Laser Optics III

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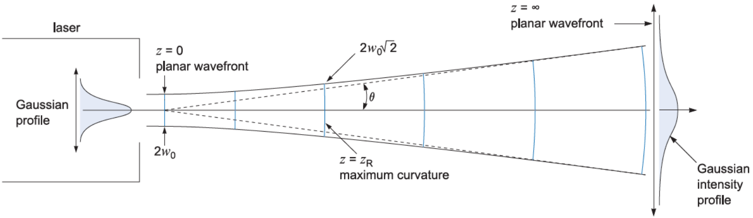
ME 677: Laser Material Processing

Contents

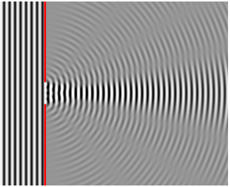


From theory of divergence:

$$w(z) = w_0 \left[1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{1/2} \quad (1)$$

$$r(z) = z \left[1 + \left(\frac{\pi w_0^2}{\lambda z} \right)^2 \right] \quad (2)$$

$w(z) \rightarrow$ beam diameter,
$r(z) \rightarrow$ radius of curvature of wavefront



Wavefronts

$$r(0) = r(\infty) = \infty$$

Therefore,

$$\frac{dr}{dz} = 0, \qquad \text{for} \quad 0 < x < \infty$$

This occurs at $z = z_R$. $z_R \rightarrow$ Rayleigh length

$$z_R = \frac{\pi w_0^2}{\lambda} \tag{3}$$

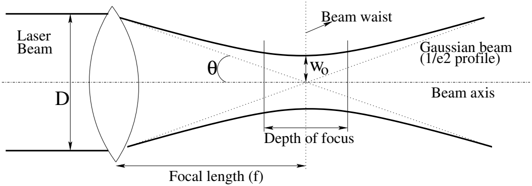
θ is defined as the far field divergence angle (see Fig, last slide)

$$\theta = \tan^{-1}\left(\frac{w(z)}{z}\right) \approx \left(\frac{w(z)}{z}\right) \tag{4}$$

For large values of z

$$w(z) \approx \frac{\lambda z}{\pi w_0}$$

$$\theta = \frac{w(z)}{z} = \frac{\lambda}{\pi w_0} \tag{5}$$



$$\theta = \frac{D/2}{f} = \frac{\lambda}{\pi w_0} \qquad (\text{for} f/D \gg 1) \tag{6}$$

$$\text{Spot diameter : } 2w_0 = \frac{4f\lambda}{\pi D} \tag{7}$$

Depth of focus (z_f) - beam length with 5% of waist diameter

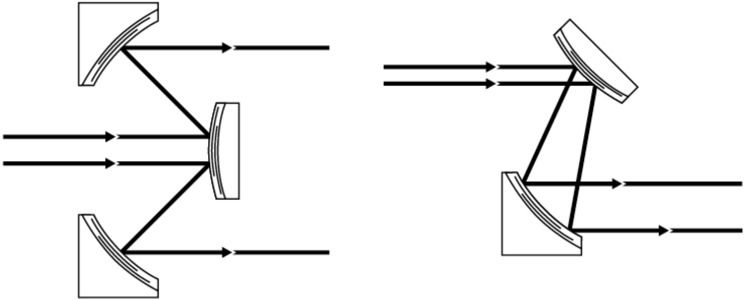
$$1.05w_0 = w_0\left[1 + \left(\frac{z}{z_R}\right)^2\right]^{1/2} \Rightarrow z_{5\%} = \pm 0.3201 z_r \tag{8}$$

$$z_f = 0.6402 z_R \tag{9}$$

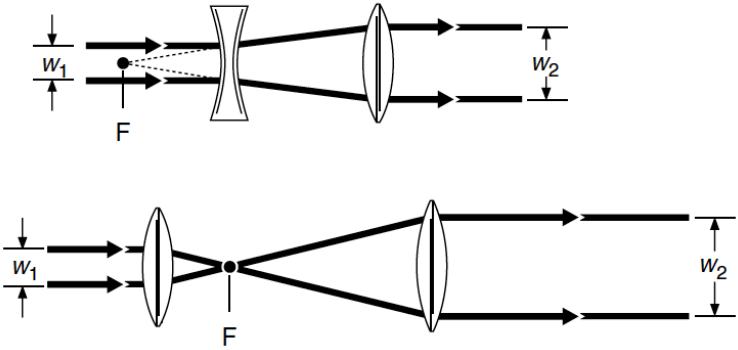
Beam Expanders

- Beam expanders are normally used for changing the size of the output beam
- From Eq. (7), the minimum spot diameter is inversely proportional to the beam diameter
- Thus, a beam expander can be used to obtain a more intensely focussed beam if its diameter is increased
- Beam size can be increased by using a series of mirrors or lenses
- Increasing the beam size also has the advantage of reducing the diffraction spreading associated with it

