Laser beam shaping in industrial applications

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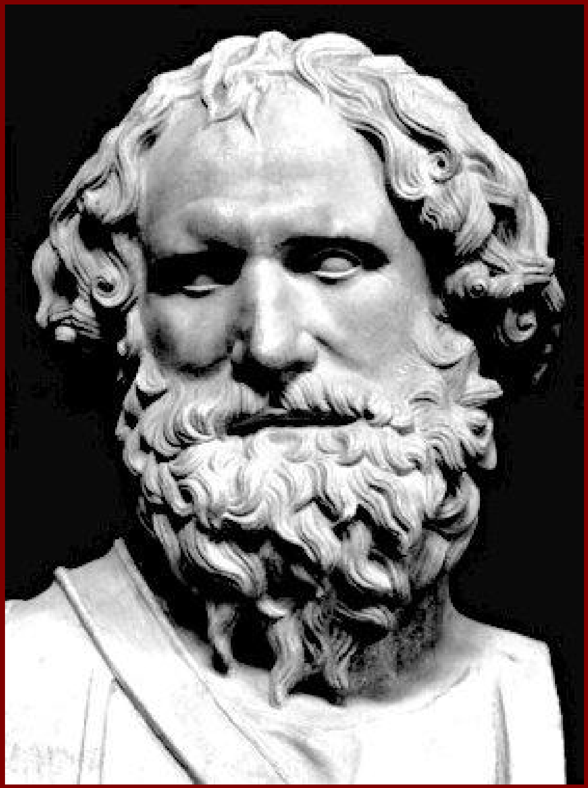
Outline

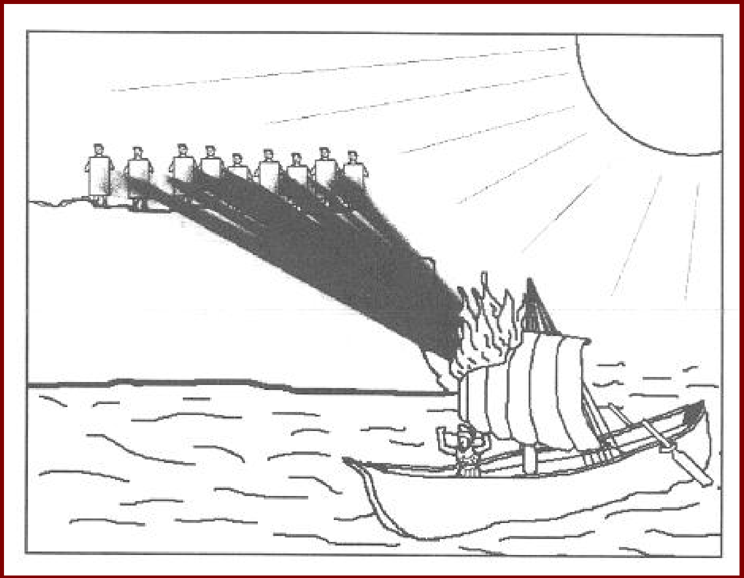
- Really brief beam shaping background
- Lasers and what they’re used for
- Theory of refractive laser beam shaping
- Demonstration
- Samples of real-life beam-shaping technology

Archimedes of Syracuse (287-212 BC)



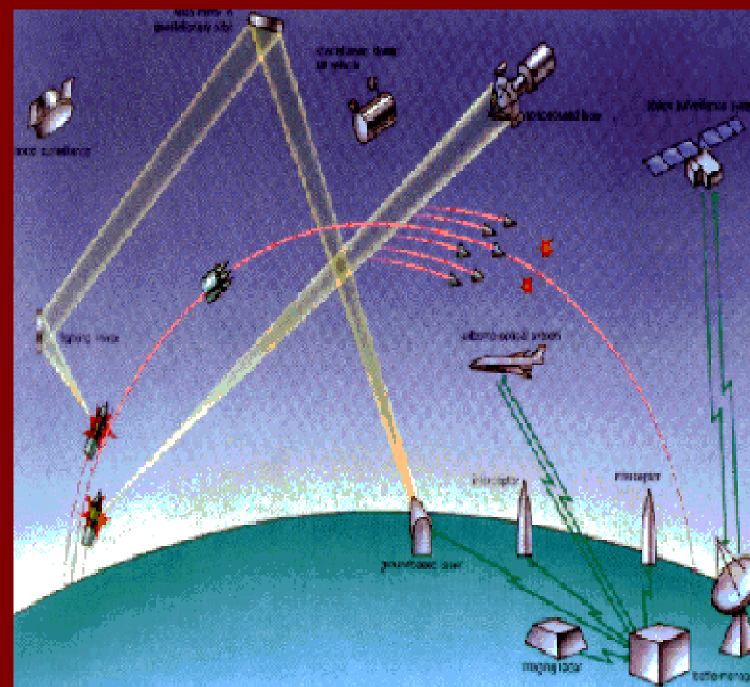
Siege of Syracuse 213 BC

- Not the most productive use of his genius (note the date)



