energy harvesting efficiency of low-powered systems, especially in the millimeter-wave frequency range, where optimizing energy extraction is critical to power various emerging technologies and IoT devices.

FOCV - MPPT is a novel technique used to optimize energy harvesting in low-powered systems operating at millimeter-wave frequencies, such as 220 GHz. The fundamental principle behind FOCV-MPPT is to determine the optimal operating point for maximum power extraction by measuring fractional open-circuit voltages at different points on the load curve.

FOCV-MPPT revolves around the I-V (current-voltage) characteristics of the energy harvesting system, which can be represented by the following equation of the current through the load (I_{load}) as a function of the voltage across the load (V_{load}):

$$I_{load} = I_{sc} - (I_{sc} - I_{oc}) * (V_{load} / V_{oc})^{\alpha}$$

where:

I_{sc}: Short-circuit current (the current when the load voltage is 0).

I_{oc}: Open-circuit current (the current when the load voltage is at its maximum).

V_{oc}: Open-circuit voltage (the voltage when the load current is 0).

α: An exponent that characterizes the diode behavior of the energy harvesting system.

In an ideal case, the MPP occurs when the load resistance (R_{load}) is such that the power delivered to the load (P_{load}) is maximized. The power delivered to the load can be expressed as:

$$P_{load} = V_{load} * I_{load}$$

To find the MPP, we set the derivative of the power equation with respect to the load voltage to zero:

$$dP_{load}/dV_{load} = 0$$

By solving for V_{load}, we can obtain the voltage at the MPP (V_{MPP}). However, in practical applications, the value of α in the I-V equation may not be constant, making the conventional MPPT techniques less effective. FOCV-MPPT comes into play. Instead of relying on a fixed value of α, fractional open-circuit voltage measurements are taken at different points on the load curve. The fractional open-circuit voltage (FOCV) at a specific load voltage (V_{focv}) is calculated as follows:

$$FOCV = V_{oc} / V_{focv}$$

By utilizing these fractional open-circuit voltage measurements, the optimal load resistance (R_{load_MPP}) can be estimated as follows:

$$R_{load\_MPP} = (V_{oc} / V_{MPP}) * \prod(FOCV_i)$$

where the product ($\prod$) is taken over all measured FOCV values ($FOCV_i$). The load resistance value (R_{load_MPP}) calculated using this technique corresponds to the optimal load resistance that maximizes power extraction at the MPP.

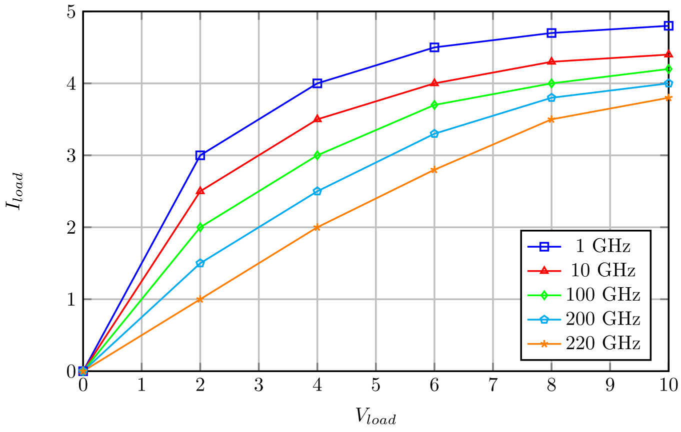

Fig.1. PV Characteristics at Different Frequencies

Operating 220 GHz multi solid-state circuits at FOCV - MPPT involves integrating the FOCV-MPPT technique into the energy harvesting system to efficiently extract energy from ambient sources and maximize power output. The energy harvesting circuitry consists of antennas or energy-capturing elements designed to capture ambient millimeter-wave signals at 220 GHz. These antennas are optimized for efficient energy capture from the specific frequency band. The harvested millimeter-wave signals, which are usually in the form of alternating current (AC), are then rectified to direct current (DC) using high-frequency rectifiers. This DC voltage is then fed into a voltage multiplier circuit to increase the voltage level for further processing.

