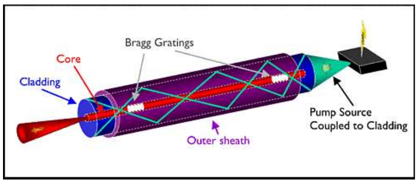
Chapter 4

Fiber laser

What is fiber laser?

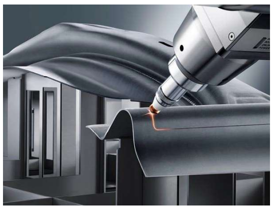
Fiber laser is a type of laser in which **the active gain medium is an optical fiber.**





Applications of fiber lasers

- Laser processing
- Laser surgery
- Laser countermeasure
- Fiber communication system
- ……




Development of fiber lasers

•In the early 1960s, Elias Snitzer et al of the American Optical Company put forward the concept of fiber laser.

•In the early 1970s, the research institutes of America and the Soviet Union began the relative research.

•From 1975 to 1985, fiber laser experienced a fast development owing to fast developed semiconductor laser technology and matured fiber fabrication process.

•In 1985, the research group of Southampton University firstly demonstrated a single mode fiber laser and then deployed some efforts on Q-switched, mode-locked and single longitudinal mode fiber lasers.

•In the late 1980s, the fabrication of fiber Bragg grating made the fiber laser with a compact all-fiber structure possible.

•In 1988, Elias Snitzer et al put forward the concept of double cladding fiber which made the high power fiber laser possible.

•In the early 1990s, with the development of the cladding pump technologies, the power levels of fiber laser had been improved with 4~5 orders of magnitude

•Now, the power of fiber laser has attained 30 kW.

Advantages of fiber lasers [光纤激光器的优点]

•High optical-to-optical conversion efficiency

•High surface area to volume ratio (i.e., great heat dissipation)

•Compact and flexible

•Excellent beam quality and stability

•Low cost

Types of fiber lasers [光纤激光器种类]

Different cavity structures:

•F-P cavity fiber laser

•Ring cavity fiber laser

•Figure-of-eight cavity fiber laser

Different gain media:

•Rare earth ions doped fiber laser

•Nonlinear effects based fiber laser

Different operation states:

•Continuous wave (CW) fiber laser

•Pulsed fiber laser

Different rare earth dopants:

•Er^{3+}-doped fiber laser

•Nd^{3+}-doped fiber laser

•Tm^{3+}-doped fiber laser

•Yb^{3+}-doped fiber laser

•Ho^{3+}-doped fiber laser

……

Different operation wavelengths:

•S-band fiber laser(1280~1350 nm)

•C-band fiber laser(1528~1565 nm)

•L-band fiber laser(1561~1620 nm)

•Mid-infrared fiber laser(2 μm~50 μm)

•Visible fiber laser (380 nm~760 nm)

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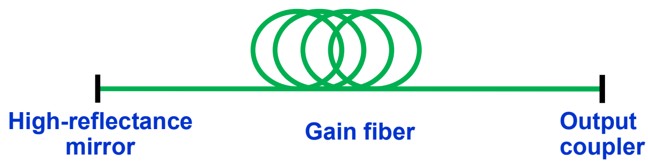
Typical structure of fiber laser



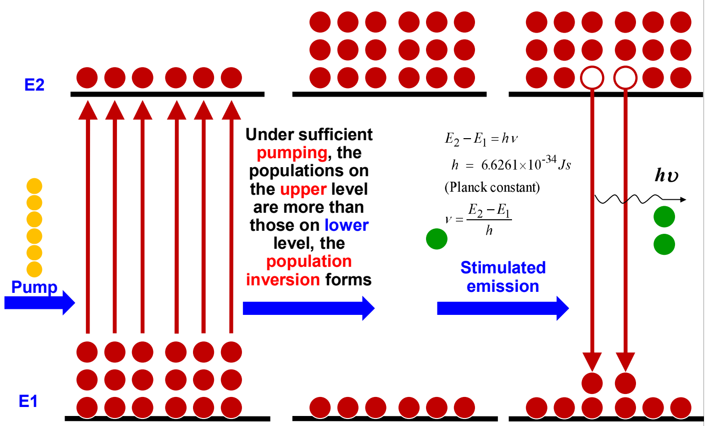
In our lessons, we mainly focus on the rare-earth doped F-P cavity fiber laser.

