Acousto-Optic Deflectors: Physics, Materials and Design

How sound in a crystal steers a laser beam, which numbers set the performance, and how AODs are used to move atoms

Technical note · October 24, 2026 · D. Hakala

Summary. An acousto-optic deflector (AOD) is a transparent crystal with a piezoelectric transducer bonded to one face. An RF signal at frequency f launches a sound wave whose strain modulates the refractive index, forming a moving phase grating of period $\Lambda = v/f$. A laser beam diffracts off this grating into a first order deflected by about $\lambda f/v$ and shifted in frequency by f. Changing f steers the beam electronically, with no moving parts, in a time set by how long the sound takes to cross the beam ($\tau = D/v$). Driving several frequencies at once makes several beams, which is why crossed AOD pairs are the standard tool for rearranging atoms in tweezer arrays.

1. What an AOD is

An AOD has four parts (Figure 1):

- **The acousto-optic crystal**, transparent at the laser wavelength and chosen for a large photoelastic response and low acoustic loss (TeO_2 for most visible and near-IR work).
- **A piezoelectric transducer**, usually a thin plate of $LiNbO_3$ bonded to one face, with electrodes on both sides. Its thickness is about half an acoustic wavelength at the center frequency, and it is electrically matched to the 50 Ω RF source.
- **An acoustic absorber** on the opposite face, so the sound travels through once and is not reflected back as a standing wave.
- **An RF driver**: a voltage-controlled oscillator (VCO) or direct digital synthesizer (DDS) followed by a power amplifier of typically 1–4 W.

