

PHYSICS

Strong interlayer coupling and chiral flat-band cascades in twisted bilayer gratings

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From atomic crystals to macroscopic material structures, twisted bilayer systems have emerged as a promising route to control wave phenomena. In few-layer van der Waals materials, however, the intrinsically weak interlayer coupling typically demands precise control of small twist angles to reach magic-angle conditions. Here, we show that twisted one-dimensional photonic crystal bilayers can overcome this limitation by accessing a regime of strong interlayer coupling—comparable to intralayer coupling. This strong coupling enables ultrawide flat-band formation even at large twist angles. We experimentally realize this regime by stacking tungsten disulfide gratings using a two-step lithography method, resulting in ultrawide chiral flat-band cascades in magic-angle twisted bilayer gratings. Our work not only provides a platform for designing photonic applications with a tunable photonic band but also explores a previously unidentified regime of physics that is unattainable in conventional solid-state-based moiré systems.

INTRODUCTION

Twisted multilayer systems offer a promising platform for engineering wave mechanics beyond conventional lattice length scales (1, 2). Geometrically, for a given twist angle θ_t between two layers and the lattice distance a the superlattice period is amplified as $L_m \sim a/\theta_t$, leading to a significant enhancement of length scales (3). A particularly intriguing phenomenon in such systems is the emergence of flat bands (4) and associated wave localization, which have played a key role in the discovery of superconductivity (5) and correlated insulators (6).

While atomic crystal structures and their van der Waals (vdW) interactions are inherently dictated by material properties, photonic moiré superlattices offer unique advantages, such as the ability to precisely control interlayer interactions and engineer a diverse range of photonic crystal geometries (7). The realizations of these effects in photonic systems are appealing for potential applications such as slow light and strong light-matter coupling (8, 9). In this context, moiré physics has been explored using various twisted two-dimensional (2D) lattice configurations, including Bravais, honeycomb, and Kagome lattices (10–19). Twisted 1D gratings have also been reported (20–25), primarily focusing on optical chirality, while flat-band phenomena have remained barely explored in these systems.

In this work, we provide experimental demonstrations of moiré systems exhibiting strong interlayer coupling and cascades of ultrawide chiral flat bands. The strong interlayer coupling is achieved in the twisted bilayer grating (TBG) structure. Correspondingly, the resonant scattering through zone folding reveals the continuous interdimensional crossover from 1D grating ($\theta_t = 0^\circ$) to 2D square lattice ($\theta_t = 90^\circ$). The resonant conditions enabled by the strong coupling produce the robust magic-angle sequences for flat bands, with the geometrically predictable interpretation. These flat bands appear

sequentially with varying twist angles, forming cascades of flat-band states. Thus, the distinct symmetry of twisted bilayer 1D grating structures leads to unconventional scattering mechanisms, setting them apart from their 2D counterparts. To realize this concept experimentally, we implement TBG structures using WS₂, a transition metal dichalcogenide with a high refractive index that enables the transfer and stacking of ultrathin layers while also minimizing interlayer spacing, making it highly suitable for constructing well-defined bilayer photonic structures (26). In such bilayer structure, the breaking of vertical symmetry induces optical chirality, leading to the emergence of chiral flat bands in the TBG structure. Notably, these flat bands exhibit ultrawide characteristics compared to previously reported chiral flat bands in photonic systems (27, 28).

RESULTS

TBG structures

We consider a TBG structure, as schematically illustrated in Fig. 1A. This structure consists of two identical dielectric WS₂ gratings, stacked with a twist angle θ_t . Unlike 2D lattices, TBG exhibits distinct geometric characteristics (Fig. 1B), as they maintain a well-defined translational symmetry at arbitrary twist angles. These lattice transformations belong to the unimodular group, capturing smooth deformations such as squeezing, shear stress, and rotations. The top and side view of the unit cell of the TBG structure used for numerical calculations are shown in Fig. 1B. The top and bottom WS₂ gratings have identical parameters—thickness h , grating period a , and grating width w —and are placed on a quartz substrate.

We analyze the photonic dispersion of the TBG structures using rigorous coupled-wave analysis (RCWA). The simulated angle-resolved transmittance spectra along the x axis with varying twist angles are shown in Fig. 1C. At small twist angles, the spectrum reveals a Dirac-like band, characteristic of 1D gratings (29). As θ_t increases, additional quadratic dispersions emerge from the low-energy region and gradually blueshifts, while the Dirac-like band remains nearly unchanged (see Supplementary Movies for detailed evolution of dispersions).

The appearance of multiple quadratic bands and the evolution of their energies suggest that they originate from zone folding induced

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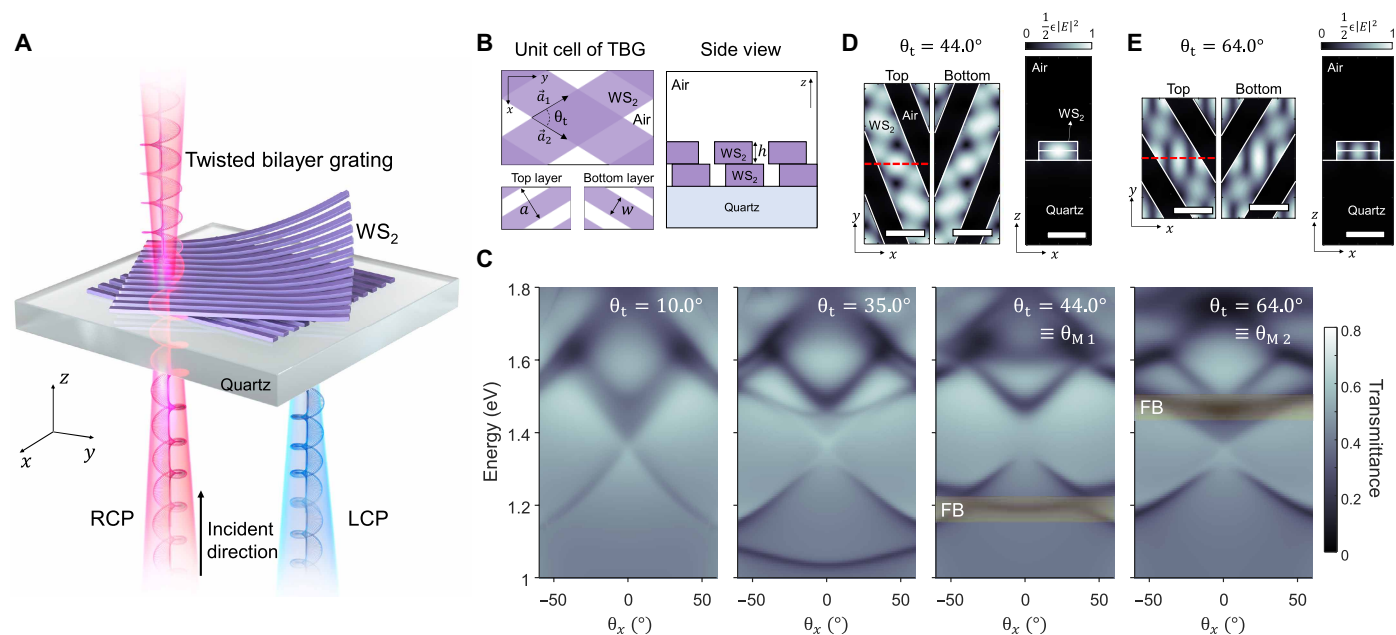


