LCOS SIMULATIONS · FTP_LCOS

LCoS fringe-projection profilometry

Amplitude (VAN and PAN) and phase-modulation approaches: performance impacts and error budgets

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What was studied

Every error source ends up as an error in the measured fringe phase Δφ. The LCoS matters only through how faithfully, how fast and how repeatably it puts the intended phase on the part.

- **Amplitude:** LCoS projects gray-level cosine fringes (VAN or PAN cell)
- **Phase:** a phase-only SLM grating's ±1 orders interfere on the part
- **Evidence:** 3 simulation scripts, setup and cell diagrams, materials workbook

REFERENCE CASE

0.53 µm

of height per mrad of phase

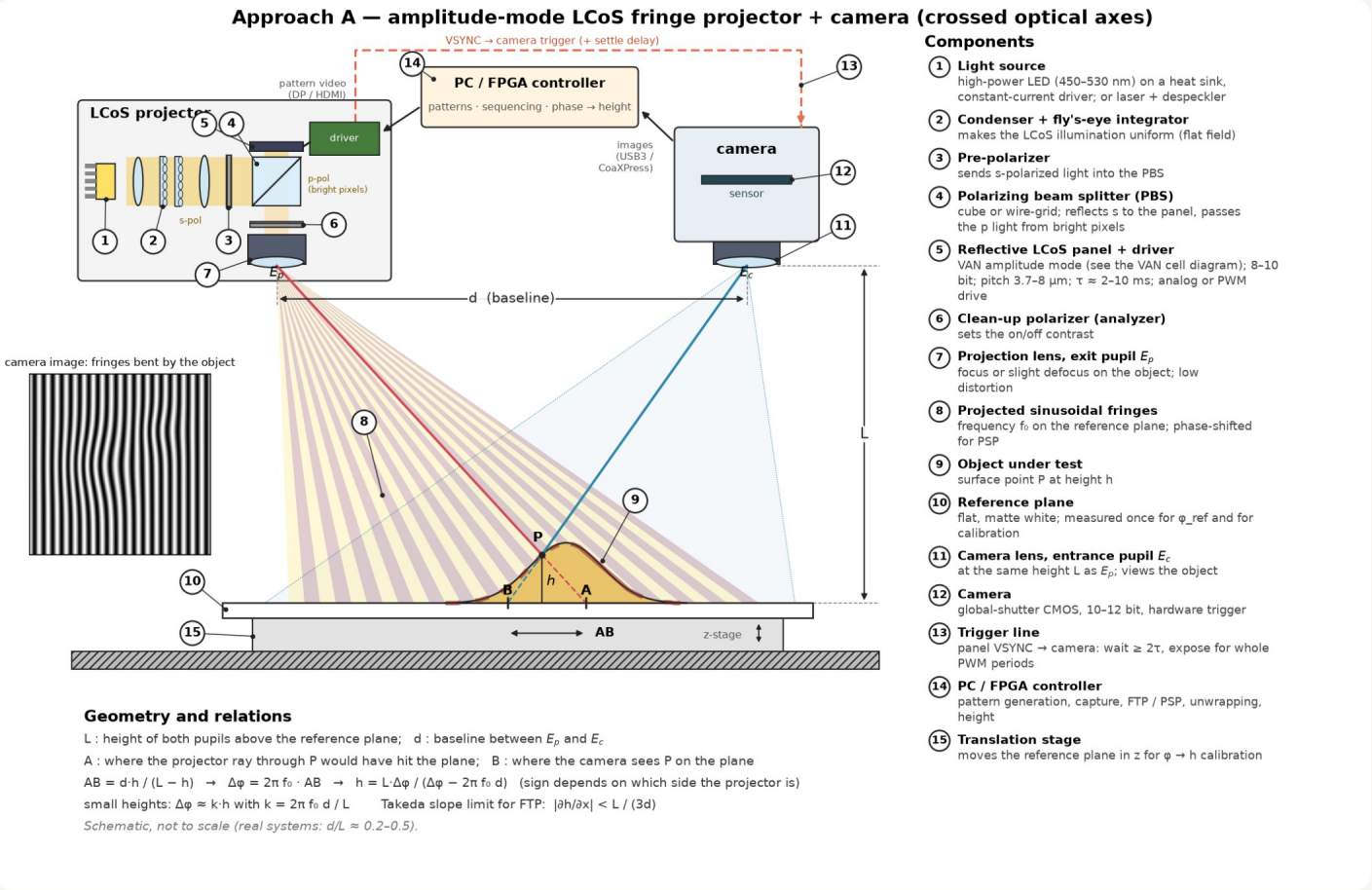
1 mm fringe period · 32 × 32 mm field, 512 px · L = 500 mm, d = 150 mm · camera noise floor 10.8 µm (4-step PSP)

