Topological optomechanically induced transparency

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

The interaction of optical and mechanical degrees of freedom can lead to several interesting effects. A prominent example is the phenomenon of optomechanically induced transparency (OMIT), in which mechanical movements induce a narrow transparency window in the spectrum of an optical mode. In this Letter, we demonstrate the relevance of optomechanical topological insulators for achieving OMIT. More specifically, we show that the strong interaction between optical and mechanical edge modes of a one-dimensional topological optomechanical crystal can render the system transparent within a very narrow frequency range. Since the topology of a system cannot be changed by slight to moderate levels of disorder, the achieved transparency is robust against geometrical perturbations. This is in sharp contrast to trivial OMIT which has a strong dependency on the geometry of the optomechanical system. Our findings hold promises for a wide range of applications such as filtering, signal processing, and slow-light devices.

Electromagnetic induced transparency (EIT) is a phenomenon arising from the constructive and destructive interferences between two different optical modes, leading to the cancellation of the light absorption within a very small spectral range called transparency window [1-3]. In the transparency window, the absorption spectrum varies very rapidly. According to the Kramers-Kronig [4] relations, such an abrupt change of the absorption coefficient comes with a rapid change of the refractive index. This gives rise to a significant reduction in the group velocity of light, enabling exciting applications such as optical buffering [5,6], photonic quantum memory [7,8], optical rotation sensing [9,10], and data synchronization [11,12].

So far, various approaches have been proposed to achieve electromagnetic induced transparency. One common and established method, known as coupled resonator induced transparency (CRIT) technique [13-17], relies on the interaction between a pair of optical resonators (with the resonance frequency of \( \omega_0 \), for example). The destructive interference between the resonators splits the spectrum of the modes into two separate peaks (one before and one after \( \omega_0 \)), opening a narrow transparent region around \( \omega_0 \). Despite its simple principle, the CRIT technique is associated with several drawbacks. In particular, the coupled resonance induced transparency is very fragile to disorder, as the characteristics of the involved resonances are exclusively enforced by the geometry. This renders controlling CRIT extremely challenging.

Another conceptually distinct route to achieve electromagnetic induced transparency is to leverage the interaction of an optical mode with mechanical motions. Under certain conditions, the strong interaction between these two degrees of freedom can result in a Fano-like resonance [18,19], characterized by an ultra-sharp peak-and-dip spectrum. In the frequency range where the dip of the Fano resonance occurs, the optomechanical system becomes completely transparent. Compared to CRIT, this type of transparency, known as optomechanically induced transparency (OMIT) [20-23], has several advantageous features. Firstly, OMIT can be tuned very easily by controlling the interaction between mechanical and optical degrees of freedom. In fact, any parameter that affects the mechanical properties of the opto-mechanical system (such as the temperature or pressure of the ambient) can be used as a tool to manipulate the characteristics of the EIT at will. Additionally, OMIT is based on only one single opto-mechanical element, representing significant miniaturization compared to the structures based on the CRIT technique (that are composed of two independent components). Yet, similar to CRIT, OMIT is sensitive to imperfections coming from fabrication tolerances, or the presence of defects, as the characteristics of the optical and mechanical parts still rely on maintaining a pristine geometry of the opto-mechanical structure.

In a seemingly unrelated field of science, artificial insulating materials with non-trivial topological band structures, known as topological insulators (TIs) [24-28], have attracted a lot of attention for their unprecedented robustness against geometrical variations. On their edges, finite-size TIs support resonant modes, whose existence is only related to the topological characteristics of the bulk system. Destroying their presence can only be achieved through drastic global modifications that close the insulating bandgaps, implying that they are robust to moderate levels of geometrical modifications [25]. This leads to strong resilience against certain types of disorder. Such an appealing feature has enabled the development of a large variety of disorder-immune...
structures in various fields of interest including photonic [28,30], phononics [31,32] and mechanics [33,34]. In this Letter, we demonstrate the possibility of achieving OMIT by engineering the topology of an optomechanical system. In particular, we show that the coupling between the optical and mechanical edge modes of a one-dimensional optomechanical crystal can give rise to a topological resonance [35], featuring a very small transparency window. Advantageously, the obtained OMIT is not related to the geometry of the optomechanical crystal, since the optical and mechanical resonances are due to topological nature of the system. The ultra-sharp spectrum of the obtained topological OMIT holds great promises for a large variety of applications such as sensing, signal processing, and optical data storage.

The working principle of a regular (trivial) optomechanical system is based on the coupling between an optical and a mechanical mode. The strong interaction between these modes creates an absorption spectrum with a very small transparency window. Since the system is topologically trivial, the characteristics of the involved resonances are mainly determined by the geometry of the opto-mechanical system. As such, the corresponding OMIT is extremely sensitive to imperfections. In order to mitigate these harmful effects, we propose to achieve OMIT based on the strong interaction between an optical and a mode whose existence is linked not to a definite geometry but to the topology of an opto-mechanical crystal (see Figure 1a). Since the topology of a system is preserved under continuous deformation of the band structure, slight to moderate geometrical perturbations may not affect the spectral characteristics of the optical and mechanical resonances. As a result, as opposed to the trivial case, the corresponding OMIT is robust (Fig. 1b).