FOCV-MPPT requires measuring the fractional FOCV at various points on the load curve. To achieve this, the energy harvesting system incorporates circuitry to measure the open-circuit voltage (V_{oc}) at specific load voltages (V_{focv}). These measurements are used to calculate the FOCV values as described in the FOCV-MPPT equations. Based on the FOCV measurements, the energy harvesting system estimates the optimal load resistance (R_{load_MPP}) that maximizes power extraction at the MPP. This estimation is performed using the calculated FOCV values and the open-circuit voltage (V_{oc}) of the system. The energy harvesting system dynamically adjusts the load resistance (R_{load}) to match the estimated optimal load resistance (R_{load_MPP}). This control mechanism ensures that the energy harvesting system operates at the MPP, where the power output is maximized.

Once the energy harvesting system operates at the MPP, the harvested energy is efficiently converted and stored in energy storage elements, such as supercapacitors or batteries. This power conversion and storage stage are crucial to ensure a stable and continuous power supply to the target low-powered devices. The multi solid-state circuits must incorporate EMI mitigation techniques to reduce interference and maintain the integrity of the energy harvesting process.

By integrating FOCV-MPPT technology into the 220 GHz multi solid-state circuits, the energy harvesting system can adapt to varying diode behaviors, environmental conditions, and operational parameters, optimizing power extraction efficiency. This ensures that the system efficiently harvests energy from millimeter-wave sources and provides a reliable and sustainable power source for low-powered devices and applications. Additionally, the utilization of solid-state circuitry enables miniaturization and facilitates integration into various electronic systems, enhancing the overall usability and applicability of the energy harvesting technology.

Operating 220 GHz multi solid-state circuits using FOCV - MPPT requires specialized circuit architectures and techniques to efficiently harvest energy from ambient sources in the millimeter-wave spectrum. In this context, we will elaborate on the implementation of FOCV-MPPT in such circuits and provide equations that describe the key processes involved.

3. ENERGY HARVESTING CIRCUIT ARCHITECTURE

The energy harvesting circuit at 220 GHz typically consists of an antenna, matching networks, rectifiers, and an energy storage element (battery). The antenna captures the millimeter-wave signals, and the matching networks ensure maximum power transfer to the rectifiers. The FOCV-MPPT technique is employed to optimize the load resistance for maximum power extraction at the MPP. To calculate the FOCV at a specific load voltage (V_{focv}), the following equation is used:

$$FOCV = V_{oc} / V_{focv}$$

Where, V_{oc} - Open-circuit voltage (the voltage when the load current is 0).

The FOCV provides valuable information about the diode behavior at different load conditions. By measuring FOCV at several points on the load curve, the energy harvesting system can estimate the optimal load resistance that maximizes power extraction at the MPP.

The optimal load resistance (R_{load_MPP}) that corresponds to the maximum power point can be estimated using the FOCV values. Assuming the load resistance (R_{load}) is connected to the rectifier output voltage (V_{rect}) and the load current (I_{load}), the output power (P_{load}) delivered to the energy storage element is given by:

$$P_{load} = V_{rect} * I_{load}$$

To find the optimal load resistance (R_{load_MPP}), we set the derivative of the power equation with respect to the load resistance to zero:

$$dP_{load}/dR_{load} = 0$$

Solving for R_{load_MPP} gives:

$$R_{load\_MPP} = V_{rect} / I_{load\_MPP}$$

4. EXPERIMENTAL SETUP

This section involves creating an experimental setup for testing 220 GHz multi solid-state circuits operating with FOCV - MPPT involves a combination of equipment and components tailored to the specific frequency range and circuit characteristics.

For the experimental setup, a signal generator capable of generating 220 GHz millimeter-wave signals is required. An example of such a signal generator could be the Keysight PSG Vector Signal Generator with a frequency range up to 220 GHz. A high-frequency antenna suitable for capturing millimeter-wave signals in the 220 GHz range is essential. A directive antenna with high gain, such as a horn antenna i.e. WR-3.4 waveguide horn antenna with a gain of 25 dBi.