Five ways to use LCoS for fringes

Approach	LCoS shows	Cell	Fringes made by	Phase step set by
A amplitude projector	Gray-level cosine	VAN (or PAN)	Projection lens	Gray levels → gamma LUT
B phase grating	Binary 0/π grating	PAN phase SLM or FLCoS	±1 orders interfere	Whole-pixel shift (exact)
C phase shifter	Uniform piston	PAN phase SLM	Two-arm interferometer	φ(g) lookup table
D polarization-multiplexed	4 polarization-coded phases	PAN + polarization camera	Single shot	Retardance accuracy
E adaptive HDR	Per-pixel dimmed pattern	VAN	As A	As A

This deck concentrates on **A (amplitude)** and **B/C (phase)**; D and E are extensions.

Approach A: amplitude LCoS projector



Panel displays a gray-level cosine; a lens images it onto the part; camera synced to VSYNC.

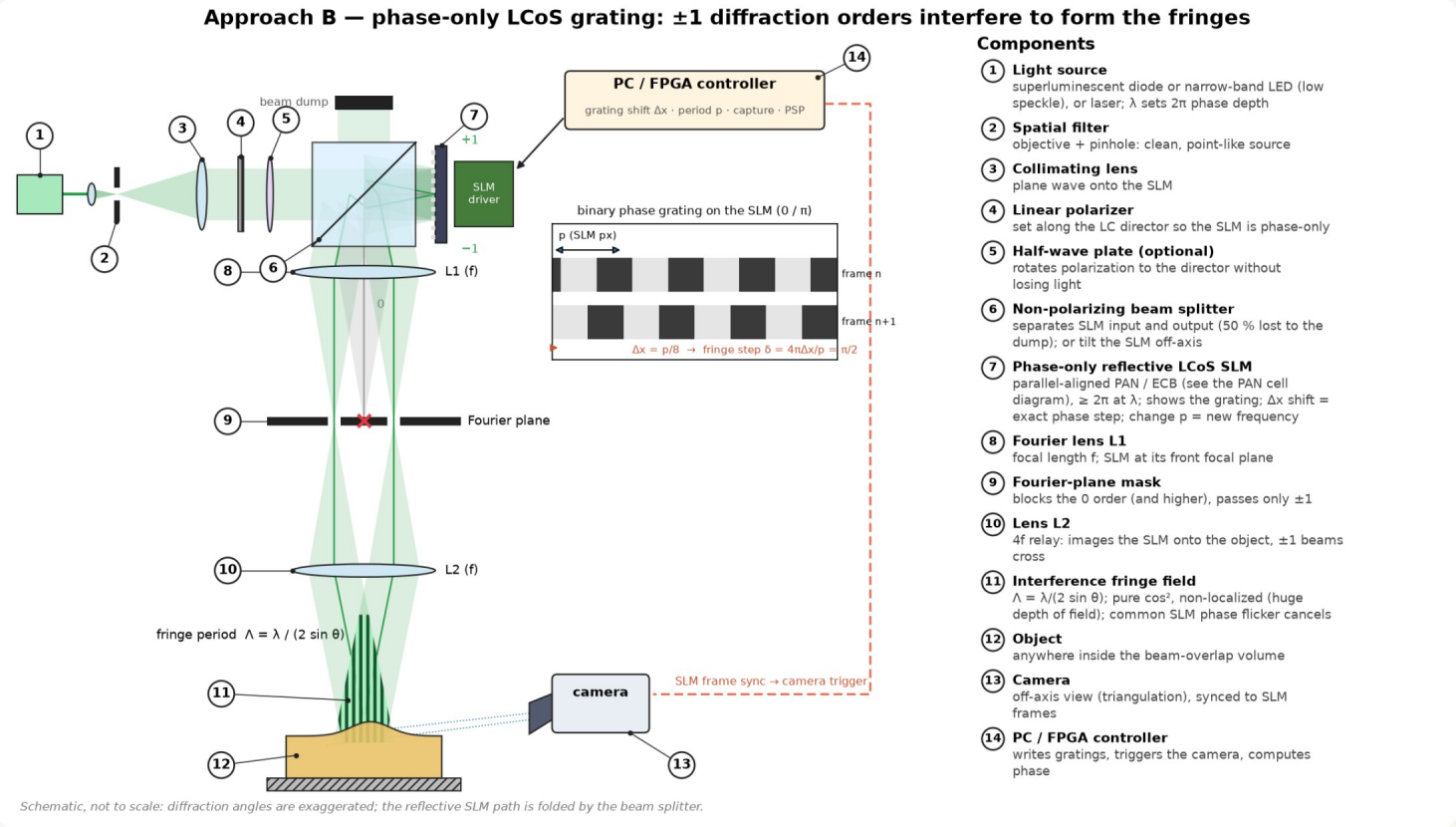
- Off-the-shelf projector architecture
- FTP (1 frame) or N-step PSP
- Keep fringe period ≥ 8–10 px
- Concrete build: 1920 × 1080, 6.4 µm VAN, 120 Hz analog

