International Journal of Engineering Materials and Manufacture (2024) 9(2) 60-80
https://doi.org/10.26776/ijemm.09.02.2024.04

Application of Metamaterial in Renewable Energy: A Review

Ali Ahmad, Abeer Asad, Pocholo Pacpaco, Claire Thampongphan and Muhammad Hasibul Hasan

Received: 16 March 2024
Accepted: 31 March 2024
Published: 15 April 2024
Publisher: Deer Hill Publications

ABSTRACT
Metamaterial advancements hold promise for compact renewable energy harvesting, capturing acoustic, electromagnetic, mechanical, and solar energy on a modest scale across global industries. Engineered structures surpass natural material limitations, offering capabilities unattainable in traditional counterparts. This investigation explores metamaterials' manipulation of acoustic, electromagnetic, mechanical, and solar energy. Mechanical metamaterials convert strain into electrical energy, applicable from interstellar travel to terrestrial infrastructure. Precision-configured acoustic metamaterials efficiently harness dispersed acoustic energy, improving renewable energy methodologies. Integration into photovoltaic cells showcases metamaterials' solar potential, with innovative designs enhancing solar energy conversion efficiency. Electromagnetic metamaterials efficiently absorb and convert frequencies into usable energy from communications and monitoring systems, in the agricultural and environmental sectors. Comparative analyses highlight noteworthy efficiency advancements, underscoring metamaterials' transformative influence on renewable energy. As they redefine the sector, implications extend to both small-scale devices and large-scale applications, positioning them as pivotal contributors. The paper critically evaluates metamaterial effectiveness in harnessing diverse energy sources, guiding future research. Metamaterial adaptability to different sizes and integration into technology reveals possibilities for compact energy sources. Ongoing research addresses scientific and economic challenges, paving the way for scaling metamaterial applications to commercial operations and emphasizing their importance in incorporating renewable energy into our technological milieu.
Keywords: Metamaterials, Energy Harvesting, Piezoelectric Materials, Renewable Energy.

1 INTRODUCTION

Renewable energy makes up a large portion of Canada's commercial energy sector, providing about 64% of Canada's electricity needs (Islam et al., 2004). Current renewable energy production takes advantage of natural resources in the form of wind, solar, hydro, biomass, geothermal, and tidal power (Islam et al., 2004). Comparatively mechanical and acoustic energy are small-scale sources. However, with the use of metamaterials, these small-scale sources can be efficiently exploited when implemented into our current technology.

Metamaterials are a new class of functional artificial materials uniquely designed to enable property manipulation for forms of energy such as mechanical and acoustic energy (Mulla et al., 2015). Metamaterials' capabilities come from the base structure and patterns of the material and elements used to construct it (Mulla et al., 2022). Physical properties such as a negative Poisson ratio, negative stiffness, and negative density (Valipour et al., 2022; Mulla et al., 2015); as well as properties with respect to electromagnetic waves, with refraction indexes of zero and atomic structures that absorb these waves fully (Qazi et al., 2019; Olabi et al., 2022) are impacted by the metamaterial construction.

With these properties, extensive research has been conducted on the application of these metamaterials for small and large-scale energy harvesting. When comparing these metamaterials for uses in energy collection, factors such as, availability, manufacturing costs and functional reliability impact implementation.

This paper will compare new and theoretical solar, mechanical, acoustic and electromagnetic metamaterials for use in energy harvesting. In the analysis of the studies and theories on these metamaterials, their respective strengths in different environments for practical energy absorption will be highlighted, with the goal of informing and focusing the scope for future research efforts.

Ali Ahmad ✉, Abeer Asad, Pocholo Pacpaco, Claire Thampongphan and Muhammad Hasibul Hasan
Toronto Metropolitan University
350 Victoria St. Toronto ON M5B 2K3
Canada
E-mail: s11ahmad@torontomu.ca

Reference: Ahmad et al. (2024). Application of Metamaterial in Renewable Energy: A Review. *International Journal of Engineering Materials and Manufacture*, 9(2), 60-80.

2 SOLAR ENERGY

Due to population increase and industrial growth, the world's energy demand has been continuously increasing. With most of the energy production (73.5% in 2017) coming from hydrocarbon sources (Qazi et al., 2019). This poses a serious problem as combustion of hydrocarbon fuel emits greenhouse gases in large quantities, which is responsible for change in weather, sea level rise, damage to the ecosystem, and severe health issues (Olabi et al., 2022). A shift towards renewable energy sources is required. One of the most widely used forms of renewable energy is solar energy, supplied predominantly by photovoltaic cells. However, conventional photovoltaic cells possess a shortcoming in efficiency due to optical characteristics of Silicon, which is a poor absorber of light (Hamouche et al., 2018). The efficiency of photovoltaic cells has been largely studied. With the recent emergence of metamaterial technologies, the application of metamaterial in solar cells has been consequently gaining more attention.

2.1 Current Issues and Limitations

The optical losses in conventional photovoltaic cells are caused through three modes: poor photon penetration into silicon, reflection in the air-glass interface in front of the cell, and unwanted transmission through the rear of the cell (Hamouche et al., 2018). Therefore, optical confinement is required to improve the light to the current efficiency of photovoltaic cells. With their unconventional properties, metamaterials can be used to create a waveguide structure for application in the silicon-based photovoltaic cells.

In a study by Hamouche et al. (2018), a multilayer planar waveguide structure based on metamaterial was analyzed for application in the photovoltaic cell using the matrix transfer method to estimate the optical parameters of the structure through numerical simulation. The results from the simulation show favorable optical response with large increase in light absorption, and reduction in reflection and transmission for normal incidence; however, the optical parameters for oblique incidence show no clear improvement. (Hamouche et al., 2018)

2.2.1 Enhancement of Photovoltaic Solar Cells Using Metamaterials

Ajmi and colleagues (Al Ajmi et al., 2023) proposed a design of low-cost multi-resonant metamaterial structure for photovoltaic cell applications to function as an anti-reflective screen when integrated into a solar panel. The design of the structure was carried out with COMSOL Multiphysics software. This structure consists of repeating $0.55\mu m$ by $0.55\mu m$ square unit cells where each unit cell contains two concentric metallic rings embedded in dielectric material.

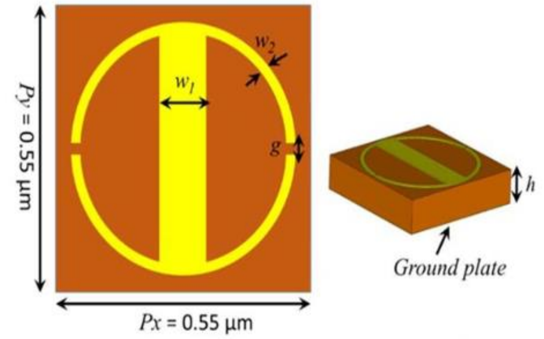


Figure 1: Proposed unit cell of multi resonant metamaterial absorber. (Al Ajmi et al., 2023)

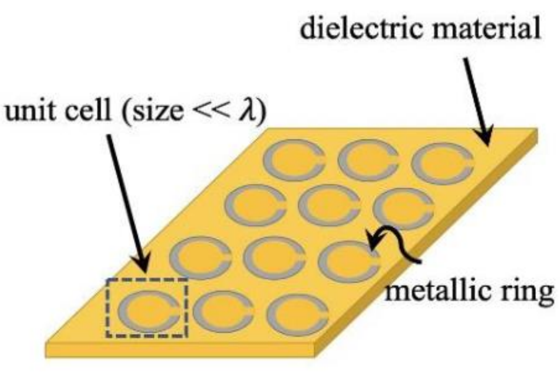


Figure 2: General view of an engineered metamaterial structure. (Al Ajmi et al., 2023)

To greatly increase the resonance of the structure, the multi-resonant absorber is made out of an electrically extremely tiny resonant square unit cell that is fashioned like two concentric metallic rings with gaps on opposing sides. The rings are composed of a 4.09 × 107S/m conductivity and 4 nm thickness of gold material (Al Ajmi et al., 2023). After that, the resonant unit cell inclusions are made periodic and printed on a low-loss Polyimide medium that is grounded and has a thickness of h = 0.12 µm and a relative permittivity of 2.88 − j0.09.As illustrated in Figure 6, the optimum dimensions for the remaining unit cell characteristics are: Px = Py = 0.55 µm, w1 = 0.11 µm, w2 = 0.02 µm, and g = 0.01 µm (Al Ajmi et al., 2023).

2.2.2 Proposed PV Solar Cell with Absorbing Screen

Numerical estimation of PV solar panel absorption strength and electron-hole generation rate with and without a metamaterial layer. Electrical study conducted to determine I-V and P-V curves, and efficiency of the PV panel with and without a metamaterial screen. The effective constitutive parameters of the proposed metamaterial absorbing screen, including $\varepsilon_{eff}$and μ_{eff}, can be obtained by numerically computing scattering parameters from the unit cell. Subsequently, ε_{eff} and μ_{eff} can be computed using derived relations based on the effective impedance Z_{eff} and refractive index n:

$$\mu_{eff} = nZ_{eff} \tag{1}$$

$$\epsilon_{eff} = \frac{n}{Z_{eff}} \tag{2}$$

Here, n represents the refractive index, Z_{eff} is the effective impedance of the metamaterial slab, μ_{eff} stands for effective permeability, and ϵ_{eff} refers to the effective electric permittivity of the metamaterial slab. Then, an optical study is carried out in COMSOL and verified by CST Microwave Studio estimated the absorption strength of the structure to be very high with three absorption peaks in the visible band, and a maximum peak reaching 99.5% at 547 *THz* (Al Ajmi et al., 2023)

Ajmi and colleagues then carried out a comparative study between a model of a conventional photovoltaic cell and a photovoltaic cell with an integrated metamaterial layer. They found that their metamaterial structure not only improves light absorption, but also provides nearly constant absorption across the visible spectrum. A subsequent electrical study on both models shows an improvement in efficiency from 7.4% to 12%. (Al Ajmi et al., 2023)

