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High-order topological states using alignment of different bandgaps in 1D superlattices

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ABSTRACT

Acoustic interface states have been evidenced in superlattices with frequencies at tens to hundreds of GHz. A recently demonstrated scheme to generate interface states in one-dimensional superlattices is based on the principle of band inversion, obtained by concatenating two periodic lattices with inverted spatial mode symmetries around the bandgap. Most of the realizations exploit a given bandgap for which there is one symmetry inversion. In this work, we present high-order topological nanophononic interface states in multilayered structures, achieved by concatenating two superlattices with different bandgap orders centered around the same frequency. In this case, inverted mode symmetries are not required to achieve the interface state, which is enabled by modifying the unit cells of the two superlattices. We showcase designs for versatile topological devices where interface states can be simultaneously created across a wide frequency range. The topological modes can be experimentally accessed in Brillouin or pump-probe experiments. The ability to explore higher bandgap order acoustic interface states in the GHz range is unique in nanophononic superlattices due to the linear dispersion relation of acoustic phonons. The demonstrated systems can thus be exploited to investigate schemes that are difficult or impossible to study in electronics or optics, due to their non-linear dispersion relations.

Keywords: Nanophononics, interface states, band inversion, 1D superlattices, one-dimensional Su-Schrieffer-Heeger model, high-order bandgaps

1. INTRODUCTION

The study of periodic lattices with two elements in their unit cell, as characterized by the Su-Schrieffer-Heeger (SSH) model within the tight-binding approximation, marks a pivotal advancement in the creation of materials exhibiting topological properties.^{1,2} This breakthrough has paved the way for the exploration of topological states across a diverse range of excitations, including but not limited to photons,³⁻⁵ phonons,⁶⁻⁸ and polaritons,⁹⁻¹¹ highlighting the versatility and breadth of applications in the field. In the specific context of multilayered periodic lattices, such as distributed Bragg reflectors (DBRs), when concatenating two DBRs with inverted spatial mode symmetries around a gap, the emergence of topological interface states at the edges of high-reflectivity bandgaps has been demonstrated, further enriching the landscape of topological phenomena.^{8,12-14} This presents intriguing possibilities, as DBR or distributed feedback (DFB) mirror-based cavities are widely used in photonics applications, enabling high-quality and reliable cavities in various configurations.¹⁵⁻²⁴ Consequently, this may offer a promising avenue to seamlessly integrate topological structures with these established photonic technologies.

In recent years, the field of nanophononics has rapidly advanced holding significant potential to contribute in various relevant technological realms for practical applications.²⁵⁻³¹ Unlike the phenomena observed in optics or electronics, the unique linear dispersion relation of acoustic phonons allows for the exploration of topological interface states across a broad frequency spectrum, from tens to hundreds of GHz, showcasing an exceptional agreement between theoretical predictions and experimental observations.^{8,32-35} In this work, we extend the exploration of topological nanophononic interface states by engineering GaAs/AlAs DBRs with the same spatial mode symmetries across different high-order bandgaps. By concatenating two superlattices without band

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inversion, but having respectively an odd and an even bandgap aligned around the same frequency, we show that a robust interface state can be formed. Specifically, the first superlattice exhibits its third bandgap around 28 GHz, while the second superlattice has its second bandgap at this frequency. Our study highlights that inverted mode symmetries around the same bandgap, or different bandgaps without inverting symmetries can work interchangeably and have the same effect in generating interface states.

Benefiting from the linear dispersion relation, such nanophononic resonators can be used to engineer topological interface states at high order bandgaps. We provide here a specific example and analysis involving such topological states. This investigation opens avenues for exploring new physical phenomena within the topological domain. We believe that the emergent platform will enable the experimental mapping of foundational textbook scenarios, and inspire more complex topological structures in the future.

2. INTERFACE STATES AT HIGH-ORDER BANDGAPS

In the realm of topological superlattices, the concept of band inversion plays a critical role in the manifestation of topologically protected states. Band inversion occurs when two modes at the edges of a bandgap, characterized by opposite symmetries, reverse their energy ordering at an interface. This pivotal transition can be induced by fine-tuning the relative thicknesses of the two constituent layers within the superlattice’s unit cell. The concatenation of two distinct superlattices, each designed with layers of differing thicknesses—thus presenting inverted band structures—facilitates the emergence of topologically protected interface states. Such states are inherently robust, owing to their topological nature, and are immune to perturbations that do not close the bandgap.^{13,14,34}

The Zak phase, θ^{Zak} , serving as the one-dimensional (1D) counterpart to the Berry phase, offers a powerful method to characterize the topological properties of multilayered acoustic devices.^{36,37} Fundamentally, the formation of an interface state between two DBRs with opposing reflection phase signs, exemplifies a basic manifestation of topology in acoustics.^{12,13} The sign of the reflection phase, positive or negative, depends on the DBR’s specific configuration. For any given n^{th} bandgap, the sign of the reflection phase ($sgn(\phi)$) is determined by the formula:

$$sgn(\phi) = (-1)^n (-1)^l \times \exp\left(i \sum_{m=0}^{n-1} \theta_m^{Zak}\right), \quad (1)$$

where l represents the count of completely filled bandgaps beneath the n^{th} bandgap. This relation indicates that an interface state at the n^{th} bandgap is contingent upon the condition that the cumulative Zak phase ($\sum_{m=0}^{n-1} \theta_m^{Zak}$) aligns with $0 + 2p\pi$ for one DBR and $\sum_{m=0}^{n-1} \theta_m^{Zak} = \pi + 2p\pi, p \in \mathbb{N}$ for the other, where p belongs to the set of natural numbers (\mathbb{N}). It is important to note that the presence of an interface state within a particular bandgap does not guarantee its occurrence across other bandgaps, given the potential variability in the sum of θ^{Zak} values across different bands.

