Planar Waveguide Illuminator with Variable Directionality and Divergence

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COGNITEK

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Motivation for New Illumination System

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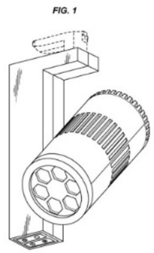
Context: Conventional LED Illumination Systems

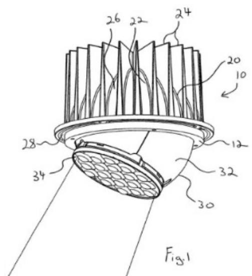
- Directional, collimated “spot” illumination.
- Diffuse “flood” illumination.
- Cannot switch due to fixed optical path.

Directional Illumination

Maxik et al.
US pat. D528,673 S



Bergmann et al.
US pat. D587,832 S



Walezak et al.
US pat. 7,744,259

Diffuse Illumination

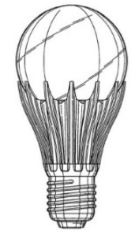
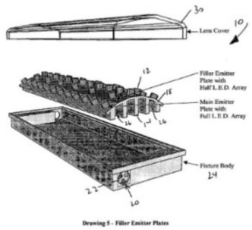
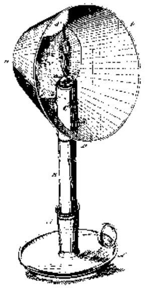


FIG. 1
Yuen
US pat. D553,267 S



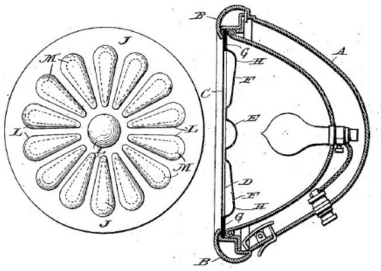
Bolta et al.
US pat. 7,234,844

- Based on old technologies:



M. C. Meigs.
US pat. 209,178 (1878)

Directional illumination =
Localized source
+ reflector (lens)

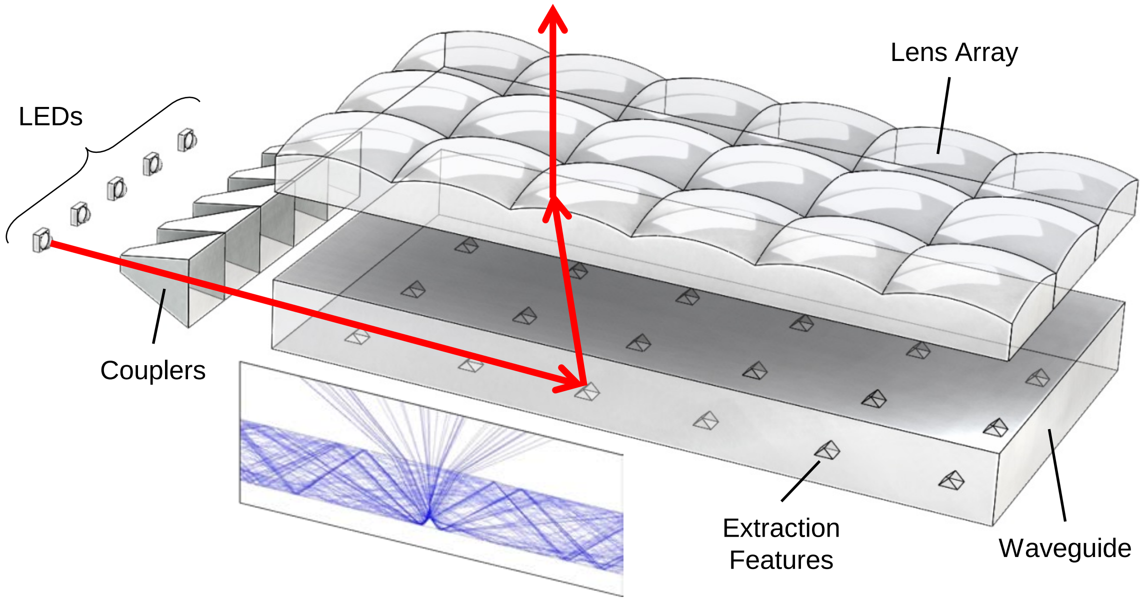


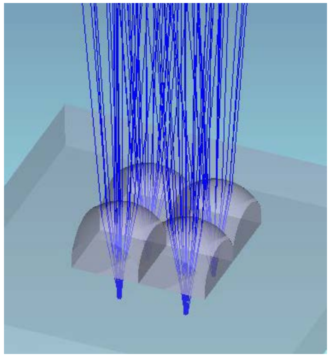
C. H. Muckenhirn
US pat. 1,288,124 (1918)

Diffuse illumination =
Localized source
+ diffuser

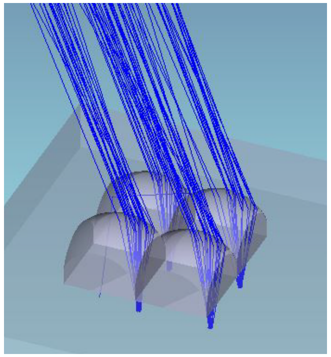
Goal: System with variable directionality and divergence for efficient use of light energy

Waveguide Based Illumination System

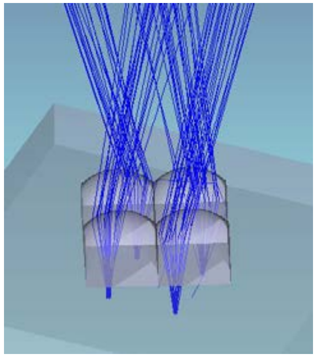




Aligned



Translated



Rotated

1) LED Sources

- High luminance, high efficacy.

2) Coupling

- Tradeoff between spatial power density and divergence.

3) Guiding and Extraction

- Confinement by total internal reflection.
- Periodic extraction features scatter light toward lens array.

4) Beam Steering & Divergence

- Lenses image extraction features to an infinite conjugate.
- Translations between lenslet and extraction arrays steer total beam by steering individual beams in the same direction.
- Rotations between arrays steer individual beams in different directions, altering divergence of the total beam.

