Twist-Angle Control of Driven Electromagnetic Response in van der Waals Heterostructures

Alpha-Lattice: Pre-Registered Three-Rung Verification Ladder

(Rungs 1–2: condensed matter / nanophotonics; Rung 3: optional correlation probe)

Chris Clifton (independent)

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Abstract. This document specifies a falsifiability-first experimental ladder for testing whether twist angle θ can act as a control parameter for a repeatable *phase-locked driven electromagnetic state* (PLDS) in van der Waals (vdW) heterostructures (Rungs 1–2), and (optionally) whether any *mechanical channel* shows a correlated change (Rung 3). The protocol is mechanism-agnostic: it does not assume that LDOS modification implies inertial change. It is pre-registered with explicit gates, thresholds, null suites, error budgets, and stopping rules designed to minimize false-positive progression.

0.0 Response Letter (aiXiv Review Response Edition)

Weakness 1: Contested theoretical foundation (HRP/SED).
Action: The protocol is now *mechanism-agnostic*. HRP/SED is not required for Rungs 1–2. Rung 3 is framed strictly as a correlation probe conditioned on state flags (O and S) plus strict nulls and kill criteria. No claim is made that modifying EM LDOS implies inertial-mass change.

Weakness 2: Experimental feasibility / over-integrated stack.
Action: Rung 1 is de-scoped to **coupon-scale vdW heteropackets only** (e.g., graphene/hBN/graphene). No aerogel scaffold, isotopic receptor, or macroscopic tiles are required for Rungs 1–2. Integration concepts are explicitly deferred beyond the scope of this protocol.

Weakness 3: Systematics / naive metrology.
Action: Rung 3 now includes (i) a quantitative error budget with worked force bounds, (ii) an instrument-limited entry criterion ($\sigma_{\Delta\eta} \leq 10^{-4}$), (iii) a five-part null suite including the balance-coupling null, (iv) blinding + preregistration, and (v) explicit stopping rules and publish-null commitment.

Review questions addressed.
(1) **Novel theoretical development:** Not claimed. The work is positioned as a falsifiable test of an *engineered driven state* with optional mechanical correlation, independent of HRP/SED truth.
(2) **Fabrication feasibility:** coupon-scale vdW stacking and twist/strain mapping are supported by established twistronics methods; this protocol commits only to that level.
(3) **Quantitative error budget:** provided in Sec. 7 with explicit bounding targets and propagation to $\sigma_{\Delta\eta}$.

1.0 Claims, Scope, and Non-Claims

Primary claim space (Rungs 1–2): twist angle θ is a control parameter for producing a *repeatable phase-locked driven electromagnetic state* (PLDS) in a vdW coupon, with quantifiable spectral/impedance/mode-map signatures.
Optional claim space (Rung 3): if PLDS can be toggled reproducibly, test whether a mechanical readout channel shows a correlated change *that vanishes across nulls.*
Non-claims:

- No claim that LDOS modification implies inertial-mass modification.
- No reliance on HRP/SED to execute Rungs 1–2.
- No propulsion claim; Rung 3 is a precision correlation test.

2.0 Twist-Angle Program and Stage-Gating (Model Specified)

Small twist angles generate long-period moiré patterns; reconstruction and heterostrain can dominate and create sharp state boundaries. This motivates exploring a low-angle window without privileging any constant.

Stage A (coarse sweep): $\theta \in [0.25^\circ, 1.10^\circ]$ on a fixed grid (Appendix A).
Stage B (ROI refinement): allowed *only if* Stage A passes the preregistered gate below.

2.1 Pre-registered gate ("3σ")

Let $R(\theta)$ be the primary EM response metric (e.g., linewidth proxy, impedance proxy, near-field contrast), computed per coupon and aggregated per grid point.
Null model (monotonic): isotonic regression under both monotonic constraints; choose the better by RSS.
Alternative model (single extremum): piecewise-linear knot model with one interior knot $\theta^\star$ (one slope sign change), optimized over the Stage-A grid.
Test statistic: $\Delta\mathrm{RSS} = \mathrm{RSS}_{\mathrm{mono}} - \mathrm{RSS}_{\mathrm{knot}}$.
Significance: permutation of θ labels within each coupon batch (or wild bootstrap if needed), ≥ 5000 draws.
Pass condition: $p < 0.003$ and the extremum region must appear in at least **two independent coupons** at neighboring θ values. Otherwise Stage B is not executed.

