LCoS Fringe-Projection Profilometry: Approaches, Performance and Error Budgets

Oct 22, 2026 · D. F. Hakala

Scope. This document pulls together the work done to date in the FTP_LCoS folder on LCoS-based fringe-projection profilometry: the method notes in FTP_using_LCoS.docx, the setup and cell diagrams, the three simulation scripts (lcos_fpp_error_sim.py, ftp_walkthrough.py, psp_walkthrough.py) and their results, the VAN-vs-PAN materials workbook, and the relevant parts of LCoS Design Issues.docx. It compares two families of system:

- **Amplitude-based (Approach A):** an LCoS panel projects gray-level sinusoidal fringes through a projection lens. Two cell types are considered: the vertically aligned nematic (VAN) panel used in commercial projectors, and a parallel-aligned (PAN/ECB) cell run as an intensity modulator between crossed polarizers.
- **Phase-modulation-based (Approach B, with variant C):** a phase-only PAN LCoS SLM writes a binary grating whose ±1 diffraction orders interfere with the object to make the fringes (B), or acts as a programmable phase shifter in a two-arm interferometer (C).

For each it sets out how the cell physics turns into measurement error, gives a component-by-component error budget built from the simulation results, and lists the companies that sell complete systems and the suppliers of LCoS devices, cells, light engines, cameras and process equipment.

Reference case used throughout (same as the simulations): 512 × 512 px camera field covering 32 × 32 mm, 1 mm fringe period on the object (16 px), L = 500 mm, d = 150 mm, sensitivity k = 1.885 rad/mm, so **1 mrad of phase = 0.53 µm of height**. Test object: three Gaussian bumps/dips up to about 3 mm. Camera noise is set so ideal 4-step PSP gives 20 mrad (10.8 µm) RMS — this is the baseline noise floor every result should be compared with.

1. Overview and main findings

Fringe-projection profilometry projects a sinusoidal pattern onto a part and views it from a second angle; height bends the fringes sideways, and the sideways shift is read as a phase. In the crossed-axes geometry

$$h = \frac{L\,\Delta\varphi}{\Delta\varphi - 2\pi f_0 d} \approx \frac{L}{2\pi f_0 d}\,\Delta\varphi$$

so, every error source in this document is ultimately an error in Δϕ. The LCoS device only matters through how faithfully, how fast and how repeatably it puts the intended phase onto the part. Five ways of using LCoS were worked through:

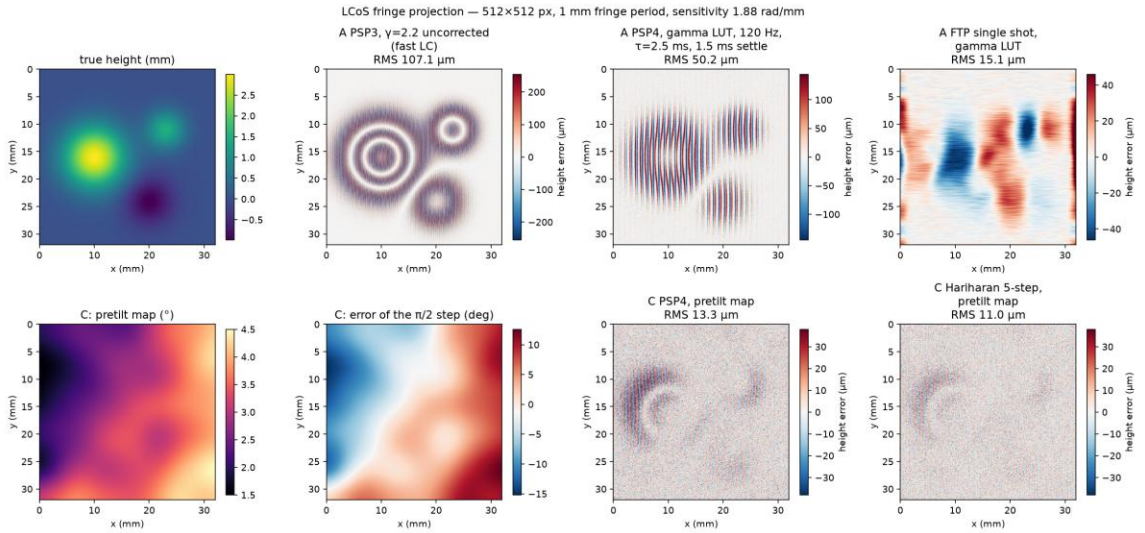
Approach	What the LCoS does	Cell	How fringes are made	Phase step set by
A amplitude	Displays gray-level	VAN (or PAN in	Imaged by a	Gray levels → needs gamma

Approach	What the LCoS does	Cell	How fringes are made	Phase step set by
projector	cosine image	amplitude mode)	projection lens	calibration
B phase grating	Displays binary 0/π grating	PAN/ECB phase SLM (or binary FLCoS)	±1 orders interfere	Whole-pixel grating shift, $\delta = 4\pi\Delta x/p$ (exact)
C phase shifter	Uniform phase piston in one arm	PAN/ECB phase SLM	Two-arm interferometer	$\phi(g)$ lookup table
D polarization-multiplexed	Projects four polarization-coded phases	PAN + polarization camera (Sony IMX250MZR)	Single shot, 4 steps at once	Retardance accuracy
E adaptive HDR	Per-pixel dimming of projected pattern	VAN	As A	As A

This document concentrates on the two families **A (amplitude)** and **B/C (phase)**; cases **D** and **E** are noted as extensions for further study.

Main findings

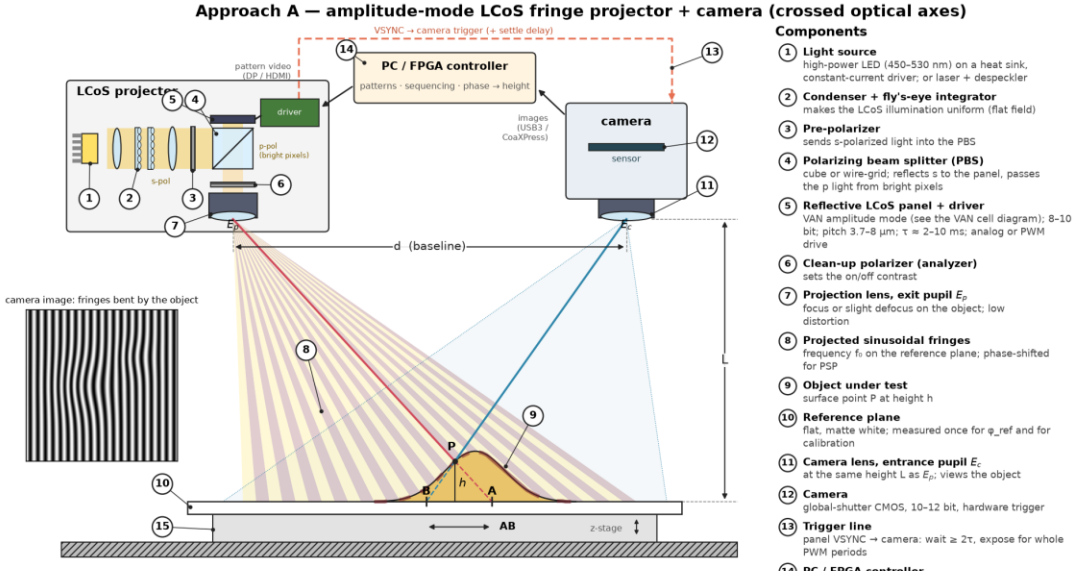
1. **Both families reach the camera-noise floor when set up correctly.** With good practice (≥ 4 steps, gamma table, cyclic drive, whole-period exposures for A; despeckled source and common-mode grating for B) the systematic LCoS-related terms total about 4–7 µm RMS against a 10.8 µm noise floor in the reference case (Section 7).
2. **Amplitude (A) is limited by the LC's time response and intensity transfer curve.** Uncorrected gamma with 3-step PSP gives 107 µm RMS; a black frame before the sequence gives 70 µm at 0.5 ms settling. These collapse to about 1 µm with 4+ steps, a gamma table and continuous cycling.
3. **Phase grating (B) removes the LC from the phase-step problem.** The step is fixed by pixel geometry, the fringes are pure $\cos^2$, and SLM flicker is common to both beams and cancels exactly in simulation. Its errors move to the optics: speckle (5.7 µm at speckle contrast 0.2, 130 µm with fully developed speckle) and parasitic interference.
4. **Phase shifter (C) is the weakest variant.** Phase flicker is not common-mode (19 µm at 0.05 rad) and pretilt non-uniformity maps straight into step error (7.9 µm for 4-step at 3° peak-to-valley).
5. **Contrast ratio hardly matters; stability does.** Fringe modulation is (CR−1)/(CR+1), so 300:1 and 3000:1 differ by under 1%. What matters is a repeatable, smooth transfer curve, fast settling and low frame-to-frame flicker — which shifts the priorities for a profilometry-optimized cell away from those of a display panel.



