Physica B 438 (2014) 1–8

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Metamaterials-based enhanced energy harvesting: A review

Zhongsheng Chen*, Bin Guo, Yongmin Yang, Congcong Cheng

Science and Technology on Integrated Logistics Support Laboratory, National University of Defense Technology, Deya str. 228, Changsha, Hunan 410073, PR China

ARTICLE INFO

Article history:
Received 22 September 2013
Received in revised form
24 December 2013
Accepted 24 December 2013
Available online 8 January 2014

Keywords:
Enhanced energy harvesting
Phononic crystals
Acoustic metamaterials
Electromagnetic metamaterials
Thermal metamaterials

ABSTRACT

Advances in low power design open the possibility to harvest ambient energies to power directly the electronics or recharge a secondary battery. The key parameter of an energy harvesting (EH) device is its efficiency, which strongly depends on the conversion medium. To address this issue, metamaterials, artificial materials and structures with exotic properties, have been introduced for EH in recent years. They possess unique properties not easily achieved using naturally occurring materials, such as negative stiffness, mass, Poisson′s ratio, and refractive index. The goal of this paper is to review the fundamentals, recent progresses and future directions in the field of metamaterials-based enhanced energy harvesting. An introduction on EH followed by the classification of potential metamaterials for EH is presented. A number of theoretical and experimental studies on metamaterials-based EH are outlined, including phononic crystals, acoustic metamaterials, and electromagnetic metamaterials. Finally, we give an outlook on future directions of metamaterials-based energy harvesting research including but not limited to active metamaterials-based EH, metamaterials-based thermal EH, and metamaterials-based multifunctional EH capabilities.

1. Introduction

Up now, batteries have still been used as a major energy source for wearable or portable devices. However, this way has several intrinsic drawbacks. For example, the total size and weight of batteries will occupy a significant fraction of an electronic system. Moreover, replacement and disposal of large amounts of batteries will be a nightmare due to their limited useful lives. As advances in low power design, power consumption of electronics becomes smaller increasingly, which opens the possibility to harvest energy from the environment to power directly the electronics or recharge a secondary battery. This kind of new techniques is called ‘Energy Harvesting (EH)’. Nowadays, EH-based autonomous power supplies are much promising for wearable devices, wireless sensors and micro-electromechanical systems (MEMS) [1].

Energy harvesting can include kinetic, electromagnetic and thermal energy [1,2], in which proper media are utilized to convert those ambient energies into electrical energy. The key parameter of any energy harvesting device is its conversion efficiency that depends strongly on the conversion medium. In the past, natural materials were often chosen as conversion media for different energy harvesting devices. However, the conversion efficiency is limited by the properties of natural material and structures. For example, vibration energy harvesting often requires materials to response at frequencies lower than 300 Hz, which are not available from natural materials. Moreover, the current focus of vibration energy harvesting is to create small, lightweight structures that couple very well to mechanical excitation [3]. Additionally, the direction of electromagnetic energy harvesting is to improve the coupling coefficient with high Q factors using artificial structures [4]. The solution of this problem is to develop innovative energy harvesting structures.

In recent years, artificial materials and structures (AMS) have shown tremendous potentials in many disciplines of science and technology. In particular, metamaterials have attracted wide attentions, such as phononic crystals [5–8], electromagnetic metamaterials [9–12], and so on. The explosion of interest is due to the dramatical physical properties for sound, elastic and electromagnetic waves which are not available in natural materials, such as negative stiffness, mass, Poisson's ratio, and refractive index. In return, these non-traditional physical behaviors also provide innovative mechanisms for energy harvesting. More and more studies have been carried out to enhance the conversion performance by metamaterials, including theoretical and experimental investigations. The goal of this paper is to outline these existed studies on metamaterials-based vibration, acoustic, electromagnetic energy harvesting and then give an outlook for future progresses.

This paper is organized as follows. Section 2 introduces basic concepts of energy harvesting and classifies existed metamaterials

* Corresponding author. Tel.: +86 731 84574322; fax: +86 731 84573361.
E-mail address: czs_study@sina.com (Z. Chen).

0921-4526/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physb.2013.12.040

for energy harvesting. Current studies on phononic crystals-based vibroacoustic energy harvesting are outlined in Section 3. Section 4 summarizes the recent progress of acoustic metamaterial (AM)-based vibroacoustic energy harvesting. Significant researches on electromagnetic metamaterial (EM)-based wireless power transmission (WPT) are presented in Section 5. Section 6 discusses some future directions. Finally a simple remark is made in Section 7.

2. Fundamentals of metamaterials for energy harvesting

2.1. Basic concepts of energy harvesting

Energy harvesting is not a new idea, whose true legacy can date to the water wheel and windmill. Harvesting energy from waste heat or vibration has been utilized for many years. However, nowadays the new content of energy harvesting techniques is the range and the breadth of their applications. The modern view of energy harvesting is to extract small amounts of energy from the environment to power small autonomous devices like wireless sensor networks and mobile electronics.