In order to provide a concrete example of topological OMIT, we consider a one-dimensional photonic crystal, based on the unit-cell shown in Fig. 2a (top panel). The unit cell consists of a thin silicon wafer perforated with a rectangular hole. The parameters $a$, $b$, $W$, $h$ are chosen as $a = 0.36 \, \mu m$, $b = 0.99 \, \mu m$, $W = 1.4 \, \mu m$, $h = 0.19 \, \mu m$ respectively. The thickness of the silicon wafer is chosen as $t = 0.22 \, \mu m$. Fig. 2a (bottom panel) represents the dispersion of the fundamental optical mode of the photonic crystal, obtained by performing numerical simulations based on a standard finite element method (Comsol Multi-physics, electromagnetic (RF) module).

In order to induce non-trivial topological features in such system, we double the size of the unit cell to fold the band, and investigate the dispersion properties of the super-cell of the crystal. Fig. 2b shows the corresponding dispersion diagram. The two dispersion bands now cross each other at point degeneracies located the edges of the (new) Brillouin zone. Such degeneracies represent a particularly relevant starting points for engineering the topology of the system, since lifting a band degeneracy may be accompanied by the exchange of topological charges. This can be achieved by introducing symmetry-lowering mechanisms. The degeneracy in the band structure of Fig. 2b is related to the sub-lattice symmetry of the super-cell, namely the reflection symmetry with respect to the position $x = a/2$. One way to break this symmetry is to reduce the distance between the holes inside the super-cell (Fig. 2c). The bottom panel of Fig. 2c illustrates the corresponding band structure. As expected, the twofold degeneracies have been split, leading to an insulating band gap. This insulating band gap is characterized by a zero topological invariant [24].
Numerical Simulations of a topological OMIT, a, we connect a finite piece of the trivial crystal to the topological one, so as to achieve photonic and phononic topological edge modes b. Profile of the corresponding optical topological edge mode at the interface between the trivial and topological crystals. c. Profile of the corresponding mechanical topological edge mode. d. (Left) Corresponding reflection spectrum of the system, exhibiting an ultra-sharp spectral line shape caused by the inference between the optical and mechanical edge modes. (Right) Corresponding transmission spectrum, featuring a very narrow transparency window (yellow region).

The alternative strategy to break the sub-lattice symmetry of the super-cell resides in increasing the distance between the holes inside the super-cell. Fig. 2d represents the corresponding band structure. Like the previous case, the crystal under investigation exhibits an insulating band gap, looking similar to that of Fig. 2c. From a topological point of view, however, this insulating band gap is different from the previous one. In particular, the latter insulating band gap is characterized by a non-zero topological order, as opposed to the former case in which the topological invariant was zero.

The most striking feature of systems with a non-trivial topology is that they support edge modes when they form a boundary with a trivial structure. In order to realize photonic edge modes, we connect a finite piece of the non-trivial crystal to the trivial one (Fig. 3a). We then perform eigen frequency simulation to find the associated topological edge mode. Inset of Figure 3b illustrates the profile of the corresponding optical edge mode. It is observed that the edge mode is localized at the interface between the trivial and topological crystals.

On top of these photonic considerations, the structure shown in Fig. 3a can also be considered as a topological phononic system, supporting a “mechanical” topological edge mode at the interface between the two crystals with opposite hopping deformation. Shown in Fig. 3c is the profile of the mechanical topological edge mode. Like its optical counterpart, the mechanical edge mode is confined to the phase transition interface, leading to a strong optomechanical interaction. By tuning the geometry of the structure, the interaction of the optical and mechanical edge modes is maximized. The coupling between the optical and mechanical topological degrees of freedom can be characterized with a parameter known as coupling length, defined as [22]
\[
L_c = \left[ \frac{\int \Delta \varepsilon^2_{E} d|E| - \int \varepsilon^2_{E} d|E|}{\int \varepsilon^2_{E} dV} \right]^{-1}
\]

in which \(E\) and \(E_n\) are the tangential and perpendicular parts of the optical field respectively. \(Q\) is the unit cell displacement of the mechanical mode, \(\Delta \varepsilon = \varepsilon_{sl} - \varepsilon_{air}\) and \(\Delta \varepsilon^{-1} = \varepsilon_{st} - \varepsilon_{air}\). By calculating the associated integrals in Eq. 1, the coupling length between the topological optical and mechanical edge modes was obtained as \(L_c = 2.01 \ \mu m\). Once the coupling length between the optical and mechanical parts is found, the reflection and transmission spectrum of the optomechanical system can be calculated by using the following formulas [22]

\[
R = \frac{-G_{s} \varepsilon_{x} / 2}{[\Omega - \omega_{m} - \Delta \varepsilon^{-1} + \varepsilon_{sl} / 2]}\]

The authors declare no conflicts of interest.

References


References