Continuous control over directionality and divergence through small mechanical actuation

Planar Micro-Optic Solar Concentrator Research

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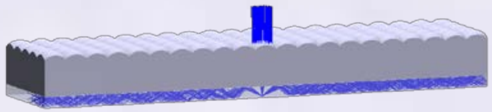
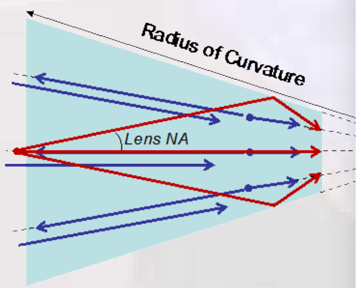
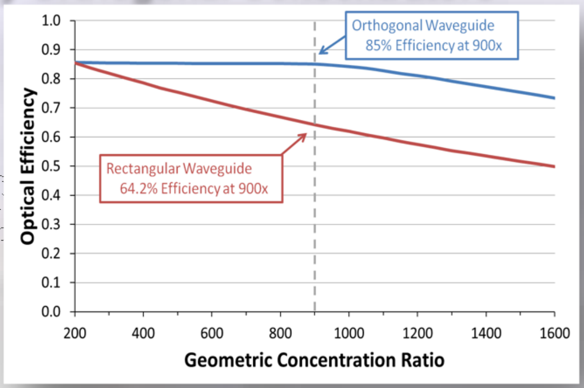
Basic Concept: Low-cost planar concentrator optics

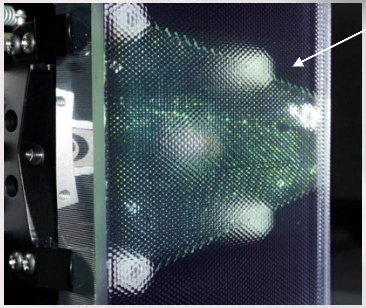


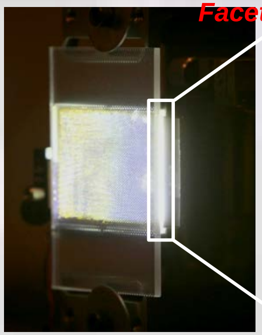
Higher-Efficiency Orthogonal Concentrators

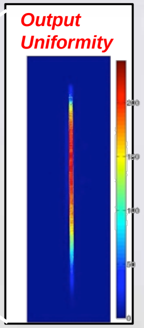




Fresnel End Mirror & Angled Injection Facets



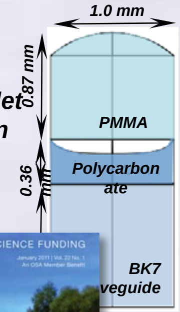


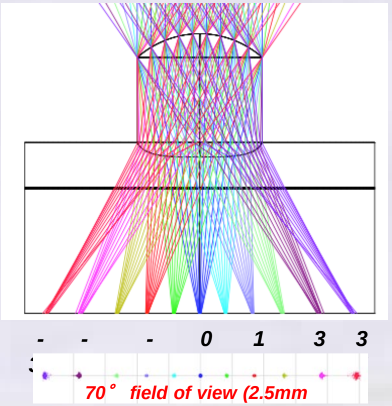


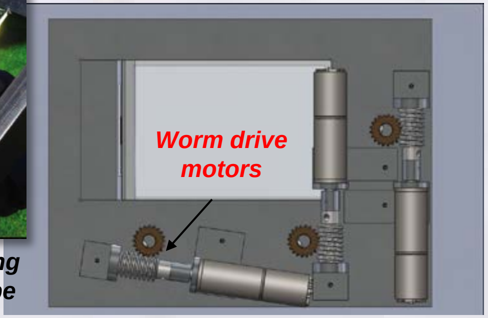
J. H. Karp et al, "Orthogonal and secondary concentration in planar micro-optic solar collectors," Optics Express, May 2011.

Micro-Tracking Waveguide Concentrator

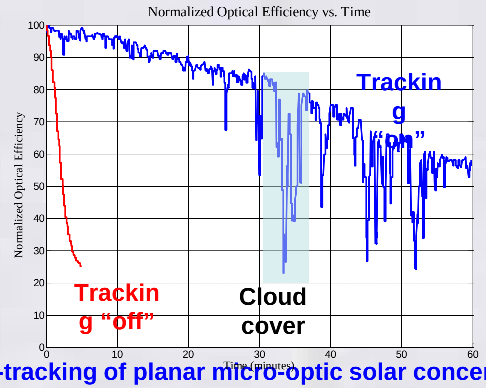
Wide Angle Doublet Microlens Design







Self-contained micro-tracking mechancial system prototype



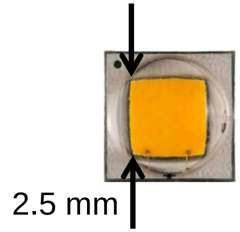
"Lateral translation micro-tracking of planar micro-optic solar concentrator," *SPIE Conference on Solar Energy & Technology*, Paper 7769-03 August 2010.

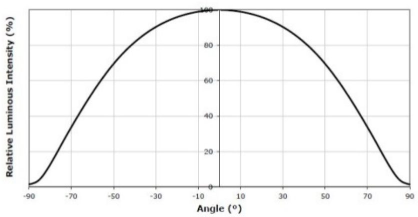
Design Considerations

LEDs

- From conservation of radiance: brightness of output determined by brightness of source.

Want large package high luminance LEDs.



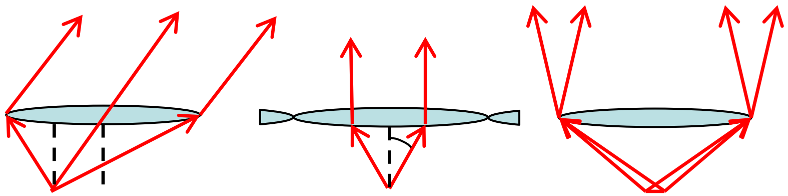


Cree Xlamp XM-L2
Active area: 2.5x2.5mm
Emittance: 116.5 lm/mm^2
Power: 6.2 W
Efficacy: 159.13 lm/W

Lenses

- Determine max. steering angle, crosstalk, and min. divergence angle.

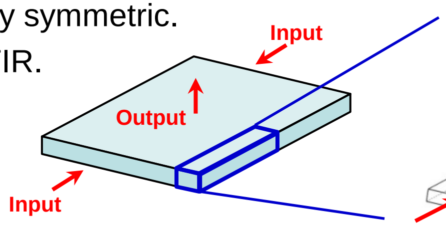
Want low F/#, low divergence source, small source.



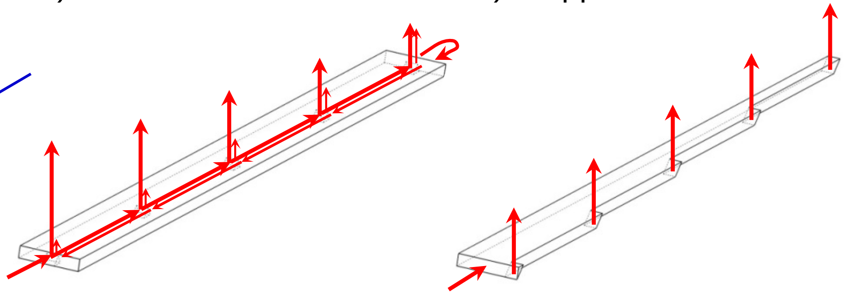
Light Guiding & Extraction

- Faceted extraction features: divergence maintaining, broadband, axially symmetric.
- Waveguide confines light by TIR.
- Two configurations:

Want thin waveguide.



