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Nonlinear propagation and control of acoustic waves in phononic superlattices

Propagation non linéaire et contrôle des ondes acoustiques dans les super-réseaux phononiques

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ABSTRACT

The propagation of intense acoustic waves in a one-dimensional phononic crystal is studied. The medium consists in a structured fluid, formed by a periodic array of fluid layers with alternating linear acoustic properties and quadratic nonlinearity coefficient. The spacing between layers is of the order of the wavelength, therefore Bragg effects such as band gaps appear. We show that the interplay between strong dispersion and nonlinearity leads to new scenarios of wave propagation. The classical waveform distortion process typical of intense acoustic waves in homogeneous media can be strongly altered when nonlinearly generated harmonics lie inside or close to band gaps. This allows the possibility of engineer a medium in order to get a particular waveform. Examples of this include the design of media with effective (e.g., cubic) nonlinearities, or extremely linear media (where distortion can be canceled). The presented ideas open a way towards the control of acoustic wave propagation in nonlinear regime.

RÉSUMÉ

La propagation d'ondes acoustiques intenses dans un cristal phononique à une dimension est étudiée. Le milieu consiste en un fluide structuré, formé par un réseau périodique de couches fluides dont les propriétés acoustiques linéaires ainsi que le coefficient de non-linéarité quadratique sont alternés. L'espacement entre les couches est de l'ordre de la longueur d'onde ; en conséquence, des effets de type Bragg tels que des bandes interdites apparaissent. Nous montrons que l'interaction entre la dispersion forte et la non-linéarité conduit à de nouveaux scénarios de propagation d'ondes. Le processus classique de distorsion de la forme d'onde, typique des ondes acoustiques intenses dans les milieux homogènes, peut être fortement altéré quand des harmoniques générées de manière non linéaire se retrouvent à l'intérieur des bandes interdites ou au voisinage de celles-ci.

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Ceci offre la possibilité de façonner un milieu de manière à obtenir une forme d'onde particulière. Les exemples donnés incluent la réalisation de milieux avec des non-linéarités effectives (par exemple, cubiques), ou de milieux extrêmement linéaires (où la distorsion peut être annulée). Les idées présentées ouvrent la voie au contrôle de la propagation des ondes acoustiques en régime non linéaire.

1. Introduction

One of the most celebrated effects of wave propagation in periodic media is the appearance of forbidden propagation regions in the energy spectrum of electrons, or band gaps. Most of the physics of semiconductors, and therefore many electronic devices, are somehow based on this concept [1]. In the late 1980's, these ideas where extended by Yablonovich and John [2] to light waves (electromagnetic waves in general) propagating in materials where the optical properties like the index of refraction were distributed periodically. These materials were named, by analogy with ordered atoms in crystalline matter, as photonic crystals. The typical scale of the periodicity is given by the wavelength. Actually, not only light but any wave propagating in a periodic medium may experience the same effects, and acoustic waves are not an exception. Sound wave propagation in periodic media has become very popular in the last 20 years in acoustics, after the introduction of the concept of sonic crystals [3]. Exploiting the analogies with other types of waves many interesting effects, as the above-mentioned forbidden propagation bands (band gaps), but also focalization, self-collimation, negative refraction, and many others have been proposed. We consider in this paper the simplest case of plane waves propagating in a 1D structure, formed by a periodic alternation of layers with different properties. Depending on the context, such a structure has been named a multilayer, a superlattice (particularly in the context of semiconductors) or a 1D phononic crystal (this include more exotic structures, as the granular crystal or lattice [4]).

The huge majority of the studies considered so far have assumed a low-amplitude (linear) regime, neglecting the nonlinear response of the medium. Intense wave propagation in nonlinear periodic media, and in particular the case of sound waves, is almost unexplored. In this paper, we present new phenomena related to acoustic wave propagation in a 1D periodic media, where both layers have a nonlinear quadratic elastic response. Nonlinear acoustic effects in such a structure have been studied only in a few works. In [5], the harmonic generation process is described in a fluid/fluid multilayered structure (water/glycerin), based in a nonlinear wave equation. Also, acoustic solitons in solid layered nonlinear media have been presented in [6]. The complementary action of nonlinearity and periodicity has been considered in [7], where an asymmetric propagation device (acoustic diode) was proposed. There, the nonlinearity and the periodicity effects on propagation are produced at different locations and its effect is considered separately. Recently, the authors studied the conditions for the efficient generation of a narrow, nondiverging beam of second harmonic in [8].

The physical phenomena discussed in this paper are the result of the interplay between nonlinearity and periodicity. Harmonic generation effects in nonlinear monoatomic (granular) lattices were recently reported by some of us in [4]. Here we describe how the geometrical and acoustic parameters of the structure can be used to control the harmonic distortion processes in a multilayer. The particular conditions required to selectively act on the nonlinearly generated spectrum, and therefore manipulate the waveform in the specific way, are presented and discussed.

The theory presented here has been developed for fluid–fluid (scalar) structures; however, the main conclusions are extendable to fluid–solid or to solid–solid multilayers, if particular conditions are given. Also, the main conclusions of this paper are independent of the frequency regime and the propagation medium of the waves (audible, ultrasound...), and therefore of the size or scale of the structure. Specially interesting is the domain when ultrasound waves belong to the Terahertz regime, where these ideas may find a great potential. The progress in miniaturization and the technological development allows us currently to create phononic multilayers at scales even in the nanometer range (each layer contains then a small number of atoms). This structures are usually made of semiconductors and are often used in particular applications as phononic mirrors to form phonon nanocavities [9], or microcavities to obtain a strong optomechanical coupling [10] (for a survey, see [11]). In a remarkable recent achievement, acoustic amplification was realized in doped GaAs/AlAs superlattices, where a SASER (Sound Amplification by the Stimulated Acoustic phonon Radiation) was demonstrated, in a device including a superlattice gain medium and GaAs/AlAs SLs acoustic mirrors [12].

The structure of the paper is as follows: in Sec. 2, we present the model for nonlinear propagation of acoustic waves in periodic media. The next Sec. 3 describes the process of harmonic generation in homogeneous media, and how it is modified by the presence of periodicity. In Sec. 4, the manipulation of the spectrum of a propagating sound wave by tuning the parameters of the layered medium is discussed. Examples of a particular case, as the case of a cubic-effective medium made out of quadratically nonlinear layers are shown. Finally, Sec. 5 presents the conclusions.

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