Why use Nonimaging Optics

Julio Chaves

LPI
LIGHT PRESCRIPTIONS INNOVATORS

01

02

Etendue
Optimum optic size
  Collimators
  Concentrators
  Summary
Edge ray principle
Maximum tolerances
  Collimators (minimum spot size)
  Concentrators (maximum acceptance)
Conclusions
References
**Etendue**
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Light flux increases with:
- Area
- Angle

More area $\Rightarrow$ More light

Constant light flux:
Angle increases $\Leftrightarrow$ Area decreases
Angle decreases $\Leftrightarrow$ Area increases

Conservation of Etendue

Wider angle $\Rightarrow$ More light
Optimum optic size

- Collimators
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Etendue

**Optimum optic size**
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Both optics $O_1$ and $O_2$ see:
- Same source size
- Same angle $\delta$

Same energy captured

Same light transfer from source to target
Optic goals:
- Efficiency: transfer to target all the light it intersects
- Minimum size (low cost)
High efficiency + Minimum size = Edge ray principle

Optic efficiency: transfer to target all the light it intersects

Point source optic
- Optic designed for a point source
- Large optic (much larger than the source)

Extended source optic
- Optic designed for extended source
- Small optic
Same size source for all configurations

Image, courtesy of LPI
Etendue

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Larger optic $O_2$ captures more Source light

Optics $O_1$ and $O_2$:

- Same Target size
- Same angle $\delta_r$

Same ability to transfer light to Target
Optic goals:
- Efficiency: transfer to target all the light it intersects
- Maximum size (maximum light capture)

Largest size with high efficiency

Optic goals:
- Efficiency: transfer to target all the light it intersects
- Maximum size (maximum light capture)

Optic: Efficient Small

Largest size with high efficiency

Optic: Efficient Optimum

Optic: Inefficient Large
High efficiency + Maximum size = Edge ray principle

Optic efficiency: transfer to target all the light it intersects

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Etendue

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Light from edge A of the source is redirected to edge F of the target

Light from edge C of the source is redirected to edge E of the target

Edge ray principle

Light from B of the source does not need to focus at a point on the target

No need for image formation

Nonimaging Optics
High tolerance to errors ⇒ Relaxed manufacture, assembly, usage ⇒ Lower cost

Optic manufactured with errors
Example: oscillations on the surface

Perfect optic

Manufacturing, assembly or other errors diffuse the light as it goes through the optic

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This solution minimizes the spot size for a given optic aperture AB

Constant aperture AB

\[ \alpha_1 \text{ decreases to } \alpha_3 \]
\[ \downarrow \]
\[ a_1 \text{ increases to } a_3 \]
\[ \downarrow \]
\[ a_2 \text{ decreases to } a_4 \]
\[ \downarrow \]
\[ \text{somewhere else in aperture AB} \]
\[ \downarrow \]
\[ \alpha_2 \text{ increases to } \alpha_4 \]
\[ \downarrow \]
\[ \text{increased spot size!} \]

Increased spot size!

This leads to increased spot size!

This solution minimizes the light angular aperture \( \alpha \) across the whole aperture AB \( \Rightarrow \text{Minimum spot size} \)

Increased spot size!
Collimator nonimaging optics minimize the spot size

Any imperfections (errors) in the optical system will “diffuse” light increasing the spot size

Since we start at the minimum, the resulting spot size will still be minimum in a nonimaging optic

Nonimaging optics maximize tolerance to errors!
This solution maximizes the acceptance angle $\alpha$ for a given optic aperture $AB$.

Constant aperture $AB$

- $\alpha_1$ increases to $\alpha_3$
  - trying to increase acceptance
  - $a_1$ decreases to $a_3$
  - $a_2$ increases to $a_4$
  - somewhere else in aperture $AB$
  - $\alpha_2$ decreases to $\alpha_4$
  - light loss!
Constant aperture $AB$

$\alpha_1$ increases to $\alpha_3$

$\alpha_2$ decreases to $\alpha_4$

This leads to light loss!

