

Metamaterials for energy harvesting

Item Type	Chapter in book
Authors	Govindaraman, Loganathan T;Arjunan, Arun;Baroutaji, Ahmad;Robinson, John;Olabi, Abdul-Ghani
Citation	Govindaraman, L.T., Arjunan, A., Baroutaji, A., Robinson, J. and Olabi, A. (2021) Metamaterials for energy harvesting. Encyclopedia of Smart Materials, Vol. 2, pp. 522-534.
DOI	10.1016/b978-0-12-815732-9.00127-3
Publisher	Elsevier
Download date	2026-03-14 09:05:12
Link to Item	http://hdl.handle.net/2436/624147

Metamaterials for energy harvesting

Loganathan Thozhuvur Govindaraman¹, Arun Arjunan¹, Ahmad Baroutaji¹, John Robinson^{1,2} and Abdul-Ghani Olabi^{3,4}

¹Additive Manufacturing of Functional Materials Research Group, School of Engineering, University of Wolverhampton, Telford Innovation Campus, TF2 9NT, United Kingdom

²6DME Ltd., Stirchley Road, Telford, TF3 1EB, United Kingdom

³Dept. of Sustainable and Renewable Energy Engineering, University of Sharjah, P.O. Box 27272, Sharjah, UAE

⁴School of Engineering and Applied Science, Aston University, Aston Triangle, Birmingham B4 7ET, UK

Abstract

Metamaterials offer significant potentials for numerous applications due to their unique acoustics, electromagnetic, optical, and mechanical properties. The increasing interest in the development of metamaterials is also driven by the inability of traditional architecture to offer novel functionalities offered by metamaterials. Recently it has been shown that the metamaterial phenomenon can be exploited for the development of energy harvesting devices especially in the field of energy scavenging at low intensity. Approaches include algorithmically arranged building blocks at the sub-micron level to achieve the desired order of response against incident energy. Furthermore, the ease of customisation with regards to metamaterials in alignment with energy sources such as acoustic, mechanical, optical and microwave offer numerous avenues for energy harvesting. For the development and selection of suitable energy harvesting metamaterial a critical understanding of their classifications, fabrication, and opportunities for customisation with respect to size, shape and lattice spacing is required, which this paper aims to provide. Furthermore, various concepts and experiments implemented to demonstrate and assess energy using metamaterials from sources such as sound waves, solar waves and mechanical vibrations are also covered.

Keywords: Metamaterials; Energy harvesting; acoustic; thermal; solar; mechanical.

1. Introduction

Metamaterials is a relatively new and emerging field of study that offers opportunities to develop materials that can be customised for enhanced optical, mechanical, acoustic or electrical functionalities [1]. This is generally achieved through tailoring the constituent material architecture from macro to nanoscale [2]. Such architecture can be constructed in two or three-dimensional repeating structural arrays based on the properties required [3,4].

Research in the field of metamaterials have been successful in demonstrating exceptional properties namely negative refractive index, negative density, negative incremental stiffness, negative Poisson's ratio, negative thermal conductivity and shape reconfigurability [2,5,6]. As opposed to bulk materials, the properties of metamaterials are dictated by the physical structure

of the artificial unit cells generally referred to as meta-atoms. As such the properties of a metamaterial can be altered by changing either the design or arrangement of the so-called meta-atoms. In doing so functionalities of metamaterials including their permittivity and permeability can also be manipulated. By controlling the size of the meta-atoms, the operating frequency region of metamaterials can also be tuned to achieve targeted behaviour [7].

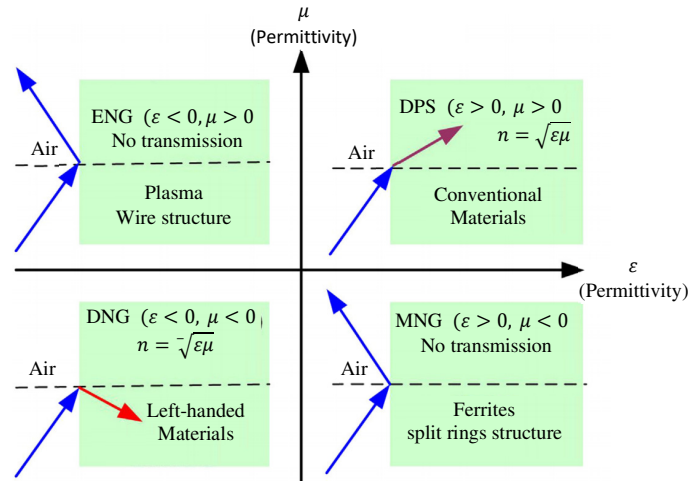


Fig. 1. Metamaterial classification based on permittivity and permeability where ENG, DPS, DNG and MNG are epsilon-negative, double-positive, double negative and mu-negative respectively [8].

The metamaterials are [9][8] classified based on the permittivity (ϵ) and permeability (μ) of the constituting medium as shown in Fig. 1. DPS or double-positive materials are those featuring positive mediums for both ϵ and μ as such this category is suitable also for most dielectric materials. ENG referred to ‘Epsilon Negative’ material architecture where $\epsilon < 0$ and $\mu > 0$ medium where most plasma can be characterised. MNG are ‘Mu Negative’ materials featuring $\epsilon > 0$ and $\mu < 0$ medium characteristics of the behaviour exhibited by Gyrotropic and magnetic materials. DNG (Double Negative) materials are where both ϵ and $\mu < 0$ medium can only be demonstrated by artificial constructs.

2. Energy harvesting

Although the development in micro-electronics has expanded drastically in recent years, the energy requirement is a limiting factor in their continuous operation. In most cases, these devices are not self-powering and feature batteries that require to be recharged through an external power source at regular intervals. Energy harvesting is emerging as a potential strategy to address this demand for both the microelectronics industry and also wearable and implantable devices [10].

In most cases, microelectronic devices have a low-power design requiring a comparatively small power consumption which opens possibilities for environment-based energy scavenging approaches. Such new techniques are collectively referred to as ‘Energy Harvesting (EH)’, which is generally considered a promising route to power wearable devices, wireless sensors and micro-electromechanical systems [8].

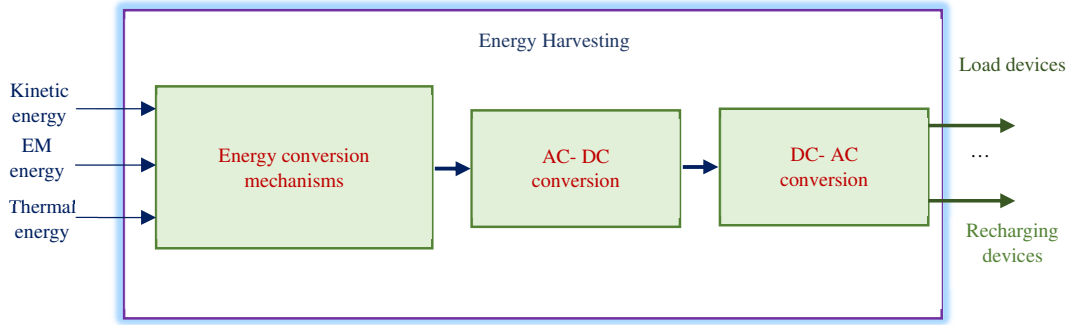


Fig. 2. Schematic representation of an energy harvesting system [8].

Fig. 2 shows the steps involved in a generalised energy harvesting process featuring environmental energy sources. The energy available in the environment is converted into AC voltage by the energy conversion mechanism, and then it is converted into suitable DC power to operate devices. Since in most cases the harvested energy is small, the efficiency of the energy conversion mechanism is critical. This is where metamaterials offer the most potential by enabling the design of efficient conversion systems for high-performance energy harvesting systems. Metamaterials achieve this by tuning their structure properties to the power source to maximise efficiency while minimising losses [3,8]. Table. 1 summarises some of the metamaterial constructs available in the literature currently being evaluated at the lab scale.

Table 1. Metamaterial energy conversion medium.

