

Disorder-Free Solitonlike Energy Transport in Moiré-Engineered Phononic Flat Bands

Chunjiang Li^{1,2,3}, Tiancheng Zhang⁴, Jiahao Cheng^{1,2,3}, Xuzhe Zhao^{1,2,3}, Shuang Zhang⁵,

Nicholas X. Fang⁴, Junqiao Wu⁶, Jiachen Li^{7,8,*}, and Kaichen Dong^{1,2,3,†}

¹*Institute of Data and Information, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China*

²*Center of Double Helix, Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, China*

³*Intelligent Passive Thermal Control Center, Research Institute of Tsinghua University in Shenzhen, Shenzhen 518057, China*

⁴*Department of Mechanical Engineering, University of Hong Kong, Hong Kong 999077, China*

⁵*Department of Physics, University of Hong Kong, Hong Kong 999077, China*

⁶*Department of Materials Science and Engineering, University of California, Berkeley, California 94720, USA*

⁷*Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

⁸*Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China*

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The pursuit of low-loss, directional energy transport and heat localization is critical in frontier fields such as hybrid quantum computing, thermophysics, and materials science. Localized phonon modes, with spatially confined vibrational energy and suppressed diffusive scattering, provide promising routes toward this goal. However, conventional approaches to phonon localization necessitate material disorder or nonlinear interactions, limiting their potential for controllable, on-demand energy routing and concentration in pristine, scalable materials. In this Letter, we demonstrate disorder-free, solitonlike phonon transport in atomic moiré superlattices (AMS), arising purely from engineered moiré interlayer interactions and characterized by non-Anderson localization and phononic flat bands. The vibrational energy is robustly confined at AA-stacking regions of 1D-AMS, and evolves into solitonlike propagation along moiré-induced channels in translational 2D-AMS. Furthermore, we show that coaxial double-wall moiré nanotubes leverage anisotropic interwall coupling to achieve simultaneous azimuthal localization and axial channelized transport, enabling programmable, low-dispersion phononic signal transmission with minimal crosstalk. By bridging concepts from classical wave physics and quantum moiré materials science, this Letter reveals a method for controlling phononic energy routing and local entropy landscapes in designed atomic structures. This moiré phononics approach holds great potential in thermal logic circuits, low-loss phonon-based communication networks, and phononic information processing in van der Waals structures.

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Introduction—Phonons, the quantized vibrations of crystal lattices, play a pivotal role in the thermal, mechanical, and electronic properties of materials [1–5]. Understanding phonon dynamics is critical for advancing technologies such as phonon-based quantum information [6,7], phononic quantum devices [8,9], thermoelectric energy conversion [10], and microscale heat management [11]. Among diverse phononic modes, localized phonons hold particular significance due to their capacity to suppress thermal transport and to host coherent states for quantum information storage [1,12–15]. Traditionally, such localized phonon modes have been realized through disorder-induced Anderson localization, which impedes phonon propagation via scattering mechanisms. Critically, disorder irreversibly changes the material structure, preventing continuous, reversible tuning of localization properties [16]. Moiré superlattices circumvent these limitations

by leveraging geometric design rather than disorder, and the advent of moiré physics marks a paradigm shift, offering deterministic control over non-Anderson-type localized phonon modes [17–21].

Moiré physics originated from the discovery of the “magic angle” in twisted bilayer graphene, where electronic flat bands host correlated insulating states and superconductivity [22–24]. This concept was subsequently generalized to various moiré superlattices—structures formed by superimposing periodic patterns with a relative twist or lattice mismatch—and offered a universal platform for band structure engineering across disciplines: in photonics, twisted bilayer photonic crystals exhibit photonic flat bands and non-Anderson-type localization [25,26]; in acoustics, moiré architectures enable topological waveguiding and localization-delocalization transitions [27,28]. While moiré-induced phonon flat bands have been theoretically predicted in systems such as twisted bilayer graphene [29,30], the dynamic propagation of localized wavepackets, channelized transport in higher dimensions, and potential for phononic information processing remain

*Contact author: jc_li@mit.edu

†Contact author: dkc22@sz.tsinghua.edu.cn

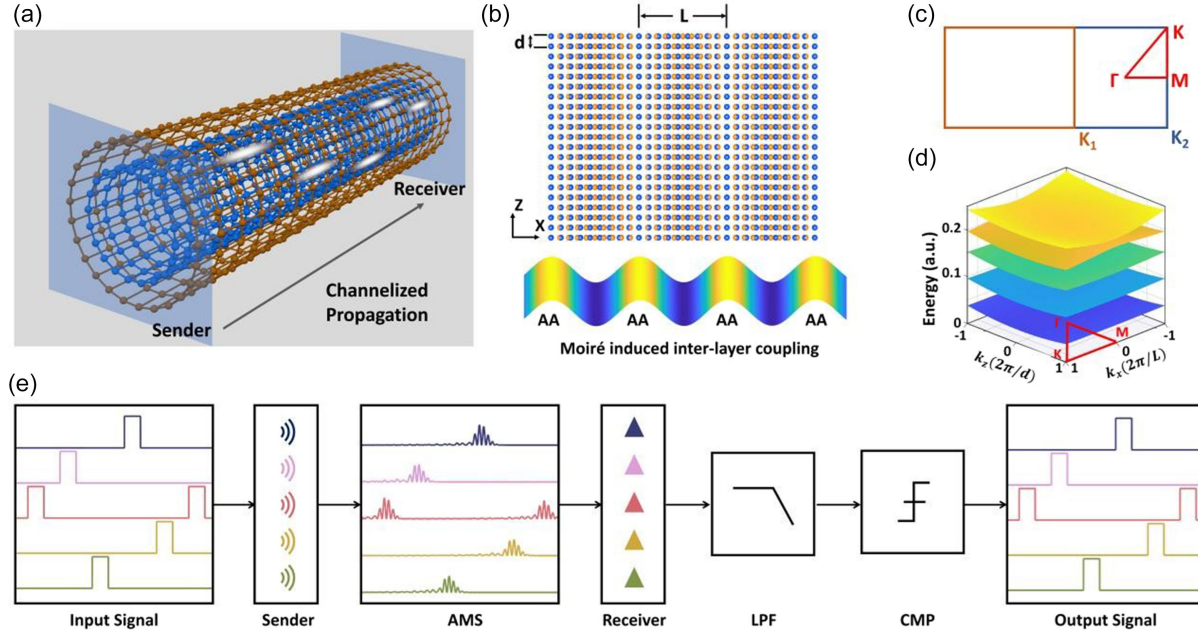


FIG. 1. Time sequential phononic signal transmission in coaxial double-wall moiré nanotube. (a) Schematic diagram of the signal transmission in coaxial double-wall moiré nanotube. (b) The moiré superlattice and geometric distribution of interlayer coupling strength. (c) The mini-Brillouin zone corresponding to the moiré superlattice. (d) 3D band structure within the mini-Brillouin zone. (e) Flowchart of the time sequential phononic signal processing. Low-pass filter (LPF), comparator (CMP).

unexplored. In our case, tailored lattice mismatch could engineer phonon dispersion and unlock unconventional energy transport mechanisms, paving the way for on-demand thermal engineering in quantum materials.