Fig. 1. Basic schematic of TBG structure. (A) Schematic of TBG structure consisting of two identical WS₂ gratings stacked with a twist angle θ_t between the top and bottom layers on a quartz substrate. Incident light propagates along the z direction. (B) Geometry of a unit cell with top and side views. In the top view, the grating period a , grating width w , and twist angle θ_t are defined, with $\vec{a}_1$ and $\vec{a}_2$ indicating the primitive lattice vector of the TBG superlattice. In the side view, each WS₂ grating has thickness h . (C) Simulated transmittance spectra of the TBG for various twist angles, at $\theta_t = 10.0^\circ, 35.0^\circ, 44.0^\circ$, and 64.0° along the x axis. Flat bands (FB) are indicated with yellowish boxes. (D and E) Simulated electric field energy density distributions for $\theta_t = \theta_{M1}$ and θ_{M2} , respectively. Left and middle panels show the electric-field profiles in the xy plane taken at the central positions of the top and bottom WS₂ layers, while the right panels show the xz cross sections along the red dashed line. Scale bars, 200 nm (white).

by the moiré superlattice in the TBG structures. Over a broad range of twist angles, clear avoided crossings between the Dirac-like and quadratic bands are observed, indicating strong interband coupling. As a result of this strong hybridization, a flat band emerges at a twist angle of approximately $\theta_t = 44.0^\circ$. Notably, the flat band persists over an exceptionally wide flat-band width of about $\pm 30^\circ$, significantly exceeding previously reported values in photonic systems (27, 30–34). As the twist angle increases further, an additional flat band emerges near $\theta_t = 64.0^\circ$, following similar band evolution. We refer to the twist angles at which flat bands emerge as magic angles. In this work, the magic angle near 44.0° is denoted as θ_{M1} , and the one near 64.0° is denoted as θ_{M2} (see supplementary note S1 for the definitions of magic angle and flat-band width). The detailed evolution of band dispersions with varying twist angle is provided in fig. S3. We also confirm the presence of flat bands across TBG structures with varying grating parameters, including thickness and grating period. While the energy level of the flat band shifts with these changes, the twist angles at which flat bands form—the so-called magic angles—remain nearly invariant. This robustness highlights the geometric origin of flat-band formation in these structures (see figs. S4 and S5).

The simulated electric field (E-field) energy density distributions at the two magic angles, θ_{M1} and θ_{M2} , are shown in Fig. 1 (D and E), respectively. The E-field energy density profiles in the xy plane taken at the center of the top and bottom WS₂ layers are shown in the left and middle panels. Corresponding xz cross-sectional distributions are obtained by horizontally slicing along the central line of the xy plane (red dashed lines) and are shown in the right panels. The strong E-field energy density distribution within the WS₂ layers confirms that the observed photonic bands originate from guided

resonance modes (GMRs). These GMRs are established as external excitation light couples to the photonic bands, manifesting as distinct transmittance minima in the far-field spectra.

Mechanism of ultrawide flat-band cascades

The avoided level crossing originates from Umklapp scattering that couples the states at k and k' across the extended Brillouin zone (BZ). To elucidate the resulting flat-band cascades, we use a coupled-mode Bloch Hamiltonian and analyze the bands in the extended BZ framework, where the coupled momenta k and k' satisfy the relation as

$$k' = k + m\vec{b}_1 + n\vec{b}_2, (m, n \in \mathbb{Z}) \quad (1)$$

Here, $\vec{b}_1$ and $\vec{b}_2$ are the primitive reciprocal lattice vectors. The reciprocal space in the extended BZ is illustrated in Fig. 2A, where the dots represent momenta coupled through the zone folding for twist angles $\theta_t = 0^\circ, \theta_{M1}$, and θ_{M2} . In the absence of interlayer interaction, only between the lateral momenta along the 1D directions ($m = 0$ or $n = 0$, indicated by red dots) are coupled by the lowest-order scattering, thereby preserving the inherent character of the single-layer structure. Consequently, the corresponding bands remain degenerate at the Γ -point and exhibit Dirac-like dispersion along the x direction, as shown in the top row of Fig. 2B. Conversely, the finite interlayer coupling introduces the higher-order scattering involving off-lateral momentum modes ($m \neq 0, n \neq 0$; blue dots). This higher-order scattering generates a quadratic dispersion band emerging from the moiré lattice, as shown in the bottom row of Fig. 2B. These theoretical predictions are confirmed by RCWA simulations (see fig. S6).