VAN vs PAN in the amplitude role

Property	VAN	PAN phase SLM in amplitude mode
Dark state	0 V; stable vs λ, gap, temperature	Needs drive; moves with Δn(T)
Usable gray range	Full, monotonic	About half (one $\sin^2$ branch)
Gap / speed	2–3 μm; τ_d 4–9 ms	3–5 μm; 2–6× slower ($\tau \propto d^2$)
Pixel pitch	3.7–8 μm	8–12.5 μm (less fringing)
Pretilt error shows as	Local gamma change	Local T(V) shift, incl. dark level
Cost / supply	Projector panels in volume	Research SLM pricing

Verdict: VAN wins every LC-related line. PAN in amplitude mode makes sense only if one SLM must serve both roles.

Approach B: phase grating, ±1 orders interfere



$$\Lambda = \lambda / (2 \sin \theta)$$

$$\delta = 4\pi \, \Delta x / p$$

$\Delta x = p/8 \longrightarrow \delta = \pi/2$

A 4-step PSP sequence is four grating positions, each an exact whole-pixel shift. New p = new fringe frequency.

Phase approach: what it gains and costs

Gains

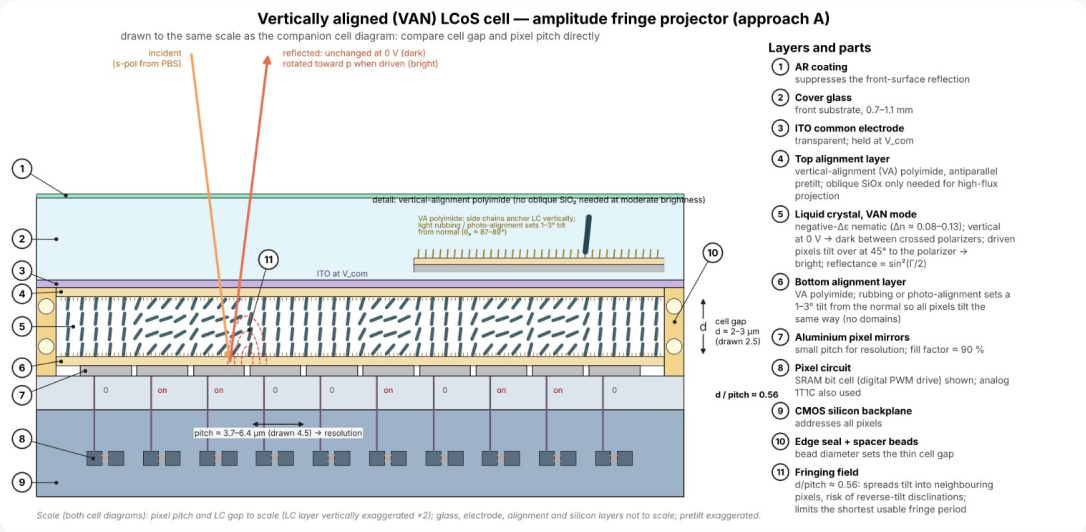
- Phase step fixed by pixel geometry
- Pure $\cos^2$ fringes: no gamma, no harmonics
- Common-mode SLM flicker cancels exactly
- Non-localized fringes: no lens DOF limit
- Binary FLCoS → kHz steps; DC balance is free

