Design & development of a nano antenna using chemical decomposition methods in IoT based nano-technology systems for energy harvesting for telecommunication sectors with AI-ML approach

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Abstract

In this research article, the development of nano antenna and energy harvesting is presented. Wirelessly interconnected devices are becoming increasingly common in today's society, forming the Internet of Things. These devices are often autonomous and continue to scale down to millimeter and even smaller dimensions, presenting major challenges for how to power them. To address this challenge, various approaches to harvesting energy from ambient or externally supplied sources have been developed, including radio-frequency, optical, mechanical, thermal, nuclear, chemical, and biological modalities. This article provides a comprehensive survey of existing approaches for energy harvesting, discussing their potential for scaling to small dimensions in the context of current technologies and possible future nanoscience developments. The article also provides an outlook on the advancements that need to be made to address the challenges of powering small-scale devices and systems. The proliferation of untethered, wirelessly interconnected devices has led to the widespread adoption of the Internet of Things (IoT). These autonomous devices, scaling down to the millimeter and sub-millimeter range, pose significant challenges in terms of providing power. In this article, we conduct a comprehensive survey of current methods for harvesting energy from ambient or externally supplied sources. These approaches encompass various modalities such as radio-frequency, optical, mechanical, thermal, nuclear, chemical, and biological sources, enabling the generation of electrical power for micro- and nano-systems. We examine the potential for scaling these energy conversion techniques to small dimensions, considering both existing technologies and potential advancements in the field of nanoscience.

Keywords Photovoltaic devices, Infrared, Communications, Nano antennas, Lithography, Chemical, etc.

1. Introduction

The increasing global demand for energy necessitates the exploration of alternative energy sources. Currently, extensive research and development efforts are underway to enhance the efficiency of photovoltaic devices. However, these devices are limited in their ability to extract energy solely from the visible region of the electromagnetic spectrum. To address this limitation, a novel device called Nano antenna has been created, capable of converting thermal energy from the infrared region of the spectrum into electricity [1]. In the near future, Nano antenna is expected to make significant contributions in various fields such as space communication, broadband wireless links, wireless optical communication, mobile communication (5G), radar detection, and higher order frequency applications. Different techniques including electron beam lithography, focused ion beam, and nanoimprinting lithography can be employed for fabricating Nano antennas. This paper will specifically focus on nanoimprinting lithography as it offers a cost-effective and high-throughput approach. Additionally, the selection of suitable materials for Nano antennas poses a significant challenge, and this paper will explore strategies to overcome this hurdle [2].

The development of self-powered systems at the microscale and nanoscale has led to transformative networks in various fields, enhancing our lives and ensuring health and safety. The Internet of Things (IoT) has already revolutionized sectors such as smart homes, medical devices, manufacturing, infrastructure, and transportation. With billions of connected devices and a rapid growth rate, the IoT has now progressed to the millimeter scale and below, known as the Internet of Tiny Things (IoT2) or Internet of Nano Things (IoNT). These smaller systems offer new functionalities and application spaces due to their high number, density, and integration capabilities. In this work, we refer to these sub-millimeter systems collectively as IoT2 [3].

IoT2 systems rely on advancements in low-power circuits and heterogeneous integration. These small autonomous devices, often referred to as "motes" in the vision of smart dust, require efficient power and energy delivery for their success. While power and energy solutions exist for systems at approximately the centimeter scale and larger, such as batteries and wired connections, scaling down below a centimeter introduces new challenges [4]. Wireless power transfer efficiency decreases significantly at millimeter and smaller dimensions, and conventional integration technologies involving printed circuit boards and physically accessible ports are not viable for IoT2 devices. The power density requirement for these systems, based on recent mm-scale systems, is approximately 100 nW/mm2. This article aims to summarize power and energy sources and considerations as systems are scaled down to the micro- and nano-scale. Special attention will be given to the outlook for IoT2 systems, taking into account the unique challenges and opportunities they present [5].