This solution maximizes the acceptance angle $\alpha$ across the whole aperture $AB$

Concentrator nonimaging optics maximize the acceptance angle

Any imperfections (errors) in the optical system will decrease the acceptance angle

Since we start at the maximum, the resulting acceptance angle will still be maximum in a nonimaging optic

Nonimaging optics maximize tolerance to errors!
Optimized (nonimaging) optic
(Maximum acceptance angle $\alpha$)

Errors diffuse the light, which now misses the receiver. Acceptance angle is reduced from $\alpha_1$ to $\alpha_2$.

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Still captures all light from source

Optimized optic manufactured with errors

Errors reduce the acceptance angle from $\alpha_1$ to $\alpha_2$; still wide enough to capture all light from source.

---

Non-optimized optic

Acceptance angle $\alpha_2$ smaller than ideal

Light loss!

Non-optimized optic manufactured with errors

Errors reduce the acceptance angle from $\alpha_2$ to $\alpha_2'$; too small and light is lost.
Collimator optic

**High efficiency + Minimum size = Edge ray principle**

Low cost

\[ \downarrow \]

**Nonimaging optics**

Concentrator optic

**High efficiency + Maximum size = Edge ray principle**

Maximum light capture
Manufacture, assembly and other errors “diffuse” the light as it crosses the optic

Nonimaging optics collimators
Minimize the spot size

Nonimaging optics concentrators
Maximize the acceptance angle

⇒ Maximum tolerances

↓

Relaxed manufacture, assembly, usage

↓

Lower cost

Why use Nonimaging Optics    Julio Chaves, LPI    July 2013
References


Roland Winston et al., *Nonimaging Optics*, Elsevier Academic Press, 2005


Pablo Benitez et al., *High performance Fresnel-based photovoltaic concentrator*, Optics Express A26, Vol. 18, No. S1, 26 April 2010

Fernando Muñoz et al., *Simultaneous multiple surface design of compact air-gap collimators for light-emitting diodes*, Optical Engineering, Vol. 43 No. 7, July 2004


Diogo Canavarro et al., *New second-stage concentrators (XX SMS) for parabolic primaries; Comparison with conventional parabolic trough concentrators*, Solar Energy 92, pages 98–105, 2013

Thank you!
Extra material:

Non-uniform sources (Kohler optics)
Kohler integrator

Uniform illumination even as the sun moves across the sky
Uniform illumination even with different source positions

High tolerance to source position errors

Uniform illumination even with non-homogeneous light sources

Color mixing
Shell mixer integrator: when put on top of a non-uniform light source, eliminates its non-uniformities

Image, courtesy of LPI

Conclusions

**Kohler integrators**
uniform target illumination even with non-homogeneous light sources:
Tolerance to source position and color mixing
SMS freeforms for illumination

Pablo Benítez, Juan C. Miñano, M. Buljan
Universidad Politécnica de Madrid, Spain

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• Introduction
• SMS 3D design method
• Application examples
• Summary
Design problems in Nonimaging Optics

• **Bundle coupling**: Source and target ray bundles are given. Maximum coupling efficiency is required.
  - Collimators
  - Condenser optics for a projector
  - Light injection into an optical fiber
  - Radiation sensors
  - Photovoltaic concentrator
  \[ E(\text{source}) \approx E(\text{target}) \]

• **Prescribed illuminance**: The source ray bundle and the output illuminance distribution on the target are given.
  - Automotive headlights
  - Street lights
  - RGB color blending
  - Backlights
  \[ E(\text{source}) < E(\text{target}) \]
  \[ E = \text{etendue} = \text{"size" of the ray bundle (in phase space)} \]

Why freeforms in Nonimaging Optics?

• When source, target or volumetric constrains are non-symmetric, symmetric solutions don’t work

• Freeforms give you more degrees of freedom

• Freeforms allow for fewer surfaces and parts because they can perform multiple functions
Design methods in Nonimaging Optics

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2D = rotational or linear symmetry  
3D = freeform

The SMS 3D

- The method solves a **partial functional differential equation**
- The solution is given as a collection points of the surfaces and their normal vectors.
- Those points can be interpolated or fitted with a NURBS surface

**Additional boundary condition**: A full curve in one of the surfaces, which can be calculated to partially control a third wavefront pair.
Single freeform vs SMS freeforms

Single freeform surface
- Design controls the position of **ONE** point of the source image
- It does **NOT** control its size, shape and rotation

SMS freeform surfaces
- Design controls **THREE** points of the source image
- Therefore, it **DOES** control its size, shape and rotation.