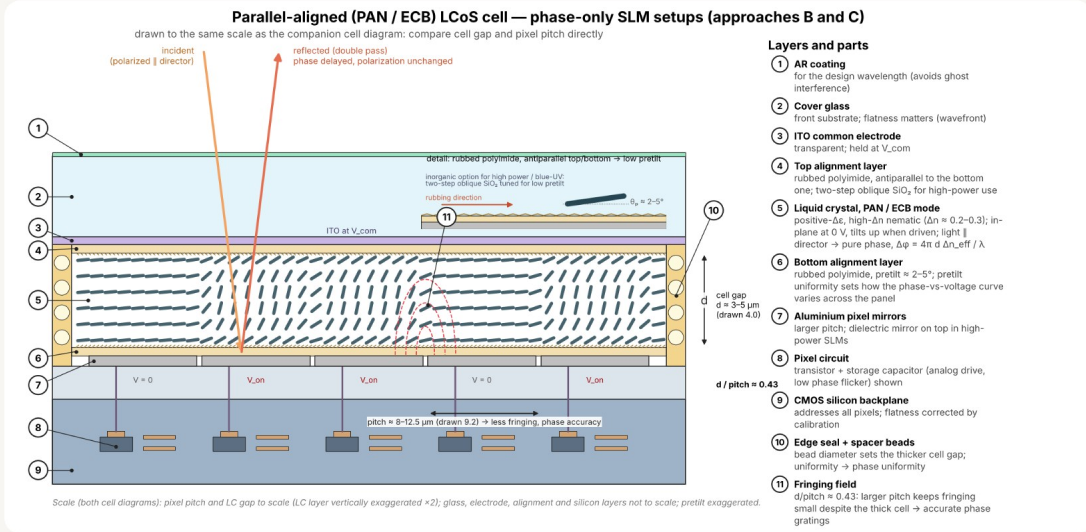
Costs

- Speckle with coherent sources (use an SLD)
- Parasitic interference: ghosts, dust, 0-order
- Nematic SLM: 10–30 ms per grating step
- Path drift once the beams separate
- Laser/SLD, spatial filter, 4f relay, research SLM

Variant C (phase shifter) is weakest: flicker is not common-mode and pretilt maps straight into step error.