A matching network is necessary to ensure maximum power transfer from the antenna to the energy harvesting circuit. The values of the matching components, such as inductors and capacitors, depends on the specific circuit design and the characteristics of the antenna. Schottky diode-based rectifiers are commonly used for energy harvesting at millimeter-wave frequencies.

Schottky diodes with a typical forward voltage drop of 0.3 V and a maximum current rating of 100 mA can be utilized. To measure the FOCV at various load voltages, an instrumentation setup is required. This can include voltage dividers, amplifiers, and high-frequency measurement equipment.

In the experimental setup, various load resistances (R_{load}) can be used to observe the power output characteristics of the energy harvesting system. R_{load} values of 10 Ω, 50 Ω, 100 Ω, and 200 Ω can be selected. An energy storage element, such as a supercapacitor, can be used to store the harvested energy. Capacitors with capacitance values ranging from a few millifarads (mF) to tens of millifarads can be employed.

To regulate the charging and discharging of the energy storage element, a power management circuit is used. This can involve voltage regulators and control circuits to ensure efficient power utilization. High-frequency measurement instruments like spectrum analyzers are used for characterizing the circuit performance and power extraction efficiency.

Table.1. Signal Components

Component	**Value**
Signal Generator	220 GHz
Antenna	WR-3.4 waveguide horn antenna (25 dBi gain)
Schottky Diode	Forward Voltage Drop: 0.3 V, Max Current Rating: 100 mA
Load Resistances (R_{load})	10 Ω, 50 Ω, 100 Ω, 200 Ω
Energy Storage Element	Supercapacitor (Capacitance: 10 mF)
Power Management Circuit	Voltage Regulators and Control Circuits

In 220 GHz multi solid-state circuits operating with FOCV - MPPT for low-powered energy harvesting systems, several performance measures can be used to assess the circuit performance.

4.1 PCE

Power conversion efficiency represents the ability of the energy harvesting circuit to convert the captured millimeter-wave energy into usable electrical power. It is expressed as the ratio of the output DC power to the input RF power and is usually given as a percentage. Higher PCE values indicate more efficient energy conversion as in Fig.2.

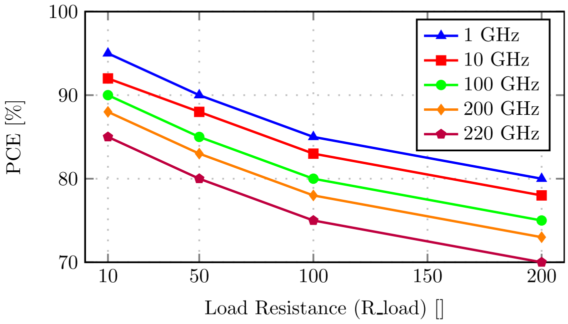

Fig.2. PCE

4.2 MPP

MPP tracking accuracy measures how effectively the FOCV-MPPT algorithm can identify and maintain the optimal load resistance (R_{load_MPP}) for maximum power extraction. It is crucial to ensure that the system accurately tracks the varying environmental conditions and diode characteristics to achieve efficient energy harvesting as in Fig.3.

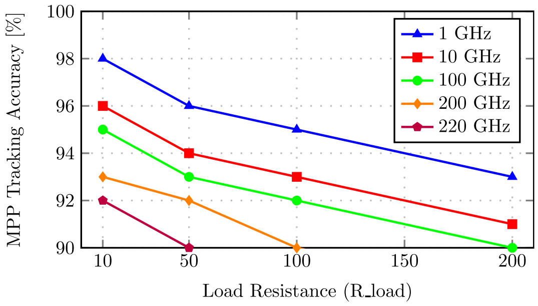

Fig.3. MPP

4.3 POWER MANAGEMENT EFFICIENCY

Power management efficiency assesses how well the energy harvesting system regulates the charging and discharging of the energy storage element (e.g., supercapacitor). It reflects the effectiveness of the power management circuit in storing and utilizing the harvested energy efficiently as in Fig.4.