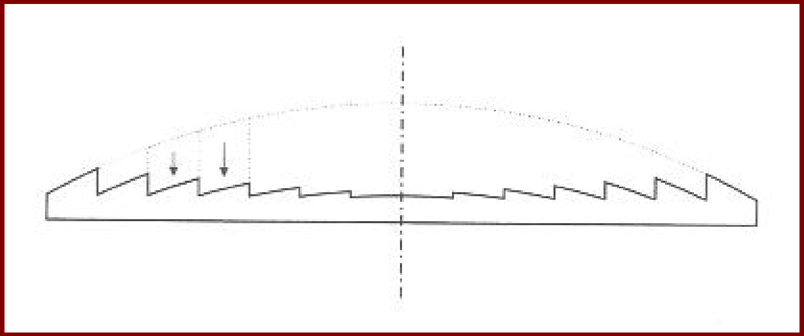
Reagan of Illinois (1911-? AD)

My beam is bigger than yours



Fresnel lenses

- Lighthouses, automotive headlights



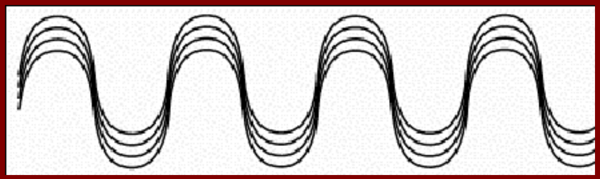
- Not much different except saves weight

Optics so far in this course:

- Two related concepts:
  - Ray direction due to refraction
  - Optical path length
- So far have been discussed separately.

Lasers

- Conventional light-sources: divergence and incoherence reduce effective intensity.
- Lasers: light is directional, monochromatic and coherent in phase.



Applications of lasers

- Microphotolithography
- Materials processing
- Laser writing
- Medicine

Our fundamental concern

- Typical laser source has non-uniform intensity distribution – a concern for industrial applications.
- Consequences?

What is laser beam shaping

- Redistribution of irradiance through an optical system.
- What's so difficult about it? Preservation of wave-front uniformity and loss-less shaping.

The case that we will deal with

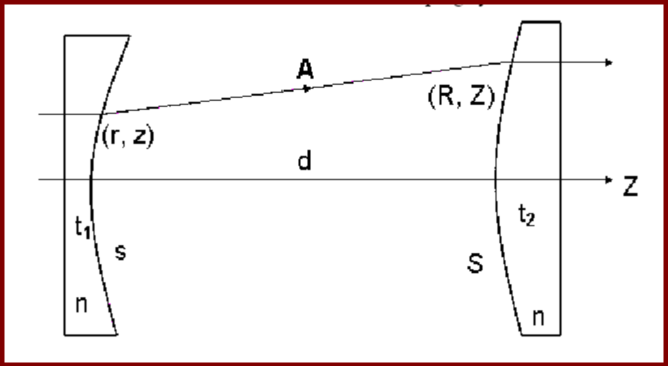
- Go from a Gaussian energy distribution to flat-top.

Different approaches possible

- Simple aperture masking (lossy)
- Diffractive optics (Fourier transforms) (way difficult, dude)
- Loss-less geometric (refractive) optics

Loss-less refractive shaping

- Two goals:
  - uniform energy balance across output
  - uniform optical distance through system



Energy Balance condition 1/2

- Energy (intensity) is conserved in a bundle of rays:

$$I_{in}\, dw = I_{out}\, dW$$

- Thus conserved also over the cross section of a beam:

$$\int_0^{2\pi} d\theta \int_0^{r} I_{in}(r)\, r\, dr = \int_0^{2\pi} d\theta \int_0^{R} I_{out}(R)\, R\, dR$$

Energy Balance condition 2/2

- Typical Gaussian intensity function:

$$I_{in}(r) = \exp[-2(r/r_0)^2]$$

- The solution of the previous integral yields *R* as a function of *r:*

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

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

(explain r_0)

Optical path length condition 1/2

• Optical path length along axis of system:

$(OPL)_0 = nt_1 + d + nt_2$

• Optical path length distance r from axis:

$(OPL)_r = nz + [(R - r)^2 + (Z - z)^2]^{½} + n(t_1 + d + t_2 - Z)$

(in our case t_1 & t_2 will be zero)

• and since wave-front uniformity must be preserved:

$(OPL)_0 = (OPL)_r$

Optical path length condition 2/2

- Combining previous equations yields:

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

- We can rewrite this, solving for ($Z - z$) as dependent on r

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

- Note that by Energy Balance condition we already have R dependent on r

Ray tracing 1/2

Rays are refracted at surfaces according to Snell's law.

