

Supplementary Information for

Thermally stable 2D YMnO₃ enabling blue visible camouflage with mid-infrared transparency

Ziyuan Zhu,^{1,†} Hanyuan Zhang,^{1,†} Rong Hu,² Yonggang Yao,^{2,*} Weilin Xu,^{1,*} and Jun Wan^{1,*}

¹ State Key Laboratory of New Textile Materials and Advanced Processing, Hubei Key Laboratory of Biomass Fibers and Eco-Dyeing & Finishing, Wuhan Textile University, Wuhan 430200, China. E-mail: wanj@wtu.edu.cn

² School of Materials Science and Engineering, State Key Laboratory of New Textile Materials and Advanced Processing, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China.

† These authors contributed equally to this work.

* Corresponding authors.

E-mail addresses: wanj@wtu.edu.cn (J. Wan); weilin_xu@wtu.edu.cn (W. Xu); yaoyg@hust.edu.cn (Y. Yao)

This PDF file includes :

Figs. S1 to S18

Tables S1 to S4

Table of Contents

Section 1. Shock confinement locks the 2D framework and Mn-O coordination rigidity	3
Section 2. Film formation defines a low-radiance boundary with cross-scale invariance	8
Section 3. The composition-phase boundary sets the visible-tuning space and the MIR-window threshold	10
Section 4. An MIR-transparent layer preserves the metallic IR boundary to close the dual-band strategy	11
Section 5. Supplementary tables for electronic-structure analysis and benchmark comparison	12

Section 1. Shock confinement locks the 2D framework and Mn-O coordination rigidity

Additional structural and spectroscopic evidence is provided in the Supporting Information. The large-area morphology of the product is further shown in Fig. S1, where SEM images reveal extended lamellar domains distributed across the sample, supporting the sheet-like growth behavior. AFM height profiles (Fig. S2) provide independent line-scan measurements of the apparent edge step heights of the nanosheets. Elemental distribution is presented in the EDS mapping images (Fig. S3), where Y, Mn, and O signals exhibit uniform spatial overlap across the sheet domains without detectable compositional segregation. Additional lattice-resolved HRTEM images (Fig. S4) further confirm the continuity of lattice fringes across the nanosheet structure. The reproducibility of phase formation across three independent microwave-shock synthesis batches is further verified by XRD patterns and Rietveld refinements, as shown in Fig. S5. Raman spectra covering the 100-1000 cm^{-1} range are shown in Fig. S6, displaying multiple phonon modes characteristic of hexagonal YMnO_3 . Additional Raman analysis for residual carbonaceous species is provided in Fig. S7. Surface chemical states are further analyzed by XPS (Fig. S8), where the core-level spectra of Y 3d, Mn 2p, and O 1s are presented with peak fitting details. Electron paramagnetic resonance measurements (Fig. S9) reveal only a weak signal at $g \approx 2.003$, indicating a low concentration of paramagnetic defect centers. The DFT-based charge-distribution and ELF analyses are shown in Fig. S10, while the polarized infrared reflectance fitting and extracted dielectric functions are provided in Figs. S11 and S12, respectively.

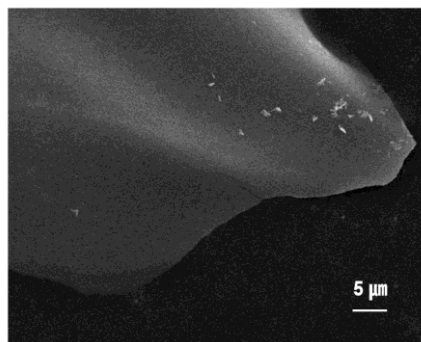


Fig. S1 Low-magnification SEM image of YMnO₃ nanosheets.