Here, we present the first exploration of moiré effects in atomic-scale phononics that does not rely on material nonlinearity, leading to the discovery of a disorder-free, solitonlike propagation mechanism. Unlike existing artificial or correlated moiré systems [25,30–35], our purely harmonic, lattice-mismatch-driven approach clarifies the unique advantages of atomic-scale phononic control, laying a solid foundation for subsequent experimental implementation [36]. Using a 1D AMS model consisting of two mismatched atom chains, we show that moiré modulated interlayer interactions induce phononic flat bands, localizing vibrational energy at AA stacking regions with negligible decay. Expanding the 1D model to two dimensions, we uncover how anisotropic coupling transforms these localized modes into solitonlike energy propagation along corresponding AA stacking channels [Figs. 1(a) and 1(b)] [39]. Notably, this channelization effect suggests the prospect of sculpting heat flux through moiré-induced localization (a purely geometric feature), hinting at on-chip thermal management strategies that redirect waste energy to harvesters or bypass heat-sensitive components. Furthermore, this atomic-scale control over phononic energy transport could facilitate sequential phononic signal transmission [Fig. 1(c)], paving the way to future phonon-based information communication and phononic quantum devices [40].

Results: 1D-atomic moiré system—We construct the one-dimensional atomic moiré system (1D-AMS) by stacking two layers of atom chains with mismatched lattice constants a (upper layer) and b (lower layer) [Fig. 2]. The periodicity L of the moiré superlattice arises from the commensurate condition $L = na = (n + 1)b$, where $n \gg 1$ is a positive integer, to ensure a slowly varying moiré potential. Interatomic interactions are governed by two mechanisms: (i) intralayer coupling, modeled as harmonic springs between nearest neighbors within each layer, with a stiffness linearly proportional to the displacement difference; (ii) interlayer coupling, mediated by a position-dependent stiffness $g(x)$ between each atom and its nearest neighbor from the opposite layer, which is spatially modulated by the moiré superlattice coordinate (x). The mode is described by the displacement field $u(x, t)$, which represents the vibration of atoms as a function of the position (x) and time (t). We focus on transverse modes due to their dominant role in moiré-induced localization in our analysis, as illustrated in the inset of Fig. 2(a). Here, we explicitly define the “AA stacking region” as the spatial domain where atoms in the upper and lower layers are vertically aligned (zero in-plane offset), corresponding to the region with the strongest interlayer coupling $g(x)$ in the moiré superlattice [36].

The dynamics of 1D-AMS is described by Newtonian equations of motion. Specifically, the displacement $u_i^j(t)$ of the j th atom in the i th chain evolves according to

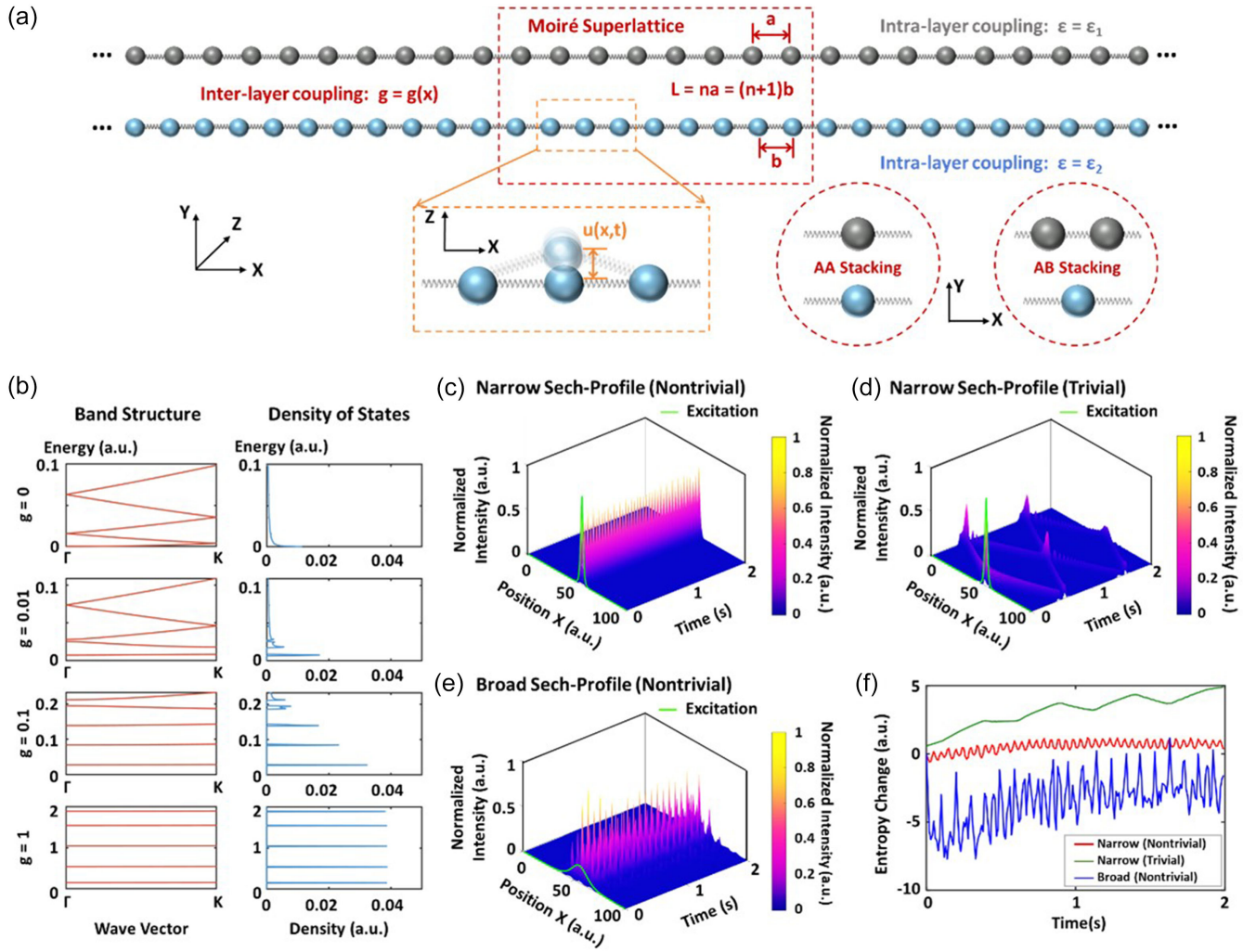


FIG. 2. Phononic flat bands and solitonlike energy transport in 1D-AMS. (a) Schematic diagram of the 1D-AMS. The red dashed box shows a single moiré superlattice, and the inset in the yellow dashed box illustrates the definition of displacement field. (b) Band structure and density of states calculated from the analytical model. Different rows of panels show different moiré modulating amplitudes. (c)–(e) Energy density evolution of time under different excitations: narrow sech-profile excitation centered at AA point without moiré interlayer coupling (d), and broad sech-profile excitation centered at the AB point (e). (f) Entropy change as a function of time extracted from the results in panels (c)–(e). The red, green, and blue curves correspond to narrow sech-profile excitation, narrow sech-profile excitation without moiré interlayer coupling, and broad sech-profile excitation, respectively.

