NOTES

IMPERIAL COLLEGE LONDON

DEPARTMENT OF PHYSICS

Laser Device Techonology

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Contents

I Lecture Notes 3

Part I

Lecture Notes

1 Important lasers and commercial applications

1.1 Important lasers

(1) **Laser diodes - compact, high efficiency**

- **Wavelength:** material dependent - AlGasAs 780nm, AlGalnP 650nm, etc.
- **Pumping:** DC electric current (simple).
- **Max wallplug efficiency:** up to 60% (very good!).
- **Key features:** compact, rugged, relatively cheap, simple electrical pumping, high efficiency, long lifetimes, etc.
- **Main applications:** optical data storage, laser pumping, telecom, material processing, etc.

(2) **Solid-state lasers - scale to high power**

- **Wavelength:** Nd^{3+}:YAG 1064nm, Er^{3+}:SIO_2 fibre 1540nm, etc.
- **Pumping:** optical - LD arrays, flashlamps, Nd laser and SHG.
- **Max wallplug efficiency:** 30% for DPSS.
- **Key features:** pulsed, high peak-power, rugged, broad λ coverage with nonlinear wavelength shifting via SHG, THG, OPA.
- **Main applications:** material processing, medical, military, telecom, scientific, etc.

(3) **CO_2 lasers - cw long wavelength**

- **Wavelength:** MIR - 10.6μm (most important), other lines $9 - 11\mu$m.
- **Pumping:** electrical discharge, DC, AC (20-50kHz), RF.
- **Output:** High average power (cw to kW level).
- **Max wallplug efficiency:** 20%.
- **Key features:** high average power (cw up to kilowatt level), good efficiency, long λ well absorbed in transparent and organic materials (e.g. water, skin).
- **Main applications:** Material processing, cosmetic skin therapies.

(4) **Excimer lasers - gas discharge, short wavelength**

- **Wavelength:** UV spectral range - ArF laser 193nm, etc.
- **Pumping:** HV electrical discharge (very dangerous!).

- **Max wellplug efficiency:** 2% (terrible!).
- **Key features:** powerful UV lasers, short λ gives small focal spot and high spatial precision, strong absorption in many materials.
- **Main applications:** photolithography (chip manufacture), material processing, material modification, corrective eye surgery, etc.

From the above discussions, we find that each type of laser has its own properties. It is impossible to combine all of the ideal properties of laser light into a single device. So we link laser properties to application advantages and benefits, so that we can choose the laser that meet the key requirements.

- **High power** - Enables material processing.
  - Rapid and localised heating of materials.
  - Can modify material properties (marking, annealing).
  - Can drive a range of peocesses.
  - High processing speeds.
  - High signal to noise in non-contact measurements (e.g. explosive detection).
- **Versatile wavelength** - Match λ to applications by the choice of material or tuning from NLO.
  - Maximise absorption for cutting (e.g. laser surgery), minimise absorption for telecom fibre etc.
  - Create short λ for smaller diffraction limited focal spots, and fine detail in microscopy and photolithography.
- **High beam quality** - Allows tight focusing, localisation of energy deposition. (We will use M^2 to describe real world imperfect beams.)
- **Short pulse duration** Δt - Enable high peak power, high time resolution for “fast” processes.
- **Versatile spectral line width** $\Delta\lambda$
  - Narrow line width enable high spectral resolution.
  - Broad line width is required to make a short pulse (e.g. high data rate communication).
- **EM wave** - Remote delivery.
  - non-contact and low force.
  - Environmental and noise immunity.
- **High coherence** - Allows interferometry.

1.2 State of the laser and photonics marketplace

- **Global laser marketplace**
  - Split 40% / 60% laser-diode / non-laser diode markets.
  - Political uncertainty, trade barriers, and pandemic all impacted global markets.
  - Rapid growth in (1) LIDAR for range finding / 3D surveying (e.g. for driverless cars). (2) Increased use in consumer devices, (e.g. lasers for smartphone facial recognition). (3) Strong future interest in “small scale” laser weapons for drone defence.
- **Global industrial laser marketplace**
  - Fibre lasers 54%, diode and excimer lasers 15%, solid-state lasers 16%, CO_2 lasers 15%.
  - Industrial laser key applications include automative, aerospace, energy, electronics, communications (smartphones), material processing (welding, cutting, marking), etc.
- **Laser applications by segment**
  - Material Processing and lithography the largest sector at 40%.
  - Communication and optical storage is the second largest sector at 27%.

2 Characterising lasers for real-world applications

TEM$_{00}$ beam is a simple single Gaussian:

$$I(r,z) = I_0 \left(\frac{w_0}{w(z)}\right)^2 \exp\left(\frac{-2r^2}{w(z)^2}\right). \tag{1}$$

This beam can be focus to a "small" spot with radius w_0. For a perfect TEM$_{00}$ beam, the spot position is only limited by diffraction, which is called the Airy disk. The F-number F is

$$F = \frac{f}{d}, \tag{2}$$

where d is the diameter of the aperture. The smallest separation x two objects can have before they significantly blur together is given as stated above by

$$x = 1.22F\lambda \sim w_0. \tag{3}$$

However, many lasers are not TEM$_{00}$. We may have multiple modes in a superposition, or there may be imperfect optics. In these cases, how to characterise the beam quality?

2.1 Beam quality factor

We use the ISO 11146 standard, which based on variance of transverse intensity profile to characterise the beam quality. Using the D46 method, the beam radium in x-direction is

$$w_x^2(z) = 4\sigma_x^2(z), \tag{4}$$

where z is the propagation distance, w_x is the beam radium in x-direction and

$$\sigma_x^2 = \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}(x-\bar{x})^2 I_z(x,y)\mathrm{d}x\mathrm{d}y}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} I_z(x,y)\mathrm{d}x\mathrm{d}y}, \tag{5}$$

with the beam centroid

$$\bar{x} = \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x I_z(x,y)\mathrm{d}x\mathrm{d}y}{\int_{-\infty}^{\infty}\int_{-\infty}^{+\infty} I_z(x,y)\mathrm{d}x\mathrm{d}y}. \tag{6}$$

In practice, we take a series of images with a CCD camera, along with a focus at different points in z. The Gaussian propagation equation gives

$$w(z) = w_0\sqrt{1 + \left(\frac{\lambda M^2 z}{\pi w_0^2}\right)^2}, \tag{7}$$

where w_0 is the minimum value of beam radium. In medium, λ will be replaced by λ/n. M^2 is the **beam quality factor** which reflects how many times diffraction limited the beam. For perfect Gaussian, we have $M^2 = 1$. For "real" beams, we have $M^2 > 1$. Some beams can even be very ugly to $M^2 > 1000$.

