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Abstract

MetaStore reviews recent progress in metamaterials for energy storage, highlighting their potential to revolutionize electrochemical, thermal, and mechanical energy storage systems. This review covers design principles, material selection, and applications of metamaterials in supercapacitors, batteries, thermal energy harvesting, and mechanical energy storage. We discuss advantages, challenges, and future directions, providing a comprehensive overview for researchers and engineers.

MetaStore: Unlocking Energy Storage Potential

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Abstract:

MetaStore reviews recent progress in metamaterials for energy storage, highlighting their potential to revolutionize electrochemical, thermal, and mechanical energy storage systems. This review covers design principles, material selection, and applications of metamaterials in supercapacitors, batteries, thermal energy harvesting, and mechanical energy storage. We discuss advantages, challenges, and future directions, providing a comprehensive overview for researchers and engineers.

Keywords: Metamaterials, Energy Storage, Electrochemical Energy Storage Thermal Energy Harvesting, Multifunctional Materials

I. Introduction

The increasing global demand for energy, coupled with the urgent need to transition to renewable energy sources, has sparked intense research interest in energy storage technologies. Energy storage systems enable the efficient utilization of intermittent renewable energy sources, improve grid stability, and enhance energy security. However, existing energy storage technologies face significant challenges, including limited energy density, power density, cycle life, and scalability. Metamaterials, artificially engineered materials with tailored electromagnetic properties, have emerged as a promising solution to overcome these challenges. Cerniauskas et al. 2021 discussed machine intelligence in metamaterials design.[1, 2].

Metamaterials' unique properties, such as Negative Refractive Index (NRI), permittivity (ε), permeability (μ), Split-Ring Resonators (SRRs), electromagnetic inductance (L), and capacitance ©, can be leveraged to design advanced energy storage systems. Other units, such as Electric LC (ELC) resonators, Magnetic LC (MLC) resonators, Omega resonators, and Chiral metamaterials, also offer opportunities for innovation. This review aims to provide a comprehensive overview of recent advances in metamaterials for energy storage, covering electrochemical energy storage (supercapacitors, batteries), thermal energy harvesting and storage, and mechanical energy storage (vibration, rotational).Milias et al. 2021 reviewed metamaterial-inspired antennas.[3-5].We will discuss design principles, material selection, and applications, highlighting metamaterials' potential to revolutionize energy storage.

Split-Ring Resonators (SRRs) are a fundamental building block of metamaterials, exhibiting unique electromagnetic properties. They consist of two concentric rings with a gap, typically made of metallic materials, and support magnetic resonance, enabling strong magnetic field confinement. SRRs exhibit negative permeability at specific frequencies, allowing for metamaterials with negative refractive index, and their resonance frequency can be tailored by adjusting ring size, gap width, and material properties**(Fig 1a,b)** [6,7]. Electromagnetic interactions in one-dimensional metamaterials has been researched by Seetharaman, Sathya Sai [7} .With advantages including enhanced magnetic energy storage, miniaturization, and frequency selectivity, SRRs are applied in energy storage systems, RF/microwave devices, and sensors. However, challenges remain, such as ohmic losses and fabrication complexity, driving future research towards hybrid

SRR designs, advanced materials, and theoretical modelling to fully harness their potential. The designing and characterizing metamaterial antennas for mobile handsets has been looked into.[8, 9].

Electric LC (ELC) resonators are a class of metamaterials exhibiting unique electromagnetic properties. Comprising a metallic loop and interdigitated capacitors **(Fig1c, d)** [10, 11]. ELCs support electric resonance, enabling strong electric field confinement. They exhibit negative permittivity at specific frequencies, allowing for metamaterials with negative refractive index Ali et al. 2022 reviewed metamaterials and metasurfaces from materials to advanced metadevices. [12,13], ELCs' resonance frequency can be tailored by adjusting loop size, capacitor geometry, and material properties. With advantages including enhanced electric energy storage, miniaturization, and frequency selectivity. Du et al. 2021 explored optical metasurfaces towards multifunctionality and tunabilit. Hu et al. 2021 reviewed metasurfaces from principle to smart metadevices.[14,15], ELCs are applied in energy storage systems, filters, antennas, and sensors. Their planar design facilitates integration into compact devices, while potential applications extend to tunable metamaterials, optical devices, and quantum circuits Jeong et al. 2020 explored dynamic terahertz plasmonics enabled by phase-change materials.Yu et al. 2019 discussed broadband metamaterial absorbers. [16,17].