A generalized energy harvesting process is to generate electrical energy from its surroundings using special conversion mechanism, as shown in Fig. 1. Here environmental energy sources may include kinetic energy in the form of vibrations and noises, electromagnetic radiation, thermal energy, and so on. Generally speaking, different mechanisms are needed for different environmental energies. The direct output of energy conversion is always an AC voltage, so it should be adjusted into a DC voltage for electrical loads or recharging.

It should be emphasized that energy harvesting is not as easy as it looks. Because the amounts of available energy being harvested are often small, the conversion efficiency is a very important performance parameter. In practice, an energy harvesting device has to be closely tuned to its power source in order to achieve high conversion efficiency, which depends strongly on the conversion medium. Currently, metamaterials are being introduced into designing innovative conversion media for high-performance energy harvesting, instead of natural materials.

2.2. Existed metamaterials for energy harvesting

The history of metamaterials started in 1968 when a theoretical investigation was first proposed by Russian physicist Veselago for electromagnetic waves (EMW) [13]. More recently, the metamaterial concept has been extended in parallel to elastic and acoustic waves (EAW) based on the similarity between the EMW and the EAW. Experimental results have revealed that metamaterials can exhibit exotic properties not easily achieved using naturally occurring materials, such as negative permittivity, negative permeability, and so on. According to currently published literatures, metamaterials used for energy harvesting mainly include phononic crystals, acoustic metamaterials, and electromagnetic metamaterials.

2.2.1. Phononic crystals

Phononic crystals are periodic dielectric or metallic structures capable of achieving negative phase velocity, which has been used to represent many different periodic fluid, elastic, and combination structures. The term of phononic crystals was first investigated in the early 1990s as the analog of photonic crystals [14]. Now it becomes a hotspot topic in condensed matter physics.

Phononic crystals now can be classified into one, two, and three-dimensional ones according to their spatial topology structures. When elastic waves propagate through phononic crystals, the special dispersive relation will produce. The frequency ranges without dispersive curves are defined as band gaps [15–17], where vibration and sound are forbidden to propagate. The realization of bandgaps within certain frequency range can be clearly explained by the negative effective mass density of the phononic crystals [18]. The existence of band gaps makes periodic materials and structures extremely appealing as mechanical filters.

Besides band gaps, one of the most interesting properties of phononic crystals is the negative refraction [19–22], which utilizes bands beyond the first Brillouin zone with Eigen frequency contours convex to the origin at specific frequencies [19]. It will cause a range of incident wave vectors to be focused in two or three dimensions. In return, these properties of band gaps just meet the challenges of low-frequency and broadband kinetic energy harvesting.

2.2.2. Acoustic metamaterials

For phononic crystals, the wavelength is required to be on the order of the lattice constants in the propagation direction at the band-gap center frequency. However, if the phase speed of the constituent material is significantly lower than that of the matrix material, a new physical phenomenon of local resonances may occur. This kind of AMS is also called as acoustic metamaterials. Liu et al. [23] firstly presented the concept of acoustic metamaterial, also called as localized resonant structures that exhibit band gaps, which provided a possible solution for the length-scale problem of band-gap materials. An introduction paper on acoustic metamaterials was published in [24]. Acoustic metamaterials have unique properties different from phononic crystals due to their own structures. For instance, their structural unit sizes are smaller than the acoustic wavelength and each unit cell contains its own mechanical oscillator.

Acoustic metamaterials are currently in the stage of infancy and most of the works were explored theoretically. Li and Chan [25] theoretically validated the possibility of the existence of acoustic metamaterials and pointed out that negative effective mass density and bulk modulus could be achieved simultaneously. Zhang [26] presented the first experimental demonstration of focusing ultrasound waves through a flat acoustic metamaterial lens composed of a planar network of sub-wavelength Helmholtz resonators. Fang et al. [27] proposed a new class of acoustic metamaterial which consists of a 1-D array of Helmholtz resonators which exhibits dynamic effective negative modulus. The design, development and characterization of acoustic metamaterials still bring forth many challenges and opportunities in materials science [24].

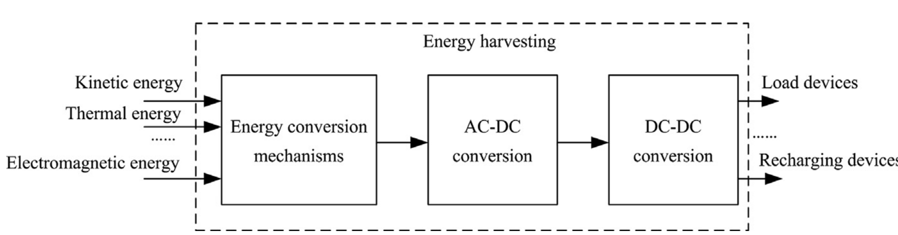

Fig. 1. Schematic diagram of generalized energy harvesting process.