Advanced Optics (PHYS690)

HEEDEUK SHIN

POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY, KOREA

Syllabus

- Goal: This course covers the various topics in the modern optics.
- Topics: Gaussian beam optics, LASER, polarization, electro-optics, nonlinear optics, Fourier optics, Guided wave optics, and other applications
- Lecturer
  - Prof. Heedeuk Shin (heedeukshin@postech.ac.kr)
  - Bldg 3, room 421
- Grading
  - Homework 30%
  - Mid term 30%
  - Final 40%
- Textbook:
  - "Fundamentals of Photonics" by Saleh & Teich (Wiley, 2007)
  - "Nonlinear Optics" by Robert W. Boyd (Academic press, 2008)
  - "Introduction to Fourier Optics" by Goodman (McGraw-Hill, 1996)

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Tuesday & Thursday

Officially 09:30 ~ 10:45,

How about 09:30 ~ 11:00?

Then no need to have make-up class

No class at 2/21 (광학회), 4/25(물리학회)

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Syllabus

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- Schedule:

1. Gaussian optics (2/21 No class)
2. Gaussian optics/LASER
3. LASER
4. Polarization optics
5. Guided-wave optics
6. Interference
7. Electro-optical effects and acousto-optical effects
8. Mid-term exam
9. Fourier optics
10. Fourier optics (4/25 No class)
11. Nonlinear Optics 2
12. Nonlinear Optics 3
13. Nonlinear Optics 4
14. Nonlinear Optics 5
15. Nonlinear Optics 6
16. Final exam

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Today

Introduction to optics

Gaussian beam

Through a lens

ABCD Law

Knife edge technique

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Introduction

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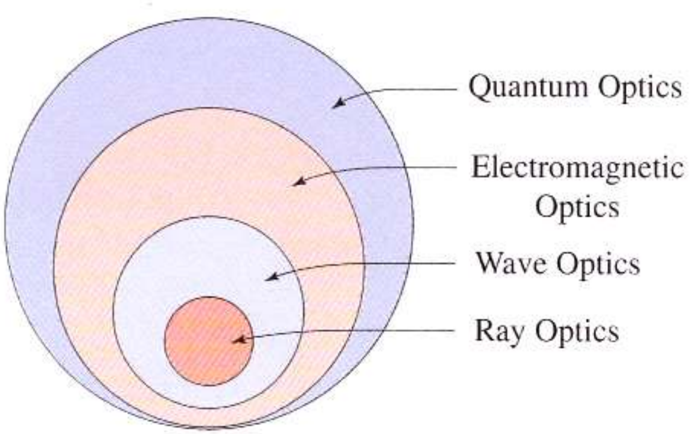
Optics

- **Optics** is the study field of the behavior and properties of light.

- Most optical phenomena can be understood by using the classical electromagnetics.

Archimedes' mirror used to burn Roman ships



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Optics vs Photonics ?

Optics

versus

Photonics

- **Optics:** the study field of the behavior and properties of light.
- **Photonics:** the science of light (photon) generation, detection, and manipulation through emission, transmission, modulation, signal processing, switching, amplification, and detection/sensing.
- Photonics is closely related to Optics.
- Photonics is used to connote applied research and development.

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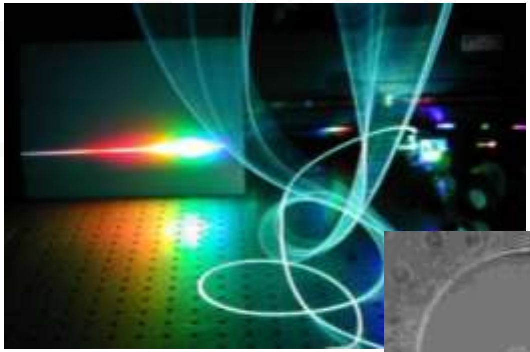
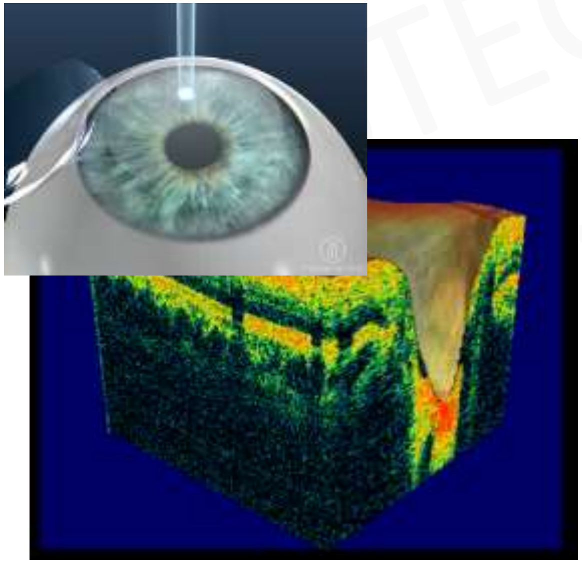
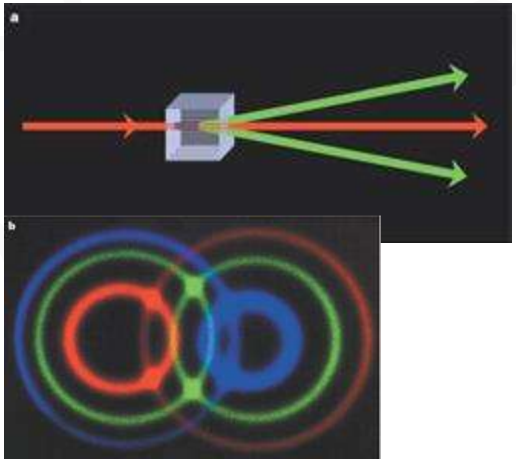
Photonics

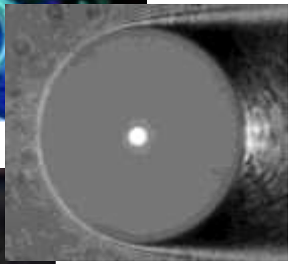
The term *photonics* more specifically connotes:

- The particle properties of light,
- The potential of creating signal processing device technologies using photons,
- The practical application of optics, and
- An analogy to electronics.









Gaussian Beam optics

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Gaussian beam

- A **Gaussian beam** is a beam of monochromatic electromagnetic radiation.
- Its transverse magnetic and electric field amplitude profiles are given by the Gaussian function
- The fundamental (or TEM_{00}) transverse Gaussian mode describes the intended output of most (but not all) lasers, as such a beam can be focused into the most concentrated spot.
- The mathematical expression for the electric field amplitude is a solution to the paraxial Helmholtz equation.