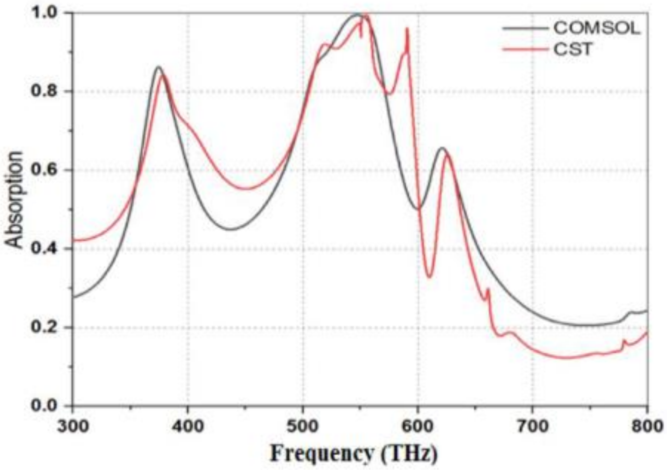


Figure 3: Numerically computed absorption through the visible spectrum. (Al Ajmi et al., 2023)

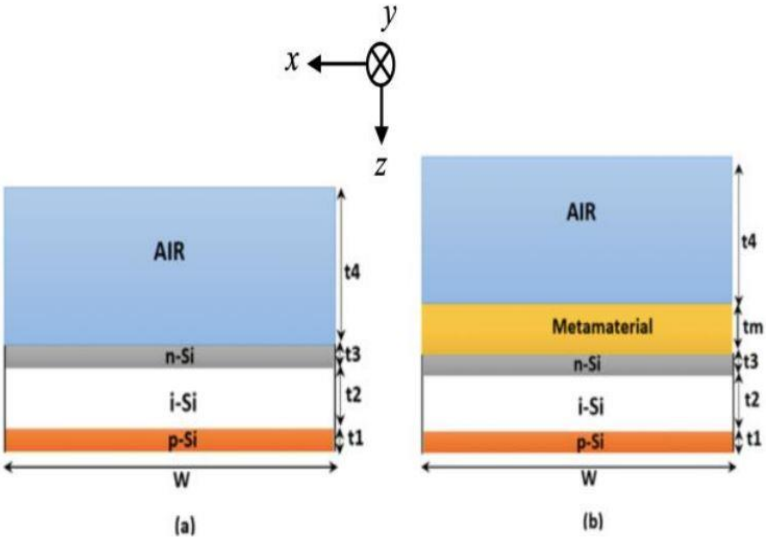


Figure 4: 2D view of the modeled solar cell without metamaterial (a) and with metamaterial (b). (Al Ajmi et al., 2023)

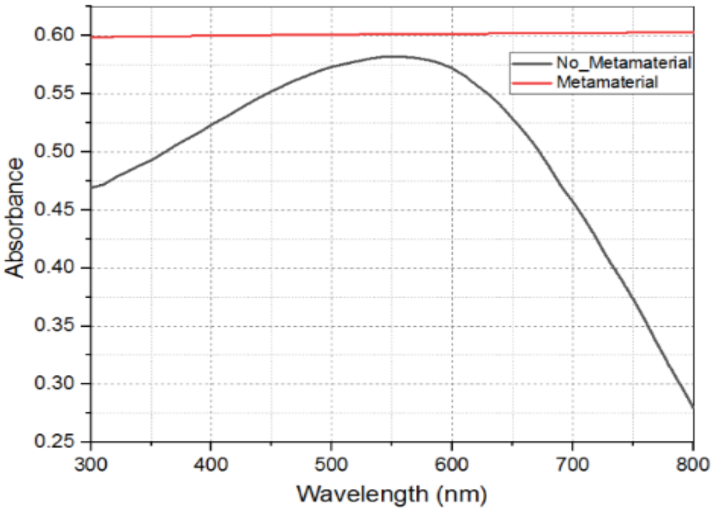
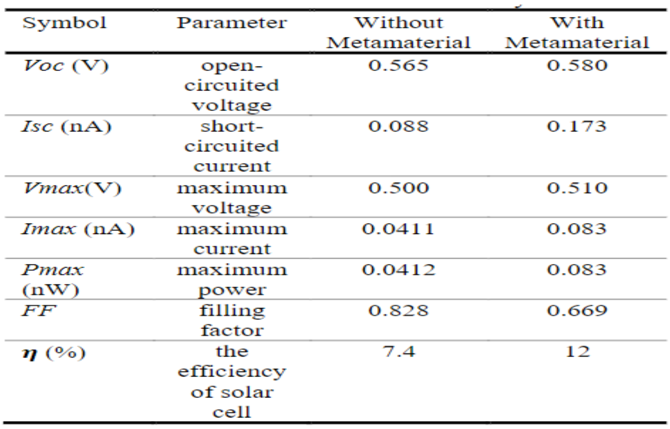


Figure 5: Graphical comparison of light absorption for solar cells with metamaterial compared to solar cells without metamaterial. (Al Ajmi et al., 2023)

Table 1: Numerical results of light absorption for solar cells with metamaterial compared to solar cells without metamaterial. (Al Ajmi et al., 2023)



Symbol	Parameter	Without Metamaterial	With Metamaterial
Voc (V)	open-circuited voltage	0.565	0.580
Isc (nA)	short-circuited current	0.088	0.173
Vmax(V)	maximum voltage	0.500	0.510
Imax (nA)	maximum current	0.0411	0.083
Pmax (nW)	maximum power	0.0412	0.083
FF	filling factor	0.828	0.669
η (%)	the efficiency of solar cell	7.4	12

2.2.3 Low-Cost Solutions

The enhanced photovoltaic cells used in the study are a low-cost example of increasing highly popular photovoltaic cells by 7.4% to 12%. These additions are done by printing sub-wavelength resonant metallic inclusions on a host of insulating materials, which can easily be done using low-cost printed-circuit board manufacturing technology (Al Ajmi et al., 2023). We are confident that integrating metamaterials into solar cells will be highly practical for developing innovative smart solar cell structures through synthesis, design, and manufacturing. We believe that this innovation makes it one of the easiest implementations of meta-material solutions since existing technologies are not removed but simply upgraded for better performance.

2.3.1 Saw Tooth Coating Design

Another design proposed by Hashmi et al, (2013) considers a saw tooth structure consisting of tapered ridges made of alternating layers of metal and insulating material. This structure is designed in such a way that light at different wavelengths would be absorbed by different layers of metamaterial. With this structure, Hashmi and colleagues designed a solar cell model with the proposed metamaterial absorber combined with an anti-reflective coating with a refraction index equal to air to minimize reflection from the silicon PN Junctions, as well as protect the cell from the environment. Simulations of the model within PC1D solar cell modeling software resulted in an increase in efficiency of the photovoltaic cell by 29.356%. (Hashmi et al., 2013)

Figure 7 illustrates the design of a multi-junction solar cell featuring an anti-reflecting coating and a layer of metamaterial with a saw tooth structure. The anti-reflective coating, composed of metamaterial with a refractive index of 1 equivalent to that of air, is crucial to reduce photon losses caused by reflection from the shiny n-type layer. By having a refractive index of one, the anti-reflective coating remains transparent to incoming light, preventing reflection and maintaining efficiency. Additionally, applying an anti-reflective coating on the glass cover helps mitigate temperature variations, dust, and other environmental disturbances that could affect the solar cell's performance and efficiency. (Hashmi et al., 2013)

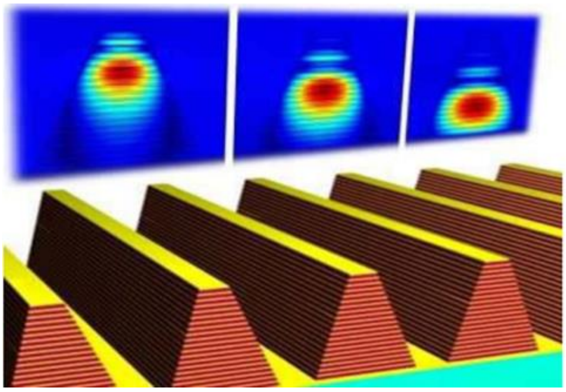


Figure 6: Proposed saw tooth metamaterial structure. (Hashmi et al., 2013)

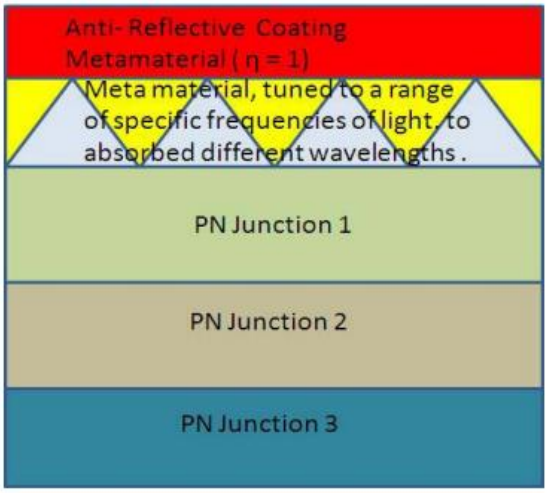


Figure 7: Two-dimensional view of modeled solar cell. (Hashmi et al., 2013)

2.3.2 Future Prospects for Solar Harvesting

Utilizing metamaterial eliminates the polarization effect of unpolarized sunlight, resulting in a manifold increase in efficiency. The saw tooth design utilizes an extremely thin layer of added material which will once again not have any significant effect on the cost of the upgrade but more of an effect with efficiency. Many new models are eco-friendly and much cheaper and thinner than traditional silica (SiO2) solar cells. There are also inexpensive metals like iron, cobalt, and nickel that occur naturally which are instead used to create new metamaterial absorbers such as the saw-tooth coating, absorbing screens and the Cone-shaped resonator (Kumar et al., 2022). Recent advancements in computerized simulations and testing have yielded promising results, indicating that solar power generation companies should consider integrating the aforementioned metamaterial technologies. The energy sector stands to gain significant advantages, including cost reductions and the adoption of greener solutions to address the ongoing global energy crisis. Increased funding in private research initiatives will expedite the integration of metamaterial upgrades in energy harvesting technologies.