$$m \frac{d^2 u_i^j}{dt^2} = \underbrace{\varepsilon_i (u_i^{j+1} - 2u_i^j + u_i^{j-1})}_{\text{intralayer coupling}} + \underbrace{g^j (u_i^j - u_i^j)}_{\text{interlayer coupling}}. \quad (1)$$

To elucidate the moiré-induced phonon dynamics, we derived a continuum model for the antisymmetric mode $\psi(x, t) = u_1(x, t) - u_2(x, t)$, which describes the out-of-phase component of vibration [17,18,41,42]:

$$\partial_t^2 \psi - c^2 (1 + \delta) \partial_x^2 \psi = v(x) \psi, \quad (2)$$

where c denotes the wave velocity inside each layer, which is set to be identical, δ is the differential operator indicating discrete dispersion, and $v(x) = 2g(x)/m$ represents the

effective moiré-periodic interlayer coupling strength [17,43]. While Eq. (1) provides the exact real-space framework necessary for simulating complex wave packet dynamics without relying on periodic boundary conditions, the continuum wave equation in Eq. (2) is derived as a standard analytical convention in lattice dynamics [35,44]. This continuum model conceptually isolates the macroscopic physical essence of the moiré potential, enables the rigorous analytical derivation of the effective Hamiltonian in momentum space via plane-wave expansion [45], and mathematically bridges our discrete lattice system with universal continuous wave mechanics.

To analytically resolve the interaction between the moiré interlayer coupling $v(x)$ and wave propagation in the

antisymmetric mode ψ , we employ a plane-wave expansion combined with Fourier analysis, leading to a set of coupled mode equations governing the temporal evolution of each wave vector component $\psi_k(t)$ [36]:

$$[\partial_t^2 - c^2(1 + \delta_k)]\psi_k = \sum_n v_n \psi_{k-nk_0}. \quad (3)$$

This equation reflects the moiré coupling's role in scattering waves between momentum states k and $k - nk_0$. Such scattering effect is simply caused by structural geometry instead of material nonlinearity. When the scattering balances with the dispersion, strong localization, and thus soliton-like phonon transport should exist in the system. For rather weak modulations ($|v_n| \ll c^2 k^2$), we take the first and second order approximations, under which ψ_k is influenced by ψ_{k+2k_0} , ψ_{k+k_0} , ψ_k , ψ_{k-k_0} , and ψ_{k-2k_0} .

This reduced coupled mode system is solved as an eigenvalue problem, where the eigen-energy and eigenmodes are obtained by diagonalizing the Hamiltonian matrix derived from Eq. (2), aligned with the computed band structure and density of states (DOS) illustrated in Fig. 2(b) [36]. As the interlayer coupling strength g increases, the scattering effect enhances, and the original parabolic dispersion splits into subbands. Furthermore, flat phononic bands emerge as g increases, coinciding with a sharp peak in the DOS. The phenomena strongly suggest flat band phonon modes and strong energy localization under certain coupling strength in both momentum space and real space.

To probe the non-Anderson localization in 1D-AMS, numerical simulations are conducted by applying Runge-Kutta methods [46] to the original dynamic equations Eq. (1) [36,37]. Several initial excitations are carefully selected to explore distinct energy transport regimes. First, a narrow sech-profile excitation centered at the AA point of the superlattice is simulated [Fig. 2(c)], leading to pronounced energy localization at the AA point. The initial profile maintained over an extended period with minimal dispersion observed, compared with the scenario without moiré interlayer interaction [Fig. 2(d)]. (The AMS systems with and without moiré interlayer couplings are referred to as nontrivial and trivial, respectively.) This strong localization is attributed to the emergence of flat bands induced by the moiré structure, rather than Anderson-like localization mechanisms associated with structural defects or disorder [47]. Conversely, a broad sech-profile excitation centered at the AB point of the superlattice is applied to the model, where a convergence effect caused by the moiré structure is expected [Fig. 2(e)]. As time evolves, the original broad excitation turns into several localized modes, locating at different AA points. These channels exhibit negligible inter-mode energy transfer, highlighting the orthogonal nature of the moiré-modulated eigenmodes and their role in enforcing robust energy localization.

To further analyze the evolution of energy distribution, we calculate the entropy, defined by

$$S(t) = - \sum_{x=1}^N p(x, t) \ln[p(x, t)],$$

[48,49], where $p(x, t) = e^{-\psi^2(x, t)} / \sum_{x=1}^N e^{-\psi^2(x, t)}$. Entropy analysis provides a quantitative means to examine the temporal evolution of energetic configuration in the system, and a nearly constant entropy profile indicates that the dynamics are solitonlike in nature. Unlike classical discrete solitons [50–52] that fundamentally rely on intrinsic material nonlinearity to dynamically balance discrete diffraction and dispersion, our atomic moiré superlattice operates in a purely harmonic regime. Here, the shape-preserving, nondiffractive propagation arises solely from the spatial moiré potential, which structurally flattens the phononic band and inherently suppresses dispersion. This purely geometric mechanism realizes linear analogs of the highly localized, robust transport traditionally associated with discrete solitons, but completely bypasses the strict requirement for material nonlinearity.

As shown in Fig. 2(f), the entropy increase after the narrow sech-profile excitation is considerably suppressed compared with the trivial condition, indicating the maintenance of the mode orderliness. Meanwhile, under the broad sech-profile excitation, the entropy suddenly decreases at the beginning because most energy is quickly constrained in the localized modes, and then gradually increases with fluctuation due to spontaneous energy diffusion. The result shows that the moiré-modulated eigenmodes are beneficial for energy localization and can enhance the stability of phonon modes.