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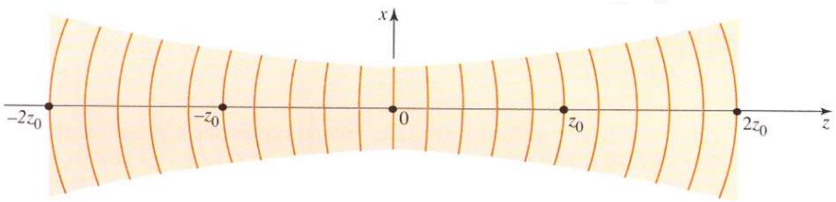
Gaussian beam

- complex amplitude $U(\boldsymbol{r})$ of the Gaussian beam:

$$U(\boldsymbol{r}) = A_0 \frac{W_0}{W(z)} \exp\left[-\frac{\rho^2}{W^2(z)}\right] \exp[-jkz + j\zeta(z)\,] \exp\left[-jk\frac{\rho^2}{2R(z)}\right],$$

- $W(z) = W_0\sqrt{1+\left(\frac{z}{z_0}\right)^2}$: beam width
- $R(z) = z\left[1+\left(\frac{z_0}{z}\right)^2\right]$: radius of curvature
- $\zeta(z) = \tan^{-1}\frac{z}{z_0}$: phase retardation
- $W_0 = \sqrt{\frac{\lambda z_0}{\pi}}$: waist radius
- $z_0 = \frac{\pi n {W_0}^2}{\lambda_0}$: Rayleigh length



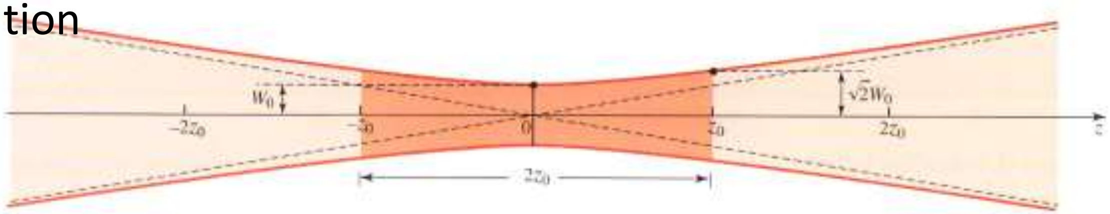


Figure 3.1-4 Depth of focus of a Gaussian beam.

$$I(\rho, \mathrm{z}) = |U(\boldsymbol{r})|^2 = I_0\left[\frac{W_0}{W(z)}\right]^2 \exp\left[-\frac{2\rho^2}{W^2(z)}\right],$$

Through a thin lens

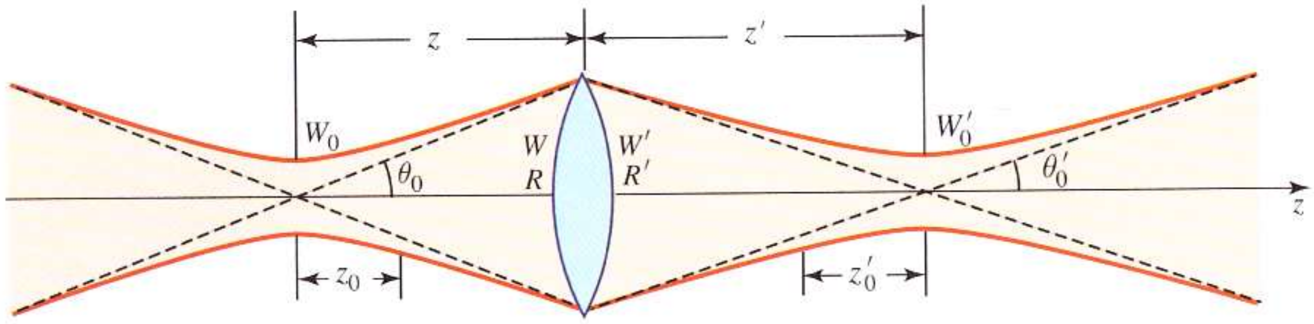


Figure 3.2-1 Transmission of a Gaussian beam through a thin lens.

- Waist radius $W_0' = MW_0$
- Waist location $(z' - f) = M^2(z - f)$
- Depth of focus $2z_0' = M^2(2z_0)$
- Divergence angle $2\theta_0' = \frac{2\theta_0}{M}$
- Magnification $M = \frac{M_r}{\sqrt{1+r^2}}$,

where $r = \frac{z_0}{z-f}$ and $M_r = \left|\frac{f}{z-f}\right|$: parameter transformation by a lens

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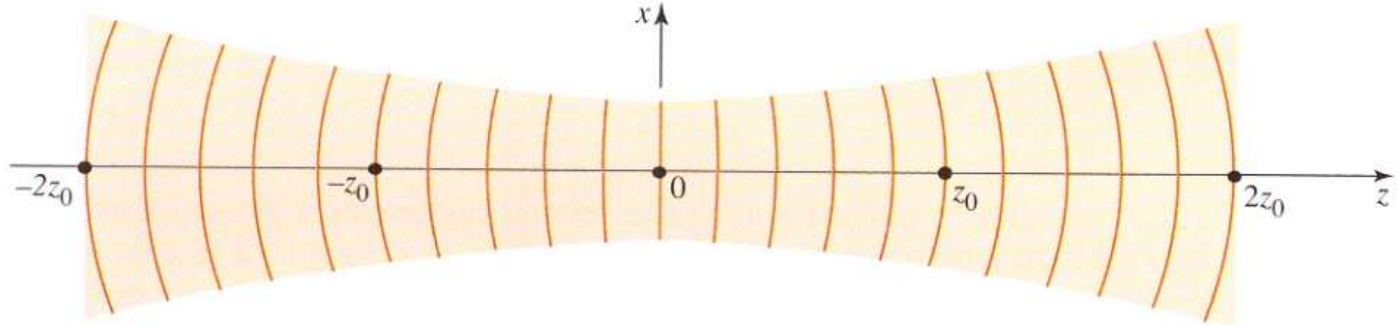
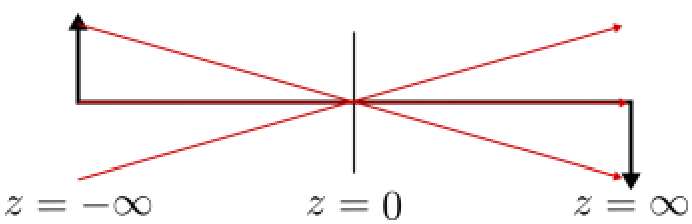
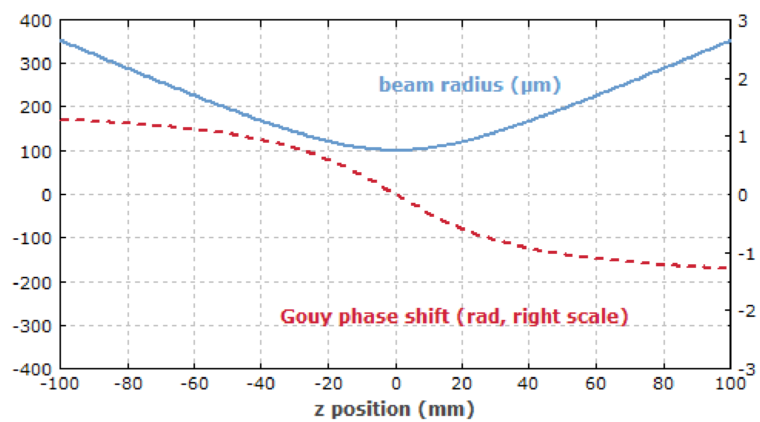


