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Experimental Observation of Topological Fano Resonances for Audible Sound

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ABSTRACT

The Fano resonance is a widespread wave scattering phenomenon observed in many different systems, from cold atom physics, to electromagnetics, electronic circuits, and acoustics. It is characterized by a very sharp and asymmetric scattering cross-section spectrum that switches from a zero to a maximum value for two close by frequencies. Such extraordinary feature has established Fano resonances as the basic principle for many applications including efficient sources and emitters, switches, interferometers, or supersensitive sensors. Yet, these resonances are difficult to achieve in practice, as they require tight geometrical tolerances and large fabrication precision to guarantee their occurrence in the desired frequency range, and the absence of parasitic peaks. In this talk, we will discuss a route for leveraging one-dimensional topological insulators to generate a novel form of sturdy Fano resonances, and experimentally demonstrate their robustness for audible sound waves. Extension to other physical systems will be briefly discussed.

Keywords: Topological insulators, Fano resonances, Acoustics, Metamaterials.

1. INTRODUCTION

Fano resonance occurs as a result of constructive and destructive interferences between two resonating states: a continuous or “bright” state and a discrete, “dark” one. Such resonances, characterized by their asymmetric and ultra-sharp line shapes, have recently drawn considerable amount of attention for realizing a large variety of optical devices with unprecedented features, including ultra-compact electromagnetically induced transparency devices, highly efficient lasers, ultra-fast switches and modulators, ultra-sharp filters, ultrathin perfect absorbers, and highly precise interferometers [1]. The ultra-sharp line shape of the Fano resonance has further been of utmost interest in sensing applications. More specifically, the peculiar line shape of the Fano resonance has been found to be extremely sensitive to geometrical and environmental perturbations. This property has established a fertile ground for realizing ultra-sensitive and accurate sensors based on such resonances [2].

The extreme sensitivity of the Fano resonance, albeit useful for sensing, is often associated with vexing practical issues. In particular, it often implies tight geometrical tolerances and large fabrication precision to guarantee its occurrence in the desired frequency range, and the absence of parasitic peaks. As a result, the advantageous properties of Fano-based devices are often mitigated by the costs associated with the required

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fabrication technology.

In a seemingly unrelated field of research, topological insulators [3-7], materials with non-trivial topological orders, have been found to provide an unconventional robustness to perturbations. In fact, it has been widely demonstrated that edge modes flowing along the boundaries of such phases of matter are protected to certain classes of defects. Such protection has enabled realization of a broad range of classical wave devices with an unusual immunity against imperfections. Following these advances, an important question naturally arises: Can the abstract concept of topology also be leveraged for building a novel form of Fano resonances with strong robustness to disorder? In this contribution, we answer positively to this question, reporting our recent findings on the observation of a novel class of sturdy Fano resonances, dubbed as *topological Fano resonances* [8].

2. TOPOLOGICAL FANO RESONANCES

To achieve topological Fano resonances, we consider the configuration shown in Fig. 1a, consisting of an acoustic waveguide in which a Su-Schrieffer-Heeger (SSH) array [9] of cylindrical obstacles is implemented. Considering the reflection symmetry of the structure with respect to the centerline of the waveguide, one can divide the corresponding modal solutions into even and odd types. Likewise, the edge modes of the SSH array are either even or odd with respect to the centerline of the guide. The odd edge mode, originating from the so-called bound states in the continuum, is completely decoupled from the continuum of waveguide modes and serves as a discrete (dark) state. The even edge mode, on the contrary, originates from multiple scattering of sound, and serves as the slowly varying background state. By slightly breaking the reflection mirror symmetry of the system, these two topological edge states can couple to each other. This creates the Fano line shape as shown in the inset of Fig. 1a. The corresponding mode profiles of the dark and bright edge states are also shown in the inset.

Since the existences of dark and bright edge modes are guaranteed by the topological properties of the surrounding insulators, the Fano line shape inherits some form of immunity against disorder. To demonstrate such salient feature, we randomly change the position of the cylinders and calculate the corresponding transmission coefficient (Fig. 1b). As it is observed in the figure, the Fano resonance is still preserved, constituting an evidence of its strong robustness to disorder.

Based on these findings we built a prototype to experimentally demonstrate topological Fano resonances and validate their robustness (Fig .2a). The sample is built from an plexiglass pipe, guiding sound waves, and nylon plastic cylindrical rods which are manually put on their specific places inside the waveguide. The waveguide is excited with a loudspeaker, and the corresponding transmitted pressure field is measured. The bottom panel of the figure illustrates the measured transmission coefficients, extracted from analyzing the corresponding standing wave pattern. As we expected from our numerical findings, the interferences between the dark and bright edge modes creates a Fano-like resonance around the frequency 2.2 kHz. In order to study the effect of disorder on the Fano line shape, we randomly move some of the obstacles from their original places as seen in Fig. 2b, and repeat our scattering test. Inset of the figure shows the corresponding transmission coefficient. It is seen that the Fano line shape is still present and no parasitic peaks are introduced to the spectrum. Yet, the Fano line shape can still shift, holding great promises for sensing applications.

