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Phononic crystals / Cristaux phononiques

Three-dimensional ultrasonic colloidal crystals

Cristaux colloïdaux ultrasonores tridimensionnels

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A B S T R A C T

Colloidal assembly represents a powerful method for the fabrication of functional materials. In this article, we describe how acoustic radiation forces can guide the assembly of colloidal particles into structures that serve as microscopic elements in novel acoustic metadevices or act as phononic crystals. Using a simple three-dimensional orthogonal system, we show that a diversity of colloidal structures with orthorhombic symmetry can be assembled with megahertz-frequency (MHz) standing pressure waves. These structures allow rapid tuning of acoustic properties and provide a new platform for dynamic metamaterial applications.

R É S U M É

L'assemblée colloïdale représente une méthode puissante pour la fabrication de matériaux fonctionnels. Dans cet article, nous décrivons comment les forces de rayonnement acoustique peuvent guider l'assemblage de particules colloïdales dans des structures qui servent d'éléments microscopiques dans les dispositifs à base de méta-matériaux acoustiques ou se comportent comme des cristaux phononiques. En utilisant un simple système orthogonal tridimensionnel, nous montrons que nombre de structures colloïdales à symétrie orthorhombique peuvent être assemblées, avec des ondes de pression stationnaires fonctionnant à des fréquences de l'ordre de quelques mégahertz (MHz). Ces structures permettent un ajustement rapide des propriétés acoustiques et fournissent une nouvelle plate-forme pour les applications de métamatériaux dynamiques.

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1. Introduction

Photonic crystals have caused a paradigm-shift in the field of photonics, starting with the seminal work of Eli Yablonovitch[1] published in 1987 [1] when these materials had never been manufactured, and were not known by that name. The concept of phononic crystals for sound waves followed a few years later. Photonic and phononic crystals share many common features, including the fact that they have both periodic internal structures. The effect of photonic crystals on light waves and phononic crystals on sound waves has been widely discussed. Today, photonic crystals appear in many areas of science, technology, medicine, and have also been discovered to be a product of nature in the biological world. There are also many potential applications of phononic crystals, and recent interest in these structures stems from the possibility of gaining previous unheralded control of sound waves, for example, controlling the path of waves leads to incredibly efficient lenses [2] or invisibility cloaking [3,4] and controlling their transmission and reflection leads to highly efficient filters [5], diodes [6–8] or super absorbers [9].

In many situations, it is highly desirable to have the ability to tune the acoustic properties of such materials by physical means. Colloidal assembly represents a powerful bottom-up approach for the fabrication of functional materials, and simple three-dimensional crystalline structures can be created by self-assembly, within the physical and thermo-dynamical confines of the system. Here, a colloidal crystal [10] stands for an ordered array of monodisperse colloidal particles, similar to a crystal in which repeating unit cells are atoms or molecules. In acoustics, colloidal crystals have established applications as phononic crystals [11–13], and this is the focus of this paper. Bulk properties of colloidal crystals depend on composition, particle size, packing arrangement, and degree of regularity. While the particle shape, size, volume fraction, charge, solvent screening lengths, *etc.* are important control parameters for colloidal phononic crystal experiments, none of them affords active control.

Acoustic radiation forces provide a convenient and effective tool for the assembly of colloidal particles into periodically arranged crystals and open up the possibility of tuning the diffraction of phononic structures. Active tunability can be achieved by tailoring the lattice of the crystal, providing new opportunities for fundamental as well for applied research. Here, we present an overview of how colloidal structures can be assembled using acoustic radiation forces, and how the phononic properties of the resulting structures can be reconfigured and reversibly tuned by manipulating the acoustic force fields.

The organisation of the paper is as follows. We start by explaining how acoustic radiation forces can be used to trap and manipulate spherical microparticles in a fluid with megahertz-frequency (MHz) ultrasound waves. Here, we consider the case of standing and quasi-standing pressure waves created by a pair of transducers or a single transducer positioned opposite to a reflector. Then, combining two or three pairs of opposing transducers we discuss the diversity of colloidal structures that can be assembled using these as orthogonal systems. This results in a fully controllable colloidal crystal made of particles trapped in a reconfigurable pattern. The acoustophoretic motion of an agglomerate of fluid or solid particles suspended in aqueous solution is discussed; this closely mimics experimental particle tracing and velocimetry. Based on knowledge of the particle trajectories, an estimate of the theoretical reconfiguration time is presented.

2. Acoustic assembly of colloidal crystals

We have recently reported on the realization of an acoustic metadevice [14] that can generate three-dimensional colloidal crystals, and demonstrated, for the first time, that it is possible to dynamically alter the geometry of the resulting crystal in real time. The reconfigurable colloidal crystal is assembled from microspheres in aqueous solution, trapped with acoustic radiation forces. The acoustic radiation force is governed by an energy landscape, determined by an applied high amplitude acoustic standing wave field, in which elastic particles move swiftly to energy minima. This creates a colloidal crystal of several cubic millilitres in volume with spheres arranged in an orthorhombic lattice in which the acoustic wavelength is used to control the lattice spacing.

The acoustic metadevice consists of two pairs of opposing parallel transducers, along with a single transducer, positioned on the base of the device in order to hold particles against gravity, Fig. 1. The levitation system, arranged vertically, lifts the particles and holds them in horizontal planes, while the manipulation system, uses counter-propagating waves to trap the particles in a grid of nodal positions. The generated acoustic landscape exerts an acoustic radiation force on the particles. The force is a second order nonlinear effect and stems from a combination of the time averaged pressure and inertial interaction between the particles and the acoustic field. It is this force that allows trapping of suspended particles at nodes or antinodes of that wave, depending on their radius as well as the compressibility and mass density of the particles and the host fluid. In the following, we expand on this narrative, and show the diversity of colloidal structures that can be assembled using a three-dimensional orthogonal system.

[1] Given the plethora of applications, it is not surprising that he has recently received the Isaac Newton Medal from the Institute of Physics, for his contributions to the field of photonics.