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Converting Many Diverging Sources into Collimated Beams – Analysis Summary

Executive Summary: Converting an array of divergent sources into collimated rays is fundamentally limited by *brightness (radiance) conservation* and *étendue*. No passive optics can increase source radiance – focusing simply trades beam diameter for angle ① ②. In practice one must match the optical system étendue to the source. For incoherent sources (LEDs, lamps), **co-illumination or imaging** by a single large lens will re-create the source pattern, yielding nonuniform output ③. Instead, common solutions include *individual collimators per source* (small lenses, reflectors or non-imaging concentrators), *microlens-array homogenizers*, or for coherent laser sources, *phased-array (coherent) beam combining*. Each method has trade-offs in alignment, efficiency, divergence, cost and complexity. For example, a large single lens covering an LED array is simple but heavy and often produces nonuniform “spotted” beams ③, whereas per-LED aspheric or Fresnel lenses yield higher uniformity at cost of many components. Non-imaging CPCs (reversed) can dramatically narrow LED divergence (~10× reduction) with modest efficiency loss ④. Laser diodes can be collimated by cylindrical/aspheric optics but require careful alignment; coherent combining (phase-locking) can boost on-axis brightness $\propto N$ (number of channels) ⑤ but demands complex phase control. We compare methods in detail below – summarizing required source properties (size, NA, coherence), array layout, optical specs (focal length, f/#), tolerances, efficiency, thermal issues, and cost/complexity. **Recommended approach:** match étendue (NA×area) at each stage ②, choose optics (f/#) to yield desired divergence, and test with beam profilers/M^2 measurements. We give design examples for (1) a 1 mm Lambertian LED array, (2) coherent laser diodes, and (3) an extended filament source.

Optical Principles: Collimation, Étendue and Brightness

Collimation means making rays parallel. A perfect point source at the focus of a lens or parabola yields ideally collimated light; but real sources have finite size and angular spread, so the output has residual divergence. **Étendue** (optical throughput) is invariant in lossless optics: roughly *area×solid-angle* is constant. In other words, *beam diameter×divergence* (or NA) remains fixed (or worsens) through optics ①. Focusing an extended source (or combining many sources) thus increases angular spread: “if we put an optical element that concentrates/focuses light, the angles of the light will increase” ①. The second law-like rule is that étendue can only stay the same or increase ⑥. Practically, this means a collimation system cannot produce a narrower beam than allowed by the source’s étendue (brightness): if the optical system’s étendue is smaller than the source’s, only a fraction of light can be collected ②. The optimum is étendue-matched optics ②.

High-NA (low f/#) optics collect more flux but also increase output divergence: $\mathrm{NA} \approx 1/(2\cdot f/\#)$ ⑦. For example, a 1 mm LED under an f=10 mm, 10 mm diameter lens yields a half-angle $\approx\arctan(0.5/10)\approx 2.9°$, i.e. ~5.8° full-angle divergence (neglecting lens aberrations). In general, divergence ≈D_src/(2f) for D_src≪f. Multiple sources on a plane complicate this: a single large lens will image each source to the far field. In particular, a plano-convex or Fresnel lens at focal distance will project each source’s image, reproducing the array pattern ③. Thus a single lens often yields *multiple* spots rather than one uniform beam. Reflectors (parabolic) similarly collimate a point at focus, but multiple foci require multiple mirrors or a segmented dish.

Brightness/Coherent Combining: For coherent (laser) sources one can use phased-array combining. In this case the on-axis beam brightness can scale with number of channels N (brightness ∝N for ideal phase-locking) [5]. Coherent combining requires stable phase relationships [8], whereas *incoherent combining* (simply overlaying beams) cannot exceed the brightness of the brightest input [5]. In practice, coherent combining (e.g. fiber/cavity combining) is complex but can preserve high beam quality, while incoherent Wavelength or polarization combining yields up to N× power but same brightness as one. We address this in the “Phased-Array” section.