$$U(\boldsymbol{r}) = A_0 A_0 \frac{W_0}{W(z)} \exp\left[-\frac{\rho^2}{W^2(z)}\right] \exp[-jkz + j\zeta(z)\,] \exp\left[-jk\frac{\rho^2}{2R(z)}\right]$$

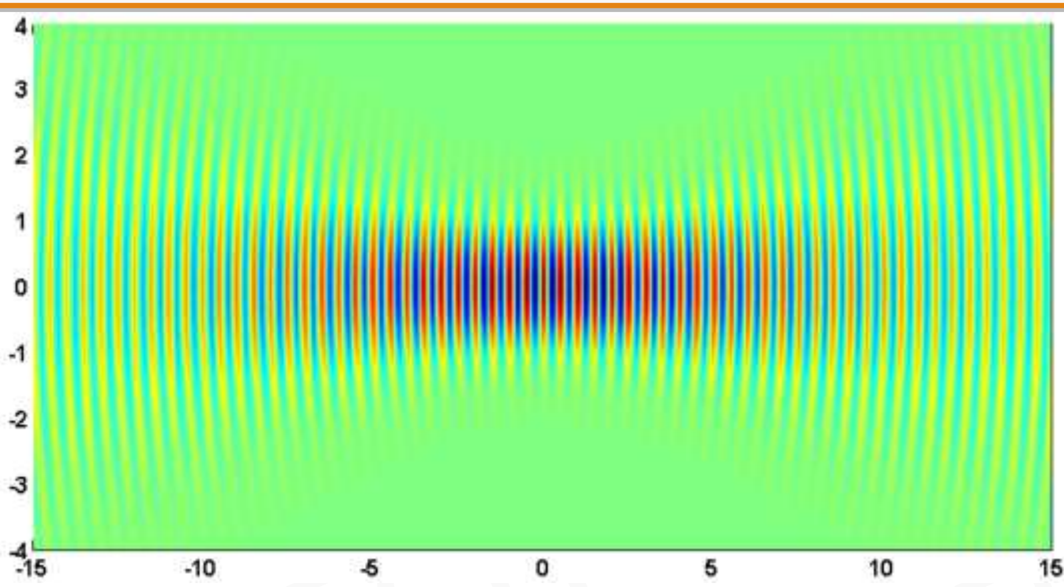
$$\exp\left[-jkz - jk\frac{\rho^2}{2R(z)} + j\zeta(z)\,\right]$$

Plane wave Wavefront bending Gouy phase



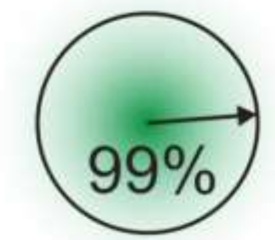


a axial phase shift when passing through its focus.



Beam power $P = \int_0^\infty I(r,z) 2\pi r \, dr$

$P = \frac{1}{2} I_0 \pi w_0^2$ [Watt]



r=1.5ω(z)

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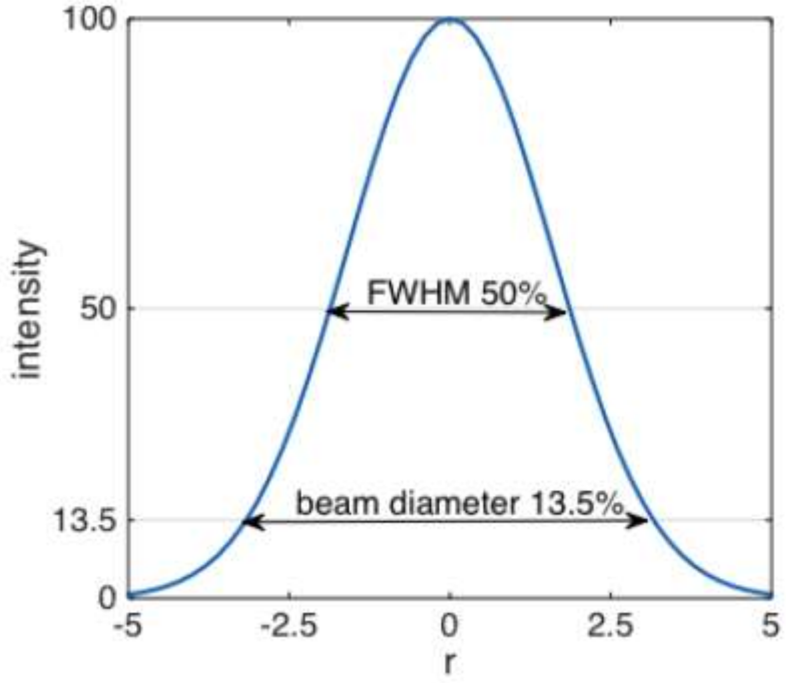


Intensity drops by factor e^{-2}

$$^{1}/_{e^{2}} \sim 0.135 = 13.5\%$$

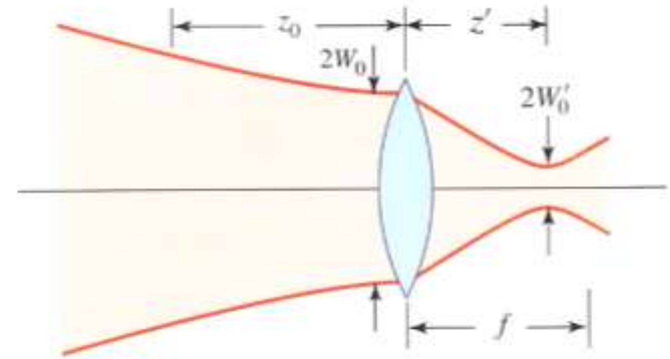
$$I(r,z) = I_0 \left[\frac{w_0}{w(z)}\right]^2 e^{-\frac{2r^2}{w(z)^2}}$$

