Design of a Phase-Only LCoS SLM for a Neutral-Atom Quantum Computer

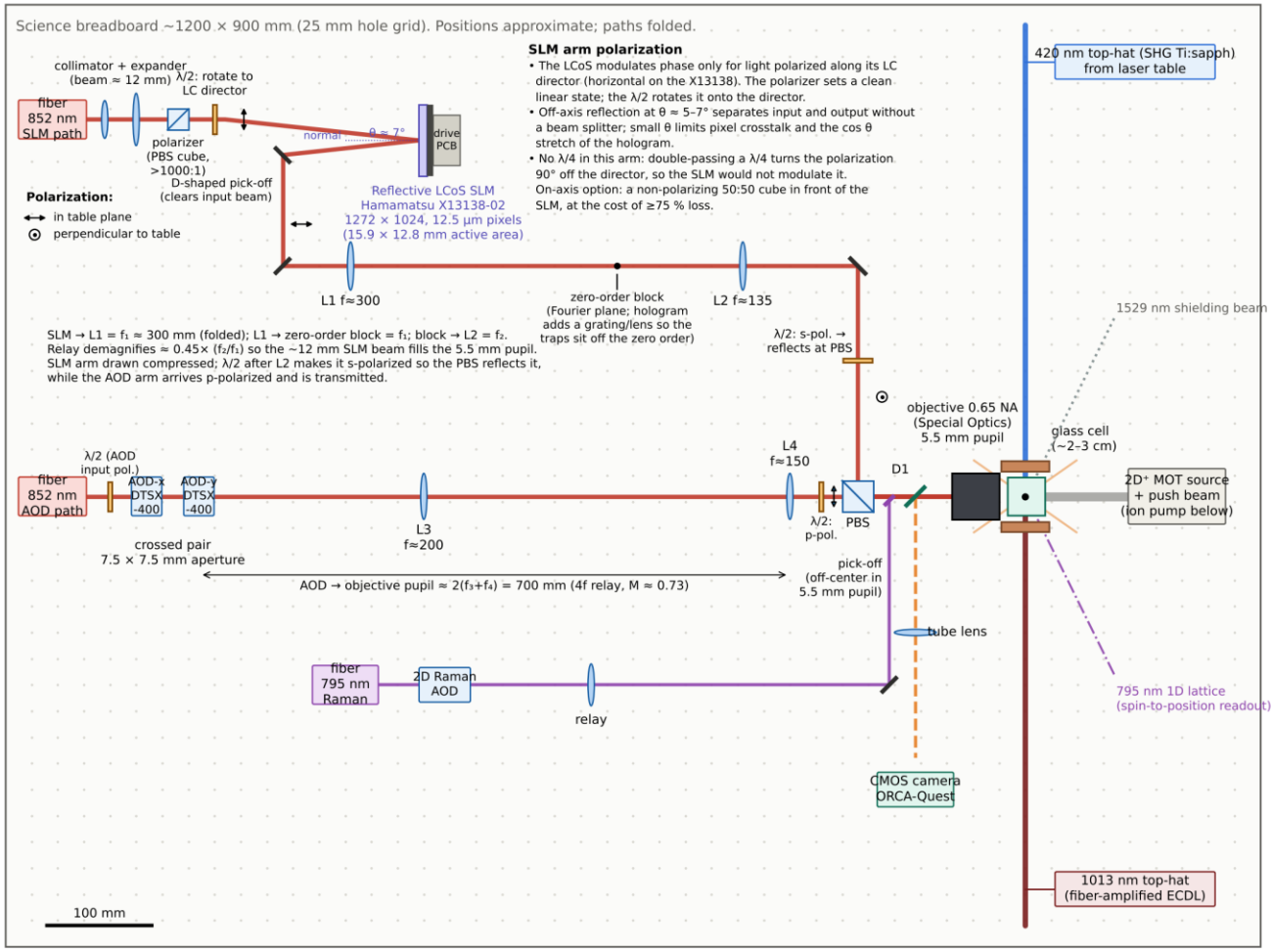
Requirements, design equations, materials, mirror and fabrication
for a QuEra-style Rb machine at 852 nm and a ^{171}Yb machine at 483–759 nm

Technical note summary

David F. Hakala

November 2, 2026

The SLM is the hologram that makes the trap array



Reflective SLM in a pupil plane, polarizer and λ/2 aligned to the LC director (Harvard/QuEra-style layout).

- A 10–15 mm beam reflects from the SLM at 3–5°; a 4f relay images it onto the objective's back aperture
- The objective Fourier-transforms the phase pattern into hundreds to thousands of tweezers
- Weighted Gerchberg–Saxton with camera or atom feedback equalizes trap depths to < 1 %
- AOD tweezers move atoms; the SLM defines the static array (SLM-only rearrangement needs > 1 kHz)
- **So the SLM sets qubit count, trap uniformity and stability, laser power and heat load**