How to measure M^2 in practical?

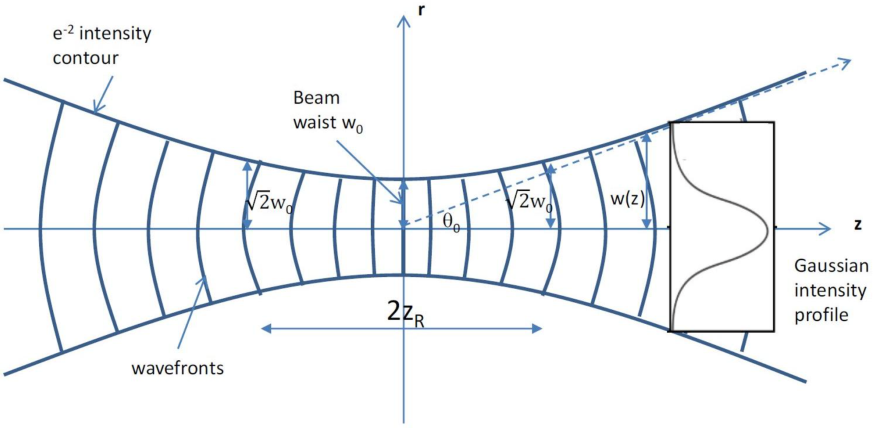

Figure 1: The Gaussian beam.

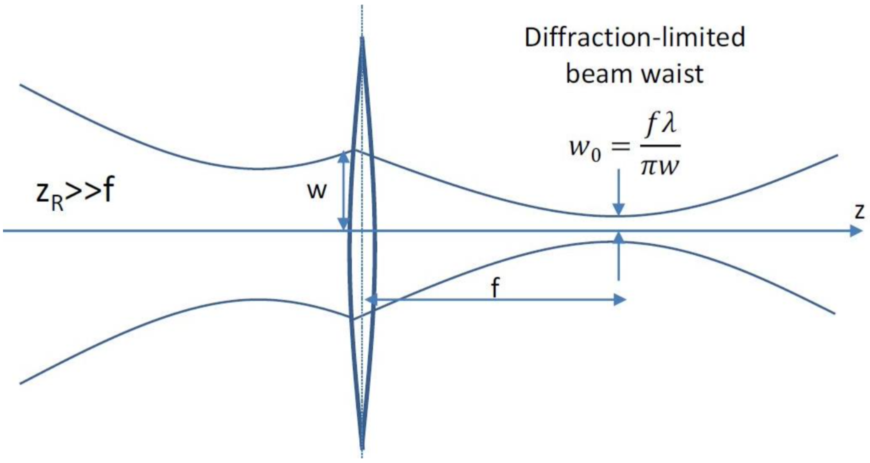

Figure 2: The diffraction-limited beam waist at the focus.

(1) Scan the system through a focus in z-direction and record the intensity as $I_z(x, y)$.

(2) Calculate $w(z)$ values using D46 definition Eqn. (4).

(3) Fit $w(z)$ to the Gaussian propagation equation Eqn. (7).

Here are some examples. The far-field beam divergence half angle with M^2 is

$$\theta_0 = \frac{M^2\lambda}{\pi w_0}. \tag{8}$$

For focusing, the minimum value of beam radium is

$$w_0 = \frac{fM^2\lambda}{w_{\text{in}}\pi}. \tag{9}$$

The Rayleigh range (the distance along the propagation direction of a beam from the waist to the place where the area of the cross section is doubled / half power) is given by

$$z_R = \frac{\pi w_0^2}{M^2\lambda}. \tag{10}$$

Over the range $(-z_R, z_R)$ the beam is roughly collimated, so $z = \pm z_R$ is a measure of the "depth of focus". The wavefront of curvature is

$$R(z) = z + \frac{z_R^2}{z}. \tag{11}$$

The $F/$ number is

$$F/ = \frac{f}{2w_{\text{in}}} = \frac{w_0\pi}{2M^2\lambda}. \tag{12}$$

2.2 Beam product parameter (BPP)

The **beam product parameter (BPP)** is defined as

$$\text{BPP} = \theta_0 w_0, \tag{13}$$

where θ_0 is the divergence half angle and w_0 is the beam radium at best focus. BPP is invariant under propagation and beam expansion using perfect optics. For a Gaussian

$$\text{BPP} = \frac{\lambda M^2}{\pi}. \tag{14}$$

2.3 Beam brightness

The **beam brightness** is defined as

$$B = \frac{I}{\Omega}, \tag{15}$$

where I is the intensity with units $[I] = \text{W/m}^2$ and Ω is the solid angle of laser beam. For a TEM$_{00}$, the solid angle $\Omega = \lambda^2/w_0^2$. The beam brightness is invariant under propagation through perfect optics. For Gaussian, we have

$$B = \frac{2P}{(M^2\lambda)^2} \propto \frac{1}{M^4}, \tag{16}$$

where P is the average power of the Gaussian and the factor $2\times$ comes from Gaussian as factor $1\times$ for an uniform top.

3 Laser diodes (LD)

3.1 Main features

- 40% of total laser market.
- Simple electrical pumping with a DC current.
- Compact $\sim 1 \times 1$ mm device.
- High wall plug efficiency $\geq 50\%$.
- Wide (discrete) spectral coverage through changing semiconductors.
- Some tuning of λ by changing the atomic ratios and temperature.
- Can be engineered to be cw or pulsed.
- Can make quite short pulses of picoseconds.
- Direct high-speed modulation by turning the drive current up / down.
- Very long lifetimes.
- Individually low cost, made by the million using chip-fabricate technology.
- Normally a small chip packaged into a sealed unit with electrical contact, possibly cooling, and temperature control.

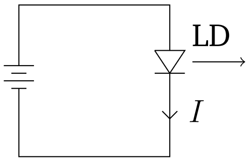

Figure 3: A LD is simple eletrical pumping with a DC current.