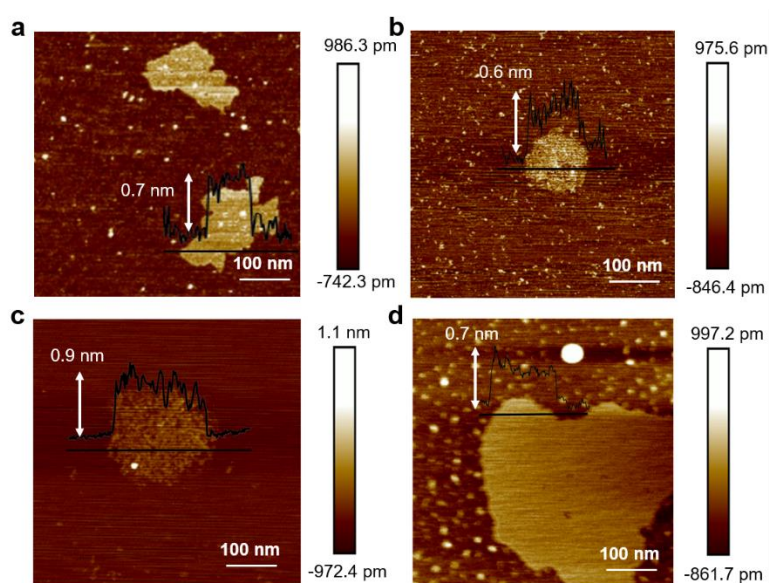


Fig. S2 AFM height profiles of YMnO₃ nanosheets.

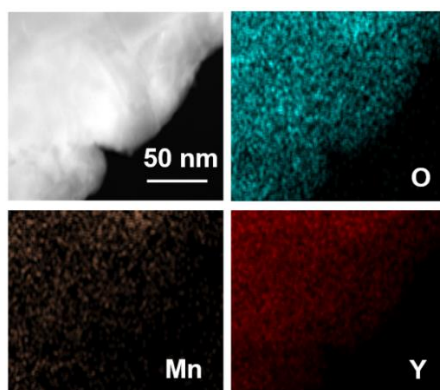


Fig. S3 EDS elemental maps of YMnO₃.

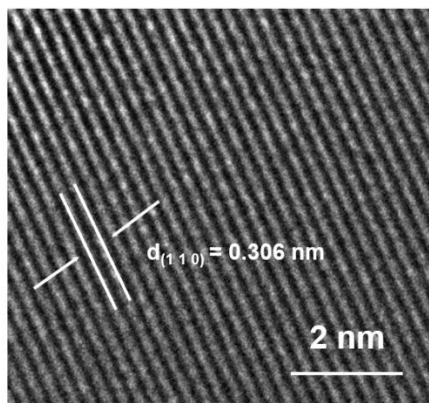


Fig. S4 Lattice-resolved HRTEM image of YMnO₃ nanosheets.

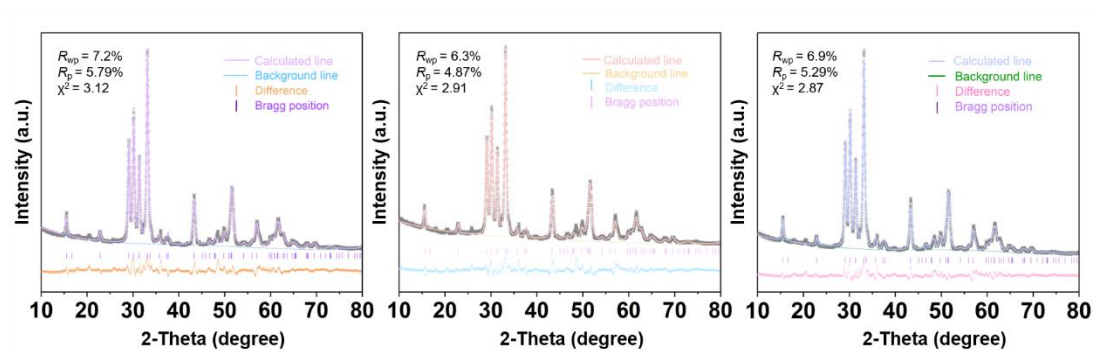


Fig. S5 Reproducibility of phase formation in repeated microwave-shock syntheses. XRD patterns and Rietveld refinements of YMnO₃ products from three independent synthesis batches.