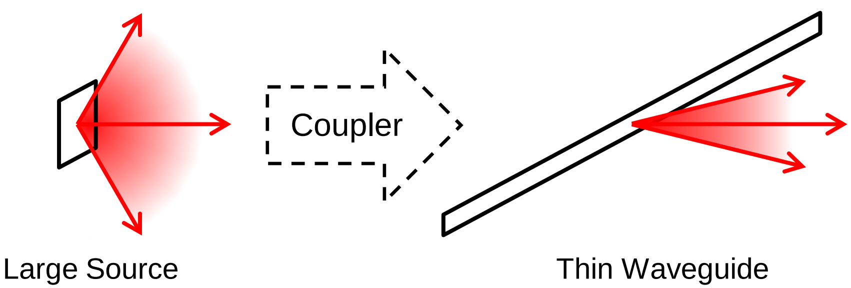
1) Constant Mode Volume 2) Stepped Mode Volume



Couplers

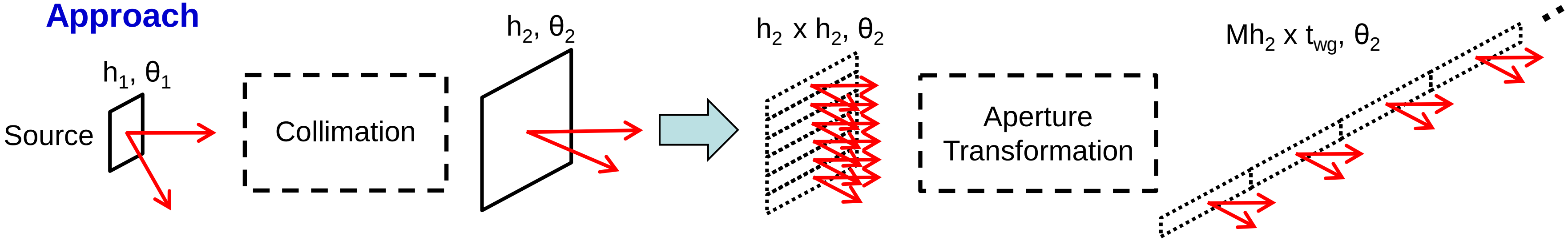
- Efficient coupler must conserve radiance.
- Impose above constraints, design becomes etendue matching problem.

Needed: efficient coupling structure.



Coupler Design

Approach



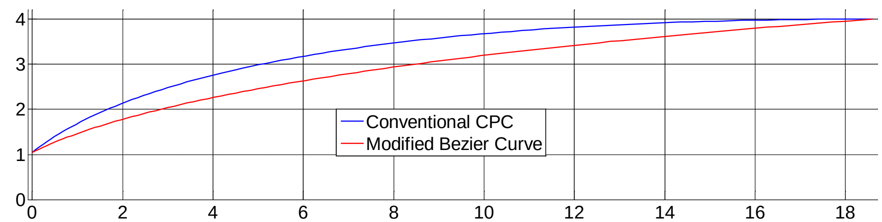
1) Collimation

- Compound parabolic concentrators (CPCs) provide nearly etendue limited concentration, and likewise, collimation.
- When used as a collimator, the conventional CPC has poor spatial uniformity at the output.
- Quadratic Bezier curve allows tradeoff between spatial uniformity and divergence.

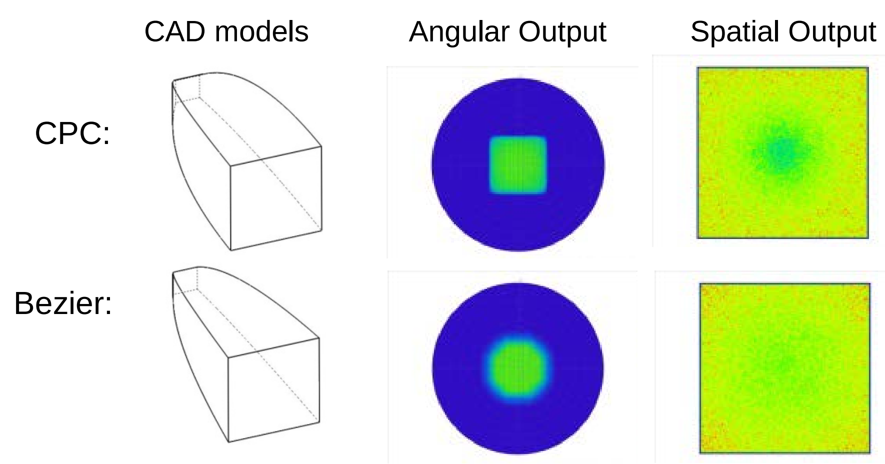
"Method to improve spatial uniformity with lightpipes", Fournier, Cassarly, Rolland, Optics Letters, Vol. 33, No. 11, June 1, 2008.

$$B(t) = (1-t)^2 P_0 + 2(1-t)tP_1 + t^2 P_2\ ,\ t \in [0,1]$$

Parameterized by variable t. Points P_0, P_1, P_2 ϵ R^2.



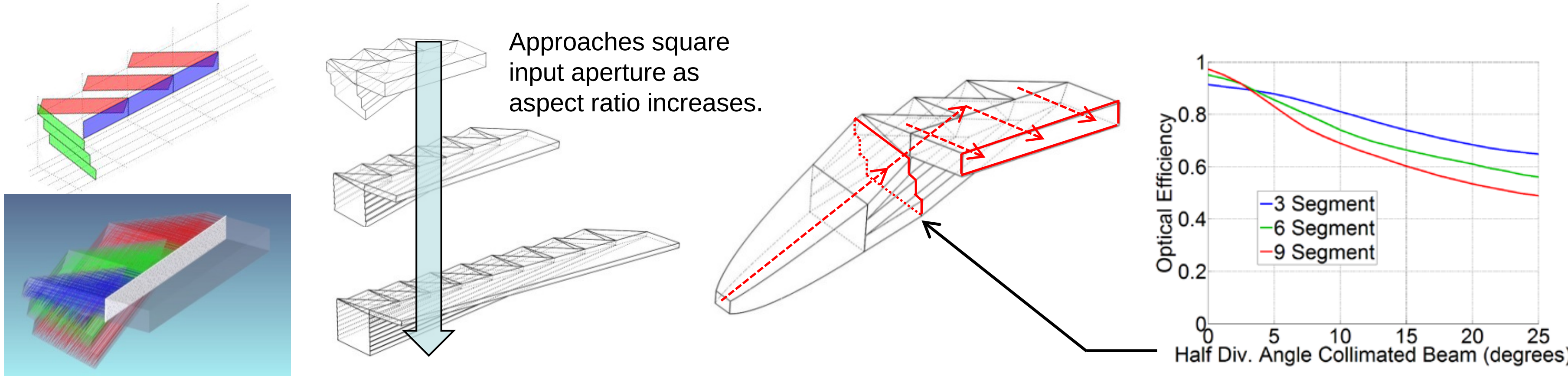
- Optimized in Nonsequential Zemax.
  - Merit function:
    - Minimize standard deviation (RMS from mean) of all nonzero intensity values.
    - Minimize radial RMS from 0º (on axis) in polar space.
  - Variables:
    - Control point (P_1) and axial length.



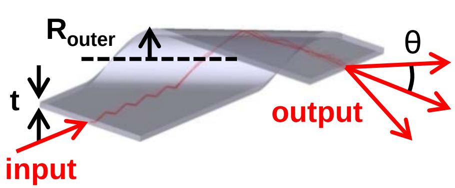
2) Space Variant Aperture Transformation

- Define structures which segment and rearrange a square aperture into a rectangular aperture.
- Designed for perfectly collimated input, modeled in Zemax for varying degrees of divergence.