What a tweezer SLM must deliver

Requirement	Why it matters	Target
Phase stroke at trap λ	Full blazing; room for LUT and aberration correction	≥ 1.1 waves double-pass
Diffraction efficiency	Laser power limits large arrays	≥ 85 % in first order
Pixel count and pitch	Number of traps and addressable field	≥ 1920 × 1152; 8–12.5 µm
Phase stability (flicker)	Intensity noise at 2× trap frequency heats atoms	< 10^{-3} rad rms, 10–500 kHz; analog drive
Optical power handling	1000–10 000 traps need 20–200 W	Dielectric mirror, active cooling, < 1 % absorption
Thermal phase drift	Trap depth and position drift	< 0.02 wave at full power
Flatness	Diffraction-limited, uniform spots	≤ 1 λ native, ≤ λ/10 corrected
Polarization	Only light along the director is modulated	Linear input, PER > 1000:1
Update rate	Static array or SLM rearrangement	60 Hz to > 1 kHz

Proposed Rb device at a glance

2.6 µm

cell gap, Δn ≈ 0.20 at 852 nm (1.22 waves)

9.2 µm

pixel pitch, 1920 × 1152 analog backplane

≈ 7700

resolvable traps at spacing/spot = 6

8.2 mW

per 1 mK Rb trap at the atoms (0.9 µm waist)

99.3 %

4-pair Nb_2O_5/SiO_2 mirror on Al (bare Al: 80 %)

≈ 9 ms

relaxation time — fine for a static array

Section 1

Device physics

LC mode · cell gap and speed · fringing and efficiency · field and trap count · flicker · power and heat

Parallel-aligned nematic is the right mode for tweezers

Choose

Parallel-aligned (PA, ECB)

Δε > 0 · director in plane

Full 2dΔn/λ swing; simplest optics; high-Δn materials available. The laser is already polarized.

Avoid

Vertically aligned (VAN)

Δε < 0 · director near normal

Boundary layers never fully tilt (0.80 of 0.94 waves in the VAN note); Δn ≈ 0.08 forces thick, slow cells.

Unneeded

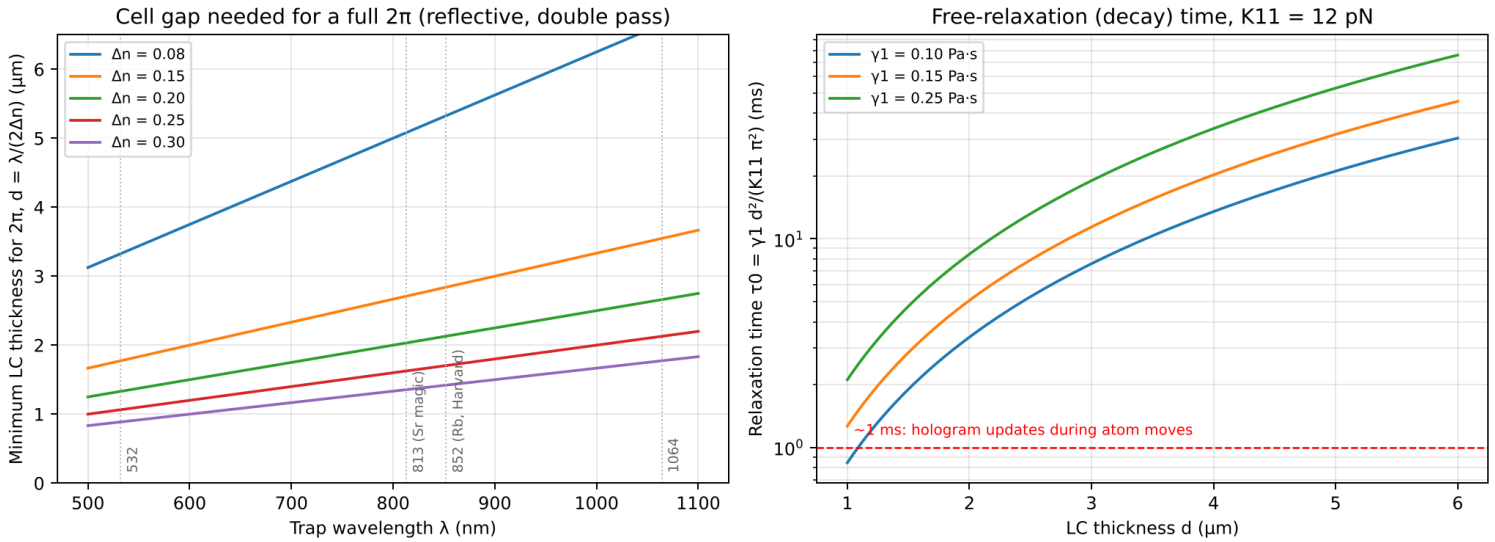
Polarization-independent

PA + polymer λ/4 or metasurface

Accepts any polarization at a cost in thickness, voltage or efficiency — buys nothing for a polarized trap laser.

Reflective phase: $\varphi(V) = (4\pi/\lambda) \int n_{eff}(\vartheta(z,V))\, dz$, so the maximum swing is $2d\Delta n/\lambda$ waves.

High birefringence buys a thin, fast cell



Minimum cell gap for 2π (left) and free-relaxation time (right), K_{11} = 12 pN.

Cell gaps include a 10 % margin; τ_0 at γ_1 = 0.15 Pa·s.