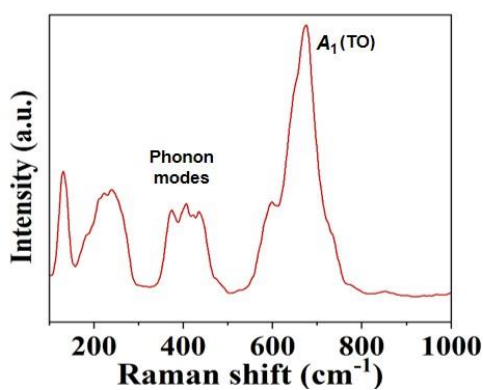


Fig. S6 Raman spectrum of YMnO₃ showing representative phonon modes, with the A₁(TO) feature marked.

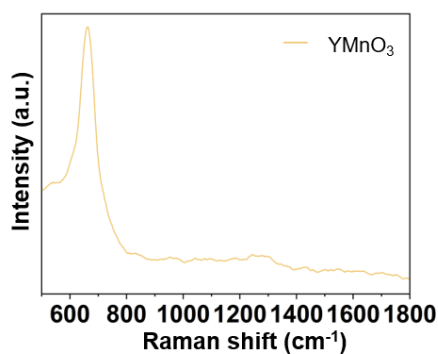


Fig. S7 Extended Raman spectrum of 2D YMnO₃ for evaluating residual carbonaceous species.

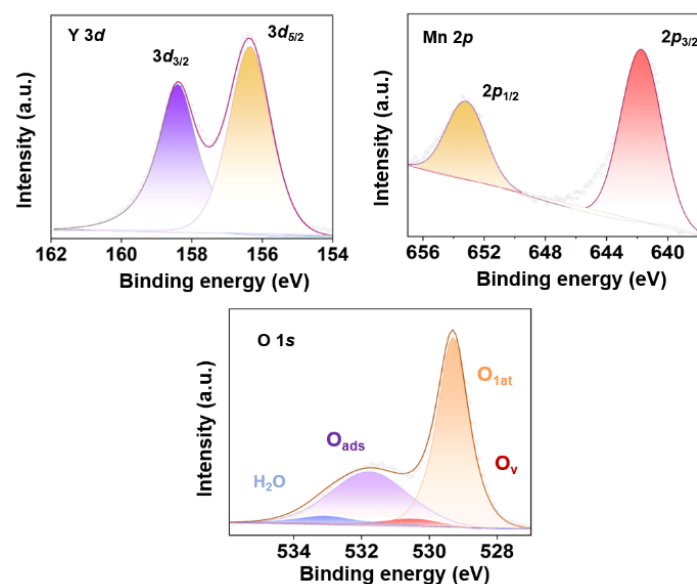


Fig. S8 High-resolution XPS spectra of the YMnO₃ nanosheets.