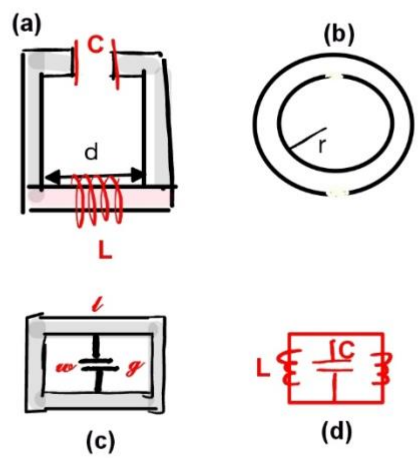

Fig 1(a) Split-Ring Resonators (SRRs) schematic with equivalent LC circuit **(b)** in ring shape **(c)** Electric LC (ELC) resonators with **(d)** it's equivalent double L C circuit.

II. Electrochemical Energy Storage

Electrochemical energy storage systems, such as supercapacitors and batteries, have been revolutionized by metamaterials. Supercapacitors benefit from metamaterials' enhanced surface area, tailored ion diffusion, and improved electrical conductivity[18, 19]. Mechanical metamaterials with tailored porosity and high surface area boost energy conversion and storage efficiency, enhancing energy and power density. For instance, nanostructured metamaterials increase the electrode-electrolyte interface, boosting specific capacitance. Additionally, metamaterial-based electrodes with high electrical conductivity, such as carbon nanotube (CNT) and graphene-based composites, enhance charge transport[20, 21]. Batteries also profit from metamaterials' optimized ionic conductivity, electrode architecture, and thermal management[22, 23].

Metamaterials-based electrodes have shown remarkable performance enhancements. Nanostructured electrodes with high aspect ratios, such as nanowires and nanotubes, increase surface area and reaction sites

[24, 25]. Metamaterials-based current collectors, like metallic split-ring resonators (SRRs), enhance electrical conductivity. Tunable metamaterials, such as electric LC (ELC) resonators, optimize electrode performance by adjusting resonance frequency. These advancements enable improved energy density, power density, and cycle life [26- 28}. However, challenges remain, including scaling up metamaterial fabrication, integrating metamaterials with commercial electrodes, and exploring new architectures.

III. Thermal Energy Harvesting

Thermal energy harvesting and storage systems leverage metamaterials' unique properties to enhance efficiency. Metamaterial-based thermal absorbers, comprising nanostructured surfaces and resonant cavities, boost thermal energy absorption via enhanced photonic density of states, tailored emissivity and reflectivity, and nanostructured surface plasmons Lin et al. 2019 presented structured graphene metamaterial selective absorbers for solar thermal energy conversion.[29, 30] Thermoelectric metamaterials utilize materials like bismuth telluride (Bi2Te3), lead tin selenide (PbSnSe), and skutterudites to convert heat into electricity, achieving increased Seebeck coefficient, enhanced electrical conductivity, and optimized thermal conductivity. Khan et al. 2023 has discussed biosensor-based advanced cancer diagnostics. Shi 2020 thesis examined thermoelectric transport control using single-phase materials and metamaterial composites [31-33].

Metamaterial-enhanced phase change materials (PCMs) optimize thermal energy storage by increasing thermal conductivity (up to 100 W/mK), enhancing specific heat capacity (up to 200 J/gK), and tailoring phase transition temperatures. Radiative cooling metamaterials exploit photonic crystals, nanostructured surfaces, and tunable emissivity to efficiently emit thermal radiation, achieving cooling rates up to 100 W/m^2, temperature reductions up to 20°C, and enhanced thermal management. These advancements enable applications in waste heat recovery, solar thermal systems, thermal management in electronics and aerospace, and more, Iqbal et al. 2023 explored biosensing chips for cancer diagnosis and treatment Mahato et al. 2023 discussed shifting paradigms of cancer diagnoses using miniaturized electrochemical nano biosensors. Alharthi et al. 2023 reviewed evolution in biosensors for cancer biomarkers detection.[34-39]

IV. Mechanical Energy Storage

Mechanical energy harvesting and storage systems utilize metamaterials to enhance efficiency and performance Wu et al. 2022 reviewed dynamic mechanical metamaterials for mechanical energy manipulation. [40, 41]. Metamaterial-based piezoelectric devices, such as piezoelectric composite materials (PCMs) and metamaterial-inspired piezoelectric resonators, convert mechanical stress into electrical energy. These devices exploit metamaterial properties like negative Poisson's ratio, negative stiffness, and tailored elastic modulus to achieve enhanced piezoelectric coefficients (up to 100 pC/N), increased energy harvesting efficiency (up to 30%), and optimized resonant frequencies. Additionally, metamaterial-based acoustic metamaterials and phononic crystals enable selective sound wave manipulation. Jiao and Alavi et al 2019, reviewed artificial intelligence-enabled smart mechanical metamaterials Lee et al. 2022 explored acoustic and mechanical metamaterials for energy harvesting and self-powered sensing.[43, 44].