Two cells, two jobs





VAN → amplitude projector

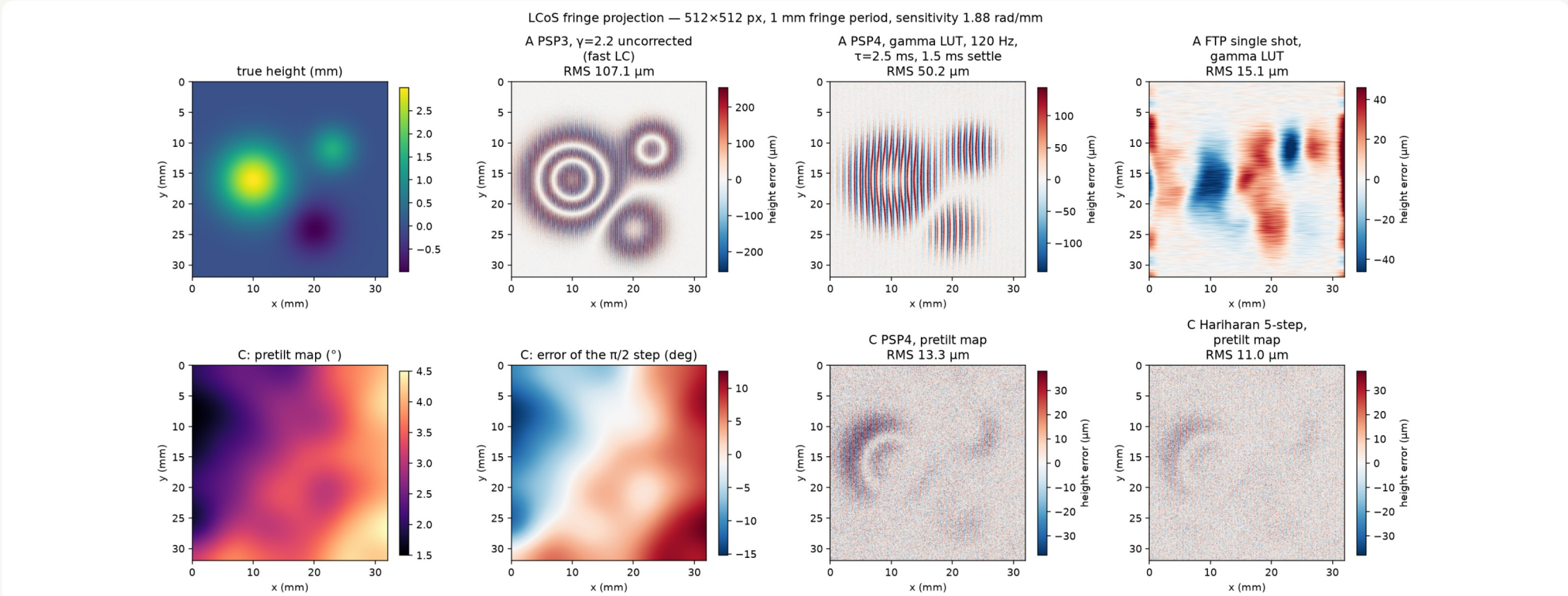
Negative Δε (MLC-6608, Δn 0.083) · pretilt 85–89° · oblique SiO_x for high flux · gamma calibration

PAN/ECB → phase SLM

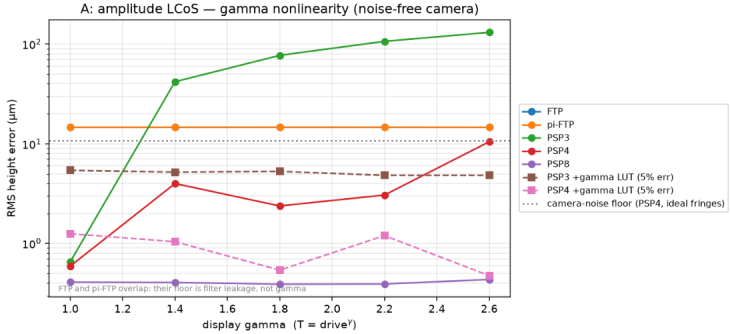
Positive Δε (E7, Δn 0.22) · pretilt 1–5° · rubbed PI or low-pretilt SiO_2 · φ(g) + flatness map

Error chain: pretilt map → local transfer curve → local phase-step error → height error