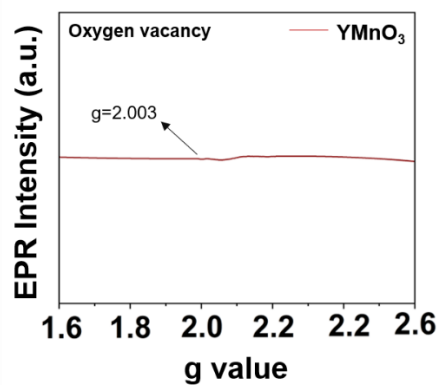


Fig. S9 EPR spectrum of the YMnO₃ nanosheets

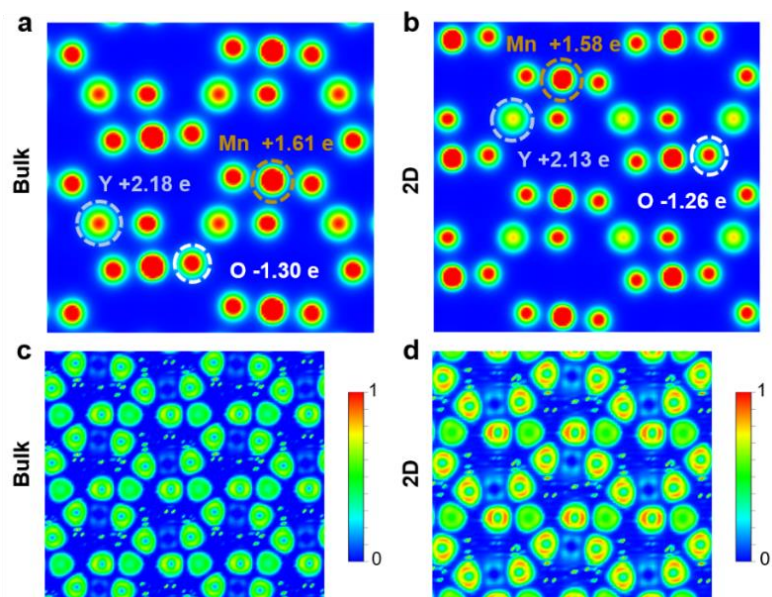


Fig. S10 DFT-based comparison of bulk and 2D YMnO₃. a, b, Bader charge distributions. c, d ELF maps plotted on a common 0-1 scale.

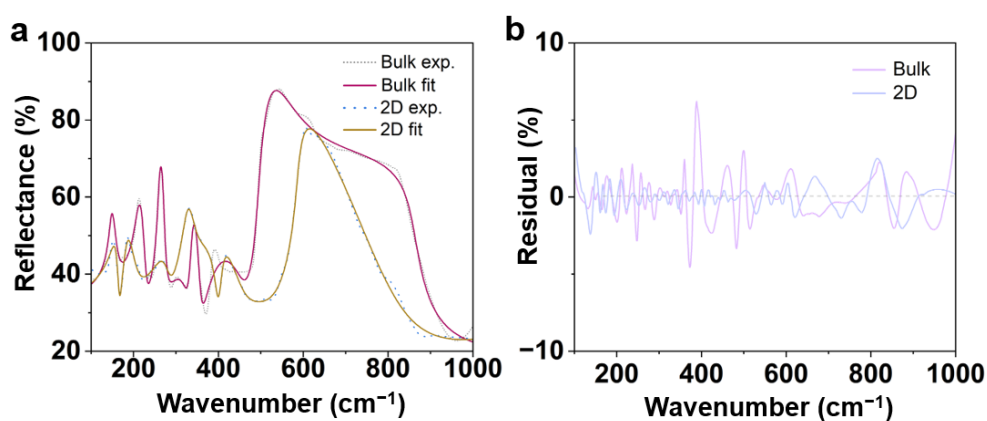


Fig. S11 Polarized infrared reflectance fitting and residual analysis of bulk and 2D YMnO₃. **a.** Experimental and FPSQ-fitted polarized infrared reflectance spectra of bulk and 2D YMnO₃. **b.** Corresponding fitting residuals, defined as $\Delta R = R_{\text{exp}} - R_{\text{fit}}$.

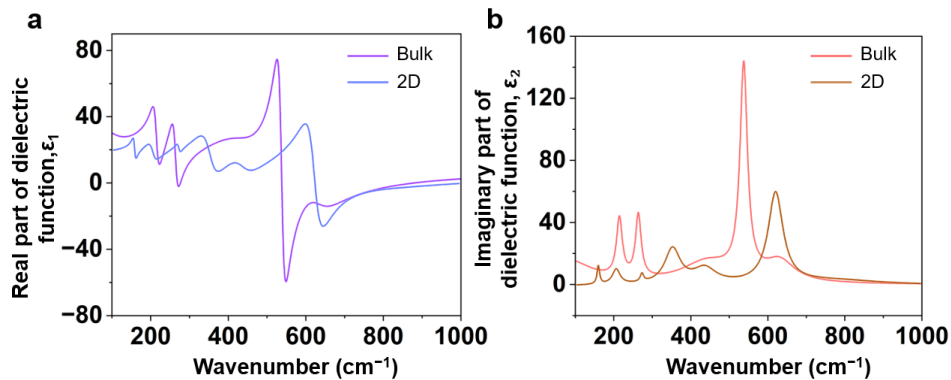


Fig. S12 Extracted dielectric functions of bulk and 2D YMnO₃. a, Real part, ϵ_1 ; narrowed and weakened negative- ϵ_1 Reststrahlen response in 2D YMnO₃. b, Imaginary part, ϵ_2 ; suppressed polar-phonon dielectric loss in 2D YMnO₃.

