“To develop a MATLAB based application to calculate the optimal length of active fiber for high power fiber laser development for forward and backward pumping configuration using runge-kutta metod”

Report submitted in partial fulfillment of the requirement for the degree of Bachelor of Technology

In

Computer Science and Engineering

By

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Course: B.Tech. (CSE-2)   Session: 2015-2019

To

Maharaja Surajmal Institute Of Technology

Affiliated to Guru Gobind Singh Indraprasth University

Janakpuri, New Delhi - 58

October   2017

LASER SCIENCE AND TECHNOLOGY CENTRE

DRDO, MINISTRY OF DEFENCE

METCALFE HOUSE, NEW DELHI – 110054

CERTIFICATE

This is to certify that Rajat Kumar, student of B.Tech 2nd year (Computer Science and Engineering), MSIT, Guru Gobind Singh Indraprastha University has successfully completed his training at LASTEC for the period from 5^{th} June 2017 – 17^{th} July 2017 under our supervision and guidance. During this period he has worked on "*D**evelopment of a MATLAB based application to calculate the optimal length of active fiber in high power fiber laser development for forward and backward pumping configuration using Runge Kutta method.***". He has put in sincere effort and has shown a great deal of enthusiasm. His conduct during the training has been excellent.

We wish him all the success in his future endeavors.

Mr. Anand Mohan
SC ***'E'***
HPFL Division

DRDO CERTI

DECLARATION

I, Rajat Kumar, student of B.Tech 2nd year (Computer Science and Engineering), MSIT, Guru Gobind Singh Indraprastha University, hereby declare that the Project Report entitled "***Development of a MATLAB based application to calculate the optimal length of active fiber in high power fiber laser development for forward and backward pumping configuration using Runge Kutta method.***" is a authentic record of my work done at Laser Science and Technology Centre, DRDO, Ministry of Defense, New Delhi, and has not been previously formed the basis for the award of any degree, diploma or other title or recognition.

Date:-

RAJAT KUMAR

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I would like to avail the opportunity to express my most sincere appreciation and deep gratitude to all those people who in a way or other have contributed positively in completion of this project.

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In my long list of people I cannot forget to express my heartful gratitude the cooperation of my parents and their unwavering encouragement that always supported and assisted me in achieving my goals. I also thank my friends colleague Pranav Atulya, Aditi Aggarwal and Aditi Rajvanshi for their support and constructive discussions.

RAJAT KUMAR

Contents

ABSTRACT

A **fiber laser** is a laser in which the active gain medium is an optical fiber doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium and holmium. They are related to doped fiber amplifiers, which provide light amplification without lasing. Fiber nonlinearities, such as stimulated Raman scattering or four-wave mixing can also provide gain and thus serve as gain media for a fiber laser.

Fiber lasers and fiber amplifiers are nearly always based on glass fibers which are doped with laser-active rare earth ions (normally only in the fiber core). These ions absorb pump light, typically at a shorter wavelength than the laser or amplifier wavelength (except in upconversion lasers), which excites them into some metastable levels. This allows for light amplification via stimulated emission. Such specialty fibers are often called *active fibers*. They are gain media with a particularly high gain efficiency, resulting mainly from the strong optical confinement in the fiber's wave guide structure.

This report is aimed at developing a MATLAB based software to calculate the optimal length of forward and backward pumping in HPFL. The photons are pumped from forward and backward directions. The output signal power is calculated using Runge Kutta method to solve differential equation formed by boundary conditions.

Using GUI in MATLAB we plot the graph of “Pump Power vs Length(Forward Pumping)”, “Pump Power vs Length(Backward Pumping)” and “Output Power vs Length”.

SYSTEM REQUIREMENTS SPECIFICATION

MATLAB based application to calculate optimal length in HPFL.

1. Purpose

The purpose of this document is to present a detailed description od MATLAB based application to calculateoptimal length in HPFL.

2. Intended Audience

The intended audiences are:

- Physicists
- Researchers
- Future Researchers to extend the ideas of Fiber Laser

3. Scope and uses

The rise in output power from rare earth doped fiber sources over the past decade, via the use of cladding pumped fiber architectures has been dramatic, leading to a range of fiber-based devices with outstanding performances in terms of output power, beam quality, overall efficiency, and flexibility with regard to operating wavelength and radiation format. This in the high power arena is largely due to the fiber's geometry, which provides considerable resilience to the effects of heat generation in the core, and facilitates efficient conversion from relatively low brightness diode pump radiation to high brightness laser output.

4. Hardware and Software requirements

- Processor : Intel Pentium® CPU B950 2.10 GHz
- Required RAM: 1.00 GB or more
- System Type: 32-bit or 64 bit OS

5. Software

- Internet facility is required.
- Windows Operating system
- MATLAB

6. Peripherals

- C
- Java Swing Components
- MATLAB

7. Assumptions and Dependencies

Assumptions:

- The user is familiar with advanced mathematics, basic concepts of lasers and fibre lasers.

Dependencies:

- The system requires Internet for proper functioning.
- Text editor required
- Internet Browser required

CHAPTER 1

LASER FUNDAMENTALS

1.1 INTRODUCTION TO LASER

The word "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. Lasers are finding ever increasing military applications -- principally for target acquisition, fire control, and training. These lasers are termed rangefinders, target designators, and direct-fire simulators. Lasers are also being used in communications, laser radars (LIDAR), landing systems, laser pointers, guidance systems, scanners, metal working, photography, holography, and medicine.