2. Energy harvesting in nano-antennas

A nano antenna is a novel solar collection device that utilizes rectifying antennas. Being a recent innovation, the nano antenna does not possess a long history. However, the concept of using antennas to harvest solar energy was initially introduced by Robert Bailey in 1973. In 1973, Bailey & James Fletcher were granted a patent for an electromagnetic wave converter that resembled modern-day nano antenna devices. Subsequently, in 1985, Alvin Marks obtained a patent explicitly describing the use of sub-micron antennas for directly converting light into electricity [6]. The nano antenna comprises three primary components: the ground plane, the optical resonance cavity, and the antenna itself (Fig. 1). The antenna absorbs the electromagnetic wave, while the ground plane reflects the light back towards the antenna, and the optical resonance cavity redirects and intensifies the light towards the antenna via the ground plane. One notable advantage of nano antennas is their high theoretical efficiency. For instance, single junction solar cells have a theoretical efficiency of only 30%, whereas nano antennas can achieve a theoretical efficiency of approximately 85%. Another advantage of nano antennas compared to semiconductor photovoltaic devices is their ability to absorb light across a wide range of frequencies. They can capture energy from sunlight as well as the infrared radiation emitted by the Earth's heat [7].

Energy harvesting for nano antennas refers to the process of capturing and converting ambient energy into usable electrical energy using miniature antenna structures at the nanoscale. Nano antennas are designed to resonate at specific frequencies and efficiently collect electromagnetic waves or other forms of energy from the environment. This harvested energy can then be utilized to power low-power electronic devices, sensors, or wireless communication systems, especially in IoT (Internet of Things) applications. Here are some key points to consider regarding energy harvesting for nano antennas, which are listed one after other [8].

Principle of Operation: Nano antennas operate based on the principles of electromagnetic induction or rectification. When exposed to electromagnetic waves, the nano antenna structure resonates and induces an alternating current (AC). This AC signal is then rectified and converted into direct current (DC) using diodes or rectifiers [9].

Size and Efficiency: Nano antennas are characterized by their extremely small size, typically on the scale of nanometers to micrometers. Due to their reduced dimensions, they can efficiently harvest energy from the surrounding environment, including ambient radio frequency (RF) signals, Wi-Fi signals, or even light in the case of optical nano antennas [10].

Energy Sources: Nano antennas can harvest energy from various sources, such as RF signals from nearby communication devices, electromagnetic radiation from power lines or electronic appliances, or even light in the visible or infrared spectrum. The choice of energy source depends on the specific application and available ambient energy [11].

Frequency Matching: The design of nano antennas involves tailoring their dimensions and resonant properties to match the frequency of the energy source they are intended to harvest. Matching the resonance frequency of the nano antenna with the source frequency enhances the efficiency of energy capture [12].

Material Selection: The choice of materials for nano antennas is crucial to achieve desired properties such as high conductivity, low losses, and tunable resonance. Metallic materials, such as gold, silver, or copper, are commonly used due to their excellent conductivity and compatibility with nanofabrication techniques [13].

Rectification and Power Management: After energy is captured by the nano antenna, it is typically rectified and converted into DC power. This process involves the use of diodes or rectifiers to convert the AC signal into a usable form. Power management circuits may also be employed to regulate and store the harvested energy efficiently [14].

Applications: Energy harvesting using nano antennas finds applications in various fields, including wireless sensor networks, IoT devices, biomedical implants, and autonomous systems. It enables self-powered and maintenance-free operation by utilizing ambient energy sources, eliminating the need for frequent battery replacements or wired power connections [15].

Challenges: Despite their potential, energy harvesting for nano antennas faces challenges, including limited available energy, the efficiency of energy conversion, and the optimization of antenna design for specific applications. Maximizing energy harvesting efficiency, reducing losses, and optimizing antenna performance remain active areas of research and development [16].