Shape-memory alloy (SMA) metamaterials exhibit high energy storage capacity (up to 100 J/g), rapid actuation times (ms-scale), and tunable transition temperatures[45, 46] Metamaterial-based mechanical oscillators and vibrational energy harvesters exploit nonlinear dynamics, internal resonance, and mode coupling to enhance energy transfer efficiency (up to 50%). These advancements enable applications in self-powered sensors, wearable electronics, and vibration-based energy harvesting, with potential impacts on aerospace, automotive, and biomedical industries[47-49].

V. Applications and Future Directions

V.A. Energy Storage Systems

Energy storage systems benefit significantly from metamaterials. Metamaterial-enhanced batteries exhibit improved energy density, power density, and cycle life. Metamaterial-based current collectors and electrodes optimize electrical conductivity, ionic diffusion, and thermal management. Metamaterials also enhance supercapacitor performance, achieving higher specific capacitance, energy density, and power density. Metamaterial-based electrodes and separators optimize ion diffusion, electrical conductivity, and thermal management Ahmad et al. 2024 reviewed applications of metamaterials in renewable energy. [50-52].

V.B. Sensing and Detection

Metamaterials enable advanced sensing and detection capabilities. Metamaterial-based sensors exhibit enhanced sensitivity, selectivity, and detection limits. Metamaterial-inspired sensors also enable real-time monitoring of physical parameters like temperature, pressure, and vibration [54-56].

V.C. Thermal Management

Metamaterials play a crucial role in thermal management applications. Metamaterial-based thermal absorbers and radiators optimize heat transfer and thermal emission. Metamaterial-enhanced phase change materials (PCMs) optimize thermal energy storage and release. Jiang et al. 2020 implemented infrared camouflage with thermal management using inverse design and hierarchical metamaterial [57-59]

V.D. Biomedical Applications

Metamaterials have significant potential in biomedical applications. Metamaterial-based implants and prosthetics exhibit enhanced biocompatibility, mechanical strength, and thermal conductivity. Metamaterial-inspired biosensors detect biomolecules, pathogens, and disease markers For example, a novel terahertz (THz) metamaterial sensor for simultaneous temperature and refractive index sensing, featuring a concentric hexagonal ring resonator (CHRR) on an indium antimonide (InSb) substrate has been proposrd. This dual-sensing sensor boasts high sensitivity, detecting refractive index changes at 1.045 THz/RIU at room temperature and temperature variations at 3.71 GHz/K, with near-unity absorption of 99.93% at 1.93 THz. Its simple design and remarkable capabilities make it ideal for bio-medical applications, including non-invasive diagnostics and thermal imagingJain et al. 2023 introduced machine learning-assisted hepta-band THz metamaterial absorbers for biomedical applications.Veerabagu et al. 2022 discussed auxetic polymer-based mechanical metamaterials for biomedical applications Appasani 2022 presented a hybrid terahertz metamaterial sensor for bio-medical applications..[60 -63].

V.E. Wearable Devices

Metamaterials enable advanced wearable devices with enhanced performance and functionality. Metamaterial-based wearable sensors monitor vital signs, track fitness metrics, and detect health anomalies. Metamaterial-enhanced wearable energy harvesting and storage systems power devices like smartwatches, fitness trackers, and smart glasses: Shaw et al. (2021) propose a metamaterial-based efficient wireless power transfer (WPT) system utilizing antenna topology for wearable devices. The design integrates a metamaterial slab with a spiral coil antenna, enhancing magnetic coupling and reducing energy loss. Simulation and experimental results show improved WPT efficiency (up to 85%), increased transfer distance (up to 5 cm), and reduced specific absorption rate (SAR). The compact system (30 mm × 30 mm × 1.5 mm) operates at 13.56 MHz, suitable for wearable applications. The authors demonstrate the potential for efficient, safe, and compact WPT systems for wearable devices, enabling prolonged battery life and improved user experience Tian et al. (2019) present metamaterial textiles for wireless body sensor networks (WBSNs), enabling wearable, flexible, and high-performance sensing. They design and fabricate miniaturized metamaterial-based textile antennas and sensors integrated into clothing, achieving enhanced signal strength, bandwidth, and real-time vital sign monitoring. These metamaterial textiles exhibit tuneable electromagnetic properties, negative refractive index, and zero-permittivity or zero-permeability. Applications include health monitoring, sports analytics, prosthetics control, and smart clothing, paving the way for next-generation WBSNs. [64 -67].