3.2 Main applications

- Telecoms - two different wavelength 1.3 and 1.5μm.
  - 1.3μm is the zero dispersion wavelength for silica fibre.
  - 1.5μm is the lowest absorption wavelength for long distance communications.
- Data storage.
- Pumping other lasers - e.g. DPSS (diode pumped solid state) system.

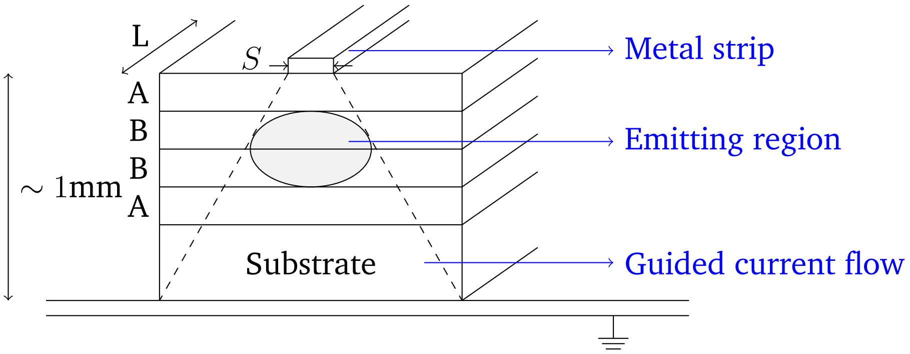

Figure 4: The heterostructure of a laser diode.

3.3 LD operating principle

The LD operating is based on a radioactive process in a PN junction:

- **P-type material:** doped with an acceptor impurity atom to create “holes”, which behave as positive charge carriers.
- **N-type material:** doped with a donor impurity atom, providing an extra electron.

3.4 LD Heterostructure

The physical structure for LD is required to support PN junction, confine light and form a cavity. Typically, we use a double-heterostructure with PN junction sandwiched between different types of semiconductor.

One of the example stack is:

A	AlGaAs	p-type
B	GaAs	p-type
B	GaAs	n-type
A	AlGaAs	n-type
Substrate		

Heterostructure LD has a much lower ($\sim 100\times$) threshold current density J for lasing, which is typically $\sim 1\text{kA/cm}^2$.

$$I_{\text{thresh}} = J_{\text{thresh}} \times S \times L, \tag{17}$$

where $L \times S$ is the active region.

3.5 Wavelength consideration

3.5.1 Band gap structure

There is an energy gap E_g between conduction band and valance band. For an ideal LD

$$E_g = \hbar\omega = \frac{hc}{\lambda}. \tag{18}$$

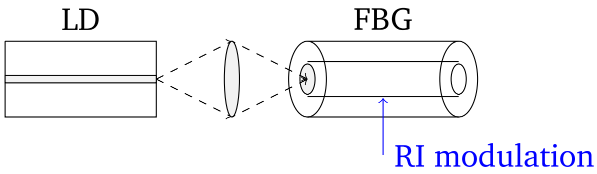

Figure 5: RI (refractive index) modulation based on FBG.

So, the minimum energy for an electron to go through the energy gap is

$$eV_g = E_g, \tag{19}$$

where V_g is the band gap voltage. For AlGaAs 830nm, the band gap voltage is

$$V_g = \frac{hc}{e\lambda} = 1.5\text{V}. \tag{20}$$

3.5.2 LD longitudinal modes

Neglect dispersion, the frequency (or wavelength) spacing is

$$\Delta\nu_m = \frac{c}{2nL}, \quad \text{or} \quad \Delta\lambda_m = \frac{\lambda_m^2}{2nL}, \tag{21}$$

where n is the refractive index. The dispersion can also contribute as group velocity v_g related to refractive index $n_g = c/v_g$. The multiple longitudinal modes can lose simultaneously in a "standard" LD, where we can modify to lase on a **single longitudinal mode (SLM)** by adding external λ control. For example, adding a **fibre Bragg grating (FBG)** has a "polled" structure to act as a λ dependent mirror.

The fundamental principle behind the operation of an FBG is Fresnel reflection, where light traveling between media of different refractive indices may both reflect and refract at the interface. The refractive index will typically alternate over a defined length. The reflected wavelength λ_B, called the Bragg wavelength, is defined by the relationship,

$$\lambda_B = 2n_{\text{FBG}}\Lambda, \tag{22}$$

where n_{FBG} is the effective refractive index of the fibre core and Λ is the grating period.

3.5.3 λ tuning

- Broad λ selection by choice of semiconductor.
- Fine (fixed) tuning by changing atomic rates. For example, Al$_x$Ga$_{(x-1)}$As has a wavelength 780 - 880nm. For $x = 0.42$, $\lambda = 780$nm, for $x = 0.52$, $\lambda = 880$nm.
- Fine "active" tuning by changing temperature. Take AlGaAs as example again, $\mathrm{d}\lambda/\mathrm{d}T \sim 0.3$nm/°C.

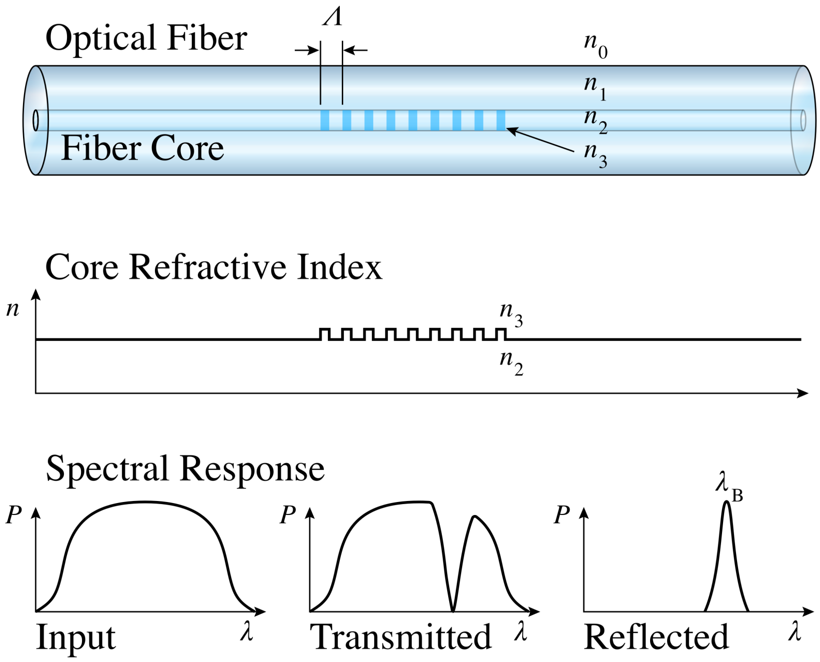

Figure 6: A FBG structure, with refractive index profile and spectral response

3.6 LD beam properties

The full angle divergence for laser beam is

$$\Delta\theta = 2\theta_0 = \frac{2M^2\lambda}{\pi w_0}, \tag{23}$$

where the beam radius $w_0 \sim \frac{\Delta x}{2}$ or $\frac{\Delta y}{2}$. So we have

