Realizing Tight-binding Hamiltonians using Site-controlled Coupled Cavity Arrays

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Abstract: Using a cavity array made up of high Q nanocavities equipped with specially designed thermo-optic island heaters for independent control, we demonstrate a programmable device implementing tight-binding Hamiltonians with access to the full eigen-energy spectrum. © 2023 The Author(s)

Photonic coupled cavity arrays (CCA) are a promising platform for realizing programmable quantum devices required for analog quantum simulation. These devices are photonic lattices made of nanocavities where the coupling between sites provides a potential map for photons to move around, and onsite spatial confinement of light for long durations allows access to non-linearity via coupling with excitonic materials. Though several works using optical CCAs demonstrating various quantum and topological phenomena have been previously reported, none of these CCAs are programmable and provide access to the individual eigenmodes of the implemented Hamiltonian.

In this work, we tackle these problems by engineering a silicon photonic CCA made of 8 high Q (~8.5 × 10⁴) racetrack resonators fabricated on a silicon-on-insulator platform using 220 nm silicon on top of 3 µm thick silicon oxide [Fig. 1(a)]. For achieving programmability, each cavity in the CCA is equipped with a specially designed thermo-optic (TO) island heater to tune the onsite potential. These TO island heaters are made up of tungsten (W) wires sandwiched between two alumina (Al₂O₃) layers [Fig. 1(b)]. In such a configuration the higher thermal conductivity of the alumina layers than that of the air/silicon oxide channel separating the islands allows for a more directional transfer of thermal energy from the heaters to the corresponding cavities. Additionally, being optically lossless in the telecommunication regime, the alumina islands allow placing of heaters at a distance to minimize absorptive losses due to the metallic heating elements. Overall, our design allows for reducing the effects of thermal crosstalk by ∼50% compared to conventionally used TO heaters while ensuring high Q-factors and small footprints needed for individual addressability of eigenmodes [1].

Figure 1: Device design & characterization: (a) Optical micrograph of the CCA (scale bar 10 µm). (b) Exploded view of the TO island heaters. Inset shows a false colored SEM image (scale bar: 2 µm) of a typical TO island (yellow: tungsten, pink: alumina, teal: silicon). (c) Measured reflection spectrum |R(ω)|² (dotted purple) along with the fit generated using the tomography algorithm (cream); a plot showing contributions of various eigenmodes of the system to |R(ω)|²; and a plot showing measured transmission spectrum |T(ω)|² (dotted purple) along with the predicted |T(ω)|² (pink). (d) Plot showing the effect of heaters on the potential profile across the device. The x-axis denotes the heater index hₙ switched ON for a particular set of measurements and the y-axis represents the change in potential profile |Δωₙ|^². The voltage applied for the measurement across heater is mapped to the color of the circular surface and the corresponding change in potential is denoted by the radii of the circle encompassing the surface (0.25 nm of change is depicted by radii of the circle in the scale bar).
The spectrum of the resulting CCA is probed via a set of grating couplers located at the first and last sites. The scattering properties of this CCA are completely described by the effective non-Hermitian Hamiltonian which incorporates the coupling to input/output ports and system losses as:

$$H_{\text{eff}}^0 = \sum_n \left( \mu_n - j \frac{\kappa_n}{2} \right) a_n^+ a_n + J_n (a_{n+1}^+ a_n + a_n^+ a_{n+1}) - j \left( \frac{\gamma_0}{2} a_0^+ a_0 + \frac{\gamma_{N-1}}{2} a_{N-1}^+ a_{N-1} \right)$$

where $a_n$ denote the onsite photonic annihilation operator, $\mu_n$ is the onsite potential given by the resonant frequency of the cavity, $J_n$ is the photonic hopping rate between $n^{th}$ and $(n + 1)^{th}$ sites, $\gamma_0, \gamma_{N-1}$ denote the coupling rates to the grating couplers and $\kappa_n$ denotes the onsite scattering/absorption losses. To map the initial Hamiltonian $H_{\text{eff}}^0$, we modified a tomography algorithm initially used for lossless lattices [2] to be applicable for general lossy 1D CCAs [3]. Using the algorithm, we were able to obtain the entire $H_{\text{eff}}^0$ via just a single reflection spectrum ($|R(\omega)|^2$) measurement of the CCA [Fig. 1(c)]. The accuracy of the obtained $H_{\text{eff}}^0$ was verified by comparing the predicted and measured transmission spectra ($|T(\omega)|^2$) [Fig. 1(c)]. We then determined the electrical characteristics of the CCA by applying a linearly increasing electrical potential $V_n$ across the heaters one at a time; measuring the $|T(\omega)|^2$ and using it along with $H_{\text{eff}}^0$ to extract the deviations in onsite potential ($\Delta \mu_n^0$ in wavelength units). We plot the effects of $V_n$ on the potential profile in Fig. 1(d). From the plot we established that the effect of thermal crosstalk is low between nearest neighbors and becomes negligible beyond third nearest neighbor sites ($n \pm 3$).

Finally, we developed a mathematical model to predict the eigen-energies of the CCA on application of a random potential profile [$V_n$] across it. Based on the observation that thermal crosstalk is restricted to $n \pm 3$ sites; in Fig. 2(a) we show how we can use an optimization model starting with the initial $H_{\text{eff}}^0$ to predict the eigen-energies of the modified Hamiltonian using a control function $f$ which depends on $\beta_i$’s (proportionality coefficients for the direct terms relating the sites: $V_i^2$), $\gamma_{j,k}$’s (proportionality coefficients for the cross-terms between sites: $V_j V_k$) and coefficients $\alpha_n$ (incorporating the effects of minor variations in heater resistances). We then fit for function $f$ across 288 measurements by minimizing the error between predicted and measured eigenvalues. The obtained $f$ is then used to predict the location of eigen-energies for 20 randomly generated potential profiles depicted in Fig 2(b). From the plot we can see that the error in prediction of eigen-energies of the modified system is < 4% using our model.

![Figure 2](image-url)

Figure 2: Electrical control: (a) Visualization depicting the optimization process for obtaining the control function $f$. All entries of $H_{\text{eff}}^0$ are in GHz, with diagonal terms denoting the deviations in resonant frequency about the mean (dark purple: +ve deviation, tan: -ve deviation) and super/sub diagonal terms denoting the hopping rates. $\epsilon_n^0$ denotes the eigenvalues of $H_{\text{eff}}^0$ (in wavelength units). (b) Prediction accuracy plot where the x-axis denotes the random generation, and the y-axis denotes the wavelength. The location of the measured eigen-energies is denoted by the dark black lines in background. The radii of the circles denote the deviation of the predicted value from measured values (scale bar on top). The color of the dots denotes the overall prediction error for that generation.

In conclusion, we demonstrated a thermally controllable CCA which can be used to realize a set of tight binding Hamiltonians with addressability to the entire eigen-energy spectrum.

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References

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