Investigation of yb³⁺ doped fiber laser

Xu, Shao Bin

2008

Xu, S. B. (2008). Investigation of yb³⁺ doped fiber laser. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/20682>

<https://doi.org/10.32657/10356/20682>

INVESTIGATION OF Yb³⁺ DOPED FIBER LASER

XU SHAO BIN

School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Master of Engineering

2008

Acknowledgements

First and foremost I would like to thank my supervisor Assoc/Prof Tang Dingyuan, for his consistent support in my project during the times, without which I would not be able to write this thesis. Our numerous scientific discussions and his many constructive comments have greatly improved this work. And I am grateful to his generosity.

I'd like to thank Dr.George Chen, for the discussion on optical design and optical design course.

I also want to thank the school of EEE, the time spent here will be a valuable fortune for me.

Finally, I am forever indebted to my parents for their understanding, patience and encouragement when it was most required.

Table of Contents

Acknowledgements.....	i
Table of Contents.....	ii
List of Figures.....	iv
Summary	vi
Chapter 1. Introduction.....	1
1.1 Motivation.....	1
1.1.1 Brief history of fiber laser development	2
1.1.2 High power double clad silica fiber laser	3
1.1.3 Why ytterbium-doped fibers	5
1.2 Objective of the project and expected outcomes	6
1.3 Major contribution of the thesis.....	7
1.4 Organization of the thesis	7
Chapter 2. Theory and numerical simulations.....	9
2.1. Basic spectroscopy of Yb ions.....	9
2.2. Band diagram and rate equations.....	12
2.3. Numerical simulations of fiber laser.....	15
2.3.1. Equations for pump power and signal power	15
2.3.2. Simulation results and discussions.....	19
Chapter 3. High-power fiber laser design considerations.....	34
3.1. General design consideration.....	34
3.2. Diode laser optics.....	35
3.3. High power pump sources selection	41
3.3.1. Fiber pigtailed laser diode bar pump sources	41
3.3.2. Bare laser diode bar pump source	43
3.4. Double clad fiber design for high power purpose.....	44
3.4.1. Why double clad fiber.....	44
3.4.2. Fiber cladding shape design	48
3.4.3. Fiber cladding size	50
3.4.4. Fiber cladding N.A design	52
3.4.5. Doping concentration consideration	52
3.5. Pump coupling design.....	53
3.5.1. Laser diode array characteristics.....	53
3.5.2. Review on high power coupling solutions.....	55
Chapter 4 High-power fiber laser experiments.....	65
4.1. Pump source.....	65
4.1.1. Pump power distribution.....	65
4.1.2. Pump laser source cooling	67
4.1.3. Pump wavelength.....	68
4.2. Double clad fiber characteristics.....	69
4.3. Coupling optics	71
4.4. Backward pumped fiber laser	76
4.4.1. Experimental setup.....	76
4.4.2. Experimental results.....	80

4.5.	Forward pumped fiber laser	82
4.5.1.	Experimental setup.....	82
4.5.2.	Experimental results and analysis	84
4.6.	Comparison between the experimental results and the simulations	85
	Chapter 5. Conclusion and Recommendations.....	92
5.1.	Conclusion	92
5.2.	Recommendations for Future Research.....	93
5.2.1.	Raman fiber laser	93
5.2.2.	Pulsed fiber laser ---- Q switched fiber laser	94
	References.....	97

List of Figures

Figure 1-1 double clad fiber structure.....	4
Figure 2-1(a) Energy level structure	10
Figure 2-2 Energy Band diagram of Yb3+	13
Figure 2-3 Schematic illustration of the fiber laser geometry	16
Figure 2-4 Fiber laser configuration with R1=1.00 and R2=0.04	20
Figure 2-5 Powers evolution along 200 m fiber	21
Figure 2-6 Evolution of the pump, forward and backward powers along the 50 m laser fiber length.....	22
Figure 2-7 Output power vs. launched pump power.....	23
Figure 2-8 Fiber laser configuration of R1=0.04, R2=1.00	24
Figure 2-9 Evolution of pump, forward and backward power (R1=0.04, R2=1.00),	24
Figure 2-10 Output power vs. launched pump power.....	25
Figure 2-11 Evolution of powers along the fiber, R1=1.00, R2=0.60	27
Figure 2-12 Evolution of power along the fiber, R1=0.60, R2=1.00	28
Figure 2-13 Output power vs. output coupler reflectivity	29
Figure 2-14 Fiber laser output power as a function of fiber length	30
Figure 2-15 fiber laser maximum output power versus doping concentration	31
Figure 3-1 laser diode and astigmatism	37
Figure 3-2 (a) Origin of astigmatism of laser diode (b) astigmatism correction by using a cylindrical lens	39
Figure 3-3. Schematic diagram of the laser diode pumped double clad fiber.....	44
Figure 3-4 index profiles of single mode rare earth fiber and double clad rare earth fiber	46
Figure 3-5 fiber accept angle	47
Figure 3-6 various cladding shapes of double clad fiber	49
Figure 3-7 estimation of fiber cladding size	51
Figure 3-8 Schematic diagram of the laser diode pumped double clad fiber	53
Figure 3-9 laser diode array [36]	53
Figure 3-10 beam profile of a laser diode array [36].....	54
Figure 3-11 laser diode bar beam shaping concepts	57
Figure 3-12 nonparallel arrangement of collimating micro-lens to laser diode bar	58
Figure 3-13 micro lens beam shaping (Fraunhofer, Germany) [44].....	59
Figure 3-14 design schematic of micro lens beam shaping (Fraunhofer, Germany) [44]	61
Figure 3-15 Limo BTS micro lens product.....	61
Figure 3-16 micro lens beam shaping experiments - 1	62
Figure 3-17 micro lens beam shaping experiments - 2	63
Figure 4-1 pump power distribution (measured by LBA-PC beam profiler)	66
Figure 4-2 typical Gaussian power distribution.....	67
Figure 4-3 pump laser wavelength tuning	69
Figure 4-4 (a) absorption spectral of Yb double clad fiber; (b) cladding pumped fiber	70
Figure 4-5 Fiber end photo of double clad fiber (under microscope).....	71
Figure 4-6 simple geometrical optics calculation	73
Figure 4-7 coupling efficiency calculation	74

Figure 4-8 forward pumping fiber laser schematic.....	77
Figure 4-9 Launching optics.....	78
Figure 4-10 Double clad fiber and HR laser cavity mirror.....	79
Figure 4-11 Measure fiber laser output power and beam performance.....	80
Figure 4-12 reversed pumping fiber laser output.....	80
Figure 4-13 fiber laser spectrum.....	81
Figure 4-14 forward pumping fiber laser schematic.....	82
Figure 4-15 forward pumping fiber laser experimental setup.....	83
Figure 4-16 forward pumping fiber laser output power vs launched pump power.....	84
Figure 4-17 forward pumping fiber laser spectrum.....	85
Figure 4-18 fiber laser output power versus launched pump power in reverse pump at $N=1 \times 10^{26} \text{ m}^{-3}$	86
Figure 4-19 fiber laser pump and signal power evolution in forward pump at low doping $N=4 \times 10^{25} \text{ m}^{-3}$	88
Figure 4-20 fiber laser pump and signal power evolution in forward pump at high doping $N=1 \times 10^{26} \text{ m}^{-3}$	88
Figure 4-21 evolution of pump, signal power in reverse pump configuration at lower doping $N=4 \times 10^{25} \text{ m}^{-3}$	89
Figure 4-22 evolution of pump, signal power in reverse pump configuration at higher doping $N=1 \times 10^{26} \text{ m}^{-3}$	89
Figure 4-23 fiber laser output power as function of fiber length at $N=4 \times 10^{25} \text{ m}^{-3}$	90
Figure 4-24 fiber laser output power as a function of fiber length at $N=1 \times 10^{26} \text{ m}^{-3}$	90
Figure 5-1 schematic of raman fiber laser pumped by Yb fiber laser.....	94
Figure 5-2 active Q-switched Yb fiber laser.....	95

Summary

Fiber lasers now compete directly in several domains with semiconductor lasers and solid-state lasers, over which they present the advantages of high brightness, excellent mode quality, high efficient coupling into a single mode fiber, and a far superior wavelength stability with temperature. Ytterbium-doped fiber lasers are amongst the most efficient of all rare-earth doped fiber lasers. A wide range of application for this versatile laser source can be anticipated.

The objective of this thesis is to develop a diode-pumped, high power ytterbium-doped CW fiber laser, and through the development of the high power fiber laser to investigate the technical know-how related to the high power active fiber devices.

To gain a better understanding on the operation of high power fiber lasers, a theoretical model on the diode-pumped double-clad fiber lasers was set up. Numerical analysis on the operation of the fiber lasers, such as the optimum fiber length, optimum doping concentration, fiber laser output power dependence on different pump directions and dependence on different output coupler reflectivity are carried on. It was found that with backward pumping configuration, higher laser efficiency could be achieved.

Technical parameters and design considerations related to fiber design, pump source selection, high power laser diode beam shaping and coupling techniques were also discussed. Based on the numerical simulation results and fiber parameter available, a diode-pumped CW high power Yb-doped fiber laser was setup. Performance of the laser under different configurations was investigated. Under 30W reversed pumping, the laser has an output power of 12 Watt, with a slope efficiency of 78%. In forward pumping configuration under the same pump condition, the fiber laser has an output of about 8 Watt with a slope efficiency of 68.7%. The experimental result is in agreement of the theoretical simulations.

Comparing the experimental results and numerical simulations obtained under different Yb-doping concentrations, we found that with our available pump power and a fiber length of 50 m, the optimized Yb-doping concentration is close to $1 \times 10^{26} \text{m}^{-3}$.

Chapter 1. Introduction

1.1 Motivation

Rare-earth doped fibers are at the core of a new and rapidly expanding branch of optics. By combining the optical gain of rare earth ions with the optical confinement of a single mode optical fiber, these fibers offer a fascinating medium with which devices that are both very small and extremely efficient are made. Because of their efficiency, compactness, mechanical and thermal stability, and excellent coupling to single mode communication fibers, these devices are now expected to play a fundamental role in several important commercial applications. Considerable work on the general subject of rare earth doped fibers has been carried out around the world, in both academic and industrial environments, and in both research and product development.

A fiber laser is the laser that uses the rare earth doped optical fiber as its gain medium. They can operate with low thresholds, and yet be pumped to produce high output powers, with optical conversion efficiencies greater than 50% ([1], P₁₁₃). Furthermore, the numerous laser transitions available from trivalent rare earth ions lend them the ability to generate light over a wide selection of wavelengths, from the ultraviolet (UV) to the mid-infrared (mid-IR), with broad tuning ranges. Pumped with a laser diode, they retain the advantage of compactness, low cost, and ease of large-scale manufacturing.

Traditionally fiber lasers are labeled as low power laser and have limited applications and commercial interest. The recent development of high power, high brightness multimode semiconductor lasers in combination with the development of cladding pump technology of fiber lasers have greatly changed the situation. Now high power fiber laser

(with CW power as high as 110 watts) has already been demonstrated [2]. Furthermore, super high power fiber lasers (with CW power of 2000 watts and 6000 watts) have emerged as products last year with so called multi-fiber pump technology [3]. Because in a fiber laser the lasing mode is restricted by the fiber core, which is normally several micrometers in diameter, the output of a fiber laser has very good beam quality. Even strong environmental perturbations will not disturb the beam quality. What makes a high power CW fiber laser even more attractive is its simplicity and absence of thermal lens effect. Because of the small fiber core and the long fiber length, heat deposition in unit length is reduced. Even in the high power operation of fiber lasers no external water-cooling is required, which significantly reduce the complexity of the laser design. Other problems associated with the high power solid-state lasers, such as the pump beam inhomogeneity, bad beam quality etc., do not exist in fiber lasers.

Fiber lasers now compete directly in several domains with semiconductor sources, over which they present the advantage of high brightness, excellent mode quality, high efficient coupling into a single mode fiber, and a far superior wavelength stability with temperature. In addition, widely tunable high power fiber lasers are attractive laser source for various applications.

1.1.1 Brief history of fiber laser development

The field of rare earth doped fibers did not fully emerged as a significant research area until 1985, when several laboratories, following the lead of Southampton University (UK) and British telecommunication Research Laboratories, combined ion-doping techniques with the mature single mode fiber drawing technology to produce the first low loss rare

earth doped fibers. These fibers were developed in response to a strong need for miniature, stable source and amplifiers compatible with standard single mode fibers for optical telecommunication systems, in part because their low pump power requirement make possible excitation with a readily available diode laser to meet the important requirement of compactness. Since then, an impressive array of novel devices has come out of this sustained effort, including fiber amplifiers and sources of tunable, CW, Q-switched, or mode-locked types operating over broad ranges of wavelengths. Particularly noteworthy is the important erbium doped fibers and devices, especially amplifiers, for use in telecommunication systems in the low-loss region of glass near $1.55\mu\text{m}$.

Today, fiber lasers have received considerable attention for numerous potential applications in optical communication, sensing, medicine, material processing, imaging, data storage, and laser ranging.

1.1.2 High power double clad silica fiber laser

This thesis is mainly about a high power Yb-doped double clad continuous wave (CW) silica based fiber laser.

Silica-based fibers are excellent candidates for high power fiber lasers for two basic reasons. First, they have an extremely high optical damage threshold, and second, their high surface/volume ratio makes heat dissipation very effective.

However, in a conventional fiber laser, the pump light is coupled into the fiber core, which imposes a major limitation on the maximum pump power that can be launched into the fiber. The reason is the coupling efficiency from a laser diode into the single mode fiber core (which is several micrometers in diameter). Several years ago Snitzer and co-

workers demonstrated a clever solution to this problem [4]. It involved what they called a double clad fiber.