3 MECHANICAL ENERGY

Current metamaterials research makes it clear that there are many different domains of energy harvesting. Solar energy harvesting shows tremendous increases in effectiveness using designs such as the saw tooth tapered ridges made up of metals and unique molecular metamaterials (Hashmi et al., 2013). The previous method uses the principles of solar wave absorption, but the versatility can also tap into mechanical wave energies. These artificially engineered materials possess unique properties not found in nature, challenging conventional perceptions of material science (Fedotov, 2017). These fascinating materials possess newfound abilities which can manipulate mechanical energy in forms of physical wave propagation, elasticity and vibrations. Mechanical metamaterials are based on static mechanics which feature auxetic, instability, Penta mode, and Origami/Kirigami structures (Lee et al., 2023). The methods offer potential solutions for powering spacecraft systems during extended missions (Jiao et al., 2023), contribute to sustainable technologies in marine exploration, and optimize energy usage in various mechanical systems, from small-scale wearable devices to large-scale smart infrastructure, revealing implementation in today's market.

3.1 Piezoelectric Material Absorbers

Commencing with the use of piezoelectric material properties for harvesting energy; mechanical strain and movement can be efficiently converted into electrical energy. This process exploits the unique ability of piezoelectric materials to generate an electric charge in response to applied mechanical stress (Jiao et al., 2021). One way to understand how mechanical stress produces energy is to examine a hexagonally Corrugated Piezoelectric Layer within a metamaterial plate from a study conducted by Pengcheng Jiao and others (Jiao et al., 2020). Employing the Euler-Bernoulli beam theory, the piezo layer experiences axial stress due to its significantly smaller thickness compared to the MM width. The transverse electric displacement of the piezo layer can be written as:

$$\delta_3 = d_{31}\sigma_1 + \epsilon_{33}^{T} E_3 \tag{3}$$

Where d_{31}, ϵ_{33}^{T} and E_3 are the piezo strain tensor, permittivity tensor, and electric field in the transverse direction, respectively, and σ_1 is the axial stress. The integral of the transverse electric displacement over the corrugation area that is, the area of the piezo layer—between the hexagonal cells A yields the total electric charge Q:

$$Q(T) = \int_{Agap} d_3 A \tag{4}$$

The voltage across the load resistance RL is obtained as:

$$V_{RL}(T) = i(T)R_L \tag{5}$$

Where i(T) represents the current in the closed-circuit condition as $i = \frac{dQ}{dT}$. Therefore, the electrical power generated from the MM-PENG is:

$$P(T) = \frac{d}{dT}\int_0^T \frac{{V_{RL}}^2}{R_L} dT \tag{6}$$

The electrical energy produced by the MM-PENG is ultimately derived as follows since the voltage across the piezoelectric patch's equivalent capacitance is equal to the voltage across the resistive load, or V = V_{RL} :

$$U(T) = \frac{1}{2}Q(T)V(T) \tag{7}$$

The transverse electric displacement incorporates relevant tensors, leading to the calculation of the total electric charge through integration. The voltage across the load resistance is then determined, enabling the calculation of electrical power generated by the MM-Piezoelectric Nanogenerator. This process efficiently converts mechanical energy, potentially from vibrations or deformations, into electrical energy, demonstrating the optimized energy harvesting capabilities of the designed MM-Piezoelectric system. (Jiao et al., 2020). Now since general piezoelectric theory is established the principles of harvesting electrical energy from mechanical energy, it can be used as a general reference to various methods present in the paper.

3.2.1 Elastic Metamaterials and Cavity Defects

Elastic metamaterials (EMMs) are specially designed materials that offer unprecedented control over elastic waves. These materials showcase unique characteristics do not present in natural substances, including features like band-gaps, negative mass density or modulus, and a refractive index of zero. Consequently, EMMs present a novel approach for directing, constraining, and isolating elastic waves (Ma et al., 2020). Using principles of point defects which is creating an imperfection in a perfect crystal structure (Buschow et al., 2004), The cavities within elastic metamaterials (EMMs) contain distinctive modes, known as cavity or defect modes, wherein elastic waves experience high levels of confinement within the cavities. These cavities have much more in-depth research of diverse arrangements and designs of such cavities (Ma et al., 2020). Research and testing done by the Joint Sino-German Research Project shows that researchers have introduced double cavities into EMM plates, causing a single cavity mode to split into two modes and widening the frequency bandwidth and harvesting that energy using piezoelectric energy harvesters (Ma et al., 2020). The EMM cavities are created with a focus on the bandgap associated with the flexural mode. Figure 8 (a) depicts the schematic diagram of an EMM cavity. To establish the cavity, a single hole (indicated by the dashed outline) is filled in the perfect EMM crystal structure.

When piezoelectric patches are attached in certain locations of the cavities depending on their size and shape, mechanical energy can be stored as electric energy due to deformation in the atomic level (Ma et al., 2020). As highlighted in the research project "For the optimal electrical load resistance of 8 $k\Omega$, more than 40 times the power amplification is achieved by the EMM cavity energy harvester" (Ma et al., 2020). Summarizing the results of study and the different mode cavities that are tested, significant power output of 4.75μW is produced compared to the reference plate which was 0.11μW.

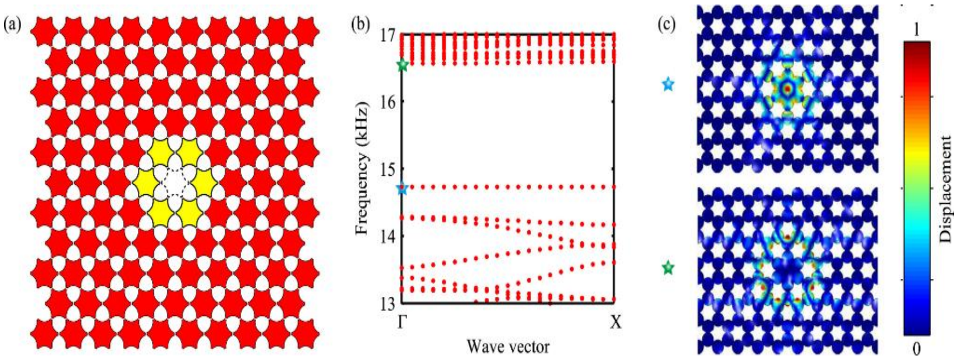


Figure 8: Crystal structure and displacement and creation of specified cavity. (Ma et al., 2020)

3.2.2 Implementation of the EMM's

The finding indicates that creating such cavities using an elastic metamaterial does in fact amplify the power generated. Evidently as the cavity size increases so does the energy harvesting increases at many different frequencies. Using the EMM cavities, it can be very useful in designing structures present in the environment. Building structures with certain metamaterial zones or patches with the described cavities can be a potential mode of harvesting energy using flexural movement. Using principles of vibrational isolation and the EMM's millimeter-scale cavity sizes, buildings, bridges and other structures can implement energy harvesting zones without direct interference. This can be beneficial as passive generation can be obtained in areas where the elastic material proposed in the study can utilize flexural frequencies and generate power. This implementation can be cost effective as it can be embedded in the framework and structure of infrastructures and serve as dual purposes as compared to traditional energy harvesting techniques that are standalone entities. The metamaterials used by the Joint Sino-German Research Project utilized primarily aluminum for their metamaterial which could prove to be a cost-effective method since the material is not composed of rare or complex materials. Structures and or building interiors may utilize the honeycomb design for aesthetic purposes with the added benefits of energy harvesting.

3.3 Interstellar Travel

Interstellar travel and high-speed movement can also recruit efficient usage of metamaterials to convert mechanical/kinetic energy into electrical energy. Included in the scientific journal "Progress in Materials Science" volume 137 highlights the idea of harvesting kinetic energy created from high-speed collision of cosmic dust particles (Jiao et al., 2023). This energy is then converted to electrical energy using piezoelectric material properties. The paper emphasizes its theoretical validation as high-speed collision particles and its effect on metamaterial energy harvesting are not tested to this day. This research highlights a great potential in nanoscale space crafts and energy harvesting. Current rapid development in space travel material manufacturing and semiconductor industries, show an immense aid in creating these proposed metamaterials for nanoscale space crafts. Using A.I, the journal has created many potential candidates for unique materials that can harvest energy (Jiao et al., 2023).

It may evidently be expensive to create and test special materials that will be exposed to high level collision and low temperatures of space. The cost may become reasonable and worth pursuing because of the small scale of the nano space crafts and the self-fueling energy created by the environment.

3.4 Wearable Kinetic Energy Harvesters

Further examples of tested energy harvesting methods consists of a wearable Piezoelectric Energy Harvester (PEH) which generates an electric charge in response to mechanical stress created by an individual walking. (Gao et al., 2021). The researchers used finite element method (FEM) analysis to simulate the dynamic compression experienced by the insoles during walking or running. The study reported that a single insole, equipped with a triple-layer PVDF structure array, could provide an output power of 8.6 mW during running. As a person walks or runs, the metamaterial in the insoles deforms and experiences dynamic compression. This mechanical stress induces a strain in the PVDF membranes within the metamaterial. The PVDF has regions with positively and negatively charged dipoles, and the mechanical stress causes these dipoles to align, resulting in the separation of charges and the creation of an electric potential (Gao et al., 2021). Initially it was noted that the created sole was uncomfortable at first because of the ceramic material used, it was then later changed to a PVDF insole that was polymer based polyvinylidene fluoride (PVDF). Many known limitations such as weight, size and fragility were tackled and solved in the research to create a hypothetical model which generates 8.6mW.

This model does create a form of energy harvesting at a small scale and with a certain distance of walking or running it can be enough to partially charge or power mobile devices after a prolonged period of running or walking. Currently much research has been done into creating the best structure to house the generation material for the insole, thus it may not be a cost-effective solution as it is still in need of further improvements such as size, weight and real-life testing is needed before it is available as a consumer product.

3.5 Ocean Wave Harvesting

Lastly, potential use in harvesting energy of natural ocean wave propagation can also be tapped in. The envisioned application involves deploying the macroscale Metamaterial-based Piezoelectric Nanogenerator (MM-PENG) in the ocean, capitalizing on the periodic vibrational energy generated by the fluctuating ocean surface. Scaling down the MM-PENG to the millimeter scale and submerging it in the ocean allows the periodic waves to serve as axial excitation, activating the energy harvesting capabilities of the system. Additionally, the larger container housing the macroscale MM-PENG offers protective shielding for diverse electrical devices, safeguarding them against the challenging marine environment (Jiao et al., 2020).