Ray trace equation of from (r,z) to (R,Z) is:

$$(\mathrm{R\text{-}r})(\mathbf{A})_z = (Z - z)(\mathbf{A})_r$$

Where A is ray vector:

$$\mathbf{A} = \frac{z'\left[n - \sqrt{1 + z'^2\left(1 - n^2\right)}\right]}{1 + z'^2}\mathbf{r}$$

$$+ \frac{\left[nz'^2 + \sqrt{1 + z'^2\left(1 - n^2\right)}\right]}{1 + z'^2}\mathbf{k}$$

Ray tracing 2/2

Previous equations can be combined to solve for *z'* as a quadratic dependent on *r*:

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

Note: *R* and (*Z* – *z*) have also been expressed in terms of *r*.

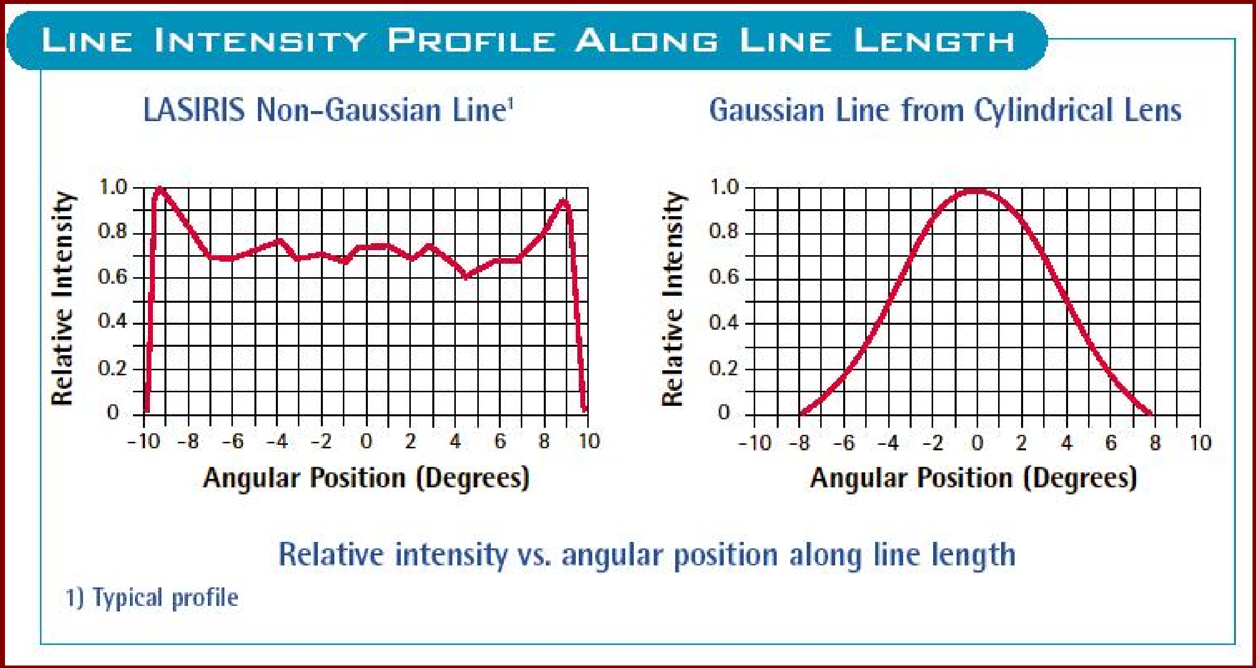
We’re left with nasty calculus

- Analytical integration of *z’*(*r*) is difficult
- We’ll do something simpler – just approximate using Riemann sums (and the opposite to derive *Z* into *Z’*).
- Demo (raytrace and OPL)

Analysis of the optical system

- Least squares fit of (*r*,*z*) and (*R*,*Z*) to a simple function.
- Used so that we can have a typical spherical or conical lens (low cost of manufacture).

Realistic output patterns



(data sheet for Vision Tech SNF Series Lasers, www.vlt.nl)

Acknowledgements

- Theory largely sourced from Chapter 4 of *Laser Beam Shaping: theory and techniques.* (Dickey & Holswade 2000). ISBN-082470398-7