Figure 1-1 double clad fiber structure

The figure above shows the structure of a standard double clad fiber. It consists of a rare earth doped fiber core, an un-doped first cladding, a second cladding with refractive index lower than index of core and index of first cladding, and coating. The left lower part of this figure is the index map of such double clad fiber. Detailed description and discussion of double clad fiber will be put in section 3.4. The outstanding benefit of this design is that because the area of the first cladding is typically several tens to 100 times larger than the core area, and because of its large NA, it is possible to inject a substantial fraction of the output power of a large area laser diode, such as a laser diode array, into the first cladding. The first cladding forms a second, highly multimode waveguide. Pump light is now efficiently coupled into the first cladding. As it travels down this cladding,

pump light, which is distributed over a large number of modes, overlaps spatially with the doped core and is absorbed by the dopant.

The price for this increased pump coupling efficiency is an increase in fiber length. Because the spatial overlap between the pump and the dopant is small, the pump power absorbed per unit length is reduced compared with a core-pumped fiber, and a longer fiber is required to excite the same total number of dopant ions. Since their inception, double clad fiber have produced lasers with several rare earth ions, and become the major fiber structure of high power fiber laser.

1.1.3 Why ytterbium-doped fibers

The main reason to choose Yb-doped fiber is that it has the highest efficiency and gain. Ytterbium is one of the most versatile ions in a silica-based host. It offers several very attractive features, in particular an unusually broad absorption band that stretches from below 850nm to above 1070nm because of the $^2F_{5/2} \rightarrow ^2F_{7/2}$ transitions. Yb-doped silica fibers can thus be pumped with a wide selection of solid-state lasers. The Yb-doped fiber laser, therefore, can generate many wavelengths of general interests: for example, for spectroscopy or for pumping other fiber lasers and amplifiers [5].

Yb^{3+} has abnormally high absorption and emission cross-section. Another well-known advantage of Yb^{3+} is the simplicity of its energy level diagram. Yb^{3+} exhibits only a ground state and metastable state; all other levels are in the UV. The absence of higher energy levels greatly reduces the incidence of multi-phonon relaxation and excited state

absorption. These combined features allow for very strong pump absorption and very short fiber lasers, and should facilitate the development of high power fiber lasers.

All these features of Yb^{3+} that are suitable for high power laser have been verified by growing power of Yb-doped fiber lasers developed by laboratories and commercial institutes all over the world.

In a word, Ytterbium-doped fiber lasers are amongst the most efficient of all rare-earth doped fiber lasers. And such a high power rare earth doped fiber laser will be a powerful tool for a large number of research works on fiber properties, and the beam shaping and fiber coupling techniques developed in this project will benefit all the diode pumped solid state laser (DPSSL) projects.

1.2 Objective of the project and expected outcomes

The objective of this project is to develop a compact, diode-pumped, high power ytterbium-doped CW fiber laser, and further to use the developed high-power fiber laser to study the nonlinear optical effects in optical fibers, such as the fiber-based wavelength conversion.

Through the development of high power fiber lasers, techniques related to rare earth doped fiber devices will be investigated. Worldwide, the technique know-how is a commercial secret. We hope that through this project, various parameters, technological hurdles and other related issues in high-power fiber laser technology can be explored.

Our target is to design and develop a continuous wave fiber laser that has output power of more than 10 Watts under a 30 Watts pumping, or even as high as 20 Watts with stronger pumping. This target is attractive both for the research and application purpose.

It is expected that with further power scaling, even higher power of CW fiber lasers can be realized.

1.3 Major contribution of the thesis

The high power double clad fiber laser was modeled numerically, and the simulation results were used to guide our high power fiber design and experiments.

The high power fiber laser design considerations were discussed in detail. These include the double clad fiber design, pump source selection and beam shaping, pump coupling design. Among these discussions, results obtained in the pump source selection and beam shaping will benefit not only the fiber laser development but also other diode pumped solid state laser development.

A CW high power fiber laser was setup. Performance of the laser under different configuration was investigated. In addition to the laser experiments, other experiments such as beam shaping of bare laser diode bar were also carried on. All these works give a solid foundation of further research on laser diode pump solid state lasers.

1.4 Organization of the thesis

The thesis is organized as following: We give a brief introduction on the history of the high power fiber lasers and the significance of the study. Based on which the motivation and the objectives of the thesis are stated in Chapter 1. Chapter 2 presents the theory of the double clad fiber lasers where rate equations model of the high power double clad fiber lasers is derived, numerically studied, and the simulation results are discussed. In

Chapter 3, the design considerations of high power fiber lasers were discussed. It starts from the fiber design, pump source selection, and then high power laser diode beam shaping. Based on these design considerations, a high power fiber laser was designed in Chapter 4. Both 12W CW output for a fiber laser under backward-pumping configuration and 8W CW output under the forward-pumping configuration have been achieved. Experimental results were analyzed and compared with the simulation results. Finally, conclusions and recommendations for future work are given in Chapter 5.

Chapter 2. Theory and numerical simulations

2.1. Basic spectroscopy of Yb ions

Silica glass is an ideal host for Yb^{3+} , although other host materials are also the subject of investigation, e.g., fluoride glasses in fiber form and numerous crystalline hosts for use in bulk or wave guide form. This thesis concentrates exclusively on Yb^{3+} : silica fibers.

Fig.2.1 shows the energy spectroscopy of the Yb^{3+} ion. Compared to other rare-earth ions, Yb^{3+} energy level is rather simple. For all optical wavelengths, only two level manifolds are relevant: the $^2F_{5/2}$ excited state and the $^2F_{7/2}$ ground-state manifold. These consist of three and four sublevels, respectively, as shown in Fig.2.1 (a). The corresponding transitions between sublevels are not fully resolved for Yb^{3+} ions in a glass host at room temperature because of the strong homogeneous and inhomogeneous broadening. Fig.2.1 (b) shows the cross sections for absorption and emission of Yb^{3+} in a germanosilicate glass. The absorption cross section has been obtained from a white-light absorption spectrum in a fiber [6]. The spectral shape of the emission was obtained from a fluorescence spectrum in the side light of a fiber, thus avoiding any distortion due to re-absorption. It should be noted that the details of

the absorption and emission spectra depend to some extent on the host glass composition.

Figure 2-1(a) Energy level structure

The Yb^{3+} energy level structure, consisting of two manifolds, the ground manifold $^2F_{7/2}$ (with four stark levels, labeled (a)-(d)), and a well separated excited manifold $^2F_{5/2}$ (with three stark levels labeled (e)-(g)).

Figure 2-1(b) The Yb³⁺ absorption and emission cross-sections

In figure 2.1.(a) and (b), the most obvious features of the absorption and emission spectra have been labeled (A)-(E) [5]. (A), the narrow line at 975 nm in both absorption and emission, corresponds to transitions between the lowest stark levels in each manifold. The absorption peak at shorter wavelengths (B) corresponds to transitions from level a to f and g, while the long wavelength shoulder in the absorption spectrum (C) corresponds to transition from level b. Laser action on the narrow peak at 975 nm (A), where emission is into the lowest stark level, is truly three-level in character. The second peak in the emission spectrum (D), with its tail extending out to 1150 nm, corresponds to transitions from level e to b, c, and d. laser action on these transitions becomes nearly four level in character at longer wavelengths, as the emission is into essentially empty levels c and d. transitions from level f are also evident (E), although very weak due to the small thermal population of the level, and laser action has not been observed on transitions from that level. In

general, in order to generate a particular laser emission wavelength, there is a wide choice of possible pump wavelengths ranging from 800 nm to 1064 nm. The slope efficiency with respect to absorbed pump power of Yb^{3+} lasers is usually dominated by the energy ratio between the laser photon and the pump photon, thus slope efficiency can be improved by pumping at wavelength close to the laser wavelength. In figure 2-1(b), pump at A with highest absorption, but due to possibility of life time quenching [21] [22] and high ASE (amplified spontaneous emission), it is not easy to operate. Pumping at C with lowest absorption, which means in order to get enough absorption and achieve high power operation, the fiber length will be longer than those pumps at A and B. Considering both absorption efficiency and laser efficiency at certain absorbed pump power, pumping at wavelength B is a suitable choice. And the pump wavelength 937nm in our fiber laser experiments in Chapter 4 is based on such consideration.

2.2. Band diagram and rate equations

Many theoretical models have been developed to simulate fiber amplifiers and fiber lasers. The general approach of modeling fiber laser is similar to modeling bulk lasers: by combining the laser rate equations, which describe the ground-state and excited-state populations of the laser ions, with the equations of evolution of the pump power and laser signal power along the gain medium [7][8].

Most published works which model fiber lasers concentrate on low-power fiber laser [8] and often ignore scattering losses [9] or the effect of some other laser parameters. In this thesis, we present a model more suitable for high power fiber laser.

The theoretical analysis is based on a spatial dependent rate equation model.

Figure 2-2 Energy Band diagram of Yb³⁺

Based on the Yb³⁺ spectroscopy described in previous section, the energy band diagram for the active lasing material is shown in Fig.2.2 above.

The evolution of Yb³⁺ populations in the energy bands is determined by several types of transitions described in Fig.2.2, such as stimulated emission and absorption, spontaneous emission and stimulated emission at the pump wavelength.

The relevant parameters defined here are as follows:

σ_{ep} and σ_{ap} are the emission and absorption cross-sections at pump wavelength, σ_{el} and σ_{al} are the emission and absorption cross-sections at lasing wavelength.

The upper lasing level population density is given by N_2 , with spontaneous lifetime of τ_2 . The ground level population density is given by N_1 . Here, we assume the total density of Yb³⁺ ions is N . Usually the doping concentration N (per unit volume) is constant, independent of position z along the fiber core.

For continuous wave (CW) lasers, the set of time-dependent rate equations describing the population change is given in (2.1)-(2.3),

$$N = N_1(z) + N_2(z) \quad (2.1)$$

$$\frac{\partial N_1(z)}{\partial t} = N_2(z) \cdot (\sigma_{ep} \cdot I_p + \sigma_{el} \cdot I_s + \frac{1}{\tau_2}) - N_1(z) \cdot (\sigma_{ap} \cdot I_p + \sigma_{al} \cdot I_s) \quad (2.2)$$

$$\frac{\partial N_2(z)}{\partial t} = N_1(z) \cdot (\sigma_{ap} \cdot I_p + \sigma_{al} \cdot I_s) - N_2(z) \cdot (\sigma_{ep} \cdot I_p + \sigma_{el} \cdot I_s + \frac{1}{\tau_2}) \quad (2.3)$$

Where I_p and I_s are the pump and laser light intensity respectively, they can be expressed with pump power P_p and signal power P_s by $I_p = \frac{P_p \cdot \Gamma_p}{h\nu_p \cdot A}$ and

$I_s = \frac{P_s \cdot \Gamma_s}{h\nu_s \cdot A}$. Here P_p and P_s are pump and signal power. ν_p and ν_s are pump

frequency and lasing frequency respectively. h is planck's constant. A is the area of the doped fiber core. The parameters Γ_p and Γ_s are the power filling factors for the pump and signal. Γ_p is the fraction of the pump power actually coupled into the doped core, which is given by the ratio between the area of the core and that of the multimode first cladding.

The generated and amplified laser light is concentrated mainly in the core, with power density $P_s^\pm(z, \lambda)$ per unit wavelength, and power-filling factor Γ_s , which is given by the LP_{01} mode. Typically $\Gamma_s < 1$; and for double clad fibers, $\Gamma_p \ll \Gamma_s$ [7] [8] [9] [10].

At steady state, $\frac{\partial N_1(z,t)}{\partial t} = \frac{\partial N_2(z,t)}{\partial t} = 0$, and the steady-state solution of the rate

equations are

$$N_2(z) = \frac{\sigma_{ap} \cdot I_p(z) + \sigma_e \cdot I_s(z)}{(\sigma_{ep} + \sigma_{ap}) \cdot I_p(z) + (\sigma_e + \sigma_a) \cdot I_s(z) + \frac{1}{\tau}} \cdot N \quad (2.4)$$

$$N_1(z) = \frac{\sigma_{ep} \cdot I_p(z) + \sigma_e \cdot I_s(z) + \frac{1}{\tau}}{(\sigma_{ep} + \sigma_{ap}) \cdot I_p(z) + (\sigma_e + \sigma_a) \cdot I_s(z) + \frac{1}{\tau}} \cdot N \quad (2.5)$$

2.3. Numerical simulations of fiber laser

2.3.1. Equations for pump power and signal power

A typical fiber laser configuration is shown in Fig.2.3. We assume that the pump power P_p at wavelength λ_p is coupled into the first cladding at $Z=0$. Z measures the length along the fiber. $P_s^+(z)$ and $P_s^-(z)$ are the signal powers propagating in the positive and negative z direction. R_1 and R_2 represent the two feedback mirrors of the laser. The fiber laser has a cavity length of L .

Figure 2-3 Schematic illustration of the fiber laser geometry

The rate equations in last section describes the populations along the Yb fiber, in order to understand the pumping and signal evolution within the fiber laser, we further introduce another set of space dependent rate equations to describe the pump and signal in fiber laser. [17] [18].

Assuming a signal light beam with intensity I_s at wavelength λ_s go through a slice of Yb fiber of length of dz , upper level atomic population density N_2 and lower level population density N_1 , the light intensity change dI_s is given by [19] [20]

$$dI_s = (\sigma_{ep} N_2 - \sigma_{ap} N_1) I_s dz$$

$$\frac{dI_s}{dz} = (\sigma_e N_2 - \sigma_a N_1) I_s$$

The term $g = (\sigma_e N_2 - \sigma_a N_1)$ represents the signal gain coefficient, since as described before $I_s = \frac{P_s \cdot \Gamma_s}{h\nu_s \cdot A}$, Γ_s is power-filling factor, and then the signal power in

the Yb fiber laser can be described as

$$\frac{dP_s(z)}{dz} = P_s(z) \cdot \Gamma_s \cdot (\sigma_e \cdot N_2(z) - \sigma_a \cdot N_1(z))$$

With the same analysis, the pump power can be described as

$$\frac{dP_p(z)}{dz} = P_p(z) \cdot \Gamma_p \cdot (\sigma_{ep} \cdot N_2(z) - \sigma_{ap} \cdot N_1(z))$$

Where $P_p(z)$ is the pump power at position z , Γ_p is the fraction of the pump power actually coupled into the doped core.

