Historical Perspective of Laser Beam Shaping

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OUTLINE

• Note some current applications
• Overview of current practices
• Historical perspective of laser beam shaping using geometrical optics
  ▪ Rotationally symmetric systems
    ➢ 1 mirror, 1 lens, 2 plano-aspheric lenses
  ▪ Non-rotationally symmetric systems
    ➢ 2 mirror with no central obscuration
  ▪ Genetic algorithm optimization methods
    ➢ 3-element spherical surface GRIN system
http://www.pthmagazine.com/newsletters/2_11_02.html

Optics and Fiber Optics

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BEAM-SHAPING TECHNOLOGY FOR OPTICAL PUMP LASERS

Unique-m.o.d.e AG, a German laser company, has introduced a 975-nm fiber-coupled diode laser specifically designed for optically pumping erbium- and ytterbium-pumped solid-state lasers.
Applications
- Semiconductor equipment for:
  • Photolithography
  • Mask control
  • Laser writing
  • Medical applications

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Current Practices of Beam Shaping*

- Process of redistributing the irradiance and phase

- Two functional categories:
  - Field Mapping
  - Beam Integrators

Physical versus Geometrical Optics

\[ \beta = \frac{2\sqrt{2\pi} r_0 Y_0}{f \lambda} \]

\( \lambda \) = wavelength, \( r_0 \) = waist or radius of input beam, 
\( Y_0 \) = half-width of the desired output dimension 
\( f \) = focal length of the focusing optic, or the working distance from the optical system to the target plane

Beam Shaping Guidelines:

- \( \beta < 4 \), Beam shaping will not produce acceptable results
- \( 4 < \beta < 32 \), Diffraction effects are significant
- \( \beta > 32 \), Geometrical optics methods should be adequate
Historical Perspective of Laser Beam Shaping
Using Geometrical Optics

• Geometrical optics intensity law:

\[ \nabla \cdot (I \mathbf{a}) = 0 \]

\[ I_1 \, dA_1 = I_2 \, dA_2 \]

• Constant optical path length condition:

\[ (OPL)_0 = (OPL)_r \]
One Element Beam Shaping Systems

• Conservation of Energy:

\[ I_1 \, dA_1 = I_2 \, dA_2 \]
Two Element Beam Shaping Systems

• Conservation of Energy: \[ R(r) = \pm \sqrt{\frac{2}{I_{\text{out}}}} \int_0^r I_{\text{in}}(u) \, du \]

• Constant OPL:

\[(OPL)_0 = (OPL)_r\]

• Equations of the optical surfaces:

\[ z(r) = \int f(r) \, dr + C \quad Z(r) = z(r) + g(r) \]
Frieden, Appl. Opt. 4.11, 1400-1403, 1965:
“Lossless conversion of a plane wave to a plane wave of uniform irradiance.”

Conservation of Energy:

\[ R(r) = \pm R_{\text{max}} \left[ \frac{1 - \exp\left(-r^2/2\alpha^2\right)}{1 - \exp\left(-r_{\text{max}}^2/2\alpha^2\right)} \right]^{1/2} \]

\[ z(r) = \int f(r) \, dr + C \]

- Intensity shaping leads to OPL variation of 20\(\lambda\)
- Need to shape of output wavefront when phase is important
- Frieden requires rays to be parallel Z-axis
- Leads to OPL variation of \(\lambda/20\)
• Kreuzer, US patent 3,476,463, 1969:

“Coherent light optical system yielding an output beam of desired intensity distribution at a desired equi-phase surface.”