Beam Focusing

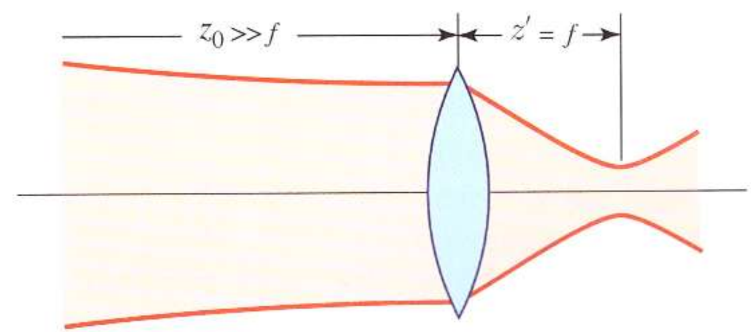
- Focusing a Gaussian beam with a lens at the beam waist

$$W_0' = \frac{W_0}{\sqrt{1+(z_0\,/f)^2}}$$

$$z' = \frac{f}{1+(f/z_0\,)^2}$$



- When $z_0 \gg f$, using $2z_0 = \frac{2\pi {W_0}^2}{\lambda}$



$$W_0' \approx \frac{f}{z_0} W_0 = \frac{\lambda}{\pi W_0} f = \theta_0\ f$$

$$z' \approx f$$

$$D = 2W_0$$

$${W_0}' \approx \frac{4}{\pi}\lambda F_\#$$, where $F_\# = \frac{f}{D}$: F-number of the lens

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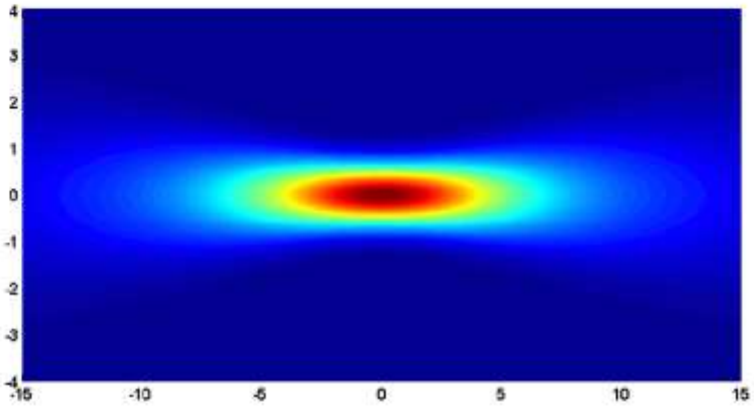
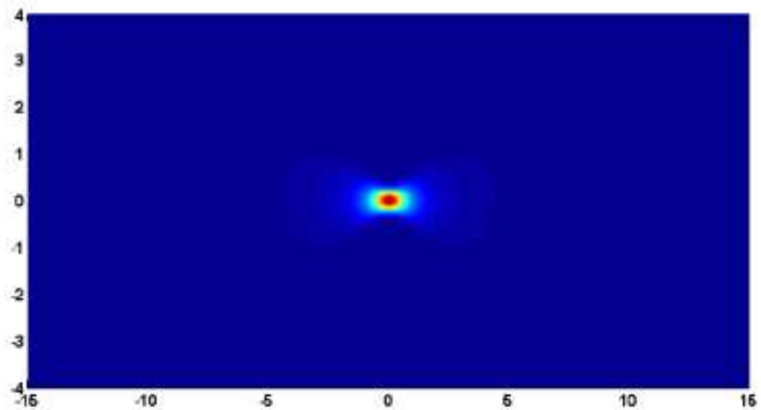

4
3
2
1
0
-1
-2
-3
-4
-15
-10
-5
0
5
10
15


4
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10
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ABCD law

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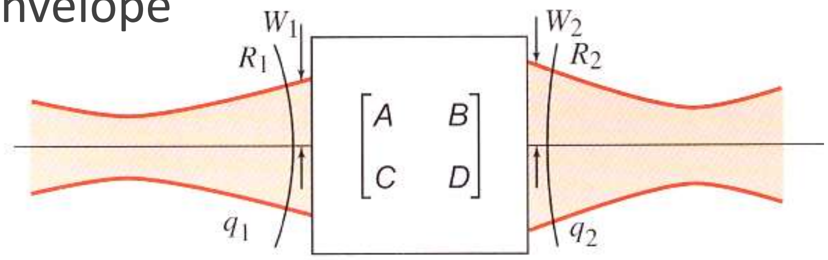
- amplitude and phase of the complex envelope

$$\frac{1}{q(z)} = \frac{1}{R(z)} - j\frac{\lambda}{\pi W^2(z)}$$



- **q- parameter**

- The Gaussian beam propagation can be described with matrix optics.

$$q_2(z) = \frac{Aq_1+B}{Cq_1+D}$$

$$R(z) = z\left[1 + \left(\frac{z_0}{z}\right)^2\right]$$

- Free space propagation ABCD

$$\begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \quad => \quad q_2 = q_1 + d \qquad (\because q = z + jz_0)$$

- Thin lens ABCD

$$\begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

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ABCD law

- Example of ABCD law

q_1

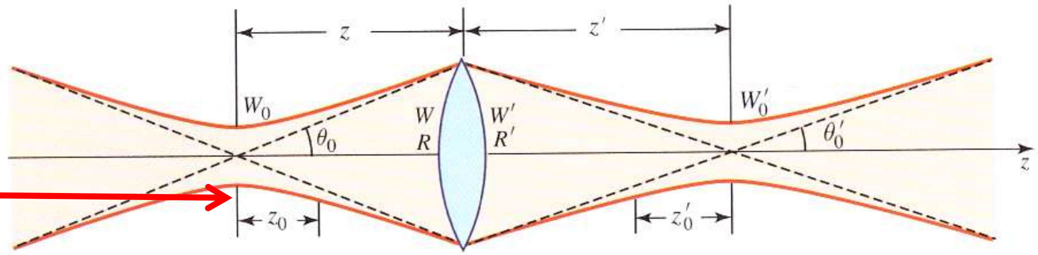

Figure 3.2-1 Transmission of a Gaussian beam through a thin lens.