These macroscale applications may at first seem extremely valuable, it may cause harm to aquatic life and disturb the environment that they are present within. Collecting the energy may pose a challenge since it will take resources and time to collect such energy and provide much more complexity. Small scale energy harvesting devices that are independent are areas of research that need more work and thought-out analysis before being implemented. Due to their small size, connecting such harvesting materials will take lots of additional resources and planning for simple connectivity. It may not be cost-effective at all to collect such little energy in unique and complex ways which are not mentioned in the research paper. The product seems cost-effective in relation to development owing to its small size and high manufacturing volume once implemented.

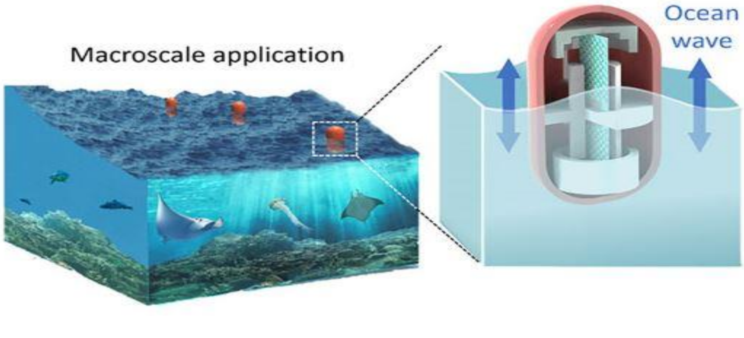


Figure 9: Model of theorized macroscopic metamaterial energy harvesters. (Jiao et al., 2020)

3.6.1 Cantilever Beam Method

Using vibration isolation and energy harvesting techniques, mechanical movement and kinetic energy in materials can assist in metamaterial usage. Bi-stable configurations and varied beam geometries have been employed to improve the efficiency of vibration energy harvesting (Li et al., 2017). In this mechanical metamaterial design, a broad array of detached cantilevers is linked to a central structural frame. This arrangement facilitates the direct connection between the propagation of bulk elastic waves through the structural frame and the intrinsic harmonic vibrations of the cantilevers (Li et al., 2017). A highly interconnected state arises when the frequency of the bulk elastic wave aligns with the harmonic frequency of the cantilever. In this scenario, the vibrational energy carried by the bulk wave is transferred to the kinetic energy of the resonating cantilevers, becoming localized (Li et al., 2017). The piezoelectric thin films then capture and convert the energy into electrical energy. This is done by introducing a sophisticated way of organizing these materials, specifically by incorporating cantilevers (rigid structures) within a repeating lattice framework, possibly at the micro or nano scale (Li et al., 2017). Forming extra microstructure in the original square lattice as seen in Figure 10. When the cantilever beams are attached the vibrational frequency is then lowered and band gaps, which are a range of frequencies in which certain materials do not allow the transmission of waves or particles are created (Honsberg & Bowden, n.d), preventing certain frequencies of vibrations from propagating. Lowering the frequency range is crucial because it aligns with the frequencies commonly found in natural environments. (Li et al., 2017)

This method is further improved when mass is added at the ends of the cantilever beams see Figure 10. The band structures are investigated through FEA. The generalized stiffness matrix, K, and the homogenized mass matrix, M, are produced in this procedure using conventional finite element discretization. Then, a unit-cell technique based on Floquet-Bloch theory and based on finite elements will be used to analyze the band properties of a periodic structure. The equations of motion are given by:

$$(K - \omega^2 M)q = 0 \tag{8}$$

Where ω is the frequency and q is a vector of the generalized nodal degree of freedom. After the d.o.f are partitioned and proper wavenumber dependent propagation conditions are imposed, the dynamics problem is recast as:

$$[K_R(\varepsilon_1, \varepsilon_2) - \omega^2 M_r(\varepsilon_1, \varepsilon_2)]q_r = 0 \tag{9}$$

Where *K*r and *M*r are reduced matrices that depend on the two-dimensional wave number vector $\varepsilon = \varepsilon_1, \varepsilon_1$. To solve this eigenvalue problem, sweep the wave vector over the contour of the irreducible Brillouin zone and solve for the corresponding ω. The result is referred to as a band structure or a band diagram, and it is a collection of dispersion relation curves that reflect the propagation modes permitted in the structure and their respective frequency ranges. The existence of band gaps is demonstrated by isolating the frequency intervals in which no modes are permitted, and elastic waves are prevented from propagating due to wave interference (Li et al., 2017).

Analyzing the test results from the experiment done by the Northwestern University it is possible to see in Figure 11, in the designated range of the band gap, marked by dashed lines, the transmission of waves comes to a halt, indicating the containment and localization of the mechanical wave within the cantilever metamaterials. Concerning the energy-harvesting capability of the engineered mechanical metamaterials exposed to longitudinal wave input, the voltage output of attached PVDF films is depicted in (c) and (d) under a constant force of 5.34 *N*. In this context, (c) and (d) showcase results from cantilevers positioned perpendicular and parallel to the excitations, respectively. The highest voltage and power outputs are observed at frequencies within the bandgap. Voltage measurements are taken across a 1 *MΩ* resistor, with current power outputs being for the specified test being 0.05 μW at a maximum voltage of 0.22 *V* (Li et al., 2017).

3.6.2 Enhancement of the Cantilever Beam Method

To enhance the voltage and power output per beam in this device, one could consider incorporating a larger tip mass, a thicker piezoelectric film, and thinner/longer cantilever beams within each unit cell (Li et al., 2017). Additional researchers such as (Umino et al., 2018) have used very similar concepts of low frequency energy harvesting and have gotten results of 47.4 μW. Proving this technological advancement opens new possibilities in the field of self-powered technology and eliminating the need for batteries and establishing low-maintenance, autonomous systems.

3.6.3 Implementation of the Cantilever Beam Method

The small size of this cantilever beam metamaterial can potentially make it a cost-effective implementation in various applications, devices, toys or equipment that undergo the simulated forces such as gym equipment, tools, handheld devices or car parts. Being able to harvest energy will make products more valuable and worth the increase in price of selective materials that use the cantilever beam method. Products will no longer require additions such as batteries or power storage facilities.

4 ACOUSTIC ENERGY

Acoustic metamaterials manifest in the real world through crystals of lattice parameters which are implemented in various ways as seen in figure 12 (Haberman et al., 2016). Acoustic metamaterials are used in ways such as insulation, wave manipulation and cloaking (Ji & Huber, 2022). They are also used industrially through two applications: absorption and transmission. The metamaterials used for absorption are porous materials, which allow for absorption through thermal and viscous traits. Whereas metamaterials used for transmission are heavy and stiff. (Romero Garcia & Hladky-Hennion, 2019)

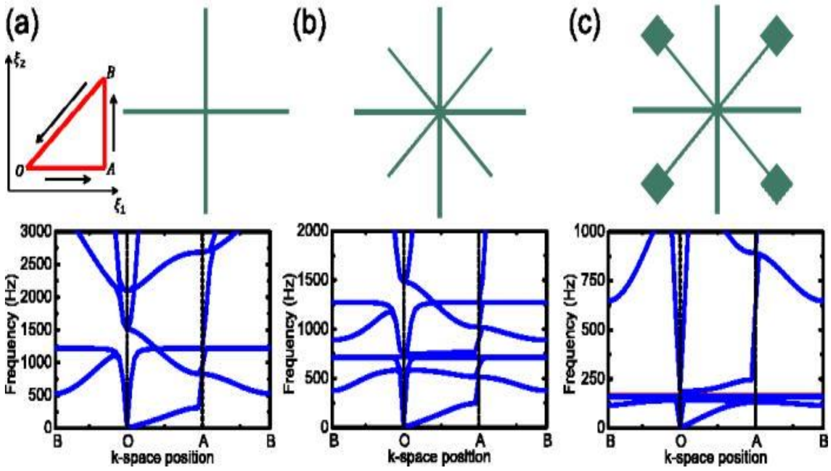


Figure 10: Band structure and square lattice of specially designed cantilever beams and masses. (Li et al., 2017)

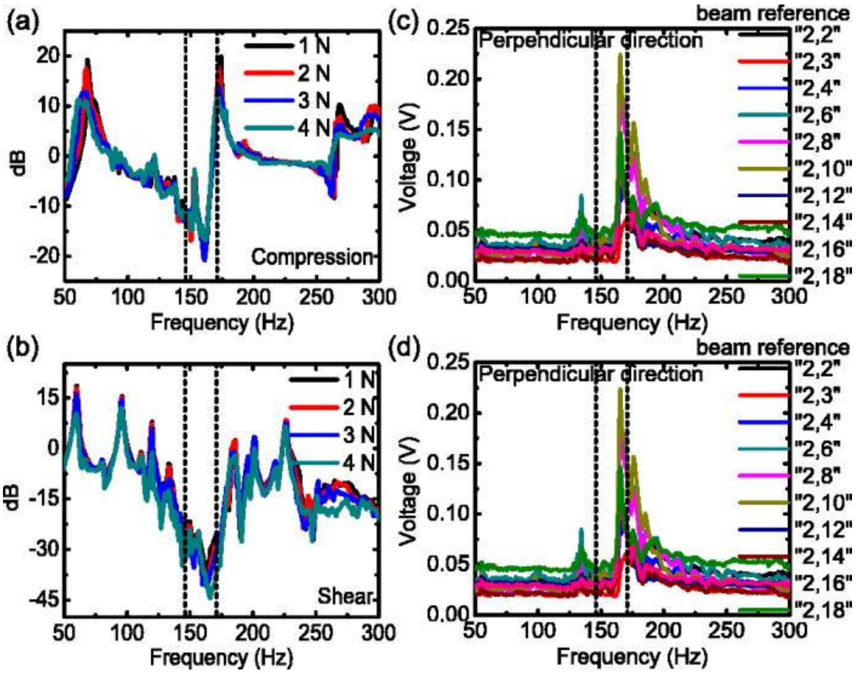


Figure 11: Voltage and frequency of a PVDF film. (Li et al., 2017)