Beam Expanders: Mirrors



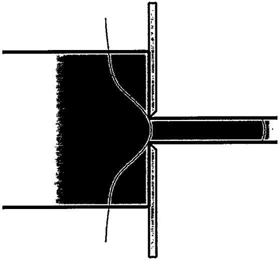
Beam Expanders: Lenses



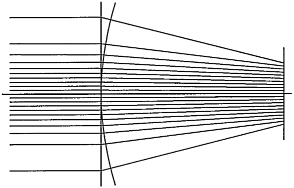
- Lenses are mounted in such a way that have the same focal point
- The size of the expanded beam is, w_2 is determined by the product of the original beam size, w_1, and the ratio of the focal length of the two lenses:

$$w_2 = w_1 \frac{f_2}{f_1} \tag{10}$$

Aperturing

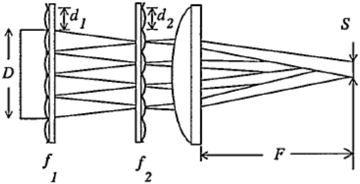


Field Mapping:



Multi Aperture:

- Input beam is broken up into beamlets by a lenslet array and superimposed by a primary lens



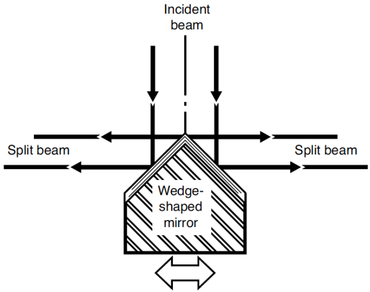
Field Mapping:

- Transform the input beam into a desired beam in a controlled manner
- Also known as refractive beam shaping

Beam Splitters

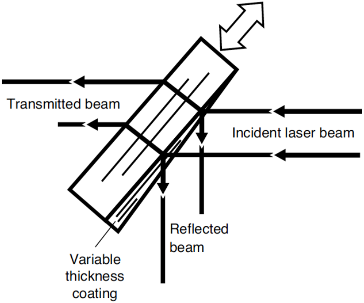
- Beam splitters are optical elements that are used to divide an incoming beam into two or more parts.

Wedge-shaped beam splitter



- For split beams to come out parallel, the wedge angle has to be 90°

Partially reflective, partially transmissive beam splitter



- Coating a transparent material such as ZnSe block with a reflective material such as inconel

Beam Delivery Systems

A beam delivery system is essentially a means for directing the laser beam from the generator to the point of application. They are of two types:

1. Conventional beam delivery
2. Fiber optic beam delivery

Conventional Beam Delivery

It is conceptually simple and consists of the following parts

1. The beam bending assemble (consists of mirrors)
2. The focussing assembly (transmissive or reflective)
3. Interconnecting beam guard tubes

- Mirrors→ Cu or Mo coated with Si (Should have very low absorptivity)
- Lens → ZnSe, KCl, GaAs and CdTe. Adjustable focusing lens to suit applications
- Beam guards for safety and protection from dust

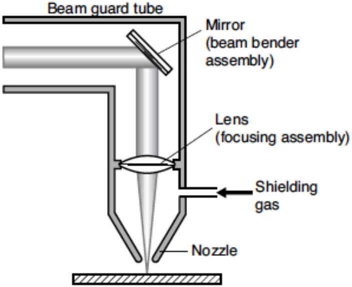


Fig: A simple beam delivery system

- Beam guards made of $\rightarrow$ aluminum tubes.
- Air cooling to prevent optical damages for high laser powers
- All the mirrors and lenses have to be aligned properly

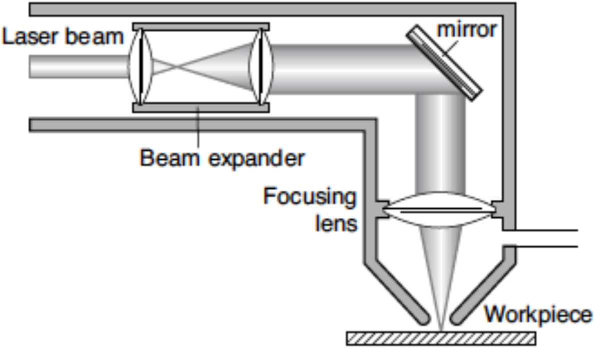


Fig: Beam delivery system with an expander

Refraction

- Speed of light c_m in any medium is given by:

$$c_m = \frac{1}{\sqrt{\mu_m \epsilon_p}} \tag{11}$$

where, μ_m and ϵ_p are magnetic and electric permeability in the medium.