Further considering amplified spontaneous emission $\Gamma_s \cdot \sigma_e \cdot N_2(z) \cdot P_0$ and scattering loss at signal wavelength $\alpha_s \cdot P_s$ (α_s is scattering loss coefficient), the equations describing the pump, forward and backward signal power changes in the laser are:

$$\frac{dP_p(z)}{dz} = P_p(z) \cdot \Gamma_p \cdot (\sigma_{ep} \cdot N_2(z) - \sigma_{ap} \cdot N_1(z)) - \alpha_p \cdot P_p(z) \quad (2.4)$$

$$\frac{dP_s^+(z)}{dz} = P_s^+(z) \cdot \Gamma_s \cdot (\sigma_e \cdot N_2(z) - \sigma_a \cdot N_1(z)) + \Gamma_s \cdot \sigma_e \cdot N_2(z) \cdot P_0 - \alpha_s \cdot P_s^+(z) \quad (2.5)$$

$$\frac{dP_s^-(z)}{dz} = -P_s^-(z) \cdot \Gamma_s \cdot (\sigma_e \cdot N_2(z) - \sigma_a \cdot N_1(z)) - \Gamma_s \cdot \sigma_e \cdot N_2(z) \cdot P_0 + \alpha_s \cdot P_s^-(z) \quad (2.6)$$

The power density P_0 represents the contribution of the spontaneous emission into the propagating laser mode and is given by $P_0 = \frac{2hc^2}{\lambda^3}$, here the factor of 2 is due to the two orthogonal polarization directions. h is Plank's constant, and c , is the speed of light in vacuum. It comes from that $P_0 = 2h\nu \cdot \Delta\nu_s$. And $\Delta\nu_s$ is the gain bandwidth [7] [13] [14] [15] [16].

In the case of laser operation, equations (2.4) to (2.6) are to be solved subject to the boundary conditions

$$P^+(0) = R_1 \cdot P^-(0) \quad (2.7)$$

$$P^-(L) = R_2 \cdot P^+(L) \quad (2.8)$$

Where R_1 , R_2 are the power reflectivity of the laser output mirror and input mirror at $z=0$ and $z=L$. In practical lasers, R_1 is realized by a fiber Bragg grating or a reflector mirror butted to the end of the fiber, R_2 is clear cleaved fiber end (reflectivity is 4%) or also a fiber Bragg grating. And it may have very narrow response (less than 1 nm), which provides the possibility of narrow line-width laser output.

To simulate the operation of high-power fiber lasers, the coupled equations are integrated by Runge-Kutta method [11] [12] [16]. The evolution of the pump and signal powers in the laser cavity are obtained. From these results the fiber laser output power is further determined.

The parameters used in the simulations of this thesis are given in Table 2.1

Parameter	λ_p	λ_s	τ	σ_{ap}	σ_{ep}	σ_e	σ_a
Value	940nm	1090nm	1×10^{-3} s	$6 \times 10^{-21} \text{cm}^2$	$2.5 \times 10^{-22} \text{cm}^2$	$2 \times 10^{-21} \text{cm}^2$	$1.4 \times 10^{-23} \text{cm}^2$

Parameter	A	N	α_p	α_s	Γ_p	Γ_s	L	R_1	R_2
Value	$5 \times 10^{-7} \text{cm}^2$	$4 \times 10^{19} \text{cm}^{-3}$	$3 \times 10^{-5} \text{cm}^{-1}$	$5 \times 10^{-5} \text{cm}^{-1}$	0.0014	0.82	50 m	1.00	0.04

Table 2-1 Fiber laser parameters used in simulation

In table 2.1, λ_p and λ_s are the pump and laser wavelengths. A is the area of the fiber core used in the experiment (diameter of the core estimated to be $8\mu\text{m}$). Because

the fiber supplier kept the doping concentration and some other parameters as commercial secrets, exact values of them are unknown, we choose doping concentration N as $4 \times 10^{25} \text{ m}^{-3}$, which is a medium value that can generate enough gain for high power fiber laser operation but far from concentration quenching (we will discuss concentration quenching in detail in section 2.3.2.4). Γ_p is calculated from the $A_{\text{core}}/A_{\text{clad}}$ used in our experiment. Γ_s is calculated from the LP_{01} mode ([7], P₃₁, P₅₈₇) as described in last section. L is the fiber length used in experiment. Absorption and emission cross sections are from Yb fiber spectroscopy. Yb upper state lifetime τ is from references [1].

2.3.2. Simulation results and discussions

The numerical model is useful. By simply varying the values of some key parameters, the major features of the fiber laser can be predicted. Thus it can provide a guide for our fiber laser design and experimental works. This is the main objective of the simulation.

In order to achieve this objective, we have taken as many parameters as possible the same value of the practical fiber laser. For those parameters that the supplier has kept for business secret and we have no equipment to measure (e.g. Yb ions doping concentration in double clad fiber), they are selected from references after a careful review of the available experimental data [5] [6]. The impact of these parameters on the fiber laser performance is also investigated.

In this section, we present the simulation results of our fiber laser under different pump configuration and laser parameters, to find out impacts of various laser parameters such as reflectivity, fiber length, pump power and pump direction on fiber

laser output. All the simulation result figures in this section are obtained from equation (2.4), equation (2.5) and equation (2.6) with boundary condition of equation (2.7) and equation (2.8), by using Matlab 7.0.

Since the maximum pump power of our pump source is 30 Watts, so most of the maximum pump power in following calculations (if not specified) are assumed to be 30 W, further calculations under higher pump powers can be carried out by simply modify the simulation parameters in Matlab scripts.

2.3.2.1 Effect of different pump directions

We firstly investigated the effects of pump direction on the fiber laser performance.

a) Forward pump configuration at $R_1=1.00$, $R_2=0.04$

Figure 2-4 Fiber laser configuration with $R_1=1.00$ and $R_2=0.04$

A forward pump fiber laser configuration is shown in figure 2.4. In this case, pump is injected from the mirror of high reflectivity; laser output is from the mirror R_2 with lower reflectivity. Here the $R_2=0.04$ is from a bare fiber end with 4% Fresnel reflection, in our fiber laser experiment with forward pumping configuration, bare fiber end is taken as output coupler, the input mirror R_1 has high transmission @ pump wavelength and high reflectivity $R_1 \geq 99\%$ @ the lasing wavelength.

Figure 2-5 Powers evolution along 200 m fiber

Figure 2.5 is the variation of the pump power $P_p(z)$ and the signal powers $P_s^+(z)$ and $P_s^-(z)$ along a 200 m fiber length. Note that the positive signal power reaches a maximum of over 17 Watts at $Z=70$ m, after that the signal power attenuates slowly despite of the fiber length increase due to the depletion of the pump power and the scattering losses. Thus, for fiber laser design, it is reasonable to take a piece of fiber with similar length to get the optimum output power with the lowest cost. We will discuss details of the optimum length calculation at the end of this section. In order to guide our experiment design, the following discussions are all limited to 50 m fiber length, which is the exact fiber length used in our experiments.

Figure 2-6 Evolution of the pump, forward and backward powers along the 50 m laser fiber length

(Pump injected from $R_1=1.00$, laser output from $R_2=0.04$)

Figure 2.6 is the variation of the pump power $P_p(z)$ and the signal powers $P_s^+(z)$ and $P_s^-(z)$ along the 50 m-laser length. The pump power is injected at $z=0$, through the $R_1=1.00$ @ 1090nm mirror, which is transparent at $\lambda = \lambda_p$ as figure 2.4 shows.

Figure 2-7 Output power vs. launched pump power

In figure 2.7 we present the power output $P_{OUT}^+ = P_s^+(L)(1 - R_2(\lambda_s))$, as a function of the pump power. The pump light is injected from the $R_1 = 100\%$ @ 1090nm mirror, and the laser output emerges from the cleaved fiber end with $R_2 = 4\%$. In this case the lasing threshold is $P_p(0) = 420\text{mW}$. The achievable output power at 30 W pump is 13.1 W. The slope efficiency is 43.71% with respect to the launched pump power.

b) Backward pump direction $R_1=0.04$, $R_2=1.00$

Next, we consider a configuration in which the laser output is from the same side where the pump light is injected as shown in figure 2.8. This configuration is used in our experiment.

Figure 2-8 Fiber laser configuration of $R_1=0.04$, $R_2=1.00$

In this case, the laser beam is separated from the pump by a 45-degree dichoric beam splitter, which has 95% transmission @ 940nm and 99% reflection @ 1090nm.

The same kind of calculations as presented previously are conducted, except that the $R_1=0.04$ mirror (bare fiber end with 4% Fresnel reflection) acts now both as the pump inject mirror and the laser output coupler.

Figure 2-9 Evolution of pump, forward and backward power ($R_1=0.04$, $R_2=1.00$),
(Pump injected from $R_1=0.04$, laser output from $R_2=1.00$)

Figure 2.9 shows the evolution of powers along the fiber length. Note that both the pump power and the negative direction signal power reach the maximum near the $R_1=0.04$ mirror.

Figure 2.10 is the laser output power as a function of the launched pump power. In this case the laser output power is $P_{\text{out}}=P_s^-(0) \times (1-R_1)=0.96 \times P_s^-(0)$. Lasing threshold is 440 mW. The achievable output power under 30 W pump is 15.4 W, and the optical-to-optical conversion efficiency is 51.21%. Both the threshold power and the output power are higher than those of the previous case. Because the pump and signal run twice of the fiber length, there is more scattering loss than forward pump configuration in (a), so it has higher threshold. And also, such double-passage makes the fiber laser get more pump absorption and thus higher output power.

Figure 2-10 Output power vs. launched pump power
(Pump injected from $R_1=0.04$, laser output from $R_1=0.04$)

2.3.2.2 Effect of the output coupler reflectivity

For bulk lasers, there exists an optimum output coupling reflectivity. Here we discuss the relation between the output power and the reflectivity of output coupler of a fiber laser.

We calculate the fiber laser output power in two situations as discussed in the previous section. One is $R_1=1.00$ and R_2 vary from 0.04 to 1.00; another is R_1 vary from 0.04 to 1.00 and $R_2=1.00$. In both configurations, pump is injected from R_1 .

a) $R_1=1.00$ and R_2 varies from 0.04 to 1.00, and the output coupler is R_2

This is the laser configuration shown in figure 2.4, the pump is injected from the $R_1=1.00$ @ 1090nm (transparent at 940 nm) mirror and the laser outputs from the R_2 mirror. In the calculation, we vary R_2 from 0.04 to 1.00 (@ 1090nm) while keep R_1 unchanged.

Figure 2.11 shows the evolution of powers along the fiber when R_2 is selected as $R_2=60\%$ while R_1 is at 1.00. Apparently the positive direction and negative direction signal powers in cavity increase, but the overall fiber laser output power $P_{out}=P_s^+(L) \times (1-R_2)$ decreases as the $(1-R_2)$ decreases as shown in figure 2.13.

Figure 2-11 Evolution of powers along the fiber, $R_1=1.00$, $R_2=0.60$

b) R_1 vary from 0.04 to 1.00, $R_2=1.00$, output coupler is R_1

This is the laser configuration shown in figure 2.8. The pump is also injected from R_1 , but in this case it is a mirror of low reflectivity, and $R_2=1.00$ (@ all wavelengths). Here, R_1 acts as input as well as output coupler. We vary R_1 from 0.04 to 1.00 while keep R_2 unchanged in order to get the optimum output coupler reflectivity.

Figure 2-12 Evolution of power along the fiber, $R_1=0.60$, $R_2=1.00$

Just like in the previous configuration, the evolution of powers changes with the output coupler reflectivity. Figure 2-12 shows the power evolution at the case of $R_1=0.6$, the signal powers of both positive and negative directions inside the cavity increase with the increase of R_1 , but the output power $P_{out}=P_s(1-R_1)$ decreases with the increase of R_1 as shown in figure 2-13.

Figure 2-13 shows the output power of fiber lasers at 30-Watts pump versus output coupler reflectivity. In both fiber laser configurations, output power decrease with the increase of the reflectivity of the output coupler.

Figure 2-13 Output power vs. output coupler reflectivity

(At 30 W pump power, 50 m fiber length)

At the same fiber length of 50 m, the configuration with stronger input mirror (forward pumping configuration, $R_1=1.00$ @1090nm, transparent @ 940nm) will get lower output power (14.4238 Watts) than the configuration with a weaker input mirror (output power 16.8997 Watts) (reversed pumping configuration, $R_1=0.04$ @ all wavelengths).

2.3.2.3 Fiber length dependence

In figure 2-14, we plot the output powers of the fiber laser as a function of the fiber length, for two laser configurations where pump was injected from $R_1=0.04$ (upper curve) and $R_1=1.00$ mirror (lower curve) separately.

Figure 2-14 Fiber laser output power as a function of fiber length

When the pump is injected from the mirror $R_1=1.00$ @ 1090 nm (transparent @ 940nm), the optimum laser length is around 80 m and the optimum output is 15.7695W. Lasing threshold power is 480mW. Note that the output power varies slowly near the optimum length, so that the similar output powers are obtained in the range of 60-80 m, one should choose the shortest acceptable length.

When the pump is injected from the $R_1=0.04$ (bare cleaved fiber end), the situation is different, the optimum laser length is longer and the optimum output is higher (120 m and 17.9476W). Lasing threshold power is 500mW. In the range of 100-140 m, the output power varies slowly.

From this figure (2-14), we conclude that, when pumping from the weaker mirror side (e.g. bare fiber end), more pump power can be absorbed. Using longer fibers, before the losses become significant a higher output powers can be obtained. In order to get the maximum fiber laser output power, in experiment section 4.4, we choose

pumping from the bare fiber end, and output also from this end, this is based on the above simulation results.

2.3.2.4 Yb doping concentration dependence

The objective of varying the Ytterbium concentration is to determine its effect on the fiber laser output power. By increasing the Yb concentration, the fiber laser output power is expected to increase as more Yb ions can be pumped to upper level and more stimulated emission will be generated

**Figure 2-15 fiber laser maximum output power versus doping concentration
(At 50 m fiber length and 30W launched pump power)**

But from figure 2-15, at fixed pump power and fixed fiber length, after the optimized doping concentration is reached, further increase Yb doping concentration cannot increase fiber laser output power.