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "light amplification by stimulated emission of radiation". A laser differs from other sources of light because it emits light coherently. Spatial coherence allows a laser to be focused to a tight spot, enabling applications like laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over long distances (collimation), enabling applications such as laser pointers. Lasers can also have high temporal coherence which allows them to have a very narrow spectrum, i.e., they only emit a single color of light. Temporal coherence can be used to produce pulses of light—as short as a femtosecond.

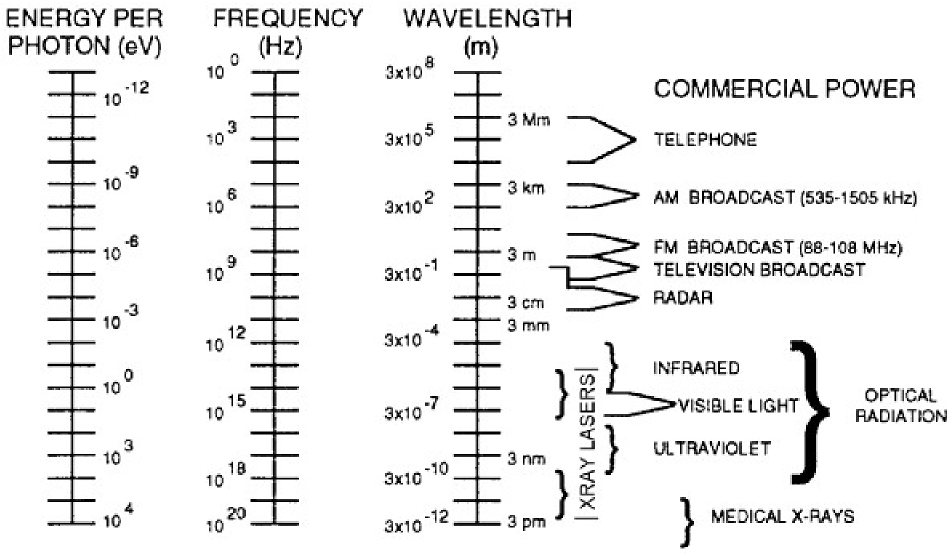

Figure 1.1. Electromagnetic Spectrum

1.2 FUNDAMENTALS OF LASER

Laser is different from other source of light by its coherence property.

- **Spetial Coherence**

  It is typically expressed through the output being a narrow beam which is diffraction-limited. Laser beams can be focused to very tiny spots, or they can be launched into beams of very low divergence in order to concentrate their power at a large distance.

- **Temporal Coherence**

  It implies polarized wave at single frequency i.e., Monochromaticity, whose phase is correlated over a relatively coherence length along the beam.

  A beam produced by a thermal or other incoherent light source has an instantaneous amplitude and phase which vary randomly with respect to time and position, and thus a very short coherence length.

1.3 DESIGN

A laser consists of a gain medium, a mechanism to supply energy to it, and something to provide optical feedback. The gain medium is a material with properties that allow it to amplify light by stimulated emission. Light of a specific wavelength that passes through the gain medium is amplified (increases in power).

For the gain medium to amplify light, it needs to be supplied with energy. This process is called pumping. The energy is typically supplied as an electrical current, or as light at a different wavelength. Pump light may be provided by a flash lamp or by another laser.

The most common type of laser uses feedback from an optical cavity—a pair of mirrors on either end of the gain medium. Light bounces back and forth between the mirrors, passing through the gain medium and being amplified each time. Typically one of the two mirrors, the output coupler, is partially transparent. Some of the light escapes through this mirror. Depending on the design of the cavity (whether the mirrors are flat or curved), the light coming out of the laser may spread out or form a narrow beam. This type of device is sometimes called a laser oscillator in analogy to electronic oscillators, in which an electronic amplifier receives electrical feedback that causes it to produce a signal.

Most practical lasers contain additional elements that affect properties of the emitted light such as the polarization, the wavelength, and the shape of the beam.

1.4 HOW LASER WORKS

- **Metastable State**

A state in which atoms or molecules remains at an excited state for some time.

Energy is supplied to the laser medium by the energy pumping system. This energy is stored in the form of electrons trapped in the **metastable states**.

Pumping must produce a population inversion (i.e., more atoms in the metastable state) before laser action can take place.

When population inversion is achieved, the spontaneous decay of a few electrons from the metastable states to a lower energy level starts a chain reaction. The photons emitted spontaneously will hit (without being absorbed) other atoms and stimulate their electrons to make the transition from the metastable energy level to a lower energy level- emitting photons of precisely the same wavelength, phase & direction.

This action takes place across the optical cavity, when the photons that they decay in the direction of the mirrors reach the end of a laser material, they are reflected back into the material where the chain reaction continues and the no. of photons increases.

When photons arrive at the partially-reflecting mirror, only a portion will be reflected back into the cavity and the rest will emerge as a laser beam.

1.5 PROPERTIES OF LASER

1. **Monochromaticity**

   Since,

   $$E = hc/\text{lemda}$$

Atomic transition leads to energy which is same for all photons thus monochromatic.

A truly monochromatic wave requires a wave train of infinite duration. The spectral emission line from which it originates does have a finite width, because of Doppler effect of the moving atom or molecules from which it comes.

Compared to the ordinary source of light, the range of frequency (line width) of the LASER is extremely small.

2. Coherence

Coherence is one of the unique property of laser light. It arises from the stimulated emission process which provides amplification. The emitted photons have a definite phase relation to each other, generating a coherent output.