- Where is the waist and how big is it?

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & z_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & z_1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 - \frac{z_2}{f} & z_1 + z_2 - \frac{z_1 z_2}{f} \\ \frac{-1}{f} & 1 \end{bmatrix}$$

$$q_2(z) = \frac{Aq_1 + B}{Cq_1 + D} = \left[\frac{1}{R_2(z_2)} - j \frac{\lambda}{\pi W_2^2(z_2)} \right]^{-1}$$

$$\frac{1}{W_2^2(z_2)} = \frac{1}{W_1^2(z_1)} \left(1 - \frac{z_1}{f}\right)^2 + \left(\frac{\pi W_1^2(z_1)}{f\lambda}\right)^2$$

$$z_2 = f + \frac{(z_1 - f) f^2}{(z_1 - f)^2 + \left(\frac{\pi W_1^2(z_1)}{\lambda}\right)^2}$$

Minimum spot size does not occur in the lens focal plane.

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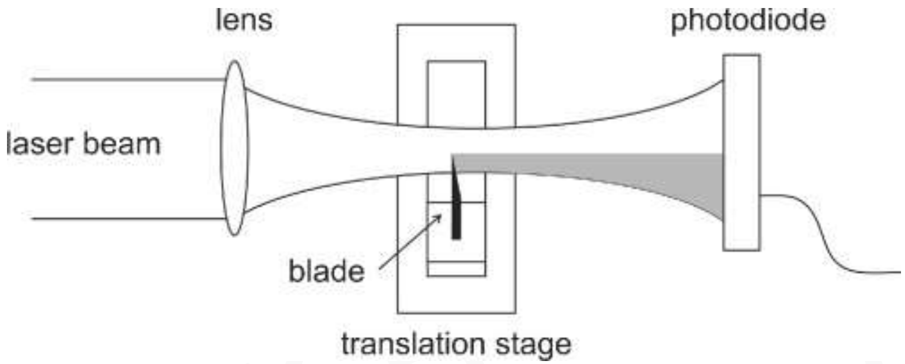
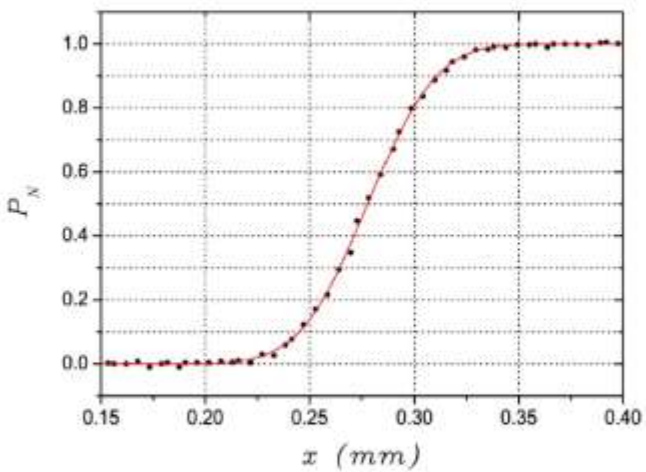
Knife edge technique

- Measures of Gaussian beam waist at position *z*



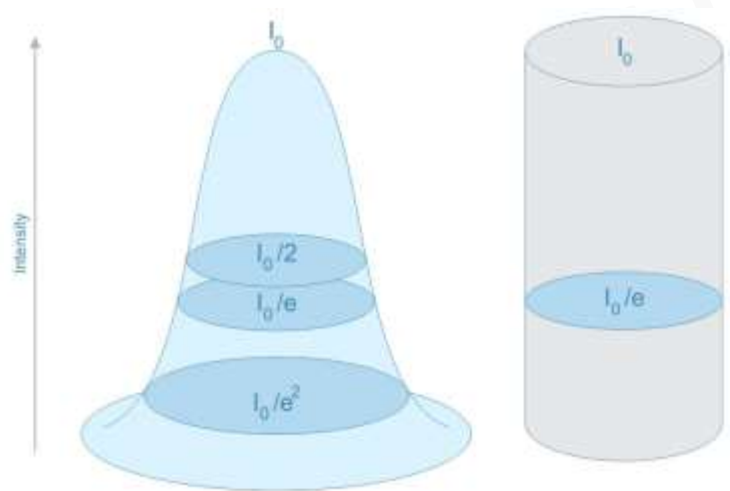
Applied Optics 48, 393 (2009)



$$X_{90\%-10\%} = 1.28W$$

Examples

- Verdi series laser



Gaussian shape beam profile

Flat-top beam profile

Verdi	G10
Wavelength (nm)	532 ±2
Pulse Format	CW
Spectral Purity (%)	>99
Output Power (W)	10[2]
Spatial Mode	TEM_{00}
Beam Quality	<1.1
Beam Circularity[3]	1.0 ±0.1
Beam Waist Diameter (mm)(FW, $1/e^2$)	2.25 ±10%
Beam Divergence (mrad)(FW, $1/e^2$)	<0.5
Beam Waist Location[4] (m)	±0.5
Beam Pointing Stability[5] (μrad/°C)	<2
Horizontal Beam Position Tolerance[6] (mm)	±<1.0
Vertical Beam Position Tolerance[6] (mm)	±<1.0
Polarization Ratio	Linear, >100:1
Polarization Direction	Vertical, ±5°
Noise (%, rms)(10 Hz to 100 MHz)	<0.02
Power Stability[7] (%)(pk-pk)	±<1
Warm-Up Time (minutes)	<10
CDRH Compliant	Yes

Examples

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- Verdi series laser
- Power: 10 W
- Area: $\pi(\frac{D}{2})^2 = \pi(\frac{2.25\ [mm]}{2})^2$
- fs laser

COHERENT.