Collimation Approaches

Single Large Collimating Optic (Lens or Reflector)

A single *large* optic (e.g. a big lens or mirror) can cover the whole source plane. If all sources lie at its focal plane, each source yields a parallel beam (but off-axis beams will be angled). **Limitations:** A single-lens collimator of an LED array will simply image the array: the output beam intensity pattern = the source pattern [3]. E.g. a 4×4 LED grid under one 50 mm lens produces 16 beamlets unless masked or diffused. Also, large optics are heavy and sensitive to alignment: each source must be near its focal point (typ. tolerance ~fraction of mm) or the beam diverges more or shifts angle. For reflectors, one big parabolic mirror would only perfectly collimate if all sources are at its focus; multiple sources require multiple mirrors or one mirror with composite focus.

Source requirements: Works best if sources are point-like or small (source diameter ≪ focal length). All sources should ideally lie in one focal plane. Coherence is not needed (works for LED, arc, etc.). The sources can be arranged arbitrarily (grid, hex, concentric), but uniform spacing eases symmetric illumination of lens. A hex grid maximizes packing of circular emitters (~90% fill vs 78% for square) but square grids simplify optics. Concentric ring sources (like lamp filaments) might be matched by ring mirrors.

Optics & Specs: Typically a single large lens (e.g. diameter D_big, focal length f_big, so f/# = f_big/D_big). To minimize divergence, make f_big large. For example, f=200 mm, D=100 mm (f/#=2) yields small NA~0.25, but the lens is bulky. Fresnel lenses can be used to reduce weight; a Fresnel of acrylic (D up to 100–200 mm) can cost <$100 for moderate f/#. A glass aspheric of this size is expensive (several k$). A parabolic reflector (D similar to lamp size) collimate if source at focus; typical lamphouses use f/D ~0.5–1.

Alignment Tolerance: Tight. Each source must lie within ~100–200 µm of focal plane for low divergence; decenter of order its active size yields multiple-degree pointing error. Off-axis sources will naturally output angled beams (tilted by source offset/f). If a common output beam is desired, one must use beam steering/tilt compensators.

Beam Divergence: Roughly source size / focal length. E.g. a 1 mm LED at f=50 mm gives half-angle ≈arctan(0.5/50)≈0.57° (full ~1.1°). But because sources also have intrinsic cone (Lambertian ±60°), using a single lens inherently clips outer rays. In practice, one expects a few degrees divergence at best unless f≫D_src.

Efficiency/Losses: One element yields 90–95% throughput (depending on AR coatings). Fresnel surfaces scatter (~92% transmission typical). Reflectors can be >95% if protected Al or Ag. However, stacking multiple large optics (e.g. lens+reflector) adds losses.

Thermal/Packaging: Large optics and many sources require heat management. Heat load under lens may cause warpage of plastic Fresnel if not cooled. Parabolic reflectors are tolerant to high flux (common in searchlights), but sources must be cooled under or behind the mirror.

Cost/Complexity: High if custom optics. One off-the-shelf large lens or Fresnel is cheapest (a$), but custom aspherics are costly (k$). A segmented mirror array (one per source) is moderate cost (each parabolic ~ a few $). Complexity of aligning many sources to one optic is high.

Design Example (LED array): 16 LED (1 mm, Lambertian, ±60°) on a 30×30 mm square. Use a single Fresnel 100 mmØ, f=100 mm (f/#=1). Place LEDs in focal plane. The system will image the 4×4 pattern on target (nonuniform). Divergence: central LED gives ~±0.5°, but combined pattern is 4×4 beams. Efficiency: ~85% (Fresnel loss + vignetting). Alignment: ±0.2 mm. (Result: not ideal uniform output ③ .)

Individual Collimating Optics (One per Source)

Collimate each source separately. This avoids imaging the entire array, instead producing one beam per source which can overlap to form a combined beam (or remain separate).

Single-Element Lenses (Aspheric, Plano-Convex, Fresnel)

Small collimators mounted directly on each emitter. **For LEDs:** short-focus high-NA plastic lenses or molded aspherics (typical f/#~1–2). For example, Thorlabs offers LED collimating lenses (f~10–20 mm) for 5 mm LEDs. Modern freeform/multi-aspheric TIR lenses (e.g. High-NA TIR from LED manufacturers) can achieve ~90% coupling efficiency with divergences of a few degrees 【43†(Abstract)}. An aspheric glass lens (D~5–10 mm) on a 1 mm LED can yield ~±3° divergence (FWHM ~6°) at ~90% throughput. **For laser diodes:** an aspheric micro-collimator with f~1–2 mm is common; divergence ~±5°×20° (due to elliptical beam) unless corrected by cylindrical microlens in fast axis. Single microlenses cost <$1 if plastic, $5–10 if glass aspheric; Fresnel micro-lenses are cheaper but have lower NA.

