ARTICLE IN PRESS

COMREN:3289

C. R. Physique ●●● (●●●●) ●●●–●●●

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Phononic crystals / Cristaux phononiques

Negative refraction and imaging of acoustic waves in a two-dimensional square chiral lattice structure

Réfraction négative et imagerie des ondes acoustiques dans une structure périodique chirale bidimensionnelle

Sheng-Dong Zhao, Yue-Sheng Wang *

Institute of Engineering Mechanics, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Phononic crystal
Chiral lattice
Acoustic wave
Negative refraction
Imaging
Beam separation

Mots-clés :
Cristal phononique
Réseau chiral
Onde acoustique
Réfraction négative
Imagerie
Séparation de faisceaux

ABSTRACT

The negative refraction behavior and imaging effect for acoustic waves in a kind of two-dimensional square chiral lattice structure are studied in this paper. The unit cell of the proposed structure consists of four zigzag arms connected through a thin circular ring at the central part. The relation of the symmetry of the unit cell and the negative refraction phenomenon is investigated. Using the finite element method, we calculate the band structures and the equi-frequency surfaces of the system, and confirm the frequency range where the negative refraction is present. Due to the rotational symmetry of the unit cell, a phase difference is induced to the waves propagating from a point source through the structure to the other side. The phase difference is related to the width of the structure and the frequency of the source, so we can get a tunable deviated imaging. This kind of phenomenon is also demonstrated by the numerical simulation of two Gaussian beams that are symmetrical about the interface normal with the same incident angle, and the different negative refractive indexes are presented. Based on this special performance, a double-functional mirror-symmetrical slab is proposed for realizing acoustic focusing and beam separation.

RÉSUMÉ

La réfraction négative et l'imagerie des ondes acoustiques dans une structure périodique chirale bidimensionnelle sont étudiées dans cet article. La cellule élémentaire de la structure considérée comporte quatre bras en zigzag, connectés dans la partie centrale par un fin anneau circulaire. La relation entre la symétrie de la cellule élémentaire et le phénomène de réfraction négative est explorée. À l'aide de la méthode des éléments finis, nous calculons la structure de bande et les surfaces équifréquence du système, ce qui nous permet de confirmer la gamme de fréquence pour laquelle la réfraction négative est obtenue. En raison de la symétrie par rotation de la cellule élémentaire, une différence de phase est introduite pour les ondes émises par un point source et traversant la structure. Cette différence de phase est liée à la largeur de la structure ainsi qu'à la fréquence de

* Corresponding author.
E-mail address: yswang@bjtu.edu.cn (Y.-S. Wang).

http://dx.doi.org/10.1016/j.crhy.2016.02.003
1631-0705/

Please cite this article in press as: S.-D. Zhao, Y.-S. Wang, Negative refraction and imaging of acoustic waves in a two-dimensional square chiral lattice structure, C. R. Physique (2016), http://dx.doi.org/10.1016/j.crhy.2016.02.003

la source, ce qui nous permet d'obtenir une image défléchie avec un angle ajustable. Le même phénomène est également démontré par simulation numérique pour deux faisceaux gaussiens incidents, avec des angles symétriques par rapport à la normale à l'interface. Dans ce cas, différents indices de réfraction négatifs sont obtenus. Sur la base de ce comportement spécifique, une dalle présentant une symétrie miroir est proposée pour réaliser la double fonction de focalisation et de séparation de faisceaux acoustiques.

1. Introduction

Negative refractions of electromagnetic waves were theoretically predicted in the left-handed materials (LHMs) by Veselago in 1968 [1], but only recently were they demonstrated experimentally [2,3]. These materials are characterized by simultaneous negative permittivity and permeability [4–9]. LHMs possess a series of unusual electromagnetic effects, including negative index of refraction [1], inverse Snell's law [6,7], reversed Doppler shift [8], and reversed Cerenkov radiation [9]. Due to the unique physical properties and potential applications, left-handed materials with negative refraction have been a hot focus of interest. The focusing of electromagnetic waves using a flat lens was first proposed by Pendary and realized by Smith et al. [2,3]. There are two cases when one achieves negative refraction: the first case is the above-mentioned LHM having the simultaneous negative permittivity ε and negative permeability μ. In this case, $\boldsymbol{k}$, $\boldsymbol{E}$ and $\boldsymbol{H}$ form a left-handed set of vectors, i.e. $\boldsymbol{S} \cdot \boldsymbol{k} < 0$ (i.e. the pointing vector $\boldsymbol{S}$ and the wave vector $\boldsymbol{k}$ are in opposite directions). The other type is based on a photonic crystal (PtC) that has an effective refractive index controlled by the band structure [10,11], and the properties are similar to the right-handed medium, i.e. $\boldsymbol{S} \cdot \boldsymbol{k} > 0$. Therefore, the negative refraction can be realized without employing a negative index or a backward wave effect.