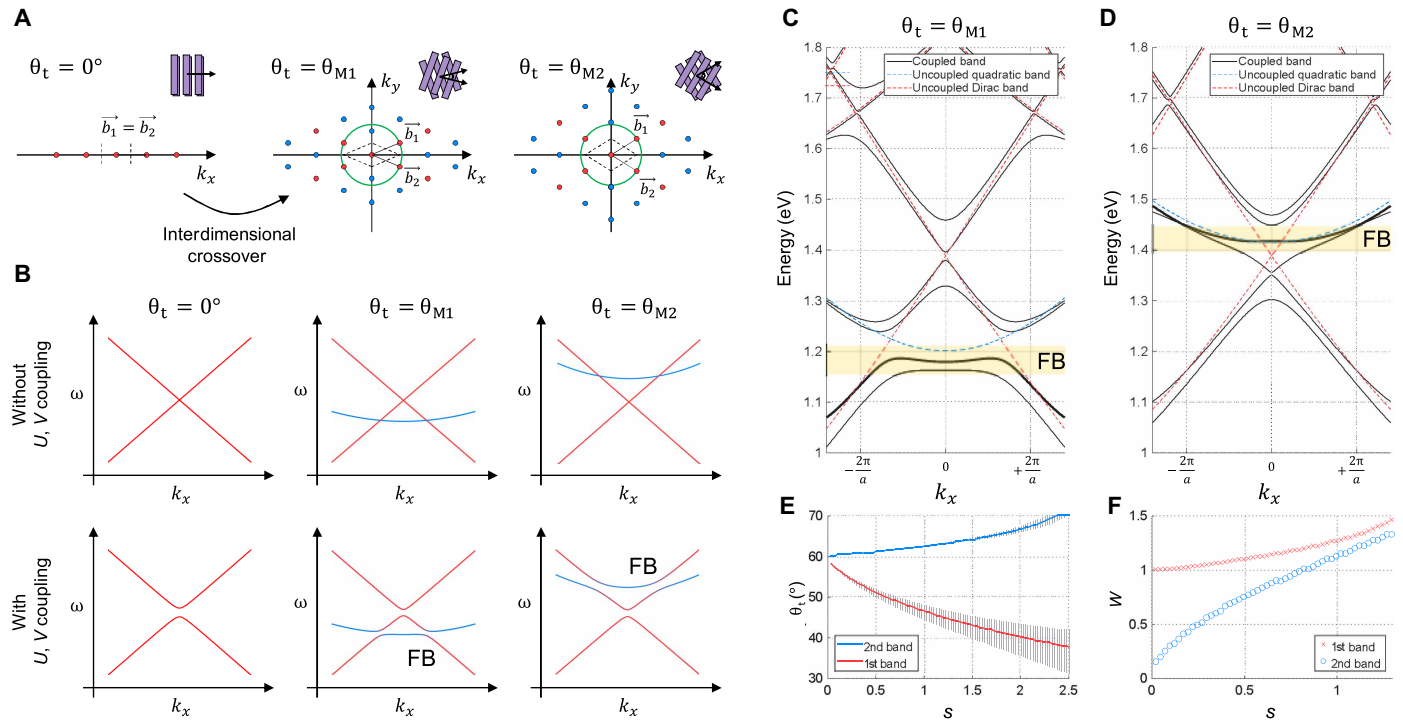


Fig. 2. Formation of flat-band dispersion. (A) Schematic of BZ folding in reciprocal space as a function of twist angle θ_t . The reciprocal vectors $\vec{b}_1$ and $\vec{b}_2$ define the BZ of superlattice. Red (blue) dots indicate the zone centers of the Dirac-like (quadratic) band, while the green circles indicate iso-energy contours. (B) Illustrative dispersions for different twist angles θ_t , showing Dirac-like (red) and quadratic (blue) bands, obtained as line cuts at $k_y = 0$ from the momentum space shown in (A). The top row shows the noninteracting case, while the bottom row shows the effect of band coupling, which leads to the formation of flat bands. (C and D) Calculated band structures at twist angles $\theta_t = \theta_{M1}$ and θ_{M2} , in the absence (dashed lines) and presence (solid lines) of band coupling. Hybridization between the Dirac and quadratic bands forms a flat band, which is indicated with yellowish boxes. (E) Magic angle versus the interband coupling strength. Colored lines (red and blue) correspond to the flat band in (C) and (D); the gray region indicates where the effective mass $m_{\text{eff}} > 1$. (F) Relative flat-band width as a function of the coupling scale factor s , where $s = 1$ corresponding to the experiment fitted parameter set.

During the interdimensional crossover from 1D to 2D driven by the increased interlayer couplings, the hybridization between the Dirac-like bands (originated from the 1D grating) and quadratically dispersive bands (from the moiré lattice) triggers a Lifshitz transition (35). At the transition point, the change of the Fermi surface topology inverts the band curvature at Γ ($m^* = \partial^2 \omega / \partial k^2|_{k=\Gamma}$), which underpins the mechanism for observed flat-band formation.

As the twist angle is varied, lateral momenta remain fixed along the constant-energy contour of the light cone in the BZ. Meanwhile, the off-lateral momenta undergo an energy shift dependent on the twisted angle due to the changing orientation of the reciprocal lattice vectors, with $\vec{b}_1 \cdot \vec{b}_2 = |\vec{b}_1| |\vec{b}_2| \cos(\theta_t)$. Notably, when these shifted quadratic bands energetically resonate with the Dirac bands, the strong band hybridization is pronounced, leading to the band flat-tening. The geometric consideration shows that the resonance occurs for any angle $\theta_t = 2\arcsin\left(\frac{p}{2q}\right)$ where p and q are arbitrary integers (see supplementary note S2 for detailed explanation). Because the resonance condition follows from geometry of zone-folding alone, it is insensitive to the material-specific parameters. To theoretically capture these phenomena, we introduce a Bloch Hamiltonian $h(\vec{k})$ expressed within the coupled-mode basis as (36), $h(\vec{k}) = \sum \left[a(\vec{k} + \vec{g})^2 \delta_{\vec{g}, \vec{g}'} + W_{\vec{g}, \vec{g}'} \right]$ where $\vec{g} = m\vec{b}_1 + n\vec{b}_2$,