Energy harvesting for nano antennas holds significant promise for powering miniature and low-power electronic systems. By efficiently capturing and converting ambient energy, nano antennas contribute to the development of self-sustainable and energy-efficient technologies, enabling the proliferation of IoT devices and other wireless applications in a wide range of sectors as shown in the Fig. 1 [17].

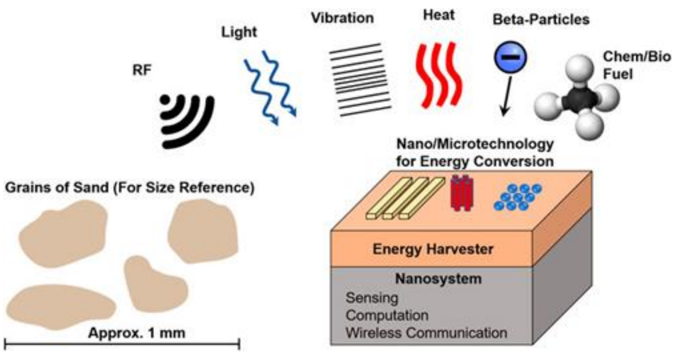

Fig. 1 : A Nano-antenna concept

3. Scope of the research work

In this section, the scope of the project work is presented in brief which gives an idea about the importance of the research work [18].

Introduction to Nano-Antennas: This section provides an overview of nano-antennas, including their concept, working principle, and potential applications in energy harvesting. It explains how nano-antennas operate and their ability to capture and convert energy from various sources [19].

Literature Review: A comprehensive literature review is conducted to summarize previous research on nano-antennas for energy harvesting. The key findings from these studies are presented, highlighting the advancements and insights gained. Furthermore, this section identifies gaps in the existing knowledge, paving the way for further research [20].

Design and Modelling: A theoretical framework is developed for designing and modelling nano-antennas specifically for energy harvesting purposes. The various design parameters are discussed in detail, emphasizing their impact on the antenna's performance. Theoretical analysis and simulations are conducted to optimize the design [21].

Fabrication and Characterization: The fabrication process of nano-antennas is described, focusing on the techniques employed. Additionally, different characterization methods used to evaluate the performance of nano-antennas are discussed. This section highlights the experimental procedures involved in verifying the theoretical predictions [22].

Experimental Results: The obtained experimental results from the fabricated nano-antennas are presented and analyzed. The data is compared with the theoretical predictions, providing insights into the antenna's actual performance and validating the design approach [23].

Applications: This section explores the potential applications of nano-antennas in energy harvesting. It discusses their integration into solar cells, wireless sensor networks, and other Internet of Things (IoT) devices. The benefits and challenges associated with employing nano-antennas in these applications are addressed, along with future prospects and possible improvements [24].

4. Objectives of the project work

The objectives of the research study are as follows [25]…

Objective 1 : Gain a comprehensive understanding of nano-antennas for energy harvesting, encompassing their working principle, design parameters, and fabrication techniques.

Objective 2 : Conduct a literature review to summarize existing research on nano-antennas for energy harvesting, pinpointing gaps and limitations in current knowledge.

Objective 3 : Establish a theoretical framework for designing and modeling nano-antennas for energy harvesting, investigating the impact of different design parameters on antenna performance.

Objective 4 : Fabricate and characterize nano-antennas for energy harvesting, utilizing various characterization techniques to assess their performance.

Objective 5 : Analyze and compare experimental results with theoretical predictions, identifying discrepancies and limitations within the current approach.

Objective 6 : Explore potential applications of nano-antennas in energy harvesting, evaluating their advantages and limitations in diverse settings.

5. Background works w.r.t. the nano-antennas

The theory behind nano antennas, similar to rectifying antennas, involves the movement of electrons in response to incident light. The oscillating electric field of the incoming electromagnetic wave causes the electrons in the antenna to oscillate at the same frequency. This movement generates an alternating current (AC) in the antenna circuit. To convert this AC current into direct current (DC) power, rectification is necessary, typically achieved using diodes. The resulting DC current can then be utilized to power an external load. Harvesting energy from radio-frequency (RF) sources is a common method used in IoT technology. RF technology has been widely adopted for applications like RFID tags and readers, enabling various functionalities such as credit card transactions, tracking devices, and more. These applications typically employ inductive coupling with coil antennas that are on the centimeter scale or larger. The efficiency of the RF link depends on factors like coil geometry, quality factor, frequency, and distance between the transmitter and receiver. However, as dimensions scale down to around 1 mm, efficiency decreases significantly [26].

