Deterministic microlens diffuser for Lambertian scatter

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Topics

✓ Lambertian diffusers
✓ Engineered diffusers
✓ Single-surface solution
✓ Dual-surface solution
✓ Summary
Lambertian diffusers

- Cosine intensity pattern
- Used for calibration purposes
- Most common example: opal glass
- Opal glass has low transmission efficiency, ~20%
- There is no other known diffuser technology capable of implementing the cosθ scatter, typical of Lambertian diffusers

$I(\theta) \sim \cos \theta$
Engineered Diffusers™

- Refractive, microlens-based diffuser
- Achromatic
- Each scatter center individually designed and fabricated
- Microlens specification and spatial distribution randomized to eliminate repetitive patterns and interference effects in the scatter
- Control of scatter distribution and intensity profiles
- Robust to fabrication errors
Engineered Diffusers™ - Examples

Holographic diffuser

Engineered Diffuser™

Uniform bandlimited scatter

* Laser light, 633nm
Engineered Diffusers™ - Examples I

Square pattern
Engineered Diffusers™ - Examples .II

Circular pattern
Control of Intensity Profiles and energy distribution

Measured 2D Profiles

Square

Aztec pyramid

Annulus

Rectangle

Measured 2D Profiles
Measured opal-glass scatter

Measured efficiency ~20%
Lambertian Scatter with Engineered Diffusers™

Single-surface solution

Dual-surface solution
Single-surface solution

Lens sag: \[ s(r) = \frac{r^2}{R + \sqrt{R^2 - (\kappa + 1)r^2}} \]

Basic design process:
- Select microlenses with R and \( \kappa \) such that scatter is flat with angle \( \theta \)
- Angular spread of each microlens is \( \pm \theta_0 \)
- Probability distribution of \( \theta_0 \) is such that total scatter adds up to desired cosine scatter
Solutions with flat scatter

- For small $\theta_0$ there is always a flat scatter solution with $\kappa \approx -1$

- As $\theta_0$ increases the optimum $\kappa$ is in the range of -0.6 to -1

\[
R = 18.9 \text{mm}, \quad \kappa = -1, \quad D = 100 \mu\text{m}
\]

\[
R = 27.1 \text{mm}, \quad \kappa = -0.83, \quad D = 100 \mu\text{m}
\]
Histogram of slopes for single-surface solution

Single-surface solution requires strong slopes to produce Lambertian scatter

*Ensemble of 200 lenses
Fabrication of Engineered Diffusers™

Resist-coated wafer

Modulated intensity

Beam scans surface

Single-point laserwriting

Finite-size Gaussian beam

Development yields resist master

50 microns

Cross section of photoresist master
Dual-surface solution

• Difficult to produce slope angles needed for the single-surface solution

• Bypass requirement of strong slope angles demanded by single-surface solution with two weaker diffusers

• Utilize two identical diffusers with small air gap

• No need for alignment
Dual-surface solution: Single diffuser scatter

Assume scatter from each diffuser takes the form:

\[
I(\theta) = \begin{cases} 
\cos^p \left( \frac{\pi \theta}{2 \theta_0} \right), & |\theta| \leq \theta_0 \\
0, & \text{otherwise}
\end{cases}
\]

Assume total scatter given by convolution of scatter from individual diffusers:

\[
I(\theta) = \int_{-90}^{90} I_0(\phi) I_0(\theta - \phi) d\phi
\]

Select \(\theta_0\) to maximize efficiency.

Calculated deviation from cosine scatter for \(\theta_0 = 60^\circ\) as a function of power \(p\).
**Optimum single-surface solution**

\[ I(\theta) = \begin{cases} 
\cos^p \left( \frac{\pi \theta}{2 \theta_0} \right), & |\theta| \leq \theta_0 \\
0, & \text{otherwise}
\end{cases} \]

- \( \theta_0 = 60^\circ \) and \( p = 0.6 \)

- Simple convolution model not correct for oblique wide-angle scatter

- Optimum parameters determined experimentally
Lambertian Scatter with Engineered Diffusers™: Dual-surface Solution

Measured efficiency ~70%
Summary

- Engineered Diffusers™ implement arbitrary intensity profiles and energy distribution

- Single-surface Engineered Diffuser™ solution exists but difficult to produce currently

- Proposed dual-surface Engineered Diffuser™ solution – two identical diffusers

- Each diffuser component has a bandlimited cosine-power scatter shape

- Fabricated dual-diffuser solution has efficiency of about 70% (~ 3 times the measured efficiency of opal glass)