"Wavelength of the laser light are in phase in space and time"

3. Directionality

Laser beam is highly directional, which implies laser light is of very small divergence. This is a direct consequence of the fact that the laser beam comes from a resonant cavity, and only waves propagating along the optical axis can be sustained in the cavity.

CHAPTER 2

Introduction: FIBER LASER

2.1.1 Definition

A **fiber laser** is a laser in which the active gain medium is an optical fiber doped withrare-earth elements suchas erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium and holmium. They are related to doped fiber amplifiers, which provide light amplification without lasing. Fiber nonlinearities, such as stimulated Raman scattering or four-wave mixing can also provide gain and thus serve as gain media for a fiber laser.

2.1.2 Common Types of Rare-earth-doped Fibers

The following table shows the most common laser-active ions and host glasses and also typical emission wavelength ranges of rare-earth-doped fibers:

Table : Common laser-active ions and host glasses and important emission wavelength.

Ion	**Common host glasses**	**Important emission wavelengths**
neodymium(Nd3+)	Silicate and phosphate glasses	1.03–1.1 μm, 0.9–0.95 μm, 1.32–1.35 μm
ytterbium(Yb3+)	silicate glass	1.0–1.1 μm
erbium (Er3+)	silicate and phosphate glasses, fluoride glasses	1.5–1.6 μm, 2.7 μm, 0.55 μm
thulium (Tm3+)	silicate and germanate glasses, fluoride glasses	1.7–2.1 μm, 1.45–1.53 μm, 0.48 μm, 0.8 μm

Ion	Common host glasses	Important emission wavelengths
praseodymium (Pr^{3+})	silicate and fluoride glasses	1.3 µm, 0.635 µm, 0.6 µm, 0.52 µm, 0.49 µm
holmium (Ho^{3+})	silicate glasses, fluorozirconate glasses	2.1 µm, 2.9 µm

The technologically most important rare-earth-doped fibers are erbium-doped fibers for erbium-doped fiber amplifiers and ytterbium-doped fibers for high-power fiber lasers and amplifiers.

2.1.3 Advantages and applications

Figure 2.1. :A laser cutting machine with a 2 kW continuous wave fiber laser

The advantages of fiber lasers over other types include:

- Light is already coupled into a flexible fiber: The fact that the light is already in a fiber allows it to be easily delivered to a movable focusing element. This is important for laser cutting, welding, and folding of metals and polymers.

- High output power: Fiber lasers can have active regions several kilometers long, and so can provide very high optical gain. They can support kilowatt levels of continuous output power because of the fiber's high surface area to volume ratio, which allows efficient cooling.
- High optical quality: The fiber's waveguiding properties reduce or eliminate thermal distortion of the optical path, typically producing a diffraction-limited, high-quality optical beam.
- Compact size: Fiber lasers are compact compared to rod or gas lasers of comparable power, because the fiber can be bent and coiled to save space.

2.2.1 Fiber Bragg Gratings

A fiber Bragg grating is a periodic or aperiodic perturbation of the effective refractive index in the core of an optical fiber. Typically, the perturbation is approximately periodic over a certain length of e.g. a few millimeters or centimeters, and the period is of the order of hundreds of nanometers, or much longer for long-period fiber gratings (see below).

The refractive index perturbation leads to the reflection of light (propagating along the fiber) in a narrow range of wavelengths, for which a Bragg condition is satisfied (→ Bragg mirrors):

$$\frac{2\pi}{\Lambda} = 2 \cdot \frac{2\pi n_{\mathrm{eff}}}{\lambda} \quad \Rightarrow \quad \lambda = 2 n_{\mathrm{eff}} \Lambda$$

2.2.2 Fabrication

The fabrication of fiber Bragg gratings typically involves the illumination of the core material with ultraviolet laser light (e.g. from a KrF or ArF excimer laser or other type of ultraviolet laser), which induces some structural changes and thus a permanent modification of the refractive index. The photosensitivity of the core glass is actually strongly dependent on the chemical composition and the UV wavelength: silica glass (as is often used for the cladding) has a very weak photosensitivity, whereas germanosilicate glass exhibits a much stronger effect, making possible a refractive index contrast up to $\approx 10-3$. A significant further increase in photosensitivity is possible by loading the fiber with hydrogen (*hydrogenated fibers*). (For that purpose, the fiber is kept in a high-pressure hydrogen atmosphere for some time.) Phosphate glasses are normally regarded as unsuitable for FBG fabrication, but special methods make this possible.

2.3.1 Master Oscillator Fiber Amplifier

The term master oscillator fiber amplifier (MOFA, MOPFA, or fiber MOPA) is a variation of the term master oscillator power amplifier (MOPA), meaning a system where the power amplifier is a fiber amplifier. The latter is usually a cladding-pumped high-power amplifier, often based on an ytterbium-doped fiber. The main attractions of such fiber-based power amplifiers are:

- A high output power can be achieved with a high power efficiency.
- The cooling system can be relatively simple.
- The beam quality can be high; it is often close to diffraction-limited.