- In vacuum:

$$c = \frac{1}{\sqrt{\mu_{m0}\epsilon_{p0}}} \approx 3 \times 10^8 m/s \tag{12}$$

where, μ_{m0} and ϵ_{p0} are magnetic and electric permeability in the vacuum.

- Refractive index n of the medium:

$$n = \frac{c}{c_m} = \sqrt{\frac{\mu_m \epsilon_p}{\mu_{m0}\epsilon_{p0}}} = c\sqrt{\mu_m \epsilon_p} \tag{13}$$

Refraction

- **Snell's Law**: Angle of incidence θ_1 and angle of refraction θ_2 are related by:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = n_{21} \qquad (14)$$

where, n_{21} is the refractive index of medium 2 relative to medium 1.

- If $n_1 > n_2$, there is a critical angle of incidence, θ_c, above which total internal reflection occurs, and there is no refraction of the incident beam.

- From Snell's law, we have:

$$\implies \sin\theta_c = \frac{n_2}{n_1} = n_{21} \qquad (15)$$

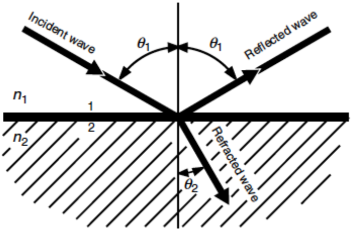
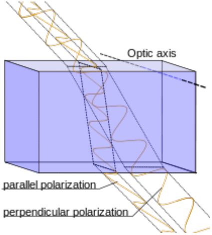
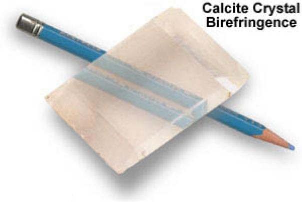


Fig: Reflection and refraction

Birefringence

- Many transparent solids are optically isotropic, meaning that the index of refraction is equal in all directions throughout the crystalline lattice.
- Birefringence occurs in anisotropic materials, and is responsible for the phenomenon of double refraction whereby a ray of light, when incident upon a birefringent material, is split by polarization into two rays taking slightly different paths.
- Two rays are produced: ordinary and extraoridinary





- Core: Inner portion through which light is propagated
- Cladding: Outer layer with a lower 'n'. Adds strength and reduces scattering loss.
- The difference in refractive indices is expressed as:

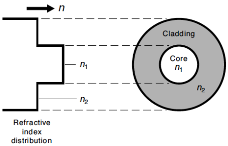
$$\Delta = \frac{n_1 - n_2}{n_1} \qquad (16)$$

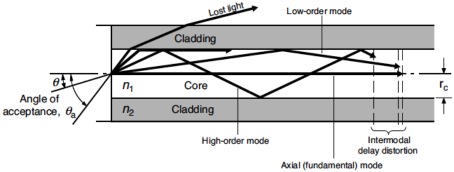
Δ is typically 0.2% for single mode and 1% for multimode

- Numerical Apperture:

$$NA = n_0 \sin\theta_a \qquad (17)$$

$$NA = \sqrt{n_1^2 - n_2^2} \qquad (18)$$





θ_a is acceptance angle

- Normalized frequency:

$$\nu_n = \frac{2\pi}{\lambda} r_c \sqrt{n_1^2 - n_2^2} \qquad (19)$$

- Permissible modes:

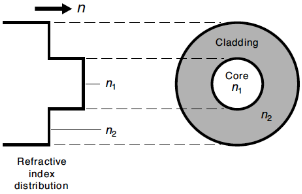
$$M_c = 4\nu_n^2/\pi^2 \qquad (20)$$

Fiber Types

1. Step-index multimode fibers
2. Single-mode fibers
3. Graded-index multimode fibers

- It has a uniform core refractive index, n_1, which abruptly changes to $n2$

$$n_1 > n_2 \tag{21}$$



- Core: Silica with n=1.46
- Has crossectional area high enough for transmitting a significant amount of energy, and supports a number of discrete modes

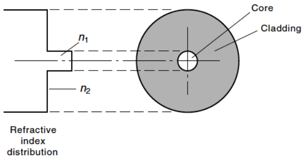
$$\nu_n \geq 2.405 \tag{22}$$

Disadvantages

- Intermodal dispersion: Rays starting at the same time become out of phase. One with smaller values of θ travels shorter distance than those with θ close to θ_a.
- Restricts fiber bandwidth or frequency range.
- Suitable for short distance applications only.