3.0 Rung 1: Fabrication Roadmap (De-scoped)

3.1 Deliverable

Planar coupons comprising a twisted vdW heteropacket (e.g., graphene/hBN/graphene). No macroscopic tiles or multi-layer scaffold integration.

3.2 Mandatory metrology

- **Twist mapping:** spatially resolved twist-angle map over the active area.
- **Strain/heterostrain mapping (mandatory):** co-registered with the twist map.

- **Defect screening:** optical + AFM spot checks; exclude bubble/void dominated regions.

4.0 Rung 2: Pumping, PLDS Flag O, and Structural Stationarity Flag S

4.1 Pump surrogate (fixed)

Amplitude-modulated optical pumping delivered by fiber, with shutterable delivery and power metering at fiber output.

4.2 PLDS flag O (binary, thresholded)

$O = 1$ only when *all* thresholds below are met; otherwise $O = 0$ (marginals default to $O = 0$).

Metric	Threshold (pre-registered)	Measurement	Notes
Linewidth narrowing	$\Gamma_{\mathrm{ON}} \leq 0.5\,\Gamma_{\mathrm{OFF}}$; stable $\pm 10\%$	spectral FWHM	Relative.
Quality factor	$Q_{\mathrm{ON}} \geq 2Q_{\mathrm{OFF}}$ and $Q_{\mathrm{ON}} \geq 50$	ringdown/S-fit	Absolute floor.
Persistence	PLDS maintained ≥ 60 s per trial	monitoring	Short dwell.
Bounded dissipation	$\lvert T - T_0 \rvert \leq 2$ K and ON/OFF trajectory match within 50 mK at equal timestamps (or preregistered nuisance regression)	thermometry	No mK-gradient claim.
Mode reproducibility	map correlation ≥ 0.80 across entries	imaging proxy	"Same state."

4.3 Structural Stationarity flag S (binary)

Goal: prevent pump-induced reconstruction/domain-wall motion from masquerading as a state effect.
$S = 1$ only if both:

(a) **Pre/post stability:** post-run twist/strain/moiré proxy maps correlate with pre-run maps at ≥ 0.90 and mean inferred twist drift $\leq 0.02°$ over active area.

(b) **In-run stability:** a fast moiré proxy observable (optical moiré imaging / ellipsometric contrast / equivalent) shows no monotonic drift exceeding a preregistered bound (default: $< 5\%$ in the proxy metric across a full run).

If either fails, set $S = 0$ and the run is invalid for any Rung-3 claim (may be analyzed as structural dynamics).

5.0 Mechanism-Agnostic Bridge

Rungs 1–2 measure EM observables. Rung 3 is a correlation test between the EM state flag O and a mechanical channel, *conditioned on* structural stationarity ($S = 1$). No mechanistic claim about inertia is assumed.

6.0 Rung 3: Mechanical Correlation Probe

6.1 Observable and inertial proxy

Primary observable: resonance shift $\Delta\omega_0$ between ON/OFF blocks. If stiffness k is held constant,

$$\Delta\eta \approx -2\,\frac{\Delta\omega_0}{\omega_0}$$

is reported as an *inertial proxy* only after the null suite passes and $S = 1$ holds.

6.2 Sensitivity entry condition

Entry condition for attempting Rung 3:

$$\sigma_{\Delta\eta} \leq 10^{-4}$$

demonstrated by calibration injections and blank toggles (no sample change).

6.3 Latency / fast-toggle / hysteresis discriminants

- **Latency:** candidate mechanical anomaly must follow $O(t)$ within ≤ 2 s (default) after transitions.
- **Fast-toggle:** repeat with pump toggling at 0.2–1 Hz; a slow reconstruction artifact should attenuate/lag.
- **Hysteresis:** if moiré proxy shows irreversible drift under pump sweeps and the mechanical channel follows it, classify as reconstruction confound.