Input Energy	Energy Conversion Medium	Reference
Broadband plasma excitation	Monolayer Cr Ti elliptical disc arrays	Liang <i>et al.</i> [11]
Broadband signal in Terahertz	Graphene-based terahertz metamaterial absorber	Qi <i>et al.</i> [12]
Microwave Energy	Chiral metamaterial	Dalgaç <i>et al.</i> [13]
	Metamaterial tunnel resonator (e-SRR and LC)	Ahamed <i>et al.</i> [14]
	Cu - Multilevel split ring resonator (SRR)	Karaaslan <i>et al.</i> [15]
	Cu - Asymmetric circular split ring resonator	Moniruzzaman <i>et al.</i> [16]
Thermal/Solar energy	Silicon-cored tungsten nanowire metamaterial	Chang <i>et al.</i> [17]
	SRR made of metal encrusted in indium antimonide (InSb)	Tang <i>et al.</i> [18]
	Copper plasmonic nanostructure metamaterial	Ma <i>et al.</i> [19]
	Bi-material diamond metamaterial additively manufactured using nylon and polyvinyl alcohol	Wei <i>et al.</i> [20]
Acoustic Energy	2D square-latticed Acoustic Metamaterial (AMM) composed of poly-lactic acid	Dong <i>et al.</i> [21]
	Solid phononic crystal with piezoelectric material	Chen <i>et al.</i> [8]
	Al plate with pillar resonators - AMM	Assouar <i>et al.</i> [22]

3. Acoustic energy harvesting

3.1. Metamaterial and Helmholtz coupled-resonator

The commonly available highly investigated natural energy resources are solar energy, wind energy, and hydropower. However, acoustic energy is also abundant available both in a natural and artificial setting. Furthermore covering unwanted acoustic energy from factory machinery, vehicles and other noise pollution sources into alternative power sources is highly beneficial [23]. As such harvesting acoustic energy and covering it into a useful form is one of the focus of acoustic metamaterials.

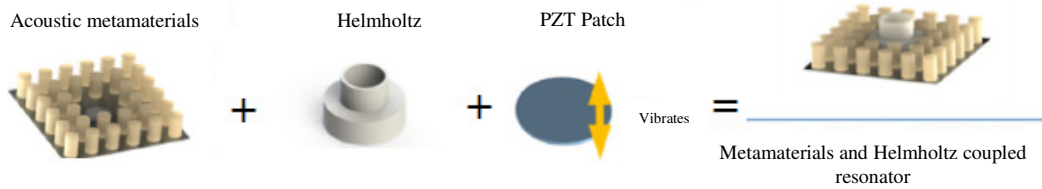


Fig. 3. Architecture of Metamaterial and Helmholtz coupled-resonator (MHCR) [23].

Ma *et al.* [23] have harvested high-density acoustic energy power for wireless sensor network by coupling metamaterial and Helmholtz coupled-resonator (MHCR). This novel method enhanced the density of sound energy density by focusing on and pressure amplification. The design comprises of three modules: a) Sound pressure focusing module of a local resonant metamaterial plate, b) Sound pressure amplification module of a Helmholtz resonant cavity, c) the power generation module of a piezoelectric (PZT) patch (Fig. 3).

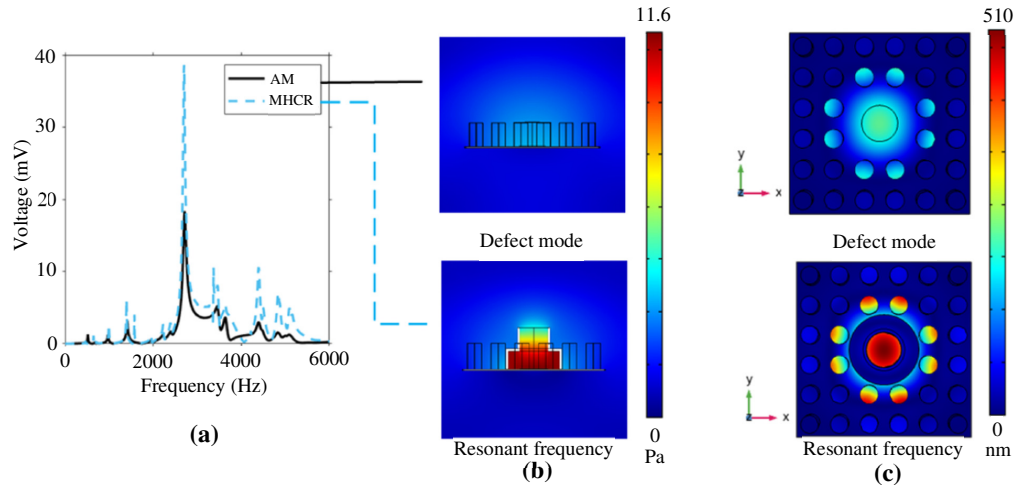


Fig. 4. Performance of the acoustic metamaterial (AM) and Helmholtz coupled-resonator (MHCR) showing (a) the circuit voltage, (b) the associated sound pressure level and (c) the displacement field.

The local modification of the acoustic metamaterial through the introduction of a centre defect made the wave band frequency be confined to the defect area increasing the acoustic energy focusing. Furthermore, the addition of Helmholtz resonator to the defect amplifies the sound pressure at the defect zone [24]. The enhanced acoustic energy is then converted into electric

energy by the piezoelectric patch attached at the defect zone [23]. The effect of resonant mode over a defect on the acoustic metamaterial in intensifying the sound waves is shown in Fig. 4. The maximum attained voltage at frequency 3000 Hz is 18 mV for the acoustic metamaterial and 38 mV for the metamaterial and Helmholtz coupled-resonator (MHCR). A similar trend can be observed for the sound pressure distribution with MHCR when compared with AM.

Metamaterial based electro elastic systems were also exploited by Carrara *et al.* [25] for enhanced structure-borne wave energy harvesting. The concepts explored in the study involved wave focusing using a metamaterial-inspired parabolic acoustic mirror (PAM) for broadband application. This was coupled with energy localisation using imperfection in a 2D lattice structure for tuned energy harvesting). The coupling of metamaterial and electro elastic domains by MEH transforms the sound wave into electrical energy. This was followed by an acoustic funnel-based waveguide which is explained in subsequent sections. The high-power density of the piezoelectric transduction enhanced the convenience with which it can be employed for energy harvesting.

3.2. Wave focusing metamaterial for energy harvesting

In this case, a linear PZT array as shown in Fig. 5 is used as the energy source and the harvester is a piezoelectric disk of 7 mm diameter and 0.2 mm thickness. The source PZT array is bonded to a 1mm thick aluminium plate which was sinusoidally excited at selected frequencies through a function generator and voltage amplifier. The resulting wave propagation field has been measured by scanning a laser vibrometer. The output voltage in Fig. 3b shows the influence of the PAM on energy harvesting in terms of output voltage and Power. The maximum power generated by the PAM-based energy harvester occurs at 55 kHz and 1.3 k Ω with 1.51 mW, whereas the free harvester produced a power of 145 μ W at 55 kHz and 1.7 k Ω .