$$\Delta\theta_x = \frac{4M_x^2\lambda}{\pi\Delta x}, \quad \Delta\theta_y = \frac{4M_y^2\lambda}{\pi\Delta y}. \tag{24}$$

3.7 LD power characteristics

The optical output

$$P_{\text{out}} = \eta_s(I - I_{\text{thresh}}), \tag{25}$$

where η_s is the slop efficiency and

$$\eta_s = \frac{P_{\text{out}}}{I - I_{\text{thresh}}}. \tag{26}$$

The wall plug efficiency (electro-optic efficiency) is given by

$$\eta_{\text{wp}} = \frac{P_{\text{out}}}{P_{\text{elec}}} \sim 50\%. \tag{27}$$

To enhance efficiency, we can combine several LDs into a single semiconductor unit, albeit at the cost of beam quality.

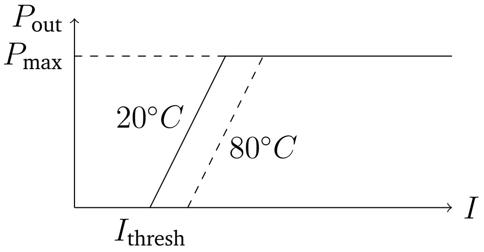

Figure 7: The output power (optical) is dependent with the input current.

3.8 High power LDs

A key application for LD is pumping solid-state lasers. This can work well with lower M^2 diodes. The output power of single LD is limited to ~ 200mW at good beam quality by facet (mirror) damage. The intensity

$$I_{\text{damage}} = \frac{P_{\text{damage}}}{\Delta x \Delta y}, \tag{28}$$

where $\Delta x \Delta y$ is the emitting area. To achieve high power LD, we can increase the emitting area of LDs.

(1) **Broad stripe laser diodes:** increase emitting area using a wider conductive stripe.

(2) **Diode bars:** integrate multiple LDs into a single slice of semiconductor.

(3) **Diode arrays:** stack diode bars vertically. Bars and stacks is common in DPSS systems.

In this way, LD acts as a pump source for a “better” laser. Here, “better” means good quality, short pulse, etc.

4 Fibre lasers

4.1 Overview

- **Key features:** gain medium doped into the core of a fibre, a long thin light guide, significant growing commercially, etc.
- **Advantages:** compact, rugged, minimal alignment, low M^2, high efficiency, large external area (good heat removal, good for high average power), operate cw at high average power (multi kW) and also pulsed (Q-switched and mode-locked) at high peak power, etc.
- **Disadvantages:** long gain medium (unwanted dispersion, nonlinear processes can build up), small core size (limited by LIDT to low single pulse energies), etc.
- **Applications:** can be configured as an oscillator or amplifier (e.g., EDFA), can operate cw and pulsed, telecoms, material processing, medical, etc.

4.2 Key properties

4.2.1 Numerical aperture (NA)

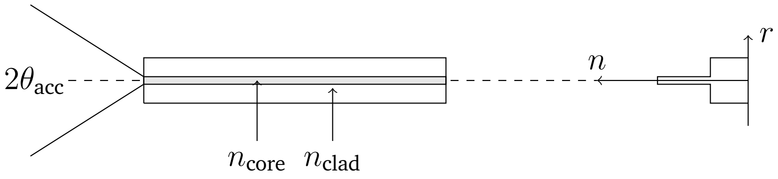

Figure 8: Caption

The numerial aperture (NA) is given by

$$\mathrm{NA} = \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}, \tag{29}$$

which related to acceptance angle:

$$\theta_{\text{acc}} = \sin^{-1} \mathrm{NA}. \tag{30}$$

The input beam radius focused should it the core size for good coupling, so that the beam quality M^2 is important.

4.2.2 Fibre dispersion

- **Modal dispersion** arises in multimode fibres because the different modes have different propagation speeds. This causes the spreading and distortion of signals in time, and it therefore limits the useable bandwidth of multimode fibres. Modal dispersion can be eliminated by using a single-mode optical fibre where the core diameter is sufficiently small (typically a few microns) that only a single propagation mode is possible at a given wavelength.

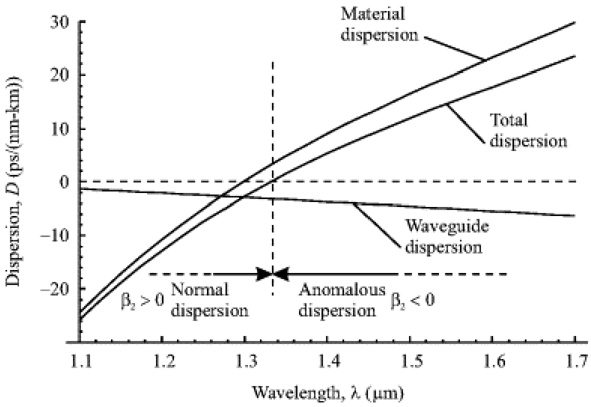

Figure 9: Material, waveguide, and total dispersion in standard single-mode optical fibre. Recall that chromatic dispersion is measured in units of ps $\text{nm}^{-1}\text{km}^{-1}$ since it expresses the temporal spread (ps) per unit propagation distance (km), per unit pulse spectral width (nm).

- **Material dispersion** arises due to the frequency dependent variation of the refractive index of all optical materials $n = n(\lambda)$. The material dispersion coefficient is given by

  $$D_{\text{mat}} = -\frac{\lambda_0}{c}\frac{\mathrm{d}^2 n(\lambda)}{\mathrm{d}\lambda^2}\bigg|_{\lambda_0}, \tag{31}$$

  where λ_0 is the laser wavelength.