How dose a fiber laser work?

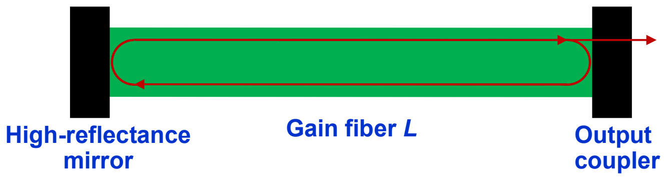
The basic elements

- Pump source: Population inversion
- Gain medium: Threshold condition of laser oscillation
- Resonant cavity: optical feedbacks

(1) Population inversion



(2) Optical feedbacks



Positive feedback obtained from optical cavity

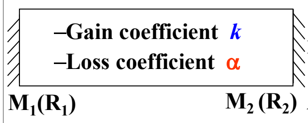
Fabry-Perot resonator -- Placing the gain medium between a pair of mirrors

Emitted photon is amplified as it passes through the gain medium and fed back by the mirrors

(3) Threshold conditions - laser losses

Total loss of the system due to a number of processes, including

1. Transmission at the mirrors (low reflectivity of mirrors)
2. Absorption and scattering at the mirrors
3. Absorption in the laser medium due to transition other than the desired transitions.
4. Scattering in the laser medium - this applies particularly to solid state lasers
5. Diffraction losses at the mirrors



From $M_1 \rightarrow M_2$, $\quad I = I_0 \exp[(k-\alpha)L]$

After reflection at M_2, $\quad I \rightarrow R_2 I_0 \exp[(k-\alpha)L]$

After a complete round trip $(M_1 \rightarrow M_2 \rightarrow M_1)$

$$G = \frac{\text{final irradiance}}{\text{initial irradiance}} = R_1 R_2 \exp[2(k-\alpha)L]$$

G > 1, a net amplification and the oscillation will follow

G < 1, the oscillation will die out

Threshold condition

k_{th}: threshold gain

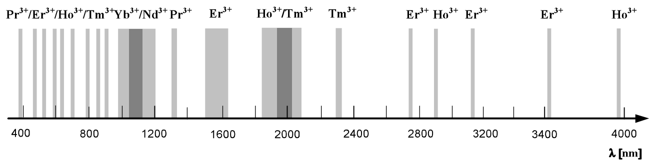
$$G = R_1 R_2 \exp[2(k_{\text{th}} - \alpha)L] = 1$$

$$k_{\text{th}} = \alpha + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

k_{th} low, easy to achieve laser action (mirror alignment is not critical and dust on mirrors can be tolerated)

k_{th} high, hard to get lasing (mirrors must have high reflectances and have to be scrupulously clean and carefully aligned)

Rare earth ions doped fiber laser



Common rare earth ions doped fiber lasers

(1)Er^{3+}-doped fiber laser

•Er^{3+}-doped fiber has a high gain at 1.55 μm waveband locating at the low loss transmission window.

•This type of fiber laser has been widely applied in fiber communication system.

(2)Yb^{3+}-doped fiber laser

•Yb^{3+}-doped fiber has a broad absorption band (800~1064 nm) and emission band (970~1200 nm)

•This type of fiber has a high operation efficiency and power level, thus has been widely applied in industry processing.

(3)Tm^{3+}-doped fiber laser

•Tm^{3+}-doped fiber has a very broad gain width at 2 μm waveband (1800~2200 nm) covering the absorption peak of water molecules (1940 nm).

•This type of fiber laser has great potential in laser surgery such as lithotripsy, soft tissue cutting, etc.

(4)Ho^{3+}-doped fluoride fiber laser

•Ho^{3+}-doped fluoride fiber has a mid-infrared emission band at 3 μm waveband which is located within the atmospheric transmission window (3~5 μm) and also covers the absorption peak of water molecule (2.94 μm).

•This type of fiber laser is suitable for atmospheric laser communication and laser surgery.

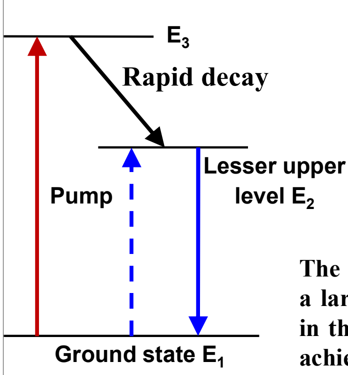
Common fiber laser systems are mainly the three-level and four-level systems .