Source Requirements: Works for any small source (≤ couple mm). Incoherent (LED) or coherent (LD). Coherent lasers will produce speckle with lens; output remains spatially coherent. Source NA must match lens NA: a 1 mm Lambertian LED (NA~0.87, half-angle 60°) needs a lens NA≥0.87 to collect all light, which is nearly impossible; in practice one captures ±45° (~NA=0.707), i.e. ~50% power ⑨ .

Array Layout: Any grid or close-packed; individual lenses must not overlap. Hex packing maximizes fill, but any regular pattern works. If beams are to be overlapped (combined), symmetric arrangement (e.g. circular array) helps uniform superposition. For imaging (if used as separate beams) pattern is irrelevant.

Optics Specs: Focal length ~2–20× source size. For 1 mm LED, f=10 mm, D=10 mm (f/#=1) yields ~0.5° half-angle; but actual performance dominated by LED source. Lower f/# (short focus) yields wider acceptance but larger divergence if lens not large. Typical example: D=5 mm, f=5 mm (f/1) lens giving NA=0.5 (30° half-angle); source extended 1 mm results in ~11° half-angle. **Fresnel or TIR lenses:** can be thin plastic; TIR designs often integrated in LED optics (they collimate chip's output nearly to parallel with ~90% light within a few degrees, then a reflector can catch edges ⑩).

Alignment Tolerance: Moderate. Each source-lens pair must be centered (misalignment ~0.1× lens diameter causes significant beam tilt/loss). Axial spacing: ±10% of focal length gives low defocus. For LED die to TIR lens, manufacturer alignment ~10–20 µm. Laser diodes need sub-micron alignment to avoid astigmatism in fast-axis lens.

Beam Divergence: Depends on source+lens. Approx beam half-angle ≈ arcsin(NA_in_output). A 1 mm LED behind f=10 mm lens yields ~3°–6°; a laser diode (3×0.6 mm stripe) with f=2 mm lenses yields ~1–2° in slow axis and ~5–10° in fast axis. Compound optics (one lens then reflector) can reduce divergence further.

Efficiency: High for single-element: 90–98% for quality glass lens (AR-coated), ~80–90% for plastic Fresnel. No imaging losses (each only sees one source). If combining beams (overlap), note incoherent overlap loses intensity per overlap geometry.

Thermal/Packaging: Each lens adds volume; but heat is localized at source and lens. Lenses can get hot if close to high-power LEDs (consider thermal expansion). Plastic lenses may degrade under intense IR.

Cost/Complexity: Many components: cost per channel ~\$1–5 (mass produced); assembly cost is high. Complexity grows linearly with source count. However, alignment of each channel is independent (parallelizable).

Variants: *Fresnel lenses* – cheaper (plastic), thinner, can make larger aperture (20–50 mm for arrays) with moderate f/#. *TIR (Total Internal Reflection) lenses* – used in LED bulbs (collimate to plane wave). *Compound Parabolic Concentrators (reverse)* – see below. *Doublet or freeform lenses* – more optical surfaces (higher cost) but can produce very uniform collimation ⑩ .

Compound Parabolic Concentrators (CPC) as Collimators

A CPC is a nonimaging device with two apertures; used normally to concentrate, but reversed it **collimates** within a designed acceptance angle. A CPC can accept a wide angle of rays and output them with limited divergence. For example, using a CPC on an LED can reduce its divergence by ~10× ④ : the referenced study found that swapping a typical lens for a CPC narrowed LED divergence 10-fold, boosting far-field intensity 70 dB (SNR) ④ . In effect, rays within the acceptance cone exit nearly parallel.

Source Requirements: Point or small extended source placed at the entrance aperture. CPC is best for Lambertian/incoherent sources. It has a fixed acceptance half-angle (design parameter θ), typically 30–60°. Sources larger than the entrance aperture diameter do not work; the source should be smallish or placed at CPC's focal spot.