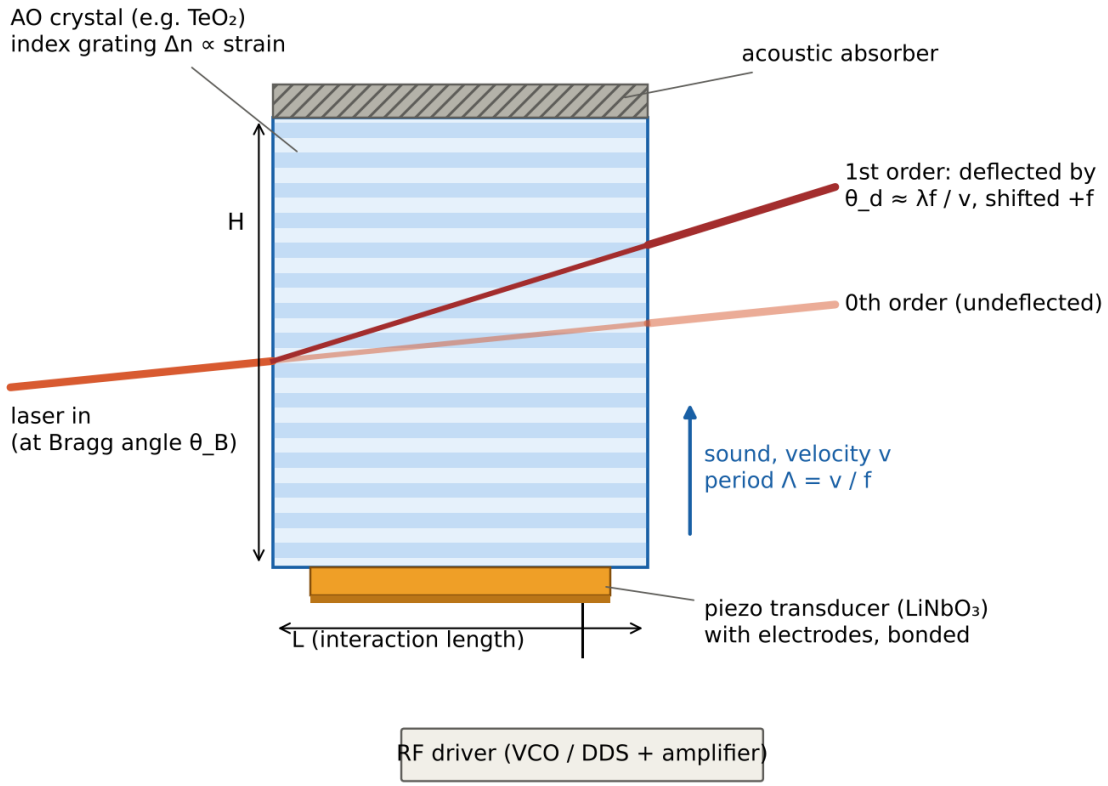


Figure 1. AOD cross-section. The transducer launches sound upward; the strain field writes a moving index grating of period Λ = v/f. The laser enters at the Bragg angle and splits into an undeflected zeroth order and a deflected, frequency-shifted first order. H is the height of the acoustic column; L is the interaction length along the beam.

2. The physics

2.1 Photoelastic effect

A sound wave is a travelling strain S. Strain changes the optical index through the photoelastic (strain-optic) tensor p:

$$\Delta n \approx -1/2\ n^3\, p\, S \tag{1}$$

For a sinusoidal sound wave the index change is sinusoidal too, so the crystal contains a thick phase grating that moves at the acoustic velocity v (0.6–6 km/s depending on material and mode). The acoustic intensity sets the strain amplitude, and therefore the grating strength.

2.2 Grating period and the Bragg regime

The grating period is the acoustic wavelength. Whether the grating behaves as thin or thick is measured by the Klein–Cook parameter Q:

$$\Lambda = \frac{v}{f}, \qquad Q = \frac{2\pi\,\lambda\,L\,f^2}{n\,v^2} \tag{2}$$

- **Q ≳ 7 (Bragg regime):** the grating is a volume grating. Light goes into essentially a single first order, and efficiency can approach 100%. All practical AODs are designed for this regime.

- **$Q \lesssim 1$ (Raman–Nath regime):** the grating is thin, like a ruled grating, and light spreads into many weak orders.

2.3 Bragg condition: momentum conservation

Diffraction is a photon absorbing (or emitting) one phonon. Energy and momentum must both be conserved, so the wave vectors close a triangle (Figure 2a), with $|k| = 2\pi n/\lambda$ and $|K| = 2\pi f/v$:

$$\mathbf{k}_d = \mathbf{k}_i \pm \mathbf{K}, \qquad \sin\theta_B = \frac{\lambda f}{2\,n\,v} \tag{3}$$