To achieve suitable efficiency at smaller scales, such as in the micrometer and nanometer range, higher frequencies and novel approaches for deep subwavelength antennas are required. Scaling to higher frequencies may be feasible for near-field systems, but the design must account for propagation losses and the efficiency of high-frequency electronics in nanosystems. Metamaterials offer a potential solution by enabling high efficiency and directionality in subwavelength dimensions. Utilizing metamaterials can help overcome the challenges of achieving efficient RF energy harvesting in smaller-scale IoT devices. Energy harvesting modalities play a crucial role in enabling IoT2 devices to access energy sources based on their specific application requirements. Various approaches are needed to cater to different energy availability scenarios. The energy source can either be obtained from the surrounding ambient environment or intentionally supplied through external excitation, depending on the particular application. Having a range of energy harvesting methods allows IoT2 devices to adapt and utilize the most suitable energy source for their intended purpose [27].

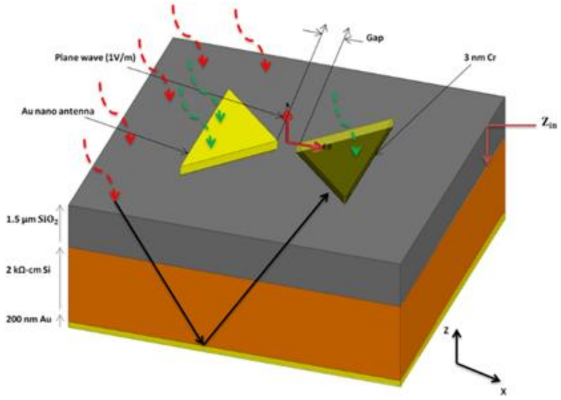

Fig. 2 : A typical nano-antenna

The fabrication of nano antennas has been accomplished through various techniques, including Electron Beam Lithography (EBL), Focused Ion Beam lithography (FIB), and Nanoimprinting Lithography (NIL). EBL and FIB lithography are expensive, time-consuming, and have low throughput. As an alternative, nanoimprinting lithography has been employed for nano antenna fabrication. It is a cost-effective, time-efficient, and high-throughput technique. In contrast to serial beam-based lithography, which employs photons, electrons, or ions to define nano patterns, NIL employs a hard mold that contains the desired surface topographic features. The mould is pressed onto a thin polymer film under controlled temperature and pressure, resulting in a thickness contrast. Resolutions as fine as 10 nm were demonstrated more than a decade ago. UV-NIL is a promising variation where a transparent mold is pressed at room temperature into a liquid precursor that is subsequently cured using UV radiation. Soft nano-imprinting techniques, utilizing polymeric flexible stamps replicated from a single master mold, have also been developed to reduce mold fabrication costs and enable large-area patterning at lower pressures. In the future, NIL holds potential as an ideal technique for cost-effective and highly reproducible realization of antenna arrays over large areas, such as for bio-optical sensors on substrates or fiber facets as shown in the Fig. 2 [28].