Example 1: Low beam headlamp design

It is a **prescribed illuminance** problem

- Specs defined by regulations (ECE, SAE)
- Typically 20 min/ max test points/ fields
- Gradient Specifications
- Homogeneity
- Car producer additional specifications
Freeform RXI automotive headlamp

Seed rib

Spines

Measured efficiencies:

- 84% HB (Al mirror; AR coatings)
- 75% LB (Al mirror; no AR coatings)

US 7,460,985 & International patents pending
Freeform RXI automotive headlamp

Jewel Eye™ LED headlamps of the 2014 Acura RLX

Example 2: RBG collimator
It is bundle coupling and prescribed illuminance problem
Example of freeform solution

The grooved 8-fold collimators
(M. Buljan et al. SPIE conference, Barcelona, 2012)
8-fold grooved XX collimator

Step 1: Design a freeform XX

- Input data: LED source dimensions, the angle of collimation, collimator’s material.
- SMS 3D design procedure is applied
Step 2: Design a grooved back reflector

While a single reflector at $z=0$ only changes the sign of $r$, the groove reflector also changes the sign of $q$.

Both reflectors leave the $p$ coordinate unchanged.
Step 2: Design a grooved back reflector

Both reflectors leave the $p$ coordinate unchanged

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D. Grabovičkić, P. Benítez, J.C. Miñano
“Free-form V-groove reflector design with the SMS method in three dimensions,”
Step 3: Apply an 8-fold symmetry

Why? See next slides…

Simulation results

- Emitting point-source on $z=0$ plane
- Far-field distribution

No grooves

Grooved
Far-field constellation

- Emitting point-source on $z=0$ plane

- Far-field distribution

Benitez, Miñano, Buljan, SMS freeforms for illumination
OSA webinar, July 10, 2013
Far-field constellation

- Emitting point-source on z=0 plane

- Far-field distribution

[Diagram showing far-field constellations with angles 90° and 135°]

Benitez, Miñano, Buljan, SMS freeforms for illumination
OSA webinar, July 10, 2013
Far-field constellation

- Emitting point-source on $z=0$ plane

- Far-field distribution

Benitez, Miñano, Buljan, SMS freeforms for illumination
OSA webinar, July 10, 2013
Simulation results

• Far field image when red LED is ON:
  • Design without grooves (left)
  • Design with grooves on the secondary mirror (center)
  • Design with grooves on both primary and secondary mirror (right)

Simulation results

True color far-field images of an RGGB LED

• No grooves (left)
• 8-fold free-form V-groove collimator (center)
• 8-fold free-form V-groove collimator + 2 deg gaussian diffuser (right)
The 8-fold RXI version

Summary

- Freeforms are specially useful when source, target or volumetric constrains are non-symmetric.

- SMS method allows designing two freeforms to control very well extended sources via three wavefronts

- It has direct application to demanding practical problems, as automotive headlamps, high CRI lamps and street lights
Acknowledgments

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Mixing Rods for Nonimaging Applications

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Outline – Mixing Rods

- Example Illuminance Distributions
- The Flip and Fold Concept (Mirror Tiling)
- LightPipe Shapes
- Round Mixing Rods with Ripples
- Practical Considerations

LightPipes Can Provide Excellent Uniformity

Some Shapes Work Great
Some are ‘ok’
Others are Not So Great
Kohler Superposition: Flip-n-Fold for Rectangular Lightpipe

Illuminance at LightPipe Output with NO Sidewall Reflections

Total Illuminance

Illuminance at Lightpipe Output is the Superposition of subdistributions

Illuminance with 5:1 Aspect Ratio Square Light Pipe

Source spatial distribution is Gaussian
Angular distribution is also Gaussian

Lightpipe

Input End

Defocused Back to Input End

Output End, No Sidewalls

Raster Plots are 5mm X 5mm
Source Intensity is Gaussian
Illuminance at input is also Gaussian

1-89

1-90
Illuminance with 10:1 Aspect Ratio Square Light Pipe

Raster Plots are 10mmX10mm
Source Intensity is Gaussian

Placing a Receiver Along the Center of the Lightpipe: ‘Through Focus’ for Square and Circular Lightpipes