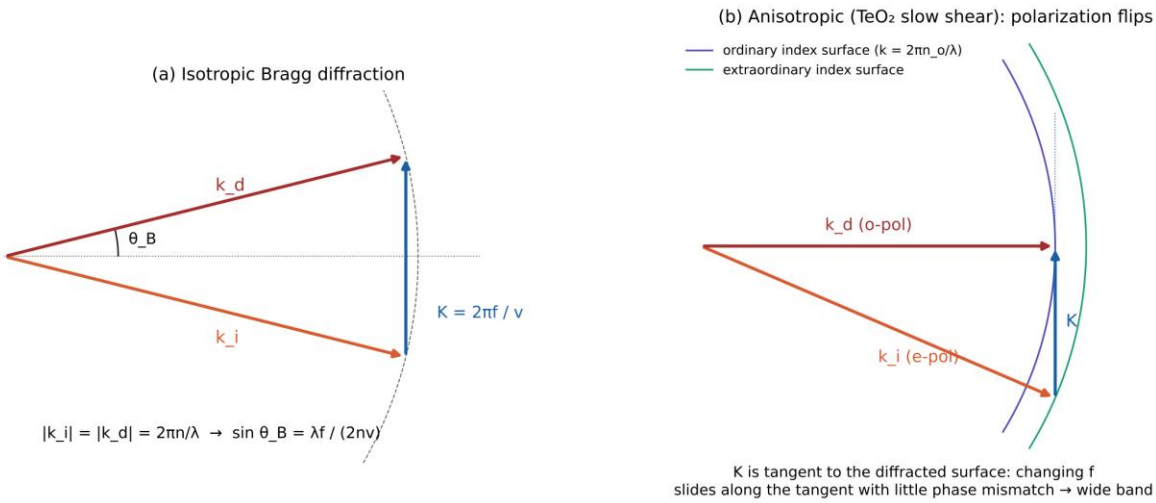


Figure 2. Wave-vector diagrams. (a) Isotropic diffraction: incident and diffracted vectors have the same length, so the triangle is isosceles and the input must be at ϑ_B. (b) Anisotropic diffraction in TeO_2: the polarization flips, the two vectors lie on different index surfaces, and with the right cut K stays tangent to the diffracted surface over a wide frequency range.

2.4 Deflection, scan range and frequency shift

Outside the crystal, refraction at the faces cancels the factor n, so the useful angles in air are:

$$\theta_d \approx \frac{\lambda f}{v}, \qquad \Delta\theta = \frac{\lambda\,\Delta f}{v}, \qquad \nu_d = \nu_i \pm f \tag{4}$$

- The deflection angle θ_d between the zeroth and first orders is proportional to the RF frequency, which is what makes the AOD a deflector: sweeping f sweeps the beam.
- The scan range $\Delta\theta$ is set by the RF bandwidth Δf over which the device still diffracts efficiently.
- Because the grating moves, the diffracted light is Doppler-shifted by exactly the RF frequency: the +1 order gains f, the −1 order loses f.

2.5 Diffraction efficiency and the figure of merit

For an acoustic power P in a column of height H and interaction length L, the first-order efficiency in the Bragg regime is:

$$\eta = \sin^2\left[\frac{\pi}{\lambda}\sqrt{\frac{M_2\,P\,L}{2H}}\right], \qquad M_2 = \frac{n^6 p^2}{\rho\,v^3} \tag{5}$$

M_2 is the material's acousto-optic figure of merit. It combines the index n, the effective photoelastic coefficient p, the density ρ and the acoustic velocity. The v^3 in the denominator is why slow-sound materials are so efficient. At low power $\eta \approx (\pi^2/2\lambda^2)\cdot M_2\cdot(L/H)\cdot P$; η reaches 100% at $P_{sat} = (\lambda/2)^2\cdot 2H/(M_2 L)$, and beyond

that the device is over-driven and efficiency falls again (Figure 3, left). Efficiency also falls as λ^2: an AOD needs about four times the power at 1600 nm that it needs at 800 nm.

2.6 Bandwidth

With the input angle fixed at the Bragg angle for the center frequency f_0, other frequencies are slightly phase-mismatched. In an isotropic device the full width at half maximum of the efficiency passband is approximately:

$$\Delta f_B \approx \frac{1.8\, n\, v^2}{\lambda\, L\, f_0} \tag{6}$$

A long interaction length L raises efficiency (Equation 5) but narrows the passband (Equation 6). Wide-band designs keep L short, use a phased-array transducer that tilts the sound beam to track the Bragg angle, or use **anisotropic diffraction** in a birefringent crystal. In TeO_2 slow-shear devices the diffracted beam changes polarization and lands on a different index surface (Figure 2b). With the crystal cut so that K is tangent to that surface, the phase mismatch stays small over roughly an octave, giving bandwidths of about half the center frequency together with very high efficiency per watt.

2.7 Speed versus resolution

A new frequency only takes effect once the new sound has filled the optical aperture D. The number of distinguishable beam positions is the scan range divided by the beam's own diffraction angle $\delta\theta \approx \lambda/D$:

$$\tau = \frac{D}{v}, \qquad N = \frac{\Delta\theta}{\delta\theta} \approx \tau\, \Delta f \tag{7}$$

This time–bandwidth product is the fundamental trade-off (Figure 3, right). A large aperture in slow TeO_2 shear gives hundreds of resolvable spots but tens of microseconds of access time; a small aperture in fast TeO_2 longitudinal mode switches in well under a microsecond but resolves only tens of spots. For a Gaussian beam (D = $1/e^2$ diameter) the spot count is about $\tau\Delta f/1.27$.