2. Approach A — amplitude LCoS fringe projector (VAN and PAN cells)

2.1 System

A reflective LCoS panel, lit through a polarizing beam splitter, displays a gray-level cosine image which a projection lens images onto the part. A camera at the triangulation angle, triggered from the panel's VSYNC, records the frames; a PC computes phase by FTP (one frame) or N-step PSP. This is the architecture of every commercial LCoS projector, so panels, light engines and drive electronics are available off the shelf.



Components

1. **Light source** — high-power LED (450–530 nm) on a heat sink, constant-current driver; or laser + despeckler
2. **Condenser + fly's-eye integrator** — makes the LCoS illumination uniform (flat field)
3. **Pre-polarizer** — sends s-polarized light into the PBS
4. **Polarizing beam splitter (PBS)** — cube or wire-grid; reflects s to the panel, passes the p light from bright pixels
5. **Reflective LCoS panel + driver** — VAN amplitude mode (see the VAN cell diagram); 8–10 bit; pitch 3.7–8 µm; τ ≈ 2–10 ms; analog or PWM drive
6. **Clean-up polarizer (analyzer)** — sets the on/off contrast
7. **Projection lens, exit pull E_p** — focus or slight defocus on the object; low distortion
8. **Projected sinusoidal fringes** — frequency f_0 on the reference plane; phase-shifted for PSP
9. **Object under test** — surface point P at height h
10. **Reference plane** — flat, matte white; measured once for φ_{ref} and for calibration
11. **Camera lens, entrance pull E_c** — at the same height L as E_p; views the object
12. **Camera** — global-shutter CMOS, 10–12 bit, hardware trigger
13. **Trigger line** — panel VSYNC → camera: wait ≥ 2τ, expose for whole PWM periods
14. **PC / FPGA controller** — pattern generation, capture, FTP / PSP, unwrapping, height
15. **Translation stage** — moves the reference plane in z for φ → h calibration

Geometry and relations

L : height of both pupils above the reference plane; d : baseline between E_p and E_c

A : where the projector ray through P would have hit the plane; B : where the camera sees P on the plane

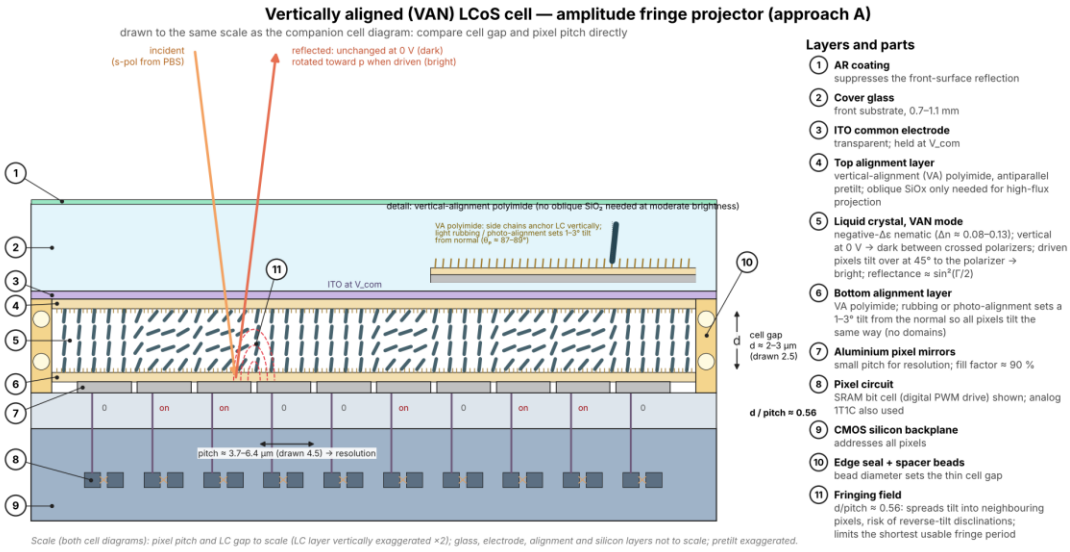
$AB = d \cdot h / (L - h) \rightarrow \Delta\varphi = 2\pi f_0 \cdot AB \rightarrow h = L \cdot \Delta\varphi / (\Delta\varphi - 2\pi f_0 d)$ (sign depends on which side the projector is)

small heights: $\Delta\varphi \approx k \cdot h$ with $k = 2\pi f_0 d / L$ Takeda slope limit for FTP: $|\partial h/\partial x| < L / (3d)$

Schematic, not to scale (real systems: d/L ≈ 0.2–0.5).

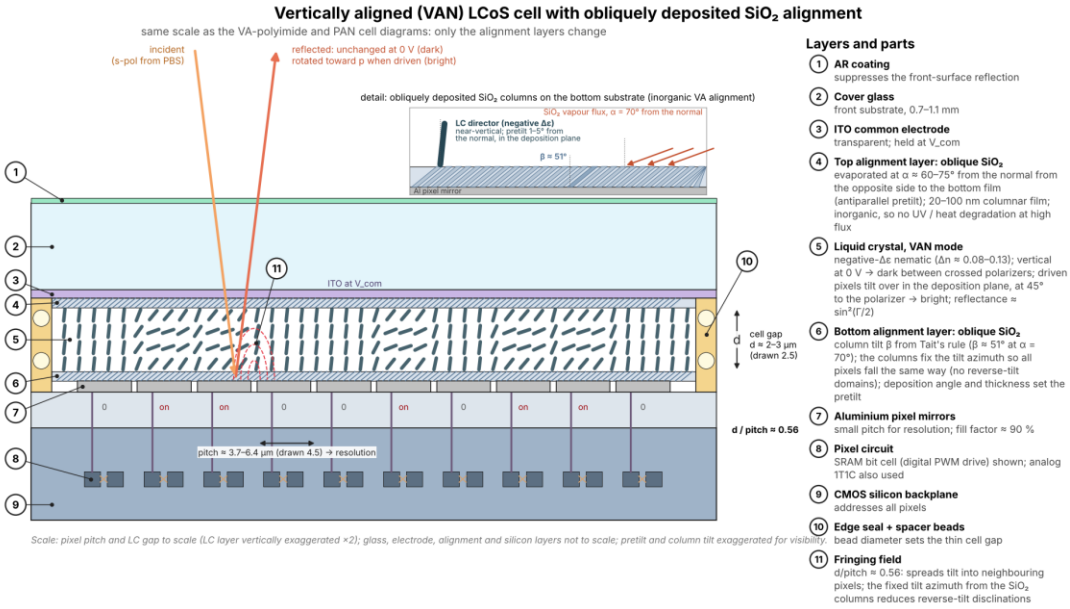
2.2 VAN cell (the natural choice for A)

At 0 V the negative-Δε molecules stand almost vertically, the reflected light keeps its polarization, and the pixel is black between crossed polarizers. Driven pixels tilt over — all in the same azimuth because of the 1–5° pretilt from the normal — and the induced retardance passes light through the analyzer.



Why it suits a fringe projector:

- **Stable black at 0 V**, independent of wavelength, cell-gap variation and temperature. The fringe minimum, and therefore the background term in the phase calculation, does not drift.
- **High contrast** (thousands to one) and good uniformity. As noted in Section 1, beyond about 100:1 contrast adds almost nothing to the phase measurement, but the stable dark state does.
- **Inorganic oblique-SiO_x alignment** survives the flux of a bright projector and gives the near-vertical pretilt; this is the GLAD process modelled in a separate Monte Carlo simulation of oblique angle evaporation.



What it costs a profilometer:

- **Strongly non-linear intensity-vs-gray curve** (effective gamma about 2–2.6). This creates fringe harmonics that 3-step PSP cannot reject (Section 6).
- **Asymmetric switching.** Decay is passive: $\tau_d = \gamma_1 d^2/(\pi^2 K_{33})$. For MLC-6608 ($\gamma_1 \approx 0.186$ Pa·s, $K_{33} \approx 18.1$ pN) a 3 µm cell gives $\tau_d \approx 9.4$ ms, which misses a 120 Hz frame (8.3 ms); a 2 µm cell gives 4.2 ms. Rise time at 5 V is about 2 ms and can be shortened by overdrive.
- **Reverse-tilt disclinations** at the edges of driven pixels next to dark ones, worst at short fringe periods; the pretilt and its uniformity control them.
- **Pixel-voltage droop** during the frame ($\Delta V = I_{leak} \cdot T_f / C_{total}$). The design rule in LCoS Design Issues — hold droop below ½ LSB, about 10 mV for 8 bits over 5 V, requiring about 42 fF node capacitance at 50 fA leakage and 120 Hz — is also the right rule for frame-to-frame fringe stability.