Lightpipes are 10X100
Input is 30 degree clipped Lambertian

Round Does Not Work Well
Uniformity with Lightpipe Shapes

Hexagon 'Mirror Tiles'

Pentagon does not 'Mirror Tile'

Illuminance at Lightpipe Output Face

Pentagon does not mirror tile and provides poorer uniformity than hexagon

Other Lightpipe Shapes

- Hexagonal and rectangular lightpipes are known to provide good uniformity if length is adequate. Other shapes are less well understood.
- It appears that shapes which uniformly fill an area with 'mirror tiling' can provide good Uniformity
  - Equilateral Triangle
  - Square sliced along diagonal
  - Equilateral Triangle sliced from apex to base
  - Others?
- Other Shapes that do not ‘mirror tile’ may provide adequate uniformity, depending upon the source distribution and lightpipe length.
Lightpipe Shape Evaluation Setup - Used for next 2 slides

Source is a small clipped Lambertian Patch (30 degree max) that is located at the center of the input face of the lightpipe.

Lightpipe length = 100mm

Area of illuminance (no sidewalls) at 100mm is
\[ \pi \times (\text{length} \times \text{tan(peak\_angle)})^2 \approx \pi \times (57)^2 = 10,471 \]

For the simulations shown, the area of the Lightpipe in all cases is 100mm², which provides ~100 overlapping regions.

Simulation Results

Equilateral triangle, square, and hexagon provide excellent uniformity
Simulation Results

<table>
<thead>
<tr>
<th>Illuminance</th>
<th>Intensity</th>
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<tr>
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<td><img src="image2.png" alt="Image" /></td>
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<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

### Practical Considerations: Length

- If flip and fold shows that 9 regions superimpose, then uniformity tends to be 'good' for square lightpipe in many situations
  - If 90% of the flux is within 27 degrees, then 6:1 lightpipe aspect ratio
- The higher the angles, the more mixing for a given length
  - Longer lightpipes help minimize structure in Pupil/Output Intensity
  - With rectangular lightpipe, the long dimension should be used for first order estimates of required length
- Computer simulations are an excellent means to assess proper length
- Structure in the illuminance distribution can be correlated which may provide structure in the illuminance distribution, which is important to consider when length must be minimized
Practical Considerations: Solid vs Hollow

- Solid has higher sidewall reflectivities but end faces must be coated to eliminate Fresnel losses.
  - Solid is normally longer
  - High flux densities can be a problem with solid
- Dirt on output face of solid will impact uniformity, but not an issue with hollow. Both hollow and solid are impacted by dirt on sidewalls.
- Hollow can be made by cutting 4 mirrors
- Solid can be made by polishing 6 surfaces
- Corners and edges can chip in both cases
- Heat Shrink Teflon can be used to protect sidewalls of solid

Adding surface structure to a mixing rod.

Elliptical Collector I

- Illumination system with source coupled into round mixing rod.
- Note that the output illuminance is highly peaked.

Elliptical Collector II

- Illumination system with source coupled into a mixing rod with perimeter ripples.
- Note that the output illuminance is extremely uniform for the same rod length as previous slide.
Elliptical Collector III
Source Shifted

- Source is shifted up within the reflector. Excellent uniformity at mixer output is still achieved.
  - Perimeter Ripples reduce Alignment Sensitivity

Straight Mixer Simulation:
RGB Smooth vs Rippled

Smooth
Rippled

3mm to 3mm diameter, 9mm long
Tapered Mixer Simulation:
RGB Smooth vs Rippled

Smooth Mixer vs Rippled Mixer
3mm to 6mm diameter, 18mm long

Tapered Simulation:
Angular Smooth vs Rippled

Smooth vs Rippled
3mm to 6mm diameter, 18mm long
Summary – Mixing Rods

• Mixing rods can provide excellent spatial uniformity, as long as the length is sufficiently long
• “Flip and Fold Concept” explains why many cases ‘work’.
• Round mixing rods usually don’t provide good uniformity, unless ripples are added.

• For more information, see
  – OSA Handbook of Optics and SPIE Short Course