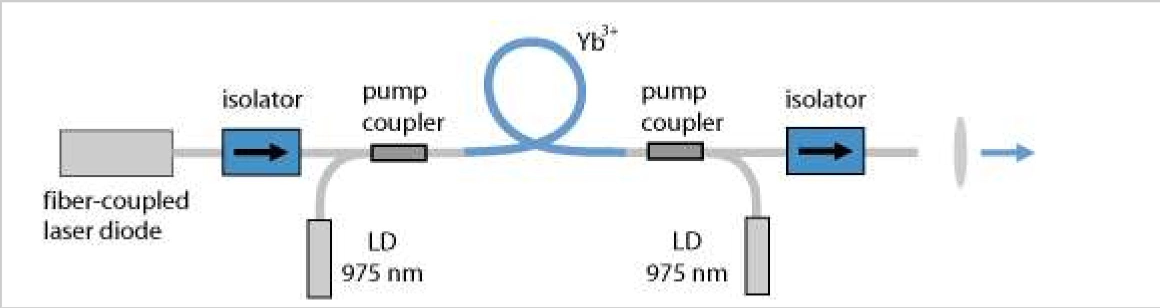

Figure 2.2: Setup of a single-stage core-pumped fiber MOPA. For higher power levels, a second amplifier stage with double-clad fiber may be added. The seed laser diode may be operated in a pulsed regime.

CHAPTER 3

Introduction : HIGH-POWER LASERS

3.1.1 Definition

Lasers with high output powers are required for a number of applications, e.g. for

- material processing (welding, cutting, drilling, soldering, marking, surface modification)
- large-scale laser displays (→ RGB sources)
- remote sensing (e.g. with LIDAR)
- medical applications (e.g. surgery)
- military applications (e.g. anti-missile weapons)
- fundamental science (e.g. particle acceleration)
- laser-induced nuclear fusion (e.g. in the NIF project)

Material processing with high-power lasers is the second largest segment of laser applications concerning global turnovers (after communications).

There is no commonly accepted definition of the property “high power”; in the context of laser material processing, it usually means multiple kilowatts or at least a few hundred watts, whereas for laser displays some tens of watts many already be considered high. In some areas, this label is assigned simply for generating a significantly higher output power than other lasers based on the same technology; for example, some “high-powered” laser pointersemit a few hundred milliwatts, whereas ordinary laser pointers are limited to a few milliwatts.

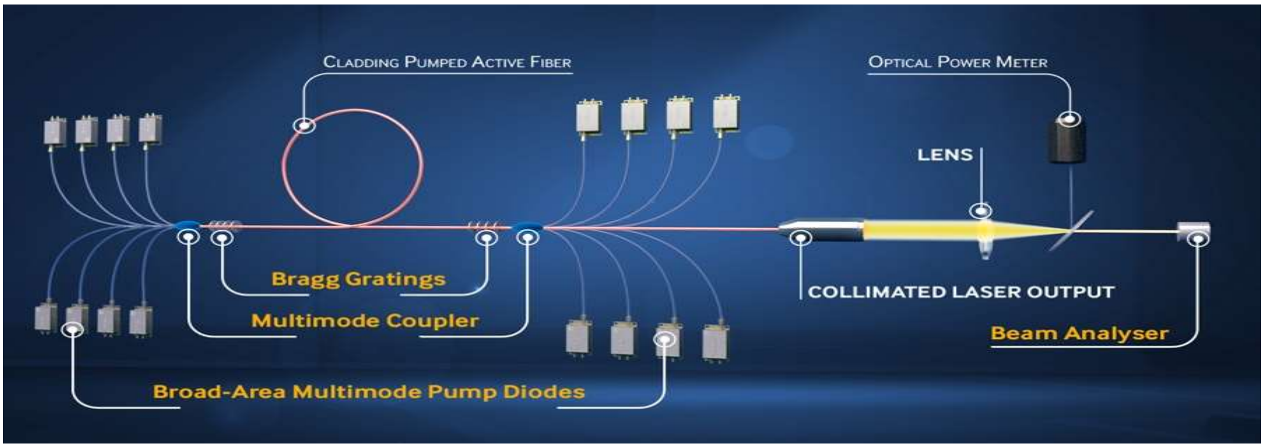

Figure 3.1. :Development of high power lasers

3.1.2 Types of High-power Lasers

There are several different types of high-power lasers:

- High-power diode bars and diode stacks have already been mentioned above as possible pump sources for solid-state lasers. They allow the generation of kilowatts of output power, but with a poor beam quality. For some applications, where beam quality is not essential, the direct use of high-power laser diodes (→ direct diode lasers) e.g. for laser welding, soldering and brazing, cladding and heat treatment, is an interesting option, offering a comparatively simple, compact, cost-effective and energy-efficient solution.
- There are various types of lamp-pumped or diode-pumped solid-state bulk lasers. Rod lasers can be optimized for several kilowatts of output power, but diffraction-limited beam quality is possible only up to a few hundred watts (with significant efforts). Slab lasers can be developed for tens of kilowatts or more with relatively high beam quality. Thin-disk lasers easily generate hundreds of watts with diffraction-limited beam quality and have the potential to reach that even at power levels well above 10 kW. The power efficiency is usually fairly good.
- High-power fiber lasers and amplifiers can generate up to a few kilowatts with close to diffraction-limited beams and high power efficiency. With relaxed beam quality requirements, even significantly higher powers are possible. Strictly, such fiber

devices are often not lasers, but master oscillator power amplifier (MOPA) configurations.

- Some gas lasers, e.g. CO2 lasers and excimer lasers, are also suitable for hundreds or thousands of watts of output power. They typically operate in different other regions than solid-state lasers, e.g. in the mid-infrared or ultraviolet region.