Cell-gap note (correction to an earlier calculation). LCoS Design Issues estimated that a 2.0 µm MLC-6608 cell ($\Delta n \cdot d = 166$ nm) reaches only 66% of peak brightness, using the transmissive formula $T = \sin^2(\pi \Delta n\, d/\lambda)$. A reflective cell is passed twice, so $T = \sin^2(2\pi \Delta n_{eff}\, d/\lambda)$ and full brightness needs only $\Delta n_{eff} \cdot d = \lambda/4 = 137$ nm at 550 nm. With 166 nm available the 2 µm cells can reach 100% at a drive voltage short of full tilt, which is why 2 µm VAN panels are practical. (The workbook's Cell Gap Calculator gives 2.77 µm only because it assumes the director reaches 60% of full Δn.)

2.3 PAN/ECB cell used in amplitude mode

A parallel-aligned cell becomes an intensity modulator if the input polarization is set at 45° to the director and the PBS acts as analyzer: $T = \sin^2(\Gamma/2)$, $\Gamma = 4\pi \Delta n_{eff}(V) d/\lambda$. There are two very different cases.

- **A phase SLM re-used as an amplitude modulator** (e.g. a Holoeye or Meadowlark SLM with the polarizer rotated). Its 2π-or-more stroke means T(V) passes through at least one full bright–dark cycle, so only one monotonic branch — roughly half the gray levels — is usable. Black sits at a

non-zero voltage that moves with temperature as Δn drifts; residual retardance of the surface-anchored layers limits contrast unless a compensator is added. The thick cell (3–5 µm) is 2–6× slower than a 2 µm VAN cell because $\tau \propto d^2$. In return the larger pitch (8–12.5 µm) reduces fringing, and drive is usually analog or high-rate with 10–12 bits.

- **A PAN cell designed for amplitude** ($\Delta n \cdot d \approx \lambda/4$, normally white ECB). This can be as thin and fast as a VAN cell and uses positive-Δε material at lower voltage, but its dark state still requires drive and remains temperature- and gap-sensitive.

Property (amplitude role)	VAN	PAN/ECB phase SLM in amplitude mode
Dark state	0 V, wavelength- and temperature-independent	Needs drive; moves with Δn(T) and gap
Usable gray range	Full, monotonic	About half (one $\sin^2$ branch)
Typical gap / speed	2–3 µm; τ_d 4–9 ms	3–5 µm; roughly 2–6× slower
Pixel pitch	3.7–8 µm	8–12.5 µm (less fringing)
Alignment	Oblique SiO_x (high flux) or VA polyimide	Rubbed polyimide; SiO_2 for high power
Pretilt non-uniformity shows as	Local gamma change	Local T(V) shift, including the dark level
Typical drive	Digital PWM or analog, 8–10 bit	Analog or fast digital, 8–12 bit
Cost and availability	Projector panels, light engines in volume	Research SLM pricing

2.4 Drive, timing and the concrete build

- **PWM vs analog drive.** Digitally driven panels make gray by bit-plane pulse-width modulation, which leaves an intensity ripple at the bit-plane rate. The simulation shows ripple error is zero when the camera exposure is a whole number of ripple periods and up to 4.7 µm otherwise (Section 6). Analog drive removes the ripple but brings the pixel-droop requirement above.
- **Sequencing.** Keep the panel cycling through the phase-step patterns continuously rather than starting from black; trigger the camera from VSYNC after a fixed settle delay.
- **Fringe period** of at least 8–10 panel pixels avoids fringing-field contrast loss.
- **Single-shot color variant:** three phase-shifted fringes in R, G and B with a color camera, at the cost of color crosstalk and object-color sensitivity.
- **Concrete build proposed in FTP_using_LCoS.docx:** 1920 × 1080, 6.4 µm VAN panel with 120 Hz analog drive, 4- to 8-step PSP plus heterodyne unwrapping, expected precision 1/1000–1/5000 of the measurement depth after averaging.

3. Approach B — phase-only LCoS: interference fringes (with variants C and D)

3.1 System

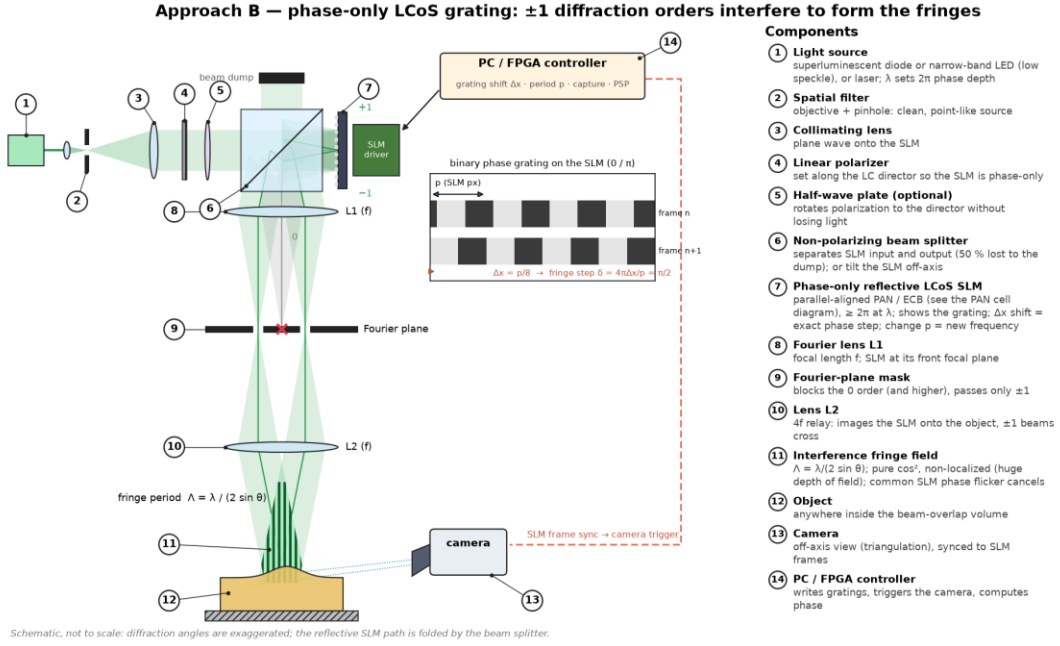
A collimated, spatially filtered, polarized beam (laser, or a superluminescent diode for low speckle) illuminates a phase-only reflective LCoS SLM aligned along with the LC director. The SLM shows a binary 0/π grating of period p pixels. A Fourier lens and a mask block the zero and higher orders and pass the ±1 orders, which a second lens relays so they cross on the object at half-angle θ. Their interference is a pure cos² fringe of period

$$\Lambda = \frac{\lambda}{2\sin\theta}$$

Shifting the grating sideways by Δx shifts the +1 order by +2πΔx/p and the −1 order by the opposite amount, so the fringe moves by

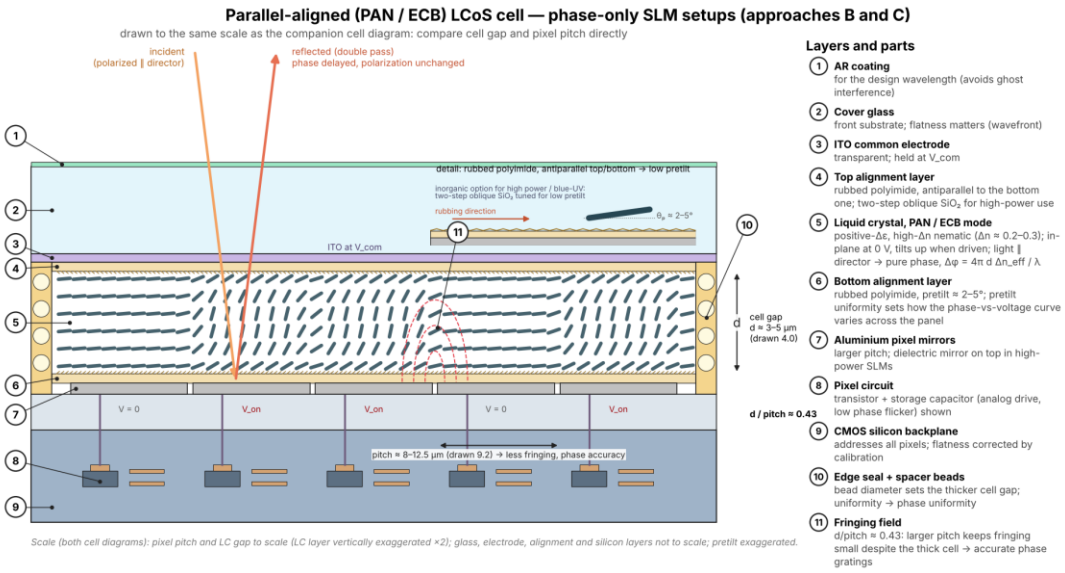
$$\delta = \frac{4\pi\,\Delta x}{p}, \qquad \Delta x = \frac{p}{8} \Rightarrow \delta = \frac{\pi}{2}$$

A 4-step PSP sequence is therefore four grating positions, each an exact whole-pixel shift. Changing p changes the fringe frequency, so heterodyne period sets need no hardware change.