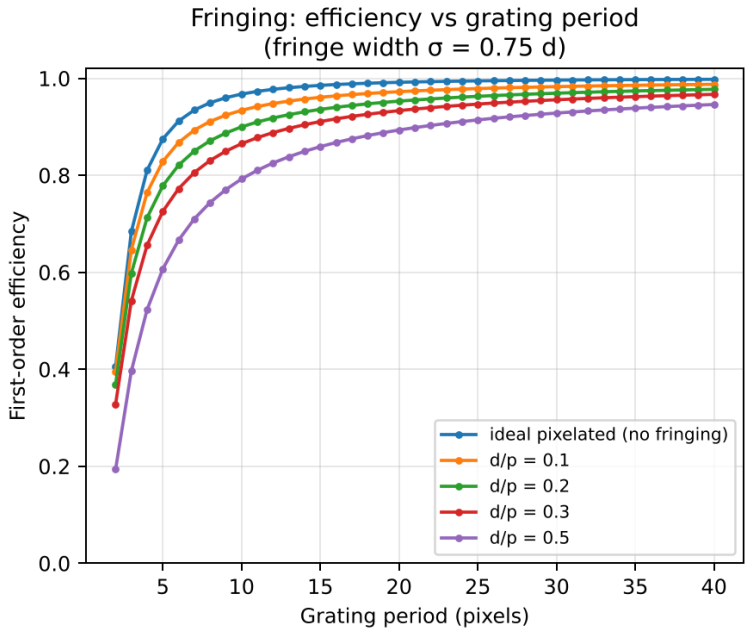
$$d_2\pi = \lambda / (2\Delta n)$$

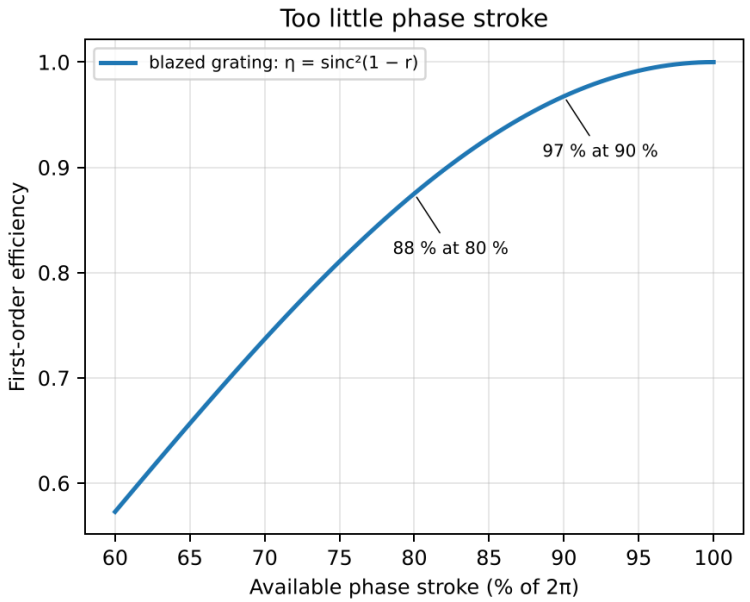
$$\tau_0 = \gamma_1 d^2 / (K_{11}\pi^2)$$

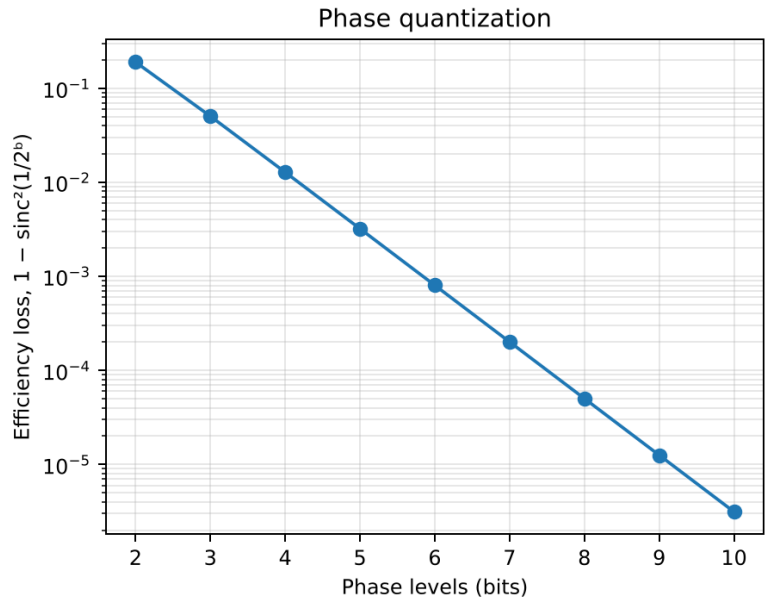
$$V_th = \pi \sqrt{(K_{11} / \varepsilon_0 \Delta\varepsilon)} \approx 1.2\ V$$

- Δn 0.08 (VA mixture): 5.9 μm, 44 ms
- Δn 0.20: 2.3 μm, 6.8 ms
- Δn 0.30: 1.6 μm, 3.2 ms
- Specify Δn at the trap wavelength, not 589 nm
- $\tau_0 \propto d^2$, so Δn buys speed quadratically

Fringing limits efficiency: keep d/p ≤ 0.3







First-order efficiency against grating period (fringing as Gaussian smoothing of width 0.75d), phase stroke, and bit depth.