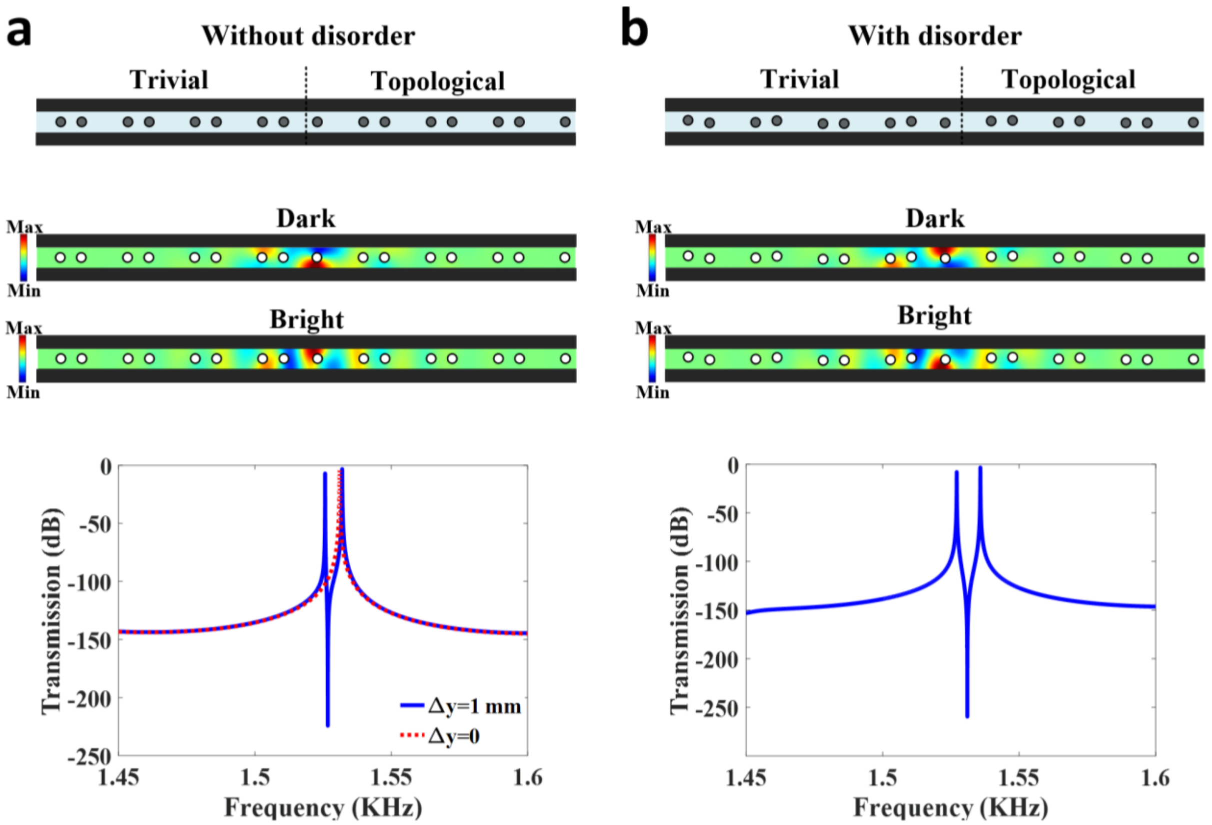

Fig.1: Topological Fano resonances, (top) A SSH array of cylinders is implemented inside an acoustic waveguide. (Middle) Profiles of the corresponding even and dark edge states, (bottom) Transmission Spectrum of the waveguide, manifesting the Fano line shape around 1.5 kHz. b, Same as a) except that some disorder is added to the sample. The Fano line shape shows strong immunity against disorder.

3. CONCLUSIONS

In summary, we showed how topology, the mathematics of conserved quantities under continuous deformation, can be leveraged to form a new form of sturdy Fano resonances, dubbed as topological Fano resonances, with an unprecedented robustness against geometrical tolerances. While we observed such type of resonances in acoustics, topological Fano resonances can also be observed in other physical platforms. For instance, by implementing a SSH array of dielectric rods inside a conventional microwave waveguide, one can realize topological Fano resonances based on electromagnetic waves. These findings altogether hold great promises for a new generation of acoustic device such as switches, sasers, modulators, etc., thereby enriching the toolkit of modern acoustic engineering [10-15].

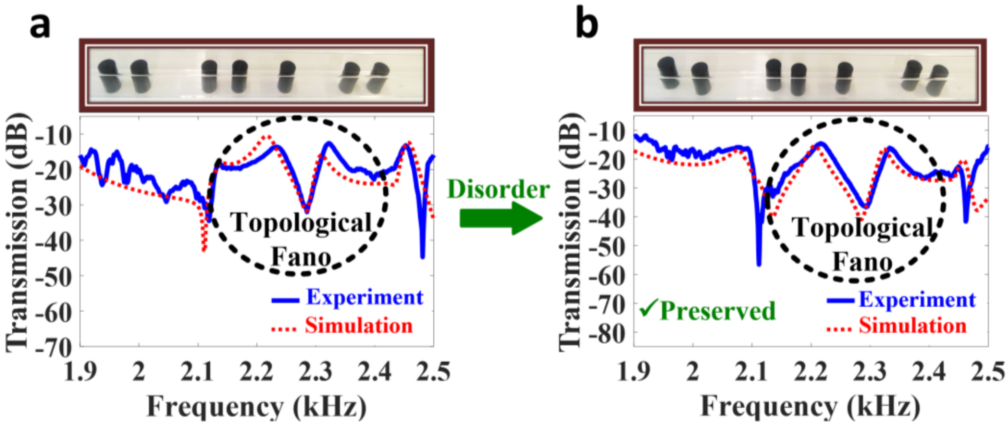

Fig. 2: Experimental demonstration of topological Fano resonances for audible sound, a, (top) A SSH array of nylon plastic cylindrical rods is implemented inside a pipe made of acrylic glass. (bottom) The spectrum exhibits the Fano line-shape caused by the interference between the bright and dark edge modes. b, Same as panel a except that some disorder is added to the configuration.

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