a is a mass constant, and $W_{\vec{g}, \vec{g}'}$ represents the coupling strength between different BZs. We focus on the leading-order coupling model by considering the coupling between the nearest-neighbor BZs ($-1 \leq m, n \leq 1$), as depicted in Fig. 2A. The effective Hamiltonian takes the explicit form as

$$h_{\text{eff}}(k_x) = \begin{pmatrix} v_{\text{eff}} k_x & U & V \\ U & -v_{\text{eff}} k_x & V \\ V & V & \frac{1}{2m} k_x^2 + E_{\text{shift}} \end{pmatrix} \quad (2)$$

where $v_{\text{eff}} = \cos\left(\frac{\theta_t}{2}\right)$, $m = 2qb \sin\left(\frac{\theta_t}{2}\right)$, $E_{\text{shift}} = 2qb \sin\left(\frac{\theta_t}{2}\right) - pb$, and U and V represent intralayer and interlayer coupling strength, respectively (see fig. S7). By comparing theoretical predictions and experimental observations, we extract Hamiltonian parameters (see supplementary note S2 for the detailed analysis). Notably, we find that the interlayer coupling strength, $V \sim 0.5 U$, approaches that of the intralayer coupling U , directly confirming that our system resides in a strongly coupled regime of the moiré superlattice.

The calculated band structures from Bloch Hamiltonian $h(\vec{k})$ with (solid lines) and without (dashed lines) couplings U and V at twist angles $\theta_t = \theta_{M1}$ and θ_{M2} are shown in Fig. 2 (C and D),

respectively. The flat bands do not form exactly at the resonance condition ($E_{\text{shift}} = 0$) but instead arise when quadratic dispersions are suppressed by coupling effects, adjustable via E_{shift} or twist angle θ_t . Stronger coupling enhances the suppression of quadratic bands, necessitating a larger E_{shift} . A larger E_{shift} causes the band crossing between quadratic and Dirac bands to occur at larger momentum, thereby broadening the flat-band range. Consequently, we can control both the magic angle and the flat-band width of the flat band with varying coupling strength.

To visualize how the flat-band features evolve with coupling strength, we introduce a dimensionless scaling factor s that uniformly scales the effective couplings in Eq. 2, i.e., $U \rightarrow sU$ and $V \rightarrow sV$. Here $s = 1$ corresponds to the experimentally fitted parameter set used throughout this work, while $s = 0$ represents the uncoupled limit. The magic angle as a function of the coupling scale s is shown in Fig. 2E, where the magic angle is identified as the angle at which the band becomes maximally flat near the Γ point. As the coupling is enhanced, the magic angle shifts away from the first resonance angle $\theta_r = 60^\circ$ (dashed line). The relative flat-band width is computed from the SD of the energy, $\sigma(k_{\text{cut}})$ evaluated within the momentum window $|k| < k_{\text{cut}}$, shown in Fig. 2F. For each value of s , $\sigma(k_{\text{cut}})$ is normalized by σ_{max} , defined as the value of σ at the largest k_{cut} considered, yielding a curve that rises monotonically from 0 to 1. The flat-band width is then identified as the k_{cut} at which $\sigma/\sigma_{\text{max}}$ first reaches a fixed threshold (here 0.5). In the figure, the resulting bandwidth is normalized by its value at $s = 1$, denoted $W_{s=1}$. A band that remains flat over a wider momentum range suppresses $\sigma/\sigma_{\text{max}}$ at small k_{cut} , pushing the crossing point to larger k_{cut} and thus yielding a larger width. The theoretical relationship between the coupling strength and the flat-band range is further supported by the results shown in Fig. 2F. These theoretical predictions are confirmed by

RCWA simulations. In the calculation, we change the thickness of Al_2O_3 layer between the bilayers to tune the interlayer interaction effectively. As the interlayer gap increases, the two magic angles for flat-band formation approach each other, and the flat-band width gradually decreases (figs. S8 to S11).

Experimental realization of ultrawide flat bands in TBG structures

For experimental demonstration, we fabricate the WS_2 TBG using a precise two-step electron-beam lithography (EBL) method (37, 38), which enables the creation of multiple twist angles within the same flake while ensuring uniform thickness and accurate angular control. The fabrication process of the TBG structure is illustrated in Fig. 3A. A 50-nm-thick WS_2 flake is first exfoliated onto a quartz substrate, followed by EBL patterning and dry etching. A thin Al_2O_3 layer is then deposited to protect the bottom structure from etching process (39). The thickness of the Al_2O_3 layer is ~ 5 nm, which is sufficiently thin to preserve the flat-band behavior (see supplementary note S3). Subsequently, a second WS_2 flake is transferred on the Al_2O_3 -coated bottom grating layer, and overlay lithography and etching are performed to form the top grating with a well-defined twist angle.

Optical micrographs of an array of fabricated TBGs are shown in Fig. 3B. The grating structures in the bottom layer are marked with green squares, and the structures in the top layers are marked with red squares. The overlapping region of the TBG structure appears as a brighter gray contrast in the optical micrographs, indicating successful bilayer formation. Further confirmation is provided by scanning electron microscopy (SEM) images (Fig. 3C), which verify that the upper and lower grating layers are well aligned and maintain consistent twist angles across the sample.