95 % → 83 %

8-pixel grating, ideal pixels → d/p = 0.3
(74 % at d/p = 0.5)

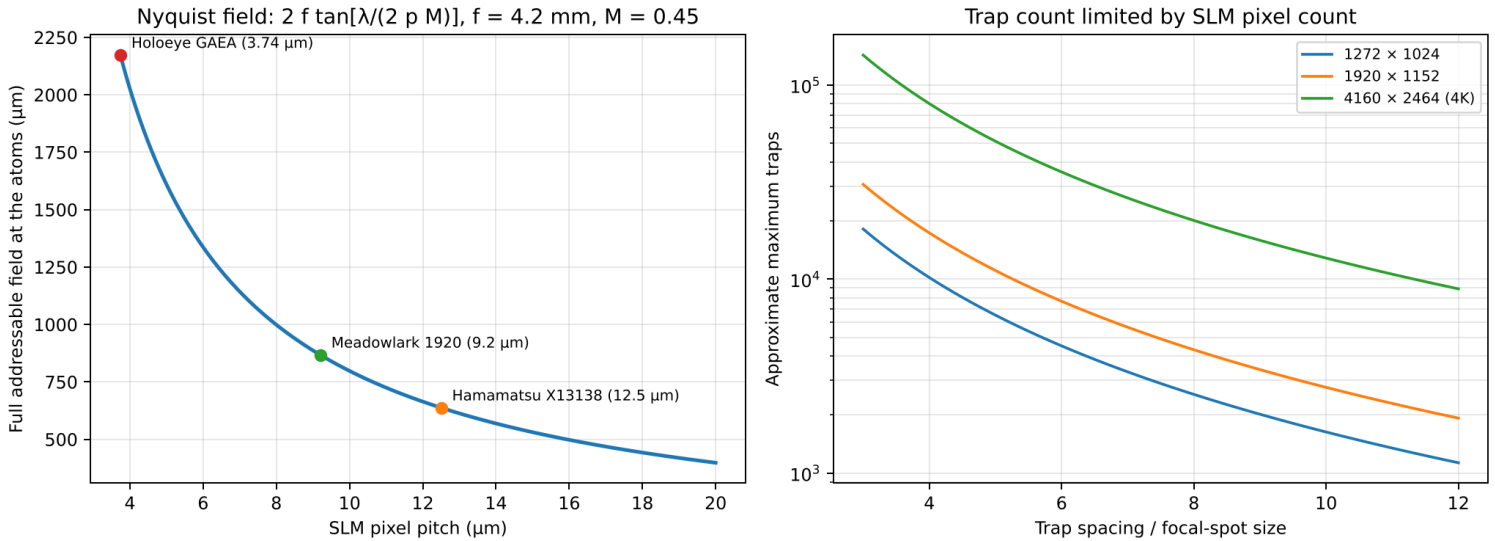
$\eta = \mathrm{sinc}^2(1 - r)$

97 % at 90 % of 2π; 88 % at 80 %

≥ 10-bit drive

LUT linearization keeps ≈ 8 effective bits

Pitch sets the field; pixel count sets the trap count



Addressable field against pitch (f = 4.2 mm, M = 0.45) and trap count against spacing/spot ratio k.

$$L = 2f \tan(\lambda / 2pM)$$

$$N \approx ½ (N_x/2k)(N_y/2k)$$

- 12.5 µm: 0.64 mm field; 9.2 µm: 0.87 mm
- Harvard uses ≈ 0.4 mm with a 12.5 µm SLM
- 1272 × 1024: ≈ 4500 traps; 1920 × 1152: ≈ 7700
- 4K 3.74 µm at 852 nm needs Δn ≥ 0.38 — not practical

Flicker heats atoms at twice the trap frequency

$$\Gamma = \pi^2 \nu^2 S(2\nu)$$

For a 100 s e-folding time at ν = 100 kHz, intensity noise must be below −130 dB/Hz at 200 kHz.

- Radial trap frequencies 50–150 kHz, axial 10–30 kHz: noise from ≈ 20 to 300 kHz matters
- Digital PWM backplanes ripple at the bit-plane frequency (tens of kHz)
- Analog backplanes ripple from polarity inversion and leakage