3.1.3 Technical Challenges

The generation of high optical powers in lasers involves a number of technical challenges:

- One requires one or several powerful pump sources. While lamp pumping was originally the only viable approach for most solid-state lasers, pumping with high-power laser diodes (diode bars or diode stacks) has become more and more widespread. Diode-pumped lasers now offer the highest output powers in continuous-wave operation. For very high pulse energies (e.g. tens of joules), lamp pumping is still more practical.
- At least for long-term continuous-wave operation, a high wall-plug efficiency is an important economic factor. Unfortunately, various technical challenges (e.g. thermal effects, see below) tend to make it more difficult at very high power levels to achieve a good efficiency.

CHAPTER 4

MATLAB OSCILLATOR TOOLBOX

4.1.1 Constants/Parameters used:

lamdap = 976e-9 //pump wavelength

lamdas = 1070e-9 //signal wavelength

dlamda = 2e-9 //linewidth

tou = 0.00085 //lifespan of yb ions

sigmaap = 1.7669e-24 //absorption cross section of pump

sigmaep = 1.7131e-24 //emission cross section of pump

sigmaas = 4.5e-27 //absorption cross section of signal

sigmaes = 3.6e-25 //absorption cross section of signal

A = 8e-10;

d = 20e-6 // core diameter

*A = pi*d^2/4 // cross section area of core*

N = 7.724e25 // yb ions

alphap = 0.00298 //reflectivity of pump

alphas = 0.00344 // reflectivity of signal

toup = 0.0025

tous = 0.88

Rso = 0.99 // Reflectivity of first grating

Rsl = 0.10 // Reflectivity of second grating

4.2.1 Runge-Kutta Method

A method of numerically integrating ordinary differential equations by using a trial step at the midpoint of an interval to cancel out lower-order error terms. The second-order formula is

$$k_1 = h f(x_n, y_n) \tag{1}$$

$$k_2 = h f\left(x_n + \tfrac{1}{2} h, y_n + \tfrac{1}{2} k_1\right) \tag{2}$$

$$y_{n+1} = y_n + k_2 + O\left(h^3\right) \tag{3}$$

(where $O(x)$ is a Landau symbol), sometimes known as RK2, and the fourth-order formula is

$$k_1 = h f(x_n, y_n) \tag{4}$$

$$k_2 = h f\left(x_n + \tfrac{1}{2} h, y_n + \tfrac{1}{2} k_1\right) \tag{5}$$

$$k_3 = h f\left(x_n + \tfrac{1}{2} h, y_n + \tfrac{1}{2} k_2\right) \tag{6}$$

$$k_4 = h f(x_n + h, y_n + k_3) \tag{7}$$

$$y_{n+1} = y_n + \tfrac{1}{6} k_1 + \tfrac{1}{3} k_2 + \tfrac{1}{3} k_3 + \tfrac{1}{6} k_4 + O\left(h^5\right)$$

4.2.2

Rate Equations for Yb doped fiber:

N11 = (PP(i)+PM(i))*sigmaap*toup/(h*nuep*A)

N22 = (PP(i)+PM(i))*sigmaas*tous/(h*nues*A)

N33 = (PP(i)+PM(i))*(sigmaap+sigmaep)*toup/(h*nuep*A)

N44 = (PP(i)+PM(i))*(sigmaas+sigmaes)*tous/(h*nues*A)

N2 = ((N11+N22)/(N33+N44+1/tou))*N

```
PPT(i) = (PpP(i)+PpM(i));

PST(i) = (PsP(i)+PsM(i));

N11 = (PPT(i)*sigmaap*toup)/(h*nuep*A);

N22 = (PST(i)*sigmaas*tous)/(h*nues*A);

N33 = (PPT(i)*(sigmaap+sigmaep)*toup)/(h*nuep*A);

N44 = (PST(i)*(sigmaas+sigmaes)*tous)/(h*nues*A);

N2(i) = ((N11+N22)/(N33+N44+1/tou))*N;
```