Section 2. Film formation defines a low-radiance boundary with cross-scale invariance

Fig. S13 presents the viscosity–shear rate relationship of the YMnO₃ nanosheet ink in comparison with a commercial blue ink. Fig. S14 shows the simulated spectral emissivity of the stainless steel (SLS) substrate used in the device-level evaluation. The broadband reflectance spectrum after prolonged air annealing is provided in Fig. S15, and the corresponding infrared thermographs before and after 900 °C/24 h air annealing are shown in Fig. S16.

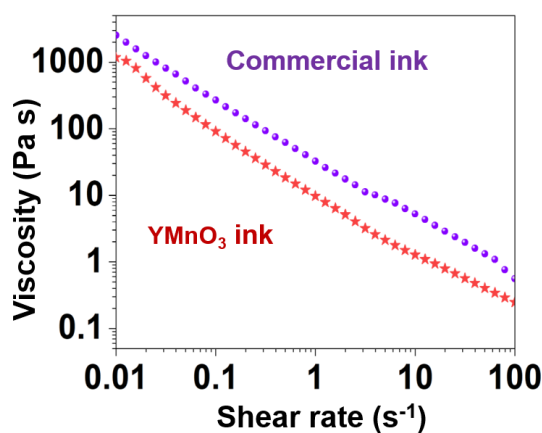


Fig. S13 Rheological properties of the YMnO₃ ink and a commercial blue ink, showing the measured viscosity as a function of shear rate.

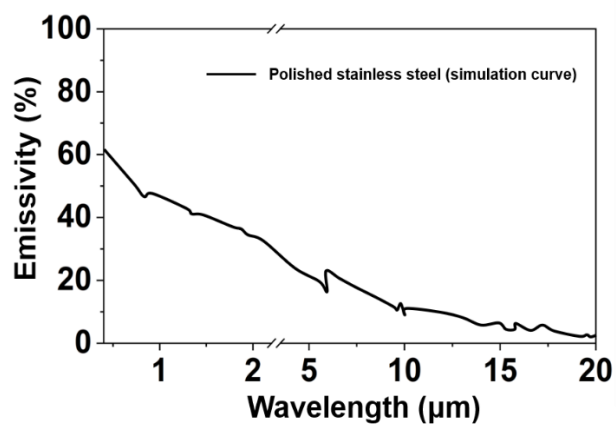


Fig. S14 Simulated emissivity spectrum of polished stainless steel.

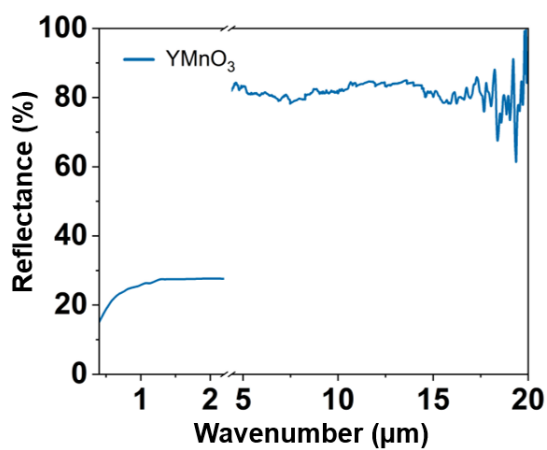


Fig. S15 Broadband reflectance spectrum of the YMnO_3 -coated sample after prolonged air annealing.

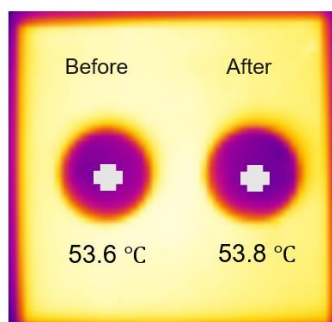


Fig. S16 Infrared thermographs of the coated sample before and after 900 °C/24 h air annealing under identical measurement conditions.

Section 3. The composition-phase boundary sets the visible-tuning space and the MIR-window threshold

Phase compositions of the samples with different x_{Mn} were quantified through Rietveld refinement using GSAS-II, and the refined phase weight fractions are summarized in Fig. S17. The refinement resolves the phase distribution among Y_2O_3 , YMnO_3 , and Mn_3O_4 as the Mn precursor fraction increases, providing quantitative support for the structural evolution discussed in the main text.