1

Analog pixel drive

Storage capacitor sized for < 1 LSB droop; polarity inversion at ≥ several kHz

2

≥ 10-bit gray levels

Room for LUT linearization

3

Thicker or more viscous cell

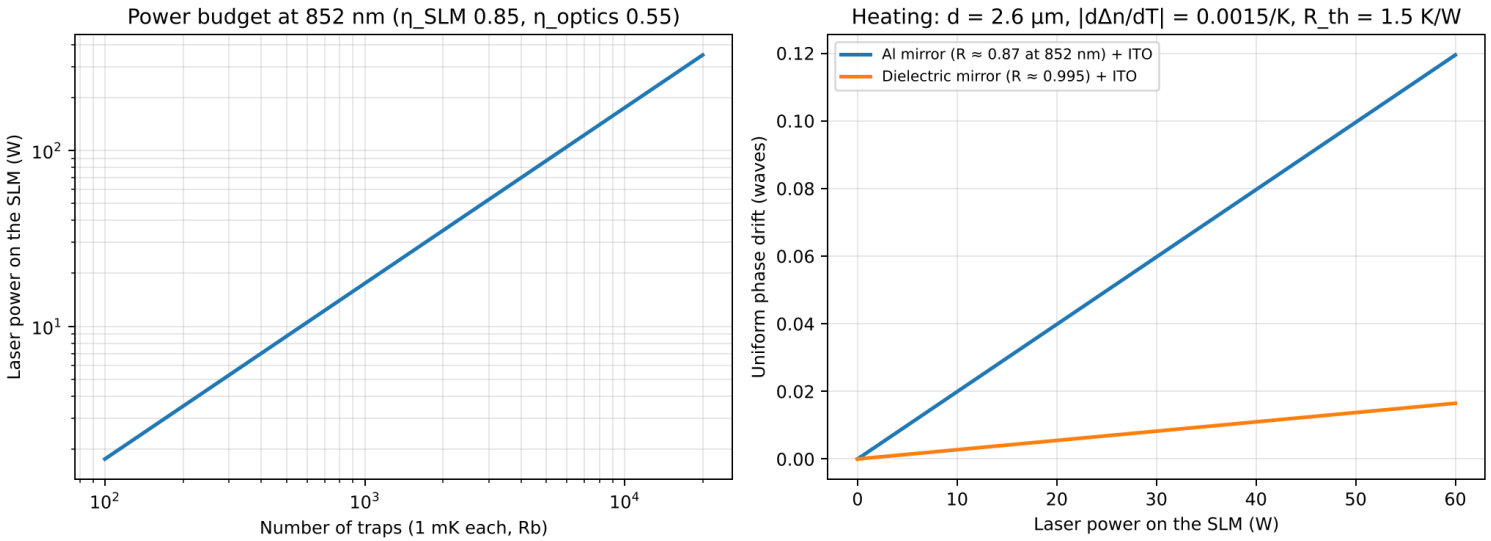
Quieter; a static-array SLM need not be fast

4

Measure it

Fast photodiode on a diffracted spot, compare with Γ at the measured trap frequencies

Power and heat: 1000 traps need ≈ 18 W on the SLM



Power on the SLM against trap count (85 % SLM, 55 % optics), and uniform thermal drift (R_th = 1.5 K/W).

A uniform drift is harmless; the beam-profile gradient acts as a weak lens and shifts relative trap depths.

18 / 53 / 175 W

for 1000 / 3000 / 10 000 traps at 1 mK

0.12 → 0.02 wave

drift at 30 W: Al mirror → dielectric mirror

- Dielectric HR mirror over the pixels
- Thin ITO/IZO; AR-coated low-absorption cover
- Die held to ±0.1 K; ramp power slowly
- Flat-top illumination spreads the heat

Polarization, flatness and calibration

1 Polarization and angle

- Input linear along the director, PER > 1000:1: polarizer after the fiber, then λ/2
- No λ/4 in the SLM arm — double-passed it rotates the polarization 90°
- Angle of incidence 3–5°: larger angles stretch the hologram and add crosstalk

2 Flatness and calibration

- Backplanes are flat to ≈ λ/2–λ before correction; target ≤ λ/10 after
- Correction map from Shack–Hartmann, interferometer, or the atoms themselves
- Phase–voltage LUT at the trap λ and temperature; per-region LUTs; pixel-crosstalk model
- Correction consumes stroke — hence the 10–20 % margin

Section 2

Materials and fabrication

Liquid crystal · dielectric mirror · alignment and cover · construction sequence

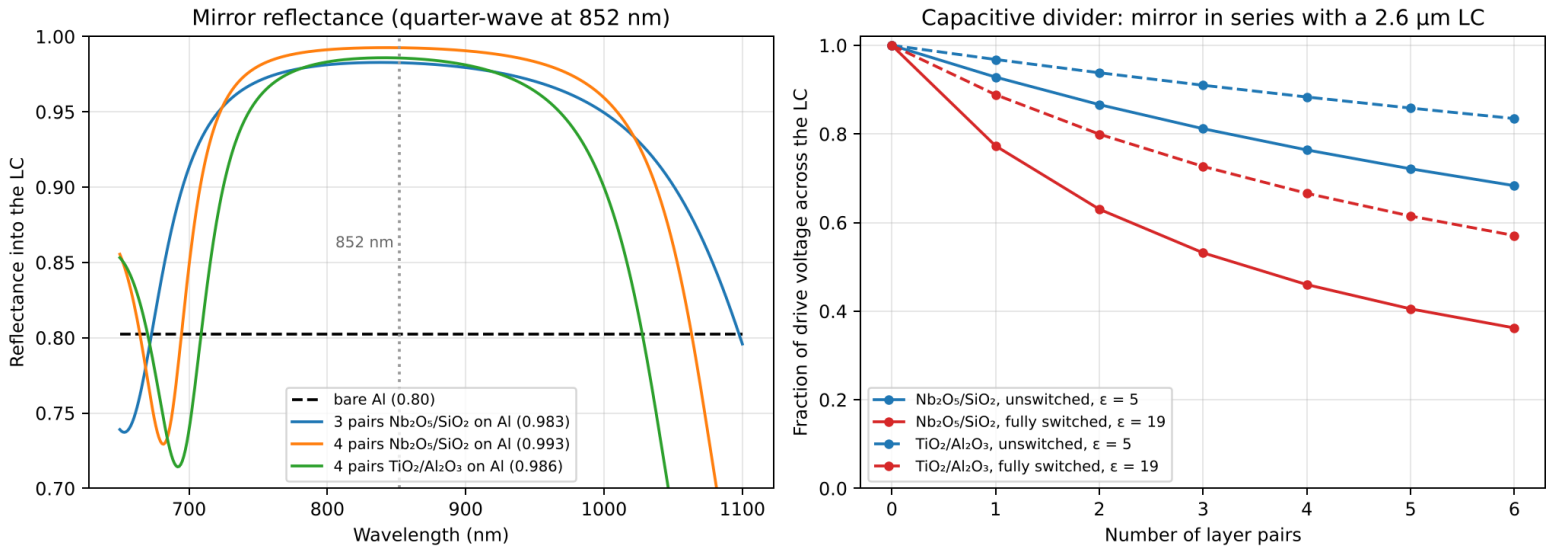
Liquid crystal: E7 to learn, fluorinated high-Δn to ship