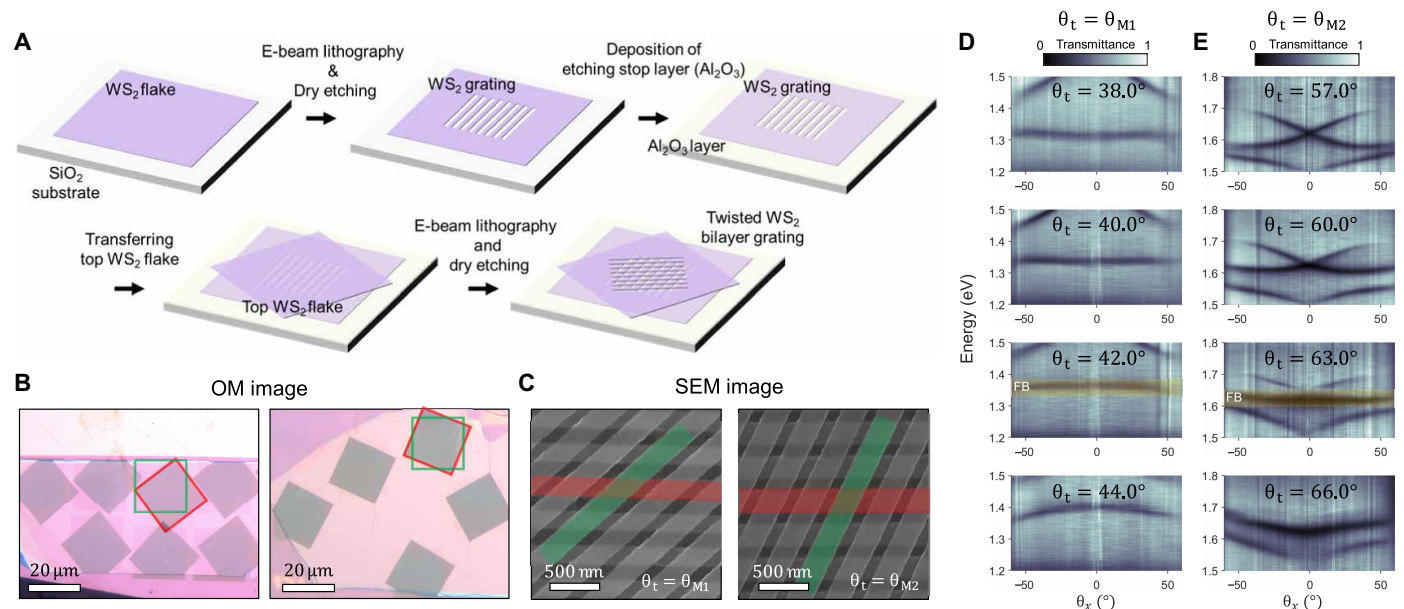


Fig. 3. Experimental realization of flat bands. (A) Schematic of fabrication process: WS_2 flake on a quartz substrate is prepared. The EBL and dry-etching process fabricate the grating pattern on the WS_2 flake. The Al_2O_3 layer is deposited by atomic layer deposition. Another WS_2 flake is stacked on the structure. Again, the patterning process is carried out with different twist angles. (B) Optical image of TBG. The blue square represents the bottom grating region, while the red square represents the top grating region. (C) Scanning electron microscopic image of TBG structure. OM, optical microscopy. (D and E) Angle-resolved transmittance spectra of TBG for different twist angles around $\theta_t = \theta_{M1}$ and θ_{M2} .

We measure the angle-resolved transmittance spectra of the TBG structures using a Fourier spectroscopy setup, with the TBG aligned to probe dispersion along the x axis (see Fig. 1B). The measured angle-resolved transmittance spectra near $\theta_t = \theta_{M1}$ and θ_{M2} are shown in Fig. 3 (D and E), respectively. As the twist angle varies, the spectra reveal changes in the curvature and convexity of the photonic bands, with flat-band formation observed around 1.24 and 1.58 eV, respectively. These flat bands persist over an exceptionally wide angular range, approximately from -50° to $+50^\circ$, far broader than previously reported values.

The experimental observations are in excellent agreement with the numerical calculation (see fig. S3). In particular, the transition of effective mass sign and the resulting avoided crossings between the Dirac-like and quadratic bands are well reproduced, validating the predicted mechanism of flat-band formation in twisted 1D photonic lattices. In addition, a sequence of magic angles at which flat bands appear is identified, each corresponding to a different resonance condition. The accompanying Lifshitz transition reflects the topological protection of the flat dispersions at the magic angles (35). A discrepancy in the magic angle is observed between experiment and

calculation, likely due to parameter uncertainties (e.g., refractive index and geometric dimensions), while the overall trend remains consistent.

Intrinsic optical chirality in TBGs

The TBG structure breaks both in-plane and out-of-plane mirror symmetries due to the relative rotation and vertical stacking of two twisted grating layers. This symmetry breaking enables the emergence of intrinsic optical chirality. To investigate this effect, we measure the angle-resolved circular dichroism (CD) spectrum. In Fig. 4A, the TBG for $\theta_t = \theta_{M2}$ exhibits a pronounced CD of about 0.45 at the flat-band energy of 1.6 eV, indicating strong optical spin-selective light-matter interaction. To verify whether the observed CD at 1.6 eV arises from intrinsic chirality rather than geometric projection effects, we analyze the full transmittance matrix under circularly polarized illumination (Fig. 4B). The matrix consists of four components: T_{LL} and T_{RR} , representing spin-preserving transmittance for left and right circular polarization (LCP and RCP) and T_{LR} and T_{RL} , representing polarization conversion between LCP and RCP. At the flat band of energy of 1.6 eV, only the T_{LL} component exhibits a