Layout: One CPC per source (or per cluster). If many LEDs, can use an array of CPCs on each LED. They may be larger than lens (entrance ~ few mm). Packing is like lens arrays – possibly hex for round apertures.

Optics Specs: Specified by acceptance angle θ and concentration ratio. The CPC exit aperture is smaller; e.g. for θ=30°, the ratio D_in/D_out = 1/sinθ ≈2. The "focal length" is determined by CPC length (≈ (D_in−D_out)/2tanθ). Example: D_in=10 mm, θ=30°, yields D_out≈5 mm, length ≈5.8 mm. Divergence ~2×θ (≈60° full-angle for 30° half-angle design, beyond which rays reject). Throughput is ~cos-weighted (Lambertian→collimated).

Alignment: Source must be centered on CPC entrance; axial ~±D/CPC length tolerance. Otherwise, efficiency drops (CPC is forgiving over its acceptance angle but miscenter shifts beam angle).

Divergence: The CPC designs a maximum output angle ~2θ. So a θ=15° CPC yields ±15° half divergence (≈30° total) for all rays. In the cited UWOC example, an LED with original ±60° was narrowed to ~±6° (10×) [4], implying a 6° half-angle (θ=6° CPC).

Efficiency: Ideal CPC has ~100% for rays within acceptance (just redirects), but real devices suffer reflectance. Plastic molded CPCs might have 90–95% internal reflectance; AR coating on exit can improve. Overall ~80–90% throughput can be expected (scattering, misalignment losses).

Thermal/Packaging: CPCs can be made of glass or plastic. They are bulky compared to simple lenses (length ~entrance diameter). Heat: if source is high-power LED, light absorption is low, so heating negligible; but mounting must handle LED heat.

Cost/Complexity: CPCs are pricier than simple lenses (precision 3D shape). A small glass CPC might be \ $10–50 each. Plastic injection-molded CPCs exist (e.g. rooftop molded lens) at lower cost per unit but high tooling. Complexity similar to lenses (one-per-source).

Example (LED+ CPC): A 1 mm LED under a CPC with θ=6° acceptance (D_in=10 mm, D_out=≈1.0 mm). The output divergence is ±6°. If original LED divergence was ±60°, this yields a ~10× narrower beam [4]. Efficiency ~80%. Alignment tolerance ~±1 mm. Beam on distant screen becomes bright and fairly uniform (no pattern), but spot is ~5× narrower.

Microlens Arrays and Homogenizers

Microlens arrays (MLAs) and integrator (fly-eye) homogenizers use *multiple small beams* to produce a uniform collimated output. Typically, a two-stage system: first *primary optics* (collimate or concentrate each source), then *MLA pairs* to scramble beams, and finally a projection lens to collimate the combined beam.

Principle: A double-sided MLA splits an input beam into many beamlets; with a second identical MLA (fly's eye) and imaging lens, the beamlets superpose incoherently in output, averaging out spatial nonuniformities. This yields very uniform intensity across the beam and a controlled divergence. Design rules (from 4f imaging) ensure the output collimated divergence equals input divergence (if system is telecentric).

Source Requirements: Generally requires multiple sources or large sources. Works best when sources are already (roughly) collimated or at least planar wavefront entering the MLA. Can combine outputs of multiple LEDs by feeding them through diffusers and MLAs. Not suited to isolated point sources without homogenizer – it's meant to homogenize a large beam. Coherence doesn't matter (incoherent design).

Array Layout: Usually uniform grid (square or hex) of identical lenslets; lenslets can be circular (hex close pack) or square. Fill factor should be high (black matrix to avoid gaps [11]). For non-rectangular source shapes, a matching arrangement (e.g. circular MLA for round aperture) is used. The input imaging of sources onto the MLA is typically via a field lens.

Optics Specs: Typical lenslet diameters ~0.5–2 mm. A "fly-eye" homogenizer might have two arrays separated by one lens' focal length (4f config). The output beam divergence is governed by the lenslets' f/#: smaller f/# (shorter focal) yields larger NA of output. Example: If each lenslet is f=2 mm, D=1 mm (f/2), the output divergence could be ±15° half-angle. The design often trades divergence for uniformity.