Stage	Material	Why	Watch out for
Test cells	Merck E7	Best-characterized; Δn ≈ 0.20 at 852 nm; Δε ≈ +14	Clears at 58–60 °C; cyano compounds sag the held voltage
Device	High-T_NI, high-Δn fluorinated mixture (or BL036–BL038)	Δn ≈ 0.22–0.24 at 852 nm; high clearing point; good voltage holding	Get 852 nm data; ask for a high-resistivity alternative to cyano-based BL mixtures
Fast option	Isothiocyanato-tolanes (UCF)	Δn 0.3–0.4; ≈ 1.5 µm cell, ≈ 3 ms	Lower photostability; not catalog products

Spec to send the supplier

- Δn ≥ 0.22 at 852 nm, 35 °C
- Δε ≥ +8
- Clearing point ≥ 95 °C
- VHR ≥ 98 % at 60 °C
- Lowest γ_1 available
- Absorption < 0.1 %/µm at 852 nm
- Stable under tens of W/cm² CW
- 500 h soak test before committing

Mirror: 4 pairs of Nb_2O_5/SiO_2 on aluminum, R ≈ 99.3 %



Stack	R	V_LC/V
Bare Al	0.80	1.00
3 pr Nb_2O_5/SiO_2	0.983	0.81 → 0.53
4 pr Nb_2O_5/SiO_2	0.993	0.76 → 0.46
4 pr TiO_2/Al_2O_3	0.986	0.88 → 0.67

Reflectance into the LC (left) and the share of drive voltage across a 2.6 µm LC (right).

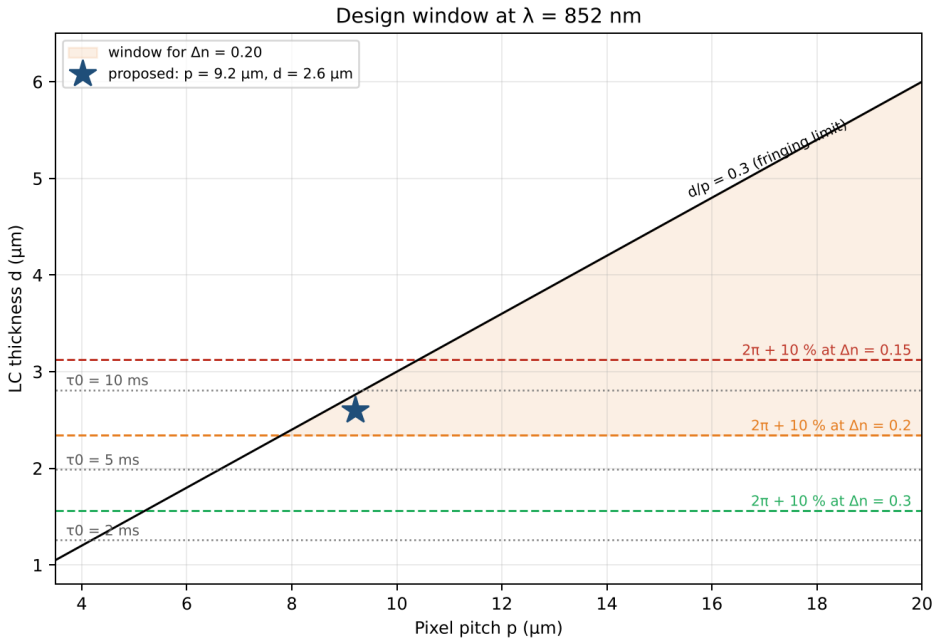
- Absorption drops from 20 % to < 1 %; Nb_2O_5 stays amorphous with low stress when ion-sputtered
- The cost is voltage: design the backplane for 8–10 V, or use Al_2O_3 as the low-index layer
- Hamamatsu (97 % at 1064 nm) and Meadowlark kW-class SLMs use dielectric backplanes; Meadowlark's 17 µm pixels reflect the fringing penalty

Construction sequence (post-CMOS, wafer level)

1. Planarize pixels (oxide fill + CMP)
2. Ion-beam sputter the stack ≤ 250 °C, ±1 %, near-zero stress
3. Anneal 200–250 °C
4. Open bond pads and ITO contact (F-based dry etch)
5. Alignment layer: rubbed PI, then OAD SiO_2
6. Sapphire cover, AR at 852 nm, thin ITO/IZO
7. 2.6 ± 0.05 µm gap on photo-spacers; seal
8. Vacuum or one-drop fill; anneal above T_NI
9. Mount on water/TEC block; calibrate LUT and flatness

Mirror · **Cell** · **Fill and mount**

Design window and proposed Rb specification



Shaded: acceptable for Δn = 0.20 at 852 nm; star: proposed design.