The simulation at a glance



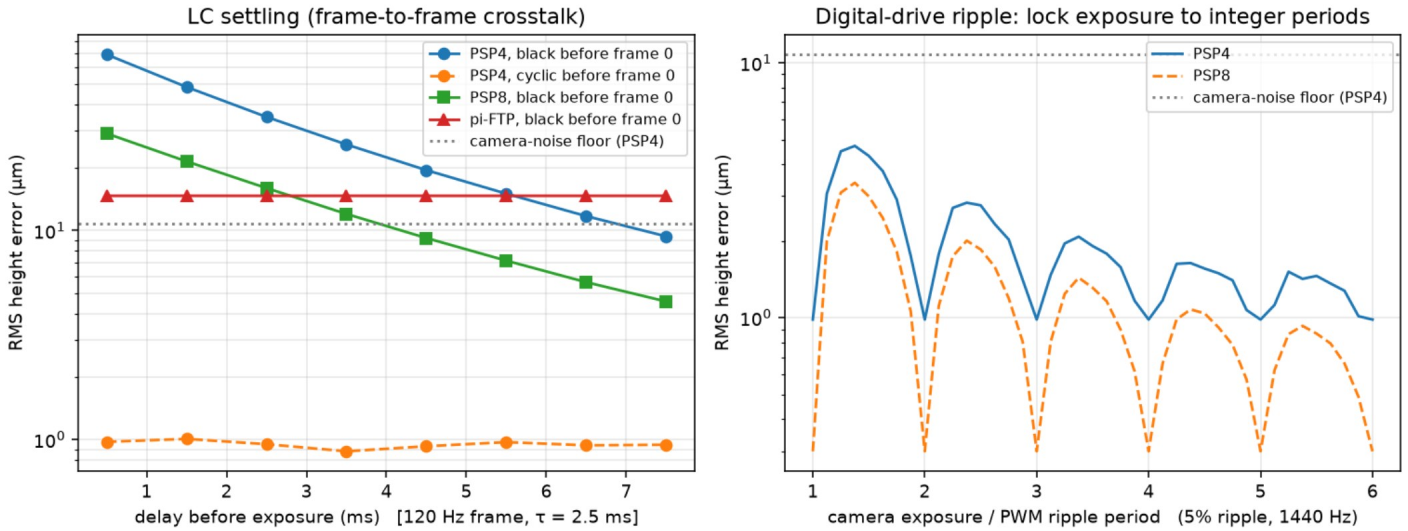
Gamma: the amplitude panel's transfer curve



At γ = 2.2	µm RMS
3-step, uncorrected	106.4
3-step + LUT (5% err)	4.8
4-step, uncorrected	3.1
4-step + LUT (5% err)	1.2
8-step, uncorrected	0.39
FTP / π-FTP	14.6

N-step PSP cancels harmonics up to order N−2. With ≥ 4 steps and a LUT, gamma is a ~1 µm term. Irrelevant to B.