This is because, in equation (2.5) and equation (2.6),

$$\frac{dP_s^+(z)}{dz} = P_s^+(z) \cdot \Gamma_s \cdot (\sigma_e \cdot N_2(z) - \sigma_a \cdot N_1(z)) + \underline{\Gamma_s \cdot \sigma_e \cdot N_2(z) \cdot P_0} - \alpha_s \cdot P_s^+(z) \quad (2.5)$$

$$\frac{dP_s^-(z)}{dz} = -P_s^-(z) \cdot \Gamma_s \cdot (\sigma_e \cdot N_2(z) - \sigma_a \cdot N_1(z)) - \underline{\Gamma_s \cdot \sigma_e \cdot N_2(z) \cdot P_0} + \alpha_s \cdot P_s^-(z) \quad (2.6)$$

After gain saturation is reached, further increasing N will result in more N_1 (ground level Yb ions density) increase than N_2 (upper level Yb ions density) increase. That means more ground level Yb ions N_1 , more absorption $\sigma_a \cdot N_1$ at lasing wavelength, and thus less pump efficiency.

The above calculation and analysis are based on the numerical model we built up in section 2.3.1. Experimentally, high concentration Yb ions in fiber [21] and silica glasses [22] have demonstrated concentration quenching.

Concentration quenching causes a reduction of the quantum efficiency. Some people attributed the quenching to impurity or to a structural defect in host [21]; in 2002, a research team in Israel did a detailed research on Yb quenching in silica glasses and proposed that the Yb concentration increased superlinearly with the total Yb concentration, suggesting that this site consists of Yb ion pairs. The doping concentration of $N \leq 1.5 - 3 \times 10^{27} m^{-3}$ for Yb^{3+} is recommended [22].

Chapter summary

In this chapter, the theory of the double clad fiber lasers was presented, rate equations model of the high power double clad fiber lasers is derived; fiber laser

configuration parameters such as pump direction, output coupler reflectivity, fiber length and doping concentration were numerically studied, the simulation results are discussed.

Chapter 3. High-power fiber laser design considerations

3.1. General design consideration

Several factors, such as the pump source, fiber selection, launching optics design, fiber laser cavity design directly affect fiber laser performance. Special consideration must be made on these factors before a fiber laser is constructed.

(a). Pump wavelength selection

Apart from the availability of sources, pump efficiency is the criteria in pump source selection. The basic consideration of selecting pump source is the good wavelength matching between the pump source and the absorption spectrum of the Yb ions in the silica fiber. As shown in figure 2.1(b), Yb ions in optical fiber have a broad absorption band; therefore, a wide range of light source could be used to pump it. Based on figure 2.1(b), it seems that pumping at 975nm could access the largest absorption cross section— $2.6 \times 10^{-24} \text{ m}^2$, however, the stimulated emission cross section is also at strongest at this wavelength, therefore, it is important to consider the effects of amplified spontaneous emission (ASE). Under appropriate conditions, strong ASE at 975 nm or even 1040 nm could occur; the ASE escape from the input end would result in a loss of pumping efficiency and hence higher thresholds. In addition, recent studies[21] [22] have shown that in silica-based hosts a fraction of the Yb ions is strongly quenched (lifetime quenching, the lifetime of the quenched population is too short to be detected, estimated at most $\sim 5 \text{ } \mu\text{s}$, while normal

decay time is 945 μ s) [21], resulting in strong unbleachable absorption around 976 nm. Because energy migrates rapidly between Yb ions, even a small percentage of quenched ions can lead to loss of inversion of most of Yb population. It means that for practical lasers and amplifiers utilizing Yb as laser ion or as a co-dopant, the pump must be detuned from 975 nm.

(b).Fiber selection.

The fiber selection is influenced by following main considerations; we'll elaborate this in section 3.4:

- a) The need for a large NA for the outer guide (first cladding);
- b) Cladding size and cladding shape;
- c) The need for a large inner core diameter to ensure a short absorption length (and hence reduce losses), but the NA for the inner core must be small enough to ensure a single mode operation of the fiber laser;
- d) A high Yb³⁺ concentration.

3.2. Diode laser optics

Fiber lasers are usually pumped by diode lasers (lower power single laser diode and high power laser diode bar and stack). In order to understand high power fiber laser design clearly, one must understand its pump source first. Let's start from single laser diode optics.

Most laser diodes (single laser diode) are of the "edge-emitting" type and they have output beams with elliptical cross sections and some associated with astigmatism.

When diode laser is used as pump source for fiber laser, the ellipticity and astigmatism of the pump beam severely reduces pump launch efficiency. [23][24]

Within a typical edge-emitting diode, the light emission is created by an electrical current flow across an active layer. There are two types of laser diodes: index-guided and gain guided. In index-guided laser diodes, the active layer has a refractive index larger than that of the material surrounding the layer. This index difference guides the laser radiation within the diode and confines the beam to the x - y cross-section of the active layer. The situation is similar to a piece of glass fiber confining and guiding a laser beam inside it. Beam powers from such single index-guided laser diode are typically in the range of a few milli-watts up to a few tens of milli-watts. In index-guided diode lasers, index-guiding is the principal guiding mechanism both parallel and perpendicular to the junction plane. In these lasers, the phase front of the optical wave is planar in both directions, and the wavefront emitted from the laser will have its waists, both perpendicular and parallel to the junction, located at the output facet of the waveguide. Index-guided diode lasers typically exhibit a small amount of astigmatism [25].

Astigmatism is an inherent property of the output beam of diode lasers. In applications requiring collimation or transformation of the diode laser's beam, this astigmatism must be considered and corrected, if the final wavefront is to approach the diffraction limit. It is the guiding mechanism of the waveguide that determines how much astigmatism will be present at the output facet of a diode laser. In a gain-guided optical waveguide, the energy is confined by surrounding the optical gain region with a region of optical loss. The refractive index of the active layer material

and its surrounding material in gain guided diode laser are the same. Gain-guiding is the guiding mechanism in the junction plane and index-guiding is the guiding mechanism perpendicular to the junction plane. In this type of laser, the wavefront exiting from the diode laser is cylindrical. The beam waist perpendicular to the junction plane is still located at the output facet of the diode laser, but the waist parallel to the junction plane is displaced a distance D behind the facet (as shown in figure 3.1). This distance is the longitudinal astigmatism inherent in the diode laser and must be considered when designing optical systems incorporating these lasers. Since the active layer of gain-guided laser diodes can be fabricated to widths of hundreds of microns such diodes can generate power up to 1 Watt or more. Without special beam shaping processing, they are usually used in applications where beam power is more important than beam quality [25][26].

Figure 3-1 laser diode and astigmatism

Because of the very large divergence of the high power laser diode (gain guided) emission, a collimating lens must be situated within several millimeters of the emission stripe, close to the window in the diode cap. A simple convex lens or a GRIN lens can be used, but in most applications, to obtain a reasonable quality beam, either an aspheric lens or a lens group is used. Both the aperture and the focal length of most diode beam collimating aspheric lenses are several millimeters.

There are several methods to remove the ellipticity and astigmatism of diode laser beam.

I. Beam circularization with an aperture

A circular aperture is often used after the collimating lens to truncate an elliptical beam to visually circular. However a small circular aperture can cause power loss as high as 80% and also diffraction rings. The beam intensity contours after the aperture is still elliptical, and the beam astigmatism cannot be removed [26].

II. Astigmatism and its correction

Considering the exact position of the emission from the diode facet, as illustrated in figure 3.2 (a), tracing the far field beam backwards, one can reach two different imaginary beam source points p_x and p_y for the x-z and y-z planes respectively. This phenomenon is called astigmatism and the linear distance between p_x and p_y is the magnitude of the astigmatism. Typically it is 50 μm for high power laser diode and 5-15 μm for low power laser diode [26].

In our fiber laser experiment, the focusing coupling lens cannot truly focus the beam in both the x-z and the y-z plane on the working plane. This is because p_x and p_y cannot be simultaneously positioned at the focal points of the launching optics.

The astigmatism can be corrected by the use of a weak cylindrical lens after the collimating lens as shown in figure 3.2 (b). The focal length required for the cylindrical lens is about 2m-4m, depending on the value of the astigmatism and the focal length of the collimating lens.

Figure 3-2 (a) Origin of astigmatism of laser diode

(b) astigmatism correction by using a cylindrical lens

III. Beam circularization with anamorphic prisms

A pair of anamorphic prisms can be used to circularize a beam with low power loss and without the imposition of strong diffraction rings. But it cannot correct the astigmatism [26]. By rotating the prisms, anamorphic prisms can enlarge or reduce the size of a beam along one axis transverse to the beam direction while keeping the beam size in the perpendicular transverse direction unchanged. Thereby, beam circularization can be realized. Although such prism pair can change the beam size, they cannot change the beam divergence. In another words, it cannot remove astigmatism. When the input beam is astigmatic, the output beam is also astigmatic.

IV. Beam circularization with a single mode fiber

The single-mode fiber rejects light that does not match the first guided mode of the fiber. Actually this is a kind of spatial modes filtration but not beam shaping. Minimal length of single-mode fiber sufficient to provide good spatial filtering is several thousands of wavelengths (usually several centimeters) [27]. The output beam from a single mode fiber has a circular cross section, no astigmatism and a good Gaussian intensity profile. But because of the small size of the single mode fiber, the power loss of this method is usually as high as 70% (refer to low power laser diode) [26].

V. Beam circularization with a micro-cylindrical lens.

Recently there has been much research and development work on new and potentially more useful methods of circularizing laser diode beams and meanwhile removing astigmatism in a cost-effective manner. These new techniques attempt to circularize the beam without significant beam power loss by re-shaping the beam profile with a diffractive or geometric (such as cylindrical) lens surface to obtain a pseudo point source or collimated beam as desired. One of these efforts has emerged based on micro-cylindrical technology developed at Lawrence Livermore National Laboratory (US patent 5,181,224). [28]

So far this is the best way to coupling single laser diode beam into single mode fiber. It can remove astigmatism and meanwhile circularize a beam from single laser diode. It has the high coupling efficiency of more than 80% [28], which is much higher than with anamorphic prism (~50%) [26] and other methods. The whole setup of the system with micro-lens is compact. When the micro lens was manufactured in large amount, it is cost effective.

The disadvantage of this method is that the small size of a micro lens and the short distance between the lens and the active layer facet of a laser diode require that the micro-lens be mounted precisely at the right position inside the diode cap. Successfully mounting a micro-lens requires skill, experience and the right tools.

3.3. High power pump sources selection

There are two kinds of high power (10W-1000W) diode laser sources suitable for pumping high power fiber lasers; the first one is with output (transport) fiber, the other is bare laser diode bar. For some high power fiber lasers requiring pump power higher than 1000W, laser diode stack can also be considered, in that case, although the design principle is the same, the pump coupling optics is more complicated.

3.3.1. Fiber pigtailed laser diode bar pump sources

The transport fiber used in fiber pigtailed laser diode bar is a multimode fiber, usually with 200 μ m diameter to 1mm diameter. This multimode fiber enable flexible laser beam delivery but at cost on the beam quality. For example, the optical invariant of common (1 μ mX1mmX40degreeX10degree) bare laser diode bar is

$$\sqrt{a \times \alpha \times b \times \beta} = \sqrt{\frac{40}{180} \times \pi \times 1\mu\text{m} \times 10000\mu\text{m} \times \frac{10}{180} \times \pi} = 34.9066 \mu\text{m}.\text{rad}$$

The optical invariant after the output (delivery) fiber with NA=0.22, 400 μ m diameter is $D \times 2\theta = 400\mu\text{m} \times 2 \sin^{-1}\left(\frac{0.22}{1.5}\right) = 117.76 \mu\text{m}.\text{rad}$, which is much larger

than the optical invariant from a bare laser diode bar, that means the laser beam quality is degraded after the delivery fiber, and the laser brightness becomes lower.

The fiber-optic beam delivery system can be optimized by selecting proper fiber and output optics. Fiber core size is an important consideration in a delivery system. Fibers with smaller fiber core size produce less degradation on laser beam quality, however the laser beam quality itself limited the smallest fiber core size, because the laser beam focused spot size has to be smaller than the fiber core in order to avoid heat effect. In addition to the laser beam quality, minimum fiber core size is also limited by the focusing optics and the numerical aperture of the fiber itself.

An optical fiber can support only a discrete number of modes. These discrete modes are determined uniquely by the fiber refractive index profile and geometry. Unsupported modes exceed a specific maximum propagation angle will leak out of fiber or be redistributed due to interference effects. A fiber can modify the properties of the laser beam, the impact is determined by the fiber type, fiber length and propagation conditions such as whether the fiber was bended.

Selection of an appropriate fiber type is another important consideration. There are two fiber types, step-index and graded-index fiber. It differs in the constancy of the refractive index through the fiber. The step-index fiber has a constant refractive index in the core and an abrupt “step” transition to a different refractive index in the cladding. Total internal reflection occurs at the core/cladding interface for all modes. The output profile from this fiber type will be the familiar “top-hat” distribution [29].

A graded-index fiber has a variable refractive index in the core cross section. The effect of this varying refractive index profile is that each mode is refracted gradually as it traverses the fiber. The profile resembles a Gaussian distribution [29].

Misalignment of the fiber at the launch end preferentially induces azimuthal modes that appear as rings or crescents in the output [29].

Another consideration of fiber is the fiber length. Light launched into the fiber has some initial distribution determined by the laser. As the light propagates in a fiber, it is converted into modes supported by the fiber or it is lost and appears as leakage or heat. This conversion, however, requires a certain length of fiber to be effected. A short fiber produces little modification to the input beam. On the other hand, a long fiber causes the output to be independent of the input distribution.

The fiber end finish should also be considered for those high power laser as high as several hundreds watts or even thousand watts.

In addition to the above four factors: fiber core size, fiber type, fiber length and fiber end finish, the output optics is also an important factor. Because of the large number of modes supported by the multimode fibers used for high-power laser beam delivery system, geometrical image analysis is appropriate for the output optics design [29].