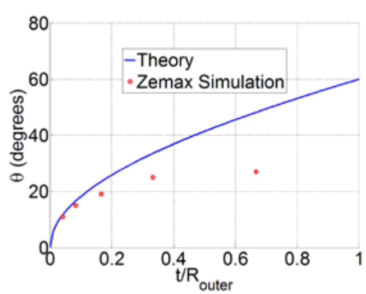
i. Faceted Structure

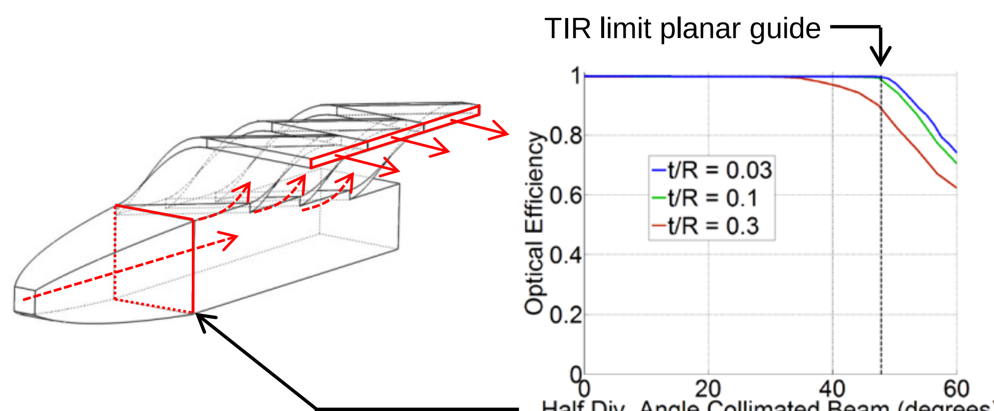


ii. Curved Structure



$$\theta = \cos^{-1}\left(1 - \frac{t}{2R_{outer}}\right)$$





“Analysis of Curved Optical Waveguides by Conformal Transformation”, Heiblum, Harris, IEEE, Vol. QE-11, No. 2, Feb 1975

Analytic Model & Optimization

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Motivation

- Optimization difficult in standard raytracing software.
- Create analytic optimization procedure.
- Show that optimal designs have useful performance.

Analytic Approach

- Use equations from imaging and nonimaging optics.
- Find optimal designs in a constrained space.
- Verify predicted performance using Zemax.

Etendue:

$$G = n^2 \int_S \int_0^{2\pi} \int_0^{\beta} \cos(\theta)\sin(\theta)\, d\theta\, d\varphi\, dS = n^2 h^2 \sin^2(\beta)$$

$$h_1 \sin(\theta_1) = h_2 \sin(\theta_2)$$

(Spatial extent) (Half div. angle)

Radiometry:

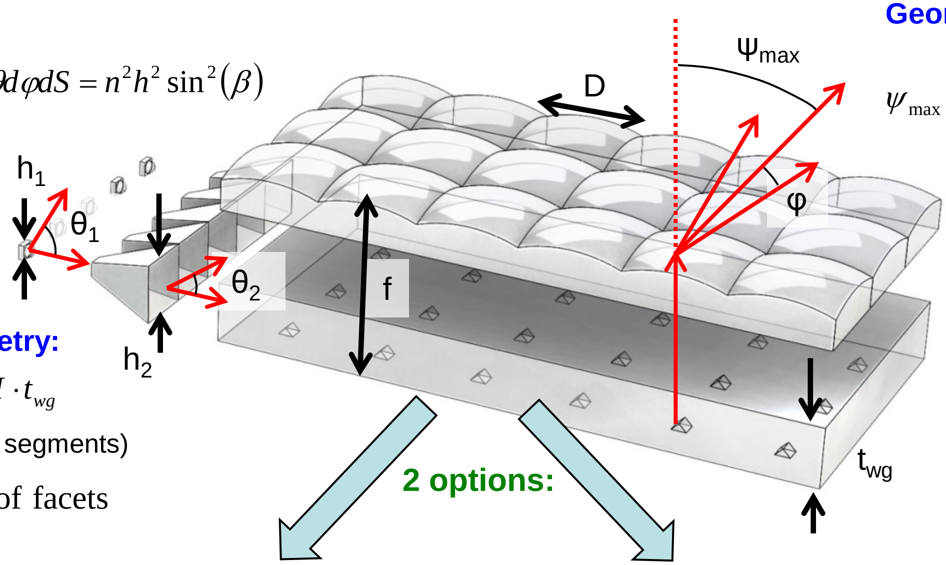
$$\eta_{beam} = \sin^2(\theta_1)$$

Geometry:

$$h_2 = M \cdot t_{wg}$$

(# of segments)

$$N = \#\text{ of facets}$$



Geometrical Optics:

(Lens F/# = f/D)

$$\psi_{max} = \sin^{-1}\left(n \sin\left(\tan^{-1}\left(\frac{1}{2(F/\#)} - \tan(\theta_2)\right)\right)\right)$$

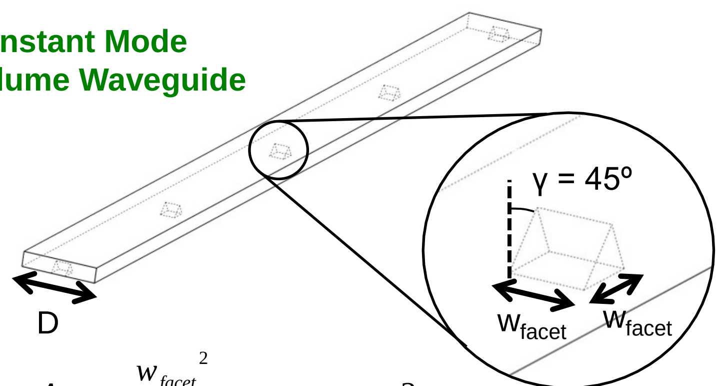
(Waveguide index) (Half divergence angle within waveguide)

(Facet width)

$$\varphi = \sin^{-1}\left(n \sin\left(\tan^{-1}\left(\frac{w_{facet}}{2f}\right)\right)\right)$$

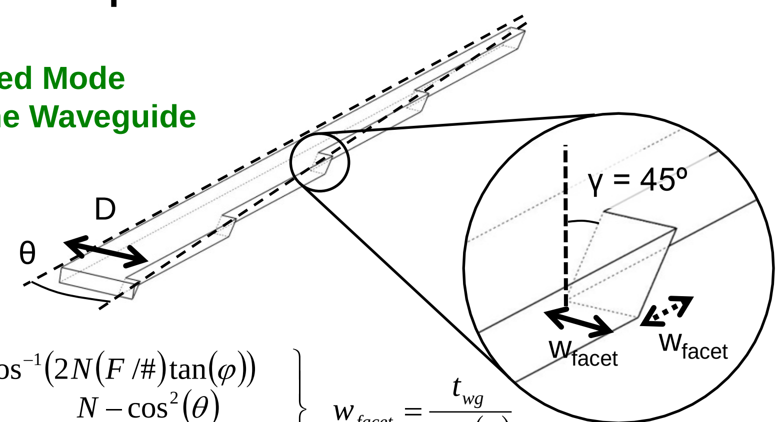
(Waveguide index) (Lens focal length)