Timing: settling and PWM ripple



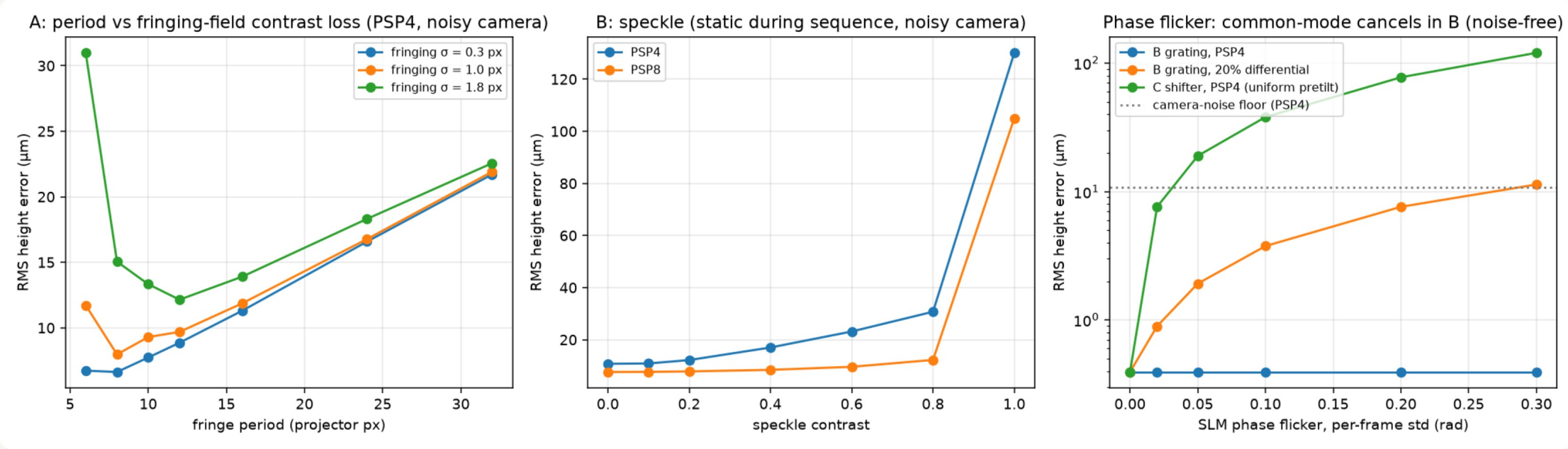
69 → 1 µm

4-step PSP: black start (0.5 ms settle) vs cycling continuously

4.7 µm

worst PWM ripple error; zero at whole ripple periods

Fringe period, speckle and flicker

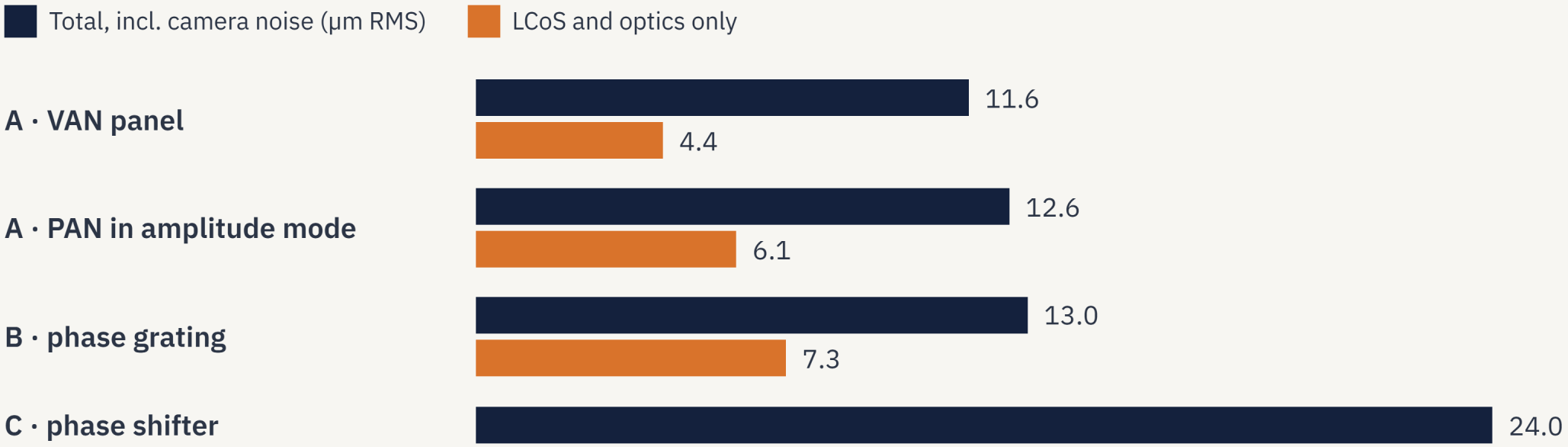


Period (A): keep ≥ 8–10 px; 6 px with heavy fringing → 31 µm

Speckle (B): 12 µm at contrast 0.2; 130 µm fully developed

Flicker: B common-mode 0; C 19 µm at 0.05 rad

Error budgets: totals



Camera noise (10.8 µm) dominates every case. Several orange terms are estimates, not yet simulated.