Verdi G-Series Family

ductor Lasers (OPSL)

System Specifications	
Average Power (W)	10 W
Wavelength (nm)	1040
Pulse Repetition Rate (MHz)	80
Pulse Duration[1] (fs)	140
Noise[2] (%)	<0.25
Power Stability[3] (%)	±0.5
M^2	<1.2
Beam Diameter (mm)	1.2 (±0.2)
Ellipticity	0.8 to 1.2
Astigmatism (%)	<10
Polarization	100:1 Horizontal

Fidelity HP
High Power Femtosecond Fiber Laser

Laser beam quality factor

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- M^2 is the formalism for a laser beam quality factor.
- M^2 indicates how close it is to being a fundamental-mode Gaussian beam.
- The focused spot diameter of a Gaussian beam is defined by

$$d_{00} = \frac{4\lambda f}{\pi D_{00}}$$

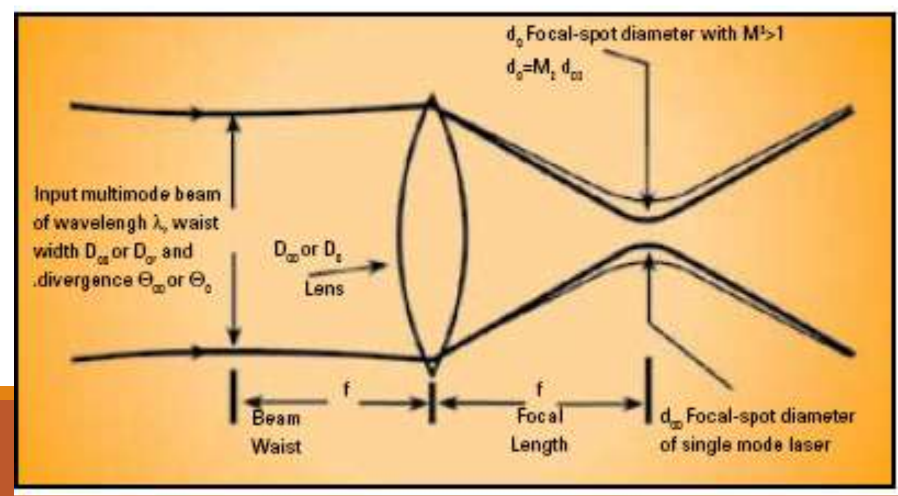
where d_{00}: the ideal focused spot diameter

f: the focal length of the focusing lens

D_{00}: the input beam waist

- When a multimode beam is focused,

$$d_0 = M^2 \frac{4\lambda f}{\pi D_0}$$



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Other solutions of Helmholtz eq.

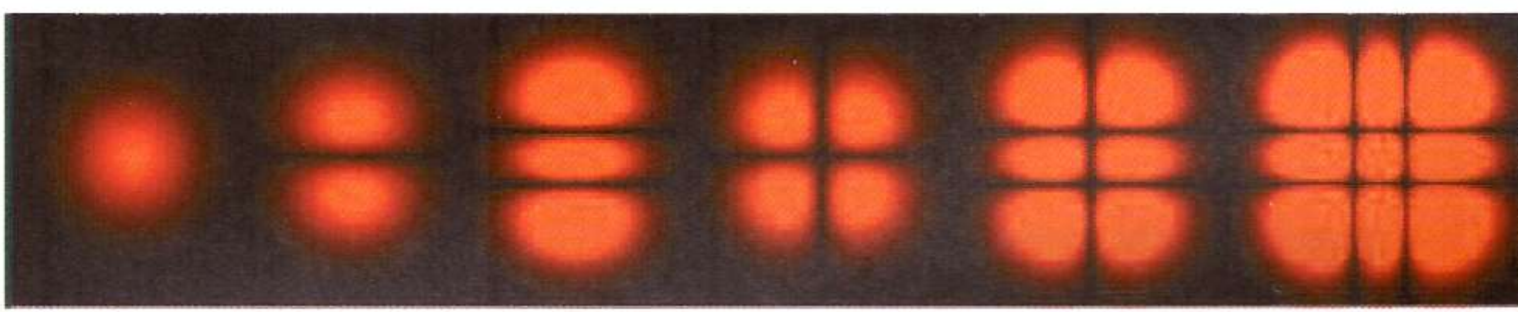
- Another solution of the paraxial Helmholtz equation:
- Hermite-Gaussian beam

$$U_{l,m}(x,y,z) = A_{l,m}\left[\frac{W_0}{W(z)}\right] G_l\left[\frac{\sqrt{2}x}{W(z)}\right] G_m\left[\frac{\sqrt{2}y}{W(z)}\right]$$

$$\times \exp\left[-jkz - jk\frac{x^2+y^2}{2R(z)} + j(l+m+1)\zeta(z)\right]$$

where $G_l(u) = H_l(u)\exp(\frac{-u^2}{2})$, $l = 0,1,2,\ldots$

Hermite-Gaussian function of order l, and $A_{l,m}$ is a constant.



(0, 0) (0, 1) (0, 2) (1, 1) (1, 2) (2, 2)

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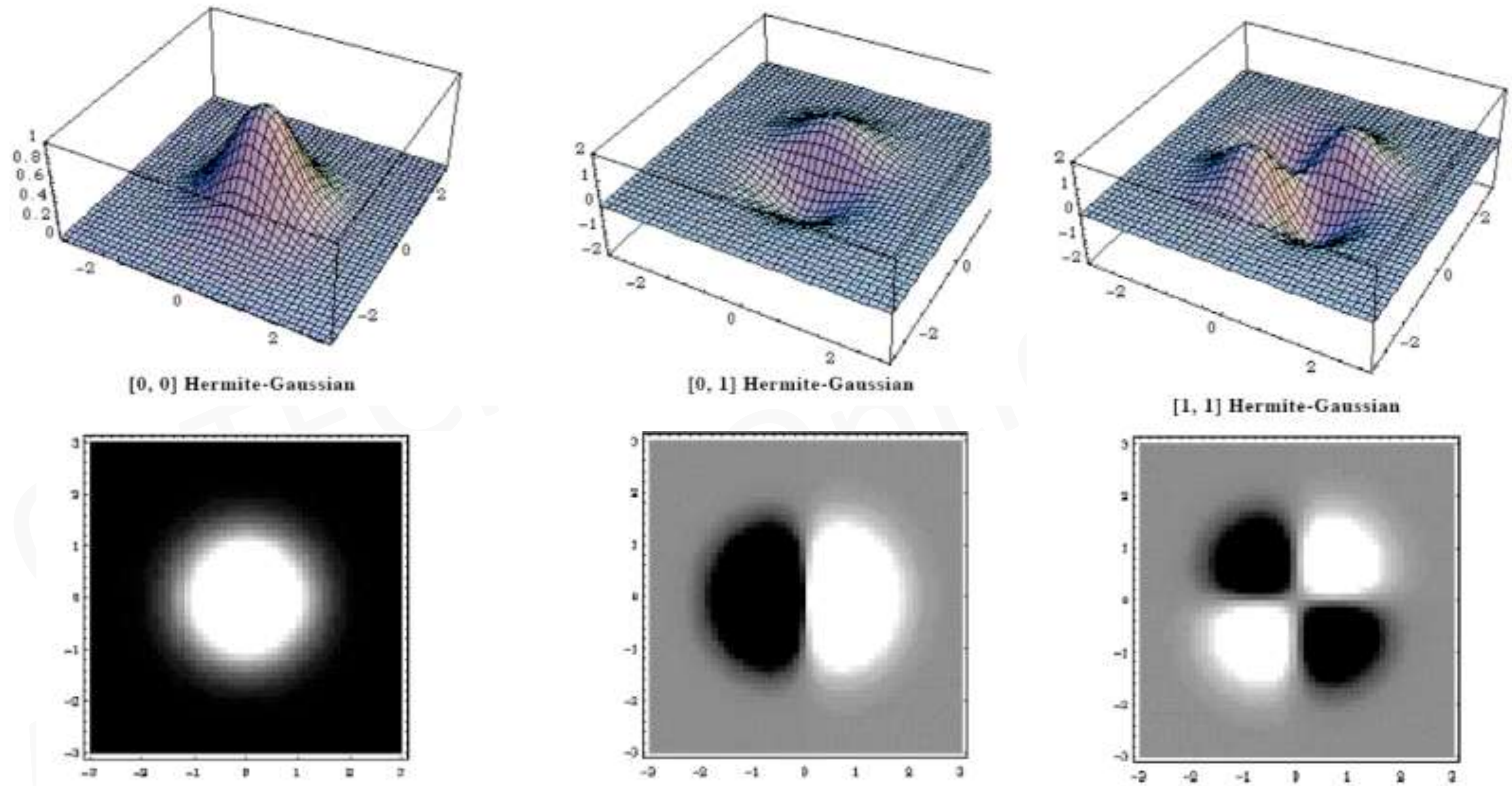
Hermit-Gaussian