3.3.2. Bare laser diode bar pump source

Compared with the fiber pigtailed laser diode bar, bare laser diode bars are of standard specifications and without much choice. Some factors need to be paid attention especially when micro-optics or diffractive optical element (DOE) method is used for beam shaping. For example, the emitter number of the laser, the smile

value (the smaller the smile value, the higher the laser beam quality) of the laser. Although selecting bare laser diode bar is not a problem, but the pump coupling of such high power laser diode bar has been a challenge until late 1990s. With the solving of this problem, comes a new era of high power fiber laser. We will discuss pump coupling of bare laser diode bar in section 3.5.

3.4. Double clad fiber design for high power purpose

3.4.1. Why double clad fiber

A fiber laser based on an ordinary doped single-mode fiber allows generating diffraction-limited output, but due to the small core diameter and NA of a single mode fiber, it restricts the pump sources to those low powers with good beam quality. On the other hand, the use of multimode fibers usually leads to poor beam quality. This dilemma has been resolved with the invention of double-clad fiber designs, which allow cladding pumping of fiber devices. Double clad fiber lasers use clad-pumping technique, where pump light is launched into the first cladding and propagates inside it. The pump light is absorbed by the Yb ion in the core when it crosses the core. A conceptual diagram is shown in figure 3-3.

Figure 3-3. Schematic diagram of the laser diode pumped double clad fiber laser

Here, the laser light propagates in a single-mode (or multimode) core, which is surrounded by an inner cladding in which the pump light propagates. Only the core is rare-earth doped. The pump light is restricted to the inner cladding by an outer cladding with lower refractive index, and also partly propagates in the single-mode core, where it can be absorbed by the laser-active ions. The inner cladding has a comparatively larger area and typically a much higher numerical aperture, so that it can support a large number of propagation modes, allowing to efficiently launching the pump light from high power laser diodes despite their poor beam quality. Such a double clad fiber with high brightness diodes has made cladding-pumping technique to generate high-power fiber laser output.

Fig 3-4 shows the index profiles of a standard single mode doped fiber (a) and a double clad fiber (b). The core of double clad fibers with diameter between 2 μm to 10 μm can be doped with different ions, such as Nd^{3+} , Yb^{3+} , Tm^{3+} ,

Figure 3-4 index profiles of single mode rare earth fiber and double clad rare earth fiber

As shown in above figure, the refractive index of fiber core is n_2 , the index of inner cladding is n_1 , and n_0 is the index of outer cladding (usually low index polymer), then the NA number of the core of double clad fiber is

$$NA_{CORE} = \sqrt{n_2^2 - n_1^2}$$

The N.A. number of the inner (pump) cladding of the double clad fiber is

$$NA_{clad} = \sqrt{n_1^2 - n_0^2}$$

In order for single mode core operation, the V number of core is [30]

$$V = \frac{\pi}{\lambda} d NA_{core} < 2.405 \Rightarrow d < \frac{2.405 \times \lambda}{\pi \times NA_{core}}$$

For example, if $\lambda = 1.1 \mu\text{m}$, $NA_{core} = 0.1$, then the core diameter should be $d < 8.58 \mu\text{m}$

For multimode step index fiber, when V number is large, the number of modes M can

be roughly expressed as $M \approx \frac{V^2}{2}$ ([30], p56)

Let's consider the power coupling between a light source and fiber, as shown in figure 3-5

Figure 3-5 fiber accept angle

Assuming the total optical power emitted from the light source is P_s , the power launched into the pump cladding is P_{launched} , the radius of emitting area (or its image) is R_s , and the radius of pump cladding is R_{clad} , then

$$P_{\text{launched}} = \begin{cases} P_s \times (NA)^2 & R_s < R_{\text{clad}} \\ \frac{R_{\text{clad}}}{R_s} P_s \times (NA)^2 & R_s > R_{\text{clad}} \end{cases} \quad ([30], p_{207})$$

From the above formula, we have the criteria for fiber selection in double clad fiber laser design

- a) The need for a large NA for the outer guide (first cladding) to ensure efficient launching of the highly divergent diode array output;
- b) Cladding size and cladding shape; increasing cladding size can improve coupling efficiency but decrease pumping absorption in unit fiber length,

so optimization of cladding shape is necessary, as discussed in section 3.4;

- c) The need for a large inner core diameter to ensure a short absorption length (and hence reduce losses), but the NA for the inner core must be small enough to ensure the single mode operation of the fiber laser;
- d) A high Yb^{3+} concentration, to ensure high output power.

3.4.2. Fiber cladding shape design

The output power generated by a fiber laser is determined principally by how much pumping light that can be launched into the fiber. Since double clad fiber (DCF) can provide large cross-section and numerical aperture, DCF have been applied extensively for high power fiber lasers. In most cases, for coupling high power pump light effectively, the ratios between radius of the first cladding to radius of the core is of the order of 10-100, and because only the doped core has significant absorption, the absorption efficiency is much lower. To improve the absorption efficiency in double-clad fibers, many schemes (such as multi-core fiber, fiber bending, etc) have been suggested in the past years. Among these schemes, the absorption efficiency of fibers with non-round inner cladding is improved by blending the pumping waves.

For double clad fiber, optimization of the fiber cross-section shapes and parameters is very important and has been carried on by several research teams [31][32][33][34]. Double clad fibers typically consist of a doped single-mode core that carries and amplifies laser signal, a large inner cladding (100 μm -400 μm) that carries the pump radiation and confines the signal, and an outer cladding that confines the pump

radiation. Due to the small area ratio A_{core}/A_{clad} , the coupling of the pump radiation from the inner cladding to the core is relatively weak. Achieving high laser efficiency depends on optimizing the coupling, which in turn depends on the cross-sectional shape of the inner cladding. Figure 3-7 illustrates a few of cladding shapes used in double clad fiber lasers.

Figure 3-6 various cladding shapes of double clad fiber

One of the difficulties encountered is that if the first cladding has a circular cross section, the skew rays miss the core and only the meridian rays are absorbed. One solution is to offset the core from the center of the first cladding. In one measurement involving an Nd-doped fiber, when the core was centered on the cladding the pump absorption was only 5% of what it would be if the same amount of dopant were uniformly distributed across the first cladding. By offsetting the core to the edge of the first cladding, the pump absorption increased to 28%. ([1], p₁₂₃). This indicates the importance of cladding shape design.

Rectangular, D-shaped, and scalloped cladding have been proposed and evaluated. A rectangular shape is particularly attractive because it matches the output pattern of a laser diode; thereby minimize the area of the first cladding [23].

3.4.3. Fiber cladding size

Next parameter need to be designed in double clad fiber design for high power purpose is the pump cladding size. Actually this cladding size is determined by the pump laser source. We can calculate it roughly. For high power laser diode bar with tens or hundreds watts, the divergence angles in two directions usually are $\alpha=40$ degrees and $\beta=10$ degrees, and the emitting area is a rectangle with $1\mu\text{m} \times 1\text{cm}$, as shown in following figure 3-7.

Assuming double clad fiber with square shape, $\text{N.A.}=0.22$, according to optical invariant, the minimum edge length of the pump clad should be

$$\alpha \times a \times \beta \times b = (D \times 2\theta)^2 \Rightarrow D = \frac{\sqrt{\frac{40}{180} \times \pi \times 1\mu\text{m} \times 10000\mu\text{m} \times \frac{10}{180} \times \pi}}{2 \times \sin^{-1}\left(\frac{0.22}{1.5}\right)} = 118.5705\mu\text{m}.$$

Figure 3-7 estimation of fiber cladding size

Here, the parameters for laser diode bar are:

$\alpha=10$ degrees represents the X direction laser light divergence angle, $\beta=10$ degrees represents the Y direction divergence angle, a represents X direction emitting length, b represents Y direction emitting length.

The parameters of double clad fiber are:

θ represents the half fiber acceptance angle, D represents the first cladding (or pump cladding) size of the double clad fiber, assuming D as the side length of a square cladding or the diameter of a circular cladding will only result in slight difference in the calculation result.

So we can understand that why the cladding size of double clad fiber in market usually ranges from $100\mu\text{m}$ to $400\mu\text{m}$.

3.4.4. Fiber cladding N.A design

Another important design consideration is the N.A. of the cladding, from section 3.4.1, the launched pump power is proportional to $(NA)^2$. So in order to get high launching efficiency, N.A. should be as high as possible. For silica-based fibers with a second cladding made of glass, the N.A. is limited to 0.4. Higher N.A. can be achieved if the second cladding is made of a low-refractive-index polymer. NA. as high as 0.6 have been realized [35]. In addition to cladding N.A, in order to get single mode output laser, the fiber core N.A should be designed to satisfy single mode requirement.

3.4.5. Doping concentration consideration

As calculated in the section 2.3.2.4 of Chapter 2, considering two kinds of rare earth doped double clad fiber with the same fiber length and pump cladding size, at the same launched pumping power level, the fiber with higher Yb^{3+} concentration will absorb more pump and generate more laser emission. That means in order to get certain fiber laser output power, higher doping concentration ensures a shorter fiber length. But recent studies have shown that a fraction of the Yb ions is strongly quenched and results in loss of laser action when pumped around 976nm ([1], P₁₇₆). Several research teams have observed life time quenching in Yb fiber [21] and Yb glass [22], it is recommended that the Yb^{3+} doping concentration $N \leq 1.5 - 3 \times 10^{27} m^{-3}$ in order to avoid life time quenching [22].

3.5. Pump coupling design

Double clad fiber lasers use clad-pumping technique, where pump light is launched into the first cladding and propagates inside it. The pump light is absorbed by the Yb ions in the core when it crosses the core. A conceptual diagram is shown in fig.3.3.

Figure 3-8 Schematic diagram of the laser diode pumped double clad fiber

3.5.1. Laser diode array characteristics

In section 3.2.2, we discussed coupling between single laser diode and single mode fiber, when comes to high power laser diode bar (1D laser diode array or even 2D laser diode stack), the coupling difficulty will be much higher. The following figure shows the structure and beam profile of a common laser diode array

Figure 3-9 laser diode array [36]

Figure 3-10 beam profile of a laser diode array [36]

As shown in above figures, the structure and geometry of the laser diode bar determine the difficulty of high-power laser-diode beams focusing and coupling. A high-power laser diode is normally found in the form of a laser-diode array (LDA), comprised of a number of emitting elements, with each element being very thin and narrow (about $1\mu\text{m} \times 3.5\mu\text{m}$), emitting less than 300 mw [36]. Usually, the emitting surface is a narrow line of 20 or more segments with multiple emitting elements (19 emitters and 46 emitters can be found in market). Thus, a high-power LDA has a broad-area light-emitting aperture of about $1\text{ cm} \times 1\mu\text{m}$. With such a configuration, commercially available high-power LDAs can provide 20W – 60W. Much higher power can be achieved by layering high-power LDA bars in stacks. For laser diode stack, which is a stack of multiple laser diode bars, the beam shaping is even more difficult. But because laser diode stack is a stack of multiple laser diode bars, the beam shaping of diode laser stack is similar to the beam shaping of the 5W-60W laser diode bar.

The raw output beam from an LDA is highly divergent and suffers from two asymmetries—astigmatism and an elliptical beam profile. The divergence angles are different in two axes, the so-called "fast axis" and "slow axis." Typical fast-axis divergence is about 40° full-width half-maximum (FWHM) and slow-axis divergence is about 10° FWHM. Sometimes the divergence can be as high as 50° x 15°. When the noncircular, astigmatic beam from the LDA is focused, the beam spot is greatly elongated, which is undesirable for most applications, and unacceptable for double clad fiber coupling. And the spacing between emitters even lowers the brightness of focusing spot.

3.5.2. Review on high power coupling solutions

3.5.2.1 Solutions brief

To permit focusing to small beam diameters, it is necessary to use an optical beam delivery system which equalizes the lateral and transverse etendues of a beam but without significantly decreasing the brightness. After the invention of EDFA in 1988, people have found the potential of further increase the power of fiber amplifier and fiber laser, and from the beginning of 1990, more and more people put efforts on the power scaling of fiber amplifier and fiber laser, a number of beam delivery schemes which attempt to solve this problem have been reported (e.g. coupling into optical fiber bundles[37][38][39], using diffractive optical components [40] or using arrays of micro-optical components [41]). Among them, following patent techniques are of representative:

- Solution 1, two-mirror beam shaping (patent owner ---- Optical Research Center, Southampton University, U.K., reference [42])
- Solution 2, two micro step mirror beam shaping (Fraunhofer Institute of Laser Technology, Germany, reference [43])
- Solution 3: multi-prism array beam shaping (patent owner -----Apollo Instrument Inc, US, reference [36])
- Solution 4: micro lens array beam shaping [44]

For the first three solutions, they have a common feature that is the beam shapers consist of a set of high reflective surfaces. For solution 1, the beam shaper is two reflective mirrors, two step mirrors for solution 2 and a set of reflective surface of the two prism groups in solution 3. The detailed techniques can be found in respective references. In this section we try to summarize some common features in these three solutions.

Figure 3-11 shows some common concepts in laser diode bar beam shaping. In this figure, the linear shape at left represents the incident beam from a laser diode bar (in the X-Y plane view from opposite of the light propagation direction); usually it is 1cm along X direction (slow axis) and 1 μ m along Y direction (fast axis).

Figure 3-11 laser diode bar beam shaping concepts

As described in section 3.5.1, the divergence angle along X (slow axis) is around 10 degrees; divergence angle along Y (fast axis) is around 40 degrees. The initial incident beam quality factors are M_x^2 and M_y^2 , here $M_x^2 \gg M_y^2 > 1$. The action of the beam shaper is to cut or chop (optically) the collimated incident beam into N sub-beams along X (slow axis) direction, and then re-direct and re-position these sub-beams into a rectangular (square) or circular shape as shown in the middle of figure 3-11. The beam quality factors after the beam shaper become $(M_x^2)' = (M_x^2)/N$ and $(M_y^2)' = (M_y^2) \times N$, in order to get best homogeneous distribution of beam quality $(M_x^2)' = (M_y^2)'$ (same beam quality factors in both X and Y direction), the number of sub-beams N is determined by $N = (M_x^2)/(M_y^2)$.