Budget detail: VAN amplitude vs phase grating

A · VAN panel

Source	µm	Basis
Camera noise	10.8	sim
Fringing field, 16 px	3.4	sim
Lens distortion / defocus	1.6	est.
Gamma drift (±2 K)	1.3	est.
Gamma LUT residual	1.1	sim
Pixel droop / flicker	1.1	est.
LC settling, cyclic	0.9	sim
Pretilt → local gamma	0.8	est.
Total / LCoS only	11.6 / 4.4	

B · phase grating

Source	µm	Basis
Camera noise	10.8	sim
Speckle, contrast 0.2	5.7	sim
Parasitic interference	3.2	est.
Path drift / vibration	2.7	est.
Differential flicker	1.9	sim
Wavelength drift	0.5	est.
Step error, gamma, flatness	0	design
Total / LCoS only	13.0 / 7.3	

Break a rule and the budget breaks

Approach	Rule broken	µm RMS	Done right
A	3-step PSP, gamma uncorrected	106	≈ 1 (4-step + LUT)
A	Start from black, 0.5 ms settle	69	0.98 (cycling)
A	Fringe period 6 px, heavy fringing	31	≈ 12 (12–16 px)
A	Exposure 1.375 PWM periods	4.7	0.98 (whole periods)
B	Fully developed speckle	130	12.2 (contrast 0.2)
B	20% differential flicker, 0.3 rad	11.3	0.39 (common mode)
C	Phase flicker 0.05 rad	18.9	— (inherent to C)

Contrast barely matters. Stability does.

Fringe modulation is (CR−1)/(CR+1): 300:1 and 3000:1 differ by under 1%. A profilometry cell needs low frame-to-frame flicker, fast settling, a repeatable gamma curve and uniform pretilt.

Recommendations

General-purpose sensor → A with VAN

Analog or locked-exposure drive, ≥ 4-step PSP, 16/18/20 px heterodyne unwrapping, continuous cycling, periods ≥ 10 px; π-FTP for moving parts.

High-DOF or fine-period → B

SLD source and 0/π grating; consider ferroelectric SLM for kHz steps. Spend effort on speckle and stray light, not the SLM.

Avoid C

Unless an interferometer is already required (very small fields).

Profilometry-optimized cell

Droop ≤ ½ LSB · 2 µm gap + overdrive · repeatable curve with temperature LUT · pretilt uniformity · contrast secondary above ~300:1.

System-level companies

Industrial metrology

ZEISS (GOM ATOS Q, Scan 1)
Hexagon (AICON)
Creaform (AMETEK)
Shining 3D
Polyga

Machine-vision 3D

Zivid · Photoneo
IDS (Ensenso)
LMI (Gocator)
Cognex · Keyence
wenglor

3D SPI / AOI

Koh Young · MIRTEC
CyberOptics (Nordson)
TRI · Saki · Omron
Parmi · Pemtron · ViTrox
Nexstar: confirmed FLCoS user

Most makers don’t disclose their modulator; many likely use TI DLP. Phase-grating (B-class) products are rare outside structured-illumination microscopy.

Major suppliers

Category	Suppliers
Amplitude LCoS panels	Sony (SXRD) · JVCKENWOOD (D-ILA) · Himax · OmniVision · Raontech · HOLOEYE
Phase-only SLMs	Hamamatsu · HOLOEYE (bought Jasper Display backplane tech, 2024) · Meadowlark (ex-BNS) · Santec · Thorlabs
Ferroelectric LCoS	Forth Dimension Displays (Kopin): kHz binary patterns and 0/π gratings
LC and alignment	Merck · JNC · DIC · JSR · Nissan Chemical
Rubbing / inspection	PREMATEC · Joyo Engineering · KLA · Hitachi High-Tech · Nikon
Cameras / sensors	Sony (IMX250MZR polarization) · Basler · Teledyne FLIR · Allied Vision · IDS · LUCID
Sources	SLDs: Exalos, Superlum · Lasers: Coherent, Toptica · LEDs: Nichia, ams OSRAM, Luminus

Next simulations

1. Ferroelectric 0/π grating version of B
2. Temperature drift of VAN gamma and PAN T(V)
3. PAN-in-amplitude model: folded $\sin^2$, d^2-scaled settling
4. Parasitic interference and path drift for B
5. Approach D with micro-polarizer extinction errors

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LCoS_Profilometry_Approaches_Performance_Error_Budgets.docx
LCoS_Profilometry_Error_Budgets_and_Suppliers.xlsx
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