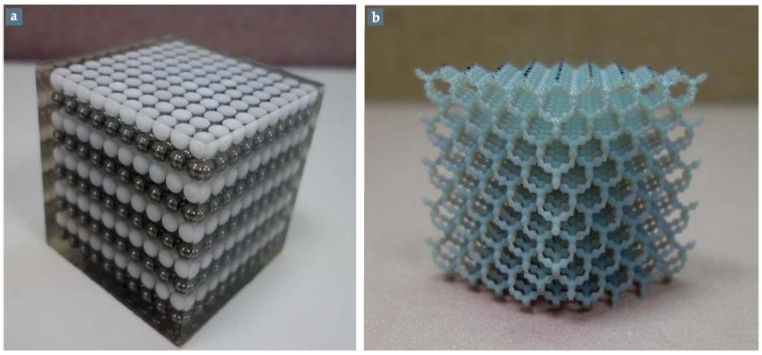


Figure 12: a) Lattice structure composed of elastic spheres within a polymer matrix and b) structure in a three-dimensional Penta mode. (Haberman et al., 2016)

4.1 Theoretical Applications of Metamaterials in Acoustic Energy Harvesting

With the influx of demand for renewable energy sources, researchers have turned to acoustic energy harvesting practices (Bansal et al., 2023). Traditional acoustic energy harvesting has however been deemed inefficient for practical usage; thus, metamaterials are being researched and implemented. Acoustic metamaterials have been found to increase the efficiency of acoustic energy to electrical energy conversion. These metamaterials allow the waves' properties to be altered to fit the energy harvesting requirements (Chen et al., 2014). The primary approach taken in order to increase the efficiency of acoustic energy harvesting is to increase and concentrate the pressure towards the harvester; as acoustic energy is plentiful, however dispersed in nature. (Sun et al., 2017)

The pressure of acoustic waves is dependent upon two primary parameters, the refractive index (n) and the impedance (Z), modeled by equation (10) and (11) respectively. In these equations the variables are defined as such; ρ is the mass density and β is the bulk modulus of the materials. (Lee & Rho, 2017)

$$n = \sqrt{\frac{\rho}{\beta}} \tag{10}$$

$$Z = \sqrt{\rho\beta} \tag{11}$$

The waveform equation model for an acoustic wave is shown as equation 12, where pressure is denoted as P. This equation shows that the values of mass density, and bulk modulus affect the pressure of the waveform as well. Thus, when comparing equation 10 through 12 it is made evident that the refractive index, impedance and pressure are dependent values. (Lee & Rho, 2017)

$$\nabla^2 P - \frac{\rho}{\beta}\frac{\vartheta^2 P}{\vartheta t^2} = 0 \tag{12}$$

Through these equations it is evident that the refractive index and pressure are directly proportional, meaning when the index increases so does the pressure. This notion has been applied to produce coiled-up metamaterials, which have a high index of refraction due to the phase delay resulting from the longer, zigzag path taken by the wave. (Lee & Rho, 2017) The relationship between the path taken and the index of refraction can be approximated by the relationship in equation 13, where l is the length of the path and h is the thickness of the metamaterial slab. (Sun et al., 2017)

$$n_{eff} \propto \frac{l}{h} \tag{13}$$

4.1.1 Transmissive Labyrinthine Acoustic Metamaterial

In research conducted by Bansal et al, (2023) a combination of labyrinthine acoustic metamaterials (LAM) and various piezoelectric films have been used to both increase the amount of acoustic energy collected and efficiency of the conversion to electrical power. The piezoelectric films used were a nanocomposite film (MoS_2-PVDF) made in the lab, commercial piezo film (LDT1-028K) and commercial PVF2 film (FS-2513P). The model used for energy harvesting, depicted in Figure 13 consists of a 40 *kHz* transducer which emits the waves, the LAM which focuses the acoustic energy to increase the input pressure, and the piezoelectric film which conducts the energy harvesting. (Bansal et al., 2023)

The labyrinthine acoustic meta surface used in the study was composed of 16 unique, 3D printed VeroClear plastic, metamaterial unit structures, as seen in figure 14. The individual meta-units allowed for the LAM to create a phase delay which optimizes the acoustic pressure, which concentrates onto the piezoelectric film. Bansal and researchers (Bansal et al., 2023) utilized methods such as Gechberg-Saxton algorithms in order to create these unique structures. The meta surface was designed particularly for the 40 *kHz* transducer, however the model is scalable thus it can be used for various frequencies. (Bansal et al., 2023)

Experimental results from Bansal et al, (2013) show the significant increase of maximum acoustic pressure when using the LAM; as without the LAM the pressure was at 20 *Pa* whereas with the LAM the pressure reaches 328 *Pa*. There is also a significant difference in the energy harvested with and without the LAM, as shown in the tabulated results of the voltages below. This type of film also vastly affected the amount of energy harvested. (Bansal et al., 2023)

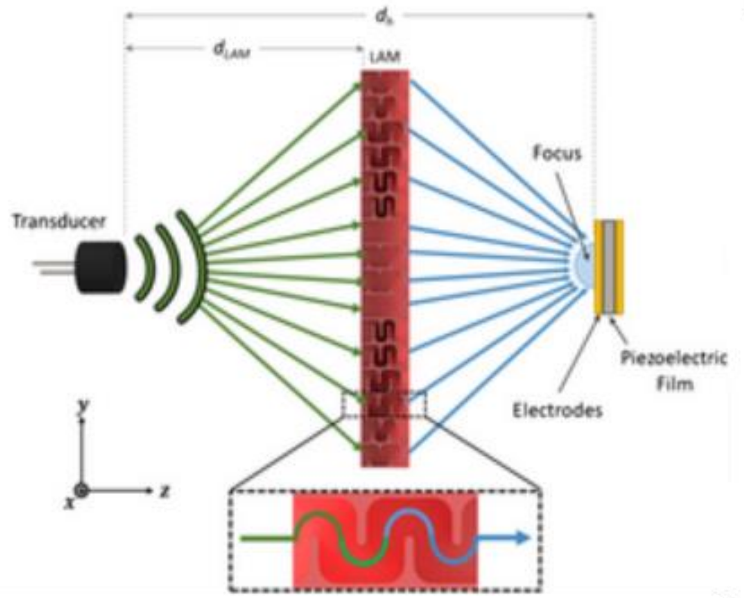


Figure 13: Labyrinthine acoustic metamaterials and piezoelectric film-based energy harvesting. (Bansal et al., 2023)

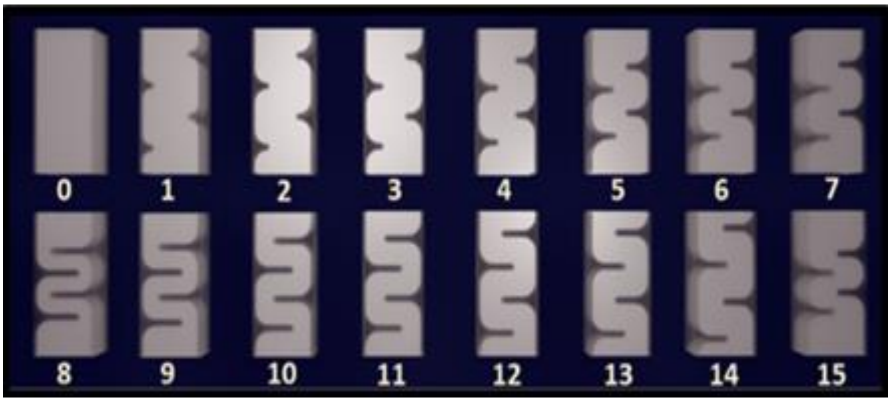


Figure 14: Metamaterial unit structures. (Bansal et al., 2023)

Table 2: Comparison of output voltage for acoustic energy harvesting (AEH) with labyrinthine acoustic metamaterials (LAM) and without. (Bansal et al., 2023)

	AEH	AEH + LAM	Gain [%]
Nanocomposite film	363	370	1.92
Piezoelectric film (LDT1-028K)	19	49	157.89
Polyvinylidene fluoride (PVF2) film (FS-2513P)	33	90	172.72

4.1.2 Coiled Acoustic Metamaterial Cavity

Sun and coworkers (Sun et al., 2017) energy harvesting system amplified the pressure using a doubly coiled-up acoustic metamaterial which is depicted in figure 15. In this system the acoustic energy is output into the zigzag metamaterial pathway, which leads to the metamaterial cavity, which further leads to the second zigzag metamaterial pathway and to the piezoelectric bimorph plate for energy harvesting.

This system increases the acoustic pressure within the system by containing the wave within the acoustic metamaterial cavity, increasing the conversion to electrical energy. This is done as the wave travels through the zigzag path, there is a high refractive index which results in a high-pressure level. Another factor contributing to the high pressure is within the cavity of the system, due to the low velocity of the wave within the cavity, the pressure is in turn high. The pressure due to the acoustic waves then converts into mechanical vibrations on the piezoelectric bimorph plate is harvested into electrical energy. (Sun et al., 2017)

Experimental results demonstrate that the use of the metamaterial based zigzag pathway and cavity combined with the piezoelectric bimorph plate resulted in an increased conversion efficiency, as seen in figure 16 Sun and colleagues (Sun et al., 2017) found that the implementation of metamaterials resulted in 6.32 times more energy to be harvested. This shows that through the use of metamaterial-based pressure concentration it is possible to increase the overall efficiency of acoustic energy harvesting. (Sun et al., 2017)

In an experiment by Liang and team members, a repeated unit coil structure is implemented as depicted in figure 17 (Liang et al., 2012). Chen and partners implemented a single unit metamaterial structure which is portrayed in figure 17 (Chen et al., 2021). Both structures tested resulted in a drastic increase in pressure due to the coiled structures, (Liang et al., 2012; Chen et al., 2021) which is necessary for efficient energy harvesting as established by Sun and colleagues. (Sun et al., 2017)

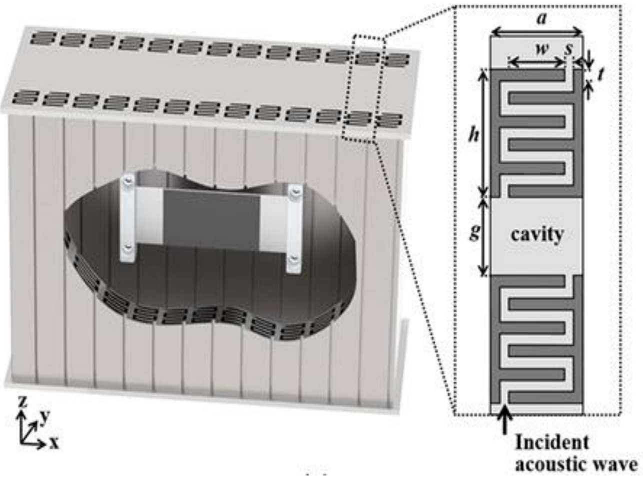


Figure 15: Doubly coiled-up acoustic metamaterial cavity system. (Sun et al., 2017)

