Fiber Laser Amplifier for Photonic Directed Energy Propulsion and Interstellar Flight

Final Report
Design Project Group 45

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Abstract:
It has been nearly 60 years since human beings successfully accomplished space travels, but no one managed to leave the solar system and explore the unknown. Only Voyager 1 was the only spacecraft which barely managed to leave the solar system after 37 years of flight. With the present propulsion technology it will at least take 10 millennium to reach the nearest stars. However with the rapid development of fiber-based lasers in recent decades, has the potential to be a disruptive technology for advanced interstellar flight capability. The cost of fiber lasers has followed Moore's Law like decrease over the last 30 years, now approaching the $1/W level. The ability of these lasers to be phase-locked & hexagonally stacked together enables them to be developed and deployed to build effective photonic lasers of kilometers in scale. Groups of such lasers could efficiently deliver gigawatts of power to spacecraft at distances exceeding the distance to the moon, providing power to photo-propelled spacecraft. The use of fiber laser amplifiers in phase locked arrays could be used to generate massive power output which would be incidentally aimed at an ultra-low weight light sail in order to propel the sail to approximately 30% the speed of light and reach the nearest stars in 20 years. Using simulation tools such as OPTIWAVE will inculcate a better knowledge on the key tweaks that have to be implemented for an efficient circuit schematic. This design project aims to construct a low-cost fiber laser amplifier with an output of about 1W. The success of this task can render the team ready for higher output powers. Furthermore, it will provide the UCSB and McGill team with a cost-benefit analysis of all the components involved to achieve the most economically optimal setup possible. The 2nd term of the design project was utilized in rigorous testing of components and assembling the laser per our approved simulated design, however the outbreak of coronavirus halted the hardware phase.

Acknowledgement:

We would like to acknowledge the following people for their contribution and support to our design project team.

● Prashant Srinivasan, a postdoctoral researcher in University of California (Santa Barbara), had helped lay the initial framework for the design. UCSB has been leading the research and laying the foundations of the project from which we adopted a sub-project to assist in their efforts. A paper published by Prashanth was used as the starting point for our fiber laser amplifier design.

● Odile Liboiron-Ladouceur, who is a Photonics professor at McGill has been considerate to help us with our doubts regarding the theory as her field of expertise is Photonics and lasers.

● Andrew Higgins, our supervisor has been actively guiding, directing our workflow along with assigning short term and long term deliverables. He has been a major source of help by providing us countless past research materials.

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Abbreviations:

- UCSB - University of California at Santa Barbara
- MOPA - Master Oscillator Power Amplifier.
- FBG - Fiber Bragg Grating
- Yb - Ytterbium
- YDF - Ytterbium Doped Fiber
- YDFA - Ytterbium Doped Fiber Amplifier
- Yb-DCF - Ytterbium Double Clad Fiber
- DE - Directied Energy
- TEM - Transverse electric & magnetic modes
- NASA - National Aeronautics and Space Administration (USA)
- DPSSL - Diode Pumped Solid State Laser
- EHS - Environmental Health and Safety
- CW - Continuous Wave
- ESD - Electrostatic Discharge
- ASE - Amplified Spontaneous Emission
- SNR - Signal to Noise ratio
- EDFA - Erbium Doped Fiber Amplifier
- PDFA - Praseodymium Doped Fiber Amplifier
- SOA - Semiconductor Optical Amplifier
- BPF - Bandpass Filter
- CMS - Cladding Mode Stripper (Also known as cladding power stripper)
- VOA- Variable Optical Attenuator

1. Introduction:

With the breakthrough in advanced technology, space travel has become a reality. Nearly 50 years ago humans landed on the surface of the moon and from then the world advanced so much that humanities are in the break of sending life to other planets and moon travel. Though space travel came a long way but the idea of interstellar flight is still a dream. It is researched that within 20 light years of sun there are at least 17 stars which are capable of providing a habitable zone.[12] These theories can soon be proved with the recent advancements in the field of directed energy. The field of photonics has seen a massive but unappreciated rise in its growth and applications in the world in the recent decade. This surge in new technology opened a portal to a whole new world of engineering thought. Photonic devices are implemented in many areas and fields from the manufacturing industry to communication systems and even medical systems, e.g. light detection, telecommunications, information processing, photonic computing, lighting, metrology, spectroscopy, holography, medicine (surgery, vision correction, endoscopy, health monitoring), bio photonics, military technology, laser material processing, art diagnostics (involving Infrared Reflectography, X-rays, Ultraviolet fluorescence, agriculture, and robotics.