4.2.3 MATLAB Code for applying RK Method Forward and Backward Pumping

```
for i = 1:1:Lz

% N2 = ((N11+N22)/(N33+N44+1/tou))*N

PPT(i) = (PpP(i)+PpM(i));
PST(i) = (PsP(i)+PsM(i));
 N11 = (PPT(i)*sigmaap*toup)/(h*nuep*A);
 N22 = (PST(i)*sigmaas*tous)/(h*nues*A);
 N33 = (PPT(i)*(sigmaap+sigmaep)*toup)/(h*nuep*A);
 N44 = (PST(i)*(sigmaas+sigmaes)*tous)/(h*nues*A);

 N2(i) = ((N11+N22)/(N33+N44+1/tou))*N; % excited ions
%Constants PpP, PpM, PsP, PsM

KpP1 = dz*(-toup*PpP(i)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*PpP(i));
% first increment for pump power in positive direction
```

```
KpP2 = dz*(-toup*(PpP(i)+.5*KpP1)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*(PpP(i)+.5*KpP1));% second increment for pump power in positive direction

KpP3 = dz*(-toup*(PpP(i)+.5*KpP2)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*(PpP(i)+.5*KpP2));% third increment for pump power in positive direction

KpP4 = dz*(-toup*(PpP(i)+KpP3)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*(PpP(i)+KpP3));% fourth increment for pump power in positive direction

PpP(i+1) = PpP(i) + (KpP1 + 2*KpP2 + 2*KpP3 + KpP4)/6;% pump power in positive direction after i'th increment
%--------------------------------------------------------

KpM1 = -dz*(-toup*PpM(i)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*PpM(i));% first increment for pump power in negative direction

KpM2 = -dz*(-toup*(PpM(i)+.5*KpM1)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*(PpM(i)+.5*KpM1));% second increment for pump power in negative direction

KpM3 = -dz*(-toup*(PpM(i)+.5*KpM2)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*(PpM(i)+.5*KpM2));% third increment for pump power in negative direction
```

```
KpM4 = -dz*(-toup*(PpM(i)+KpM3)*(sigmaap*(N-N2(i)) - sigmaep*N2(i)) - alphap*(PpM(i)+KpM3));% fourth increment for pump power in negative direction

PpM(i+1) = PpM(i) + (KpM1 + 2*KpM2 + 2*KpM3 + KpM4)/6;% pump power in negative directin  after i'th increment

%SSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSSS

KsP1 = dz*(tous*PsP(i)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*PsP(i));;% first increment for signal power in positive direction

KsP2 = dz*(tous*(PsP(i)+.5*KsP1)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*(PsP(i)+.5*KsP1));;% second increment for signal power in positive direction

KsP3 = dz*(tous*(PsP(i)+.5*KsP2)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*(PsP(i)+.5*KsP2));;% third increment for signal power in positive direction

KsP4 = dz*(tous*(PsP(i)+KsP3)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*(PsP(i)+KsP3));;% fourth increment for signal power in positive direction

PsP(i+1) = PsP(i) + (KsP1 + 2*KsP2 + 2*KsP3 + KsP4)/6;% signal power in positive directin  after i'th increment
```

```
%----------------------------------------------------------

KsM1 = -dz*(tous*PsM(i)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*PsM(i));% first increment for signal power in negative direction

KsM2 = -dz*(tous*(PsM(i)+.5*KsM1)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*(PsM(i)+.5*KsM1));% second increment for signal power in negative direction

KsM3 = -dz*(tous*(PsM(i)+.5*KsM2)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*(PsM(i)+.5*KsM2));% third increment for signal power in negative direction

KsM4 = -dz*(tous*(PsM(i)+KsM3)*(sigmaes*N2(i) - sigmaas*(N-N2(i))) + tous*sigmaes*N2(i)*Pos - alphas*(PsM(i)+KsM3));% fourth increment for signal power in negative direction

PsM(i+1) = PsM(i) + (KsM1 + 2*KsM2 + 2*KsM3 + KsM4)/6;% signal power in negative directin  after i'th increment


%Go = N*toup*sigmaap*PpP(i+1)*nues/(nuep*Psat) - N*tous*sigmaas;

%GsZ(i+1) =  Go/(1+(PsP(i+1)+PsM(i+1))/Psat);
```

```
Pout(i+1) = PsP(i+1)-PsM(i+1);%final signal output

z(i+1) = z(i)+dz;


%PpP(40)*Rpl + PL

Pres=PpP-PpM;

 end
```

4.2.4 Boundary Conditions:

- PsM(i) = 51.780 //Initial signal power for Backward Pumping
- PsP(i)=PsM(i)*Rso //Initial signal power for Forward Pumping
- check=PsM(i+1)*Rsl //check boundary condition
- Pout(i) = PsP(i) - PsM(i) //output signal power

CHAPTER 5

MATLAB CODE AND OUTPUT

Code available at:

https://drive.google.com/open?id=0Bz2_QZavheyWRVdxS0ZZdnNkMDQ

https://drive.google.com/open?id=0Bz2_QZavheyWQmowYUNsT1dzS3c

OUTPUT:

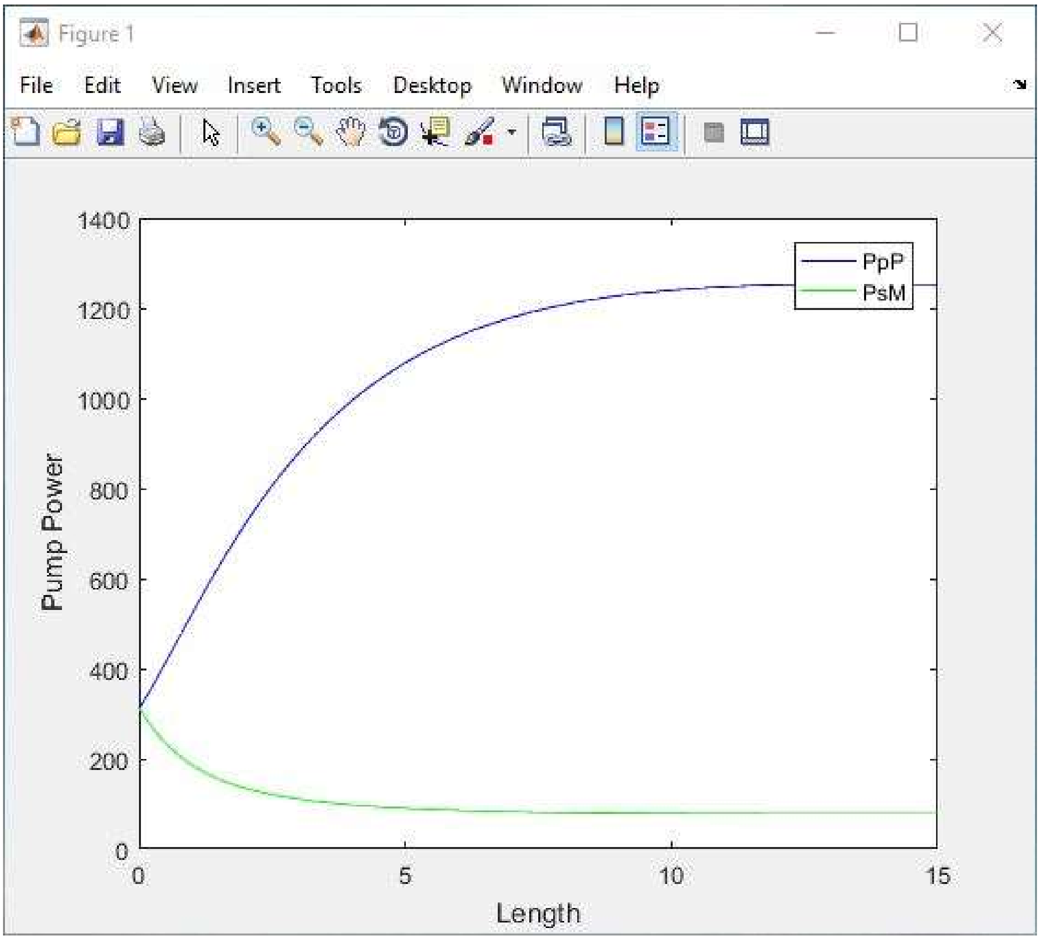

Figure 5.1. : Forward Pumping

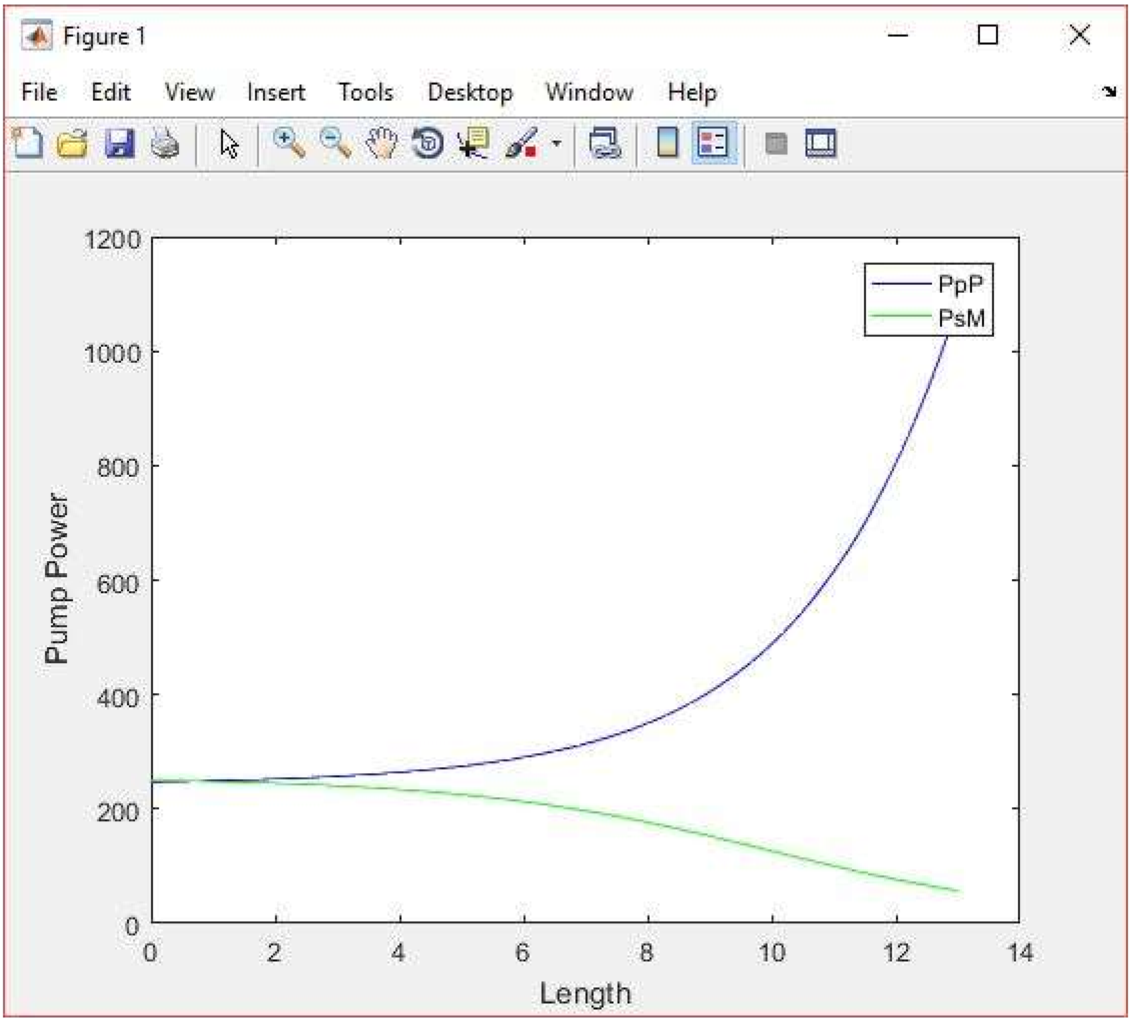

Figure 5.2. :Backward Pumping

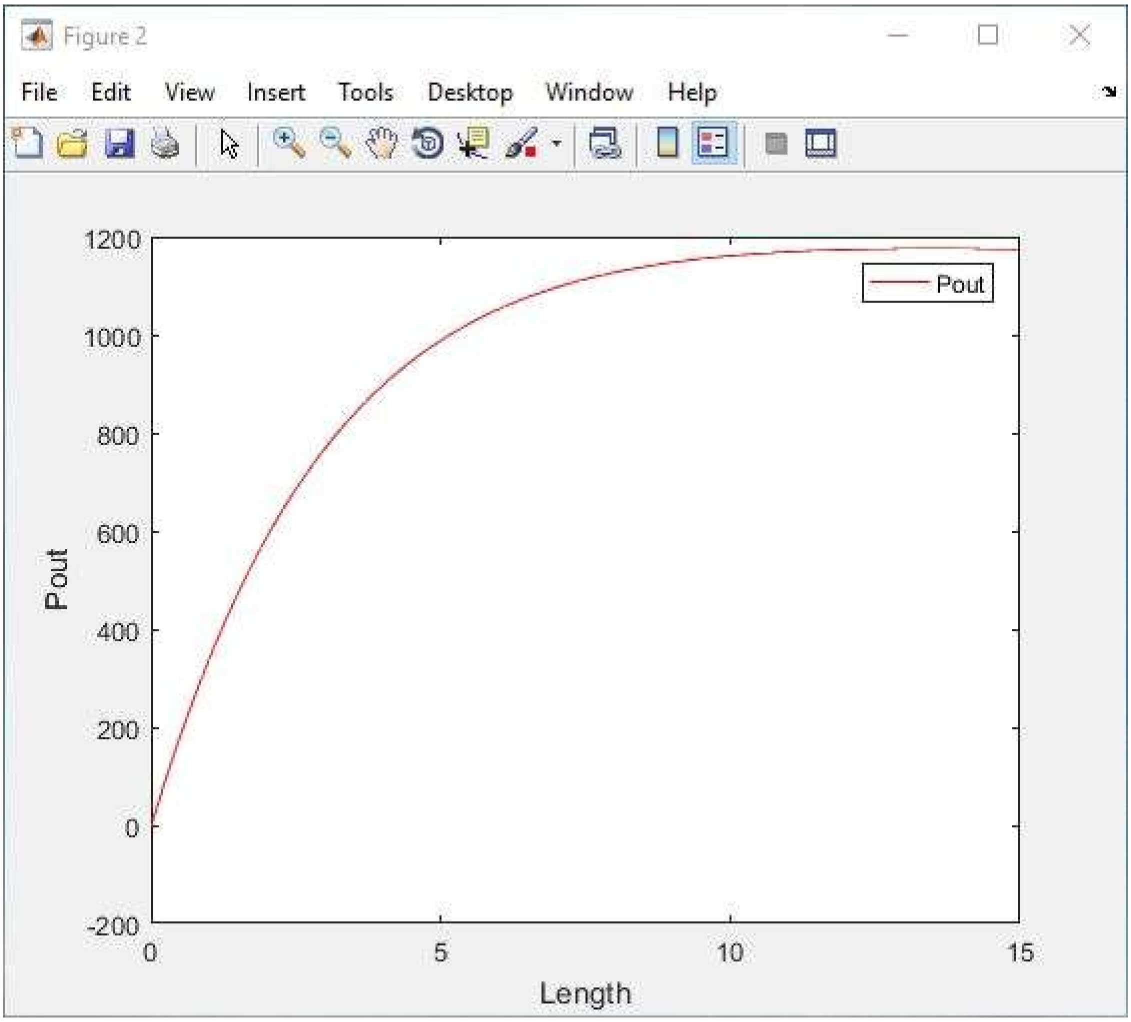

Figure 5.3. : Output Power

Results:

- Single signal gain = 6.017
- Slope Efficiency = 87%
- Residual Pump Power = 17.82 W
- Optimum Active Fiber Length for Backward Pumping = 13 m
- Optimal Active Fiber Length for Forward Pumping = 15 m

Conclusion and Future Scope:

The rise in output power from rare-earth-doped fiber sources over the past decade, via the use of cladding-pumped fiber architectures, has been dramatic, leading to a range of fiber-based devices with outstanding performance in terms of output power, beam quality, overall efficiency, and flexibility with regard to operating wavelength and radiation format. This success in the high-power arena is largely due to the fiber's geometry, which provides considerable resilience to the effects of heat generation in the core, and facilitates efficient conversion from relatively low-brightness diode pump radiation to high-brightness laser output.