1) Constant Mode Volume Waveguide



$$A_{facet} = \frac{w_{facet}^2}{2} \qquad w_{facet} < 2t_{wg}$$

2) Stepped Mode Volume Waveguide



$$\begin{cases} \theta = \cos^{-1}\left(2N(F/\#)\tan(\varphi)\right) \\ \tan(\theta) = \dfrac{N - \cos^2(\theta)}{N(N-1) + \cos(\theta)\sin(\theta)} \end{cases} \qquad w_{facet} = \frac{t_{wg}}{\tan(\gamma)}$$

Optimized Design Performance

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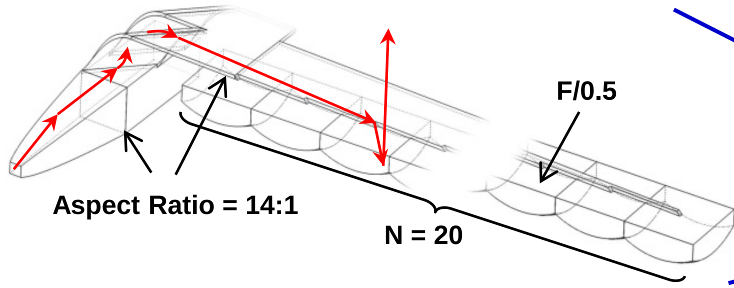
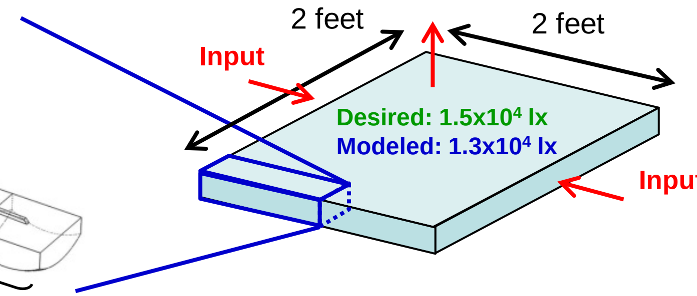
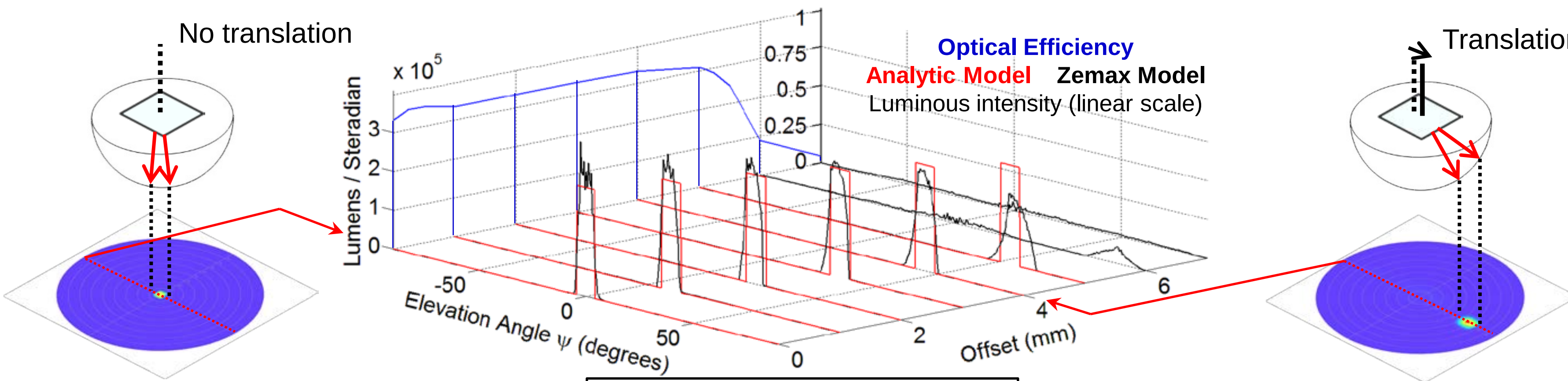
Physical realization of optimal stepped mode volume design:

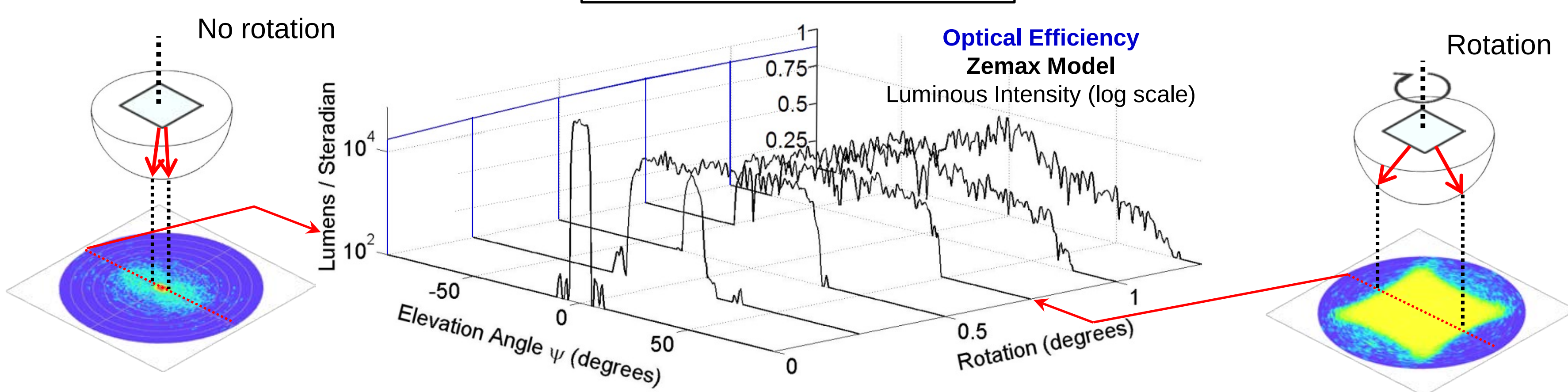
- Cree Xlamp XML2
- Curved coupling structure
- F/0.5 reflective spherical lenses
- 40 x 40 lenses in full system.







Good agreement between models

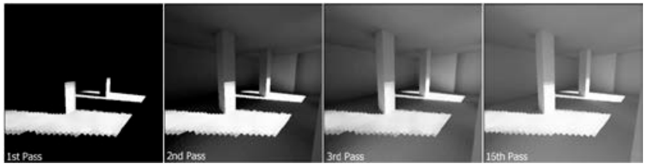


Simulated System Application

Far field intensity modeled in Zemax, exported as .ies file.
Room illumination modeled in Dialux software using radiosity method.