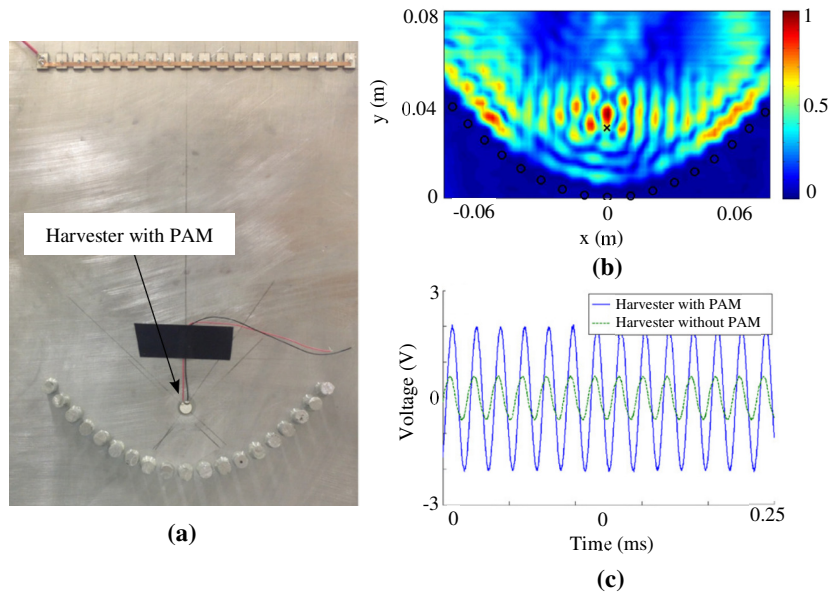


Fig. 5. Wave focusing type metamaterial energy harvesting technique [25] where (a) shows the experimental architecture, (b) the resulting RMS velocity field for excitation at 50 kHz and (c) voltage output comparison with and without PAM.

3.3. Wave localization using a 2D lattice with an imperfection

In this method, an internal defect in the form of a circle or rectangle has been introduced by breaking the lattice periodicity of the stubs by removing one as shown in Fig. 6 [25,26]. The observed frequency response function at the defect by the metamaterial energy harvester shows the amplitude peaks at 35 Hz and 63 Hz (Fig. 6b) representing the first and second mode of the defect. The comparative red line represents the performance observed for the stubbed region. The implemented alternative wiring configurations allowed the piezoelectric plate to harvest power without cancellation at each mode. The top and bottom electrodes are all wired together to harvest from the first mode, while the top electrode of one-half was wired to the bottom of the other and vice versa to harvest from the second mode.

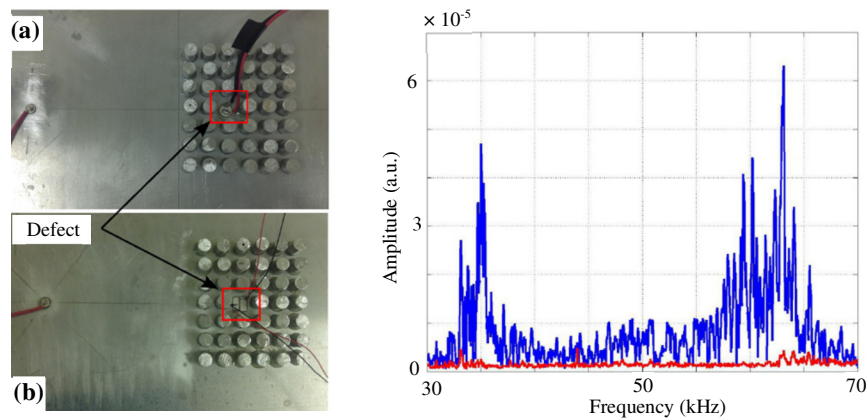


Fig. 6. Metamaterial energy harvester made from 2D lattice structure made of aluminium stubs [25] where (a) shows a circular energy harvester, (b) rectangular energy harvester and (c) frequency response observed.

3.4. Wave-guiding by acoustic funnel

In the acoustic funnel technique, a metamaterial region featuring repeating pillars to capture circular crested waves generated by a single point piezoelectric source as shown in Fig. 7 is used. The pillar array behaves similar to a mirror reflecting the incident waves and narrowing their propagation within the desired path (Fig. 8c) [25]. As shown in Fig. 8b, the metamaterial energy harvester (MEH) system is superior demonstrated by the increased power generation.

The performance comparison of the metamaterial system with free harvesters showed performance improvement in energy harvesting. As such the MEH concept can enable potential system-level applications such as low-power electricity generation for structural monitoring sensor networks and acoustic energy harvesting by absorbing undesired noise at the low-frequency domain [8,27,28].

The novel design of metamaterials allows wave conversion at sub-wavelength scales targeting enhanced functionalities such as acoustic focusing, acoustic transmission, diffuse reflection and amplification through the exploitation of the resonance phenomenon [21,29,30]. Notable examples include the work by Jia *et al.* [29] where a two-way spiral-shaped metamaterial and its

array showed significant sound energy enhancement through opposite transmission behaviours in orthogonal directions.

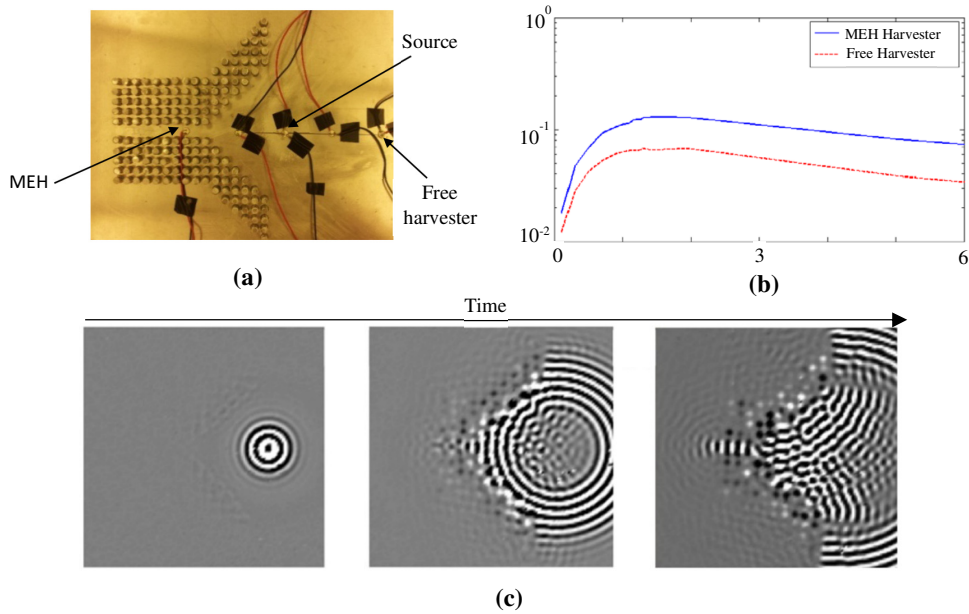


Fig. 7. Acoustic funnel metamaterial energy harvester [25] where (a) shows the periodic arrangement of aluminium pillars, (b) the resulting power generation from the metamaterial energy harvester (MEH) system in comparison with free harvester and (c) the wavefield recorded at an excitation of 100 kHz at successive time intervals demonstrating wave confinement by the funnel.

At the operational frequency (4.8 – 5.8 kHz) the sound energy enhancement was recorded to be more than 10.75 dB. In the construction proposed by Jia *et al.* the interaction of the incident sound waves (5.04–6.5 kHz) showed anisotropic acoustic behaviour where the transmittance of the gradient metamaterial was found to be drastically improved in the y -direction in comparison to x . This anisotropic ability of the metamaterial is promising in manipulating transmission bandwidths and can be used for wider applications such as energy harvesting system, non-destructive acoustic testing technology, sound signal modulation device and imaging applications [29].

4. Thermal and solar energy harvesting

Wang *et al.* [31] experimentally studied the radiation properties of visible and near-infrared wavelengths in electromagnetic waves interacting with metamaterials for solar energy harvesting [32]. In general, there are four mechanisms available for measuring the electromagnetic wave absorption namely: localised surface plasmon resonance (LSPR), Magnetic dipole resonance, surface plasmon polaritons (SPPs) and intrinsic absorption (IA). It has been shown that the SPP contributes significantly to the effective functioning of metamaterials.

SPPs are electromagnetic waves that travel along with metal-dielectric or metal-air interface combinations, practically in the infrared or visible-frequency. The term ‘surface plasmon polariton’ explains that the wave involves both charge motion in the metal (surface plasmons) and electromagnetic waves in the air or dielectric (polariton) as shown in Fig. 8, where, E refers to the electric field vector, H_y to the Magnetic field vector in y . In the case of metamaterials, EM

waves absorption in SPPs is by the electron conduction at the interface between negative and positive permittivity materials which are vibrating in resonance with the stimulated incident EM waves at specific wavelengths.