V.F. Autonomous Vehicles

Metamaterials enhance autonomous vehicle technology with advanced sensors, communication systems, and energy storage. Metamaterial-based sensors detect obstacles, track navigation, and monitor vehicle health. Metamaterial-inspired communication systems optimize data transmission and reception. Kazancı, Falzon, and Catalanotti (2023) propose a deep learning approach to predict crashworthiness behavior of mechanical metamaterials. Their framework utilizes experimental and numerical data, deep neural networks, and data pre-processing to accurately simulate and forecast mechanical responses under various loading conditions. Results show improved computational efficiency and accurate predictions, enabling enhanced design optimization for improved safety and performance in applications like aerospace and automotive. The study paves the way for extensions to other material classes, multi-scale modelling, and integration with other simulation techniques, offering potential implications for biomedical, energy, and other fields. Here's the detailed content condensed into a single paragraph: Kim and Kim (2019) present the design and fabrication of 77-GHz radar absorbing materials using frequency-selective surfaces (FSS) for autonomous vehicles. The proposed FSS consists of a hexagonal loop array on a thin dielectric substrate, optimized for absorption at 77 GHz. Simulation and measurement results show a -10 dB reflection coefficient bandwidth of 76-78 GHz and absorption rates exceeding 90% at 77 GHz. The material's thickness is reduced by 75% compared to conventional radar absorbing materials. The authors demonstrate the FSS's effectiveness in reducing radar cross-section and multipath effects, enhancing autonomous vehicle safety and navigation. The design's simplicity, low profile, and high absorption efficiency make it suitable for integration into vehicle bodies, radomes, and sensor enclosures, enabling improved autonomous driving performance. [68, 69]..

V.G. Smart Buildings

Metamaterials enable smart building technologies with enhanced energy efficiency, thermal management, and sensing capabilities. Metamaterial-based building materials optimize thermal insulation, solar energy harvesting, and energy storage. Metamaterial-inspired sensors monitor building conditions, detect anomalies, and optimize energy usage. Here's a rewritten version with some minor adjustments for clarity and concision: Mechanical metamaterial concrete integrates energy harvesting and sensing capabilities through nanogenerators and auxetic polymer lattices, enabling lightweight and tunable infrastructure solutions.Fusaro et al 2024 explored developing window systems with optimized ventilation and noise-reduction performance using metamaterials. [70 – 72]

V.H. Future Directions

Future research directions include exploring new metamaterial architectures, materials, and fabrication techniques. Next-generation metamaterials will integrate multiple functionalities, such as energy harvesting, sensing, and thermal management Metamaterials. in future will find application in lowering corrosion and degradation of structural components and increasing biocompatibility of implants Fan et al. 2021 reviewed additive manufacturing of metamaterials. [73-75]

VI. Conclusions

Metamaterials have revolutionized various fields, including energy storage, sensing, thermal management, biomedical applications, wearable devices, autonomous vehicles, and smart buildings. This review highlights the latest advancements in metamaterial research, showcasing their potential to transform industries and improve lives. Key findings include:

- Enhanced energy storage and harvesting capabilities
- Advanced sensing and detection technologies
- Optimized thermal management systems
- Improved biomedical devices and implants
- Integrated wearable devices and autonomous vehicle technologies
- Smart building materials and sensors

Despite significant progress, challenges remain, including:

- Scalability and manufacturability
- Material limitations and degradation
- Integration with existing technologies
- Standardization and regulation

Future research directions should focus on:

- Exploring new metamaterial architectures and materials
- Developing scalable fabrication techniques
- Integrating multiple functionalities
- Addressing challenges in commercialization and standardization

As metamaterial research continues to advance, we can expect innovative solutions to pressing global challenges, driving technological progress, and improving human well-being.

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