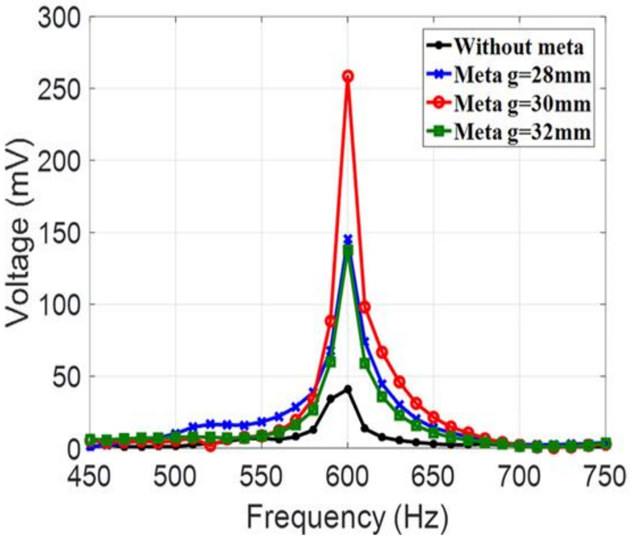


Figure 16: Output voltage vs. Frequency. (Sun et al., 2017)

A variable wave input was experimented with in order to increase the absorption of sound energy while maintaining the coiled structure. Almeida and colleagues successfully executed a structure through which the input is at the midpoint of the structure and follows a path along either side of the slit, into coiled metamaterial structures as shown in figure 18. (Almeida et al., 2021). Li and Yan experimented with a wave transmitted through micro-perforations on the top surface of the structure, which resulted in a substantial increase of frequency, as depicted in figure 19. (Li et al., 2023).

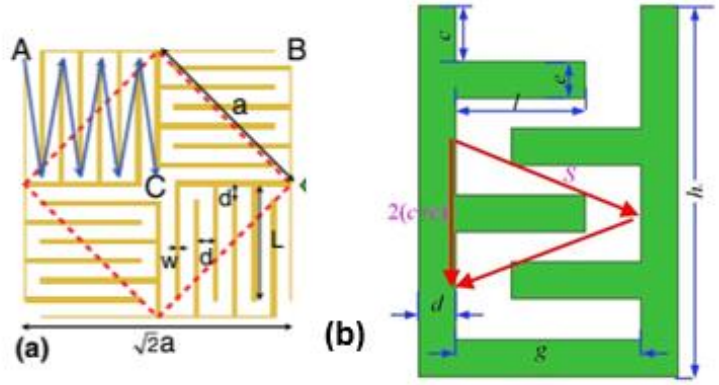


Figure 17: (a) Repeated coiled-units implementation (Liang et al., 2012). (b) Decreased pathway coils. (Chen et al., 2021)

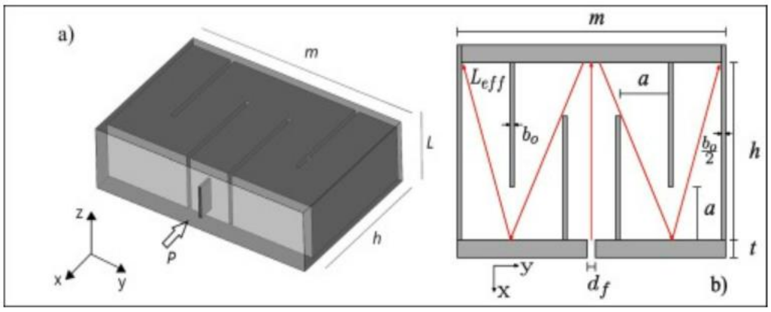


Figure 18: Implementation of a coiled system where the input wave comes through the midpoint along the widest part of the system. (Almeida et al., 2021)

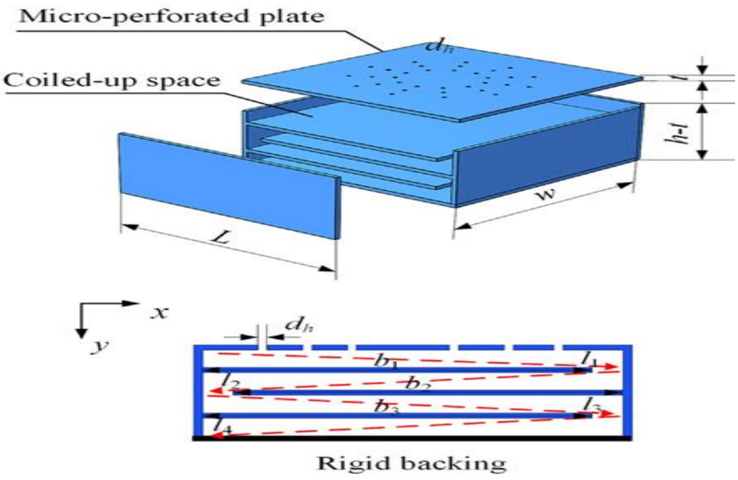


Figure 19: A coiled system where the input wave comes through the perforations from the top of the system. (Li et al., 2023)

4.2 Analysis of Practical Applications

Applications of metamaterial based acoustic energy harvesting are limited as the field of research is relatively new. The use of acoustic energy is primarily on a small scale for systems such as, portable technology. However, even on a small scale, application of this energy harvesting technique does not produce adequate power and must be used in combination with other energy harvesting techniques. (Cook-Chennault & Sastry, 2008) Furthermore the efficiency of harvesting is dependent on frequency, where low frequency waves are found to be less efficient. Indicating a need for further research for the energy harvesters to adapt according to the frequency of the waves. Due to the lack of efficiency and limited research on acoustic energy harvesting, the costs of manufacturing are also high when compared to other energy harvesting methods. (Romero Garcia & Hladky-Hennion, 2019) These key factors of cost and efficiency adaptability can be improved with further research and development within the field of acoustic energy harvesting; however, it is currently not the preferred method. Through recently conducted research it is evident that metamaterials can lead to the progression and implementation of acoustic energy harvesting as a means of renewable energy in the future.

5 ELECTROMAGNETIC ENERGY

5.1 Limitations

With the increase of dense electromagnetic fields in industrial and urban environments contributed to by radio and telecommunications transmitters and their increasing availability, researchers have turned to electromagnetic fields for energy harvesting (Góra & Lopato, 2023; Nowak, 2021). Previous attempts have been made to exploit the energy potential from EM fields based on antennae systems but have been deemed disadvantageous due to the antennae systems' low absorption rates of EM field energy and low geometric compactness. (Nowak, 2021) The availability of dense EM fields is currently only found within dense urban and industrial regions, limiting its potential usage in applications outside of these areas (Nowak, 2021)

5.2 Electromagnetic Wave Absorption Theory

EM metamaterials utilize two effective methods of absorbing EM energy, split ring resonators (SSRs) and electrically coupled LC resonators (ELCs) (Gu et al., 2010). SSRs work by the generation of Drude-Lorentz type resonant responses, dependent on magnetic fields along with thin wires to generate a broadband electrical response (Gu et al., 2010; Watts et al., 2012).

Theoretically, electromagnetic waves on a boundary may be reflected, transmitted, absorbed, scattered, or excite surface electromagnetic waves (SEW) (Watts et al., 2012). These parameters can be calculated using the Drude-Lorentz model of wave permittivity and permeability:

$$\widetilde{\varepsilon_r}(\omega) = \varepsilon_\infty + \frac{\omega_P^2}{\omega_0^2 - \omega^2 - i\gamma_e\omega} \tag{14}$$

$$\widetilde{\mu_r}(\omega) = \mu_\infty + \frac{\omega_{p,m}^2}{\omega_{0,m}^2 - \omega^2 - i\gamma_m\omega} \tag{15}$$

From these parameters, transmissibility and absorptivity coefficients of the material are desired, found as the variables *R* and *T*. Equations (14) and (15) describe the Drude-Lorentz model, where ω_p and $\omega_{p,m}$ are the center frequencies of the oscillator, γ_e and γ_m are the damping frequencies ε_∞ and μ_∞ are the static permittivity and permeability, respectively. The Drude parameters of the material are known and then used to find the transmissibility and absorptivity, which in the case of EM metamaterials, material choice desired transmissibility is 0 and absorptivity near-perfect (Watts et al., 2012). ELCs work similarly in generating a Lorentzian response, without the use of thin wires due to the ELC material's permittivity (Gu et al., 2010).

5.3.1 Split Ring Resonator (SRR) Design

In a study conducted by Nowak, 2021, a proposed multilayer split ring resonator (SSR) cell matrix was analyzed for absorptions of microwaves and higher frequencies (Nowak, 2021). The resonant metamaterial design consists of mainly metallic structures embedded into a dielectric environment and a unit cell size of 44.8mm by 44.8*mm* for a selected frequency of approximately 250 *MHz.* This structure is designed to absorb resonant EM field energy, in which its selected effective absorption frequency bands can be found by the superposition of multiple cell matrices with different resonance frequencies (Nowak, 2021). These unit cells were then tested in both planar and transverse matrix structures as seen in figure 21 (Nowak, 2021).