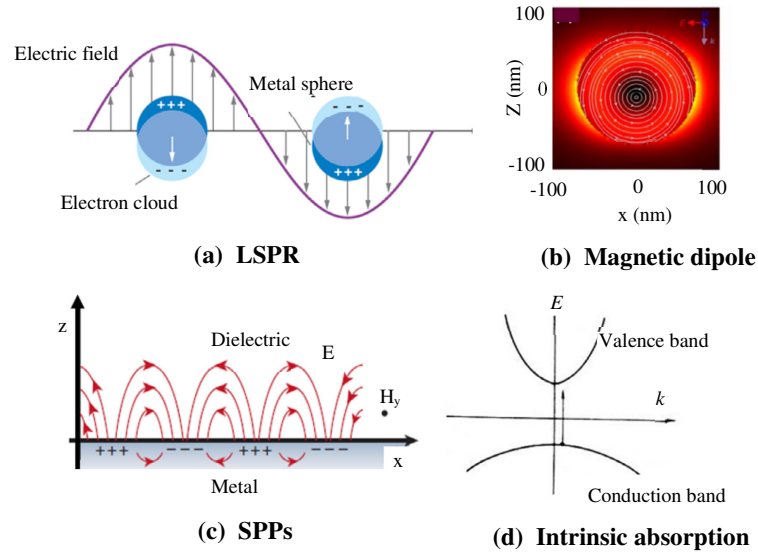


Fig. 8. Different mechanisms for absorption enhancement by nanoparticles and metamaterials [31] where (a) shows the localised surface plasmon resonance (LSPR), (b) Magnetic dipole resonance, (c) surface plasmon polaritons (SPPs) and (d) intrinsic absorption (IA).

As summarised by Wang and Ping [31] the following concepts based on dielectric property namely the slow light and the gradient index effects are most suitable to enhance the absorption efficiency of the metamaterial. This phenomenon of having a negative dielectric is called a slow light effect, which can trap lights of a different wavelength. On the other hand, the gradient index phenomenon works on the principle of gradual increase in the effective dielectric function of the metamaterial to large values.

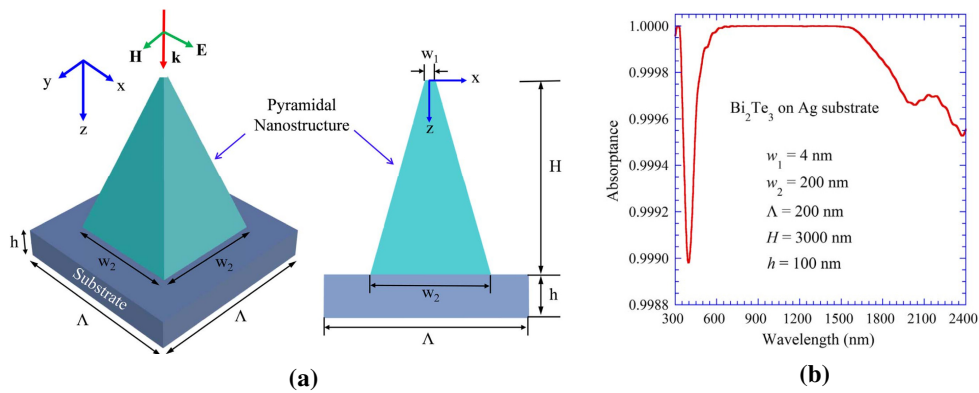


Fig. 9. Schematic illustration and performance of the periodic Bi_2Te_3 pyramids where (a) shows the pyramidal architecture on a thin film where the direction of the incident light is indicated by the wave vector k , which is parallel to z and (b) shows the resulting absorbance of the architecture [33].

As shown in Fig. 9, the structures with a gradually increasing cross-section from top to bottom such as that of a pyramid show an increase in the dielectric function from top to bottom. The

increase in dielectric function contributes to the increase in refractive index from another medium (water) to the material. As a result, the incident angle of the light gradually changes to a vertical suppressing reflection effect and increases the absorption of the light [31].

The example constructs [33] uses the Bi_2Te_3 anisotropic material with both metallic and dielectric responses to electromagnetic waves, whose absorptance was measured experimental by forming a pyramidal nanostructure on a silver substrate as shown in Fig. 9. The structure was submerged in water where it was observed that the absorptance of this Bi_2Te_3 pyramid is equal to 1 in the wavelength range 300 – 2400 nm taking 97% of solar energy. This was made possible by trapping shorter wave at the top of the pyramid and larger wave at the bottom attributed to the slow- light and gradient index effect. Thus, it is proved to have perfect absorption by surface plasmon polaritons (SPPs) in metamaterials irrespective of narrow or broadband absorption.

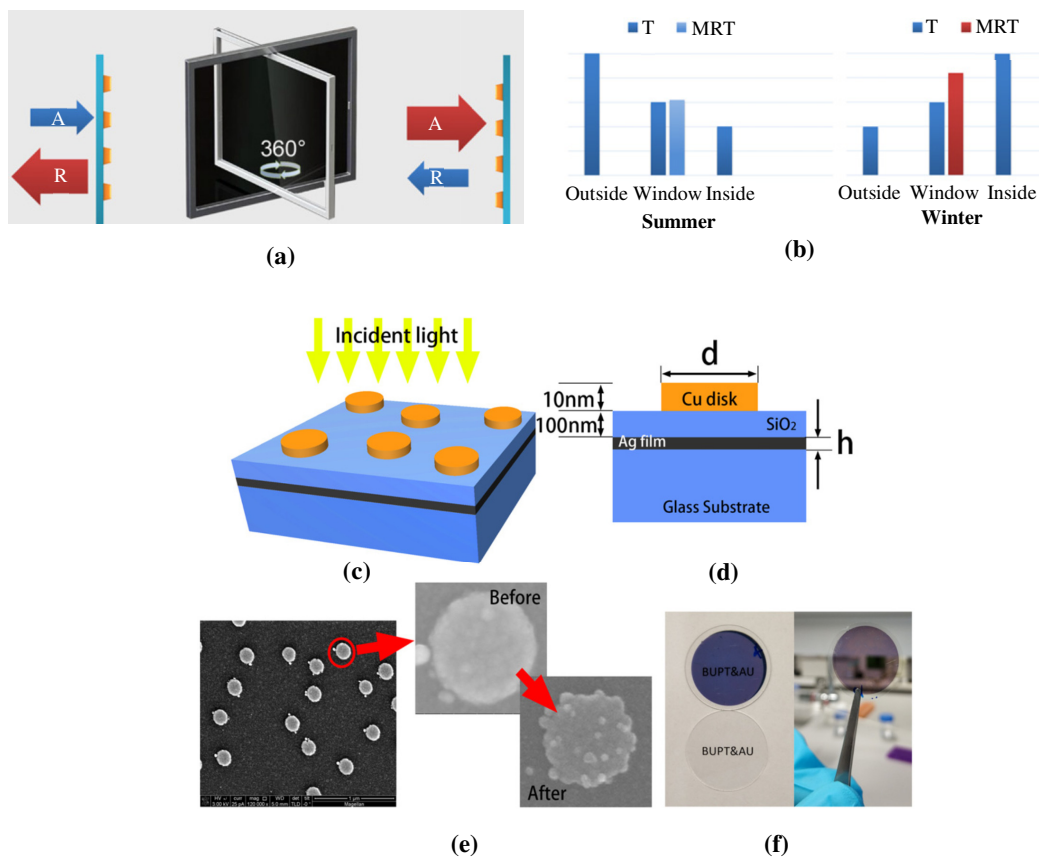


Fig. 10. Schematic representation of the directional absorption transparent glazing applied to windows [19] where (a) shows the directional nature of the architecture allowing solar energy harvesting both in winter and summer. (b) The effect on mean radiant temperature (MRT) brought by a nanostructure is higher in winter in comparison to summer. (c) The cross-section schematic of nano-structured architecture and the (d) corresponding compositions. (e) The scanning electron microscopy (SEM) images of fabricated disks and the insets are the shapes of the disk before and after reduction treatment. (f) Photographs of designed meta-surfaces and glass substrate on white paper.