- **Wave guide dispersion** arises from the wave guide effects.

In some case we can balance material dispersion and wave guide dispersion (Fig. 9).

For optical fibres, the dispersive pulse broadening

$$\Delta t_{\text{broad}} = D \times L \times \Delta\lambda. \tag{32}$$

It is easier to compensate for dispersion than loss (active gain needed) in a long distance system.

4.2.3 Absorption or attenuation

Ultra-pure SiO_2 has an attenuation of 0.2dB/km, where dB is a log scale, i.e.,

$$1\text{dB} = 10\log_{10}\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right). \tag{33}$$

- 3dB attenuation $\sim 50\%$.
- 20dB attenuation $\sim 1\%$.
- 30dB attenuation $\sim 0.1\%$.

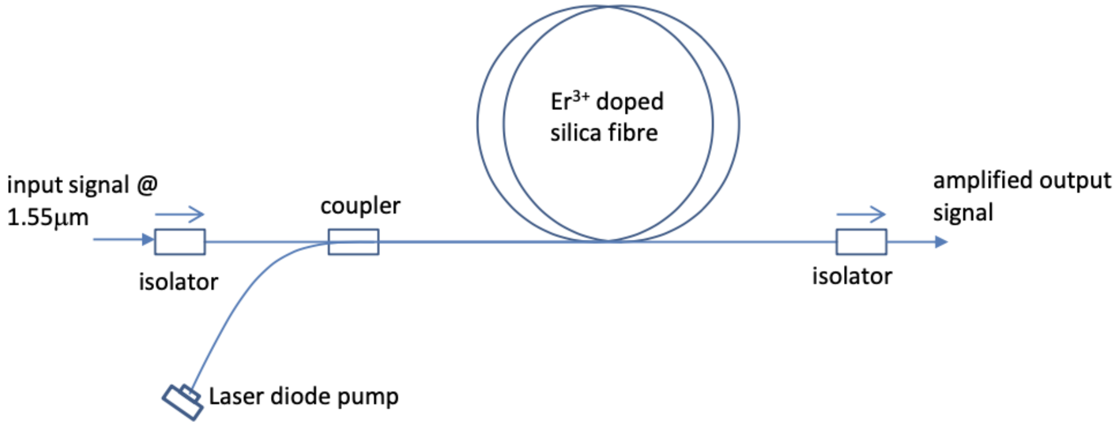

Figure 10: A basic EDFA operating at 5.5μm.

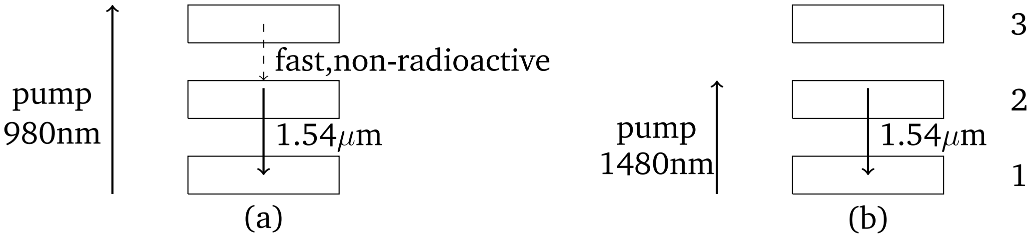

Figure 11: Two pumping schemes.

4.3 Erbium doped fibre amplifier (EDFA)

The erbium-doped fiber amplifier (EDFA) is the most deployed fiber amplifier as its amplification window coincides with the third transmission window of silica-based optical fiber. The core of a silica fibre is doped with trivalent erbium ions (Er^{3+}) and can be efficiently pumped with a laser at or near wavelengths of 980 nm and 1480 nm, and gain is exhibited in the 1550 nm region.

There are two pumping schemes. Method (b) gives a lower energy pump photon and lower quantum defect, so there is less heating. However, when we use some of level 2 as a pump band, there is less band width and more noise in the laser output. We can combine both pump methods at the same time.

4.4 Fibre oscillators

Fibre oscillator requires gain module and resonant cavity.

4.4.1 CW operation

We use FBG as a λ-dependent reflector to reflect lasers.

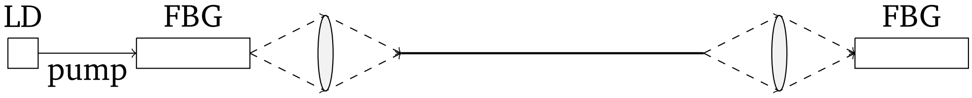

Figure 12: Use FBG as a λ-dependent reflector to reflect lasers.

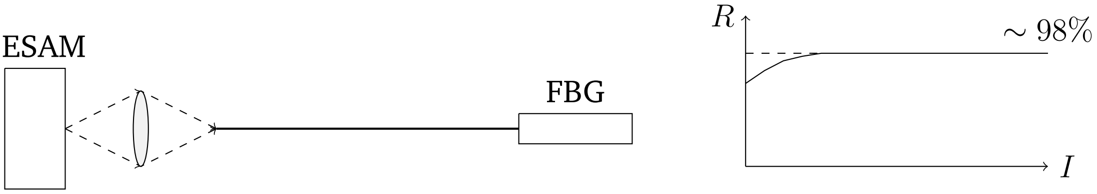

Figure 13: (a) Use a SESAM as reflect mirror. (b) The reflectivity R is intensity dependent.

4.4.2 Pulsed oscillator

We need to control gain or loss on a fast (ns - fs) timescale. It is commonly to use a **semiconductor saturable absorbed mirror (SESAM)**, which reflectivity R is intensity dependent. In this way, we can amplify the signal.

4.5 High power fibre lasers

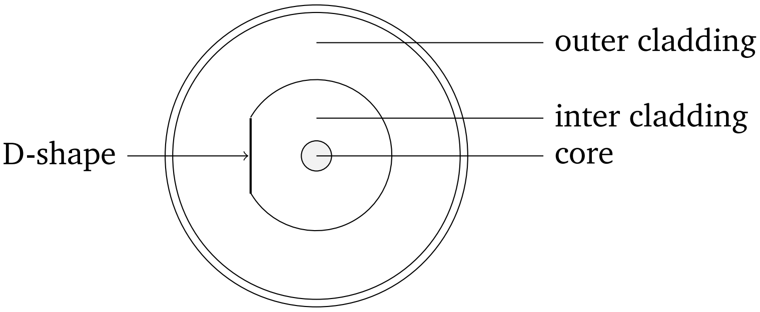

Figure 14: The structure of a "double clad" fibre.