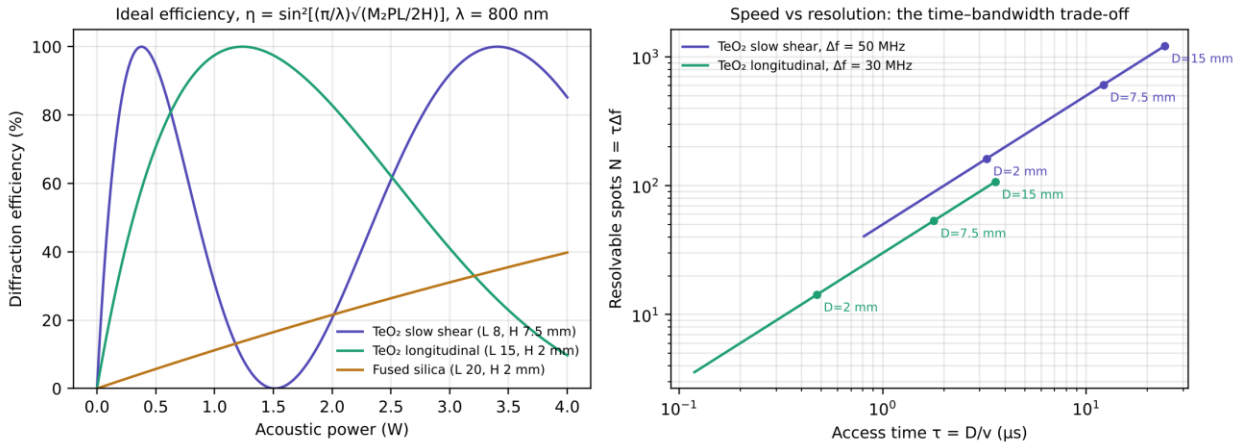


Figure 3. Left: ideal efficiency versus acoustic power at 800 nm for three materials and geometries (Equation 5). Right: resolvable spots versus access time as the aperture D changes. Computed with aod_calculator.py.

3. Materials and their parameters

Approximate textbook values (Uchida and Niizeki; Dixon). Use the vendor's data for a specific device.

Material (mode)	Optical range	n	v (km/s)	ρ (g/cm³)	M_2 (10^{-15} s³/kg)	Typical use
TeO_2 slow shear [110]	0.35–5 µm	2.26	0.617	6.0	~793	High-resolution deflectors
TeO_2 longitudinal [001]	0.35–5 µm	2.26	4.20	6.0	34.5	Fast modulators and deflectors
Fused silica, longitudinal	0.2–2.5 µm	1.46	5.96	2.2	1.51	UV, high power
Crystal quartz, longitudinal	0.2–2 µm	1.54	5.97	2.65	~1.5	UV, high power
$PbMoO_4$, longitudinal	0.42–5.5 µm	2.39	3.63	6.95	36.3	Visible modulators
GaP, longitudinal	0.6–10 µm	3.31	6.32	4.13	44.6	Fast, red/near-IR
Germanium, longitudinal	2–20 µm	4.0	5.50	5.33	~180	CO_2 laser (10.6 µm)
$LiNbO_3$, longitudinal	0.4–4.5 µm	2.20	6.57	4.64	~7	GHz devices; transducers

TeO_2 (paratellurite) dominates near-IR tweezer work. Its slow shear mode has an extremely low velocity and a huge M_2, which buys efficiency and resolution at the cost of speed; its longitudinal mode is about seven times faster. **Fused silica and quartz** are inefficient but handle UV and very high power. **Germanium** is the standard for 10.6 µm CO_2 lasers.