Another method to absorb solar energy is by exterior window surface polishing by nanostructure glazing that allows transparent multi-directional solar absorption. Such architectures can be used as structural supports for enabling buildings as solar harvesting arrays without affecting the

aesthetics [19]. Nanostructured metamaterials with mean radiant temperature (MRT) are appropriate in such a thermal management system to harvest solar energy. The working scheme of glazed metamaterials for solar energy harvesting according to the season to regulate temperature is shown in Fig. 10.

The plasmonic meta-surface used in the analysis was constructed by hole mask colloidal lithography (HMCL) on a glass substrate with 6 nm silver layers covered by 100nm SiO₂ film and a short-ranged ordered array of Cu disks (d=100 nm, t=10 nm) as shown in Fig. 10. The absorption of radiation is through the excitation of surface plasmon around the Cu disk that is coupled with the absorption Ag film. This combined absorption resulted in a rise of 25% at 800 -900 nm wavenumber with moderate transparency for the energy harvesting metamaterial [19].

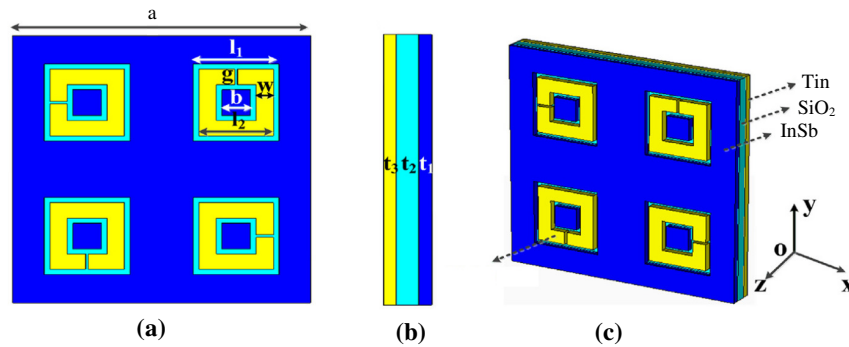


Fig. 11. Schematic representation of the three-layer metamaterial absorber for solar energy harvesting where (a) shows the front view, (b) side view and (c) perspective [18].

Metamaterial absorbers for absorbing solar radiation in the range 400 – 750 THz has been constructed using hybrid three layers made of metal split ring resonators (SPR) kept as a top layer in the slot of indium antimonide (InSb) with dielectric material SiO₂ of 10 nm thick as gap-filling material to avoid metal contacts [18]. This three-layer metamaterial at a thickness of 56 nm is shown in the 11a [18]. The solar radiation absorption by ultrathin three-layer metamaterial showed broadband absorption with more than 90% efficiency with peak absorption at 578.4 THz. Tang *et al.* [18] used the Drude model for complex permittivity [34] of InSb to enable sensing application. The resulting architecture exhibited the ability to enhance the absorption spectrum with temperature rise. This ultra-thin three-layer metamaterial absorber is the possible candidate for use in THz, infrared, optical region or microwave region [35].

Recently nanostructured and additively manufactured metamaterials have become an active research domain in the field of radiative heat transfer for thermal energy harvesting [36,37]. The silicon-cored WNW (Tungsten nanowire) shown in Fig. 12 was fabricated by depositing thin layers of tungsten at 1Å/S deposition rate on 2D Si - NW (nanowire) [17]. The thermal performance of the fabricated metamaterial was evaluated at concentrated solar irradiation up to 20 suns (1 sun = 1.5 kW/m²) using a developed solar test kit of a 1kW solar simulator, 1 ft³ volume vacuum chamber, optical filters, and mirrors. Based on test runs the yield of the metamaterial absorber was calculated to be superior enhancing the energy harvesting performance.

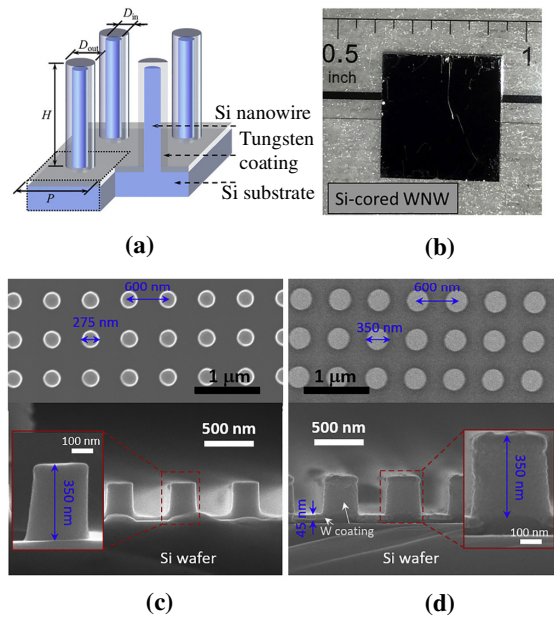


Fig. 12. Si core nanostructured metamaterial where (a) shows the structural schematic of Si-cored tungsten nanowire metamaterial as a selective solar absorber. (b) the fabricated Si-cored metamaterial sample. (c) Top-view and cross-sectional scanning electron microscopy (SEM) images of bare SiNW array with nanowire and (d) Top-view and cross-sectional SEM images of Si-cored WNW array after thick tungsten is conformally sputtered on the silicon surfaces. [17]

5. Mechanical energy harvesting

The mechanical, thermal, optical, electronic, acoustic and transport properties of metamaterials can be manipulated through targeted architecture [38]. The phenomenon of architecture manipulation of metamaterial lends itself to their application in shape morphing, cloaking and high strength to weight ratios. As such metamaterial can be sustainability designed for energy harvesting while allowing the required load-carrying capacity.

Mechanical properties of metamaterials result from a superposition of many different factors, namely bulk material, manufacturing parameters, defects from fabrication, unit cell geometry, cell size, parametrization, unit cell distribution, connection, and periodicity. In most cases, the unit cells featured in metamaterial are highly intricate with high aspect ratio and tailored properties. Therefore, for an effective design of metamaterial, a critical understanding of their repeating unit cell is required.

Elastic metamaterials (EMMs) are a class of metamaterial that are specifically engineered to allow properties such as bandgaps, negative mass density and/or modulus, and zero refractive indexes. They are used to manipulate elastic waves for guiding, confining, and isolating. As such they offer a potential application of energy harvesting through flexural deformation controlled through carefully introduced defects [39] or cavities [40]. These so-called cavities in an elastic metamaterial confine the modes of the elastic waves leading to energy harvesting.

Cavity based approaches at a limited bandwidth have been demonstrated by Ma *et al.* [40] for potential energy harvesting as shown in Fig. 13. The architecture featured an elastic metamaterial using a plate of aluminium where cavities were deliberately introduced for localisation of the elastic waves resulting in improved energy harvesting. The experiment used a reference plate without cavities to demonstrate the influence of the cavities on energy generation. The resonant frequency coincided with the cavities and increases the desired outcome of the test. It was shown that the measured output voltage from the oscilloscope is three times higher than the reference plate thus exhibiting energy amplification by the elastic metamaterial cavity.