There are multiple guiding structures for laser and pump modes. Pump injected into inner cladding and outer cladding confines pump light. D-shape helps scatter pump light into core along the length of fibre.

This structure allows for efficiency use of the high power that laser diode pump.

5 Designing solid-state lasers

Gain medium typically a transparent “host” glass pr crystal, and doped with a few percent by weight of lasant ions.

5.1 Choice of gain material

- **Crystals** typically “good” thermal conductors, but limited size at high quality.
- **Glasses** have $10\times$ lower thermal conductivity, but available at large (~ 1 m^2) size.

5.2 Laser amplification in gain medium

We can characterise the gain medium by exponential loss efficient α and exponential gain coefficient γ. The gain coefficient is given by

$$\gamma = \sigma(\omega)\Delta N, \tag{34}$$

where $\sigma(\omega)$ is the *frequency-dependent cross-section* for stimulated emission and absorption. $\Delta N = N_2 - N_1$ is the population difference, where N_1 is the population in the upper laser level (ULL), N_2 is the population in the lower laser level (LLL). The threshold condition for laser gain is $\Delta N > 0$, that is, a population inversion $N_2 > N_1$. However, this requires the active pumping of the population into the upper laser level by an external power source. Since under normal conditions of thermal equilibrium, we have $N_1 \gg N_2$ given by the Boltzmann distribution.

For an ideal 4-level laser system, the population difference N_0 is given by

$$\Delta N_0 \approx R\tau_{21}, \tag{35}$$

where R $(m^{-3}s^{-1})$ is the pumping rate and τ_{12} is the spontaneous decay time from ULL to LLL.

A weak beam (i.e. one where the intensity $I \ll I_{\text{sat}}$, the saturation intensity) travelling in the z-direction through a gain medium is amplified according to a simple exponential law with a small signal gain coefficient γ_0

$$I(z) = I_{\text{in}}\mathrm{e}^{\gamma_0 z}. \tag{36}$$

The small signal **gain factor** for a gain medium of length L is given by

$$G_0 = \mathrm{e}^{\gamma_0 L}. \tag{37}$$

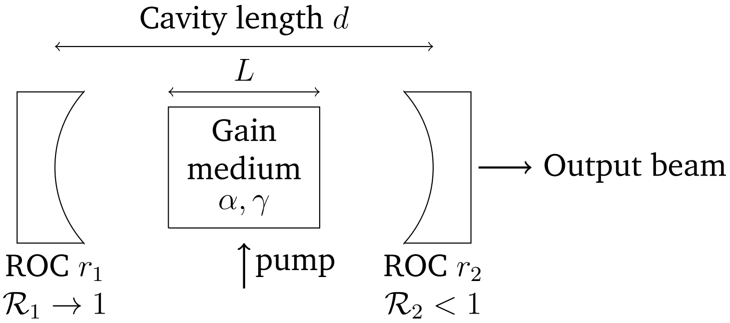

Figure 15: Anatomy of an ideal laser oscillator.

5.3 Cavity design

Cavity stability condition is defined by the parameters:

$$0 \leq g_1 g_2 \leq 1, \tag{38}$$

where $g = 1 - d/r$.

Steady state oscillation requires that the round trip gain equals to the round trip loss, i.e.,

$$\mathcal{R}_1 \mathcal{R}_2 \mathrm{e}^{2L(\gamma_0 - \alpha)} = 1, \tag{39}$$

which gives a threshold (minimum) value for the gain coefficient

$$\gamma_{\text{thresh}} = \alpha - \frac{\ln(\mathcal{R}_1 \mathcal{R}_2)}{2L}, \tag{40}$$

and thus a threshold value for the population difference:

$$\Delta N_{\text{thresh}} = \frac{1}{\sigma} \left(\alpha - \frac{\ln(\mathcal{R}_1 \mathcal{R}_2)}{2L} \right). \tag{41}$$

As the output coupler is made less reflective (decreasing $\mathcal{R}_2$), a larger fraction of the intra-cavity photons can escape, but this also increases the cavity losses and thus reduces. Because of this trade-off, there is an optimum value of $\mathcal{R}_2$ that *maximises* P_{out} given by:

$$\mathcal{R}_{2,max} = 1 - (\sqrt{g_0 \Lambda} - \Lambda), \tag{42}$$

where $\Lambda = 2\alpha L - \ln \mathcal{R}_1$ and $g_0 = 2\gamma_0 L$.

5.4 Longitudinal modes and modelocking

Steady-state oscillation within a laser cavity requires that the radiation field reproduces itself exactly each round trip. This condition means that a laser of cavity length d can only oscillate at one or more discrete frequencies known as the **longitudinal modes**:

$$\nu_m = m \frac{c}{2nd}, \quad m = 1, 2, 3, \ldots, \tag{43}$$

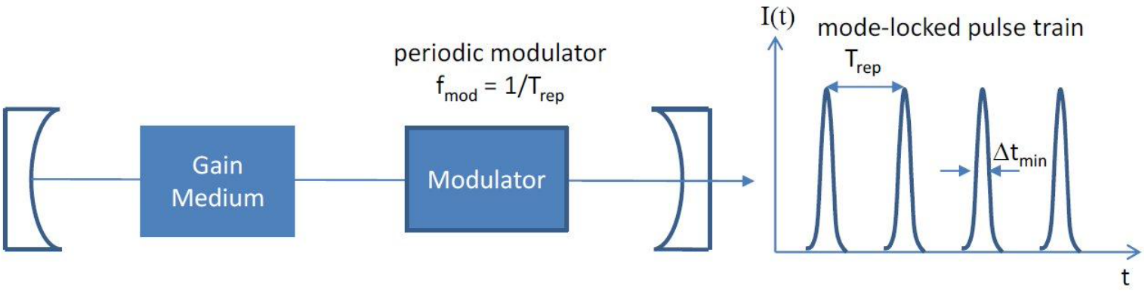

Figure 16: Modelocking.