3.2 PAN/ECB phase cell

With the light polarized along the director, the cell changes only optical path: Δϕ = 4πdΔn_eff(V)/λ for the double pass. A full 2π needs 2dΔn ≥ λ (1.2 µm minimum at 532 nm with E7, Δn ≈ 0.22; thicker for 1064 nm or with margin). Approach B needs only 0 and π, which relaxes the stroke requirement by half and makes the cell thinner and faster than a full-2π SLM.



3.3 Why B is attractive

- **The phase step is geometry, not calibration.** No gamma, no $\phi(g)$ table and no pretilt map enters the step size; static non-uniformity of the SLM only alters diffraction efficiency and a fixed wavefront that cancels against the reference-plane measurement.
- **Pure sinusoids.** Two plane waves give exactly $\cos^2$; harmonic lobes vanish, so FTP's slope limit moves from $L/(3d)$ toward L/d with π-shift FTP.
- **Common-mode flicker cancellation.** The two orders come from the same pixels, so frame-synchronous phase flicker shifts both equally and the fringe does not move. The simulation confirms zero added error for uniform flicker up to 0.3 rad.
- **Non-localized fringes:** no projection lens depth-of-field limit; the part can sit anywhere in the overlap volume.
- **Fine periods** set by θ rather than by panel pixels.
- **Binary FLCoS option (assessment, not yet simulated).** Because only 0 and π are needed, a ferroelectric LCoS (Forth Dimension Displays) can write the grating with ~100 µs switching, giving kHz-rate phase steps. FLC needs DC balancing by displaying the inverse image; for a $0/\pi$ grating the inverse is the same grating moved by $p/2$, which shifts the fringe by 2π — an identical pattern. DC balancing is therefore free. This is why ferroelectric SLMs are already used for structured-illumination microscopy and 3D solder-paste inspection.

3.4 What it costs

- **Speckle** with coherent sources: the main error term (Section 6). Use an SLD or narrow-band LED with just enough coherence for the near-zero path difference of the symmetric ±1 beams.
- **Parasitic interference** from ghost reflections, dust and leaked zero order; needs AR-coated optics and a clean Fourier mask.
- **Light efficiency:** a binary grating sends at most 2 × 40.5% into ±1, and a non-polarizing beam splitter costs 75% on the double pass (or fold the SLM off-axis). Acceptable for camera exposure with a laser or SLD.

- **Settling of a nematic SLM:** 10–30 ms per grating change for a thick PAN cell, i.e. 4-step PSP at about 10–25 sets/s (not an error if the camera waits).
- **Path stability:** the two beams separate after the relay; vibration and air turbulence over the sequence appear as phase noise.
- **Cost and alignment:** laser/SLD, spatial filter, 4f relay and a research SLM, versus a projector module for A.

3.5 Variant C — LCoS as a phase shifter in an interferometer

The SLM applies a uniform piston (0, π/2, π, 3π/2) to one arm of a two-beam interferometer. The step depends on the $\phi(g)$ lookup table at each pixel, so pretilt and gap non-uniformity become step errors, and phase flicker is not common-mode. Simulated: 4-step error 7.9 µm from a 3° peak-to-valley pretilt map (4.5 µm with Hariharan 5-step), and 19 µm from 0.05 rad flicker. C is useful only where an interferometer is already needed (e.g. very small fields).

3.6 Variant D — polarization-multiplexed single shot

A PAN cell encodes four phase-shifted fringes on four polarization states read simultaneously by a 2×2 micro-polarizer camera (Sony IMX250MZR). This gives single-shot PSP, but the step size depends on retardance accuracy and the micro-polarizer extinction; it has not been simulated.

4. Cell physics and construction: VAN vs PAN

The fringe algorithms only see camera intensity, so the LC mode is chosen by the LCoS's job: VAN for an amplitude projector, PAN/ECB for phase. TN is avoided because it rotates polarization as well as retarding it (amplitude and phase change together) and has lower, more wavelength-dependent contrast; ferroelectric LCoS is the choice for fast binary patterns.

4.1 Materials and construction (summary of LCoS_VAN_vs_PAN_alignment_materials_construction.xlsx)

Feature	VAN amplitude projector	PAN/ECB phase SLM
Dielectric anisotropy Δε	Negative, about −3 to −6	Positive, about +5 to +15
Birefringence Δn	0.08–0.13	0.2–0.3+ (0.35–0.45 for thin fast cells)
Example mixture	Merck MLC-6608 (Δn 0.083, Δε −4.2)	Merck E7 (Δn 0.22, Δε +14, T_NI ≈ 58 °C)
Speed-setting elastic constant	K_{33} (bend)	K_{11} (splay)
Cell gap	2–3 µm	3–5 µm+ (2π at longest λ)
Pretilt	85–89° from substrate	1–5° from substrate, antiparallel
Alignment layer	Oblique SiO_x (for high flux)	Rubbed polyimide; low-pretilt SiO_2 for high flux

Feature	VAN amplitude projector	PAN/ECB phase SLM
	or VA polyimide	application power/UV
Polarization optics	PBS + analyzer + compensator	Input polarizer only
Flatness	Focus only	Critical: appears as wavefront error, needs flat-field map
Gap uniformity affects	Contrast, gray uniformity	Phase directly ($\Delta\phi \propto d$)
Pixel mirror	Aluminum	Aluminum or dielectric stack (high power)
Calibration	Gamma curve	$\phi(g)$ per wavelength + spatial flatness map
Temperature	Some regulation	Often actively controlled ($\Delta n(T)$ moves the LUT)

Two trade-offs dominate the PAN design: high Δn keeps the cell thin and fast ($\tau \propto \gamma_1 d^2/K\pi^2$), but the cyano and tolane compounds that give high Δn absorb closer to the UV and are less photostable; and the thicker the cell, the wider the fringing-field "flyback" zone at each grating edge, which scatters light into unwanted orders.

4.2 Alignment and pretilt — where the systematic errors start

Pretilt sets which way the director falls and how the transfer curve looks. Classic oblique SiO_2 results (Janning, 1972, and later work) give:

Deposition angle	LC alignment	Pretilt	Use
≈ 60°	Perpendicular to plane of incidence	≈ 0° (degenerate → domains)	Not alone for PAN
≈ 80–85° grazing	In plane of incidence	≈ 15–30°	Loses phase range
Two-step / surface treatment	In-plane, controlled	≈ 2–10°	PAN/ECB phase SLM
Oblique SiO_x + homeotropic treatment	Near-vertical	1–5° from normal	VAN projector

The GLAD Monte Carlo (column tilt β vs deposition angle) is the tool for locating the intermediate PAN window; pretilt follows β but also depends on column-induced roughness.

The error chain modelled in the simulations is:

> ***pretilt map → local transfer curve (gamma for VAN, φ(g) for PAN) → local phase-step error → height error***

For rubbed polyimide the pretilt follows the rubbing strength $L = N \cdot M \cdot (1 + 2\pi Rn/v)$ (N rubs, pile depth M, roller radius R, speed n, stage speed v). Process window from the folder notes: PI film 20–40 nm,

cure 180–230 °C (below the CMOS limit), roller 400–800 rpm, stage 10–20 mm/s, pile depth 0.2–0.4 mm held to ±0.02 mm, antiparallel misalignment within ±0.5° (beyond ±1° reverse-tilt disclinations appear), followed by ionizer bars and 1 MHz megasonic cleaning. Pile-depth variation across a 300 mm wafer is the direct physical source of the pretilt maps in fig4.

4.3 Inspection of the alignment layer and cell

Defect	Detection	Example equipment (from folder notes)
Rubbing streaks, alignment skips	Polarized-light birefringence mapping	Custom macro-inspection
Fibers, particles, scratches	Grazing darkfield laser scatter	Hitachi High-Tech LS series; KLA Surfscan
PI thickness, stains	Brightfield spectroscopic reflectometry	Nikon NEXIV VMZ-S with wafer loader
Pretilt, gap, disclinations in filled cells	Conoscopy, crossed-polarizer imaging, interference fringes when driven	Lab polarizing microscope / custom