6.4 Null suite (mandatory)

1. Off-ROI geometry (e.g., $\theta = 2^\circ$).
2. Detuned pumping such that PLDS thresholds fail ($O = 0$).
3. Dummy thermal load (matched absorption/heating).
4. Full EM shielding + bias reversal.
5. Balance-coupling null: non-twisted coupon with identical pump delivery.

6.5 Kill criteria (expanded)

Reject any Rung-3 interpretation if: effect appears in any null; effect tracks temperature/charge/magnetic logs; $S = 0$; effect requires cumulative run history; or long-lag behavior inconsistent with a state toggle.

7.0 Quantitative Error Budget (Rung 3)

7.1 Artifact classes and bounding targets

Artifact	**Bounding target**	**Estimator / handle**	**Maps to**
Radiation pressure / stray light	$P_{\text{stray}} < 1$ mW; leakage $< 1\%$	photodiode + shutter blanks; calorimetry	torque bias
Electrostatics (charge/patch)	$V_{\text{rms}} < 10$ mV; stable ± 2 mV	Kelvin probe/KPFM; bias reversal; neutralization	force/torque
Thermal / radiometric	vacuum $< 10^{-5}$ Torr; $\Delta T_{\text{arm}} < 10$ mK per toggle window	multi-point thermometry; symmetric design; dummy load	drift
Magnetic coupling	residual $B < 10$ nT; gradients < 1 nT/cm	shielding; magnetometer logs; magnetic dummy	torque
Vibration / seismic	characterize; exclude bands	accelerometer logs; isolation; blank runs	noise floor

7.2 Worked magnitude bounds (sanity checks)

For torsion arm radius $r = 2.5$ cm:

- **Radiation pressure:** reflected stray optical power P yields $F \approx 2P/c$. For $P = 1$ mW, $F \approx 6.7 \times 10^{-12}$ N and $\tau \approx Fr \approx 1.7 \times 10^{-13}$ N·m.
- **Electrostatic patch estimate:** with area $A = 1$ cm^2, gap $d = 1$ mm, $V_{\text{rms}} = 10$ mV, $F \sim \epsilon_0 A V^2/(2d^2) \sim 4 \times 10^{-14}$ N (geometry dependent). Bias reversal and Kelvin mapping are required.

7.3 Propagating to $\sigma_{\Delta\eta}$

Report $\sigma_{\Delta\eta}$ from the measured $\Delta\omega_0$ uncertainty plus bounded systematic terms propagated in quadrature. If systematic terms dominate and cannot be reduced below the entry threshold, terminate Rung 3 and publish an upper bound.

8.0 Stopping Rules, Blinding, Replication

8.1 Stopping rules

- Stage B only if Sec. 2.1 gate passes.
- Rung 3 futility stop: if after 50% of planned toggles $\sigma_{\Delta\eta}$ remains $> 3\times$ the entry target without improvement under documented mitigation, terminate and publish null/upper bound.
- If repeated runs fail $S = 1$ (structural stationarity), terminate Rung 3 and publish Rungs 1–2 plus structural-dynamics note.
- **Publish-null commitment:** Rungs 1–2 will be published regardless of Rung-3 outcome.

8.2 Blinding and preregistration

Pump-state labels are randomized by a key-holder not involved in analysis. Scripts are frozen and time-stamped before unblinding (OSF). Any peeking is logged; results become exploratory.

8.3 Inter-lab reproducibility

Any positive Rung-1 extremum or candidate Rung-3 correlation claim requires at least one independent replication attempt prior to strong interpretation.

Appendix A: Sweep Schedule

Stage A: $\theta = \{0.25, 0.35, 0.45, 0.60, 0.80, 1.10\}^\circ$ (1–2 coupons each).
Stage B (conditional): smallest region containing extremum; default ROI $\theta \in [0.35^\circ, 0.55^\circ]$ with step 0.02°, $n \geq 7$ coupons.

Appendix E: References (selected, load-bearing)

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