where n is the refractive index of medium. The spacing of the longitudinal modes in frequency is thus

$$\Delta\nu_m = \frac{c}{2nd}, \quad \text{or} \quad \Delta\lambda = \frac{\lambda^2}{c}\Delta\nu_m. \tag{44}$$

If N longitudinal modes are mode-locked, the minimum pulse duration is given by

$$\Delta t_{\text{min}} = \frac{1}{N\Delta\nu_m}, \tag{45}$$

where $N\Delta\nu_m$ is the longitudinal mode spacing. If each pulse in the train has an energy of pulse E_{pulse}, then the average power in the pulse train at a repetition rate T_{rep} is

$$P_{\text{avg}} = \frac{E_{\text{pulse}}}{T_{\text{rep}}}. \tag{46}$$

The peak power of an individual pulse is then

$$P_{\text{peak}} = \frac{E_{\text{pulse}}}{\Delta t_{\text{min}}}. \tag{47}$$

5.5 Slope efficiency

The output power

$$P_{\text{out}} = \eta_s(P_{\text{pump}} - P_{\text{thresh}}), \tag{48}$$

where η_s comprise of multiple terms. Here we show some of them:

- **Quantum defect** η_Q

$$\eta_Q = \frac{\hbar\omega_{\text{laser}}}{\hbar\omega_{\text{pump}}} = \frac{\lambda_{\text{pump}}}{\lambda_{\text{laser}}} \tag{49}$$

- **Volume overlap** η_v

$$\eta_v = \frac{\text{volume of laser mode}}{\text{volume we pump}} = \frac{\int_0^\infty G(r)I(r)2\pi r \mathrm{d}r}{\int_0^\infty I(r)2\pi r \mathrm{d}r}, \tag{50}$$

where $G(r)$ is the normalised gain distribution.

There are two special cases:

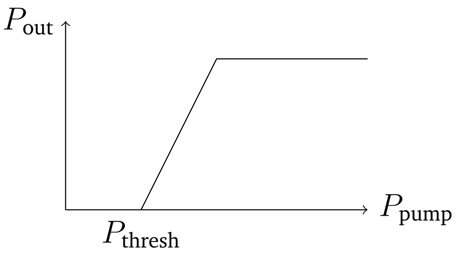

Figure 17: The power relation.

(1) Side pumping: For $w_l > w_p$, $\eta_v = 1$; for $w_l < w_p$, $\eta_v = w_l^2/w_p^2$.
(2) End pumping: For $w_l \sim w_p$, $\eta_v \sim 1$; for $w_l < w_p$, $\eta_v = 2w_l^2/(w_l^2 + w_p^2)$.

We can use this vibration of η_v to mode lock a laser.

- **Transport efficiency** η_t: quantifies loss of pump light, moving from source to gain material.
- **Pump spatial overlap** η_λ. For flash lamp, η_λ is "low".
- **Losses from cavity** η_c

$$\eta_c = \frac{T_2}{L_i + T_2}, \tag{51}$$

where $T_2 = 1 - R_2$ is the output transmission and $L_i = 1 - R_1 \mathrm{e}^{-2\alpha L}$ is the loss parameter.

6 Thermal effects in lasers

6.1 Deriving a laser rod temperature distribution

Ignore the rod ends, in steady state, the heat conduction equations

$$\frac{\mathrm{d}^2T}{\mathrm{d}r^2}+\frac{1}{r}\frac{\mathrm{d}T}{\mathrm{d}r}+\frac{Q'}{\kappa}=0, \tag{52}$$

where $Q'=P_H/\text{volume}$ is the heat input per unit volume and κ is the conductivity. The standard solution is

$$T(r)=T_s+\frac{Q'}{4\kappa}(R_0^2-r^2). \tag{53}$$

For steady state, the heat removal is equal to heat input. So we have

$$P_H=2\pi R_0L\times h_t(T_s-T_c), \tag{54}$$

where h_t is the heat transfer coefficient. For most material, we have $\mathrm{d}n/\mathrm{d}T>0$. So we have

$$n(0)-n(c)=\frac{Q'}{4\kappa}\frac{\mathrm{d}n}{\mathrm{d}T}r^2. \tag{55}$$

So, the working process may change cavity stability or trigger damage.

6.2 Managing thermal effects

- Choose high κ material, e.g. a crystal.
- Improve $\mathrm{d}n/\mathrm{d}T,\kappa$. e.g. cooling to liquid nitrogen temperature.
- Change shape of gain material to get more surface area, sample different parts of temperature gradient to average out $\mathrm{d}n/\mathrm{d}T$.
- Wait a long time for thermal recovery.

Part II

Guided Self-Study

7 Laser induced damage threshold (LIDT)

Different elements of the optics in a high-power laser system can fail catastrophically in fundamentally different ways, and this failure splits into two broad categories:

- **Surface damage** is driven by heating and melting for "longer" ($\sim$ ns) pulses, and ionisation by laser electric field and multi-photon processes for short (ps - fs) pulses. This damage is enhanced by scratches, dirt, multilayer boundaries, etc. **Surface damage is probabilistic**, so damage thresholds may appear worse for larger beams, as they are more likely to hit a defect.
- **Bulk damage** thresholds are typically much higher than the thresholds for surface damage. Bulk damage is driven by *Kerr effect*, which is a $\chi^{(3)}$ nonlinearity and gives rise to an intensity-dependent refractive index $n = n_o + n_2 I$. This may cause "*self-focussing*".

Damage can "hop" from place to place! Once damage has occurred, it can self-propagate as diffraction creates new hot spots.

The LIDT (laser induced damage threshold) describes the energy per unit area or "*fluence*" beyond which an optic is likely to damage. It is typically given in units of J/cm^2. **LIDT is wavelength λ dependent and pulse duration τ dependent:**

$$\text{LITD} \propto \sqrt{\tau}, \quad (\tau > 20\text{ps}), \tag{56}$$

$$\text{LITD} \propto \lambda. \tag{57}$$

Manufacturer LIDT values should be taken as a guide, not a guaranteed safe limit, particularly given their statistical nature. As a result, we should include a sensible safety factor of $\sim 2\times$ or more and aim to operate well below the maximum fluence specification in real world systems.

8 Designing a NIF replacement

The **National Ignition Facility (NIF)** laser is currently the worlds largest system. Now we want to design a system to replace it.