Alignment: Moderately tight. MLAs must be parallel and spaced precisely (spacings of a few mm). Source image must fill MLA uniformly. Misalignment (shift between MLA1 and MLA2) causes artifacts. Typically microns to tens of microns tolerance between elements.

Divergence: Determined by final condensing lens. If the homogenizer output is taken through a field lens at infinity focus, the divergence $\approx$ lenslet numerical aperture. The Fraunhofer example used “cylindrical lens arrays… for rectangular area” and achieved “high-brightness RGB” with uniform output ⑪. In practice, divergences of ±5°–±15° are common to trade for uniformity.

Efficiency: Typically lower than single lenses – multiple surfaces and aperture stops. The Fraunhofer paper [20] reported >76% uniformity with total throughput ~89% ⑩ (that was a specific TIR+reflector design). In a typical fly-eye, each MLA has ~95% (with AR) and two give ~90%, plus one more lens (~95%) yields ~85% overall. Non-ideal fill (gap between lenslets) also reduces efficiency.

Thermal/Packaging: Large due to multiple elements. Cooling not directly needed by lens but sources still need heat sinks. Often used in projectors and stage lighting – those systems manage heat externally.

Cost/Complexity: Moderate-high. Precision MLAs cost \$$10–50$ per pair depending on size and material. System requires careful mechanical assembly. However, they can collimate and homogenize *many sources at once*, sometimes replacing a bundle of individual lenses. A fly’s eye homogenizer (single channel, e.g. for one LED) is cheap (\$5–20), but a multi-LED imaging homogenizer (with field lens, etc.) is complex.

Example (LED homogenizer): A 4×4 LED panel (1 mm each) with a microlens homogenizer. First collimate each LED via a small lens (f=10 mm). Then use a 10 mm FL field lens to project LEDs onto a double-sided MLA (hex hex lenslets D=1 mm). Finally use a projection lens to re-collimate. Result: output beam ~100 mm uniform disk, divergence ±5°. Throughput ~85%. Uniformity >90% across beam ⑪.

Phased-Array / Coherent Beam Combining (Lasers Only)

If sources are spatially *coherent* (e.g. lasers), one can use *coherent beam combining* to form a single diffraction-limited beam whose brightness scales with number of channels. Two broad types: **spectral/polarization combining** (incoherent sum of beams) yields power $\propto N$ but not brightness, and **coherent combining** (phase-locked superposition) yields brightness $\propto N$ under ideal conditions ⑤.

Principle: In coherent combining, N laser beams (ideally identical wavelength) are overlapped with controlled phase so they interfere constructively on-axis. In a phased-array, active phase modulators or self-organizing coupling locks phases. The result is an on-axis lobe whose intensity $\propto N^2$ (peak) but beam area also grows $\propto N$ (aperture of array), so brightness (power/area/solid-angle) $\propto N$ relative to one beam ⑤. If not phase-locked, incoherent overlap yields only linear sum of intensities (no brightness gain).

Source Requirements: Must be mutually coherent and phase-locked. Typically single-mode lasers (e.g. fiber lasers, diode lasers in MO or external-cavity setups). Source beam quality (M^2) should be nearly diffraction-limited (M^2~1). Outputs often require matching elliptical profiles.

Layout: Lasers arranged in an aperture array. Common patterns: 1D stacks (linear array) or 2D hexagonal/rectangular grids. The far-field beam shape depends on array geometry (e.g. hex yields hexagonal aperture beams). Pitch (center-to-center spacing) affects far-field lobe spacing – small pitch (dense array) means wide main lobe, and large pitch means multiple lobes (diffraction orders). For coherent combining, pitch ~λ is ideal (like phased array antenna) but not practical for large lasers; typically beam expanders are used after combining to form a single beam.

Optical Specs: Each channel is already collimated (diode+collimator or fiber output). A beam combiner (e.g. diffraction grating tree, cavity, or fiber coupler array) merges them. No additional “collimating lens” per se unless using external optics. If beams are elliptical, cylindrical lenses or anamorphic prisms pre-collimate axes. The effective f/# is defined by beam diameter and divergence of each laser (e.g. a 1 mm×0.1 mm diode at f=1 mm has f/#~1). After combining, the composite beam diffraction limit is set by array aperture (D_eff ≈ array side length), so half-angle ≈1.22 λ/D_eff.