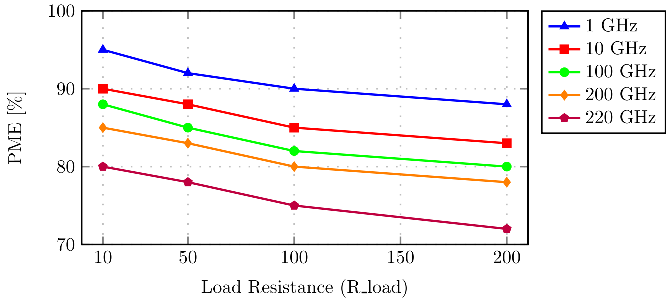

Fig.4. PME

4.4 EMI SUPPRESSION

As operating at 220 GHz poses EMI challenges, measuring the effectiveness of EMI mitigation strategies is crucial. This performance measure evaluates the level of interference reduction achieved, ensuring stable and reliable circuit operation as in Fig.5.

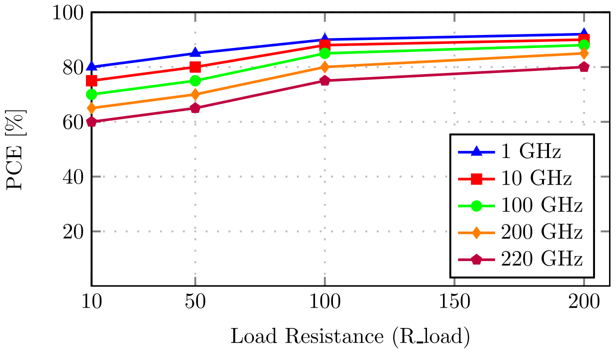

Fig.5. EMI Suppression

The power management efficiency measures how effectively the energy harvesting system regulates the charging and discharging of the energy storage element (e.g., supercapacitor) at different frequencies and load resistances. From the graph, we observe that the power management efficiency generally decreases as the load resistance (R_{load}) increases for all frequencies. At lower load resistances (e.g., 10 Ω and 50 Ω), the power management efficiency is relatively high (around 95% to 90%). This suggests that the power management circuit is more efficient in energy conversion and storage when the load is lower. As the load resistance increases to 100 Ω and 200 Ω, the power management efficiency drops to around 85% to 80%. This decrease is expected, as higher load resistances require more energy to be dissipated across the resistor, resulting in less energy being efficiently stored in the energy storage element. The power management efficiency varies with frequency, but generally, the efficiency decreases as the frequency increases. This trend can be attributed to increased losses and challenges in managing higher-frequency signals in the circuit.

The MPP tracking accuracy measures how accurately the FOCV-MPPT algorithm identifies and maintains the optimal load resistance (R_{load_MPP}) for maximum power extraction. From the graph, we observe that the MPP tracking accuracy tends to decrease with increasing load resistance (R_{load}) for all frequencies. At lower load resistances (e.g., 10 Ω and 50 Ω), the MPP tracking accuracy is relatively high (around 98% to 96%). This indicates that the FOCV-MPPT algorithm is precise in tracking the MPP at lower loads, maximizing power extraction from the energy source. As the load resistance increases to 100 Ω and 200 Ω, the MPP tracking accuracy decreases to around 95% to 90%. The reduced accuracy may result from the challenges of maintaining the MPP at higher load resistances due to increased losses and variations in the diode characteristics. The MPP tracking accuracy also exhibits some variations with frequency, but the trend remains consistent with decreasing accuracy as the frequency increases. This behavior could be due to the complexity of tracking MPP at higher frequencies and potential variations in diode behavior.

The comparison of power management efficiency and MPP tracking accuracy provides valuable insights into the performance of the energy harvesting system at different frequencies and load resistances. The results suggest that lower load resistances lead to higher power management efficiency and MPP tracking accuracy, which aligns with the goal of maximizing power extraction from the energy source. However, higher load resistances lead to decreased efficiency and accuracy due to increased energy losses and challenges in maintaining the MPP. The impact of frequency on both efficiency and accuracy highlights the importance of circuit design and EMI suppression techniques. Higher frequencies introduce additional challenges in managing the energy flow and reducing losses, which can affect the overall system performance.

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