In such a way, the beam quality factor along fast axis direction M_x^2 increased N times while the beam quality factor along slow axis direction M_y^2 reduced N times, $M_x^2 \approx M_y^2$, the linear shape beam from laser diode bar are grouped and re-position in a rectangular (square) or circular geometry with equal beam quality in both X and Y directions. The resulting beam can be focused with conventional lens to a spot of smaller diameter than the focusing spot without beam shaping.

Next we describe the working principle of the micro lens array beam shaping method which we made some initial steps experimentally, and it is a cost effective and efficient method in power scaling of high power fiber laser.

3.5.2.2 Micro lens array beam shaping

(Fraunhofer Institute for Applied Optics and Precision Engineering, reference [44])

One of the novel parts of this beam shaping is that the collimating GRIN cylindrical micro lens is arranged nonparallel with respect to the laser diode bar. As shown in figure 3-12, the micro lenses are rotated by a 9° angle around the z-axis.

Figure 3-12 nonparallel arrangement of collimating micro-lens to laser diode bar

It is important that these micro lenses have outstanding off-axis collimation performance, thus all the beams from different emitters along X-direction (slow axis) can be collimated with such nonparallel arrangement. This causes a simultaneous collimation and angular separation of the single emitter beams in the Y-direction (fast axis).

Figure 3-13 depicts the concept of the micro optical beam transformation system.

Figure 3-13 micro lens beam shaping (Fraunhofer, Germany) [44]

A director lens deflects the collimated single emitter beams in the x-z plane. Because different single emitter beams are separated along Y-direction by the nonparallel collimation arrangement, they are separated angularly after the director lens. In the focal plane, each beam from different single emitter forms an individual beam stripe, the number of beam stripes corresponds to the emitter number of the laser diode bar, all the beam stripes are separated along Y-direction again forming a nearly square cross section laser beam. In such a way, the $1\text{cm} \times 1\mu\text{m}$ linear shape laser diode bar beam is transformed to be a square shape beam.

As the single emitter beams are well separated along Y-direction in the director's focal plane, they can be further transformed separately. This can be done by another redirection component located in the director's focal plane. The redirection can be realized in different ways: a group of thin prisms, an array of Fresnel deflector or an array of blazed diffraction gratings. The redirector compensates the different propagation directions in X-Z plane introduced by the first director lens.

After passing the redirector the resulting beam is highly symmetric in both X and Y direction of cross section. Thus it is possible to focus the beam with conventional optical lens to a nearly circular spot. Finally, a relay lens consisting of two achromatic doublets is used to focus all beams into a small highly symmetric spot.

A detailed design of the whole beam transformation system is shown in figure 3-14.

Figure 3-14 design schematic of micro lens beam shaping (Fraunhofer, Germany) [44]

Actually such kind of beam shaping micro optical system has been commercialized in Germany; following figure 3-15 is the photo of such product from LIMO Pte, Ltd Germany. We have carried on some initial experiments in high power diode laser beam shaping

Figure 3-15 Limo BTS micro lens product

With the above commercial micro lens chip, we have got beam shaped square laser spot with roughly uniform power distribution from bare laser bar. The following photos show some of the beam shaping experiments we carried on.

Figure 3-16 micro lens beam shaping experiments - 1

We carried on some experiments in 2004 on laser diode beam shaping. Figure 3-16 shows the micro-lens chip on mount in front of the 40W laser diode bar. Figure 3-17 show the overall experimental setup.

Nowadays, with the latest micro-optical chip product, it is claimed that the coupling efficiency between high power laser bar and 200 μ m diameter fiber can reach as high as over 60% www.limo.de .

Figure 3-17 micro lens beam shaping experiments - 2

In summary, all above techniques have a common idea; which is to rearrange the power distribution from a linear shape to a rectangular or a circular one. This is possible because the optical invariant of the laser diode is not very high, which make it possible to be beam shaped and coupled into a double clad fiber. For example, a laser diode bar with 40W output power has normally a divergence angle α along the 1mm direction is 10 degrees, the divergence angle β along the $1\mu\text{m}$ direction is 30-40 degrees, the optical

invariant of it is $\alpha \times a \times \beta \times b = \frac{10}{180} \times \pi \times 1\mu\text{m} \times \frac{40}{180} \times \pi \times 10000\mu\text{m} = 1218.47\mu\text{m}^2.\text{rad}^2$.

The optical invariant of a double clad fiber (for example, the OFS double clad fiber used

in our experiments with NA=0.45 and cladding diameter 210 μ m, assuming refractive index n=1.5) is

$$(D \times 2\theta)^2 = \left(210\mu\text{m} \times 2 \times \sin^{-1}\left(\frac{0.45}{1.5}\right) \right)^2 = 16376.6\mu\text{m}^2.\text{rad}^2.$$

The optical invariant of the pump cladding of double clad fiber is comparable with that of the laser diode bar, so theoretically it is possible to launch such laser beam from laser diode array into the double clad fiber. This is the theoretical basis of coupling laser diode bar into double clad fiber.

Chapter summary

In this Chapter, the design considerations of high power fiber lasers such as fiber design, pump source selection, and high power laser diode beam shaping were discussed. Based on these design considerations, a high power fiber laser was designed in Chapter 4.

Chapter 4 High-power fiber laser experiments

An Yb^{3+} -doped silica fiber laser pumped at 937nm by a 30 watts laser diode array was designed and setup. Output power up to 11.6 Watts under the reverse pumping configuration and up to 8 watts under the forward pumping configuration was achieved

4.1. Pump source

The pumping source used was a high brightness ~937nm wavelength fiber array packaged (FAP) laser diode bar. The fiber array is made of 19-fiber bundled within an 800 μm diameter aperture [45]. The termination is a SMA 905 fiber optic connector. The maximum output power of the pump source is ~30 W.

4.1.1. Pump power distribution

In order to understand the pump source well and further design the coupling optics, the power distribution of the pump light from the delivery fiber was experimentally measured with a laser beam profiler LBA-PC. As shown in following figures: figure 4-1 are photos taken by a CCD camera and frame grabber of LBA-PC laser beam profiler. The central spot is the peak pixel location of the beam. Fig 4-1(a) is 2-D beam profile; the overlay grid is for coarse measurement purpose. The curves are cross section beam profile along X and Y axis drawn through the peak of the beam. The grayscale plot is given which enables the user to tell intuitively which the high power and low power spots in the beam are. The contour lines overlays in 16 levels represent different power levels.

Figure 4-1 pump power distribution (measured by LBA-PC beam profiler)

(a) 2-D beam profile with cross section along X-Y axis

(b) 3-D beam profile

Fig 4-1 (b) is a 3-D beam profile. It gives an intuition of what the beam profile really looks like.

Figure 4-1 shows that the pump power has a gauss-like power distribution. For comparison, a typical gauss power distribution with the same peak power and same beam width simulated with Matlab is shown in figure 4-2.

A Gaussian beam is described as

$$I = I_0 \cdot e^{-2 \left[\left(\frac{x-x_0}{w_x} \right)^2 + \left(\frac{y-y_0}{w_y} \right)^2 \right]} \quad (4-1),$$

Here I = power at the point (x, y)

I_0 = power at the Gaussian center

x = x location of pixel

x_0 = x location of the Gaussian center

w_x = horizontal radius at $1/e^2$ of energy (beam width in X direction)

y = y location of pixel

y_0 = y location of the Gaussian center

w_y = vertical radius at $1/e^2$ of energy (beam width in Y direction)

Figure 4-2 typical Gaussian power distribution

In designing our experiments, we assumed that the power distribution of our pump source is Gaussian. This assumption is justified by the following considerations:

- 1) The experimentally measured pump power distribution is a Gaussian-like profile;
- 2) The experimental results show that the design error due to this assumption is within tolerance.
- 3) One of the references [29] makes such assumption after detailed investigation on fiber delivery system of high power laser diode.

4.1.2. Pump laser source cooling

For applications with less than 50 W thermally dissipated power per laser bar conductively cooled heat sinks are preferred. Pure copper heat sinks with their high

thermal conductivity achieve a good thermal performance [46]. The FAP laser base is a gold-plated copper machined flat for good thermal contact to its mounting surface, and it is mounted on a fine grinded copper heat sink. Water flows quickly in this heat sink and bring the exchanged heat from laser diode out.

4.1.3. Pump wavelength

The laser wavelength of the pump source is a function of the laser diode temperature and operating current [45].

The precise semiconductor operating wavelength is a function of laser diode junction operating temperature; the laser diode junction operating temperature is in turn a function of the operating current and case temperature. The operating wavelength can be calculated using the formula given below:

$$\lambda_{op} = \lambda_c + \left(\frac{d\lambda}{dt} \right) \cdot (T_{LD} - T_{test}) + \left(\frac{d\lambda}{dt} \right) \cdot R_{th} \cdot \left[\left((I_{act} \cdot V_{op}) - P_{act} \right) - \left((I_{op} \cdot V_{op}) - P_{op} \right) \right]$$

,

Here:

λ_{op} — operating wavelength λ_c — center wavelength

$d\lambda/dt$ — temperature coefficient of wavelength

T_{LD} — laser diode case operating temperature

T_{test} — laser diode case test temperature

R_{th} — thermal resistance between laser diode junction and laser diode case

I_{act} — actual operating current P_{act} — actual operating power

V_{op} — operating voltage I_{op} — test operating

P_{op} — operating power

Among above parameters, T_{LD} , I_{act} and P_{act} are measured in experiments when operating the laser diode; all others are from specification and data sheet of the pump laser product. In the above equation, the second term reflects the wavelength change due to changes of laser diode case temperature; the third term reflects the changes due to heating of laser diode junction from applied drive current.

With the formula and measured operating current, laser diode operating case temperature and laser output power, we get the wavelengths tuning range of the pump source as below:

Figure 4-3 pump laser wavelength tuning

4.2. Double clad fiber characteristics

The gain fiber is a single-mode, Ytterbium-doped fiber. It has a low N.A. for the core, high N.A. for the silica cladding. The absorption spectral is shown in

figure 4-4 (a). The absorption of the collected light by the ytterbium core dopant allows that the fiber can be used to construct a fiber laser by incorporating an input pump source and reflectors on the fiber ends. The fiber geometric design is shown in figure 4-4 (b).

Figure 4-4 (a) absorption spectral of Yb double clad fiber; (b) cladding pumped fiber

The double clad fiber has the following features:

- Star-shape cladding gives efficient mode mixing of pump light (e.g., scatter skew rays) and thus help ensure that pump light is efficiently directed to the core of the fiber which comprises the active material, and improves splice ability. The multi-lobed pump cladding enhances the transfer efficiency from the pump cladding to the circular core. [31][32][34]
- Tough low-index polymer coating gives high cladding NA.
- Small core NA leads to a small beam size laser beam output.

Several detailed fiber parameters are:

$$NA_{\text{core}} < 0.175 \quad NA_{\text{clad}} = 0.45$$

Diameter of the first cladding= $210\mu\text{m}$

Figure 4-5 is a photo of the cleaved fiber end under microscope, from which we can see the fiber core and cladding shape clearly:

Figure 4-5 Fiber end photo of double clad fiber (under microscope)

4.3. Coupling optics

In order to get highest fiber laser output power, it is required to couple as much as possible pump light into the pump cladding of the double clad fiber. Thus coupling optics design is critical in high power fiber laser experiments.

Design specification:

Light source (object in optical design) — simplified to be an $800\mu\text{m}$ diameter light source with Gaussian distribution [29], $\text{NA}=0.22$

Target (Image in optical design) — a $210\mu\text{m}$ diameter fiber cladding with $\text{NA}=0.45$

Requirement — highest coupling efficiency

Based on the above requirement, the design criteria of the launching optics are to get a focused spot size as small as possible, at best less than the double clad fiber's first cladding ($210\mu\text{m}$). Meanwhile the NA of the coupling lens should be smaller than the NA of the first cladding of the fiber (0.45 in this case).

Firstly, we used a specialized collimation package of laser diode to shape the output of the laser diode bar. Secondly, we choose a special coupling lens (20x OFR coupling lens for laser diode & fiber-optic applications). Both lens are designed for IR wavelength, so there is very little insertion loss (less than 5% according to test). The reason we choose aspheric lens is because it can correct larger optical aberration than a common spherical single lens, thus a single aspheric lens can replace a group of spherical lenses. In this way an aspheric lens will have better thermal performance under high pump power than spherical lenses with the same optical performance.

The focal length of the collimation package is $f_1=11\text{mm}$; clear aperture is 6.2mm. The focal length of the coupling lens is $f_2=8\text{mm}$, and clear aperture is 8mm.

Focusing spot size

With geometric optics we can calculate the focusing spot size after the launching optics. The following figure 4-6 describes the launching optics. The first lens F1 represents the collimator; the second lens F2 represents the coupling lens. In our experiments, the focal length of the first one is 11mm and the focal length of the coupling lens is 8mm. The height of object is the radius of the output fiber of the pump laser, and $D_1=400\mu\text{m}$. Through geometric optics we can get the focusing spot size $D_2/D_1=f_2/f_1$.

Figure 4-6 simple geometrical optics calculation

For $\Phi=800\mu\text{m}$ laser output fiber, the calculated focusing spot size is $581.818\mu\text{m}$.

Also using LBA-PC beam analyzer, we can measure the focusing spot size in experiments via a $2f$ system which is used to introduce power attenuation to protect sensitive camera from high power damage. In the experiment, the real focusing spot size is about $600\mu\text{m}$ for $800\mu\text{m}$ fiber and $300\mu\text{m}$ for $400\mu\text{m}$ fiber taper. This verifies the calculation results.

Beam divergence angles and N.A.

From optical invariant we have $D_1 \times \theta_1 = D_2 \times \theta_2$, here θ_1 and θ_2 represent the beam divergence and focusing angle of the source side and target side. Thus the beam focusing angle is determined by $\theta_2 = (D_1 \times \theta_1) / D_2 = (f_1 / f_2) \times \theta_1$. In the case of $f_1 = 11\text{mm}$ and $f_2 = 8\text{mm}$, the beam focusing angle $\theta_2 = 0.30$, which is far less than the NA of the fiber pump cladding 0.45. Therefore, it is believed that all the pump power launched

within the fiber cladding could be coupled into the pump cladding and propagates as effective pumping.