- Three-level system: Er^{3+}, Tm^{3+}, etc.
- Four-level system: Yb^{3+}, Nd^{3+}, etc.

In our lessons, we will take the Er^{3+}- doped fibers as the examples to show how the three-level fiber laser systems work. [三能级系统]

- Three-level fiber laser system

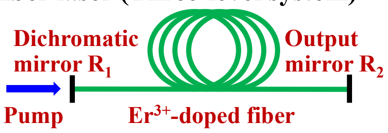
What is the three-level system?

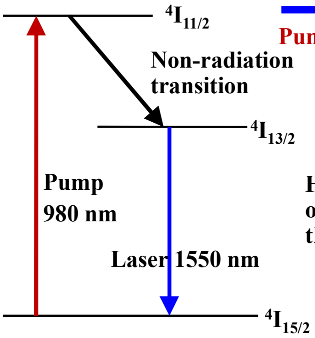


- **The lifetime of E_3 level is very short.**
- **The populations on E_3 level are released to E_2 level via non-radiation transition quickly.**
- **E_2 level is metastable level**

The rapid decay from E_3 to E_2 allows a large build up population of atoms in the metastable level E_2 in order to achieve inverse population of $N_2>N_1$.

Example: Er^{3+}-doped fiber laser (Three-level system)





How do we describe the operation of the Er^{3+}-doped fiber laser theoretically?

Rate equations (Describe the population density evolution on each laser level with the time t and position z) 速率方程

$$\frac{\mathrm{d}N_2(z,t)}{\mathrm{d}t}=-\frac{\eta_s\delta_e}{h\nu_s A}(P_s^+ + P_s^-)N_2+\frac{\eta_s\delta_a}{h\nu_s A}(P_s^+ + P_s^-)N_1+\frac{\delta_p\eta_p}{h\nu_p A}P_pN_1-\frac{N_2}{\tau_2}$$

$$N_1(z,t)+N_2(z,t)=N_t$$

- N_t is the total Er^{3+} ions dopant concentration
- N_1 and N_2 are the populations density on ground state ($^4I_{15/2}$) and metastable state ($^4I_{13/2}$) levels, respectively.
- δ_e and δ_a are the emission and absorption cross-sections of signal laser, respectively. δ_p is the absorption cross-section of the pump laser.
- P_p is the pump photons density, P_s^+ and P_s^- are the signal photons densities at the forward and backward directions, respectively.
- η_s and η_p are the overlap factors of signal and pump with the doped zone.
- v_s and v_p are the frequencies of the signal and pump lasers.
- τ_2 is the lifetime of the metastable state ($^4I_{13/2}$) level, A is the effective core area and h is the Plank constant.
- z is the position along the fiber axis.

Variation rate of the populations density on metastable state ($^4I_{13/2}$)

$$\boxed{\frac{\mathrm{d}N_2(z,t)}{\mathrm{d}t}}=-\boxed{\frac{\eta_s\delta_e}{h\nu_s A}(P_s^+ + P_s^-)N_2}+\boxed{\frac{\eta_s\delta_a}{h\nu_s A}(P_s^+ + P_s^-)N_1}+\boxed{\frac{\delta_p\eta_p}{h\nu_p A}P_pN_1}-\boxed{\frac{N_2}{\tau_2}}$$

Stimulated-emission rate

Re-absorption rate

Pump rate

Radiative and multiphonon relaxation rate[弛豫]

$$\frac{\delta_p\eta_p}{h\nu_p A}P_pN_1=\boxed{\frac{\delta_p\eta_p}{h\nu_p A}P_p}\times N_1$$

$$N_1(z,t)+N_2(z,t)=N_t$$

Absorbed pump population density per volume

The lifetime of excited state ($^4I_{11/2}$) level is very short, therefore all the populations on this level from $^4I_{15/2}$ level are quickly released to $^4I_{13/2}$ level, i.e., the $^4I_{11/2}$ is almost empty. So N_3 is almost equal to zero.