1.1 Origin of Interstellar Flight Theory

The official organization that recognized the potential of lasers to be used in DE propulsion for interstellar travel was Breakthrough Starshot by Breakthrough Initiatives. This project was founded in 2016 by Yuri Milner, Stephan Hawking and Mark Zuckerberg. The goal was to develop a proof-of-concept fleet of light sail spacecraft named StarChip, which will be capable of travelling to the Alpha Centauri star system about 4.37 light years away.[13] The organization soon gained popularity among innovative organizations and potential tech investors. Soon after the organization had a steadfast expansion with magazine/journal features and developed collaborative ties with multiple state of the art research institutes like UCSB.

1.2 UCSB Collaboration

Philip M Lubin who is the lead for the research at UCSB had laid a technical framework through which they were able to design the fiber laser amplifier which was the first elemental step in the process. This setup is as follows. A hexagonal 10W laser amplifier is to be adjacently stacked to form a phase locked directed energy array. This setup is to span 100km radius, providing a combined high-power beam approximately 100GHz, focused onto the light sail. This will propel the light sail into relativistic flight with a speed of 1/4c.[12] This gives the sail the propulsion required to travel interstellar distances. Thus DP45 based their project on the framework laid by Professor Lubin's team. The team simulated and constructed a design borrowed from researchers from UCSB. With the help of their published research papers we were able to lay a plan for the completion of 1W Fiber Optic Laser.

1.3 Goal of the Project

Our main objective is to build an economically feasible yet optimal fiber optic laser amplifier, which is being simulated and constructed based on a design borrowed from researchers at UCSB. We used their published research papers as our starting point and reference. Our main goal is to construct the laser amplifier with an amplification gain of 20dB i.e., a 10mW input amplified to 1W. The success of this will not only improvise on the work by UCSB but will make it much more cost effective which could eventually reduce the overall costs for the next generation, real time deployment of DE laser arrays.

2. Background

2.1 Physics & Conceptual Background

This section aims to provide basic background on the physics behind the semiconductor sources and devices we will be employing in our project.

2.1.1 Solid state semiconductor sources

The seed laser employed in our project is a 1064 nm FBG (fiber bragg grating) stabilized single mode solid state semiconductor source. A laser or an optical oscillator is essentially an optical amplifier with a feedback mechanism. Solid state semiconductor lasers are formed by confining charge carriers in a region by adding two wide-bandgap semiconductors (confining layers, generally P doped) to both ends of a narrow-bandgap semiconductor (active layer, generally N doped). After which electrical or optical pumping would provide power to the electrons in the valence band for them to invert, i.e, ascend to the conduction band leaving a hole behind. Three main transitions occur simultaneously in the laser: spontaneous emission, stimulated absorption, and stimulated emission. Spontaneous emission occurs when an excited electron spontaneously drops to the valence band producing a photon inturn. It is an inherent phenomena that contributes to noise within a laser and can only be minimized, not eliminated. Stimulated absorption occurs when an electron in the valence band absorbs a photon and ascends to the conduction band. This phenomena contributes to noise within a laser. Stimulated emission occurs when an incident photon is absorbed by an electron in the conduction band, exciting it to an unstable state at which it descends to the valence band producing coherent photons in turn. This is the main amplification mechanism in a laser and requires inversion to occur. The dielectric interface between the active layer and the confining layers effectively create a partially reflective mirror due to the difference in refractive indices. This effect also occurs between the narrow-bandgap material and its other adjacent dielectric interfaces. This reflection creates the oscillation condition, under which a standing electromagnetic wave is created within the active layer. The standing wave corresponds to photons that exist within the active layer (the active medium). These photons create a cascade effect under which stimulated absorption occurs causing stimulated emission, and hence the feedback aspect. This occurs until gain saturation is achieved, under which the medium has no more unsaturated doped ions to produce gain. Fiber bragg gratings are used in semiconductor sources as specific wavelength filters. They are essentially periodic etching on the surface of the active layer that vary the refractive index. This variation reflects wavelengths proportional to the periodicity and hence the variation in refractive index.

2.1.2 Optical Amplifiers

An optical amplifier is a cylindrical dielectric, usually glass material such as silicon dioxide, doped with an active element. The doped atoms absorb photons provided by an external pump at a lower energy and emit photons at a higher energy. In an optical amplifier, light can be directly amplified without having to convert the optical signal into an electrical signal. A basic block schematic for an optical amplifier is as shown in figure 1.