2D-atomic moiré system—The 1D-AMS model reveals the intrinsic localization behavior of the system, suggesting that such localization can be utilized to realize spatially confined energy transport. Hence, we generalize our analysis to its two-dimensional counterpart (2D-AMS), constructed by periodically translating 1D-AMS along the z -axis with periodicity d [Fig. 3]. This lattice inherits the moiré periodicity along the x axis from 1D-AMS, while introducing translational symmetry along the z axis, enabling exploration of vibrational dynamics in a 2D geometry [36]. Consistent with our definition, the AA stacking region in 2D-AMS manifests as continuous lines extending along the z axis (i.e., the translational symmetry direction)—this is a direct two-dimensional extension of the discrete AA stacking points in 1D-AMS [36]. The governing equations in the Newtonian form can be expressed by [17,53]

$$\begin{aligned} m \frac{d^2 u_i^{j,l}}{dt^2} = & \underbrace{\epsilon_{x,i} (u_i^{j+1,l} - 2u_i^{j,l} + u_i^{j-1,l})}_{x\text{-direction intralayer coupling}} \\ & + \underbrace{\epsilon_z (u_i^{j,l+1} - 2u_i^{j,l} + u_i^{j,l-1})}_{z\text{-direction intralayer coupling}} \\ & + \underbrace{g^j (u_i^{j,l} - u_i^{j,l})}_{\text{interlayer coupling}}. \end{aligned} \quad (4)$$

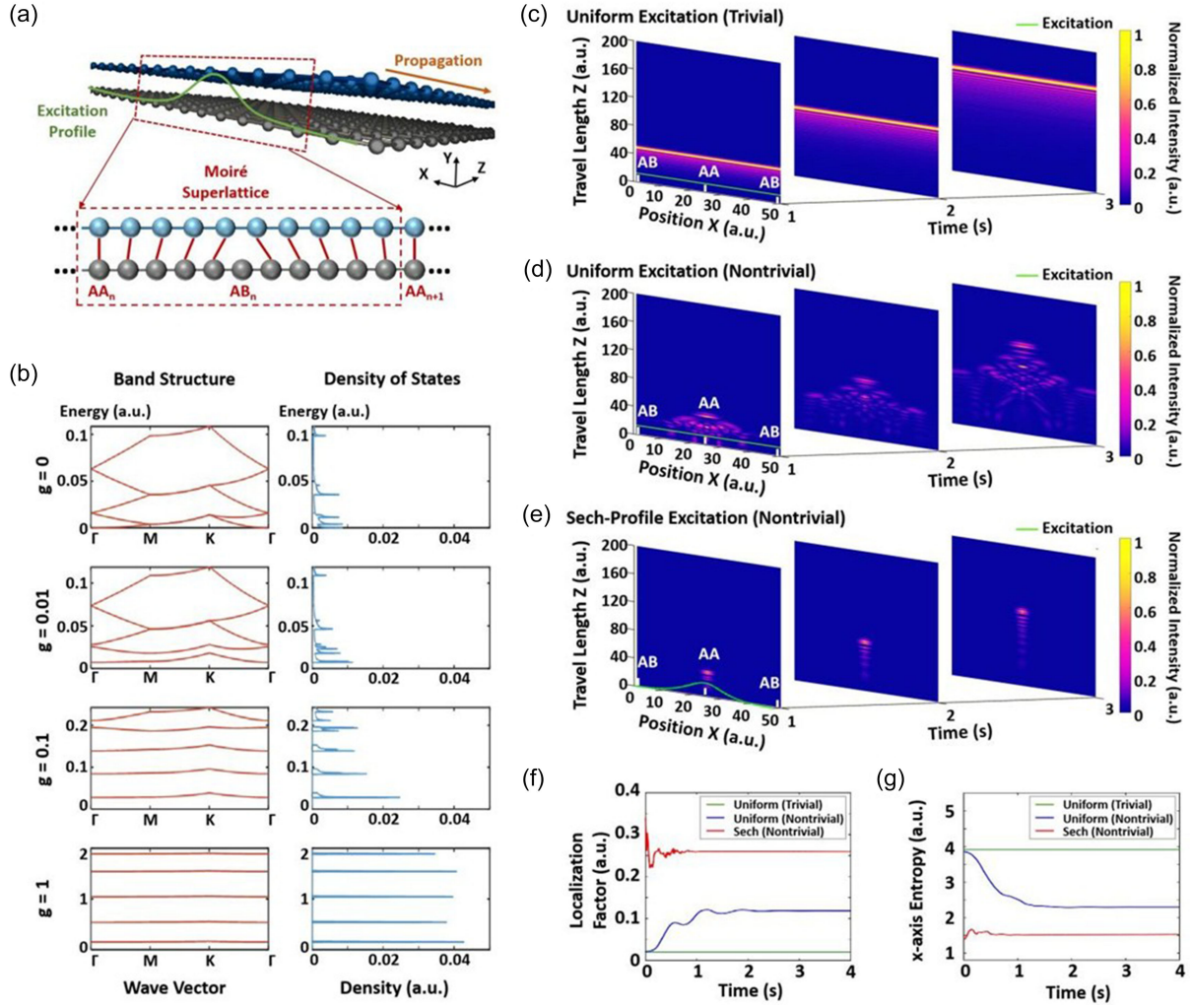


FIG. 3. Phononic flat bands and solitonlike energy transport in 2D-AMS. (a) Schematic of 2D-AMS, where the red dashed box shows the cross-sectional structure within one superlattice. (b) The band structure and density of states calculated numerically across the mini-Brillouin zone. Different rows of panels show different moiré modulating amplitudes. (c)–(e) Energy density evolution of time under (c) uniform excitation without moiré inter-layer coupling; (d) uniform excitation; (e) sech-profile excitation. (f),(g) Temporal evolution of the localization factor (f) and x-axis entropy (g) extracted from the results in panels (c)–(e). The green, blue, and red curves correspond to uniform excitation but without moiré interlayer coupling, uniform excitation, and sech-profile excitation, respectively.

The same theoretical approach is applied on this model to finally extract the moiré antisymmetric mode. Similarly, the analysis here is exclusively on z -polarized antisymmetric vibrations, described by the displacement field $\psi(x, z, t)$:

$$(\partial_t^2 - c_x^2(1 + \delta_x)\partial_x^2 - c_z^2(1 + \delta_z)\partial_z^2)\psi = v(x)\psi, \quad (5)$$

where c_x is the intrinsic wave velocity along the x axis, and c_z is the intrinsic wave velocity along the z axis. Similarly, δ_x and δ_z represents the discrete dispersion operators along the x axis and z axis, respectively [36].

Using the same methodology applied to 1D-AMS, we calculate the phononic band structure and density of states for 2D-AMS across the first Brillouin zone [Fig. 3(b)] [36]. Increasing the interlayer coupling coefficient g induces a progressive splitting of the original parabolic bands into

multiple subbands. Notably, flat bands emerge at critical coupling strengths, coinciding with sharp peaks in the DOS plot. These flat bands arise from the moiré-modulated interlayer coupling $v(x)$, which leads to the scatter effect between modes k_x and $k_{x \pm nk_0}$. This behavior mirrors the atom-chain results, but with a critical distinction: in the 2D system, flat bands coexist with dispersive propagating modes along the k_z axis, enabling anisotropic energy dynamics—strong localization along the x axis and dispersive propagation in the $+z$ direction.