Parameter	Proposed value
LC mode / material	PA nematic, Δn ≈ 0.20–0.24 at 852 nm, T_NI ≥ 95 °C
Cell gap	2.6 µm (1.22 waves)
Pixels	9.2 µm, 1920 × 1152 (d/p = 0.28)
Backplane	Analog, ≥ 10-bit, 8–10 V, fast inversion
Mirror	4 pr Nb_2O_5/SiO_2 on Al, R ≈ 99.3 %
Alignment	Planar, 2–5° pretilt; OAD SiO_2 goal
Cover / gap	Sapphire, AR 852 nm; 2.6 ± 0.05 µm
Thermal / power	±0.1 K; ≥ 50 W CW (≈ 3000 traps)
Efficiency / flicker	≥ 85 % (16 px); < −130 dB/Hz, 20–300 kHz

Section 3

What changes for a ^{171}Yb machine

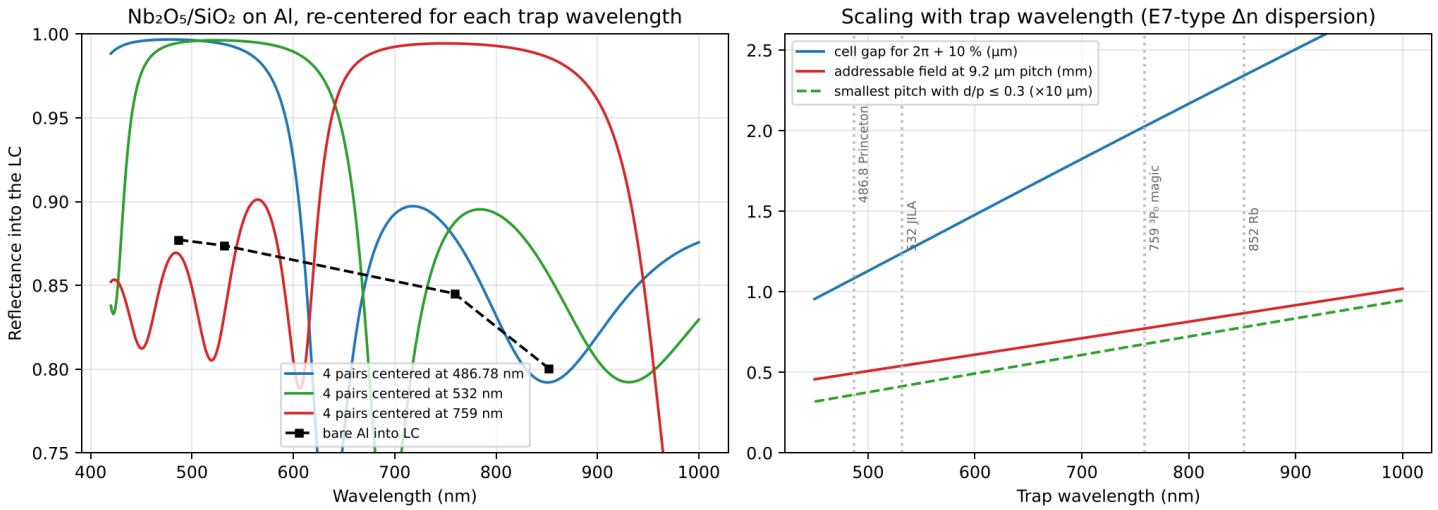
Nuclear-spin qubits in a J = 0 ground state · narrow-line 556 nm imaging · blue/green or 759 nm traps

^{171}Yb trap wavelengths follow narrow-line imaging

Group	Trap λ	Why	Array	Depth / power
JILA (Kaufman)	532 nm	High-power laser; not magic for $^1S_0$–$^3P_1$ in ^{171}Yb	Crossed AODs, 0.6 NA, 10 × 10	≈ 0.8 mK at ≈ 6 mW
Princeton (Thompson)	486.78 nm	Magic for $^1S_0$–$^3P_1$ ($m_{F'} = \pm 1/2$): image and cool in trap	Crossed AODs, 0.6 NA	≈ 5 mW during imaging
Atom Computing	483 nm + 459.6 nm hiding	Mid-circuit readout with data qubits shielded	Static array + AOD; cavity lattices, 1225 sites	≈ 350 µK
$^3P_0$ qubits	759.35 nm	Magic for $^1S_0$–$^3P_0$ clock transition	–	≈ 2–3× power per trap (estimate)

Power per trap is similar to Rb: ≈ 7 mW per mK at 532 nm against 8.2 mW at 852 nm, so the thermal design carries over — except at 759 nm, which needs more power.

Blue/green traps: thinner, faster, smaller — less stable



Mirror re-centered for each trap λ (left); cell gap, field and minimum pitch against λ (right).