Simulations of the model in prototype energy harvesting circuits resulted in an energy conversion efficiency of 56% for the frequency of 332 MHz, accounting for energy losses at each stage of the energy transmission and determined the maximum obtained power at approximately 10.9 mW. (Nowak, 2021)

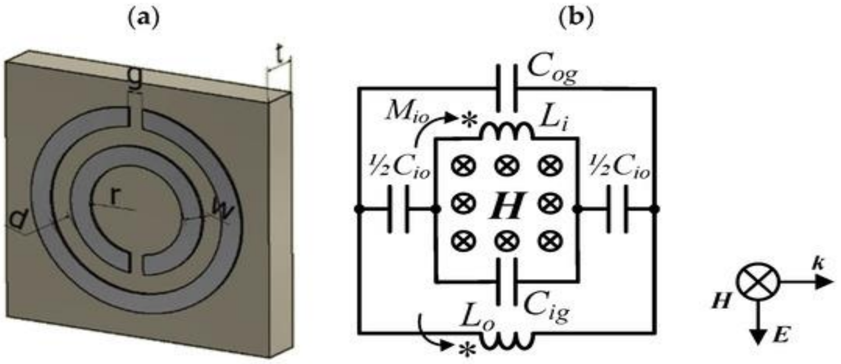


Figure 20: Proposed magnetic split ring resonator unit cell (**a**) geometric model, and (**b**) Simplified resonance circuit model. (Nowak, 2021)

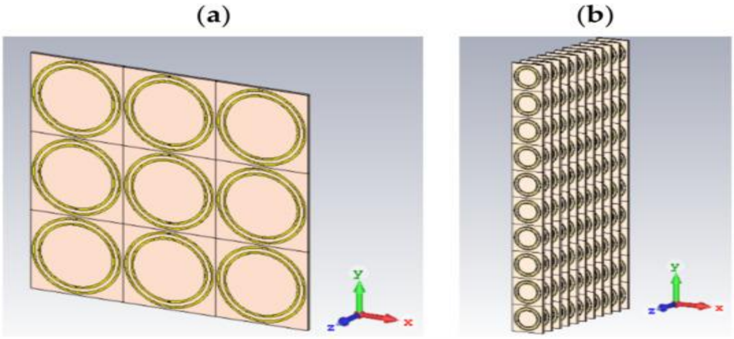


Figure 21: View of (a) SRR two-dimensional planar matrix and (b) SRR two-dimensional transverse matrix. (Nowak, 2021)

5.3.2 Electric-Inductive-Capacitive (ELC) Resonator Design

A study by Almoneef & Ramhani, (2015) proposed an array of Electric-Inductive-Capacitive (ELC) resonators that consisted of two face-to-face split rings embedded in a dielectric material, a ground plane, and a load connected between the top and bottom conductive layers through a via, with the purpose of the study to achieve near-perfect absorption for the resonators and is viability (Almoneef & Ramhani, 2015). The physics theory for the proposed ELC design utilizes the top layer to couple the incident electric field and couple the electromagnetic fields using the antiparallel current between the two layers, as depicted in figure 22 (Watts et al., 2012).

The numerical simulation resulted in a 97% efficiency of power absorbed to the load, and as a proof-of-concept, a 13 by 13-unit cell ELC resonator array was constructed and tested, showing a 93% efficiency of power absorbed directed to the load. (Almoneef & Ramhani, 2015)

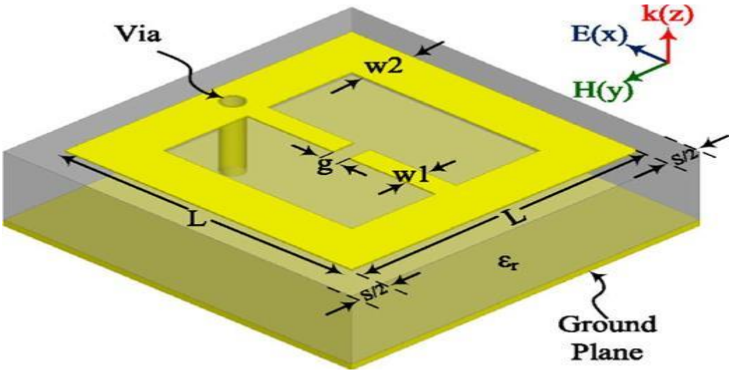
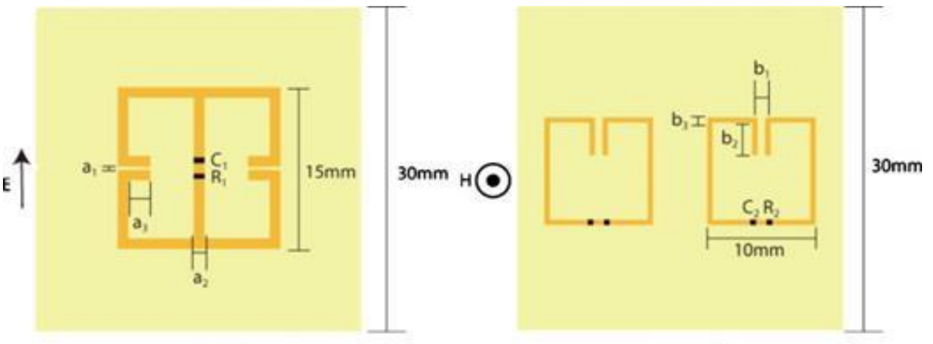


Figure 22: Proposed unit cell design of ELC resonator. (Almoneef & Ramhani, 2015)

5.3.3 ELC-SRR Combination Design

As proved by Gu et al, (2010) both structures described above can also be combined to reduce abortion losses, proposing a design that uses a combination of alternating ELC and SSR unit cells to achieve EM absorption (Gu et al., 2010). Figure 23 shows the individual SSR and ELC unit cells, and the sandwich-like structures of the constructed experimental design (Gu et al., 2010).

Experimental results of only EM absorption showed a peak absorption of 99% at 2.4 GHz with a full width at half maximum (FWHM) of 700 MHz (Gu et al., 2010). No simulations of this proposed design have been conducted for the efficiency of the absorption to potential energy storage devices, but the experimental findings verify the capabilities of EM metamaterials and encourage further research into the subject.



(a) ELC (b) SRR

(a) ELC Sandwich (b) SRR Sandwich (c) ELC-SRR Sandwich

Figure 23: SSR and ELC unit cells and their respective sandwich-like construction. (a) SSR unit cell design and sandwich; (b) ELC unit cell design and sandwich; (c) Alternating construction of SSR and ELC sandwiches. (Gu et al., 2010)

5.4 Future Prospects for Electromagnetic Harvesting

The study of EM metamaterials limits research and findings to only the cell size, array size, effective frequency and absorption efficiencies of their EM metamaterial prototypes, compared to the study conducted by (Nowak, 2021) and other metamaterial designs that also incorporates an experimental system to converting the absorbed energy into usable power. These generalized results regarding the sizes and efficiencies of the EM metamaterial allow potential researchers in the field to easily prototype designs and simulations, as data regarding power absorbed may not be as useful, given the small quantity of energy EM metamaterials collect. Currently, the array size to energy absorbed ratio is the biggest limitation to EM metamaterials' practical uses in the field besides the cost. The location and sizes of the devices used in the system are many times smaller than that of the cell array. Improvements to the designs can be achieved with lumped elements, where EM metamaterials with different effective frequencies are stacked within one unit cell to cover a wider range of frequencies, all while maintaining the original array size (Nowak, 2021; Almoneef & Ramhani, 2015).

6 DISCUSSIONS

Each metamaterial discussed above, although having undergone only experimental testing, has shown its theoretical potential effectiveness in energy harvesting. These advancements have shown optimal applications of metamaterials into small devices such as sensors, and have the potential to be used in devices as a supplementary source of power; rather than a primary source or as a means of recharging the main source. Solar metamaterials appear to be optimal in increasing the efficiency of solar absorption when compared to current solar and photovoltaic cell technology which primarily use silicones. Mechanical metamaterials are advantageous when implemented into products that experience constant wear and vibrations. Acoustic metamaterials interact with waves which shows advantages and increased efficiency due to wave property manipulation. Electromagnetic (EM) metamaterials focus mainly on the metamaterial's ability in frequency absorption in the fields of wireless communication and distance measurement to control input and output frequency signals. The amount of energy collected depends on several factors of the electromagnetic waves, such as the intensity of the signal, the signal transmission device's efficiency, and the size of the energy storage device. (Nowak, 2021)

Solar metamaterials are more efficient when implemented into large-scale energy harvesting with large absorption surface areas, when implemented as a layer of photovoltaic cells, similar to those of current solar farms (Al Ajmi et al., 2023). Commercially, large scale methods if researched thoroughly may be a pivoting factor in energy harvesting in existing and new structures. If manufacturers are able on a large scale to create new aluminum EMM's or silicone-based metamaterials for solar energy, it may reduce costs to implement in large structures and reduce cost in purchasing volume of outsourced energy used which can attract potential customers. Applications of solar metamaterial into small-scale devices would prove equally or less effective to traditional photovoltaic cells as the surface area of the absorption surface decreases, due to its decreased interaction with light.

Mechanical and acoustic metamaterials however find strengths in smaller devices and technologies, as proposed by their use in the insoles of shoes (Gao et al., 2021) and micro technology (Cook-Chennault & Sastry, 2008) respectively. This is due to the nature of smaller devices more prone to more frequent changes in kinetic energy and exposure to stress, and strain. As the acoustic metamaterial under study is dependent on piezoelectric films (Bansal et al., 2023, similar to mechanical metamaterials (Li et al., 2017), the implementation of both acoustic and mechanical metamaterials to assist one another increases the overall effectiveness of energy harvesting within a single device or sample. However, smaller devices including wearable products like the shoe insole (Gao et al., 2021) will require custom machining and intricate engineering which will raise the price and no longer be seen as a consumer product for little energy production, not suitable for the average consumer. In the case of acoustic metamaterials, due to the lack of frequency adaptability the implementation would be both expensive and lack in efficiency without the specified frequency (Romero Garcia & Hladky-Hennion, 2019). Scalable models such as the transmissive labyrinthine acoustic metamaterial (Bansal et al., 2023) can accommodate various frequencies, however each time the system would require remodeling which is both inconvenient and expensive.

Studies for electromagnetic energy harvesting have shown the limitations in the collected energy, as in the split ring resonator design, the power ranges in the milliwatts (Nowak, 2021). Advancements in technology are allowing for smaller devices requiring less voltage, making electromagnetic metamaterials a more viable addition in energy production. Electromagnetic metamaterial usage can possibly see effective usage when implemented into wireless communications and automated systems, including the agricultural, environmental, and military sectors where monitoring and closed loop systems using sensors are needed.

The potential sustainable implications of the discussed metamaterials can also be realized, following further research of their applications into new technologies that have a positive impact on the environment. Overall, the advantages these metamaterials have when interacting with different renewable energies make them a great technology in harvesting energy to potentially improve and create new forms of small-scale energy sources to power our current technology.