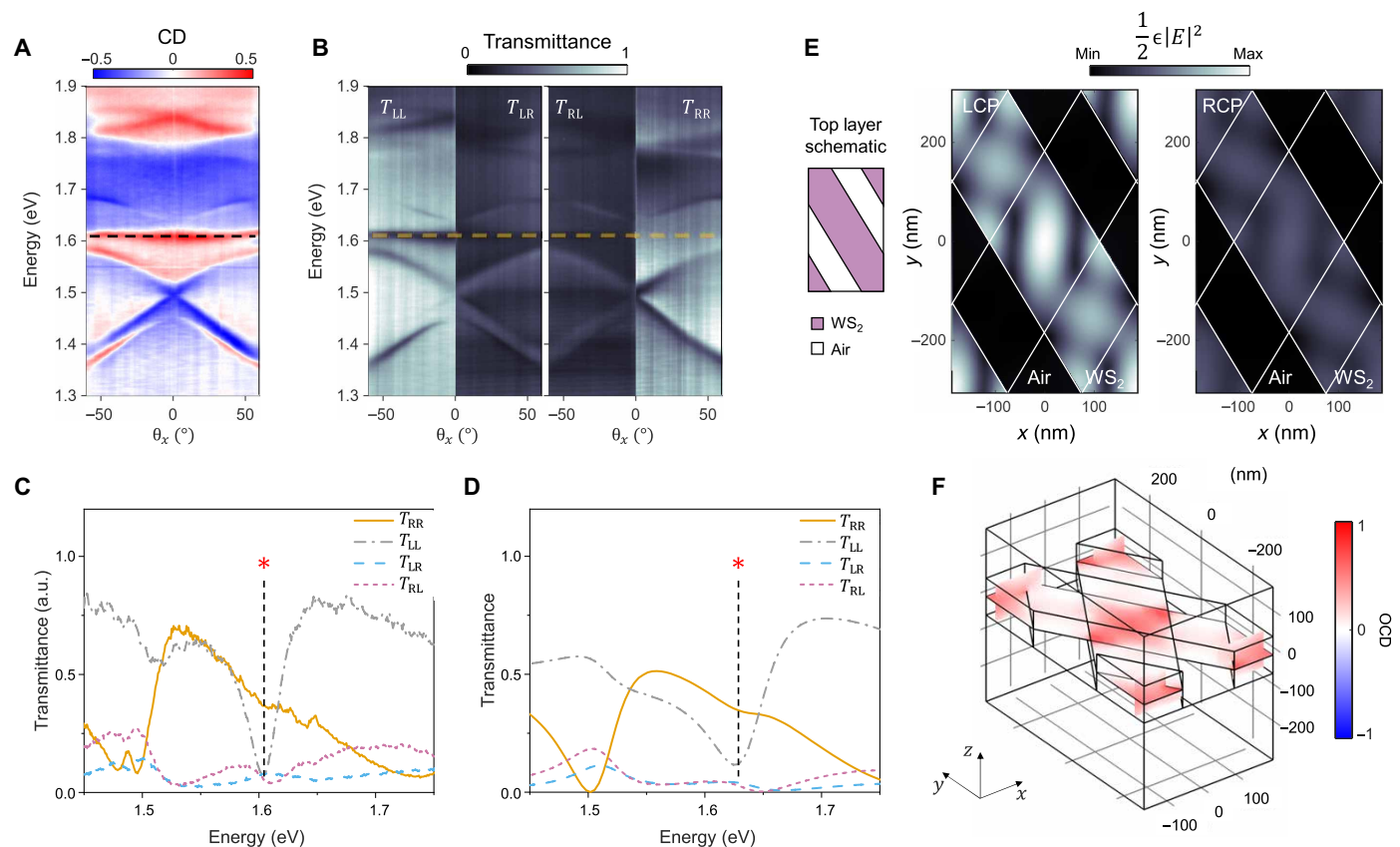


Fig. 4. Intrinsic optical chirality in twisted bilayer gratings. (A) Measured angle-resolved CD spectrum at $\theta_t = \theta_{M2}$. The dashed line denotes the energy of the chiral flat-band mode. The dashed line indicates the chiral flat-band resonance at 1.6 eV. (B) Measured angle-resolved transmittance matrix components (T_{RR} , T_{RL} , T_{LR} , and T_{LL}) under circularly polarized illumination. Because of mirror symmetry in the momentum space, each component is plotted by combining two symmetric halves. (C) Polarization-resolved transmittance spectra measured at normal incidence ($\theta_x = 0$). The asterisk marks the spectral dip associated with the chiral flat-band resonance. (D) Numerically calculated polarization-resolved transmittance spectra under normal incidence. The asterisk marks the resonance position of the chiral flat band at 1.6 eV. (E) Simulated E-field energy density distribution at 1.6 eV under RCP and LCP excitation. The field is strongly localized between the two gratings under LCP illumination, indicating spin-selective mode excitation. (F) Optical chirality density (OCD) distribution of the chiral eigenmode at 1.6 eV, showing strong chiral field localization within the overlapping region of the two gratings.

sharp transmittance dip, while T_{RR} remains flat, and T_{RL} and T_{LR} are nearly zero—indicating that the chiral flat-band mode couples selectively and directly to LCP without inducing polarization conversion.

We further validate these features by examining the transmittance matrix at normal incidence, presented in Fig. 4 (C and D), which represent cross-sectional data from Fig. 4B. Both experimental and simulated spectra consistently show the same optical spin-selective signature: a pronounced dip in T_{LL} at 1.6 eV, with all other components remaining featureless. These results confirm that the chiral mode is helicity preserving and cannot be attributed to asymmetric excitation, supporting its classification as an intrinsically chiral photonic flat band.

To understand the origin of this intrinsic chirality, we perform finite element method (FEM) simulations of the near-field distribution. As shown in Fig. 4E, under LCP illumination, the E-field is strongly concentrated in the overlapping region of the TBGs, whereas RCP illumination results in relatively negligible field concentration. We quantify the local chirality by calculating optical chirality density (OCD), defined as $\tilde{\chi}_l = \left(\frac{c}{\omega}\right) \text{Im}[D^* \cdot B]$ (40). The simulated OCD distribution in Fig. 4F reveals intense local angular momentum density concentrated at the overlapping grating region, consistent with the formation of a spin-polarized eigenmode.

A comparison with the lower-angle flat-band condition ($\theta_l = \theta_{M1}$) further highlights the geometrical origin of the intrinsic chirality. As shown in fig. S12, the CD contrast at θ_{M1} is significantly reduced, accompanied by the appearance of cross-polarized transmission components (T_{RL} and T_{LR}), indicating polarization mixing. Near-field simulations (fig. S13) show that the field distributions under LCP and RCP illumination remain largely similar, in contrast to the strongly spin-selective response observed at θ_{M2} (fig. S14).

These differences arise from the geometry of the twisted anisotropic gratings. At θ_{M2} , the relative rotation produces a unit cell with a higher degree of symmetry breaking, supporting a robust intrinsically chiral mode. In contrast, the reduced asymmetry at θ_{M2} leads to increased polarization mixing and a weaker, less robust chiral response. Together, these results demonstrate that the chiral flat band at θ_{M1} originates from a geometrically induced intrinsic chiral eigenmode enabled by strong interlayer coupling.

