PHONONICS 2015: 3nd International Conference on Phononic Crystals/Metamaterials, Phonon Transport and Phonon Coupling

Paris, France, May 31-June 5, 2015

PHONONICS-2015-0453

Efficient Second Harmonic Generation of Narrow Beams in 2D Sonic Crystals

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Abstract: In this paper we report the efficient second harmonic generation in 2D sonic crystals with quadratic nonlinearity. We design and we test numerically the proposed structure with tuned parameters using the nonlinear FDTD method and we show the high conversion efficiency of the second harmonic, as well as the possibility to generate narrow beams of second harmonics and enhancement of sound control.

A high amplitude acoustic wave travelling in a fluid develops higher harmonics as it propagates through the medium. In a homogeneous fluid, such nonlinearly generated harmonics grow during propagation because of the lack of dispersion. The presence of a periodic distribution of scatterers, or 2D sonic crystal (SC) introduces strong dispersion in the wave propagation. It can create bandgaps if the wave propagation at particular frequencies is not allowed. The combination of the effects of nonlinearity (harmonic generation) and periodicity (different phase speed for the different harmonics and evanescent waves) results in a tremendous ability in manipulating sound waves like self-collimation, focalization, negative refraction… etc, which are not available in natural materials. Among the practical applications of the sound propagation in a nonlinear medium, the second harmonic generation seems to be particularly relevant[1,2]. In a nonlinear, nondispersive acoustic medium, a propagating high-amplitude harmonic wave transforms into a shock wave. The process can be also understood as the growth of harmonics, initially absent, during the propagation due to cumulative energy transfer[3]. For most common homogeneous nonlinear media, the acoustic energy transfer between the fundamental wave (FW) and the generated second harmonic (SH) is very efficient due to the weak dispersion and (as a consequence) the phase matching between the Bloch modes corresponding to FW and SH beams. However, for a strongly dispersive medium, like a periodic medium, the energy transfer between the FW and SH depends not only on the local nonlinearity of the medium but also on the phase matching conditions between both fields[4] that, in general, are not fulfilled. As a result, the generated SH field no longer grows linearly with propagation. Therefore three necessary simultaneous conditions have to be fulfilled for an efficient SH generation in a periodic medium: 1) self-collimated propagation for both FW and SH beams, 2) phase matching of both interacting waves and 3) a sufficient spatial coupling between the corresponding FW and SH Bloch modes. The self-collimation or non-diffraction regime is necessary for both FW and SH wave beams to avoid the spread of energy by spatial dispersion[5,6]. Moreover, in order to obtain efficient nonlinear interaction, phase matching and sufficient spatial coupling should also be ensured.

Here we consider a 2D sonic crystal with square symmetry, consisting of a periodic distribution of rigid cylinders as scatterers immersed in water. We study systematically the SH generation process in the proposed structure and we proceed as follows: in a first step, we calculate using the Plane Wave Expansion (PWE) method the dispersion relations (frequency versus wave vector), the band diagrams and isofrequency contours of the designed 2D periodic structure. Secondly, we search for the simultaneous fulfillment of the two basic conditions, that is, self-collimation (corresponding to flat regions in the isofrequency contours) and phase matching for both frequencies, FW and SH. The results are

summarized in Fig. 1. Third, we estimate by using again the PWE method, the spatial nonlinear coupling of Bloch modes corresponding to the FW and SH fields. We show that this condition, together with self-collimation and phase matching, is necessary for an efficient SH generation. Finally, we perform Finite-Differences in Time-Domain (FDTD) simulations of the full nonlinear problem, considering that, up to second order, the host fluid presents quadratic nonlinearity. We demonstrate indeed that the SH generation of acoustic narrow beams is efficient. The calculated beam profiles are shown in Fig. 2. For the proposed 2D crystal, the simulations of the nonlinear problem show that at long distances the SH generation of narrow beams is even more efficient than for plane waves in homogeneous materials.

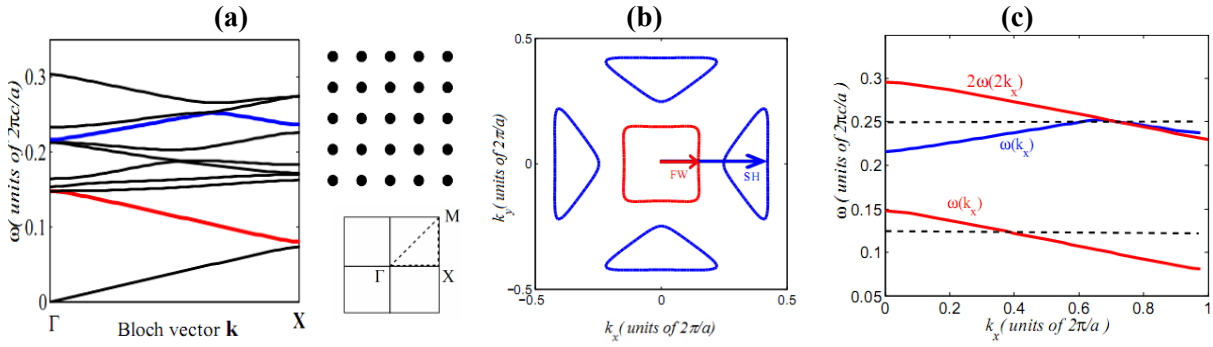


Figure 1 (a) Band structure obtained by the PWE method for a square lattice 2D SC made of rigid cylinders immersed in water. Red and blue lines mark the bands (2nd and 8th) for which simultaneous non-diffractive propagation in Γ-X direction is expected for both FW and SH respectively, **(b)** Isofrequency contours for the 2nd band and the 8th band, **(c)** Dispersion curves for simultaneous self-collimation of FW (red contour) and SH (blue contour).

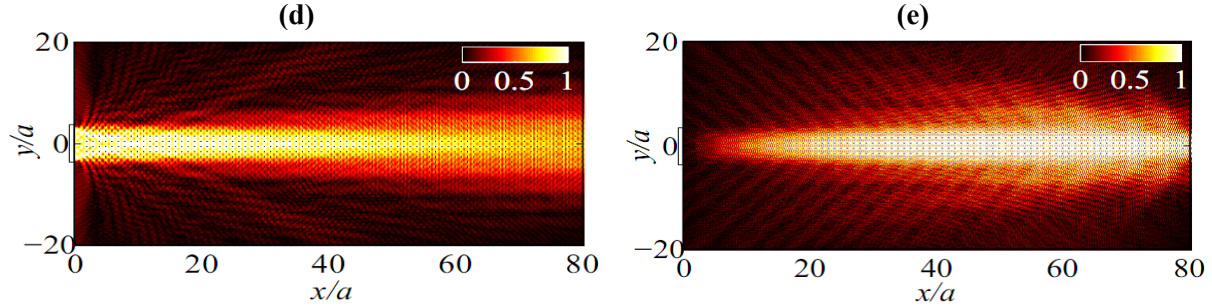


Figure 2 Nonlinear FDTD results of the spatial pressure field distribution of FW **(d)** and SH **(e)** in the 2D SC when the three conditions of SH generation are fulfilled. Color-bar indicates the normalized units.

Acknowledgments: EL-M.Hamham acknowledges EU-EMMAG program for his postdoctoral fellowship and L.M.García-Raffi acknowledges support by MINECO and FEDER, under Grant MTM2012-36740-c02-02.

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