To test the capability of localization, we first demonstrate numerical simulations with uniform excitation. Different from the 1D scenario, here we focus on only one superlattice with periodic boundary conditions for better understanding both the localization and the propagation mechanism [36]. When the moiré-modulated interlayer

coupling is zero, noted as the trivial condition, the simulation result shows x -axis uniform distribution and $+z$ -direction propagation with intrinsic velocity as well as strong dispersion [Fig. 3(c)]. With the same uniform excitation, when the moiré coupling increases, the localization effect appears, and energy tends to localize around the AA stacking regions as it propagates in the $+z$ direction [Fig. 3(d)]. This localization is attributed to the moiré flat band, which traps energy at AA points with decreased wave velocity, leading to slower wave propagation than the trivial condition. However, the energy remains delocalized along the x axis due to the overlap of the uniform excitation with multiple eigenmodes. Further dispersion in the z axis further redistributes the energy, resulting in a hybrid profile that combines localized and delocalized components.

To overcome the delocalized components in the uniform excitation scenario, we set up a numerical simulation based on a sech-profile excitation, which provides an initial energy distribution that is centered at the AA point. Under the geometric modulation of the moiré coupling, the profile along the x axis is tightly confined near the AA stacking regions, maintaining the highly localized energy distribution [Fig. 3(e)]. Such strong localization also originates from the moiré flat band, which can also be illustrated by the scattering effect of the moiré modulation term in Eq. (5). Along the z axis, since no modulating effect can compensate for the discrete dispersion term, the propagation, though much slower than the former scenarios, also shows broadening effects with tailings behind the wave front but does not affect the localization along the x axis. In stark contrast, without moiré modulation, the wave packet will rapidly diffuse throughout the superlattice due to the dispersion along the x axis [36].

The localization behavior and energy dynamics in 2D-AMS are quantitatively analyzed with the localization factor (LF) and x -axis entropy, as depicted in Figs. 2(f) and 2(g). Under uniform excitation with trivial conditions, 2D-AMS holds limited LF and high x -axis entropy, indicating the absence of localization and maximal disorder along the x axis. On the contrary, nontrivial 2D-AMS with uniform excitation shows a transition where the LF increases and x -axis entropy decreases, reflecting a redistribution of energy from an initially disordered state toward localization at the AA stacking regions. Moreover, the sech-profile excitation exhibits the most pronounced localization, with the highest LF and a consistently ultralow x -axis entropy, indicating robust confinement of energy around AA stacking regions. This optimal performance is generated from the perfect alignment between the sech profile and the moiré flat-band eigenmode structure, which maintains energy localization by minimized mode competition.

Finally, we evaluate the structural robustness of the proposed mechanism under realistic conditions [36,54]. By considering both global mismatch error in moiré periodicity and local random mismatch error arising from stochastic

atomic displacements, we find that the phononic flat bands and localization metrics remain remarkably stable. The relative fluctuations in bandwidth and DOS concentration are confined to $<1.4\%$ even at a 10% mismatch error level. Furthermore, our analysis reveals that the inclusion of higher-order Fourier components—inherent to realistic interlayer potentials—actually further enhances the band flatness and localization strength. These results confirm that the moiré-induced localization is quantitatively robust and experimentally feasible in real van der Waals systems.

Coaxial double-wall moiré nanotube—To further explore the scalability and experimental potential of moiré-enabled energy localization, we extend 2D-AMS to coaxial double-wall moiré nanotubes (CDWMN). In this system, the moiré geometry along the azimuthal direction is intrinsic because of the difference in radius, while the structure along the axial direction is still translationally symmetric and semi-finite [Fig. 4(a)] [38]. Without loss of generality, the number of superlattice along the circumference is set to be five, and each superlattice has the same structure as that of AMS, leading to five lines of AA points—i.e., the AA stacking regions in CDWMN. Consistent with our definition, these regions manifest as discrete axial channels distributed azimuthally, namely channels $AA_1 - AA_5$ [36]. Each AA channel is expected to be a controllable energy transmission pipeline, which can be modulated by the coupling mechanism as well as the excitation profile [Fig. 4(b)].

The same excitation simulations are performed as above, showing that the excitation energy will quickly converge into the nearby AA channel(s) [36]. All the AA channels are isolated from each other, with almost no energy interchange. Therefore, we shift the center of the sech-profile excitation to study the relationship between excitation and energy distribution among the channels after convergence. For demonstration, we symmetrically choose five examples from centering nearby AA_2 to nearby AA_4 and excited CDWMN. As illustrated in Fig. 4(c), when the excitation center is in between two AA channels, the energy will be only separated into the two nearest AA channels. The closer the excitation center to the AA point, the higher energy concentration are shown in the corresponding AA channel. This result indicates the fact that energy can be collected and split into nearest AA channels, and the energy ratio can be adjusted by simply shifting the excitation profile distribution.

The excitation center is further swept along the azimuthal direction. Five receivers (RX_1-RX_5) corresponding to the AA channels are set at the ending AA points and continuously collect temporal signals. The signal ratio of five receivers is defined as an integration of receiving energy within the time period denoted as the red box region in Fig. 4(c), normalized by the total input energy. Results in Fig. 4(d) reveal a periodic modulation in the signal ratios, consistent with the moiré periodicity. The signal ratio at each AA channel peaks when the excitation aligns with its