Alignment Tolerance: Extremely tight. Phase must be controlled to within fractions of a wavelength (sub-nm path length). Pointing must align beams within microradians. As a rule, alignment tolerances are orders of magnitude tighter than for incoherent optics. Vibration or thermal drift must be corrected by feedback loops.

Beam Divergence: Ideally diffraction-limited: θ ≈ λ/D_eff. If combining N equal beams in a square array of side $\sqrt{N}$×d (pitch), the brightness limit is B_combined ≈N×B_single [5]. In practice, residual phase error broadens beam (reducing Strehl). Combined M^2 ≈N (if filled array) unless phase errors.

Efficiency: Active combining systems (master-oscillator power-amplifier + interferometric combiner) can reach 80–90% efficiency [12] [5]. Losses arise from imperfect coupling, splitting, and phase control. Fiber coupled combiners may add 10–20% loss. Coherent polarization combining can be >95% (e.g. stacking). Incoherent (spectral) combining can be >90% but yields no brightness gain.

Thermal/Packaging: Lasers need heat sinks; combiners need stable mounts. Fiber/solid optics allow remote packaging. High power demands active cooling. Coherent arrays require temperature stabilization to maintain wavelength/phase.

Cost/Complexity: Very high. Each laser ~$hundreds, plus feedback electronics and beam-splitting optics. Research systems (kW lasers) are multi-million-dollar. Complexity includes dynamic phase control loops. However, for niche applications (e.g. directed energy, LiDAR) it’s the only way to achieve >kW at diffraction-limited quality [12].

Example (Laser Diodes): 4×4 array of 1 W single-mode diodes (1064 nm, elliptical 1×0.1 mm). Each diode has 0.3°×10° divergence after micro-collimators. Beams are expanded to fill 10 mm×10 mm aperture, then coherently combined in a diffractive tree. Output: ~4 W, near-diffraction limited (divergence ~0.05°) if phase-locked. Combined brightness ≈4× that of single diode [5].

Comparison of Collimation Methods

The table below contrasts key aspects of each method. Note these are approximate “order-of-magnitude” guidelines; actual design requires detailed simulation.

Method	Source size/NA/ Coherence	Array Layout	Optics (f, D, f/#)	Alignment	Divergence	Efficiency
Single large lens/ reflector	Sources small relative to lens; incoherent; any NA	Large uniform grid or ring; all sources at common focus	e.g. D=100–200 mm, f=100–200 mm (f/#≈1); or parabolic mirror diameter≈sources' envelope	±0.1–0.5 mm axial, 0.1 mm lateral; off-axis beams tilt by Δθ≈x/f	~source_size/f (°); array pattern (multiple beams)	~85–95% (AR lens or mirror)
Individual small lenses	Each source small (≤ few mm); NA matched; incoherent or coherent	Independent per source; hex or grid packing	e.g. D=5–20 mm, f=5–20 mm (f/#=1–2)	±50 µm lateral, ±5% focal distance; each channel separately	≈arctan((D_src/ 2)/f) (°); a few deg typical	~90–98% (glass AR); 80–90% (plastic)
Aspheric / TIR LED optics	Small LED die (~1 mm); incoherent	On each LED; covered by molded optic	Complex aspheric, f~10–20 mm, f/ #~0.5–1	Lens molded to LED – manufacturer-aligned (~10–20 µm)	Few degrees (±3–10°) with high uniformity [10]	~89–95% [10]
Fresnel lens (large)	Incoherent; good for large source area	One lens covering array	D large (50–200 mm), f similar (f/#≈1–2)	±1 mm tolerances; image offset causes blur	Similar to single-lens above; multiple spots	~80–90% (scattering loss)
Parabolic reflectors (per source)	Point or line sources at focus; incoherent	One mirror per source; simple grid	e.g. D=10–50 mm, exact parabola shape, f=D/2 typical	Source must sit at focus ±0.1 mm; tilt shifts beam	Nearly zero if point; for line source yields fan beam	95–98% (metal mirror)
CPC (reverse)	Small source; acceptance angle θ design; incoherent	One CPC per source or cluster	D_in ~5–15 mm, acceptance 10–30°; length ~fcalc	±0.5 mm centering; length ±10%	≈±θ (full ~2θ); can be very narrow (e.g. 6°) [4]	~80–90% (reflective or plastic)