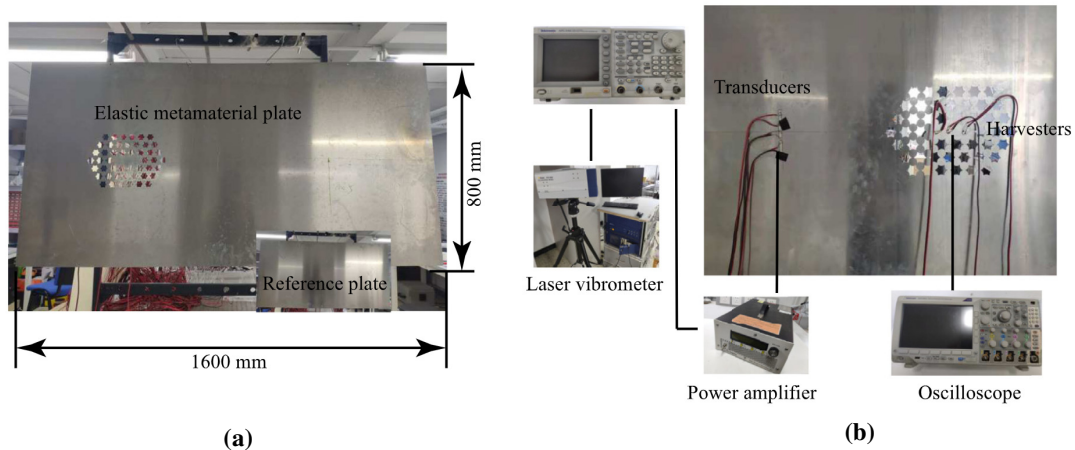


Fig. 13. An elastic metamaterial where (a) shows the photograph of the fabricated specimen with cavities and (b) shows the experimental setup for characterising the energy harvester [40].

Designing metamaterial architecture by lattice arrangement is a new horizon offering opportunities for extracting targeted and exotic material properties. When conceived appropriately, the material properties of such architectures are advantageous to conventional solid continuum materials where performance is often driven by the relative density [41]. Based on the Maxwell rule, the topology of unit cells plays a vital role in the mechanical performance of cellular structures. As such the 2D and 3D lattices are generally classified based on their bend or stretch dominated behaviour. Generally, stretch dominated structures offer high modulus and yield strength when designing lightweight materials for structural applications [42,43].

Xue *et al.* [42], have considered plate lattice structure in the designing of mechanical metamaterials by taking unit cells in specific combinations using Simple Cubic (SC), Body Centred Cubic (BCC) and Face Centred Cubic (FCC). The SC unit cell consists of three-square plates of length L and thickness t . The BCC unit cell consists of six rectangular plates of length $\sqrt{2}L$, width L , and thickness t . The FCC unit cell consists of four regular hexagonal plates with a side length of $[(\sqrt{2}/2) L]$, the plate thickness of t , and eight regular triangle plates with a side length of $[(\sqrt{2}/2) L]$. The formulated lattice unit cells are shown in Fig. 14.

Hybrid lattice unit cells as shown in Fig. 14b were developed by combining the fundamental unit cells and fabricating using additive manufacturing. The representation of each model has value '2' in the bracket and a superscript '3' indicating the numbers of unit cells in each direction and the number of directions in the array, respectively. The lattice architectures were mechanically

tested in compression mode at different strains and both the compressive performance and specific energy absorption were analysed as shown in Fig. 15a and 15b, respectively. It can be seen that for both compressive stress and specific energy absorption the metamaterial architecture showed improved performance in comparison to their mono-unit cell counterparts [42].

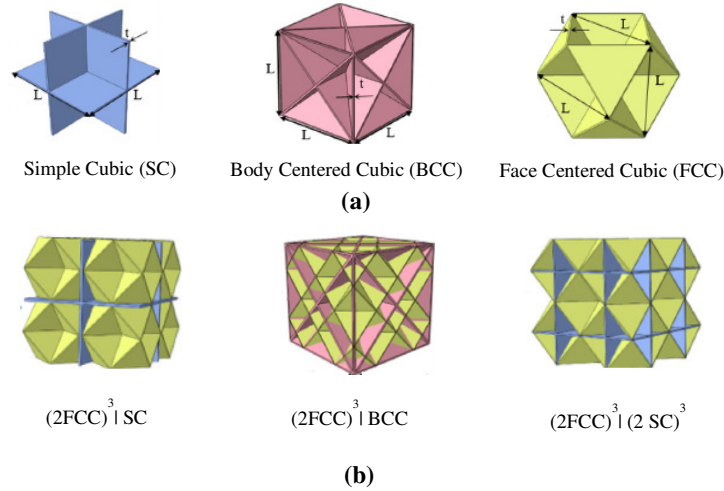


Fig. 14. Plate lattice metamaterials developed by Xue *et al.* [42] where (a) shows the basic building blocks and (c) the hybrid metamaterial architecture.

Energy harvesting from vibration is quite attractive due to the availability of abundant vibro-acoustic sources. Vibration energy can be trapped by methods like piezoelectric, electric induction, magnetic induction, and hybrid techniques. The piezoelectric vibration energy harvesting (PVEH) uses the deformation (strain) of the material to generate power and it has high compatibility with the micro-electro-mechanical systems (MEMS) process [44].

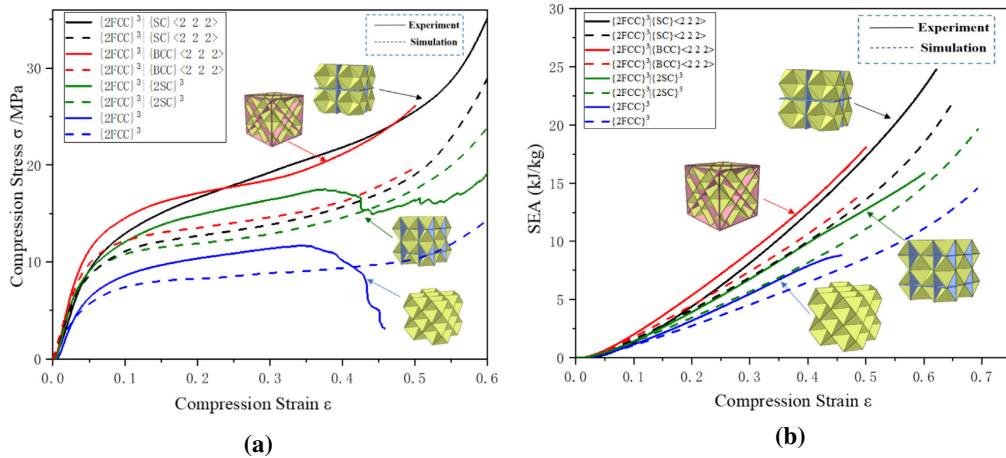


Fig. 15. Mechanical performance of the plate-lattice metamaterials where (a) shows the compressive stress and (b) the specific energy absorption [42].

In most cases, structural resonance is the foundation of vibration energy harvester (VEH) systems. Generally, the most available low-frequency load is around 100 Hz, which is the factor

to consider for trade-off on miniature vibration energy harvesters. The challenge in designing metamaterials for vibrational energy harvesters is the size and the energy that can be harvested. To capture the vibration at low frequency, the metamaterial device should be flexible allowing for large deformation. One of the most notable work in this regard was from Ryo *et al.* [45] where a metamaterial-based cantilever beam was developed as shown in Fig. 16.

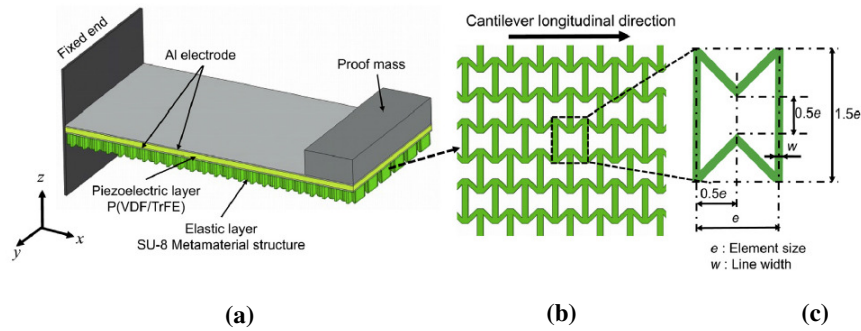


Fig. 16. A metamaterial-based vibrational energy harvester showing (a) the cantilevered architecture, (b) the re-entrant metamaterial elastic layer and (c) the corresponding unit cell parameters [45].

