LIGHT EXTRACTION FROM LIGHT EMITTING DIODES

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Motivation

LEDs are
- Cheap
- Efficient
- Clean
- Fast
- Tunable
Optical Problem

- Most semiconductor materials are optically dense
- Total internal reflection traps light
Light Extraction Efficiency

Region 2
\( \mu_2, \varepsilon_2 \)

Region 1
\( \mu_1, \varepsilon_1 \)

\( \theta_c \)

\( z = \alpha \)

\[ P_{rad} = \iiint_{\Omega} S(x, y, \alpha) \cdot d\Omega \]

LEE = \( \frac{1}{P_{rad}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(x, y, \alpha) \cdot \hat{z} \, dx \, dy \)
Example: Isotropic Radiator

\[
T(\theta, \phi) = \begin{cases} 
1 & (\theta \leq \theta_c) \\
0 & (\theta \geq \theta_c) 
\end{cases}
\]

\[
G(\theta, \phi) = 1
\]

\[
\text{LEE} = \frac{1 - \cos \theta_c}{2}
\]

Perfect antireflection
Directionality

- Convert to polar coordinates and account for directive gain.
- Integrate transmittance over the top hemisphere.
- Treat LED sources as Hertzian dipoles.

\[
LEE = \frac{1}{4\pi} \int_{0}^{2\pi} \int_{0}^{\pi/2} T(\theta, \phi) G(\theta, \phi) \sin \theta \, d\theta \, d\phi
\]
Perpendicular Hertzian Dipole

\[ G(\theta, \phi) = \frac{3}{2} \sin^2 \theta \]

\[ \text{LEE} = \frac{1}{2} + \frac{1}{16} \left[ \cos(3\theta_c) - 9 \cos(\theta_c) \right] \]
Parallel Hertzian Dipole

\[ G(\theta, \phi) = \frac{3}{2} \left( 1 - \sin^2 \theta \cos^2 \phi \right) \]

\[ \text{LEE} = \frac{1}{2} - \frac{1}{32} \left[ 15 \cos(\theta_c) + \cos(3\theta_c) \right] \]
Multiply LEE by 2 if a mirror is placed at the back contact.

Typical semiconductor indices range between 2.5 and 4.0.

LEE is generally limited to 5% or less!
\[ G(\theta, \phi) = 4 \cos \theta \]

\[ \text{LEE} = \sin^2 \theta_c \]
Lambertian LEE

![Graph showing the relationship between Refractive Index and Critical Angle for different AR and FR conditions. The graph demonstrates how the Lambertian LEE changes with varying refractive indices and critical angles.]
Index-Matched Sphere w/ ARC

Antireflective coating
Surface Roughening