3. RESULTS AND DISCUSSION

A first demonstration that superlattices of different bandgap orders centered around the same frequency can be used to generate interface states has been provided by Rodriguez et al.⁸ It is crucial to understand that the principle of generating interface states is not universally applicable across bandgaps of different orders. We provide a characteristic demonstration of this in Figure 1. As illustrated in Fig. 1, an interface state arises when the modes flanking the bandgaps of interest exhibit identical symmetries in both superlattices. In this case one superlattice has its second bandgap aligned with the third bandgap of the second one. However, this is not the case if both DBRs have the same bandgaps aligned, or different bandgaps that are both odd or both even. This observation leads to a general rule: interface states are formed between an even and an odd bandgap when both display the same symmetries. Conversely, when concatenating two bandgaps that are both odd or both even, the creation of an interface state necessitates inverted symmetries between the two. The rationale behind this distinction lies not solely in the cumulative Zak phase contributions but also significantly in the order of the bandgap itself. The variation in the bandgap order introduces a nuanced complexity in the phase differences

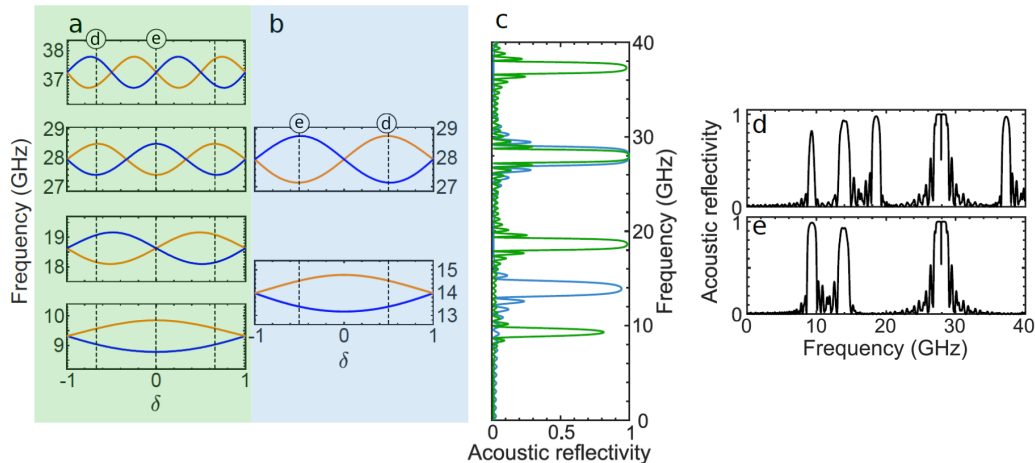


Figure 1. Illustration of the alignment of different acoustic bandgaps sharing the same frequency for two concatenated DBRs. (a, b) The third bandgap in superlattice a and the second bandgap in superlattice b exhibit identical central frequencies, demonstrating the alignment necessary for hybrid resonator formation. (c) Simulated acoustic reflectivity profiles for both DBRs, with the green and blue lines corresponding to panels a and b, respectively. (d, e) Simulated acoustic reflectivity spectra for two configurations of concatenated DBRs embedded within a GaAs matrix, with the ratio of the DBR unit cells, δ , indicated by the dashed lines in panels a and b.

of the reflection coefficient, underscoring the importance of both the Zak phase sum and the bandgap order in determining the possibility of interface state formation. This visualization highlights the reflective characteristics and frequency alignment of the two superlattices.

Topological interface states are renowned for their remarkable resilience against disorder, a feature that is critically advantageous for a variety of applications, notably in transport and flawless data communication.^{20,38,39} The principles described here, involving the generation of interface states either through band inversion or the combination of different bandgap orders around the same frequency, inherently maintain the central frequency of the bandgap despite potential variations in the unit cell ratio, δ . This robustness to any compositional inaccuracies, or even roughness, is integral to the construction of topological resonators. Such variations could naturally arise from factors like material intermixing or compositional inconsistencies during the epitaxial growth processes of superlattice layers.^{40,41} Our numerical analyses have confirmed that the interface mode’s robustness is consistently preserved across all studied bandgap orders, even when subjected to layer thickness ratio fluctuations, in agreement with Ref. 8.

In conclusion, through this study we have demonstrated a characteristic example elucidating the nuances involved in utilizing superlattices with differing bandgap orders around the same frequency. This investigation not only confirms the practical viability of utilizing this method for the development of topological resonators, but also accentuates the potential of superlattices as a refined tool for the exploration and exploitation of topological phenomena. Consequently, this opens up new pathways for innovative applications that leverage the unique properties of topological nanophononic interface states.

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