Coupling efficiency estimation

Figure 4-7 coupling efficiency calculation

Figure 4-7 is used to demonstrate the integral overlap method to calculate coupling efficiency between a Gaussian pump source and a multimode double clad fiber. The curve represents that the pump source has a Gaussian distribution, which can be described with equation 4-1,

$$I = I_0 \cdot e^{-2 \left[\left(\frac{x-x_0}{w_x} \right)^2 + \left(\frac{y-y_0}{w_y} \right)^2 \right]}.$$

Take the pump cladding diameter of the double clad fiber $2a=210\mu\text{m}$ (experimental fiber parameter), the focusing spot size of the pump source $2w_0=581.818\mu\text{m}$ (calculated spot size from geometric optics).

Then the integral of Gaussian function from minus infinity to plus infinity

$\int_{-\infty}^{\infty} I(x, y) ds$ represents all pump power.

Because pump beam focusing angle less than N.A. of the pump cladding (focusing angle $\theta_2 < \text{N.A. cladding}$), all pump power within cladding are effective pump, the overlap $\int_{-a}^a I(x, y) ds$ of the pump cladding and Gaussian curve represents the launched power, the areas ratio between shaded area and overall Gaussian function area

$$\eta = \frac{\int_{-a}^a I(x, y) ds}{\int_{-w_0}^{w_0} I(x, y) ds}$$

is the coupling efficiency.

The calculated coupling efficiency based on this simplified overlap integral method for practical experimental parameters is 53%, and the experimental coupling efficiency is 45%, the error analysis is as following stated.

Error analysis

The errors come from the following sources:

- a) The Gaussian distribution assumption. Although the measured power distribution has a Gaussian-like profile, it deviates from the exactly Gaussian distribution, this is the biggest error source
- b) The Fresnel reflection of the fiber end accounts for 4% power loss
- c) The insertion loss (reflection) of the launching optics.
- d) The misalignment in experiments.

4.4. Backward pumped fiber laser

4.4.1. Experimental setup

Figure 4-8 shows the schematic of the fiber laser setup:

Figure 4-8 forward pumping fiber laser schematic

The pump source was discussed in section 4.1 in detail; its maximum pump power is 30 watts. The center wavelength of the pump source is 937nm, which can be tuned within several nm by changing the operation temperature.

The laser cavity consists of

The 50 m Yb³⁺ doped double clad fiber described in [section 4.2](#) as the gain medium;

Front cavity mirror— the 4% Fresnel reflection of the bare fiber end was used as the input mirror;

Back cavity mirror— a dielectric mirror with reflectivity >99% was used as the end cavity mirror.

Figure 4-9 Launching optics

As shown in above photo (figure 4-9), pump laser was first collimated by the collimator, then passes through a 45 degree beam splitter which is high transmission @ 937nm (pump wavelength) and high reflection @ 1093nm (signal wavelength), and focused by the aspherical lens into the pump cladding of the double clad fiber, which is mounted on a 3D adjustable fiber mount stage. With careful alignment about 45% of the effective pump power can be coupled into the fiber.

Figure 4-10 Double clad fiber and HR laser cavity mirror

The 50 m double clad fiber was put on a metal plate (figure 4-10 left). Both the pump and laser beams were reflected back at the end of the fiber by a high reflection mirror (figure 4-10 right). After one single trip, the residual pump power was measured (at the other fiber end) to be around 1W (pumped at 30 W pump), the residual pump after one round trip (measured in the upper optical path after the 45 degree beam splitter) can be neglected. The laser beam was coupled out of the cavity by the 45 degree beam splitter (high reflectivity at 1093nm). And we measured the fiber laser output in upper optical path after the 45 degree beam splitter as shown in following figure 4-11.

Figure 4-11 Measure fiber laser output power and beam performance

4.4.2. Experimental results

The figure 4-10 shows the measured fiber laser output power versus the launched pump power.

Figure 4-12 reversed pumping fiber laser output

As can be seen, the maximum output power of the fiber laser is 11.6 watts; the maximum launched pump power is 14.8 watts, the coupling efficiency is 45%. The slope efficiency is around 78%, close to the quantum efficiency of 85.6%. The laser threshold is 0.6W.

Figure 4-13 shows the laser spectrum

Figure 4-13 fiber laser spectrum

The peak wavelength is at 1095.5nm and the line width of the free running fiber laser is ~5nm. By using the wavelength selection techniques such as the FBG or bulk optical gratings, it can be compressed to less than 1nm [1].

Compared with the simulation results, we can estimate the doping concentration of the double clad fiber used is around $1 \times 10^{26} \text{m}^{-3}$, detailed discussion in section 4.6.

4.5. Forward pumped fiber laser

4.5.1. Experimental setup

The schematic of the forward pumped fiber laser setup is shown in figure 4-14, different from the backward pumped configuration shown in figure 4-8, we used a dichroic mirror as the front mirror, the left fiber end was cleaved perpendicularly and butt-coupled to mirror M_1 as the input port of the fiber laser, the dichroic mirror has high transmittance at 940nm (pump wavelength) and high reflectivity at 1093nm (lasing wavelength). The laser output is now from the right bare fiber end. A 45 degree beam splitter (high transmission @940nm and high reflection @ 1093nm) was used to divide fiber laser output and residual pump after the right fiber end. The 4% Fresnel reflection acts as the rear cavity mirror of the fiber laser.

Figure 4-14 forward pumping fiber laser schematic

Same as the reversed pumping configuration fiber laser experiments, a 30W fiber coupled laser diode bar was used as the pump source, the pump light from the $\Phi=800\mu\text{m}$ transport fiber was collimated with a $f=11.0\text{mm}$ collimator and focused by a $f=8\text{mm}$ aspherical lens onto the pump cladding (diameter $\Phi=210\mu\text{m}$) of the double clad fiber, which is butt-coupled to the input dichroic mirror M_1 . The Yb^{3+} doped double clad fiber is 50 m in length. When the pump beam propagates through the fiber, it is absorbed by the Yb ions in the single mode fiber core, generating stimulated emission at 1095nm. This laser light was confined within the single mode core and output from the other fiber end.

The following figure shows the experimental setup of this forward pumped fiber laser:

Figure 4-15 forward pumping fiber laser experimental setup

In this experiment, one of the key factors to improve coupling efficiency and fiber laser output power is the alignment of the input mirror. It must be strictly vertical to the input fiber. In order to achieve the optimum coupling between the pump beam and fiber, the input fiber end should be tightly attached to the input mirror. In experiments, a He-Ne laser was used to align the input mirror to make

it perpendicular to the optical fiber. The input mirror was mounted on a 3-axis stage and a tilted mounting plate with as many freedoms as possible

4.5.2. Experimental results and analysis

Figure 4-16 shows the fiber laser output power versus launched pump power under the forward pumping configuration.

Figure 4-16 forward pumping fiber laser output power vs launched pump power

A maximum output power of 7.91 watts was obtained at the maximum launched pump power of 11.5 watts, which gives a slope efficiency of around 68.7%. The output power increased linearly with the launched pump power. The laser has a threshold of 0.5W.

This slope efficiency obtained under the forward pumping configuration is lower than that obtained under the reverse pumping configuration. The reason is that for the current fiber laser, the residual pump power was not reflected back by the end mirror as in reverse pump configuration, which cause less effective pumping.

However, the threshold power is lower than that of the reversed pumping laser because less scattering loss exists in the current laser.

Figure 4-17 shows the spectrum of the fiber laser. The peak wavelength is 1094.5nm, which is shorter than that of the fiber laser under reversed pumping.

Figure 4-17 forward pumping fiber laser spectrum

This is because under reversed pumping, as a result of re-absorption with longer optical path in Yb fiber, the lasing wavelength is shifted to the longer wavelength side.

4.6. Comparison between the experimental results and the simulations

From section 4.5 we know that the experimental fiber laser slope efficiencies for forward pumping and reverse pumping are 68.7% and 78% respectively, while in chapter 2, the slope efficiencies in both configurations are 44% and 51% respectively, what result in such a big discrepancy between experimental results and simulation results?

Look back into our simulation, in section 2.3, we mentioned that some parameters of the fiber are taken from references but not from fiber supplier because fiber supplier reserve those parameters as business secrets. As we discussed in section 2.3.2.4, Yb ions

doping concentration N has big impact on the fiber laser output power. In table 2-1, we have taken $N=4\times 10^{25} \text{ m}^{-3}$, from figure 2-15, if we take an optimized doping concentration $N=1\times 10^{26} \text{ m}^{-3}$, keep other parameters same as chapter 2 and carry on the same simulation as in chapter 2, the laser slope efficiency will be quite different.

Figure 4-18 fiber laser output power versus launched pump power in reverse pump at $N=1\times 10^{26} \text{ m}^{-3}$

Based on the new simulation results at $N=1\times 10^{26} \text{ m}^{-3}$, the lasing threshold is at 480mW, the achievable output power at 30W launched pump is 23.4838W, and the slope efficiency for fiber laser under reverse pumping configuration is around 78.28%, almost same as the slope efficiency we got in experiments.

From this we understand that the doping concentration of the fiber used in our experiments is an optimized doping concentration, it is likely close to $1\times 10^{26} \text{ m}^{-3}$.

In order to understand the impact of doping concentration on fiber laser performance clearly, we put some simulation results at lower doping concentration ($N=4\times 10^{25} \text{ m}^{-3}$) and higher doping concentration ($N=1\times 10^{26} \text{ m}^{-3}$) as following:

Figure 4-19 and figure 4-20 describe the powers evolution in forward pumping fiber laser at lower doping concentration and higher doping concentration.

Figure 4-21 and figure 4-22 describe the evolution of pump, signal power in reverse pump configuration at lower doping concentration and higher doping concentration respectively.

Compared with those powers evolution calculated at lower doping concentration $N=4 \times 10^{25} \text{ m}^{-3}$ (figure 4-20), the power evolution of the fiber laser at higher doping concentration $N=1 \times 10^{26} \text{ m}^{-3}$ remains similar trend as in lower doping concentration, but steeper. In another words, at fixed 30 watts launched pump power and with fixed 50 m fiber length, under both forward pumping and reverse pumping configuration, higher doping concentration fiber laser can get higher signal powers (including positive direction signal and negative direction signal). More pump power is absorbed in high doping fiber laser than in lower doping concentration, less residual pump is left at the end of 50 m fiber length.

Figure 4-19 fiber laser pump and signal power evolution in forward pump at low doping $N=4 \times 10^{25} \text{ m}^{-3}$

Figure 4-20 fiber laser pump and signal power evolution in forward pump at high doping $N=1 \times 10^{26} \text{ m}^{-3}$

Figure 4-21 evolution of pump, signal power in reverse pump configuration at lower doping $N=4 \times 10^{25} \text{ m}^{-3}$

Figure 4-22 evolution of pump, signal power in reverse pump configuration at higher doping $N=1 \times 10^{26} \text{ m}^{-3}$

Furthermore, we compare the optimized fiber lengths of fiber laser under lower doping concentration (as shown in figure 4-23) and higher doping concentration (as shown in figure 4-24).

Figure 4-23 fiber laser output power as function of fiber length at $N=4 \times 10^{25} \text{ m}^{-3}$

Figure 4-24 fiber laser output power as a function of fiber length at $N=1 \times 10^{26} \text{ m}^{-3}$

From figure 4-23, figure 4-24, we can see that the optimized fiber length of higher doping concentration ($N=1 \times 10^{26} \text{ m}^{-3}$) fiber is at around 40-60m, and highest fiber laser output power is nearly 25 watts. And the optimized fiber length of lower doping concentration ($N=4 \times 10^{25} \text{ m}^{-3}$) fiber is around 80-100m; the highest achievable output power is around 18 watts.

In summary, higher doping concentration results in shorter optimized fiber length and higher fiber laser output power than lower doping concentration.

From the simulation results of different doping concentration, compared with the experimental results we got, we can conclude that the doping concentration of the fiber used in our experiments is an optimized doping concentration close to $1 \times 10^{26} \text{ m}^{-3}$. This may explain why the fiber supplier didn't release the parameter to us. At this doping concentration level, under fixed 30 watts pump, the optimized fiber length is around 40-60m, and the fiber length used in our experiments is 50 m which is within the optimized range.

Chapter summary

In this chapter, both 12W CW output for a fiber laser under backward-pumping configuration and 8W CW output under the forward-pumping configuration have been achieved. Experimental results were analyzed and compared with the simulation results.

Chapter 5. Conclusion and Recommendations

5.1. Conclusion

High power double clad fiber lasers have many attractive features and have been investigated intensively. They have shown great potential in various application fields. This thesis presents the first home made high power fiber laser in our university and has investigated the “know how” on the high power fiber laser technology.

A theoretical model describing the operation of the high power double clad fiber laser has been setup. Based on this model, we have numerically investigated performance of the fiber laser under various conditions such as different pump directions, different coupler reflectivity. The optimum fiber length, the impact of doping concentration and scattering loss were also numerically studied. The numerical results provide clear guidance on our fiber laser design and experiments.

Although double clad fiber lasers have been studied worldwide intensively, only a few laser diode beam shaping techniques have been patented, which is the crucial part for injecting high power pump beam into fiber laser. We have made a detailed discussion on the high power fiber laser development. This includes the fiber design, fiber laser cavity design; pump laser diode array beam properties, pump beam shaping. The discussions regarding the beam shaping and pump source selection are also useful for the diode pumped solid state laser (DPSSL) research.

A high power Yb double-clad fiber laser was setup and experimentally investigated. Under reverse pumping, a maximum output power of 11 watts was demonstrated. Under forward pumping, 8 watts output power was obtained. The experimental results were further compared with numerical results. Further-more, we have analyzed problems related to coupling efficiency.