Method	Source size/NA/ Coherence	Array Layout	Optics (f, D, f/#)	Alignment	Divergence	Efficiency
Microlens array homogenizer	Requires imaging multiple sources; moderate coherence not needed	Sources can be imaged onto MLA; uniform output area	Lenslets ~0.5–2 mm (f/# few) with field lens; follow by projection lens	~10–50 µm MLA alignment; source-to-MLA imaging critical	Design-dependent (e.g. ±5–15° typical)	~80–90% after AR (multiple surfaces) [11] [10]
Coherent phased array	Laser beams; each nearly diffraction-limited; coherence required	Precisely spaced (often sub-mm spacing for phased effect)	Each channel collimated (e.g. D=1–5 mm); combined aperture ~ few cm	Extremely tight: λ/10 phase, µrad beam pointing	≈λ/D_array (diffraction-limited); very narrow	~80–90% (splitter/ combiners) [12] [5]

***Preferred Layouts:* For incoherent arrays, a *hexagonal packing* maximizes fill factor and symmetry [11], beneficial for uniform illumination and lens packing. Concentric ring arrays may be used for circular optics. For coherent arrays, a filled 2D grid yields one central lobe (no grating orders) if the array aperture is contiguous.**

***Key Trade-Offs:* A single optic is simple but often nonuniform (pattern reproduction) [3]. Per-source collimators yield better uniformity but multiply parts count. Large f/# optics give low divergence but require big lenses; small f/# compact optics accept more flux but output wider beams. Homogenizers achieve uniformity at expense of additional optics and some loss. Coherent combining maximizes brightness but is very expensive and only for lasers. All methods obey brightness limits – you cannot get a narrower beam without either using more output area or accepting higher f/# (so more aperture) [1] [5].**

Design Examples

1. **LED Array (1 mm Lambertian)**: Suppose a 5×5 array of 1 mm LEDs (Lambertian ±60°) on a 10×10 mm grid. Options:

2. *Single Lens:* Use a 100 mmØ Fresnel (f=100 mm). Expect 5×5 beamlets, each ~±0.5° divergence, total efficiency ~80%. Nonuniform.
3. *Individual Lenses:* Mount 5×5 aspheric lenses (D=10 mm, f=10 mm, f/1). Each LED outputs ~±6° half-angle (source-limited) 【43†(Abstract)】. Overlap beams, ~90% total light. Alignment ±0.1 mm.
4. *CPC:* Attach 5×5 CPCs (D_in=10 mm, θ=10°). Each LED beam shrinks to ±10°. More directional intensity but only ~50% of LED power collected (acceptance 10° vs 60° initial).

5. *Homogenizer:* Image the array onto a fly's eye: use a 25 mm focal field lens, then 4×4 double-MLA (1 mm lenses) and output lens. Achieves a ~25 mm collimated uniform spot, ±5° divergence, ~85% throughput ⑪ .

6. **Laser Diode Array (Elliptical, Coherent)**: 16 single-mode diodes (1300 nm) arranged in 4×4 at 2 mm spacing. Each diode's raw divergence ~10°×30°.

7. *Individual Collimation:* Two-axis collimation: a fast-axis micro cylindrical lens (f=1.5 mm) and slow-axis asphere (f=10 mm) yield ~1°×3° beam each. Alignment to <50 μm for both axes.

8. *Coherent Combining:* Use fiber or cavity approach. Collimate each to 2 mm beam, feed into a Butler matrix or diffractive coupler. Phase-lock to yield single output. Expected divergence ~ λ/(8 mm) ~0.05° (diffraction-limited), brightness ~16× that of one diode ⑤ . Efficiency ~80%.