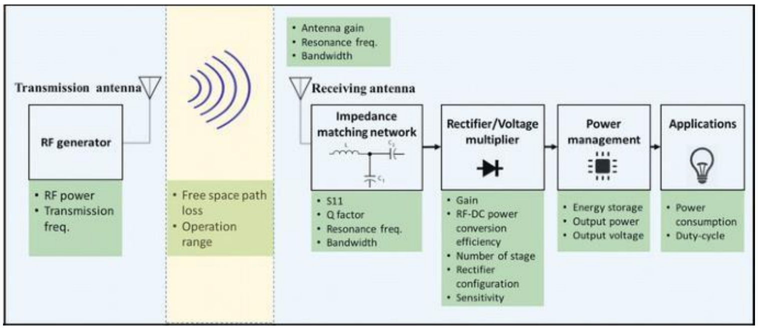

Fig. 3 : An overview of antenna energy harvesting

A wireless power transmission system can be defined as a mechanism that transfers electrical power between two locations in the Earth's atmosphere without the need for wires or any physical medium. The origins of RF power scavenging in open space can be traced back to the late 1950s when a microwave-powered helicopter system was introduced. Subsequently, the concept of power harvesting or energy scavenging emerged, referring to the process of harnessing energy from the surrounding environment using various techniques such as thermoelectric conversion, vibration excitation, solar energy conversion, and pressure gradients. This approach holds significant potential for replacing small batteries in low-power electronic devices and systems. The diagram illustrates the structure of an RF energy harvesting system and highlights the key factors that contribute to its overall performance as shown in the Fig. 3 [29].

Fig. 4 : Experimental work carried out & the results observed in the Multimeter

The Fig. 3 gives the experimental work carried out & the results observed in the multimeter. The working principle of a nano antenna relies on the interaction between light and its physical structure, typically composed of metallic nanoparticles arranged in a specific pattern. When light interacts with the nano antenna, it can excite the electrons within the metallic nanoparticles, resulting in surface plasmon resonance. This resonance causes the nanoparticles to oscillate, generating a localized electromagnetic field that can interact with nearby materials such as molecules or other nanoparticles. The design of a nano antenna can be optimized to enhance desired properties, such as the intensity and directionality of the electromagnetic field. Consequently, nano antennas find utility in various applications, including sensing, imaging, and data communication.

The working principle is centered on the ability of metallic nanoparticles to interact with light and produce a localized electromagnetic field, which can be exploited for diverse applications. However, material selection in nano antenna fabrication presents challenges, particularly with gold (Au) and silver (Ag), as they exhibit skin effect at higher frequencies. This effect impacts the efficiency of nano antennas by reducing the effective cross-sectional area of the wire and increasing resistance. To address this issue, alternative materials like graphene and carbon nanotubes (CNT) are being explored. These materials do not display skin effect at higher frequencies, making them promising candidates for nano antenna fabrication. In this paper, we delve into the details of nano antennas based on CNT and graphene, exploring their potential advantages and applications [30].

6. AI-ML approaches for the design process

The design and development of a nano antenna using chemical decomposition methods in IoT-based nanotechnology systems for energy harvesting in the telecommunications sector can be approached using AI (Artificial Intelligence) and ML (Machine Learning) techniques. Here's a step-by-step explanation of the process:

Problem Formulation: Clearly define the problem statement and objectives of designing and developing a nano antenna for energy harvesting in IoT-based nanotechnology systems. Identify the requirements and constraints specific to the telecommunications sector.

Data Collection: Gather relevant data related to nano antenna designs, chemical decomposition methods, IoT systems, energy harvesting techniques, and telecommunications requirements. This data can be collected from research papers, academic literature, industry standards, and experimental data.

Feature Extraction: Extract key features from the collected data that are important for designing and developing the nano antenna. These features may include antenna dimensions, material properties, chemical decomposition techniques, IoT system parameters, and telecommunications requirements.

Training Data Preparation: Prepare a labelled dataset by combining the extracted features with corresponding target variables. The target variables could include antenna performance metrics, energy harvesting efficiency, or any other relevant metrics specific to the telecommunications sector.

Model Selection: Choose appropriate AI and ML algorithms that are well-suited for solving the problem at hand. This could involve using regression models, classification algorithms, or even neural networks, depending on the specific requirements and complexity of the problem.

Model Training: Train the selected ML model using the labeled dataset prepared in step 4. This involves feeding the input features to the model and adjusting the model parameters iteratively to minimize the error or maximize the performance metric.

