Photonic Topological Baths for Quantum Simulation

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Abstract: Using coupled arrays of up to 16 high Q nanocavities we experimentally realized quantum photonic baths based on the Su-Schrieffer-Heeger model and investigated the effect of fabrication induced disorder on these baths by probing individual super-modes. © 2022 The Author(s)

Recent advances in controlling topological properties of photonic lattices have shown that novel forms of light-matter interaction can be realized in such systems owing to the topological protection of the resulting quantum many body states [1,2]. To reach this regime of interacting photons for quantum simulation in optical domain we need to implement the topological phases on lattices made with high quality (Q) factor and low mode volume resonators with spectral accessibility to individual super modes. However, due to unavoidable imperfections in nanofabrication, high Q optical resonator arrays are inherently prone to disorder in their resonant frequencies. This uncontrolled disorder can be a huge impediment in constructing topological baths suitable for studying various quantum optical phenomena. Typical coupled cavity arrays used to demonstrate topological states in the optical domain operate in a regime where fabrication induced disorder is comparable or greater than the relevant hopping rates between the cavities [3]. In this report, by increasing the effective mode overlap between resonators sites we overcame the effects of the underlying disorder and experimentally realized topological quantum baths which are photonic analogs of the SSH model.

The SSH bath made of cavities with resonant frequency \( \omega_0 \) with hopping rate \( J_1 \) and \( J_2 \) can be described by the Hamiltonian

\[
\mathcal{H}_B = \sum_i \omega_0 (a_i^+ a_i + b_i^+ b_i) + J_1 (b_i^+ a_i + a_i^+ b_i) + J_2 (b_i^+ a_{i+1} + a_i^+ b_{i+1})
\]

where \( a_i^+ (a_i), b_i^+ (b_i) \) denote the site bosonic creation (destruction) operators at site \( A \) and \( B \) of the \( i \)th unit cell. This bath supports topologically non-trivial phases [4] depending on whether \( J_1 < J_2 \) which is termed as the ‘topological’ phase or \( J_2 > J_1 \) which is termed as the ‘trivial’ phase. In presence of fabrication disorder this bath Hamiltonian is modified to

\[
\mathcal{H}_B^\text{D} = \mathcal{H}_B + \sum_i (\delta_{a_i} a_i^+ a_i + \delta_{b_i} b_i^+ b_i)
\]

where \( \delta_{a,b} \) denote the random disorder in resonator frequency drawn from a Gaussian distribution with standard deviation \( \sigma \). It is straightforward to see that the eigen-properties of this system Hamiltonian depend on the relative values of \( J_1 - J_2, J_1 + J_2 \) and \( \sigma \). Hence, we define a dimensionless parameter:

\[
\eta = 2\sigma / (J_1 + J_2)
\]

as the measure of relative disorder present in our system.

Figure 1: Disorder study: (a) Modulus of amplitude of bound state wavefunction (normalized) as we sweep across \( \eta \) averaging over \( 10^4 \) disorder realizations per \( \eta \). The schematic depicts a quantum emitter coupled to a SSH bath in trivial phase at a site of sub-lattice \( A \). The coherent emitter-cavity coupling rate is \( g = (J_1 + J_2) / 10. 25^\circ \) denotes the position of emitter in the array. Amplitudes on sub-lattice \( A \) are in red and on sub-lattice \( B \) are in green. Transmission spectrum \( |S_{21}|^2 \) of a photonic bath with \( B \) sites; averaged across \( 10^4 \) disorder realizations per \( \eta \) (b) Trivial phase, (c) Topological phase.
For using SSH baths for quantum simulation the key ingredient is realization of photonic bound states formed when quantum emitters lying in the middle of the band gap ($\omega_0$) are coupled to a SSH bath [2]. Hence, in Fig. 1(a) we first study the effect of disorder on this type of bound state. Without any disorder, the bound state envelope extends towards the only one direction and occupies only a specific sub-lattice. Presence of diagonal disorder breaks the chiral symmetry of the Hamiltonian, and the bound state loses its special properties as $\eta$ increases. Despite this in the region where $\eta \ll 1$ the bound state exists with strong localization towards one direction and vanishing amplitudes on the conjugate sub-lattice. Once fabricated, photonic baths are experimentally characterized by measuring the transmission spectrum $|S_{21}|^2$ as relevant bath parameters can be extracted in a straightforward manner from such a measurement. Therefore, in Fig 1(b), (c) we plot the effect of increasing disorder $\eta$ on the transmission spectra of the baths. It is evident from the plots that operating in the regime $\eta \ll 1$ is also critical for using transmission spectra to accurately characterize the system.

To realize these baths, we implemented the model on a SOI platform as coupled cavity arrays made from racetrack resonators which are 60 $\mu$m long with a 12 $\mu$m long coupling region. To obtain two differing hopping rates between the resonators, we kept the inter-resonator gap to be either 90 $nm$ or 110 $nm$ which corresponded to $J_1 = 163$ GHz and $J_2 = 122$ GHz [Fig. 2(a)]. Each device was probed via a set of grating couplers located at the first and last site. From statistical analysis of the probed super-modes of the devices the $\eta$ value for disorder persisting after adjusting for the mean frequency was calculated as $\eta = 0.056$ ($<< 1$). In lattices with up to 8 sites we observed spectral accessibility to all the modes and global disorder characterized by mean frequency of spectral modes had minimal effects on devices. This allowed for a clear comparison of band gap formation in the case of trivial phase and existence of two edge modes lying inside the band gap in the topological phase [Fig. 2 (b)]. For photonic baths with more than 8 sites all modes are not clearly observable due to vanishing amplitudes further away from the mean frequency and increasing effects of disorder on the spectrum. Despite this, the device design allowed for realization of photonic baths (here, trivial phase) with up to 16 sites [Fig. 2(c)]. We observed a clear band gap formation with $\Delta = 0.107$ THz which is within 3% of the theoretical prediction. As discussed such a photonic bath can be used to endow several special properties to coupled emitters also described in detail in an earlier work [1,2].

Figure 2: (a) Optical micrographs of a photonic SSH bath. (b) Normalized transmission spectrum of a SSH photonic bath with 8 sites. Upper plot (red) depicts the trivial phase, whereas the lower plot (blue) depicts the topological phase. We can observe the band gap (shaded) formation in trivial phase, and the existence of edge modes in middle of the band gap in topological phase. The schematic depicts the ports i.e., the grating couplers used for transmission measurement. (c) A SSH photonic bath made of 8 unit cells i.e., 16 sites in trivial phase.

In conclusion, using coupled cavity arrays we experimentally demonstrated topological photonic baths which are optical analogs of the SSH model. We studied the effect of fabrication induced disorder on these baths and demonstrated the steps required to overcome its effects [5].

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