The techniques in high power fiber laser and bare laser diode bar beam shaping have been investigated. The developed high power fiber laser can be used for fiber nonlinear optics and sensors applications. It is point out that with stronger pump source, the laser output power can be further improved and scaled to several tens of watts. Meanwhile, the beam shaping technique using the micro lens package can realize low cost pump.

5.2. Recommendations for Future Research

5.2.1. Raman fiber laser

It is a traditional application to use high power fiber laser as pump source of Raman fiber laser.

Stimulated Raman scattering is an important nonlinear process that can turn optical fibers into broadband Raman amplifiers and Raman fiber lasers. In many nonlinear media, spontaneous Raman scattering converts a small fraction (typically 10^{-6}) of the incident power from an optical beam to another optical beam by frequency downshift ([47], P₃₁₇). And signal amplification using Raman Effect is one of the technologies to realize optical fiber amplifier in optical communication system. In order to fully realize Raman amplifier, a very intense pump wave must be launched into a small fiber core, high power rare earth doped double clad fiber laser provide such a possibility. In 2003, research team in Singapore has demonstrated a 10W Raman fiber laser [48] by using a 20W commercial Yb fiber laser at 1070nm. In 2004, another research team in Singapore DSO demonstrated a world record 13W Raman fiber laser also pumped by a 100W commercial Yb fiber laser at 1092nm [49].

The schematic of a Raman fiber laser can be shown as following figure:

Figure 5-1 schematic of raman fiber laser pumped by Yb fiber laser

Home made Yb fiber provide a flexible high power pump source of Raman fiber laser. And such flexible Raman fiber laser can be used in further nonlinear fiber optics research.

5.2.2. Pulsed fiber laser ---- Q switched fiber laser

Short pulse lasers are useful in telecommunication and sensor systems. There are two kinds of techniques for the generation of short optical pulses, one is known as Q-switching [50] and the other is mode-locking [51] [52]. The characteristics of single-mode fiber lasers such as: good spatial mode and high average power, at the same time represent a limit in average power for these devices, when operated in Q-switched regime.

Here we consider only the Q-switched operation because this technique allows us to increase the peak power by several orders of magnitude compared with the continuous wave fiber lasers.

What is a Q switched laser? What Q represents?

Q represents the quality factor of an optical cavity, which is defined as the ratio of energy stored in the cavity to that lost per round trip.

The operation of a Q-switched laser can be described as following:

Initially the losses of the cavity are set at a very high value, lowering the Q value of the cavity, and the gain medium is excited. As the losses are high, normally the laser is unable to reach threshold. Thus the population inversion in cavity builds up to a value that is well in excess of the value that would be achieved under normal conditions.

At a certain point, the losses are abruptly reduced to their normal values, then the signal gain is much larger than the losses and it results in rapid building up of laser output power, which saturates the maximum gain in a very short time period. Gain saturation obtained at that point is so strong that makes the inverted population well below the threshold population level, thus stop laser action again. Then a laser pulse is the result of this rapid rise and fall of the intra-cavity flux.

Q-switching operation can be obtained using mechanical, acousto-optic, electro-optic methods, or by the use of a saturable absorber such as Cr-YAG, all of them are compatible with fiber lasers. Rapid modulation of the cavity can be achieved by using an acousto-optic modulator (AOM) which commonly offers high switching speeds.

Figure 5-2 active Q-switched Yb fiber laser

Figure 5-2 depicts an active Q-switched fiber laser, an acousto-optic modulator (AOM) with diffraction efficiency $>85\%$ at its first order is inserted into the double clad fiber laser between the high reflection mirror and fiber end, a focusing lens of 10mm focal length is used to expand and refocusing the laser beam from fiber laser. Here the fiber end should be angle (e.g. 45°) cleaved and polished in order to avoid lasing between front mirror and bare fiber end Fresnel reflection before the AOM. This work will explore the techniques in Q-switching operation of double clad fiber laser, and provide high energy pulse laser for non-linear fiber optics research.

References

References

- [1] Michel J. F. Digonnet, *Rare-earth-doped fiber laser and amplifiers*, New York, Marcel Dekker, Inc, 2001.
- [2] Dominic, S.MacCormack, R.Waarts, S.Sanders,, “110 w fiber laser”, *Electron. Lett.* 1999, **35**, pp. 1158-1160.
- [3] From the webpage of the IPG Photonics Inc., <http://www.ipgphotonics.com/> .
- [4] Luis Zenteno, “High-power double-clad fiber lasers”, *IEEE J.Lightwave Technology*., no 9, vol 11, pp.1435-1446, 1993.
- [5] H.M.Pask, Robert J.Carmen, David C.Hanna, “Ytterbium-doped silica fiber lasers: versatile sources for the 1-1.2 μ m region”, *IEEE J. Select. Topics Quantum Electron.*, vol. 1, pp.2-13, 1995.
- [6] R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, “Ytterbium doped fiber amplifiers”, *IEEE J. Quantum Electron.*, vol. 33, pp.1049–1056, July 1997.
- [7] E. Desurvire, *Erbium-Doped Fiber Amplifiers*. New York: Wiley, 1994.
- [8] C. Barnard, P. Myslinsky, J. Chrostowsky, M. Kavehrad, “Analytical model for rare-earth-doped fiber amplifiers and lasers,” *IEEE J.Quantum. Electron.*, vol. 30, pp. 1817–1830, Aug. 1994.
- [9] Hardy and R. Oron, “Signal amplification in strongly pumped fiber amplifiers,” *IEEE J. Quantum Elect.*, vol. 33, pp. 307–313, Mar. 1997.
- [10] A.A.Saleh, R.M.Jopson, J.D.Evankow, J.Aspell, “Modeling of gain in Erbium-doped fiber amplifiers”, *IEEE Photonics Technology Letters*., vol. 2, pp. 714-717, 1990.
- [11] C.Randy Giles, Emmanuel Desurvire, “Modeling erbium-doped fiber amplifiers”, *J. Lightwave Technology*.,no 2, vol 9, pp. 271-283, 1991.
- [12] Stuart D. Jackson, Terence A. King, “Theoretical modeling of Tm-doped silica fiber lasers”, *J.Lightwave Technology*., no 5, vol 17, pp. 948-956, 1999.
- [13] Emmanuel Desurvire, Jay R.Simpson, “Amplification of spontaneous emission in erbium-doped single-mode fibers”, *J.Lightwave Technology*., no 5, vol 7, pp.835-845, 1989.
- [14] E. Desurvire, M. Zirngibl, H. M. Presby, D.Digiovanni, “Characterization and modeling of amplified spontaneous emission in unsaturated erbium-doped fiber amplifiers”., no 2, vol 3, pp.127-129, 1991.
- [15] C.H.Henry, “Theory of spontaneous emission noise in open resonators and its application to lasers and optical amplifiers”, *J.Lightwave Technology*, no 3, vol LT-4, pp.288-297, 1986.
- [16] Shampine L.F., M.W. Reichelt, and J. Kierzenka, “Solving Boundary Value Problems for Ordinary Differential Equations in MATLAB with bvp4c,” 2000, available at <ftp://ftp.mathworks.com/pub/doc/papers/bvp/>.
- [17] Emmanuel Desurvire, *Erbium doped fiber amplifier*, John Wiley & Sons Inc, 1993, p11
- [18] Michel J. F. Digonnet, *Rare-earth-doped fiber laser and amplifiers*, New York, Marcel Dekker, Inc, 2001, p540-542.
- [19] Yariv, *quantum electronics*, Wiley, 1975

References

- [20] A. E. Siegman, *Lasers*, University Science Books, 1986.
- [21] R. Paschotta, J. Nilsson, "life time quenching in Yb doped fibers", *Optics communications* V136, p375-378, 1997
- [22] Z. Burshtein, "Impurity Local Phonon Nonradiative Quenching of Yb³⁺ Fluorescence in Ytterbium-Doped Silicate Glasses", *IEEE Journal of Quantum Electronics*, vol 36, no. 8, 2000
- [23] Liu, J.Song, K.Kamatani, K.Ueda, "Rectangular double clad fiber laser with two-end-bundled pump", *Electronics Letters*, no 18, vol 32, pp.1673-1674, 1996.
- [24] L.Cheng, D.Y.Shen, J.Song, Nam Seong Kim, K.Ueda, "Analysis of high power double-clad fiber lasers side pumped by multiple diode lasers in V-groove configuration", *CLEO Pacific Rim 1999*, pp.805-806.
- [25] Masud masuripur, http://www.optics.arizona.edu/masud/laser_diode.pdf
- [26] Coherent Laser Corporation Auburn Group, "Laser diode technical note 1", <http://www.coherent.com/Downloads/LaserDiodeTechNote1Rev2.pdf>, from Coherent Laser Website, www.coherentinc.com.
- [27] O. Wallner and W. R. Leeb, "Minimum length of a single-mode fiber spatial filter", *J. Opt. Soc. Am. A* 19, 2445 (2002).
- [28] Suganda Jutamulia, Blue Sky Research Inc, "Improving laser diode/fiber optic coupling efficiency using microlens optics", from www.fiberopticonline.com, 4/30/2001, <http://www.fiberopticonline.com/content/news/article.asp?docid={e83ce59a-3a5c-11d5-a770-00d0b7694f32}>.
- [29] White paper from <http://www.lightpath.com/WhitePapers.htm>, LightPath Technologies, Inc, Argonne National Laboratory Technology Development Division, "Selecting a High-Power Fiber-Optic Laser Beam Delivery System", 1996
- [30] Keiser,Gerd, *optical fiber communications*, 3rd edition, Mc Graw Hill (International Edition) 2000, p56, p207
- [31] Dmitrii Kouznetsov, Jerome V. Moloney, "Efficiency of pump absorption in double-clad fiber amplifiers. I. Fiber with circular symmetry", *J.Opt.American.B.*, no 6, vol 18, pp.743-749, 2001.
- [32] Dmitrii Kouznetsov, Jerome V. Moloney, Efficiency of pump absorption in double-clad fiber amplifiers. II. Broken circular symmetry, *J.Opt.American B*, Vol. 19, Issue 6, pp. 1259-1263 (June 2002).
- [33] Dmitrii Kouznetsov, Jerome V. Moloney, Efficiency of pump absorption in double-clad fiber amplifiers. III. Calculation of modes, *J.Opt.American B*, Vol. 19, Issue 6, pp. 1304-1309 (June 2002).
- [34] Martin H.Muendel, "Optimal inner cladding shapes for double-clad fiber lasers", *CLEO*, 1996.
- [35] D.J.Digiovanni, M.H.Muendel, "High power fiber lasers" *Optics & Photonics News*, 10:26-30, 1999. <http://www.osa-opn.org/>
- [36] Peter Wang, Beam-shaping optics deliver high-power beams, *Archives: Laser Focus World*, vol 37, issue 12, Dec, 2001
- [37] H Zbinden and J E Balmer, *Opt Lett* 15, 1014 (1990)
- [38] Th Graf and J E Balmer, *Opt Lett* 18, 1317 (1993)
- [39] M S Kierstead and T M Baer, *Conf Lasers and Electro-Optics*, OSA Technical Digest Series, vol. 10, p.490 (Optical Society of America, Washington, DC, 1991)

References

- [40] J R Leger and W C Goltsos, IEEE J. Quantum Electron. 28, 1088 (1992)
- [41] S Yamaguchi, T Kobayashi, Y Saito and K Chiba, Opt. Lett. 20, 898 (1995)
- [42] W. A. Clarkson and D. C. Hanna, "Two-mirror beam-shaping technique for high-power diode bars," Opt. Lett. Vol 21, issue 6, 375- (1996)
- [43] Treusch, Hans-Georg; Du, Keming; Baumann, Markus; Sturm, Volker; Ehlers, Bodo; Loosen, Peter, "Fiber-coupling technique for high-power diode laser arrays", Proc. SPIE Vol. 3267, p. 98-106, Laser Resonators, Alexis V. Kudryashov; Pierre Galarneau; Eds., 1998
- [44] Goering, Rolf; Schreiber, Peter; Possner, Torsten, "Micro-optical beam transformation system for high-power laser diode bars with efficient brightness conservation", (Fraunhofer-Institute for Applied Optics and Precision Engineering), Proc. SPIE Vol. 3008, p. 202-210, Miniaturized Systems with Micro-Optics and Micromechanics II, M. Edward Motamedi; Larry J. Hornbeck; Kristofer S. Pister; Eds.
- [45] Coherent User's manual, "Fiber array packaged (FAP- I^{TM}) laser diode bars".
- [46] Institute of laser technique, Germany, <http://www.ilt.fraunhofer.de/eng/ilt/pdf/eng/products/Heatsinks.pdf>, "design of laser diode heat sink", Fraunhofer
- [47] Agrawal, G.P, "nonlinear fiber optics" 2nd edition, Academic Press Inc, 1995, p317
- [48] Z. Xiong, Member, IEEE, Member, OSA, N. Moore, Z. G. Li, and G. C. Lim, "10-W Raman Fiber Lasers at 1248 nm using Phosphosilicate Fibers", Journal Of Lightwave Technology, Vol. 21, NO. 10, October 2003, p2377-2381.
- [49] S. K. Sim, H. C. Lim, L. W. Lee, L. C. Chia, R. F. Wu, I. Cristiani, M. Rini and V. Degiorgio, "High-power cascaded Raman fibre laser using phosphosilicate fiber", Electronics Letters 10th June 2004 Vol. 40 No. 12
- [50] Mears R.J., Reekie L., Poole S.B., Payne D.N., "Low-threshold, tuneable, CW and Q-switched fibre laser operating at 1.55 μ m", Elect. Lett. Vol. 23, No. 3, pp. 159, (1986)
- [51] Alcock I.P., Tropper A.C., Ferguson A.I., Hanna D.C., "Q-switching, mode locking and tuneable operation around 0.9 μ m of a neodymium-doped monomode fibre laser, "IEEE proceedings, Vol. 134-J (3), pp. 183, (1987)
- [52] Duling I.N., Goldberg L., Weler J.F, "High-power, mode-locked neodymium fibre laser by an injection-locked diode array", Elect. Lett. Vol. 24, No. 21, pp. 1333, (1988)