Proof of Concept for an Ultrasensitive Technique to Detect and Localize Sources of Elastic Nonlinearity Using Phononic Crystals

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The appearance of nonlinear effects in elastic wave propagation is one of the most reliable and sensitive indicators of the onset of material damage. However, these effects are usually very small and can be detected only using cumbersome digital signal processing techniques. Here, we propose and experimentally validate an alternative approach, using the filtering and focusing properties of phononic crystals to naturally select and reflect the higher harmonics generated by nonlinear effects, enabling the realization of time-reversal procedures for nonlinear elastic source detection. The proposed device demonstrates its potential as an efficient, compact, portable, passive apparatus for nonlinear elastic wave sensing and damage detection.

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In recent years, phononic crystals (PCs) have attracted great attention due to their unconventional dynamic behavior, with effects such as negative refraction [1], frequency band gaps [2,3], wave filtering or focusing [4–6], acoustic cloaking [7–9], subwavelength sensing [10,11], etc. Their periodic structure, rather than single material constituents, is responsible for their behavior, which exploits Bragg scattering [12,13]. Their attractive properties to act as stop-band filters [12] or to concentrate energy in selected frequency ranges [14] makes them potentially interesting for nonlinear elastic source detection and to reveal the presence of defects, e.g. cracks, in a sample. This is because, in general, a nonlinear response is generated at the defect location and several possible features may appear, including the generation of higher order harmonics [15–17] or subharmonics [18,19], the nonlinear dependence of the elastic modulus and of attenuation coefficients on strain [20–22], and, as a consequence, the shift of the resonance frequency with increasing excitation amplitude [23,24] and the failure of the superposition principle [25,26]. All of these possible signatures can be used to detect and monitor the presence and evolution of damage, exploiting the greater sensitivity of nonlinear detection techniques compared to conventional linear ones [27].

In the past years, nonlinear imaging techniques such as *b* scan, *c* scan, and tomography [28] have attracted much interest. A particularly robust and efficient approach is the combination of time reversal (TR) and nonlinear elastic wave spectroscopy (NEWS). This technique (TR-NEWS) exploits space-time focusing of the wave field achieved in TR [29] and applies it to a defect acting as a source of nonlinear elastic waves [30–33]. The scattered signal is recorded, the frequency generated by the primary source is filtered out using a bandpass filter, and the resulting signal is time reversed and reinjected by the receiver: due to the ($t \rightarrow -t$) symmetry, the wave field back propagates to its original (nonlinear) source, focusing energy at the defect location at a specific time. Many studies have proved the efficiency and robustness of TR-NEWS in various configurations, for different types of nonlinear sources [34–36] and in assorted experimental conditions [31]. However, TR-NEWS relies—as do most of the techniques for both the detection and the location of damage—on extensive signal manipulation (normally, digital filtering), which might be critical in the case of short signals and/or when continuous signal acquisition is required (such as in acoustic emissions). Furthermore, the nonlinear components of the wave field are often very small, if not submerged by the noise level, making it difficult to detect and estimate them. The concept adopted in this Letter overcomes these limitations, combining TR-NEWS and phononic crystals in order to introduce a technique capable of filtering out and concentrating energy in target frequency ranges. We experimentally demonstrate the feasibility and the efficiency of this technique, providing the proof of concept for an ultrasensitive phononic crystal device to detect and localize nonlinear elastic sources such as cracks or delaminations.

A schematic representation of the experimental setup is given in Fig. 1. The sample is a pristine $300 \times 300 \times 3\ \mathrm{mm}^3$ aluminum plate (the density $\rho = 2700\ \mathrm{kg/m}^3$, the Young's modulus $E = 70$ GPa, and the Poisson's ratio $\nu = 0.33$),