Power evolution equations

Describe the intra-cavity distributions of the pump and signal laser

$$\boxed{\frac{\mathrm{d}P_p(z)}{\mathrm{d}z}}=-\boxed{P_p\eta_p\delta_pN_1}-\boxed{\alpha_pP_p}$$

Pump loss per length

The absorbed pump power per unit length

Pump power evolution with the position

$$\boxed{\frac{\mathrm{d}P_s^+(z)}{\mathrm{d}z}}=\boxed{P_s^+\eta_s(\delta_eN_2-\delta_aN_1)}-\boxed{\alpha_sP_s^+}$$

Forward signal laser loss per length

The generated forward signal laser per unit length

Forward signal laser power evolution with position

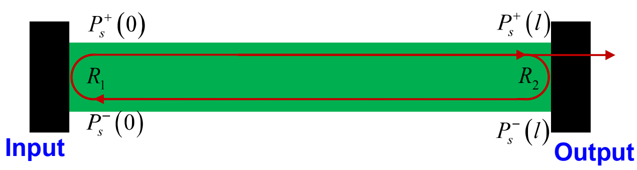
$$\boxed{\frac{\mathrm{d}P_s^-(z)}{\mathrm{d}z}}=-\boxed{P_s^-\eta_s(\delta_eN_2-\delta_aN_1)}+\boxed{\alpha_sP_s^-}$$

Backward signal laser loss per length

The generated backward signal laser per unit length

Backward signal laser power evolution with position

Boundary conditions:



In the FP cavity, there are a series of boundary conditions.

$$P_s^+(0)=R_1P_s^-(0)$$

$$P_s^-(l)=R_2P_s^+(l)$$

Solution:

(1) To solve the rate equations at the steady state, we can obtain

$$\frac{\mathrm{d}N_2(z,t)}{\mathrm{d}t}=0$$

$$N_2(z,t)=function2(P_s^+,P_s^-,P_p)$$

$$N_1(z,t)=function1(P_s^+,P_s^-,P_p)$$

(2) Substituting the above expressions into the power evolution equations.

(3) Combined with boundary conditions, using the four-order Runge Kutta algorithm, we can obtain

$$P_s^+(z),P_s^-(z),P_p(z)$$

Examples:

$N_t = 1.0\times10^{25}\,\mathrm{m}^{-3}$

$\delta_e = 6.5\times10^{-25}\,\mathrm{m}^2, \delta_a = 7\times10^{-25}\,\mathrm{m}^2, \delta_p = 1.75\times10^{-25}\,\mathrm{m}^2$

$\eta_s = 0.6, \eta_p = 0.811$

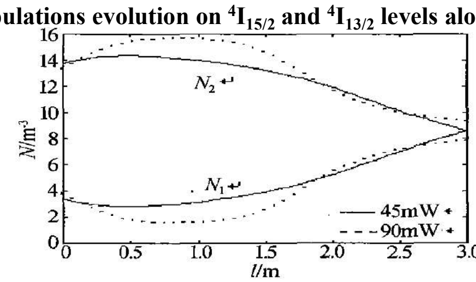
$\lambda_p = 980\ \mathrm{nm}, \lambda_s = 1550\ \mathrm{nm}$

$\tau_2 = 12\ \mathrm{ms}, A = 5.8\times10^{-11}\,\mathrm{m}^2, h = 6.626\times10^{-34}\,\mathrm{J\cdot s}$

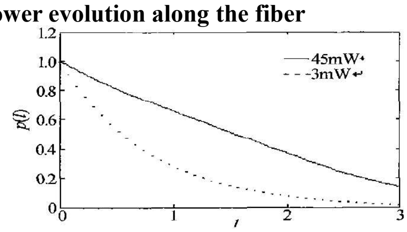
$R_1 = 0.98, R_2 = 0.04$

$\alpha_p = 1.1\ \mathrm{dB/km}, \alpha_s = 0.2\ \mathrm{dB/km}$

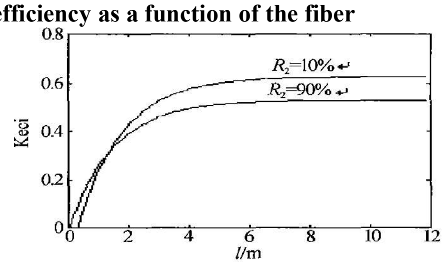
The populations evolution on $^4I_{15/2}$ and $^4I_{13/2}$ levels along fiber



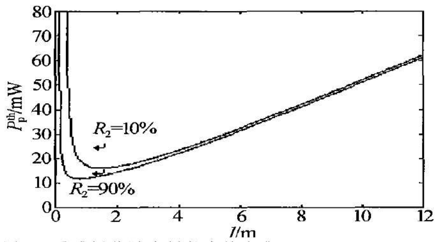
The pump power evolution along the fiber