Very recently, these investigations in electromagnetic materials have been extended to acoustic and elastic media, and the acoustic and elastic LHMs have been proposed through phononic crystals (PnCs) by many researchers [12–18]. The negative refraction was realized by a metamaterial slab with simultaneously negative mass density and modulus [19–21]. Most of the studies were also devoted to PnCs with solid scatterers immersed in a fluid (liquid or air) matrix, in which only longitudinal waves propagate [16–18] and the negative refraction is observed at the lowest valence band. Single mode and high transmission are the advantages of the negative refraction in the lowest valence band. This negative index PnC can help us to break the diffraction limit and realize the focusing of the waves by a flat superlens [16]. The waves generated from a source include propagating waves and evanescent waves. These latter carry the subwavelength details of the source and can be amplified by the lens made of a negative index material; therefore, a subwavelength imaging is achieved. This kind of lens is expected to have significant applications such as coupling or integration with various types of acoustic devices. Ke et al. [22] studied two-dimensional (2D) phononic crystals made of stainless steel rods immersed in water and assembled in a triangular crystal lattice. Recently, Alexey Sukhovich et al. [16] experimentally studied this kind of structure and confirmed the existence of negative refraction phenomenon. They obtained negative refraction by employing circular equi-frequency surfaces (EFSs) in the second band. Liu et al. [23] extended the study of negative refraction imaging effect to a 2D three-component phononic crystal consisting of square arrays of coated cylinders in a liquid matrix. High-intensity-focused ultrasound is a new kind of noninvasive treatment technology. Therefore, achieving high-quality near-field medical imaging is significant. For this kind of applications, it seems necessary to consider a structure that can be easily handled; and it is more appropriate to consider a PnC slab made of a solid matrix rather than of a fluid one. As it is well known, negative refraction phenomena in PnCs made of solid matrices are more complex due to the coupling of the longitudinal and transverse waves [24–28]. Vasseur et al. [25] experimentally evidenced the negative refraction of longitudinal waves in a 2D PnC with a solid matrix. Hladky-Hennion et al. [28] theoretically and experimentally investigated a PnC slab made of a single metallic phase and displayed perfect negative index matching and focusing capability when surrounded with water. Very recently, Zhou et al. [29] studied the acoustic super focusing and imaging by a general isotropic solid acoustic metamaterial and discussed the influence of the shear modulus on the spatial focusing resolution. Addouche et al. [30] demonstrated super resolution imaging of surface acoustic waves using a phononic structure; and they also described an all-angle negative refraction effect of surface acoustic waves in two-dimensional phononic crystals [31].

As for chiral phononic crystals, Spadoni et al. [32] have investigated the dispersive properties of chiral-like systems; Zhu et al. [33] presented a solid chiral microstructure capable of achieving sub-wavelength negative refraction of elastic waves. In this paper, we propose a kind of square chiral lattice structure made by etching periodic vacuum holes in a homogeneous solid matrix. The superlens is surrounded with a biological fluid like water; and the water is just in contact with outside surfaces of the constructed slab [28]. To the best of our knowledge, most negative refraction images reported in the literature were implemented with square-symmetrical configurations. There are few reports on rotationally symmetrical (chiral) structures for focusing the acoustic waves. The lattice structure proposed in the present paper consists of four zigzag bending arms connected through a thin circular ring at the central part. Wang et al. [34] proposed several kinds of 2D square zigzag lattice structures and verified that the bending arms can depress the bands. We show in this paper that based on this feature, a flat band can be found in the low-frequency region and a M-centered EFS is indeed obtained. In

Please cite this article in press as: S.-D. Zhao, Y.-S. Wang, Negative refraction and imaging of acoustic waves in a two-dimensional square chiral lattice structure, C. R. Physique (2016), http://dx.doi.org/10.1016/j.crhy.2016.02.003