Complex amplitude (arb. units)



Other solutions of Helmholtz eq.

- Laguerre-Gaussian beam

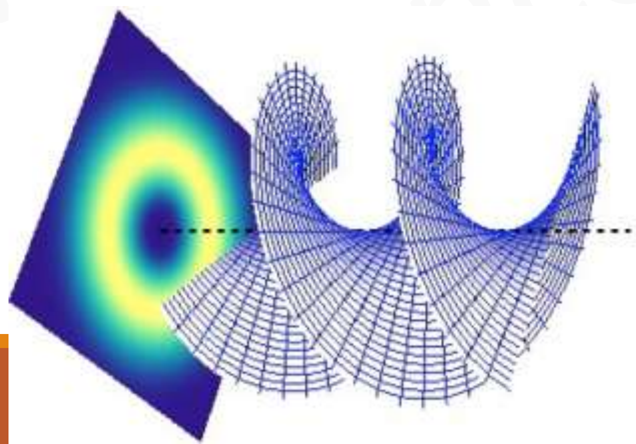
$$U_{l,m}(\rho,\phi,z) =$$

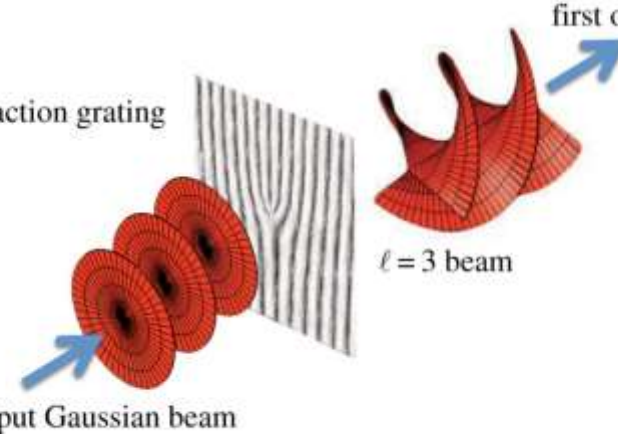
$$A_{l,m}\left[\frac{W_0}{W(z)}\right]\left(\frac{\rho}{W(z)}\right)^{l} \mathrm{L}_m^l\left(\frac{2\rho^2}{W^2\,(z)}\right)\exp\left(-\frac{\rho^2}{W^2\,(z)}\right)$$

$$\times \exp\left[-jkz - jk\frac{\rho^2}{2R(z)} - jl\phi + j(l+2m+1)\zeta(z)\right]$$

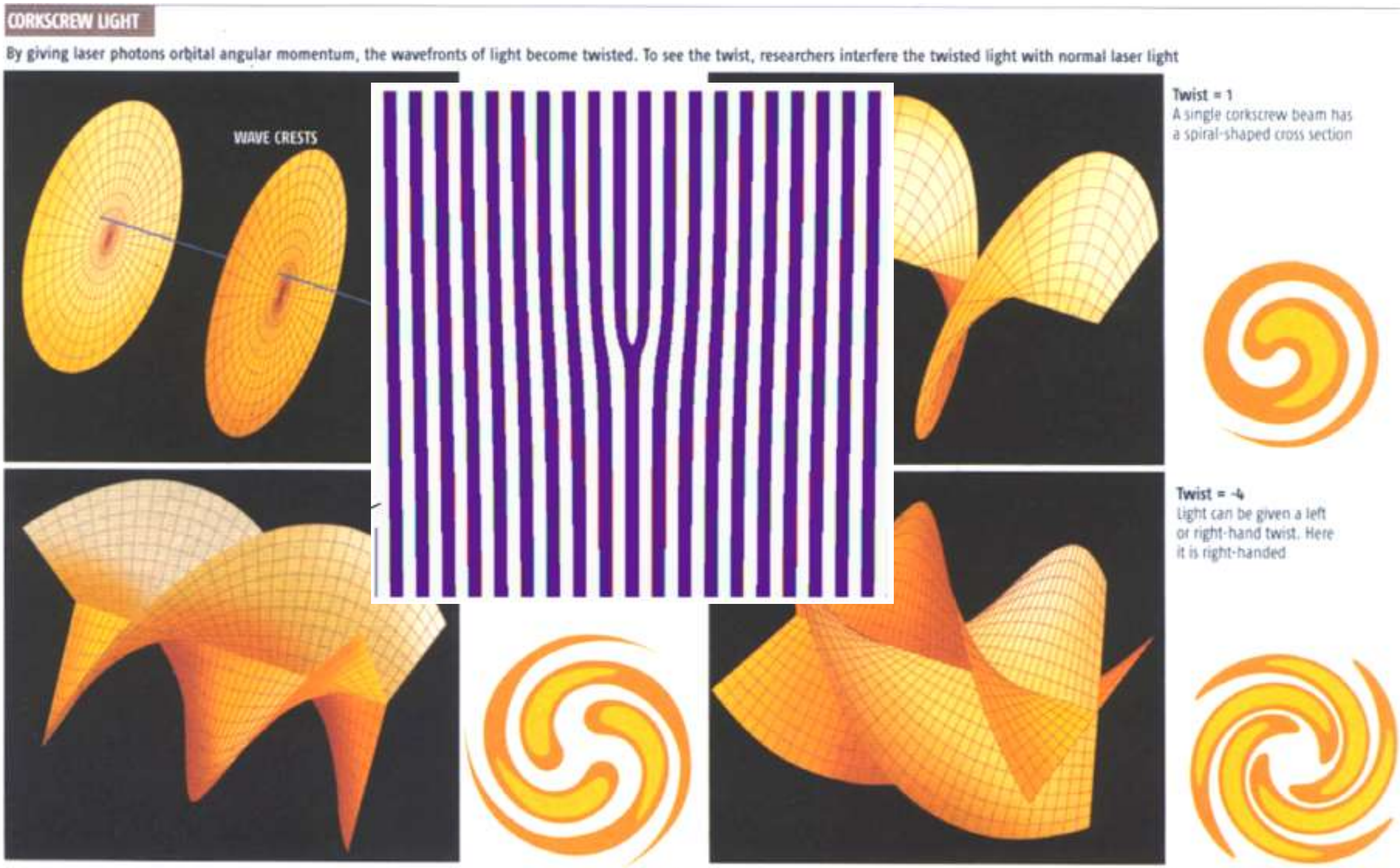
where $\mathrm{L}_m^l(u)$: the generalized Laguerre polynomial function