DISCUSSION

In summary, we realize the TBG in the strong interlayer coupling regime that is unattainable in electronic systems. The enhancement of the interlayer interaction is attributed to the strong wave function overlapping between layers in the photonic platform. As a result, flat-band formation persists even at relatively large twist angles, enabled by the strong interlayer coupling in the photonic structure. Moreover, we emphasize that the flat-band width is exceptionally wide, even compared to previously reported photonic platforms. This is primarily attributed to the high refractive index of WS_2 . When using other optical materials for the same TBG structure—such as hBN (41), a typical vdW material—the flat-band width becomes narrower (see fig. S15). This behavior can be understood by considering that the slope of the Dirac-like band (i.e., the group velocity) is inversely proportional to the refractive index. A lower index leads to a steeper Dirac-like dispersion and a reduced effective mass in the quadratic band, thereby limiting the extent of the flat band in momentum space.

We note that the mechanism responsible for flat-band in our system differs from that of previously reported moiré flat-bands. In twisted 2D lattices, the formation of flat bands with large moiré superlattices leads to real-space localization of optical modes within each superlattice. In contrast, the flat bands in our twisted grating system arise from strong band hybridization, mediated by twist-induced Umklapp scattering. The resulting avoided crossings suppress the group velocity and produce flat dispersions over a broad momentum range. Unlike conventional moiré platforms that rely on large superlattice formation, our mechanism enables flat-band formation without requiring a substantial expansion of the unit-cell size. In typical moiré systems, the superlattice period can be an order of magnitude larger than the original lattice, whereas in our system, the flat band condition is achieved with an effective structural period only ~ 2 to 3 times the original lattice constant. This allows access to flat-band physics at a much shorter length scale.

In addition, 1D twisted grating system has structural robustness compared to conventional 2D moiré lattices. While 2D systems exhibit spatially varying stacking that makes their optical response highly sensitive to interlayer translation, the 1D grating remains spatially uniform and globally periodic at any twist angle. This translation-insensitivity ensures stable implementation, as the flat-band characteristics are preserved regardless of the precise lateral alignment between the layers. Moreover, the flat-band feature in our system remains robust against small variations in the twist angle, as changes of 1° to 2° do not suppress or modify the flat-band behavior (fig. S3). This robustness arises through strong interlayer coupling in the photonic system (7), in contrast to conventional electronic systems, where the band structure is highly sensitive even to sub-degree variations in the twist angle (4).

A key advantage of bilayer photonic crystals based on vdW materials is their combination of structural tunability and ease of fabrication. In contrast to conventional dielectric materials, which typically require complicated planarization or additional deposition steps that introduce a finite spacer layer (42, 43), vdW materials enable direct transfer stacking without planarization, allowing precise control of the interlayer spacing and potentially reducing the separation gap to near zero (26).

Our theoretical model suggests that flat-band formation does not necessarily require a twisted bilayer structure. For example, a single-layer diamond-patterned photonic crystal, which integrates the geometry of two layers into one patterned layer, can exhibit a band structure similar to that of a twisted bilayer system. Our analysis of TBG provides fundamental insights into the conditions that foster flat-band emergence, offering a robust theoretical framework for designing novel geometries that support flat bands. Nonetheless, a bilayer configuration introduces optical chirality, which is absent in the single-layer counterpart, making it particularly advantageous for applications that require chiral optical response.

Furthermore, the flat-band response in the present TBG structure provides a directional form of flat-band engineering because the flat-band conditions along k_x and k_y do not coincide (fig. S18). Although a fully isotropic 2D flat band is not realized in this system, practical photonic applications remain feasible within this anisotropic framework. In particular, the anisotropic flat-band dispersion is suitable for direction-selective slow light and enhanced photonic density of states along a chosen propagation direction. These anisotropic flat-band behaviors support practical photonic functionalities,

as demonstrated by room-temperature lasing at flat-band bound states in the continuum (33) and directional flat-band lasing in silicon waveguide-integrated metasurfaces (34). More in general, the ability to manipulate flat bands in photonic systems holds significant potential for applications requiring a high optical density of states, such as enhanced Purcell effects (44, 45), lasing (18, 34), and other strong light-matter interaction phenomena (18). In this context, our TBG platform combines a directional slow-light response with intrinsic optical chirality, providing a route toward spin-selective slow light and chiral light-matter interactions, and opens pathways for novel photonic applications leveraging the unique properties of moiré photonic systems.

The flexibility of photonic structures plays a key role in this work. Unlike atomic systems, photonic platforms allow for the design of complex geometries that are otherwise unfeasible. The intrinsic localization associated with the flat-band formation highlights how the interplay between strong interlayer coupling and nontrivial intralayer ordering can stimulate novel research directions within condensed matter physics. Our work thus presents an ideal platform for investigating future moiré-based materials.

MATERIALS AND METHODS

Sample fabrication

TBG structures were fabricated using 50-nm-thick multilayer WS₂ flakes through a series of nanofabrication processes. The WS₂ flakes were mechanically exfoliated from bulk crystals (2D semiconductors) and transferred onto a quartz substrate using a polydimethylsiloxane stamping method. To fabricate the bottom grating structure, EBL was performed at 30 keV on a positive e-beam resist (AR-P 6200.09, Allresist) spin coated at 4000 rpm for 45 s, followed by a soft bake at 180°C for 1 min. To suppress surface charging during EBL, a conductive polymer (ESPACER 300Z, Resonac) was spin coated at 2000 rpm for 40 s. The developed patterns were obtained using amyl acetate for 7 min, followed by a rinse with isopropyl alcohol for 30 s. Inductively coupled plasma reactive ion etching was then used to etch the grating structure on the WS₂ flakes. The etching was performed under the following conditions: SF₆ [40 standard cubic centimeter per minute (SCCM)] and O₂ (10 SCCM) gas flow, with a bias and source power of 50 W, for a duration of 40 s. After etching, the remaining resist was removed using a resist remover (AR 600-71, Allresist). A conformal 5-nm-thick Al₂O₃ protective layer was deposited via atomic layer deposition to encapsulate and protect the bottom grating structure. To fabricate the top grating, an additional WS₂ flake was transferred onto the Al₂O₃ layer. Alignment marks enabled angle-controlled EBL to fabricate the top grating at a desired twist angle relative to the bottom layer. A similar etching process was then performed; however, the underlying Al₂O₃ layer served as an etch stop, preventing damage to the bottom grating. Last, any residual resist was removed, completing the fabrication of the twisted bilayer WS₂ grating structure.