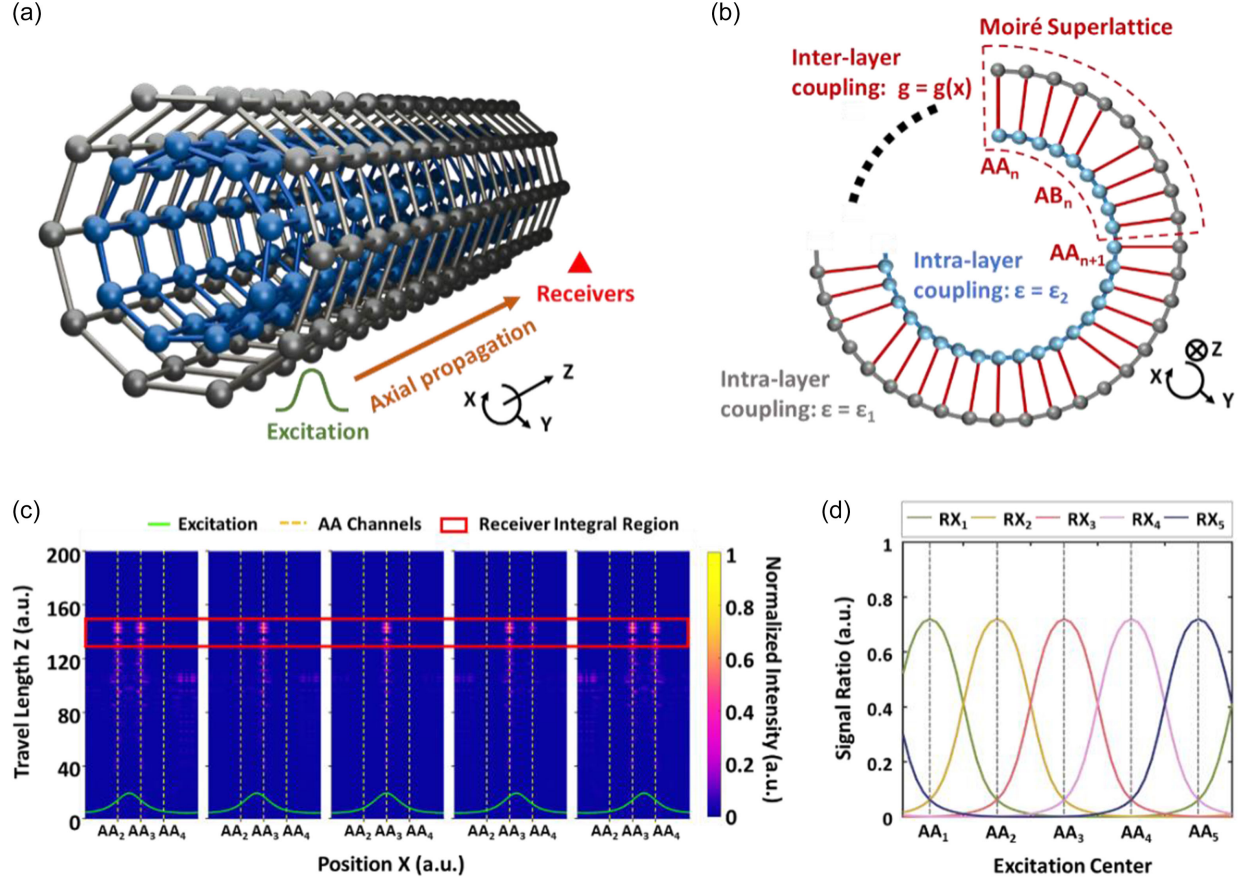


FIG. 4. Channelized energy transport and selective excitation in CDWMN. (a) Schematic of CDWMN. (b) Cross-sectional view showing the moiré superlattices and alternating AA channels. (c) Energy density distribution after the same time period while shifting the excitation profile along the azimuthal direction. The red box demonstrates the signal integral region to evaluate the total energy arriving at the receivers. (d) Signal ratio of five receivers with the excitation center scanning azimuthally.

corresponding AA point, with interchannel crosstalk below 10% over 150 lattices of traveling. The periodic oscillations in signal ratios with suppressed crosstalk make CDWMN an exceptional platform for programmable energy routing, where the energy could be allocated to different channels by excitation position.

Such discovery strongly suggests the possibility of applying such a system to information communication [6]. Hence, time sequential signals along CDWMN are delivered across the five AA channels, and the input signals are restored by the receivers. To demonstrate this, sinusoidal input signals with sech distribution [Fig. 5] are sent through different AA channels with programmed time series [Fig. 5(b)]. The received signals are postprocessed by conventional signal processing methods containing low-pass filter and comparator, leading to almost perfect restoration of time-series information [Fig. 5(c)]. This continuous excitation will also make the energy localization in AA channels persistent, leading to negligible information loss during the signal propagation through a predetermined channel. Note that nearly zero crosstalk is observed between adjacent channels due to strong energy

localization. The dispersion in the z axis can be alleviated by adjusting the degree of z -axis dispersion or by subsequent rectification and filtering of the signal.

Discussion—This Letter establishes a theoretical framework for controlling vibrational energy transport via geometric moiré engineering in atomic superlattices. By combining analytical modeling and numerical simulations, we demonstrate that moiré-induced antisymmetric flat bands in 1D and 2D atomic moiré superlattices enable non-Anderson localization and solitonlike energy propagation. These phenomena arise purely from structural symmetry breaking rather than material nonlinearity or disorder, offering a deterministic strategy for phononic energy confinement and routing.

The 1D-AMS model reveals that spatially modulated interlayer coupling creates phononic flat bands, leading to robust energy localization at AA points. Extending this to 2D-AMS uncovers anisotropic dynamics, where energy is simultaneously confined along the moiré-modulated direction and channelized along the translationally symmetric axis. In CDWMN, this anisotropy facilitates programmable, low-dispersion phononic signal transmission with

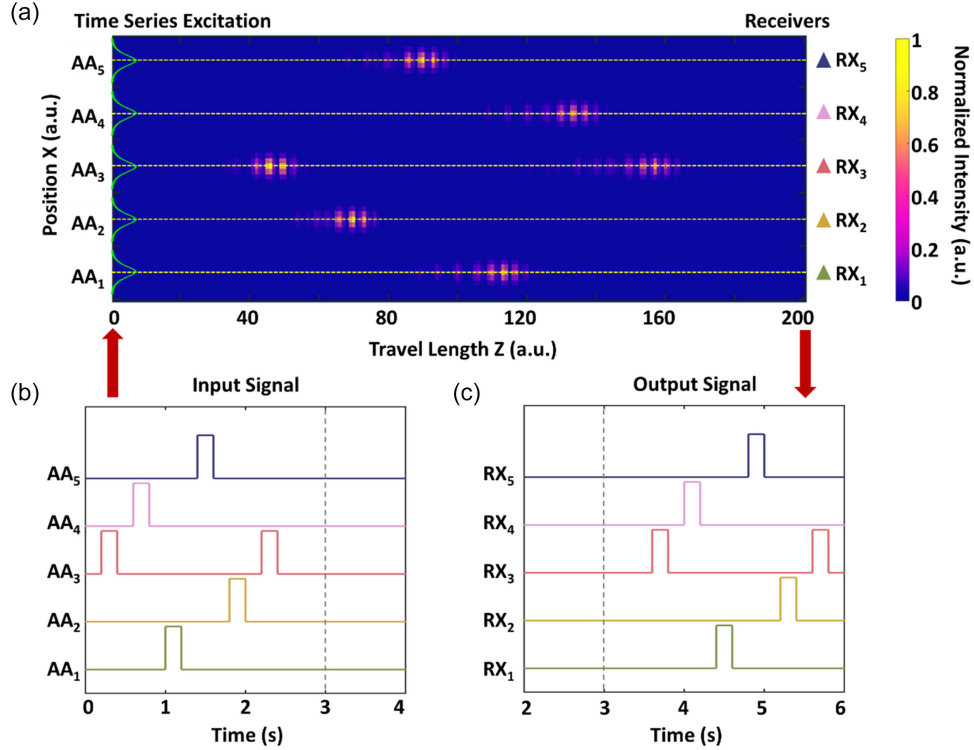


FIG. 5. Time sequential information transport along CDWMN. (a) Snapshot of the propagating time series signal at $t = 3$. (b) Input time series signal. (c) Recovered output signal after propagation and postprocessing.

minimal crosstalk, a feat unattainable in conventional waveguides reliant on material properties or nonlinear effects.