With the advent of reliable, high-brightness,diode pump lasers– and of double-clad fibers to facilitate coupling the pump light into the fiber – fiber lasers are entering kilowatt power range with diffraction-limited beam quality. Compared to bulk solid-state lasers, the chief advantage of fiber lasers is their outstanding heat-dissipation capability, which is due to the large ratio of surface to volume of such a long, thin gain medium. Fiber lasers and amplifiers have a very high single-pass gain and therefore low laser thresholds and can be efficiently pumped with diode lasers. Moreover, the broad gain bandwidth, the compactness, robustness and simplicity of operation make fiber lasers attractive for a host of applications. Rare-earth-doped PCFs offer several unique properties, which allow an upward scaling of the performance compared to conventional fiber lasers. Their main advantages are the very high pump core NA and an extended possible mode area of truly single-mode cores. More generally, these latest investigations of transferring more functionality to the fiber by microstructuring indicate that such systems have an enormous potential to scale the performance of next generation laser systems.

BIBLIOGRAPHY

- Principles of Lasers by Orazio Svelto
- Fiber Lasers by Oleg G. Okhotnikov
- Laser Engineering by Kelin J. Kuhn

REFERENCES:

- https://www.rp-photonics.com/
- https://en.wikipedia.org/wiki/Laser
- https://en.wikipedia.org/wiki/Fiber_laser