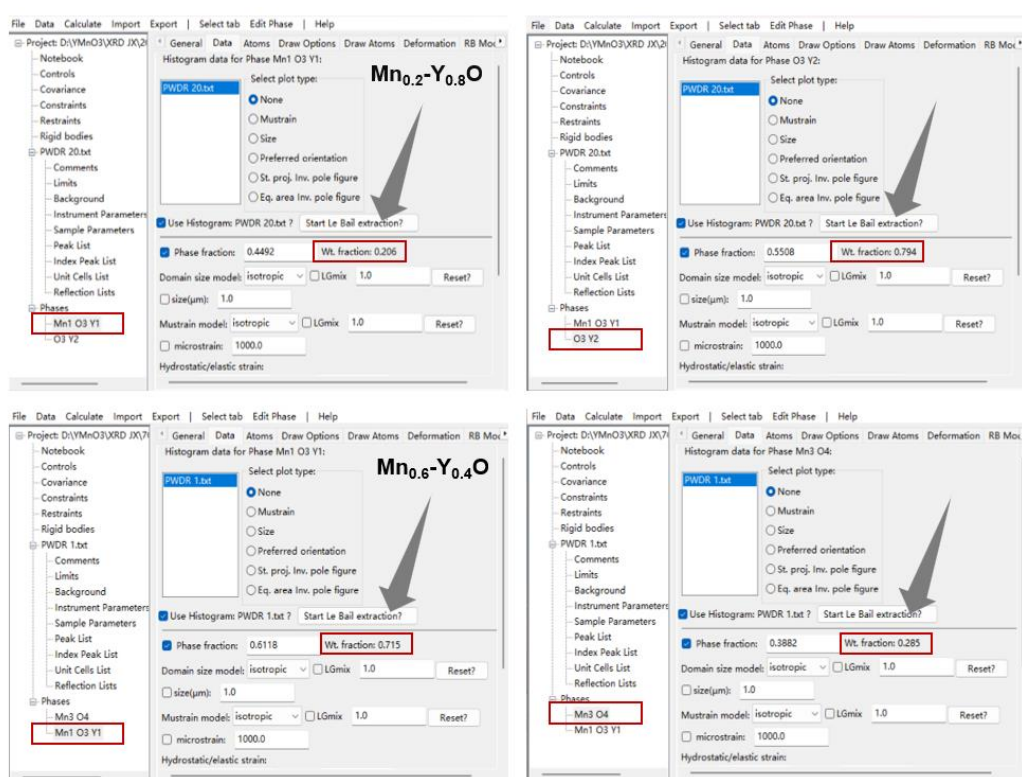


Fig. S17 Representative screenshots of the GSAS-II Rietveld-refinement interface showing the refined phase weight fractions used in Fig. 4f.

Section 4. An MIR-transparent layer preserves the metallic IR boundary to close the dual-band strategy

Fig. S18 presents the corresponding infrared thermography data for the steady-state hot-plate experiments across the entire temperature series. The thermographic images and extracted temperature distributions consistently show that the apparent temperature difference between the uncoated and YMnO_3 -coated surfaces increases progressively with the set temperature. This behavior provides experimental support for the amplification of ΔT observed in Fig. 5e and reflects the increasing influence of the low-emissivity metallic boundary condition on the detected radiance at elevated temperatures.