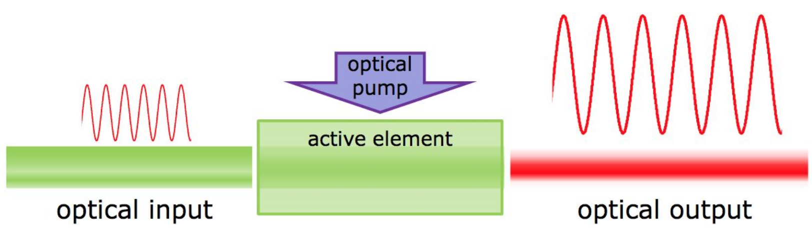

Figure 1: Depicted - Optical amplifier in a block schematic

A DFA (doped fiber amplifier) works on the principle of population inversion. Unlike lasers optical amplifiers do not have a feedback mechanism. The active element in the DFA absorbs the photons supplied by an external source (Pump) leading to population inversion (electron supply to higher energy levels). The incoming optical input signal sets off stimulated emission. The gain provided by the amplifier is decided by 3 factors:

- Optical pump power
- Frequency of the incoming signal
- The localised power of the signal at any point inside the active element.

Optical amplifiers are characterized using the following criteria:

- Gain - Ratio of input power(dB) versus output power(dB)
- Gain Efficiency - Gain as a function of input power (dB/mW)
- Gain Bandwidth - Range of wavelengths over which the amplifier is effective

- Gain Saturation - Maximum output power beyond which no amplification is achieved.
- Noise - Undesired signals of varying power and wavelength due to the physical properties of the hardware elements used.

There are different types of optical amplifiers such as:

- Rare earth fiber amplifiers
  - Erbium doped fiber amplifiers (EDFA)
  - Praseodymium doped fiber amplifiers (PDFA)
- Raman and Brillouin amplifiers
- Semiconductor optical amplifiers (SOA)

In the context specific to our project, we will be building a YDFA(Ytterbium doped fiber amplifier) and more specifically a YDFA with the gain medium being a Yb-DCF(Ytterbium doped double clad fiber). We chose the Yb doped double clad fiber as the gain medium due to the following reasons:

- YDFA has better gain characteristics compared to EDFA. EDFA gives a maximum gain of about 48dB with 30m length of fibre around 1550nm signal wavelength and pump power of 10W. While YDFA achieved about 62dB gain with only 8m fibre length and pump power of 5watt around 1030nm signal wavelength.[7]
- The double cladding enables better beam profile characteristics, high wall-plug efficiencies, superior reliability and maintenance-free operation. Moreover, double clad fibres are better suited for high power applications due to its dispersion characteristics within cladding and hence, is a preferred choice for our project.

2.1.3 Devices in The Circuit Schematic

The optical amplifier discussed above is an active optical device i.e., it needs an external energy source. Thus active devices are the one which requires power to operate. Passive devices on the other hand do not require an external energy source and can manipulate the incident optical signal directly. The passive devices in our hardware are specifically used to account for unwanted noise and protection of upstream components that could be damaged due to back reflecting power. Mentioned below are all the devices assigned for building the fiber optic laser.

The **Active devices** incorporated in our schematic are:

1064nm Seed Laser (30mW):

Figure: Seed Laser

Output from seed laser is the source which is passed through an amplifier to produce a greater output

975nm Pump Laser Diode (20W):

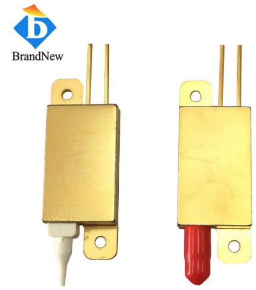

Figure: Pump Laser Diode

Pump Laser Diode gives the required excitation energy for the gain fiber. In other words its gives the required high power output.

The **Passive devices** incorporated in our hardware schematic are:

Variable Optical Attenuator:

Figure: Variable Optical Attenuator

The VOA is used to tune the output power from the seed laser. The team aims to attenuate the 30mW seed to output a power of about ~10mW.

Bandpass filter (BPF):

Figure: Bandpass Filter

It is a micro optic device based on environmentally stable thin film filter technology. The function of BPF is to block out any unwanted emission and any residual pump light. The components are characterized with high isolation, low insertion loss, high return loss, excellent environmental stability and high power handling capability.

Single Stage Isolator:

Figure: Single Stage Isolator

It's a 1064 nm Polarization insensitive isolator features a compact package, low insertion loss, high isolation, high return loss and excellent environmental stability and reliability. It is ideal for suppressing back reflecting high power in order to protect the seed laser.

Pump Signal Combiner:

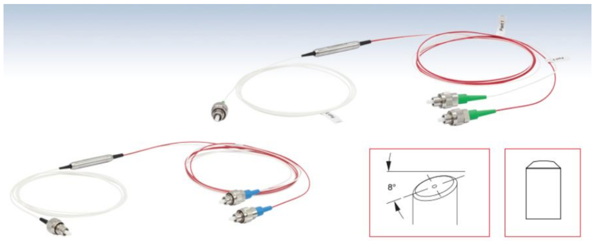

Figure: Pump Signal Combiner

Its application is to combine the pump laser and couple that power with the seed signal.