Single-Mode Fibers

- Another form of step index fibers, where the core is much smaller.
- Also the difference in refractive indices is much smaller



- All higher order modes are cut-off, only the fundamental mode propagates

$$\nu_n < 2.405 \tag{23}$$

- The reduction in ν_n is achieved either by a reduction in core diameter or a reduction in index difference
- Eliminates intermodal dispersion and a much greater bandwidth is thus obtained.

Disadvantages

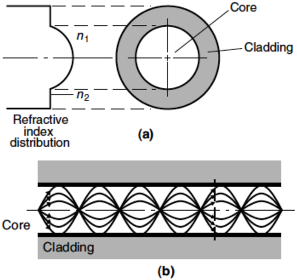
- Due to minute core size, installation is more difficult, especially with respect to alignment during joining.

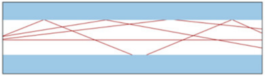
Graded-Index Fibers

- 'n' of the core varies (is graded) from a maximum, n_1, at the center of the core to the value, n_2, of the cladding:

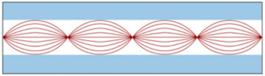
$$n_r = \begin{cases} n_1\sqrt{1 - 2\Delta\left(\frac{r}{r_c}\right)^{k_1}}, & 0 \leqslant r \leqslant r_c \\ n_1\sqrt{1 - 2\Delta}, & \text{r} > r_c \end{cases}$$

- $k_1 = \infty$ for step-index
- $k_1 = 2$, light from a point source experiences periodic focusing.
- For modes with larger entrance angle, the travel path is longer. however, they travel in a medium with lower refractive index, with greater velocities.





Multimode, Step-Index



Multimode, Graded Index

Beam Degradation

1. Dispersion or distortion
2. Optical losses

Dispersion

1. Chromatic (material) dispersion
2. Waveguide dispersion
3. Modal dispersion

Optical Losses

1. Input-coupling losses
2. Connector/splice losses
3. Fiber losses
4. Output-coupling losses

Concept of Group Velocity or Group Delay in Fiber Optics

Monochromatic electromagnetic plane wave propagating in a dielectric medium:

$$E(x,t) = E_0 \cos(k_w x - \omega t) \tag{24}$$

By considering, phase of the wave to be constant, i.e. $k_w x - \omega t =$const., we obtain the phase velocity, also known as the wave velocity, u_w, as:

$$u_w = \frac{dx}{dt} = \frac{\omega}{k_w} = \frac{c}{n} \tag{25}$$

where, n is the refractive index of the medium and c is the light velocity in free space.

For a non-monochromatic source, the phase velocity in a dispersive medium may be determined using the center wavelength. However, it is customary to use the group velocity, u_g. The inverse of the group velocity is referred to as χ_g:

$$u_g = \frac{1}{\chi_g} = \frac{dx}{dt} = \frac{d\omega}{dk_w} \tag{26}$$

We can write:

$$\chi_g = \frac{dk_w}{d\omega} = \frac{1}{c}\frac{d}{d\omega}(n\omega) \tag{27}$$

$$= \frac{1}{c}\left(n + \omega\frac{dn}{d\omega}\right) = \frac{n_g}{c} \tag{28}$$

where, n_g is referred to as group index.

$$n_g = n + \omega\frac{dn}{d\omega} \tag{29}$$

$$= n - \lambda\frac{dn}{d\lambda} \tag{30}$$

The group velocity and group delay can be expressed as:

$$u_g = \frac{1}{\chi_g} = \frac{c}{n_g} \tag{31}$$

Chromatic Dispersion

- Also refers to as material dispersion. It results from non-linear variation of refractive index with the wavelength of light, i.e. $n(\lambda)$
- A dielectric medium whose n varies with wavelength is known as dispersive dielectric medium
- Laser beams are not in reality monochromatic, but have a very small wavelength band, $\Delta\lambda$.
- Consider a light source with wavelength band $\Delta\lambda$ that spreads between λ_1 and λ_2 and is centered at λ_0. If it propagates over a single-mode fiber of length L_f, the difference in arrival times of energies propagated by the wavelengths λ_1 and λ_2, the delay distortion or pulse broadening, $\Delta\tau_{cd}$, can be expressed as:

$$\Delta\tau_{cd} = L_f[\chi_g(\lambda_1) - \chi_g(\lambda_2)] = \frac{L_f}{c} n_g(\lambda_1) - \frac{L_f}{c} n_g(\lambda_2) \qquad (32)$$

$$= -\frac{L_f}{c}\frac{dn_g}{d\lambda}\Delta\lambda \qquad (33)$$

We have,

$$n_g = n - \lambda \frac{dn}{d\lambda} \tag{34}$$

$$\frac{dn_g}{d\lambda} = \frac{dn}{d\lambda} - \frac{dn}{d\lambda} - \lambda \frac{d^2 n}{d\lambda^2} \tag{35}$$

$$= -\lambda \frac{d^2 n}{d\lambda^2} \tag{36}$$

Pulse broadening in a chromatic dispersion in a single-mode fiber can be expressed as:

$$\Delta\tau_{cd} = \frac{L_f}{c} \lambda \frac{d^2 n}{d\lambda^2} \Delta\lambda \tag{37}$$

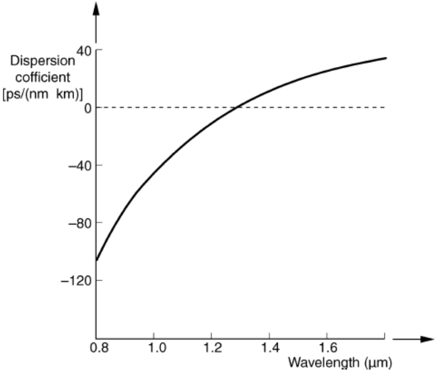
$$\Delta\tau_{cd} = L_f \left(\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2} \right) \Delta\lambda \tag{38}$$

$$= L_f D_d \Delta\lambda \tag{39}$$

D_d is dispersion coefficient, with units ps/(km-nm).

Problem

Consider a beam of wavelength 1.0μm propagating through a fiber of length 5 km, and whose dispersion coefficient is as shown in Fig. below. If the spectral width $\Delta\lambda$ of the beam is 0.05 μm, determine the pulse broadening due to chromatic dispersion.



- Results from the fact that the propagating characteristics of a mode depend on the beam wavelength
- Longer wavelengths have a longer path since they reflect at more oblique angles with the cladding
- It can be shown that pulse broadening $\Delta\tau_{wd}$, due to waveguide dispersion may be expressed as:

$$\Delta\tau_{wd} = \frac{L_f}{c}\frac{\Delta\lambda}{\lambda}(n_2 - n_1)D_w(\nu_n) \tag{40}$$

  where, D_w is a dimensionless dispersion coefficient
- The pulse broadening due to waveguide dispersion is relatively small compared to chromatic dispersion

Intermodal dispersion

- Intermodal dispersion results from differences in the distances propagated by the different modes sustained by the fiber
- If all the rays in a step-index fiber (see Fig in Slide 19) start out at the same instant, the bouncing rays reach the end of the fiber at a later time than the axial ray.
- The temporal delay (dispersion) in the arrival times of the rays causes delay distortion or change in the spectrum of the original input beam.
- A simple approximation of the pulse broadening due to intermodal distortion can be expressed as:

$$\Delta\tau_{md} = t_{max} - t_{min} = \frac{L_f n_1 \Delta}{c} \tag{41}$$

where, t_{max} and t_{min} are travel times of slowest and fastest modes.

- For step-index fibers, the modal dispersion is more than the chromatic dispersion

Problem

Determine the modal pulse broadening for a 5 km fiber with core and cladding refractive indices n_1=1.48 and n_2=1.46, respectively.

Optical Losses

1. Input-coupling losses
2. Connector/splice losses
3. Fiber losses
4. Output-coupling losses

Fiber Losses

- Losses in the fiber result in attenuation of the beam as it propagates through the fiber
- The attenuation is expressed as the ratio of input power to output power (in decibels) per unit length of fiber:

$$\alpha_l = \frac{1}{L_f} 10 \log_{10}\left(\frac{q_{in}}{q_{out}}\right) \tag{42}$$

- Ultraviolet absorption

$$\alpha_{uv} = K_{uv} e^{\frac{a_{uv}}{\lambda}} \tag{43}$$

- Infrared absorption

$$\alpha_{ir} = K_{ir} e^{\frac{-a_{ir}}{\lambda}} \tag{44}$$

- Rayleigh Scattering

$$\alpha_{RS} = K_{rs}/\lambda^4 \tag{45}$$