Orbital angular momentum (OAM)





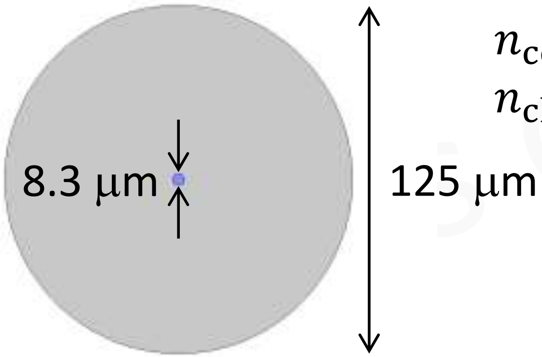
Beams with angular momentum



http://www.physics.gla.ac.uk/Optics/projects/AM/

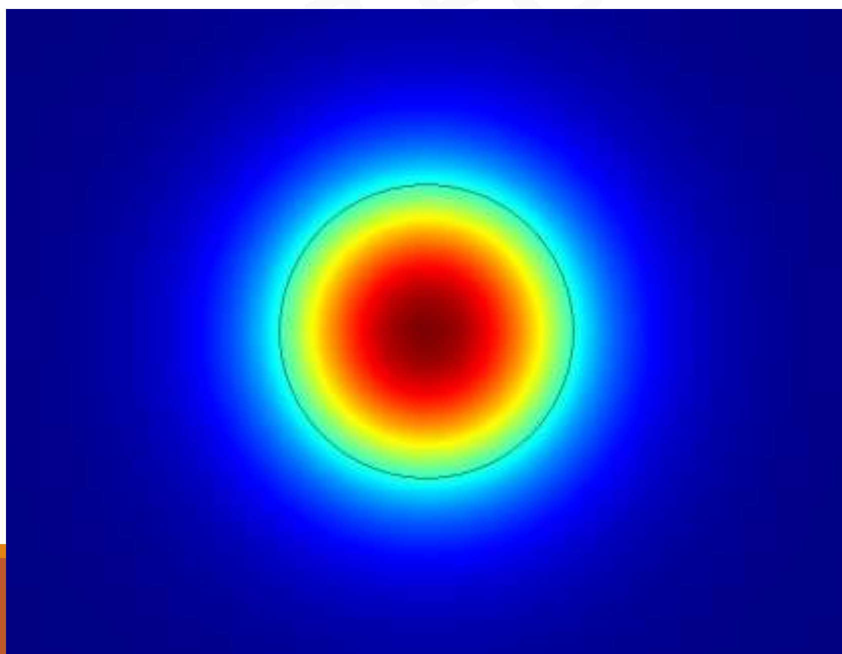
Optical fiber mode

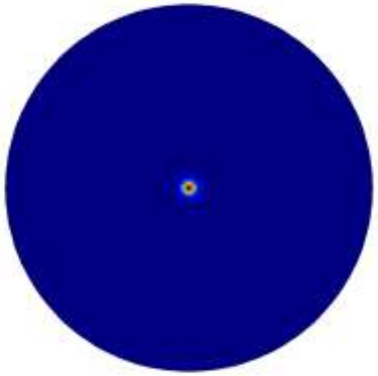
- Modes in optical fiber
  - Definition of mode: self-consistent electric field distributions in waveguides, optical resonators or in free space.
  - In other words, its transverse intensity profile or the distribution of light energy across the fiber.



n_{core} = 1.45205,
n_{cladding} = 1.44681

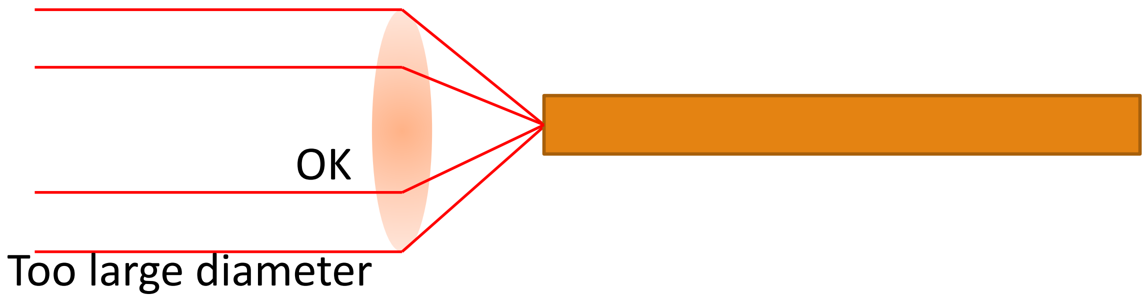
- What determines modes?
  - Boundary conditions





Coupling light to fiber

- NA of lens < NA of fiber



- Mode size matching

$$\mathrm{MFD} = \varnothing_{\mathrm{spot}} = \frac{4\lambda f}{\pi D}, \mathrm{or}\ f = \frac{\pi D(\mathrm{MFD})}{4\lambda}$$

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