	486.8	532	759	852
d (μm)	1.08	1.24	2.03	2.34
τ_0 (ms)	1.5	2.0	5.2	7.0
min pitch (μm)	3.6	4.1	6.8	7.8
mirror R	0.997	0.996	0.994	0.992

1 **Thin and fast**

1.1–1.25 μm, ≈ 2 ms: rearrangement without exotic LCs

2 **Small pixels**

4K, 3.74 μm at 486.8 nm: ≈ 1.2 mm field, ≈ 29 000 traps

3 **Photostability**

No tolanes in the blue; OAD SiO_2 alignment required; soak at trap λ

4 **One mirror, many λ**

Stack at ≈ 500 nm: R > 99 % from 440 to 560 nm

5 **Qubit ignores trap light**

J = 0: depth nonuniformity does not dephase the qubit

Specification changes for ^{171}Yb

Parameter	Rb, 852 nm	^{171}Yb, 483–487 nm	^{171}Yb, 532 nm	^{171}Yb, 759 nm
Cell gap	2.6 µm	1.1–1.2 µm	1.25–1.35 µm	2.0–2.2 µm
LC	Δn 0.20–0.24; high VHR	Photostable fluorinated; no tolanes	As 487 nm	As Rb
Pixels	9.2 µm, 1920 × 1152	3.7–4 µm, 4K	4–5 µm, 4K or 2.5K	8–9.2 µm, 1920 × 1152
Mirror	4 pr at 852 nm, 0.97 µm	4 pr at ≈ 500 nm, 0.55 µm, ≥ 99.5 % 455–535 nm	4 pr at 532 nm, 0.60 µm	4 pr at 759 nm, 0.86 µm
Alignment	PI → OAD SiO_2	OAD SiO_2 required	OAD SiO_2 preferred	PI → OAD SiO_2
Response τ_o	≈ 9 ms	≈ 2 ms	≈ 2–2.5 ms	≈ 5–6 ms
Power handling	≥ 50 W	≥ 50 W + blue soak test	≥ 50 W	≥ 100 W

Section 4

Verification and outlook

How to prove the device, and how its properties map onto qubits

Verification plan

1	**Phase–voltage curve**	At the trap λ and several temperatures
2	**Mirror and divider**	Witness-piece spectra; compare with a bare-Al cell
3	**Diffraction efficiency**	Blazed gratings of 2–40 px; zero-order fraction
4	**Flicker spectrum**	Fast photodiode, 1 Hz–1 MHz
5	**Thermal drift**	Against power with the real beam profile; thermal lensing
6	**Long-term stability**	≥ 500 h at full power: efficiency, LUT drift, discoloration
7	**With atoms**	Light-shift uniformity; lifetime and heating vs a single tweezer

Relevance to neutral-atom arrays

SLM property	Atom-level effect
Efficiency, power handling	Number of traps at a given depth — qubit count
Pixel count, pitch	Field of view, array size, spacing options for Rydberg blockade (2–10 µm)
Phase accuracy, fringing	Trap-depth uniformity → uniform light shifts (Rb), loading and imaging
Flicker	Parametric heating → lower gate fidelity, more atom loss
Thermal drift	Slow depth and position changes between calibrations
Polarization purity	Zero-order light, stray traps, background at the atoms
Update rate	Whether the SLM can take part in rearrangement

Yb

For ^{171}Yb

- The nuclear-spin qubit barely sees the trap light, so uniformity matters for loading, cooling and 556 nm imaging, not qubit frequency
- Photostability in the blue/green becomes an SLM lifetime question
- Trap light is switched off upstream with an AOM for Rydberg pulses (both species)

Recommendations and next steps

- Build E7 test cells on a bare-Al and a 4-pair Nb_2O_5/SiO_2 backplane; measure the divider and phase–voltage curve at 852 nm
- Establish OAD SiO_2 conditions for planar alignment with 2–5° pretilt
- Request a high-T_NI, high-VHR fluorinated mixture with 852 nm (and 487/532 nm) data; start the 500 h soak
- Decide Rb (852 nm, 9.2 µm) or ^{171}Yb (blue/green, ≈ 4 µm) as the first target — it sets pitch, cell gap and mirror

Key references

- Zhang, You, Chu, Light Sci. Appl. 3, e213 (2014) — phase-only LCoS fundamentals
- Lazarev et al., Opt. Express 27, 16206 (2019) — LCoS beyond the display
- Knottnerus et al., arXiv:2501.01391 (2025) — SLM rearrangement
- Pause et al., Optica 11, 222 (2024) — > 1000-qubit tweezer array
- Savard, O'Hara, Thomas, Phys. Rev. A 56, R1095 (1997) — noise-induced heating
- Persson et al., Opt. Express 20, 22334 (2012); Moser et al., Opt. Express 27, 25046 (2019) — crosstalk
- Jenkins et al., Phys. Rev. X 12, 021027 (2022) — ^{171}Yb at 532 nm
- Ma et al., Phys. Rev. X 12, 021028 (2022) — ^{171}Yb at 486.78 nm
- Norcia et al., Phys. Rev. X 13, 041034 (2023); PRX Quantum 5, 030316 (2024) — Atom Computing
- Hamamatsu and Meadowlark high-power LCoS-SLM product data; Gauza, Wu et al. (UCF) — high-Δn LCs
- Full list (24 references) in the unified technical note