7 RECOMMENDATIONS

1. As current studies for these metamaterials, specifically acoustic, have only shown experimental trials of the metamaterials, further testing, and widespread application of the metamaterials into current technology must be performed to ensure effectiveness and viability.
2. Execution of acoustic energy harvesting has been explored on a small scale thus far, meaning further scaled research must be conducted prior to large-scale use of the energy harvesting techniques explored by Bansal and colleagues, (Bansal et al., 2023) and Sun and coworkers (Sun et al., 2017).
3. Solar energy is being used at a wide scale and the application of solar metamaterial can introduce a significant benefit even with a small improvement in efficiency. Current studies show the potential for effective and practical silicone metamaterial application. Mixing further studies, especially practical experiments, are highly recommended.
4. With emerging research and technological advancements in microscopy and computing algorithms, metamaterials can become evidently more advanced and specified for specific tasks in energy harvesting worldwide.
5. With further research, the metamaterials discussed have the potential to increase the efficiency of renewable energy harvesting, on both small- and large-scale applications to create more incentive in its development and implementation into our current technologies. Increases of 40 times power amplification in EMMs show the difference between designed materials and traditional materials.
6. The potential of metamaterials in renewable energy harvesting manifests uniquely across solar, mechanical, and acoustic domains. Solar metamaterials exhibit remarkable efficiency improvements, making them particularly promising for large-scale energy production. Their capacity to address escalating energy demands aligns with global needs. On the other hand, mechanical and acoustic metamaterials, while more versatile, find their strength in micro-scale applications, generating energy in the microvolts region for smaller scale areas such as small battery packs and portable device powering.
7. In the realm of metamaterials for renewable energy, a dynamic synergy between cutting-edge simulations and rigorous real-world testing is propelling research to new heights. Advanced techniques like finite element method (FEM) analysis are actively refining theoretical models, while empirical validations ensure practical

applicability. This tandem approach, witnessed across solar, mechanical, and acoustic metamaterials, accelerates innovation, and enhances the reliability of findings as this collaborative momentum continues and a spike in research is witnessed.

REFERENCES

1. Al Ajmi, H., Bait-Suwailam, M., Masoud, M., & Shafiq, M. (2023). EFFICIENCY ENHANCEMENT OF PHOTOVOLTAIC SOLAR CELLS USING METAMATERIALS ABSORBING SCREEN. *The Journal of Engineering Research (Print)*, *19*(2), 85–94.
2. Almeida, G. d. N., Vergara, E. F., Barbosa, L. R., & Brum, R. (2021). Low-frequency sound absorption of a metamaterial with symmetrical-coiled-up spaces. *Applied Acoustics*, *172*, 107593.
3. Almoneef, T. S., & Ramahi, O. M. (2015). Metamaterial electromagnetic energy harvester with near unity efficiency. *Applied Physics Letters*, *106*(15), 153902.
4. Bansal, S., Choi, C., Hardwick, J., Bagchi, B., Tiwari, M. K., & Subramanian, S. (2023). Transmissive Labyrinthine Acoustic Metamaterial-Based Holography for Extraordinary Energy Harvesting. *Advanced Engineering Materials*, *25*(4), 2201117-n/a.
5. Buschow, K.H., Cahn, R.W., Flemings, M.C., Ilschner, B., Kramer, E.J., & Mahajan, S. (2004). Encyclopedia of Materials: Science and Technology. MRS Bulletin, 29, 512.
6. Chen, T., Jiao, J., & Yu, D. (2021). Enhanced broadband acoustic sensing in gradient coiled metamaterials. *Journal of Physics. D, Applied Physics*, *54*(8), 85501.
7. Chen, Z., Guo, B., Yang, Y., & Cheng, C. (2014). Metamaterials-based enhanced energy harvesting: A review. *Physica. B, Condensed Matter*, *438*, 1–8.
8. Cook-Chennault, K. A., Thambi, N., & Sastry, A. M. (2008). Powering MEMS portable devices—a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems. Smart Materials and Structures, 17(4), 043001–043001 (33).
9. Fedotov, V. (2017). Metamaterials. *Springer Handbook of Electronic and Photonic Materials*, 1-1.
10. Gao, S., Gain, A. K., & Zhang, L. (2021). A metamaterial for wearable piezoelectric energy harvester. *Smart Materials and Structures*, *30*(1), 15026.
11. Góra, P., & Łopato, P. (2023). Metamaterials' Application in Sustainable Technologies and an Introduction to Their Influence on Energy Harvesting Devices. *Applied Sciences*, *13*(13), 7742.
12. Gu, S., Barrett, J. P., Hand, T. H., Popa, B.-., & Cummer, S. A. (2010). A broadband low-reflection metamaterial absorber. *Journal of Applied Physics*, *108*(6), 064913–064913-6.
13. Haberman, M. R., & Guild, M. D. (2016). Acoustic metamaterials. *Physics Today*, *69*(6), 42–48.
14. Hamouche, H., & Shabat, M. M. (2018). Computational analysis of metamaterial–aluminum–silicon solar cell model. *Optical and Quantum Electronics*, *50*(12), 1–15.
15. Honsberg, C., & Bowden, S. (n.d.). Band gap. Retrieved from https://www.pveducation.org/pvcdrom/pn-junctions/band-gap.
16. Imtiaz, M.H, & Hashmi, G. (2013). Towards High Efficiency Solar Cells: Composite Metamaterials. Global Journals of Research in Engineering, 13(F10), 11–16. Retrieved from https://engineeringresearch.org/index.php/GJRE/article/view/861.
17. Islam, M., Fartaj, A., & Ting, D. S.-. (2004). Current utilization and future prospects of emerging renewable energy applications in Canada. *Renewable & Sustainable Energy Reviews*, *8*(6), 493–519.
18. Jiao, P. (2023). Mechanical energy metamaterials in interstellar travel. *Progress in Materials Science*, *137*, 101132.
19. Jiao, P., Hasni, H., Lajnef, N., & Alavi, A. H. (2020). Mechanical metamaterial piezoelectric nanogenerator (MM-PENG): Design principle, modeling and performance. *Materials & Design*, *187*, 108214.
20. Jiao, P., Yang, Y., Egbe, K. J. I., He, Z., & Lin, Y. (2021). Mechanical Metamaterials Gyro-Structure Piezoelectric Nanogenerators for Energy Harvesting under Quasi-Static Excitations in Ocean Engineering. *ACS Omega*, *6*(23), 15348–15360.
21. Ji, G., & Huber, J. (2022). Recent progress in acoustic metamaterials and active piezoelectric acoustic metamaterials - A review. *Applied Materials Today*, *26*, 101260.
22. Kumar, R., Singh, B. K., & Pandey, P. C. (2022). *Cone-Shaped Resonator-Based Highly Efficient Broadband Polarization- Independent Metamaterial Absorber for Solar Energy Harvesting*. doi:10.21203/rs.3.rs-2280426/v1
23. Lee, D., Nguyen, D. M., & Rho, J. (2017). Acoustic wave science realized by metamaterials. *Nano Convergence,* 4(1), 3–3.
24. Lee, G., Lee, S.-J., Rho, J., & Kim, M. (2023). Acoustic and mechanical metamaterials for energy harvesting and self-powered sensing applications. *Materials Today Energy*, *37*, 101387.
25. Liang, Z., & Li, J. (2012). Extreme acoustic metamaterial by coiling up space. *Physical Review Letters*, *108*(11), 114301–114301.
26. Li, Y., Baker, E., Reissman, T., Sun, C., & Liu, W. K. (2017). Design of mechanical metamaterials for simultaneous vibration isolation and energy harvesting. *Applied Physics Letters*, *111*(25), 251903.
27. Li, Y., & Yan, J. (2023). Acoustic transmission characteristics based on coiled-up space metamaterials. *Applied Acoustics*, *203*, 109199.

28. Ma, T.-X., Fan, Q.-S., Li, Z.-Y., Zhang, C., & Wang, Y.-S. (2020). Flexural wave energy harvesting by multi-mode elastic metamaterial cavities. *Extreme Mechanics Letters*, *41*, 101073.
29. Mulla, B., & Sabah, C. (2015). Perfect metamaterial absorber design for solar cell applications. *Waves in Random and Complex Media*, *25*(3), 382–392.
30. Nowak, M. (2021). Metamaterial-Based Sub-Microwave Electromagnetic Field Energy Harvesting System. *Energies (Basel)*, *14*(12), 3370.
31. Olabi, A. G., & Abdelkareem, M. A. (2022). Renewable energy and climate change. *Renewable & Sustainable Energy Reviews*, *158*, 112111.
32. Qazi, A., Hussain, F., Rahim, N. A., Hardaker, G., Alghazzawi, D., Shaban, K., & Haruna, K. (2019). Towards Sustainable Energy: A Systematic Review of Renewable Energy Sources, Technologies, and Public Opinions. *IEEE Access*, *7*, 63837–63851.
33. Romero Garcia, V., & Hladky-Hennion, A.-C. (2019). *Fundamentals and Applications of Acoustic Metamaterials: From Seismic to Radio Frequency* (Vol. 1.). ISTE, Ltd.
34. Sun, K. H., Kim, J. E., Kim, J., & Song, K. (2017). Sound energy harvesting using a doubly coiled-up acoustic metamaterial cavity. *Smart Materials and Structures*, *26*(7), 75011.
35. Tan, T., Yan, Z., Zou, H., Ma, K., Liu, F., Zhao, L., … Zhang, W. (2019). Renewable energy harvesting and absorbing via multi-scale metamaterial systems for Internet of things. *Applied Energy*, *254*, 113717.
36. Umino, Y., Tsukamoto, T., Shiomi, S., Yamada, K., & Suzuki, T. (2018). Development of vibration energy harvester with 2D mechanical metamaterial structure. *Journal of Physics. Conference Series*, *1052*(1), 12103.
37. Valipour, A., Kargozarfard, M. H., Rakhshi, M., Yaghootian, A., & Sedighi, H. M. (2022). Metamaterials and their applications: An overview. *Proceedings of the Institution of Mechanical Engineers. Part L, Journal of Materials, Design and Applications*, *236*(11), 2171–2210.
38. Watts, C. M., Liu, X., & Padilla, W. J. (2012). Metamaterial Electromagnetic Wave Absorbers. *Advanced Materials (Weinheim)*, *24*(23), OP98–OP120.