4. Worked examples

Outputs of the accompanying calculator (aod_calculator.py) for two typical near-IR tweezer deflectors at 800 nm:

Quantity	TeO_2 slow shear	TeO_2 longitudinal
Center frequency, bandwidth	100 MHz, 50 MHz	80 MHz, 30 MHz
Aperture D; L; H	7.5 mm; 8 mm; 7.5 mm	2 mm; 15 mm; 2 mm
Acoustic wavelength Λ	6.17 µm	52.5 µm
Deflection at f_0 (air)	130 mrad	15.2 mrad
Scan range Δθ	64.8 mrad	5.7 mrad
Access time τ	12.2 µs	0.48 µs
Resolvable spots (uniform / Gaussian)	608 / 479	14 / 11
Ideal saturation power P_{sat}	0.38 W acoustic (real devices: ~1–2 W RF)	1.2 W acoustic
Passband	~50 MHz (anisotropic cut)	~75 MHz (Equation 6)
Klein–Cook Q	467	12
Optical frequency shift	+100 MHz	+80 MHz

The ideal efficiency formula is an upper bound for TeO_2 shear: the off-axis anisotropic cut, acoustic walk-off and 50–80% RF-to-acoustic conversion mean commercial slow-shear AODs typically need 1–2 W of RF for 70–85% efficiency. Treat the calculator's power numbers as a lower limit and take efficiency from the datasheet.

5. Practical behavior to account for

- **Two axes.** Two AODs crossed at 90°, either close together or joined by a relay, give independent x and y steering.
- **Several beams at once.** Driving the transducer with a sum of frequencies produces one beam per tone at angle $\lambda f_k/v$, each carrying its own frequency shift f_k. The tones share the RF power, so each beam gets roughly 1/N of the efficiency budget.
- **Intermodulation.** Nonlinearity in the amplifier and in the acousto-optic interaction creates spurious tones such as $2f_i - f_j$, which appear as weak ghost beams. Backing the amplifier off compression and choosing tone phases with a low crest factor (for example, Schroeder phases) reduces them.
- **Chirp lensing.** If the frequency changes while sound fills the aperture, the grating period varies across the beam and acts as a cylindrical lens along the scan axis, with focal length given by Equation 8. Fast sweeps therefore defocus the beam in one direction; at 1 MHz/µs in TeO_2 shear at 800 nm, F is about 0.5 m.
- **Settling.** A new frequency needs about $\tau = D/v$ to fill the aperture. Shrinking the beam speeds this up but costs resolvable spots.
- **Thermal effects.** Watts of RF heat the transducer and crystal. Thermal gradients shift the beam and change the efficiency over the first seconds to minutes after a power change, so drive duty cycles should be kept steady or the system recalibrated.
- **Polarization.** Anisotropic TeO_2 devices need a specific input polarization (often circular or a specified linear state) and rotate the polarization of the diffracted beam.

The chirp-lens focal length for a sweep rate df/dt is:

$$F \approx \frac{v^2}{\lambda\,(df/dt)} \tag{8}$$

6. Relevance to neutral-atom arrays

AODs are the standard way to move atoms in optical-tweezer arrays.

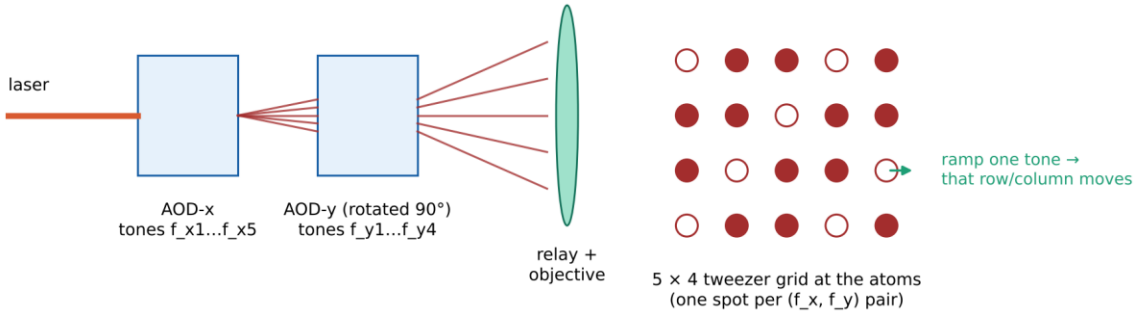


Figure 4. Crossed AODs driven with multi-tone RF create a grid of movable tweezers, one spot per (f_x, f_y) pair. Filled circles are loaded atoms. Ramping one tone moves the whole corresponding row or column.