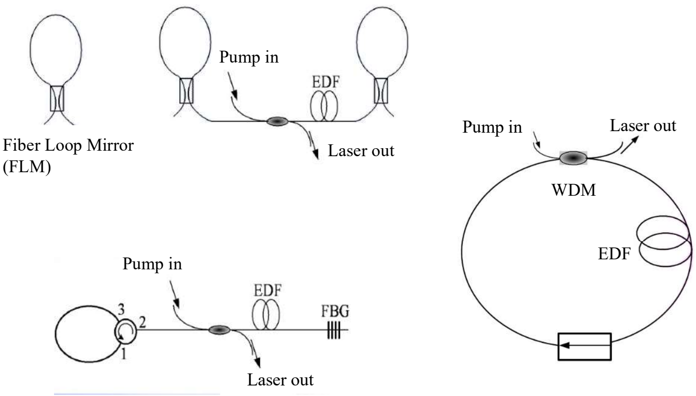
The slope efficiency as a function of the fiber



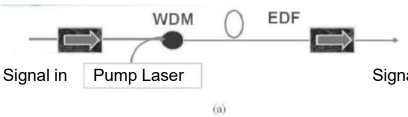
The laser threshold as a function of the fiber



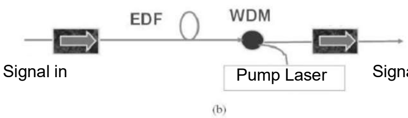
Cavity Structures



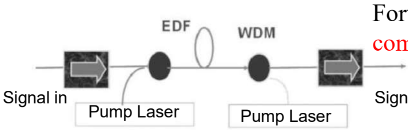
EDFA



Forward pumping: low noise, but easy to get gain saturation增益饱和



Backward pumping: high noise, but not easy to get gain saturation

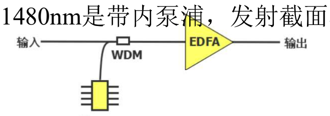


Forward & backward pumping: combine the advantages

Pump wavelength can be 980 or 1480 nm.

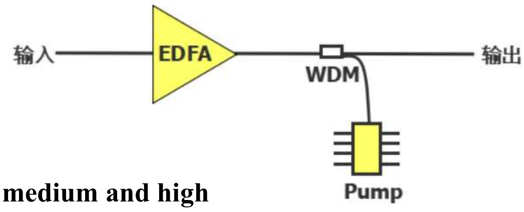
Pump lights at these two wavelengths can also be used together to get high efficient and low noise at the same time.

[Why?]另外，为什么泵浦光源的波长选在980nm或1480nm呢？其实，泵浦光源的波长可以是520nm、650nm、980nm、和1480nm，但实践证明波长1480nm的泵浦光源激光效率最高，次之是波长980nm的泵浦光源。&主要是由铒离子的能级差决定的，用1480是典型的二能级系统；而980是三能级系统。&980泵浦方式的功率转换效率高，噪声系数小&原因是980nm泵浦光可以使Er3+跃迁到三能级，粒子反转数较高。而1480nm泵浦的EDFA具有较高的噪声系数，因为1480nm是带内泵浦，发射截面不为0，离子数难以完全反转。



The pump light and signal light are injected into the erbium-doped fiber from the same end, and the pump light at the input end of the erbium-doped fiber is strong, so the particle inversion excitation is also strong, and the signal is strongly amplified as soon as it enters the fiber. However, due to the absorption factor, the pump light will be attenuated along the length of the fiber, so that the gain saturation is reached at a certain fiber length and the noise is increased.

The pump light and signal light of reverse pumping are pumped in from the opposite direction, when the optical signal is amplified to a very strong level, the pump light is also very strong, not easy to reach saturation, so the noise performance is better.



low, medium and high

泵浦方式	泵浦转化效率	噪声特性	输出功率
同向泵浦	低	低	低
反向泵浦	中	高	中
双向泵浦	高	中	高

The two pump light sources of bidirectional pumping are pumped in the forward and backward directions, respectively, so that the impurity particles in the EDFA are fully stimulated. This pumping method combines the advantages of codirectional pumping and reverse pumping, so that the pump light is evenly distributed in the optical fiber, so that the gain is also evenly distributed in the optical fiber.