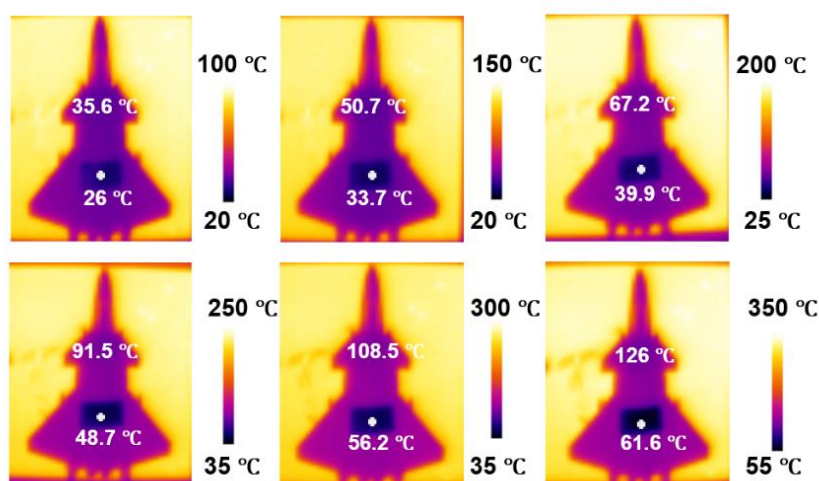


Fig. S18 Hot-plate IR thermography at 100-350 °C.

Section 5. Supplementary tables for electronic-structure analysis and benchmark comparison

Table S1 summarizes the Bader net-charge comparison of bulk and 2D YMnO₃, providing quantitative support for the DFT-derived charge-distribution analysis shown in Fig. S10. Table S2 lists representative LO–TO splitting values extracted from effective FPSQ fitting of polarized infrared reflectance spectra. Table S3 summarizes the mean dynamic effective charges estimated from infrared phonon oscillator strengths. Table S4 compares representative blue inorganic materials, MIR-transparent oxides, and selected ultrathin metallic films reported in the literature, including their visible coloration characteristics, MIR optical responses, configurations, and thermal stability.

Table S1. Bader net-charge comparison of bulk and 2D YMnO₃.

Structure	q_Y / e	q_{Mn} / e	$q_{O,avg} / e$	O-site charge range / e
Bulk	+2.18	+1.61	-1.26	-1.30 to -1.24
2D	+2.13	+1.58	-1.24	-1.26 to -1.22

Table S2. Representative LO-TO splitting values extracted from effective FPSQ fitting of polarized infrared reflectance spectra.

Mode	Sample	$\omega_{TO} / \text{cm}^{-1}$	$\omega_{LO} / \text{cm}^{-1}$	$\Delta\omega_{LO-TO} / \text{cm}^{-1}$	Reduction of $\Delta\omega_{LO-TO}$ relative to bulk
1	Bulk	208.01	227.79	19.78	—
1	2D	184.90	201.21	16.31	17.54%
2	Bulk	258.25	273.19	14.94	—
2	2D	272.65	285.33	12.69	15.06%
3	Bulk	369.00	463.15	94.16	—
3	2D	407.65	459.41	51.76	45.03%
4	Bulk	493.92	862.53	368.62	—
4	2D	587.73	827.59	239.86	34.93%

Table S3. Mean dynamic effective charges estimated from infrared phonon oscillator strengths for bulk and 2D YMnO₃.

Sample	Mean $Z_{Y/Mn}^*$ estimated from IR oscillator strength	Mean Z_O^* estimated from charge neutrality
Bulk	4.92	-3.28
2D	4.55	-3.03

Table S4. Benchmark comparison of representative blue inorganic materials, MIR-transparent oxides, and selected ultrathin metallic films for dual-band camouflage applications.

Material	Material type	Visible optical origin	Visible appearance	MIR metric / emissivity	Configuration	Max. T	Ref.
Prussian Blue	Coordination framework	Intervalence charge transfer	Blue	$\varepsilon \approx 0.1$	PB/PE/Al bilayer low-emissivity film	300 °C	Nat. Sustain. 2022, 5, 339-347
CoAl ₂ O ₄	Spinel oxide	Co ²⁺ d-d transition	Blue	$\varepsilon > 0.9$	Reported ceramic pigment	1400 °C	RSC Adv. 2015, 5, 87932-87939
Y ₂ O ₃	Cubic oxide	–	White	$\varepsilon \approx 0.15$	2D Y ₂ O ₃ film/coating	1100 °C	J. Mater. Chem. A 2025, 13, 39330
Ultrathin Au film	Metallic film	Thickness-enabled visible transparency	–	Low emissivity	Ultrathin metallic film	–	Nano Lett. 2024, 24, 16270-16275
2D YMnO ₃ (this work)	2D hexagonal oxide	Mn-O electronic modulation	Blue	$\varepsilon \approx 0.13$	2D YMnO ₃ Coating on SLS	900 °C	This work