- **Rearrangement.** After stochastic loading, a crossed AOD pair with multi-tone RF picks up atoms and drags them from reservoir sites into the target pattern, typically in tens to hundreds of microseconds per move. The static array usually comes from an SLM hologram, with the AOD tweezers handed off on top of it, so the SLM and AOD grids must line up to a fraction of the waist.

- **Gentle transport.** Moves use smooth frequency ramps (for example, minimum-jerk profiles) to limit heating. Because efficiency varies across the band and chirp lensing changes the spot size during a sweep, each tone's amplitude is pre-compensated so the trap depth stays roughly constant during the move.
- **Frequency-shifted tweezers.** Each AOD tweezer carries a different optical frequency. Neighboring traps interfere only at MHz beat notes, which time-average out, so there is no static interference corrugation between them. Intermodulation tones, however, can create weak stray traps that must be kept below the depth that captures atoms.
- **Sizing.** A TeO_2 slow-shear pair at 800 nm with Δf = 50 MHz and D = 7.5 mm resolves about 600 spots per axis with 12 µs access time. That is ample for arrays of a few hundred sites per axis; transport speed is limited by atom heating rather than by the deflector.
- **Shuttling between zones and 3D.** In architectures with separate storage, entangling and readout zones, AOD tweezers move whole groups of atoms between zones. Adding a chirped AOD pair as an acousto-optic lens shifts the focus axially for 3D shuttling.

7. Using the calculator

aod_calculator.py, saved alongside this note, evaluates every equation above for any material in the table:

- python aod_calculator.py — TeO_2 slow shear at 800 nm with the defaults in Section 4.
- python aod_calculator.py --material teo2_long --f0 80 --bw 30 --D 2 --L 15 --H 2 --P 1 — the fast example.
- python aod_calculator.py --chirp 1.0 — adds the chirp-lens focal length for a 1 MHz/µs sweep.
- python aod_calculator.py --plot — saves efficiency-versus-power and passband plots next to the script.
- python aod_calculator.py --list — lists the materials and their constants.

It prints warnings when the design leaves the Bragg regime (Q < 7), when the isotropic passband is narrower than the requested bandwidth, when H is smaller than the beam, or when the drive exceeds saturation.

Further reading

[1] A. Korpel, *Acousto-Optics*, 2nd ed., Marcel Dekker, 1997.

[2] J. Xu and R. Stroud, *Acousto-Optic Devices: Principles, Design, and Applications*, Wiley, 1992.

[3] N. Uchida and N. Niizeki, "Acoustooptic deflection materials and techniques," *Proc. IEEE* 61, 1073–1092 (1973).

[4] R. W. Dixon, "Photoelastic properties of selected materials and their relevance for applications to acoustic light modulators and scanners," *J. Appl. Phys.* 38, 5149–5153 (1967).

[5] W. R. Klein and B. D. Cook, "Unified approach to ultrasonic light diffraction," *IEEE Trans. Sonics Ultrason.* 14, 123–134 (1967).

[6] I. C. Chang, "Acoustooptic devices and applications," *IEEE Trans. Sonics Ultrason.* 23, 2–22 (1976).

[7] M. Endres et al., "Atom-by-atom assembly of defect-free one-dimensional cold atom arrays," *Science* 354, 1024–1027 (2016).

[8] D. Barredo et al., "An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays," *Science* 354, 1021–1023 (2016).

References are listed for further reading; verify details before citing. Material constants are approximate. Figures 1, 2 and 4 are schematic; Figure 3 and Section 4 were computed with aod_calculator.py.