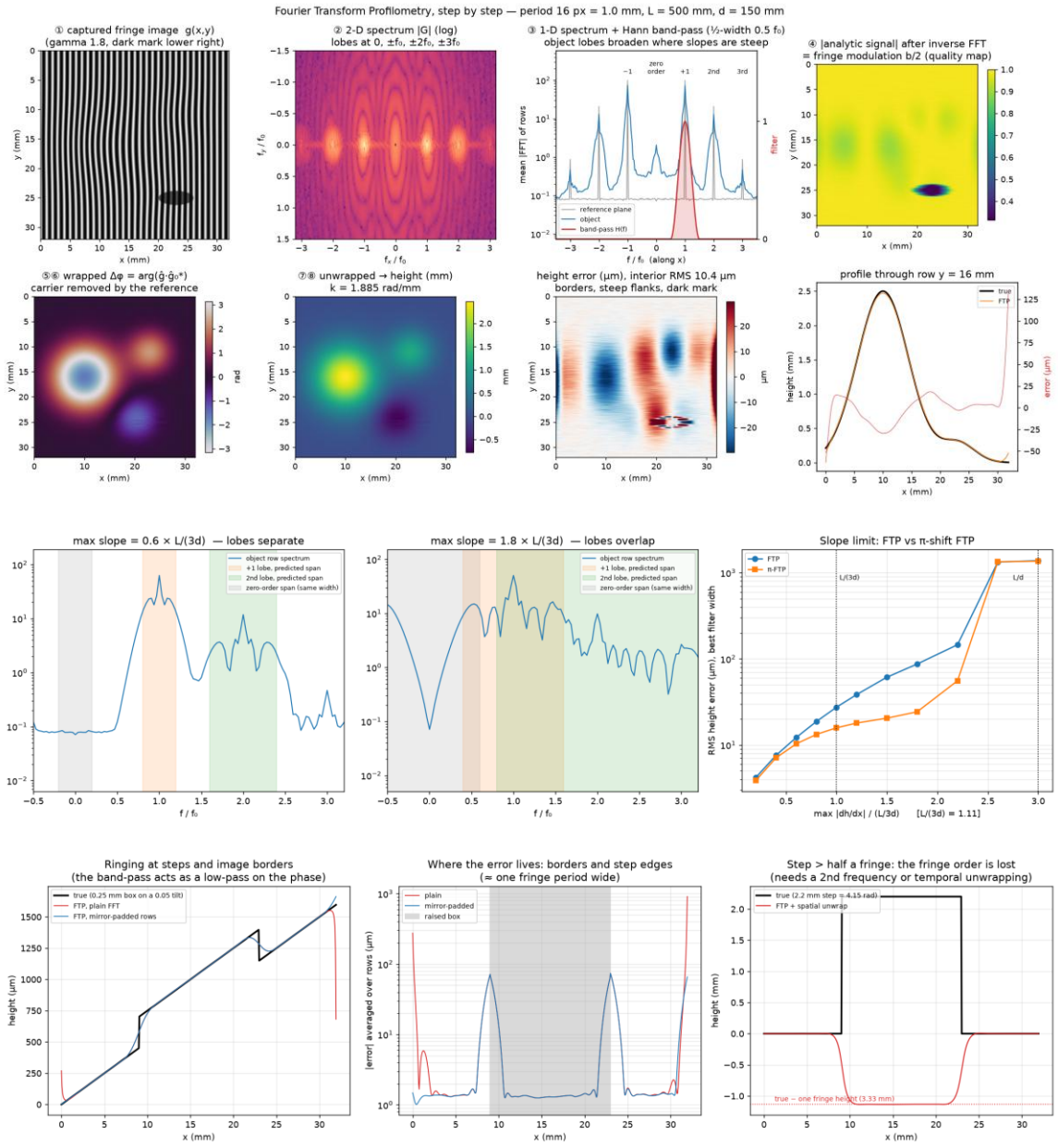
5. Phase retrieval: FTP and PSP (walkthrough results)

Both approaches feed the same algorithms. The walkthrough scripts use the reference geometry so the numbers compare directly.

5.1 Fourier-transform profilometry (one frame)

The fringe image $g = a + b\cdot\cos(2\pi f_o x + \phi)$ has three spectral lobes (zero order, +1, −1) plus harmonics if the fringe is not a pure sinusoid. FTP keeps the +1 lobe with a band-pass (raised cosine, half-width $0.5f_o$), inverse-transforms, multiplies by the conjugate of the reference-plane result, and takes the angle.

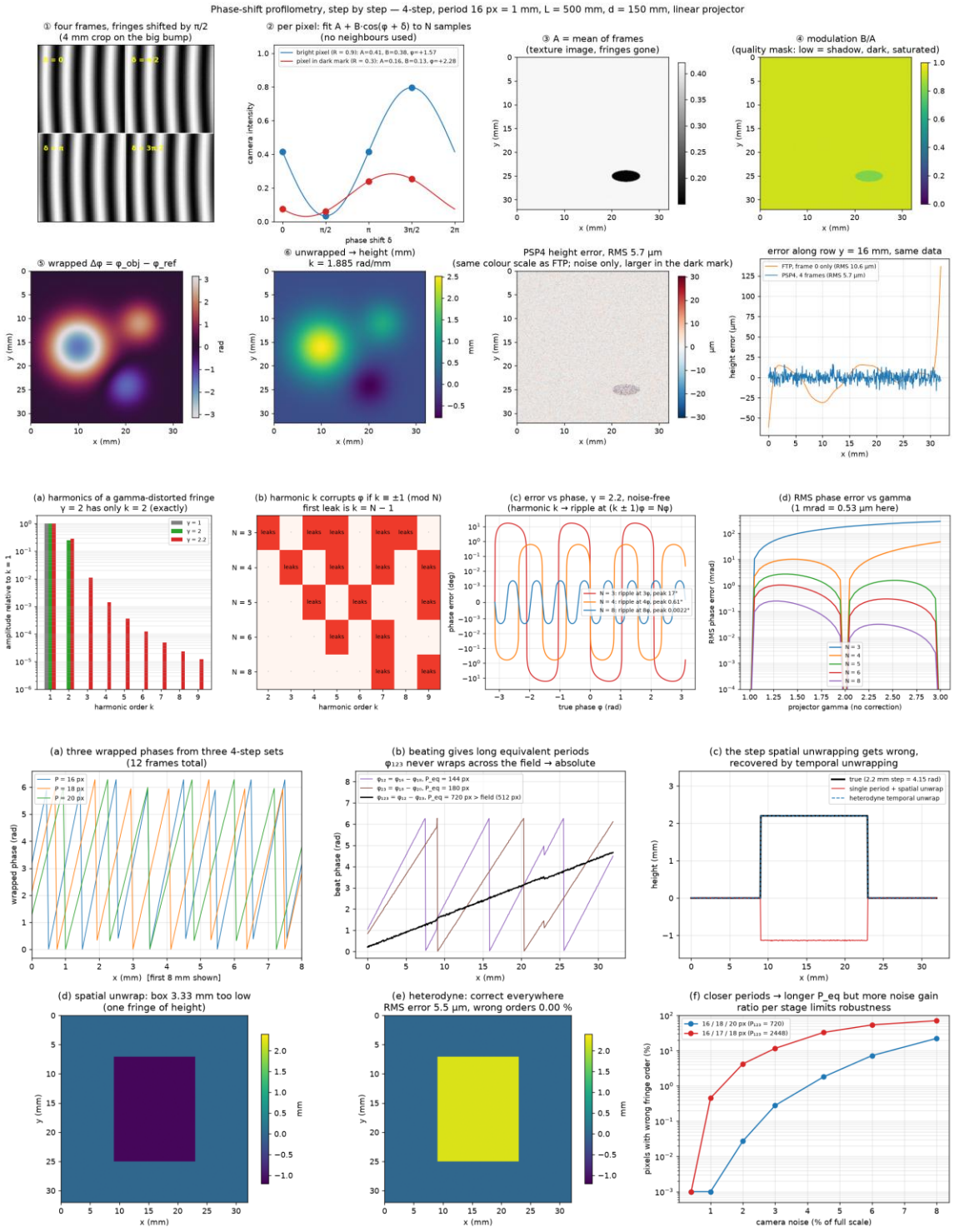
- Gamma-tolerant (the filter rejects harmonics) and motion-proof (one exposure); also immune to LC settling.
- Lateral resolution is about one fringe period; errors ring at edges and image borders (fixed largely by mirror padding).
- **Slope limit** $|\partial h/\partial x| < L/(3d)$ (L/d for π-shift FTP); simulated error 27/87 µm at 1×/1.8× the limit for FTP vs 16/24 µm for π-FTP; both fail above about 2.6×.
- Interior error in the walkthrough: about 10–15 µm RMS.



5.2 N-step phase-shifting profilometry

With N frames shifted by 2π/N, each pixel is solved alone: $\phi = -\text{atan2}(\Sigma I_n \sin\delta_n, \Sigma I_n \cos\delta_n)$. Harmonic k leaks into the phase only when $k \equiv \pm 1 \pmod N$, so N-step PSP cancels harmonics up to order N−2.

- 4-step PSP on identical data: **5.7 µm RMS vs 10.6 µm** for FTP on one frame; PSP error is random, FTP's is smooth blobs plus >100 µm at borders.
- At γ = 2.2 the peak phase ripple is 17° (N = 3), 0.6° (N = 4), 0.002° (N = 8).
- **Heterodyne unwrapping** with periods 16/18/20 px (12 frames) gives synthetic periods of 144, 180 and 720 px, longer than the 512 px field; the 2.2 mm step is recovered with 5.5 µm RMS and no fringe-order errors up to about 1% camera noise. Closer periods (16/17/18 px) extend range (2448 px) but fail earlier with noise.