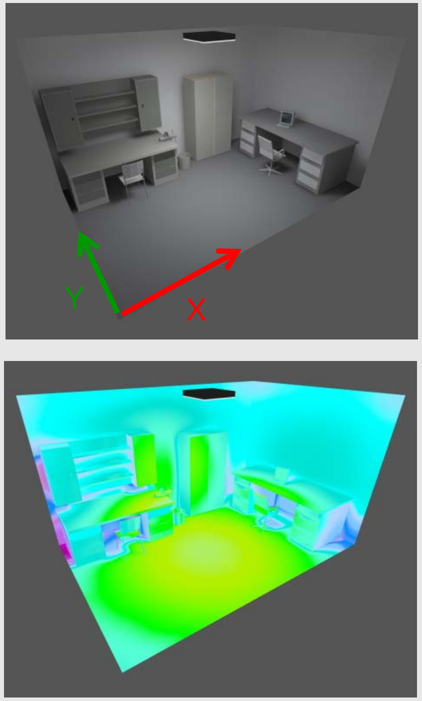
- FEM approach to global illumination. Applies to Lambertian surfaces. Iterates through subsequent scattering steps until convergence.

$$B(x)dA = E(x)dA + \rho(x)dA\int_S B(x')\frac{\cos\theta_x \cos\theta_{x'}}{\pi r^2}Vis(x,x')dA'$$

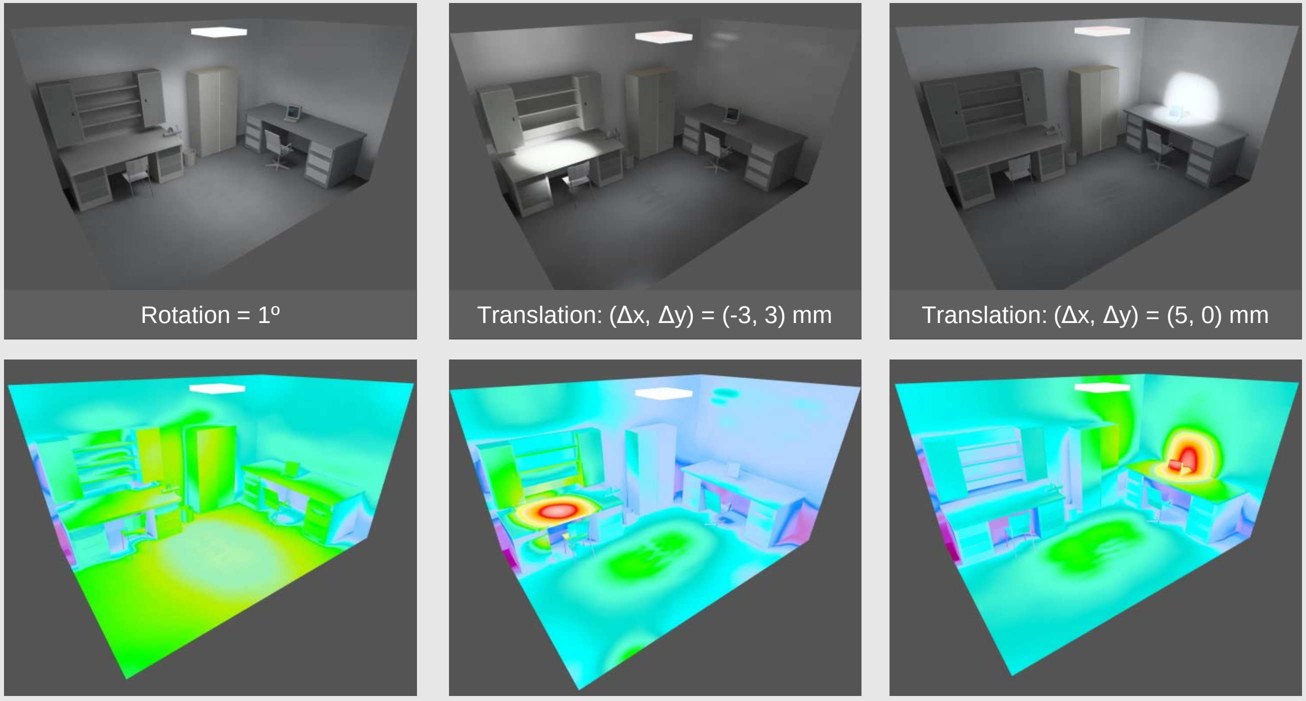


Iterative solution to radiosity method.

Conventional 2x2’ system (53W, 4000lm)



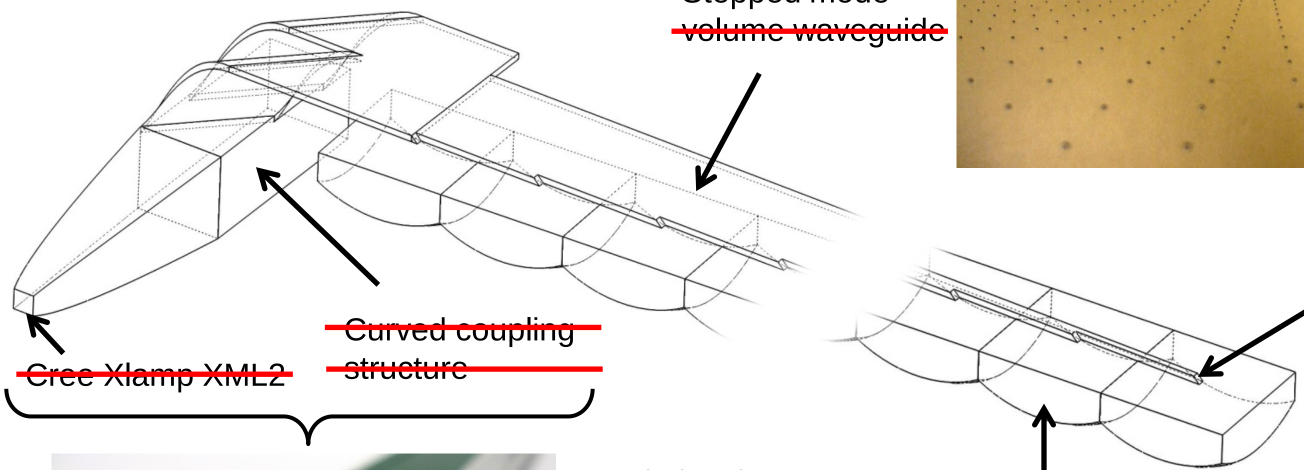
UCSD SMV2a optimized design, 2x2’ aperture (54.82W, 5700lm)

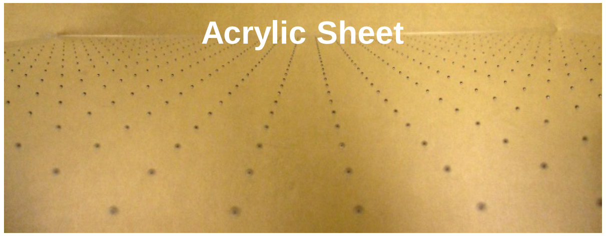


*Nonlinear Scale

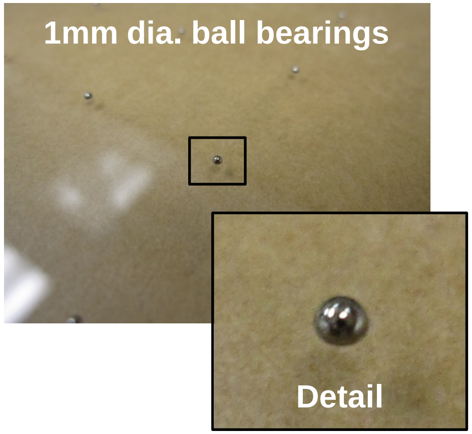
~~Optimized System Components~~ Prototype Components