The architecture harvest energy at a small frequency band by decreasing the bending stiffness and increasing the strain. The reduction in bending stiffness was achieved by a thin flexible metamaterial structure for an elastic layer that can exhibit a large deformation for a small strain. The piezoelectric layer was made of polyvinylidene fluoride (VDF/TrFE), a copolymer of vinylidene fluoride (VDF), and ethylene-trifluoride (TrFE), with flexible and high piezoelectricity. The elastic layer consisted of a negative-type thick photoresist SU-8 (Nippon Kayaku Co.; SU-8 3005) and was fabricated by the photolithography process. The study showed that all fabricated metamaterial harvester exhibits lower resonance frequency and higher output power in comparison to a flat plate architecture. The significant rise in the resonant frequency and output power-driven by the higher flexibility and uniform strain distribution allowed the miniaturization of the architecture [45].

6. Challenges

Despite the lab-scale progress in 2D and 3D metamaterials, numerous challenges prevail when it comes to implementing metamaterials in real life [7]. One of the key issues in this regard is mass production, scalability of the sub-micro architecture [46]. Currently, fabrication techniques such as selective laser melting (SLM), electron beam lithography (EBL), direct laser writing (DLW), nanoimprint lithography (NIL) and self-assembly (SA) are being widely experimented. While these fabrication techniques can accommodate the design complexity of metamaterial architecture, reducing cost and enabling large-scale manufacturing to require further simplification at the metamaterial design stage [46–48].

7. Conclusion

Developments in metamaterials have opened a gateway in energy harvesting from a range of environmental sources. In general, the research in energy harvesting metamaterial if focused around four key classes namely, double-positive (DPS), epsilon-negative (ENG), mu-negative (MNG) and double-negative DNG. The sources targeted by energy harvesting metamaterials include vibro-acoustics, thermal/solar and mechanical with varying degree of success. For acoustic energy scavenging, confining the wave to a focal point to enhance its intensity and then capturing it to produce usable power seems to be the common approach. In most cases, the metamaterial design included modification of the lattice arrangement with a defect along with a resonator and wave path design. When it comes to solar or thermal radiation harvesting, the dielectric nature of the material and material structure are explored through purpose build pyramid and directionally architecture. For mechanical energy harvesting, metamaterial cross-plane lattice and ultrathin flexible structure with high specific energy absorption were the directions explored. Based on the areas covered, the inevitable conclusion has to be that the next decade will see a revolution and proliferation of metamaterials for energy harvesting, and the constituting components are currently being developed as presented in this paper.

References

- [1] C. Fowler, J. Zhou, A Metamaterial-inspired approach to RF energy harvesting, ArXiv. (2017) 1–11.
- [2] J. Shi, A.H. Akbarzadeh, 3D Hierarchical lattice ferroelectric metamaterials, *Int. J. Eng. Sci.* 149 (2020) 103247. <https://doi.org/10.1016/j.ijengsci.2020.103247>.
- [3] T.J. Cui, L. Li, S. Liu, Q. Ma, L. Zhang, X. Wan, W.X. Jiang, Q. Cheng, *iScience II Information Metamaterial Systems, ISCIENCE.* 23 (2020) 101403. <https://doi.org/10.1016/j.isci.2020.101403>.
- [4] A. Arjunan, M. Singh, A. Baroutaji, C. Wang, Additively manufactured AlSi10Mg inherently stable thin and thick-walled lattice with negative Poisson's ratio, *Compos. Struct.* 247 (2020) 112469. <https://doi.org/10.1016/j.compstruct.2020.112469>.
- [5] A. Arjunan, M. Demetriou, A. Baroutaji, C. Wang, Mechanical performance of highly permeable laser melted Ti6Al4V bone scaffolds, *J. Mech. Behav. Biomed. Mater.* 102 (2020) 103517. <https://doi.org/10.1016/j.jmbbm.2019.103517>.
- [6] A. Arjunan, A. Baroutaji, A.S. Praveen, A.G. Olabi, C.J. Wang, Acoustic Performance of Metallic Foams, in: *Ref. Modul. Mater. Sci. Mater. Eng.*, Elsevier, 2019. <https://doi.org/10.1016/B978-0-12-803581-8.11561-9>.
- [7] G. Yoon, I. Kim, J. Rho, Challenges in fabrication towards realization of practical metamaterials, *Microelectron. Eng.* 163 (2016) 7–20. <https://doi.org/10.1016/j.mee.2016.05.005>.
- [8] Z. Chen, B. Guo, Y. Yang, C. Cheng, Metamaterials-based enhanced energy harvesting: A review, *Phys. B Condens. Matter.* (2014). <https://doi.org/10.1016/j.physb.2013.12.040>.
- [9] R.W. Ziolkowski, Metamaterial-based source and scattering enhancements : from microwave to optical frequencies, (2014). <https://doi.org/10.2478/s11772-006-0022-0>.
- [10] G. Zhou, L. Huang, W. Li, Z. Zhu, Harvesting ambient environmental energy for wireless sensor networks: A survey, *J. Sensors.* 2014 (2014). <https://doi.org/10.1155/2014/815467>.
- [11] C. Liang, Y. Zhang, Z. Yi, X. Chen, Z. Zhou, H. Yang, Y. Yi, Y. Tang, W. Yao, Y. Yi, A broadband and polarization-independent metamaterial perfect absorber with monolayer Cr and Ti elliptical disks array, *Results Phys.* 15 (2019) 102635. <https://doi.org/10.1016/j.rinp.2019.102635>.
- [12] L. Qi, C. Liu, S.M. Ali Shah, A broad dual-band switchable graphene-based terahertz metamaterial absorber, *Carbon N. Y.* 153 (2019) 179–188.