Model Validation and Optimization: Evaluate the trained model's performance using validation data or cross-validation techniques to ensure its effectiveness and generalizability. Optimize the model further if necessary, by fine-tuning hyperparameters or adjusting the feature set.

Prediction and Design Optimization: Once the model is trained and validated, it can be used to predict the performance of different nano antenna designs. The ML model can help optimize the antenna design parameters based on specific requirements, such as energy harvesting efficiency or communication range.

Iterative Refinement: If the predicted antenna designs do not meet the desired specifications, iterate through the process by incorporating new data, refining features, adjusting the ML model, or incorporating additional constraints.

Implementation and Testing: Implement the optimized nano antenna design in a real-world IoT-based nanotechnology system. Perform thorough testing to validate the design's performance, energy harvesting capabilities, and its compatibility with telecommunication requirements.

Continuous Monitoring and Improvement: Monitor the performance of the deployed nano antenna in real-world scenarios and collect feedback. This data can be used to further improve the AI-ML models and optimize the design iteratively.

By applying an AI-ML approach, the design and development of a nano antenna for energy harvesting in IoT-based nanotechnology systems can be enhanced, leading to improved efficiency, cost-effectiveness, and better alignment with the specific requirements of the telecommunications sector. The circuit used for testing is shown in Fig. 5.

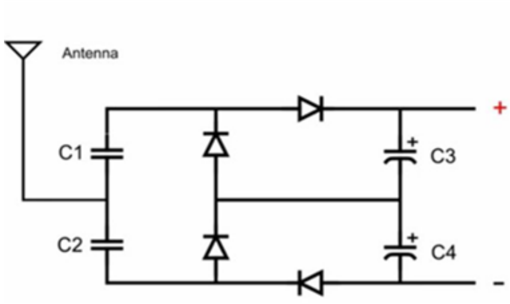

Fig. 5 : Circuit used for testing

7. Applications & Advantages

Nano antennas have a significant impact across various fields, including space communication, optical wireless communication, mobile communication, radar object detection, broadband wireless links, terahertz detection, high-speed wireless data transfer, and nano photonic applications. These applications hold immense potential and are expected to become a reality in the near future. In this research article, we provide a detailed exploration of selected applications that leverage nano antennas along with some experimental works carried out with the results. Regarding the size, the nano antennas are extremely small, measuring just a few tens of nanometers. Their compact size enables their utilization in confined spaces, such as nano electronics and nano photonics applications. When selectivity is considered, the nano antennas can be designed to specifically interact with certain wavelengths of light. This selectivity makes them valuable for applications involving selective detection and sensing. When sensitivity is considered, due to their small dimensions, nano antennas exhibit high sensitivity and can detect minute amounts of light. This characteristic is advantageous for applications like biological sensing and imaging. In view of the efficiency, the nano antennas enhance the interaction between light and matter, leading to improved efficiency in various applications, including solar cells, photodetectors, and light-emitting diodes (LEDs). When the tunability is considered, the nano antennas offer the ability to adjust their interaction with different wavelengths of light by altering their shape and size. This tunability makes them versatile for a wide range of applications.

8. Conclusion

The increasing global demand for energy cannot be met solely by non-renewable sources, highlighting the need to maximize energy extraction from renewable sources. Solar energy is a prominent renewable source, but current photovoltaic devices still face challenges in achieving optimal conversion efficiency. In this context, we explore the potential of a new device called the nano antenna, which converts heat energy into electrical energy and significantly enhances solar cell efficiency. This technology holds great promise for space applications, with space agencies such as NASA and ISRO utilizing solar cells as power sources in space shuttles. Nano antennas offer a compelling solution due to their efficient fabrication process using Nanoimprinting lithography, requiring minimal material compared to solar cells while delivering higher efficiency. Additionally, nano antennas find application in plasmonic electronic circuits, converting dissipated heat energy from electrical connections and electronic components into electrical energy. This functionality contributes to lower operating temperatures for such devices.

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