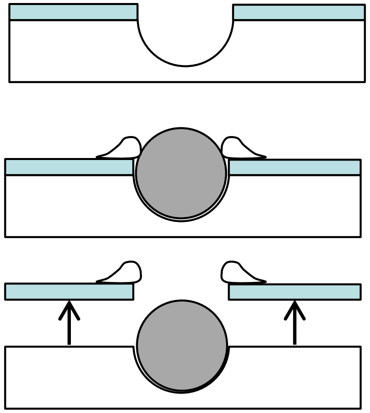
SMV2a Optimized Design

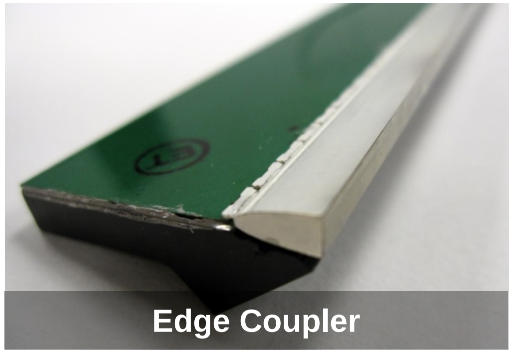




0.1 x 24 x 24 inches. Machined with 1mm diameter hemispherical holes.
Upper bound on absorption measured: $\alpha = 1\ m^{-1}$



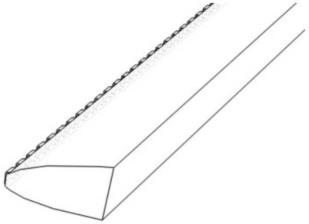




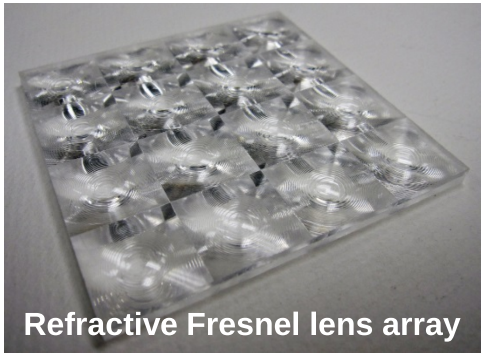
PCB designed to provide adequate heat sinking using thin FR4 substrate and silver adhesive.

LEDs registered with high precision using custom fixture during reflow soldering.

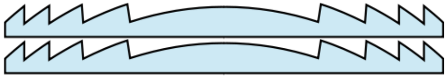
SunLED right angle SMD LED



Designed CPC, Sputtered Silver



Two F/1.04 lenses oriented grooves out = F/0.7 lens in PMMA.
Array is 4 x 4 lenses = 3 x 3 inches.



Prototype Model and Measurement

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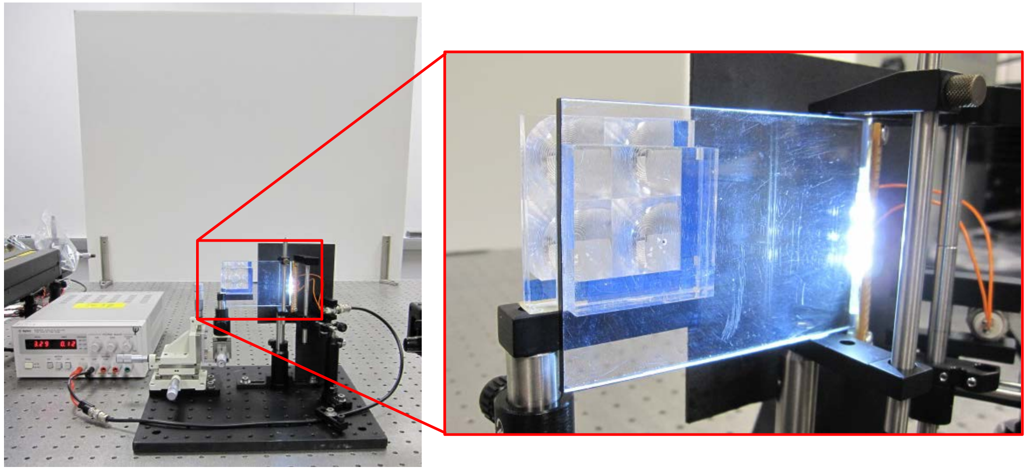
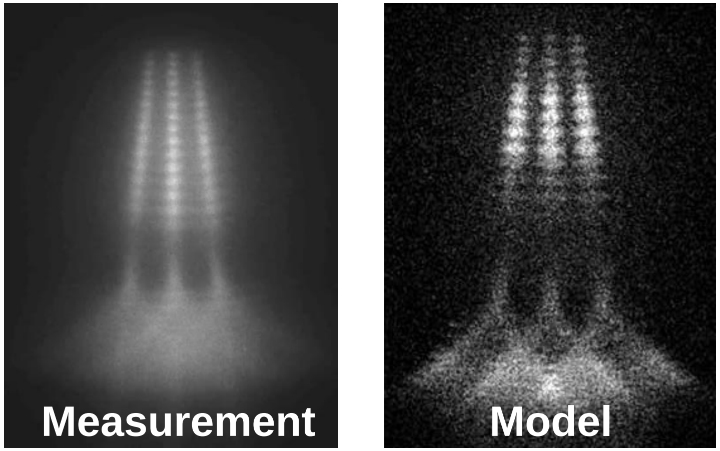
<u>"Unit Cell System":</u> Lab measurement to determine performance.

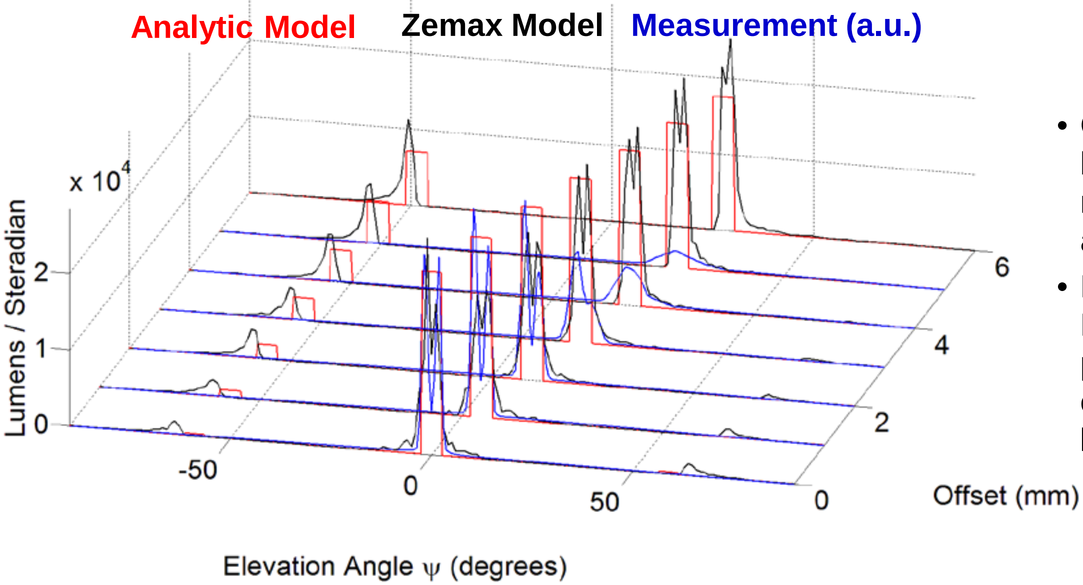


Far field intensity pattern:

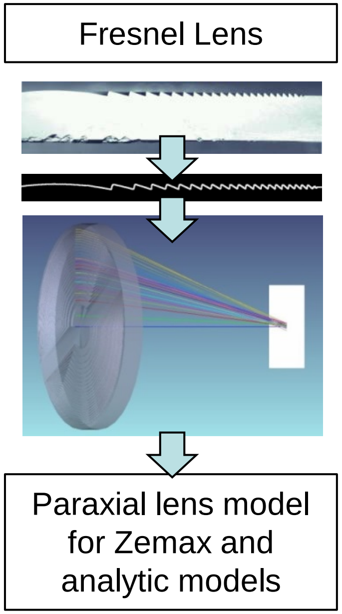


Superposition of 3 patterns from 3 LEDs.

Far Field Pattern Cross Section, Luminous Intensity



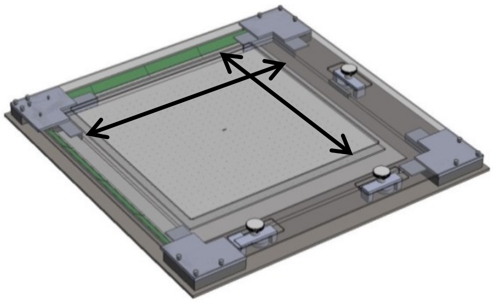
- Good agreement between analytic model, Zemax model, and measurement.
- Non-ideal off-axis Fresnel lens performance eliminates crosstalk lobes.

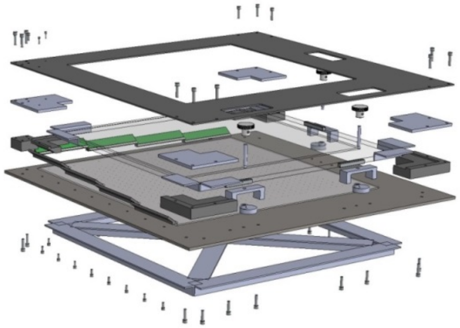


Experimental System

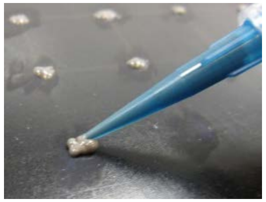
CAD Design

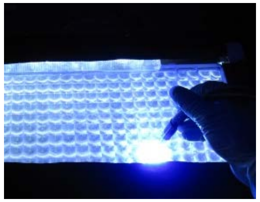
- Magnetic eccentric cams as actuation mechanism.
- 28 x 28 lens array.
- 304 LED sources coupled to 2 edges of waveguide.

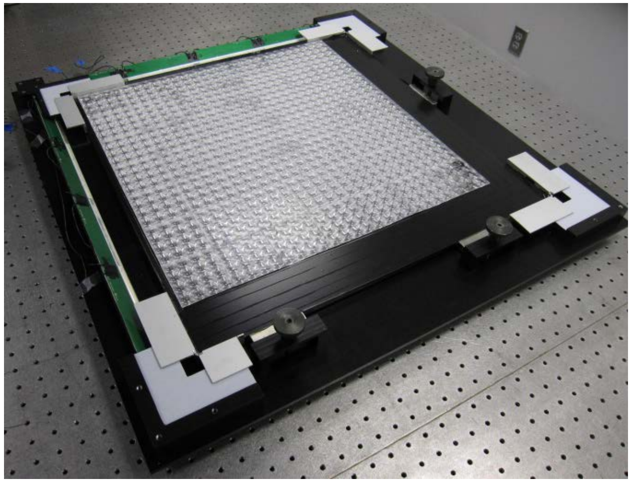


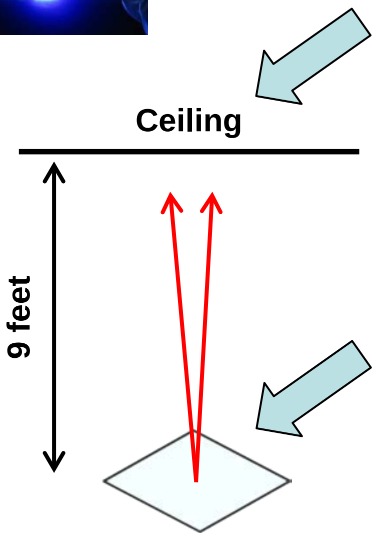


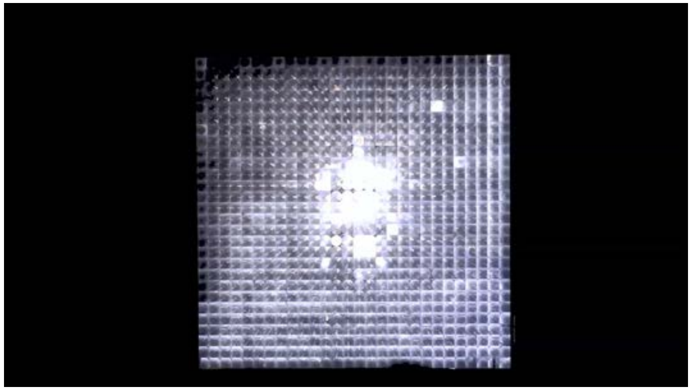
System Fabrication and Test



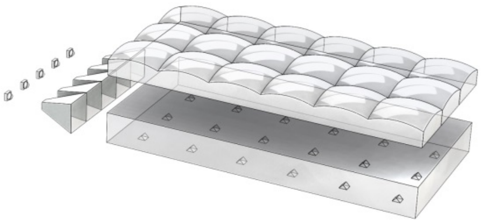


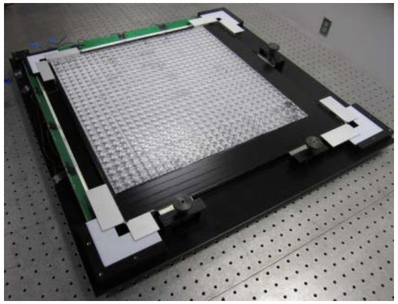






- **Design of new illumination system**
  - Continuously variable directionality and divergence allows efficient use of light energy.
  - Optimized designs can achieve performance metrics matching those of conventional illumination systems, while simultaneously providing new functionality.
- **Prototype demonstration**
  - Measurements of unit cell prototype validate the accuracy of Zemax and analytic models used in design process.
  - Full 2’ x 2’ experimental system provides proof of principle in a large aperture system.





Thank you

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