	FTP	PSP (N-step)
Frames	1 (π-FTP: 2)	3 or more (12 with heterodyne)
Per-pixel phase	No (≈ one period)	Yes

	FTP	PSP (N-step)
Moving parts	Excellent	Poor unless frames are fast
Gamma / harmonics	Filtered	Need LUT or N ≥ 4
LC settling	Irrelevant	Must be managed (A)
Typical accuracy	1/100–1/500 of period	1/1000 of period or better

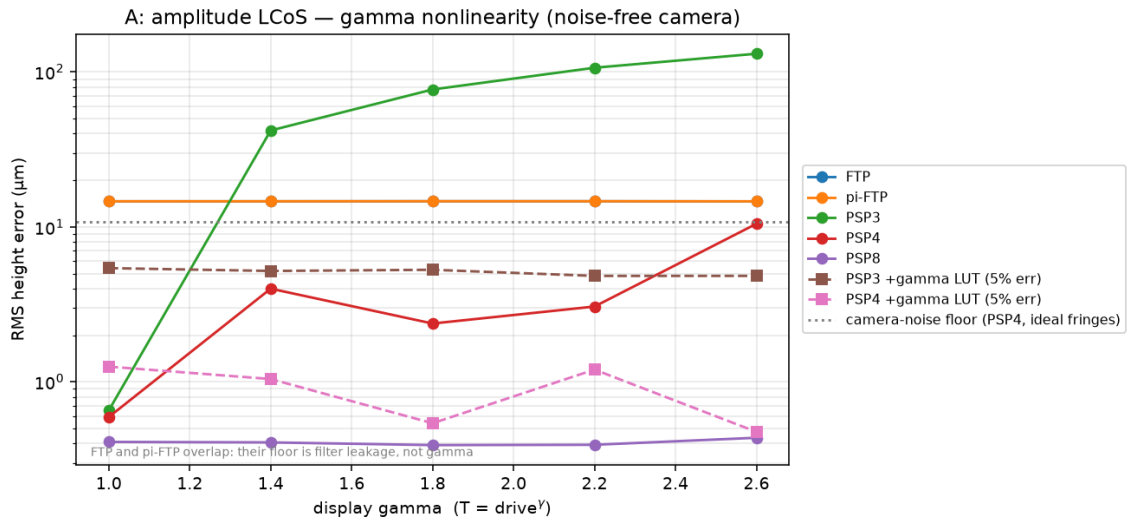
6. Performance impacts of each LCoS effect (simulation results)

All numbers are RMS height error over the 32 × 32 mm field from lcos_fpp_results/summary.csv. Studies other than the noise floor and the speckle/period scans were run noise-free, so they isolate the LCoS effect; the noise-free 4-step baseline is 0.39 µm.

6.1 Gamma (intensity transfer curve) — Approach A

Method	γ = 1.0	1.4	1.8	2.2	2.6
PSP3 uncorrected	0.65	41.9	77.0	106.4	131.0
PSP4 uncorrected	0.59	4.0	2.4	3.1	10.5
PSP8 uncorrected	0.41	0.41	0.39	0.39	0.44
PSP3 + LUT (5% error)	5.4	5.2	5.3	4.8	4.8
PSP4 + LUT (5% error)	1.3	1.0	0.54	1.2	0.48
FTP / π-FTP	14.6	14.6	14.6	14.6	14.6

(µm RMS.) PSP4 dips near γ = 2 because a pure square law makes only a 2nd harmonic, which 4-step cancels. **Impact:** with ≥ 4 steps and a gamma table, gamma is a ~1 µm term; 3-step PSP is unusable on a VAN panel without calibration. Gamma is irrelevant to B (pure cos²).

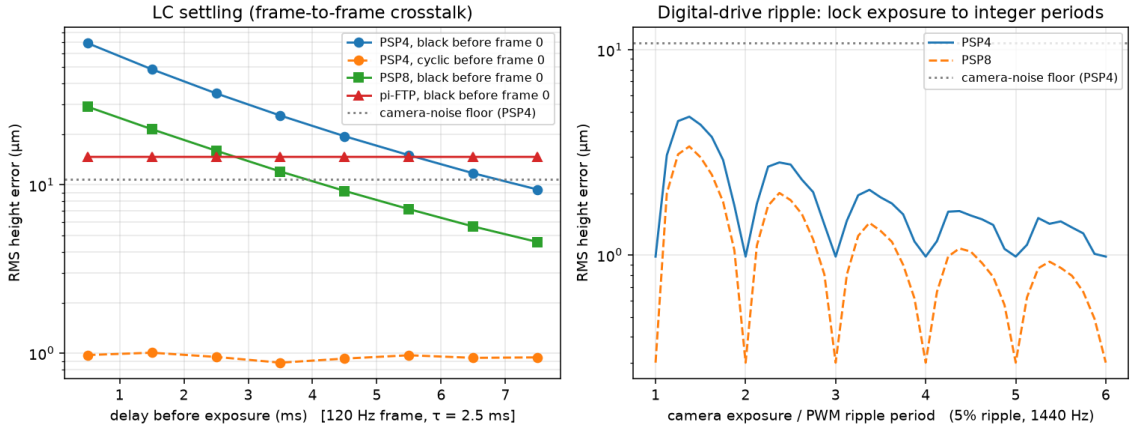


6.2 LC settling and PWM ripple — Approach A

Settle delay after VSYNC (120 Hz, τ = 2.5 ms)	0.5 ms	1.5 ms	3.5 ms	5.5 ms	7.5 ms
PSP4, black before frame 0	69.2	48.4	25.7	15.0	9.4
PSP8, black before frame 0	29.0	21.4	12.0	7.2	4.6
PSP4, cycling continuously	0.98	1.0	0.88	0.97	0.95
π-FTP	14.6	14.6	14.6	14.6	14.6

Impact: starting a PSP sequence from black puts the transient into the first frame only, which is a large, structured error; keeping the panel cycling makes every frame see the same history and the error drops 70-fold to about 1 µm. For a thick PAN cell in amplitude mode, scale delays with d^2.

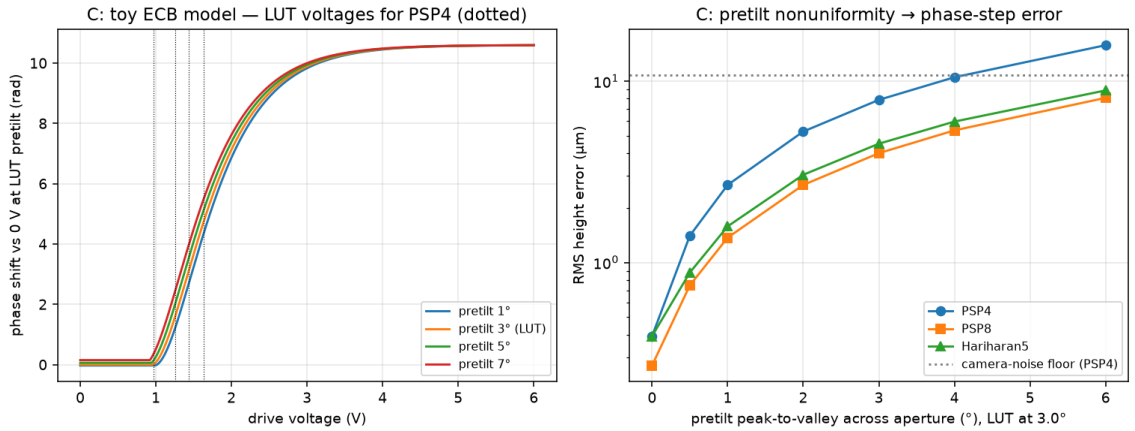
PWM ripple (exposure in units of the ripple period): PSP4 error is 0.98 µm at whole periods and peaks at 4.7 µm at 1.375 periods; PSP8 peaks at 3.4 µm. **Impact:** lock exposure to whole bit-plane cycles, or use analog drive.



6.3 Pretilt non-uniformity — Approach C (and A's local gamma)

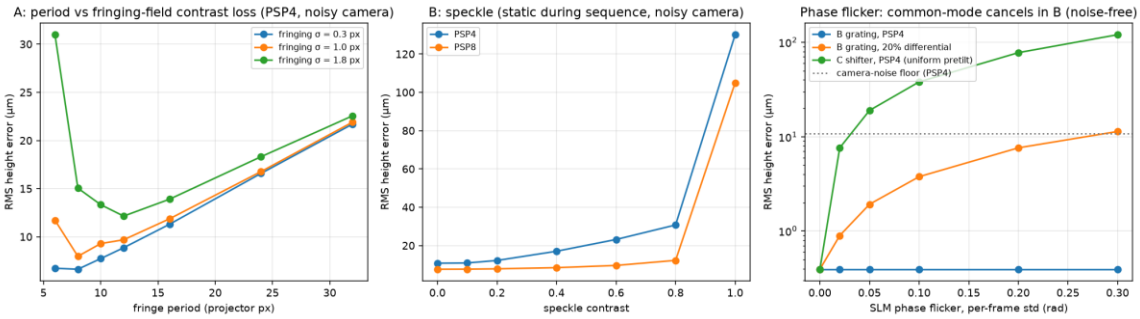
Pretilt peak-to-valley	0°	0.5°	1°	2°	3°	4°	6°
PSP4	0.39	1.4	2.7	5.3	7.9	10.5	15.7
Hariharan 5-step	0.39	0.88	1.6	3.0	4.5	6.0	8.9
PSP8	0.27	0.75	1.4	2.7	4.0	5.3	8.1

A 3° peak-to-valley map gives ±12° local step error. **Impact:** roughly 2.6 µm per degree for 4-step, halved by step-error-tolerant algorithms. B is immune (step set by geometry); A sees it only as a local gamma change, largely rejected by N ≥ 4.