**Conservation of Energy & Ray Trace Equations:**

\[ r + \mathcal{R}(s, S) \sin \theta - R_{\text{max}} \left[ \frac{1 - e^{-2(r/r_0)^2}}{1 - e^{-2(r_{\text{max}}/r_0)^2}} \right]^{1/2} = 0 \]

**Constant OPL:**

\[ d(n - 1) + \mathcal{R}(1 - n \cos \theta) = 0 \]

**Mirror Surface Equations:**

\[
Z(r) = \int_{0}^{r} \frac{dr}{\sqrt{(n^2 - 1) + \left(\frac{(n-1)d}{R-r}\right)^2}}
\]

\[
Z(R) = \int_{0}^{R} \frac{dR}{\sqrt{(n^2 - 1) + \left(\frac{(n-1)d}{R-r}\right)^2}}
\]
Energy Balance:

\[ R = \sqrt{\frac{r_0^2}{2I_{out}}} \left[ 1 - \exp\left(-2r^2/r_0^2\right) \right] \]

\[ I_{out} = \frac{r_0^2}{2R_{max}^2} \left[ 1 - \exp\left(-2r_{max}^2/r_0^2\right) \right] \]

Ray Trace Equation:

\[ z' = \frac{-(R-r)(Z-z) \pm (n/n_0)(R-r)\sqrt{(Z-z)^2 + (R-r)^2}}{(1-(n/n_0)^2)(Z-z)^2 - (n/n_0)^2(R-r)^2} \]

\[ z(r) = \int f(r)dr + C \]

Constant OPL:

\[ (Z-z) = \frac{n(n-n_0)d + \left[n_0^2(n-1)^2d^2 + (n^2-n_0^2)(R-r)^2\right]^{1/2}}{n^2-n_0^2} \]

\[ Z(r) = z(r) + g(r) \]
Non-Rotationally Symmetric System


- Differential Power
  \[ I_{in}(x, y)dx\,dy = I_{out}(X, Y)dX\,dY \]
- Conservation of Energy: Ein=Eout
- Magnifications of ray coordinates
  \[ m_x(x) = \frac{1}{x} \left[ C_1 \int_0^x \frac{a_x(u)\,du}{A_x(um_x(u))} + C_2 \right] \]
- OPL condition
- Determine sag z(r) of first surface
- Determine inverse magnification
- Determine sag Z(R) of second surface
Two Mirror Beam Shaping System
Shealy & Chao, Proc SPIE 4443-03, 2001

Input beam has 1-to-3 beam waist in x-to-y directions:

\[ I_{in}(x, y) = \exp \left[ -2 \left( \frac{x}{x_0} \right)^2 \right] \exp \left[ -2 \left( \frac{y}{y_0} \right)^2 \right] \]

\[ I_{out} = A_{X_0} A_{Y_0} = \text{const} \]
Genetic Algorithm Optimization Method


- Can a spherical-surface GRIN beam shaping system be designed using catalog GRIN materials?
- Problem is well suited for Genetic Algorithms:
  - discrete parameters
    - Number of lens elements
    - GRIN catalog number
  - Continuous parameters: radii, thickness
Beam Shaping Merit Function
Used in GA Optimization

\[ M = \frac{M_{\text{Diameter}}M_{\text{Collimation}}}{M_{\text{Uniformity}}} = \frac{\exp\left[-s\left(R_{\text{Target}} - R_N\right)^2\right]\exp\left[-\left(1 - \prod_{i=1}^{N}\cos^Q(\gamma_i)\right)^2\right]}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[I_{\text{out}}(R_i) - \frac{1}{N}\sum_{k=1}^{N}I_{\text{out}}(R_k)\right]}}\]

\[ R_{\text{target}} = \text{Output Beam Radius} \]
\[ R_N = \text{Marginal Ray Height on Output Plane} \]
\[ \gamma_i = \text{Angle i}^{\text{th}} \text{ Ray Make with the Optical Axis} \]
\[ Q \text{ and } s = \text{Convergence Constants} \]
Determining when a Solution is Found

\[ M_{\text{best}} \]

\[ \text{Generation} \]

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3-Element GRIN Shaping System
Summary and Conclusions

- Geometrical methods for design of laser beam shaping systems uses:
  - Conservation of energy within a bundle of rays,
  - Constant optical path length condition.

- Numerical and analytical techniques have been used to design a 1 and 2-element beam shaping systems.

- Laser beam shaping merit function used with genetic algorithms to design a 3-element GRIN system with spherical surface lenses.