The implications of this theory span transformative applications across thermal management, phononic communication, and quantum technologies. Critically, moiré flat bands provide a geometric mechanism to suppress or redirect heat flow without material disorder, enabling anisotropic thermal insulators with ultralow conductivity in specific directions—a key advance for mitigating heat dissipation in nanoscale electronics and quantum devices [5,15,41,55,56]. Concurrently, our proposal of coaxial double-wall moiré nanotube architecture demonstrates near-zero dispersion and high channel fidelity in phononic signal transmission, even in mechanically hostile environments (e.g., ultralow temperatures), offering resilience for communication in extreme conditions. Further, the long-lived localized phonon states supported by moiré flat bands establish a platform for phonon-based quantum memory and enhanced electron-phonon coupling, potentially enabling exotic quantum phases. The mathematical parity with quantum soliton models (e.g., Jackiw-Rebbi model [57]) inspires future phonon physics exploration and thermal materials engineering. Together, these advances bridge classical wave physics and quantum mechanics through deterministic geometric design, redefining paradigms for phonon transport. Experimental validation of this framework could leverage spectroscopic characterization of

moiré-engineered materials (e.g., transition metal dichalcogenide bilayer heterostructures [58–61], or coaxial double-wall nanotubes with slight radius differences [38,62,63]) combined with spatially resolved thermal transport measurements under symmetry-breaking conditions. The required normalized interlayer coupling constant (0.01 to 1) for observing this solitonlike energy transport is physically sound and readily accessible in realistic van der Waals systems under ambient or moderately pressurized conditions [38,58,64–68], as well as in highly tunable classical wave platforms [36]. To further validate the universality and experimental relevance of this framework, we have numerically reproduced the proposed mechanisms in classical optical and acoustic moiré waveguide arrays [36]. Future work could explore hybrid moiré platforms integrating phononic, electronic, and photonic functionalities, paving the way for multifunctional devices governed by geometric design principles.

In conclusion, our findings establish geometric moiré engineering as a new platform for controlling vibrational energy transport. The discovery of non-Anderson localization and solitonlike energy channels in AMS reveals a new framework governing wave dynamics in symmetry-broken lattices. These phenomena enable manipulation over phonon propagation, aiming at future phononic technologies such as phonon-based quantum memory, on-chip thermal routers, and hybrid electron-phonon systems.

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Data availability—The data that support the findings of this study were generated by numerical simulations. The source code and parameters used to generate the simulations is publicly available [69].

- [1] M. L. Williams and H. J. Maris, *Phys. Rev. B* **31**, 4508 (1985).
- [2] J. M. Ziman, *Electrons and Phonons: The Theory of Transport Phenomena in Solids* (Oxford University Press, New York, 2001).
- [3] J. Maire, R. Anufriev, R. Yanagisawa, A. Ramiere, S. Volz, and M. Nomura, *Sci. Adv.* **3**, e1700027 (2017).
- [4] C. Kittel and P. McEuen, *Introduction to Solid State Physics* (John Wiley & Sons, New York, 2018).
- [5] X. Qian, J. Zhou, and G. Chen, *Nat. Mater.* **20**, 1188 (2021).
- [6] H. Qiao *et al.*, *Nat. Phys.* **21**, 1801 (2025).
- [7] H. Qiao *et al.*, *Science* **380**, 1030 (2023).
- [8] C.-L. Zou and L. Sun, *Nat. Phys.* **21**, 336 (2025).
- [9] T. Neuman, M. Eichenfield, M. E. Trusheim, L. Hackett, P. Narang, and D. Englund, *npj Quantum Inf.* **7**, 121 (2021).
- [10] J. Zhou, Bolin Liao, Bo Qiu, Samuel Huberman, Keivan Esfarjani, Mildred S. Dresselhaus, and Gang Chen, *Proc. Natl. Acad. Sci. U.S.A.* **112**, 14777 (2015).
- [11] G. Chen, *Nat. Rev. Phys.* **3**, 555 (2021).
- [12] S. Hu, Z. Zhang, P. Jiang, J. Chen, S. Volz, M. Nomura, and B. Li, *J. Phys. Chem. Lett.* **9**, 3959 (2018).
- [13] M. N. Luckyanova *et al.*, *Sci. Adv.* **4**, eaat9460 (2018).
- [14] J. Mendoza and G. Chen, *Nano Lett.* **16**, 7616 (2016).
- [15] Y. Ni and S. Volz, *J. Appl. Phys.* **130**, 190901 (2021).
- [16] P. Anderson, *50 Years of Anderson Localization*, edited by P. W. Anderson (World Scientific Publishing Co. Pte. Ltd, Singapore, 2010).
- [17] M. Koshino and Y.-W. Son, *Phys. Rev. B* **100**, 075416 (2019).
- [18] Lukas P. A. Krisna and M. Koshino, *Phys. Rev. B* **107**, 115301 (2023).
- [19] M.-L. Lin *et al.*, *ACS Nano* **12**, 8770 (2018).
- [20] I. Maity, A. A. Mostofi, and J. Lischner, *Phys. Rev. B* **105**, L041408 (2022).
- [21] N. Suri, C. Wang, Y. Zhang, and D. Xiao, *Nano Lett.* **21**, 10026 (2021).
- [22] R. Bistritzer and A. H. MacDonald, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 12233 (2011).
- [23] Y. Cao *et al.*, *Nature (London)* **556**, 80 (2018).
- [24] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, *Nature (London)* **556**, 43 (2018).
- [25] K. Dong, T. Zhang, J. Li, Q. Wang, F. Yang, Y. Rho, D. Wang, C. P. Grigoropoulos, J. Wu, and J. Yao, *Phys. Rev. Lett.* **126**, 223601 (2021).
- [26] T. Zhang *et al.*, *Nat. Commun.* **14**, 2097 (2023).
- [27] S. Fan, C. Han, K. He, L. Bai, L.-Q. Chen, H. Shi, C. Shen, and T. Yang, *Adv. Mater.* **37**, 2418839 (2025).
- [28] Q. Wei, X. Zhang, W. Deng, J. Lu, X. Huang, M. Yan, G. Chen, Z. Liu, and S. Jia, *Nat. Mater.* **20**, 812 (2021).
- [29] E. Cappelluti, J. A. Silva Guillen, H. Rostami, and F. Guinea, *Phys. Rev. B* **108**, 125401 (2023).
- [30] M. Angeli, E. Tosatti, and M. Fabrizio, *Phys. Rev. X* **9**, 041010 (2019).
- [31] L. Du, M. R. Molas, Z. Huang, G. Zhang, F. Wang, and Z. Sun, *Science* **379**, eadg0014 (2023).
- [32] H. Qin, S. Chen, W. Zhang, H. Zhang, R. Pan, J. Li, L. Shi, J. Zi, and X. Zhang, *Nat. Commun.* **15**, 9080 (2024).
- [33] X. Zhang, T. Liu, Q. Zhang, X. Fan, F. Wu, and C. Qiu, *Phys. Rev. B* **111**, 125143 (2025).
- [34] E. Y. Andrei, D. K. Efetov, P. Jarillo-Herrero, A. H. MacDonald, K. F. Mak, T. Senthil, E. Tutuc, A. Yazdani, and A. F. Young, *Nat. Rev. Mater.* **6**, 201 (2021).
- [35] N. W. Ashcroft and N. D. Mermin, *Solid State Physics* (Holt, Rinehart and Winston, New York London, 1976).
- [36] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/jdbw-p719> Sec. 10 for details of comprehensive comparison with existing moiré systems; Sec. 14 for details of geometric manifestations of the AA stacking region across dimensions; Sec. 1 for details of the dynamic equations and Hamiltonian analysis of the 1D-AMS; Sec. 2 for details of the band structure and DOS calculation for the 1D-AMS; Sec. 3 for details of the numerical simulation for the 1D-AMS, which includes Ref. [37]; Sec. 4 for details of the geometric construction of 2D-AMS; Sec. 5 for details of the dynamic equations and hamiltonian analysis of the 2D-AMS; Sec. 6 for details of the band structure and DOS calculation of the 2D-AMS; Sec. 7 for details of the numerical simulation for the 2D-AMS; Sec. 8 for details of the systematic analysis of energy localization; Sec. 12 for details of statistical robustness against mismatch errors; Sec. 13 for details of impact of higher-order Fourier harmonics, which includes Ref. [38]; Sec. 9 for the details of the numerical simulation of the CDWMN; Sec. 15 for details of experimental feasibility and parameter estimates; Sec. 11 for details of classical wave analogs.
- [37] C. A. De Moura and C. S. Kubrusly, *The Courant-Friedrichs-Lewy (CFL) Condition* (AMC, 2013), 10.1007/978-0-8176-8394-8.
- [38] G. Gordeev, S. Wasserroth, H. Li, B. Flavel, and S. Reich, *Nano Lett.* **21**, 6732 (2021).
- [39] T. Dauxois and M. Peyrard, *Physics of Solitons* (Cambridge University Press, Cambridge, England, 2006).
- [40] W. Fu, Z. Shen, Y. Xu, C.-L. Zou, R. Cheng, X. Han, and H. X. Tang, *Nat. Commun.* **10**, 2743 (2019).
- [41] L. P. Krisna, T. Kawakami, and M. Koshino, *J. Phys. Soc. Jpn.* **94**, 044602 (2025).
- [42] Nguyen N. T. Nam and M. Koshino, *Phys. Rev. B* **96**, 075311 (2017).
- [43] Q. Gao and E. Khalaf, *Phys. Rev. B* **106**, 075420 (2022).
- [44] G. Chen, *Nanoscale Energy Transport and Conversion: A Parallel Treatment of Electrons, Molecules, Phonons, and Photons* (Oxford University Press, New York, 2005).
- [45] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari Rouhani, *Phys. Rev. Lett.* **71**, 2022 (1993).

