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Broadband Acoustic Non-reciprocity in a Passive, Nonlinear Metamaterial

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Abstract: The paper presents a numerical study on a periodic triangle-shaped structure that breaks reciprocity passively over a broad range of frequency and energy, while preserving the frequency content of the signal. The proposed structure contains strong nonlinearity and geometric asymmetry that contributes to a direction-dependent dispersion relationship.

Introduction

Acoustic reciprocity, which is widely observed in linear time-invariant systems, refers to the property that wave transmission pattern remains the same when the source and receiver are switched. Non-reciprocity, on the other hand, violates this symmetry and can be used to control wave propagation and manufacture desired propagation patterns. To break reciprocity, multiple approaches (active and passive) have been studied recently. While active manner often relies on odd-symmetry field or time-variant parameters, passive manner achieves non-reciprocity by combining geometric asymmetry and nonlinearity in the structure. In this field, researchers have studied a number of acoustic devices that allow one-way propagation[1, 2]. However, these devices either change the frequency content of the sending signal, or have a strict restriction on the range of sending frequency. In this paper, we propose a passive, nonlinear, periodic structure, which achieves giant non-reciprocity for a range of input frequency and energy with minimal distortion of the sending frequency.

System Description

The proposed system, depicted in Fig. 1, consists of 5 nonlinear unit cells sandwiched by two identical waveguides. Each nonlinear unit cell contains 16 masses coupled by linear springs, cubic springs and dampers. The system is a shear lattice, and it has an up-down symmetry so that the wave propagation is one-dimensional. Depending upon the propagating direction, the two waveguides are named sending waveguide and receiving waveguide, respectively. System parameters are provided in Table 1.

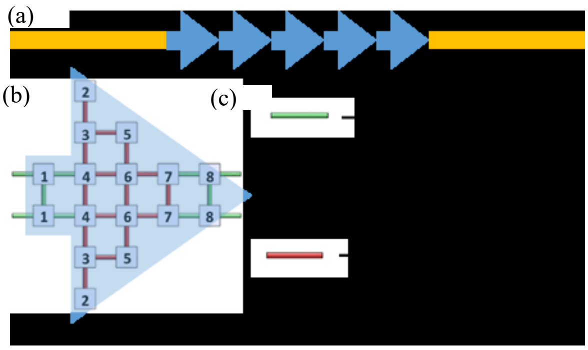

Figure 1 A schematic of (a) the system (b) an isolated unit cell and (c) the spring-damper model for the coupling

The input signal is generated by a continuous harmonic oscillation in a force control at the start of the sending waveguide. We stop the simulation before the reflected wave interferes with the source to ensure the input energy for L-R and R-L are the same.

Parameter	m_1, m_3, m_6 & m_8	m_2	m_4	m_5	m_7
Value	0.05 kg	0.0616 kg	0.0733 kg	0.07 kg	0.3911 kg
Parameter	k_1 (Between 1 & 4)	k_1 (Others)	k_2	k_{NL}	c
Value	400 N/m	200 N/m	20 N/m	2 E9 N/m^3	0

Table 1 System parameters in SI unit.

Analysis Approach

This section contains two parts: i) a numerical approach to calculate the dispersion relationship of the nonlinear unit cells domain[3] and ii) a quantification measure for non-reciprocity. To obtain the dispersion relationship, we fix the amplitude of the sending signal and sweep its frequency. At each frequency, we apply the Fast Fourier Transformation (FFT) over the steady-state responses of mass 1 from two adjacent nonlinear unit cells. For each mass, the FFT reveals the dominant frequency and corresponding amplitude and phase. The phase difference then leads to the real part of the wave-number.

To quantitatively study non-reciprocity, we provide a possible non-reciprocity measure here:

$$\delta = \frac{\int_O^T |E_i - E_j|\, dt}{\int_O^T |E_i + E_j|\, dt} \tag{1}$$

where T is the simulation time, E_i and E_j stands for the mechanical energy contained in the nonlinear unit cell close to the receiving waveguide for L-R and R-L, respectively. The non-reciprocity measure is bounded between 0 and 1, where 0 refers to reciprocal and 1 being perfectly non-reciprocal.

Results

The numerical results are displayed in Figure 2. In Fig. 2(a), we depict the dispersion curves of the nonlinear unit cells, and the measure of non-reciprocity at each input frequency. The blue lines denote L-R propagation, and red ones denote R-L. Note that in the diagram we only depict the acoustic and 1st optical branch for both direction. The other branches are sufficiently far from the region of interest. The horizontal bar represents the non-reciprocity measure at each frequency, and the color of the bars refers to the power of sending signals (since we fix the amplitude, the power increases as the frequency goes up). As shown, the L-R dispersion curves (both acoustic and 1st optical branch) rise higher, which creates giant non-reciprocity regions (highlighted in green boxes), where the frequency falls in the bandgap of R-L but pass-band of L-R. Figure 2(b) verifies the non-reciprocity by showing the time/frequency response of a signal whose frequency lying in the green box (shown as the black arrow in Fig. 2(a)). As documented in the time response plots, the wave propagates in L-R direction but not the other way. Note that the L-R transmitted wave preserves the sending frequency as indicated in the frequency response plots.

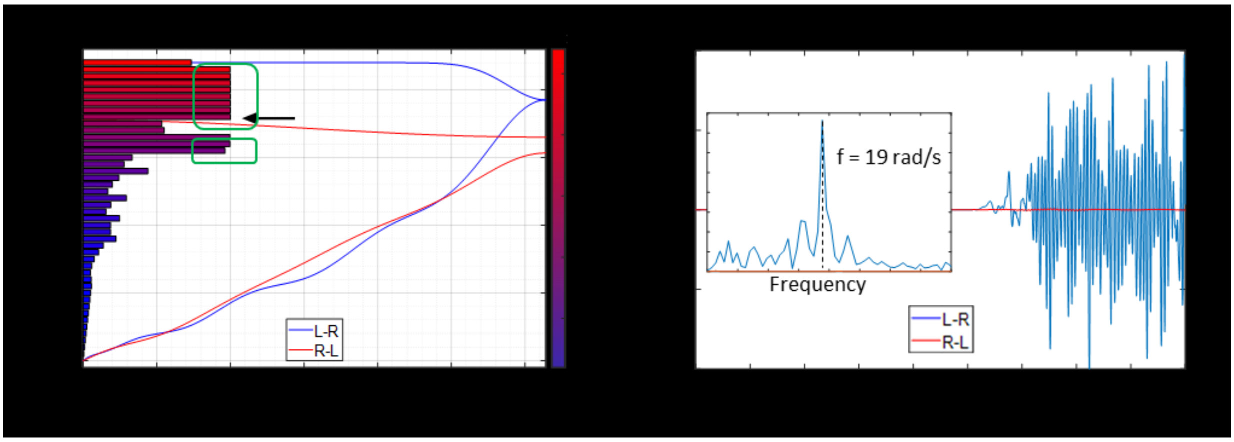

Figure 2 (a) The dispersion relationship of the nonlinear unit cells for L-R and R-L propagation and non-reciprocity measure. (b) The time/frequency response showing non-reciprocity.

Conclusions

The proposed system utilizes nonlinearity and geometric asymmetry to break acoustic reciprocity. The results show that giant non-reciprocity was achieved for a range of input frequency and energy, while the sending frequency is well-preserved.

References

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