- <https://doi.org/10.1016/j.carbon.2019.07.011>.
- [13] Ş. Dalgaç, M. Bakır, F. Karadağ, E. Ünal, M. Karaaslan, C. Sabah, Characterization of chiral metamaterial sensor with high sensitivity, *Optik (Stuttg)*. 202 (2020). <https://doi.org/10.1016/j.ijleo.2019.163673>.
- [14] E. Ahamed, M.R.I. Faruque, A.M. Tamim, M.T. Islam, M.F. Bin Mansor, M.B. Ahmmed, Enhancement of magnetic field intensity with a left-handed metamaterial tunnel resonator for obstacle sensing, *Chinese J. Phys.* 70 (2021) 91–105. <https://doi.org/10.1016/j.cjph.2020.12.020>.
- [15] M. Karaaslan, M. Bağmancı, E. Ünal, O. Akgol, C. Sabah, Microwave energy harvesting based on metamaterial absorbers with multi-layered square split rings for wireless communications, *Opt. Commun.* 392 (2017) 31–38. <https://doi.org/10.1016/j.optcom.2017.01.043>.
- [16] M. Moniruzzaman, M.T. Islam, G. Muhammad, M.S.J. Singh, M. Samsuzzaman, Quad band metamaterial absorber based on asymmetric circular split ring resonator for multiband microwave applications, *Results Phys.* 19 (2020) 103467. <https://doi.org/10.1016/j.rinp.2020.103467>.
- [17] J.Y. Chang, S. Taylor, R. McBurney, X. Ying, G. Allu, Y. Bin Chen, L. Wang, Enhancing solar-thermal energy conversion with silicon-cored tungsten nanowire selective metamaterial absorbers, *IScience*. 24 (2021). <https://doi.org/10.1016/j.isci.2020.101899>.
- [18] J. Tang, Z. Xiao, K. Xu, Ultra-thin metamaterial absorber with extremely bandwidth for solar cell and sensing applications in visible region, *Opt. Mater. (Amst)*. 60 (2016) 142–147. <https://doi.org/10.1016/j.optmat.2016.07.023>.
- [19] R. Ma, D. Wu, Y. Liu, H. Ye, D. Sutherland, Copper plasmonic metamaterial glazing for directional thermal energy management, *Mater. Des.* 188 (2020) 108407. <https://doi.org/10.1016/j.matdes.2019.108407>.
- [20] K. Wei, X. Xiao, J. Chen, Y. Wu, M. Li, Z. Wang, Additively manufactured bi-material metamaterial to program a wide range of thermal expansion, *Mater. Des.* 198 (2021). <https://doi.org/10.1016/j.matdes.2020.109343>.
- [21] H. Dong, S. Zhao, Y. Wang, L. Cheng, Journal of the Mechanics and Physics of Solids Robust 2D / 3D multi-polar acoustic metamaterials with broadband double negativity, 137 (2020) 1–15.
- [22] B. Assouar, M. Oudich, X. Zhou, Acoustic metamaterials for sound mitigation, *Comptes Rendus Phys.* 17 (2016) 524–532. <https://doi.org/10.1016/j.crhy.2016.02.002>.
- [23] K. Ma, T. Tan, Z. Yan, F. Liu, W.H. Liao, W. Zhang, Metamaterial and Helmholtz coupled resonator for high-density acoustic energy harvesting, *Nano Energy*. 82 (2021) 105693. <https://doi.org/10.1016/j.nanoen.2020.105693>.
- [24] L. Wu, Y. Wang, K. Chuang, F. Wu, Q. Wang, W. Lin, H. Jiang, A brief review of dynamic mechanical metamaterials for mechanical energy manipulation, *Mater. Today*. xxx (2020) 1–26. <https://doi.org/10.1016/j.mattod.2020.10.006>.
- [25] M. Carrara, M.R. Cacan, J. Toussaint, M.J. Leamy, M. Ruzzene, A. Erturk, Metamaterial-inspired structures and concepts for elastoacoustic wave energy harvesting, *Smart Mater. Struct.* 22 (2013). <https://doi.org/10.1088/0964-1726/22/6/065004>.
- [26] T. Tan, Z. Yan, H. Zou, K. Ma, F. Liu, L. Zhao, Z. Peng, W. Zhang, Renewable energy harvesting and absorbing via multi-scale metamaterial systems for Internet of things, *Appl. Energy*. 254 (2019) 113717. <https://doi.org/10.1016/j.apenergy.2019.113717>.
- [27] A. Arjunan, Acoustic absorption of passive destructive interference cavities, *Mater. Today Commun.* 19 (2019) 68–75. <https://doi.org/10.1016/j.mtcomm.2018.12.012>.
- [28] A. Arjunan, Targeted sound attenuation capacity of 3D printed noise cancelling waveguides, *Appl. Acoust.* 151 (2019) 30–44. <https://doi.org/10.1016/J.APACOUST.2019.03.008>.
- [29] X. Jia, M. Yan, M. Hong, Sound energy enhancement via impedance-matched anisotropic metamaterial, *Mater. Des.* 197 (2021) 109254. <https://doi.org/10.1016/j.matdes.2020.109254>.
- [30] A. Arjunan, C. Wang, M. English, M. Stanford, P. Lister, A computationally-efficient numerical model to characterize the noise behavior of metal-framed walls, *Metals (Basel)*. 5 (2015) 1414–1431. <https://doi.org/10.3390/met5031414>.
- [31] Z. Wang, P. Cheng, Enhancements of absorption and photothermal conversion of solar energy enabled by surface plasmon resonances in nanoparticles and metamaterials, *Int. J. Heat Mass Transf.* 140 (2019) 453–482. <https://doi.org/10.1016/j.ijheatmasstransfer.2019.05.085>.
- [32] J. Wang, G. Dai, J. Huang, Thermal Metamaterial: Fundamental, Application, and Outlook,

- IScience. 23 (2020) 101637. <https://doi.org/10.1016/j.isci.2020.101637>.
- [33] Z. Wang, Z.M. Zhang, X. Quan, P. Cheng, A perfect absorber design using a natural hyperbolic material for harvesting solar energy, *Sol. Energy*. 159 (2018) 329–336. <https://doi.org/https://doi.org/10.1016/j.solener.2017.11.002>.
- [34] D. Saeedkia, *Handbook of Terahertz Technology for Imaging, Sensing and Communications*, 2013. <https://doi.org/10.1533/9780857096494>.
- [35] K.S.L. Al-Badri, Y.S. Alwan, M.F. Khalaf, Ultra-thin dual-band perfect metamaterials absorber for microwave applications, *Mater. Today Proc.* (2021). <https://doi.org/10.1016/j.matpr.2020.12.300>.
- [36] J. Robinson, M. Stanford, A. Arjunan, Stable Formation of Powder Bed Laser Fused 99.9% Silver, *Mater. Today Commun.* (2020) 101195. <https://doi.org/10.1016/j.mtcomm.2020.101195>.
- [37] J. Robinson, A. Arjunan, M. Stanford, I. Lyall, C. Williams, Effect of silver addition in copper-silver alloys fabricated by laser powder bed fusion in situ alloying, *J. Alloys Compd.* 857 (2021) 157561. <https://doi.org/https://doi.org/10.1016/j.jallcom.2020.157561>.
- [38] S.C.L. Fischer, L. Hillen, C. Eberl, Mechanical metamaterials on the way from laboratory scale to industrial applications: Challenges for characterization and scalability, *Materials (Basel)*. 13 (2020). <https://doi.org/10.3390/MA13163605>.
- [39] S.H. Jo, H. Yoon, Y.C. Shin, B.D. Youn, A graded phononic crystal with decoupled double defects for broadband energy localization, *Int. J. Mech. Sci.* 183 (2020) 105833. <https://doi.org/10.1016/j.ijmecsci.2020.105833>.
- [40] T.X. Ma, Q.S. Fan, Z.Y. Li, C. Zhang, Y.S. Wang, Flexural wave energy harvesting by multi-mode elastic metamaterial cavities, *Extrem. Mech. Lett.* 41 (2020) 101073. <https://doi.org/10.1016/j.eml.2020.101073>.
- [41] M. Abdelhamid, A. Czekanski, Impact of the lattice angle on the effective properties of the octet-truss lattice structure, *J. Eng. Mater. Technol. Trans. ASME*. 140 (2018) 1747–1769. <https://doi.org/10.1115/1.4040409>.
- [42] R. Xue, X. Cui, P. Zhang, K. Liu, Y. Li, W. Wu, H. Liao, Mechanical design and energy absorption performances of novel dual scale hybrid plate-lattice mechanical metamaterials, *Extrem. Mech. Lett.* 40 (2020) 100918. <https://doi.org/10.1016/j.eml.2020.100918>.
- [43] T.N. Tran, A. Baroutaji, Q. Estrada, A. Arjunan, H. Le, N.P. Thien, Crashworthiness analysis and optimization of standard and windowed multi-cell hexagonal tubes, *Struct. Multidiscip. Optim.* (2021). <https://doi.org/10.1007/s00158-020-02794-y>.
- [44] H. Toshiyoshi, S. Ju, H. Honma, C. Ji, MEMS vibrational energy harvesters, *Sci. Technol. Adv. Mater.* 20 (2019) 124–143. <https://doi.org/10.1080/14686996.2019.1569828>.
- [45] R. Ichige, N. Kuriyama, Y. Umino, T. Tsukamoto, T. Suzuki, Size optimization of metamaterial structure for elastic layer of a piezoelectric vibration energy harvester, *Sensors Actuators, A Phys.* 318 (2021) 112488. <https://doi.org/10.1016/j.sna.2020.112488>.
- [46] C.M. Soukoulis, M. Wegener, Past Achievements and Future Challenges in 3D Photonic Metamaterials, *Nat. Photonics.* (2011) 523–530.
- [47] B. Gong, X. Zhao, Z. Pan, S. Li, X. Wang, Y. Zhao, C. Luo, A visible metamaterial fabricated by self-assembly method, (2014) 4–10. <https://doi.org/10.1038/srep04713>.
- [48] A. Baroutaji, A. Arjunan, M. Ramadan, J. Robinson, A. Alaswad, M.A. Abdelkareem, A.-G. Olabi, Advancements and prospects of thermal management and waste heat recovery of PEMFC, *Int. J. Thermofluids.* 9 (2021) 100064. <https://doi.org/https://doi.org/10.1016/j.ijft.2021.100064>.