6.4 Fringe period, speckle and phase flicker

- **Fringing field (A).** Phase error at 6 px period rises from 34 mrad (blur σ 0.3 px) to 156 mrad (σ 1.8 px); at ≥ 12 px the extra error is small. Height error has an optimum near 8–12 px because shorter periods also raise sensitivity. **Keep P ≥ 8–10 px.**
- **Speckle (B).** PSP4: 10.8 µm at contrast 0, 12.2 at 0.2, 17.0 at 0.4, 30.7 at 0.8 and 130 µm at fully developed speckle (C = 1). PSP8 is more tolerant (7.6 → 12.2 µm up to C = 0.8). **Keep speckle contrast ≤ 0.2.**
- **Phase flicker (B vs C).** B with uniform flicker: 0.39 µm at every level up to 0.3 rad (exact cancellation). B with 20% of the flicker differential between the two orders: 1.9 µm at 0.05 rad, 11.3 µm at 0.3 rad. C: 7.6 µm at 0.02 rad, 19 µm at 0.05 rad, 120 µm at 0.3 rad.



6.5 System-level performance comparison

	A: VAN projector	A: PAN in amplitude mode	B: phase grating	C: phase shifter
Steps per second (nematic)	120 (one per frame)	30–60	10–25	10–25
With FLCoS	kHz binary patterns (binary-defocus PSP)	—	kHz (0/π grating)	—
Depth of	Projection-lens limited	Lens limited	Unlimited in beam	Unlimited

	A: VAN projector	A: PAN in amplitude mode	B: phase grating	C: phase shifter
field			overlap	
Finest period	≈ 8–10 panel px	≈ 8 px	Set by θ, sub-pixel equivalent	Set by interferometer
Calibration burden	Gamma LUT, timing	Gamma LUT (folded), temperature	Reference plane only	ϕ(g) map, pretilt map
Dominant error	Camera noise; fringing; settling if mishandled	Temperature drift, settling	Speckle, parasitic fringes	Flicker, path drift
Hardware cost	Low (projector module)	Medium (research SLM)	Medium–high (SLM, laser/SLD, relay)	Medium–high

7. Error budgets

Method. Each line is the error that source adds on its own, in phase (mrad) and in height at 0.53 µm/mrad. Terms marked *sim* come from summary.csv: where the simulated case already included camera noise or the 0.74 mrad noise-free baseline, that part was removed in quadrature (√(total² − base²)). Terms marked *est.* are engineering estimates not yet simulated and should be treated as placeholders to be measured. Lines are combined by root-sum-square, which assumes they are independent. Operating point for each: 4-step PSP, reference geometry, good practice as stated.

7.1 Approach A, VAN panel (120 Hz analog drive, 2 µm cell, gamma LUT, continuous cycling, P = 16 px)

Source	mrad	µm	Basis
Camera shot and read noise	20.3	10.8	sim
Gamma residual, LUT with 5% error	2.1	1.1	sim
LC settling, cyclic sequence	1.6	0.9	sim
PWM ripple (analog drive, or whole-period exposure)	0	0	sim
Fringing field at 16 px (blur σ 0.3 px; 9.4 mrad at 1.0 px)	6.4	3.4	sim
Pixel droop / frame flicker held to ½ LSB	2.0	1.1	est.
Gamma drift between calibrations (±2 K)	2.5	1.3	est.
Pretilt non-uniformity → local gamma (mostly rejected by N = 4)	1.5	0.8	est.
Projector distortion / defocus after reference subtraction	3.0	1.6	est.

Source	mrad	µm	Basis
Total (RSS)	**22.0**	**11.6**	
LCoS and optics only (no camera noise)	**8.4**	**4.4**	

7.2 Approach A, PAN/ECB phase SLM used in amplitude mode (60 Hz, 4 µm cell)

Source	mrad	µm	Basis
Camera noise (≈ 2% lower modulation)	20.7	11.0	sim, scaled
Gamma residual on a folded $\sin^2$ curve, LUT 5–10%	3.2	1.7	sim, scaled
LC settling, cyclic, τ 6–10 ms	6.0	3.2	est. from sim trend
PWM ripple	0	0	analog drive
Fringing field at 16 px	6.4	3.4	sim
Frame flicker	2.0	1.1	est.
Δn(T) drift moves the whole T(V), including black (±2 K)	5.0	2.7	est.
Pretilt non-uniformity → local T(V)	3.0	1.6	est.
Lens distortion / defocus	3.0	1.6	est.
Total (RSS)	**23.7**	**12.6**	
LCoS and optics only	**11.6**	**6.2**	

7.3 Approach B, phase-grating interference (PAN SLM, SLD source)

Source	mrad	µm	Basis
Camera noise	20.3	10.8	sim
Speckle, contrast 0.2	10.8	5.7	sim
SLM phase flicker, 20% differential at 0.05 rad	3.5	1.9	sim
Phase-step error (whole-pixel grating shift)	0	0	by design
Gamma / harmonics	0	0	by design
Static SLM flatness and pretilt map	0	0	cancels with reference plane
Differential path drift and vibration over a sequence	5.0	2.7	est.
Parasitic interference (ghosts, dust, zero-order leak)	6.0	3.2	est.
Wavelength drift → period scale	1.0	0.5	est.

Source	mrad	µm	Basis
Total (RSS)	**24.5**	**13.0**	
LCoS and optics only	**13.8**	**7.3**	

7.4 Variant C, phase shifter (for comparison)

Source	mrad	µm	Basis
Camera noise	20.3	10.8	sim
Pretilt map 3° PV, Hariharan 5-step (14.8 mrad for PSP4)	8.5	4.5	sim
Phase flicker 0.05 rad	35.7	18.9	sim
Path drift between separate arms	15.0	8.0	est.
$\phi(g)$ LUT and temperature	8.0	4.2	est.
Total (RSS)	**45.2**	**24.0**	

7.5 Reading the budgets

- **The camera dominates in the reference case.** A and B are within 10% of each other in total. Reducing camera noise (larger full well, averaging, PSP8: 14.3 mrad floor) exposes the LCoS terms, where A-VAN (4.4 µm) currently beats B (7.3 µm) — but A's terms are mostly fixed by the panel, while B's are mostly optical-hygiene estimates that could be driven down.
- **A's budget assumes discipline.** Break any one rule and its line jumps: 3-step instead of 4-step (→ 106 µm), start from black (→ 48–69 µm), wrong exposure (→ up to 4.7 µm), period below 8 px (→ up to 31 µm at 6 px with heavy fringing).
- **B's budget is robust to the LCoS** but sensitive to coherence: speckle contrast 0.4 adds 9 µm and fully developed speckle 130 µm.
- **PAN in amplitude mode** is workable but worse than VAN in every LC-related line; it makes sense only if one SLM must serve both an amplitude and a phase role.
- **As a fraction of depth:** 4–7 µm systematic on a 3 mm range is about 1/400–1/700 per pixel; spatial averaging and PSP8 move this toward the 1/1000–1/5000 projected for the concrete build.

8. Comparison and recommendations

Criterion	A (VAN amplitude)	B (phase grating)	Better
Total error, reference case	11.6 µm	13.0 µm	≈ equal
LCoS-related error	4.4 µm	7.3 µm (mostly optics est.)	A today, B potentially
Robustness to LC	Needs LUT, timing	Insensitive by construction	B

Criterion	A (VAN amplitude)	B (phase grating)	Better
imperfections	discipline		
Speed (nematic)	120 steps/s	10–25 steps/s	A
Speed (ferroelectric)	kHz binary (binary-defocus)	kHz 0/π gratings, DC balance free	Tie
Depth of field	Lens-limited	Non-localized	B
Shiny / rough surfaces	Incoherent, no speckle	Speckle risk	A
Cost, size, supply chain	Projector modules in volume	Laser/SLD, relay, research SLM	A

Recommendations

1. **For a production or general-purpose 3D sensor, build A with a VAN panel**, analog or locked-exposure PWM drive, ≥ 4-step PSP plus 16/18/20 heterodyne unwrapping, continuous pattern cycling, and fringe periods ≥ 10 px. Use π-FTP for moving parts.
2. **For high-DOF, fine-period or microscopic work, build B** with an SLD and a 0/π grating; consider a ferroelectric SLM for kHz stepping. Budget effort on speckle and stray-light control rather than on the SLM.
3. **Avoid C** unless an interferometer is already required.
4. **A profilometry-optimized LCoS differs from a display panel.** Ranked requirements for an amplitude cell: (i) temporal stability — pixel droop ≤ ½ LSB, low flicker, DC balance; (ii) speed — 2 µm gap, overdrive, τ well inside a frame; (iii) a smooth, repeatable transfer curve with a temperature sensor and LUT; (iv) pretilt uniformity (rubbing pile depth ±0.02 mm, or uniform GLAD SiO_x); (v) contrast is secondary above ~300:1. For a phase cell used in B: 0/π stroke only (thinner, faster), high Δn, small pixel gaps to sharpen grating edges, and flatness mattering less because it cancels.