8.1 Saturation fluence and its implications

At high fluence (high energy per unit area) the population inversion ΔN_0 stored in an amplifier will be depleted. When small signal gain $G_0 = \exp(\sigma \Delta N_0 L)$ is reduced by $1/\mathrm{e}$ ($\approx 37\%$) the amplifier is "saturated" and most available energy extracted. **Saturation fluence** describes the energy per unit area which saturates a laser medium,

$$F_{\text{sat}} = \frac{h\nu}{\sigma} = \frac{hc}{\lambda\sigma}, \tag{58}$$

where $h = 6.626 \times 10^{-34}$J/Hz is the Planck constant. The saturation fluence is typically $\sim 1000\times$ higher in solids than in gases. For 4-level solid state materials, $F_{\text{sat}} \sim 1 - 10$ J/cm^2.

Now we have two implications:

(1) If we require lots of energy, we need to use a large area beam or multiple beams in our amplifiers.

(2) We can't efficiently extract energy from a single amplifier in one pass starting with a small amount of input energy. We need to use a significant fraction of F_{sat} (say 10%) for efficient energy extraction.

8.2 Reuse a gain medium

Some elegant (but more complex schemes) re-use the gain medium several times to allow a very low energy pulse to build up to the point where it saturates the gain.

- **MOPA (master oscillator, power amplifier):** Run output of a few nJ to mJ energy oscillator through linear series of larger and larger amplifiers, expanding the beam in between.
- **Geometric re-use of the gain medium:** Find a way of passing an initially low-energy seed beam through a gain medium multiple times. Elegant, but be can complex to do.
- **Multi-pass and regenerative amplifiers:** Trap pulse in a cavity containing an amplifier, bounce it through gain medium multiple times, then "switch" out using a Pockells cell.
- **Scale up to multiple parallel beam lines:** Run many beams in parallel if required energy exceeds size of largest available single amplifier.

9 Laser material processing

9.1 Light matter interactions

To interact with bulk matter, light must first penetrate the surface, and the fraction of light in a beam able to do this is limited by the Fresnel reflectivity

$$R_f = \left(\frac{n_1(\lambda) - n_2(\lambda)}{n_1(\lambda) + n_2(\lambda)}\right)^2, \tag{59}$$

where n_1 and n_2 are the refractive indices either side of a boundary. Once past this boundary, the intensity of light in the medium then falls off as a function of propagation distance z and absorption coefficient α as follows

$$I(z) = (1 - R_f)\mathrm{e}^{-\alpha z}. \tag{60}$$

This sets a length δ into which the laser propagates and can deposit energy. This is closely related to the skin depth in a plasma or a metal.

9.1.1 Interaction regimes

- **Photothermal** ($\Delta t \gg T_{\text{therm}}$). The laser pulse are much longer than the thermalisation time, processes dominated by heating, melting, and vaporisation. Useful for cutting or welding, for purely thermal analysis.

- **Photochemical** ($\Delta t \ll T_{\text{therm}}$). Picosecond or femtosecond lasers or UV lasers with a photon energy $h\nu >$ chemical bond energy. Little heating, direct bond breaking through single or multi-photon processes – used for machining explosives !

- **Photophysical** ($\Delta t \sim T_{\text{therm}}$). Mixed regime, combination of thermal and bond-breaking processes. Note that some lasers deliver short pulses in a continuous train, which means both high average and high peak power.

9.2 Advantages and disadvantages of laser maching

- **Advantages:**
  - Cleaner cuts, narrower ”kerf” (slit made by cutting process).
  - Limited HAZ (heat affected zone) from tool friction.
  - No mechanical force on workpiece, useful for thin or fragile material, e.g. glass display panels, thin metal sheets.
  - Fast.
  - No tool wear.
- **Disadvantages:**

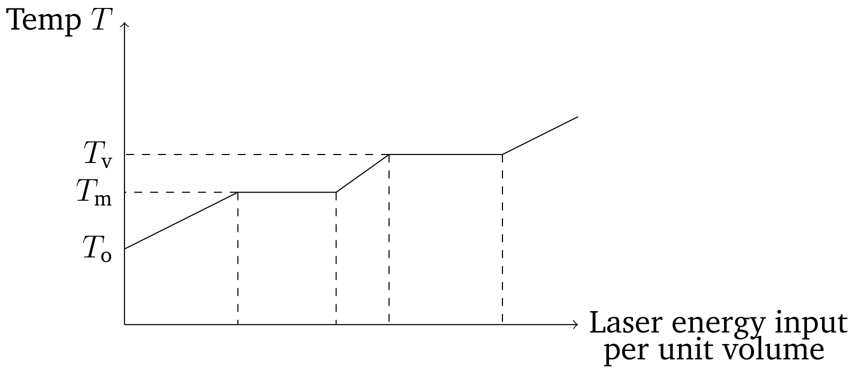

Figure 18: Simple analysis of energy input to material.

- Limited cutting depth $\sim$ Rayleigh length z_R.
- Additional safety measures needed in work environment.
- Initial tooling expense.

9.3 Energy input analysis

- Heat to melting point: $Q_\text{om} = \rho C_p(T_\text{m} - T_\text{o})$.
- Melting: $Q_\text{m} = \rho L_\text{m}$.
- Heat to vaporisation point: $Q_\text{mv} = \rho C_p(T_\text{v} - T_\text{m})$.
- Vaporisation: $Q_\text{v} = \rho L_\text{v}$.

9.3.1 Energy input for welding

We need to melt material at the edges of workpieces. Energy input required

$$Q_\text{weld} = Q_\text{om} + Q_\text{m} = \rho[C_p(T_\text{m} - T_\text{o}) + L_\text{m}]. \tag{61}$$

9.3.2 Energy input for cutting

Sum contributions to energy input to move material from room temperature through melt and onto vaporisation:

$$Q_\text{cut} = Q_\text{om} + Q_\text{m} + Q_\text{mv} + Q_\text{v} = \rho\left[C_p(T_\text{v} - T_\text{o}) + L_\text{m} + L_\text{v}\right]. \tag{62}$$

Consider volume of material thickness H to heat, swept out by chord width $2w_0$ (focal spot width) moving along surface at cutting speed V_c. The volume of material that we cut is $2w_0HV_c$. So, the power required is

$$P_\text{cut} = \frac{2w_0HV_cQ_\text{cut}}{\eta_\text{absorption}}. \tag{63}$$