9. **Extended Filament (Lambertian Cylinder ~10×1 mm)**: Use a parabolic reflector (diameter ~40 mm, f~20 mm) behind the lamp (filament at focus). This yields a fan-shaped beam: narrow (~1–2°) in one plane, wide (~60°) in orthogonal. To collimate further, place a second parabolic mirror in front (dual reflector system). Efficiency ~95%. Sources on large reflector require cooling and space.

Implementation & Validation

Implementation Steps:
1. **Define requirements:** Determine desired beam size and divergence, total power, and target uniformity. Note source properties (size, spectrum, incoherent vs coherent).
2. **Select method:** Based on coherence and layout. For LEDs, likely per-source optics or homogenizer; for lasers, consider coherent combining.
3. **Optical design:** Use ray-tracing to choose lens focal lengths, f/#, and spacing to match étendue. Example: set f such that source fits within aperture and yields desired NA. For homogenizers, design MLA focal lengths per [20].
4. **Prototype components:** Acquire lenses, reflectors, or MLAs. Assemble source array on heat sink/PCB, mount optics. Ensure sources are at designed focal distance and centered.
5. **Alignment:** Align each collimator: adjust axial distance to minimize divergence (measure beam waist or image). For arrays, align collimators symmetrically. For coherent arrays, iterate phase locking with feedback loops.

Testing/Validation:
- **Beam profile:** Use a beam profiler or camera at various distances. Measure divergence (beam radius growth with distance) and check uniformity. For incoherent, simply inspect far-field spot on screen or photodiode array.
- **M^2 measurement:** For lasers, use M^2 test (multiple beam waist vs distance) to quantify quality. Coherent combined beams should approach $M^2 \approx 1$ (diffraction-limited).
- **Intensity uniformity:** Measure irradiance across beam cross-section (for homogenizer or array). Aim

≥90% uniformity if needed.
- **Power/efficiency:** Measure total output power vs sum of sources. Losses indicate misalignment or component inefficiency.
- **Tolerances:** Test sensitivity by shifting optics/sources slightly. Determine alignment margins. Document any required stability (e.g. mechanical mounts, thermal control for coherent systems).

Collimation Test (Incoherent): A simple method is to project the collimated beam onto a wall far away (10–100 m). A small spot indicates good collimation. Alternatively, place a lens to focus the beam and measure spot size (smaller than source image means good collimation).

Beam Profiler: For detailed analysis, capture 2D beam profile at a fixed distance. Fit to Gaussian or top-hat to extract divergence (FWHM angle).

Note: If parameters (source size, acceptance angle, etc.) were unspecified, clearly document assumptions (e.g. LED Lambertian 120°, lamp filament length 10 mm, etc.). All designs above assumed visible/IR wavelengths.

Sources: The above synthesis draws on classical optics and modern literature. Key references include conservation of étendue ① ②, LED collimator designs ⑩ ③ ④, microlens homogenizer research ⑪, and coherent combining studies ⑫ ⑤.

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① ⑥ Collimation, Etendue, Nits (Background for Understanding Brightness) – KGOnTech
https://kguttag.com/2017/08/10/collimation-etendue-nits/

② ⑦ Technical Note: Etendue and Optical Throughput Calculations
https://www.energetiq.com/etendue-and-optical-throughput-calculations

③ UV LED Lens Technology
https://www.radtech.org/proceedings/2008/papers/052.pdf

④ Compound parabolic concentrator for LED-based underwater optical communication transmitter - ScienceDirect
https://www.sciencedirect.com/science/article/abs/pii/S1874490724002295

⑤ ⑧ Towards Ultimate High-Power Scaling: Coherent Beam Combining of Fiber Lasers
https://www.mdpi.com/2304-6732/8/12/566

⑨ Background theory and concepts of illumination design – Ansys Optics
https://optics.ansys.com/hc/en-us/articles/42661769138451-Background-theory-and-concepts-of-illumination-design

⑩ Design of optical system for collimating the light of an LED uniformly - PubMed
https://pubmed.ncbi.nlm.nih.gov/24979645/

⑪ Homogeneous LED-illumination using microlens arrays
https://publica.fraunhofer.de/entities/publication/60c15abe-2f30-4dcb-81de-57541885268f

⑫ backend.orbit.dtu.dk
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