Suggested next simulations (to replace the *est.* lines in Section 7): temperature drift of the VAN gamma and PAN T(V); a PAN-in-amplitude model with the folded $\sin^2$ curve and d^2-scaled settling; parasitic-interference and path-drift models for B; a binary FLCoS version of B; and Approach D with micro-polarizer extinction errors.

9. Companies selling system-level profilometry products

Context first. Most commercial fringe-projection products do not say which modulator they use, and many use Texas Instruments DLP micromirror engines because binary patterns switch at kHz rates. LCoS competes where analog gray levels without dithering, high fill factor, or phase modulation matter. Where a supplier's modulator is confirmed it is stated; otherwise the entry is a system-level competitor or customer, not a confirmed LCoS user.

9.1 Industrial 3D metrology (amplitude fringe projection, Approach A class)

Company	Products	Notes

Company	Products	Notes
ZEISS (GOM Metrology)	ATOS Q, GOM Scan 1, ScanBox, ScanCobot	Narrow-band blue LED fringe projection with heterodyne phase; stereo cameras (confirmed 2026 application report)
Hexagon	AICON SmartScan / StereoScan structured-light scanners	Metrology-grade fringe projection
Creaform (AMETEK)	Go! SCAN and related white-light scanners	Handheld structured light
Shining 3D	EinScan series	Low-cost structured light
Polyga	Compact / H-series scanners	Structured light

9.2 Machine-vision 3D cameras for automation

Company	Products
Zivid (Norway)	Zivid 2/2+ structured-light color 3D cameras
Photoneo (Slovakia)	PhoXi 3D scanner, MotionCam-3D
IDS Imaging (Ensenso)	Ensenso stereo + pattern-projector cameras
LMI Technologies	Gocator snapshot (structured light) sensors
Cognex	3D-A series area-scan structured-light cameras
Keyence	VR-series wide-area 3D measurement; 3D vision systems
wenglor	ShapeDrive structured-light 3D sensors

9.3 Electronics inspection: 3D SPI and 3D AOI (phase-shifted fringe projection)

Company	Notes
Koh Young (Korea)	Market leader in 3D SPI/AOI using multi-direction phase-shift moiré projection
CyberOptics (part of Nordson since 2022)	3D SPI/AOI with multi-reflection suppression sensors
MIRTEC (Korea)	3D SPI and AOI with moiré projection
Test Research Inc. (TRI, Taiwan)	3D SPI/AOI
Saki (Japan), Omron (VT series), Parmi, Pemtron, ViTrox	3D SPI/AOI

Company	Notes
Nexstar Technology (Korea)	Nexman GENIO 3D AOI/SPI — **confirmed LCoS user**: $1 M production order (June 2022) for Kopin/Forth Dimension Displays ferroelectric LCoS SLMs to project structured light

9.4 Phase-modulation (Approach B class) systems

Commercial industrial profilometers based on ±1-order interference from an LCoS grating are rare; the architecture is mainly found in **structured-illumination super-resolution microscopy**, where ferroelectric SLMs write the 0/π gratings at kHz rates, and in research systems built from Holoeye, Hamamatsu or Meadowlark SLMs. For microscopic and wafer-scale surface metrology the incumbents use other principles (white-light interferometry: Zygo, Bruker; confocal and focus variation: Sensofar, Bruker Alicona, Keyence), which define the performance an Approach-B product would have to beat.

10. Major suppliers

10.1 LCoS for amplitude projection (Approach A)

Supplier	Relevant products	Fit for profilometry
Sony	SXRD VAN panels; Polarsens sensors (see cameras)	Highest-quality VAN projector panels; sold mainly inside Sony projectors
JVCKENWOOD	D-ILA VAN panels	As Sony; projector-integrated
Himax Technologies	LCoS microdisplays and modules, in-house LCoS processing (FY2025 20-F lists industrial uses)	Merchant supply of panels and light engines
OmniVision	LCoS microdisplays and drivers (AR, pico)	Small, fast panels
Raontech (Korea)	LCoS microdisplays	Merchant microdisplays
Forth Dimension Displays (Kopin)	Ferroelectric LCoS microdisplays	kHz binary patterns, structured light
HOLOEYE Photonics	Amplitude microdisplays and development kits	Lab prototyping with drivers

10.2 Phase-only LCoS SLMs (Approaches B, C, D)

Supplier	Products / notes
Hamamatsu Photonics	LCOS-SLM X10468/X13138/X15213 series, incl. high-power versions with dielectric mirrors

Supplier	Products / notes
HOLOEYE Photonics (Germany)	PLUTO-2.1, GAEA-2.1 (4K), LETO-3; bought Jasper Display Corp.'s fast digital backplane technology and inventory in February 2024
Meadowlark Optics (US)	High-speed analog phase SLMs (1920 × 1152, 512 × 512); owns the former Boulder Nonlinear Systems commercial SLM line
Santec	SLM-200/-300 series, high fill factor, telecom and instrumentation
Thorlabs	Exulus phase SLMs and SLM kits
Forth Dimension Displays (Kopin)	Binary ferroelectric SLMs (e.g. QXGA-3DM) — the natural device for kHz 0/π gratings in Approach B
Chinese suppliers	Several (e.g. UPOLabs, Xi'an CAS Microstar) — not verified here

10.3 Cell materials and process equipment

Category	Suppliers
Liquid crystals	Merck KGaA (licristal®, e.g. MLC-6608, E7), JNC, DIC
Polyimide alignment	JSR, Nissan Chemical
Rubbing machines	PREMATEC (RLF/RLD series: 1–3000 rpm rollers, ±47° rubbing angle, ±40 µm gap tracking); Joyo Engineering
Wafer/film inspection	KLA (Surfscan), Hitachi High-Tech (LS series), Nikon (NEXIV VMZ-S)
Cover glass	Corning (Eagle XG), Schott (Borofloat)

10.4 Cameras, sources and optics

Category	Suppliers
Image sensors	Sony (Pregius global shutter; IMX250MZR polarization sensor for Approach D)
Machine-vision cameras	Basler, Teledyne FLIR, Allied Vision, IDS, LUCID Vision Labs (polarization models), Baumer
SLD / low-coherence sources (B)	Exalos, Superlum, Thorlabs, Hamamatsu
Lasers	Coherent, Toptica, Thorlabs, Hamamatsu
High-power LEDs (A)	Nichia, ams OSRAM, Luminus

Category	Suppliers
Competing modulator	Texas Instruments DLP (and engine makers such as Young Optics)

Sources and items to verify

Folder material used: FTP_using_LCoS.docx; LCoS Design Issues.docx; LCoS_VAN_vs_PAN_alignment_materials_construction.xlsx; lcos_fpp_error_sim.py and lcos_fpp_results/summary.csv with fig1–fig5; ftp_walkthrough.py and psp_walkthrough.py with their figures; setup_diagrams_2.py with setup A, B, C1, C2, C3; Technical Information _ PREMATEC Corporation.pdf.

Web sources checked:

- ZEISS fringe projection application report 2026 — GOM/ATOS products, blue-light heterodyne projection.
- Kopin: $1 M FLCoS SLM order from Nexstar Technology (June 2022)
- Holoeye purchase of Jasper Display LCoS technology (Feb 2024)
- Meadowlark acquisition of Boulder Nonlinear Systems commercial products
- Himax Technologies Form 20-F, FY2025
- Forth Dimension Displays (overview)
- PREMATEC rubbing machines

To verify before relying on them:

- Material constants (Δn, $\Delta \varepsilon$, γ_1, K) are literature values; check current Merck datasheets at the working wavelength and temperature.
- Product model numbers and current ownership of smaller SLM and microdisplay suppliers (Chinese SLM makers, Raontech, OmniVision product status) were not individually checked.
- Modulator technology inside most named system products is not published; only Nexstar (FLCoS) is confirmed.
- All *est.* lines in the error budgets are estimates pending simulation or measurement.
- The simulated LC model for Approach C is simple (uniform response plus pretilt-dependent step error).