- [46] J. C. Butcher, *Applied Numerical Mathematics* **20**, 247 (1996).
- [47] H. Ochoa and R. M. Fernandes, *Phys. Rev. Lett.* **128**, 065901 (2022).
- [48] C. Cercignani, *J. Stat. Phys.* **87**, 1097 (1997).
- [49] B. Sorkin, H. Diamant, and G. Ariel, *Phys. Rev. Lett.* **131**, 147101 (2023).
- [50] F. Lederer *et al.*, *Phys. Rep.* **463**, 1 (2008).
- [51] H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, *Phys. Rev. Lett.* **81**, 3383 (1998).
- [52] J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, *Nature (London)* **422**, 147 (2003).
- [53] S. Moore *et al.*, *Nat. Commun.* **12**, 5741 (2021).
- [54] J. Jung, A. Raoux, Z. Qiao, and A. H. MacDonald, *Phys. Rev. B* **89**, 205414 (2014).
- [55] S. Han *et al.*, *Appl. Phys. Lett.* **118**, 189902 (2021).
- [56] M. N. Luckyanova *et al.*, *Science* **338**, 936 (2012).
- [57] R. Jackiw and C. Rebbi, *Phys. Rev. D* **13**, 3398 (1976).
- [58] Y. Wang, Z. Wang, W. Yao, G. B. Liu, and H. Yu, *Phys. Rev. B* **95**, 115429 (2017).
- [59] M. Yankowitz, S. Chen, H. Polshyn, Y. Zhang, K. Watanabe, T. Taniguchi, D. Graf, A. F. Young, and C. R. Dean, *Science* **363**, 1059 (2019).
- [60] D. Guerci, K. P. Lucht, V. Crepel, J. Cano, J. H. Pixley, and A. Millis, *Phys. Rev. B* **110**, 165128 (2024).
- [61] C. Woods *et al.*, *Nat. Phys.* **10**, 451 (2014).
- [62] M. Endo, H. Muramatsu, T. Hayashi, Y. A. Kim, M. Terrones, and M. S. Dresselhaus, *Nature (London)* **433**, 476 (2005).
- [63] B. Zhao *et al.*, *Nature (London)* **591**, 385 (2021).
- [64] K. Kim, A. DaSilva, S. Huang, B. Fallahazad, S. Larentis, T. Taniguchi, K. Watanabe, B. J. LeRoy, A. H. MacDonald, and E. Tutuc, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 3364 (2017).
- [65] M. Yankowitz, J. Jung, E. Laksono, N. Leconte, B. L. Chittari, K. Watanabe, T. Taniguchi, S. Adam, D. Graf, and C. R. Dean, *Nature (London)* **557**, 404 (2018).
- [66] P. Moon and M. Koshino, *Phys. Rev. B* **90**, 155406 (2014).
- [67] Y. Zhang, Noah F. Q. Yuan, and L. Fu, *Phys. Rev. B* **102**, 201115(R) (2020).
- [68] S. Zhao *et al.*, *Adv. Sci.* **9**, 2103460 (2022).
- [69] C. Li, Disorder-free Solitonlike Energy Transport in Moiré-engineered Phononic Flat Bands, Zenodo, 2026, [10.5281/zenodo.20680871](https://zenodo.org/record/20680871).