RCWA simulation

Angle-resolved transmittance spectra of the TBG structure were calculated using RCWA developed in MATLAB. The used parameters are as follows: grating period a is 320 nm, grating width w is 192 nm, and grating thickness h is 50 nm for each layer. We assume the cover medium is air ($n_{\text{air}} = 1$), and the substrate is quartz with a refractive index $n_s = 1.48$ in the calculation. We assume permittivity

of WS₂ materials using the following Lorentz oscillator model, $\epsilon(E) = \epsilon_{\infty} + \sum \frac{f_m}{E_m^2 - E^2 - i\gamma_m E}$, where E is an energy, E_m is resonance energy, f_m is oscillator strength, and γ_m is damping coefficient for m th oscillator. $\epsilon_{\infty} = 12$, $E_1 = 1.97$ eV, $E_2 = 2.4$ eV, $E_3 = 2.69$ eV, $E_4 = 2.95$ eV, $f_1 = 0.83$ eV², $f_2 = 1.38$ eV², $f_3 = 3.18$ eV², $f_4 = 30$ eV², $\gamma_1 = 0.04$ eV, $\gamma_2 = 0.18$ eV, $\gamma_3 = 0.16$ eV, and $\gamma_4 = 0.52$ eV (46). The resultant refractive index of WS₂ is plotted in fig. S16.

FEM analysis

The near-field distributions and eigenmodes of the TBG and diamond-shaped photonic crystal structures were calculated using 3D FEM simulations implemented in COMSOL Multiphysics. The TBG structures were modeled as laterally infinite arrays on a quartz substrate. Bloch periodic boundary conditions were applied along the x and y directions, while perfectly matched layers were used along the z direction to prevent spurious reflections. To identify chiral eigenmodes, the eigenfrequency solver was used to extract their resonant frequencies and associated quality factors. To simulate the CD observed in angle-resolved transmittance experiments, a circularly polarized plane wave was incident from the substrate side at a tilted angle. The transmitted power, represented by the Poynting vector, was integrated over the simulation domain to obtain the angle-resolved transmittance spectrum.

Measurements

The angle-resolved transmittance spectrum is measured using a broadband plasma light source (XWS-30, ISTEQ) and the Fourier optics technique (see fig. S17). We use two microscope objective lenses to focus white light on the structure and to collect the transmitted light. The objective lens for focusing the white light has a magnification of $\times 20$ and a numerical aperture (NA) of 0.95, and the objective lens for collecting the transmitted light has a magnification of $\times 40$ and an NA of 0.95. The transmitted light collected by the objective lens is collimated through a 4F lens alignment for obtaining a Fourier image, and the signal was measured by a spectrometer with a charge-coupled device detector. In addition, we use the vertical entrance slit of the spectrometer to slice only the $\theta_y = 0$ of the signals. Moreover, a quarter-wave plate, a half-wave plate, and a linear polarizer are used to select the polarization of light.

Supplementary Materials

The PDF file includes:

Supplementary Text
Figs. S1 to S18
Legends for movies S1 and S2

Other Supplementary Material for this manuscript includes the following:

Movies S1 and S2

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Acknowledgments: M.J.P. thanks C.-H. Yi and H. C. Park for discussions. **Funding:** This work was funded by the National Research Foundation of Korea (NRF) of the Korean government (MSIT) under grant nos. RS-2024-00335222 (D.C., S.-J.L., S.-W.C., D.-J.S., and S.-H.G.), RS-2025-25465325 (D.C., S.-J.L., S.-W.C., D.-J.S., and S.-H.G.), RS-2025-16070482 (C.B.B., S.P., and M.J.P.), RS-2026-25607155 (C.B.B., S.P., and M.J.P.), RS-2025-25446099 (C.B.B., S.P., and M.J.P.), RS-2025-03392969 (C.B.B., S.P., and M.J.P.), and RS-2026-25532741 (S.-W.C., D.-J.S., and S.-H.G.). **Author contributions:** Conceptualization: D.C., S.-J.L., S.P., M.J.P., and S.-H.G. Methodology: D.C., S.-J.L., S.-W.C., C.B.B., S.P., D.-J.S., and M.J.P. Software: D.C., S.-J.L., C.B.B., S.P., and M.J.P. Validation: D.C., S.-J.L., S.-W.C., S.P., D.-J.S., and M.J.P. Formal analysis: D.C., S.-J.L., S.-W.C., C.B.B., S.P., D.-J.S., and M.J.P. Investigation: D.C., S.-J.L., S.-W.C., C.B.B., S.P., D.-J.S., and M.J.P. Resources: D.C., S.-W.C., D.-J.S., M.J.P., and S.-H.G. Data curation: D.C., S.-W.C., S.P., and M.J.P. Writing—original draft: D.C., S.-J.L., C.B.B., S.P., D.-J.S., M.J.P., and S.-H.G. Writing—review and editing: D.C., S.-J.L., S.P., D.-J.S., M.J.P., and S.-H.G. Visualization: D.C., S.-J.L., S.-W.C., C.B.B., S.P., and M.J.P. Supervision: M.J.P. and S.-H.G. Project administration: M.J.P. and S.-H.G. Funding acquisition: M.J.P. and S.-H.G. **Competing interests:** The authors declare that they have no competing interests. **Data, code and materials availability:** All data and code needed to evaluate and reproduce the results in the paper are present in the paper and/or the Supplementary Materials. This study did not generate new materials.

Submitted 20 November 2025

Accepted 16 July 2026

Published 28 August 2026

10.1126/sciadv.aed8846

Strong interlayer coupling and chiral flat-band cascades in twisted bilayer gratings

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Sci. Adv. **12** (35), eaed8846. DOI: 10.1126/sciadv.aed8846

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