Cladding Mode Stripper (CMS):

Figure: Cladding Mode Stripper

A device, especially a coating with a Refractive Index equal to or slightly greater than that of an optical fiber's cladding, that removes modes propagating through the cladding by allowing them to radiate out of the fiber

2.1.4 Brillouin Scattering

Brillouin scattering is the main cause of loss in our power amplification setup in the YDCF amplifier. Brillouin scattering occurs when an incident photon is converted into a photon of different energy and hence characteristics (e.g, mode, wavelength) due to the vibrations of the lattice or acoustic phonons. Acoustic phonon waves couple to optical electromagnetic waves via electrostriction, producing the photon characteristic shift.

Stimulated brillouin scattering can occur at low powers if gain is pushed beyond 20dB in one amplifier. This is the primary reason that sets an upper bound on the gain achievable in our project.

2.2 Aerospace Background

Deeply inspired by the rising technology of fiber laser amplifiers, we wanted to explore how the laser can be employed in the aerospace industry. Fiber lasers are arguably the most disruptive laser technology to emerge in the last decade. Being electrical engineers and with one of us minoring in Aerospace engineering, we wanted to explore how we could integrate electrical components in aerospace applications which can lead to various advantages and sustainable solutions. The interdisciplinary collaboration has led to many advancements. Fiber laser amplifiers are widely being used in the aerospace industry due to their innate technological applications. Some of the applications covered in our report include directed energy for propulsion. Fiber Lasers offer features that are critical to the Directed Energy platform.

In our research we came across numerous articles related to space activities that are being conducted by NASA. The papers outlined the advantages of fiber laser amplifiers are how they can be used for several space applications. The rapid development of Fiber-based lasers in recent decades has the potential to be a disruptive technology for advanced space flight, potentially evolving into interstellar flight capability. Interplanetary spacecraft today rely on chemical or electric propulsion powered by solar photovoltaics. The limited energy density of the chemical fuel and sunlight prevent these approaches from achieving distant propagation throughout the solar system. The integration of photonics will be the focal point for laser scalable propulsion to enable interstellar flight. This could lead to a revolution in interplanetary flight and help open a path to human flight to Mars.

A good place to start would be to highlight the key advantages of Fiber Laser Amplifier. Fiber lasers and amplifiers have the potential for superior beam quality (TEM00), high electrical efficiency (>30% wall-plug), lower maintenance, higher reliability, smaller footprint, ruggedness and easier transportability when compared to traditional DPSSL systems. All these attributes are relevant to NASA's future missions [1]. These attributes make fiber lasers and amplifiers excellent candidates for future space-based applications with benefits including[1]:

- Low susceptibility to optical misalignment and contamination (fusion splices)
- Strong leverage from the laser and telecommunications industries
- High-reliability pump laser diodes [leveraged from telecommunications]
- Numerous pump laser diode and fiber laser/amplifier suppliers
- Upsurge in performance, including orders of magnitude power increases over the last several years with predicted future increases (recently 2 kW single-mode average power [4], 1 MW peak power [5] have been achieved)

- Distributed thermal load
- Low part count
- Radiation-tolerant devices available
- Space-qualified CW version (low peak power) available
- Large wavelength range availability
- Tunable, diverse-wavelength reliable, low-cost, space-qualified single-frequency laser diode seed sources available for Master Oscillator Power Amplifier architecture
- Scalable to very high powers with both single-device and multi-device architectures
- Eye-safe (wavelengths longer than retinal thermal damage) versions available
- Er and Nd have wavelength compatibility with scientifically important atmospheric trace gas (e.g. H_2O,CO_2, CH_4, O_2) spectral features
- High wall-plug efficiency (> 30%)
- Pump diodes are physically separated from the active laser region allowing better thermal management.

With all of the benefits mentioned above it is clear that Fiber Lasers are extremely versatile and efficient in their functionality. From research, we observed that fiber technology has a power efficiency that is desirable for several aerospace applications. We plotted a graph in excel with the data we extracted. We observed that there is a linear increase in average power and peak power as shown in Figure 2. Table 1 shows the data we used to visualize the change.

Peak Power(Watts)	Peak Power (dBm)	Average Power(Watts)	Average Power(dBm)
1500	61.76	200	53.01
3000	64.77	300	54.77
6000	67.78	600	57.78
9000	69.54	900	59.54
12000	70.79	1200	60.79
15000	71.76	1500	61.76
18000	72.55	1800	62.55
20000	73.01	2000	63.01

Table 1:High Power Efficiency: Average Power Output at a corresponding Peak Power Input[2]

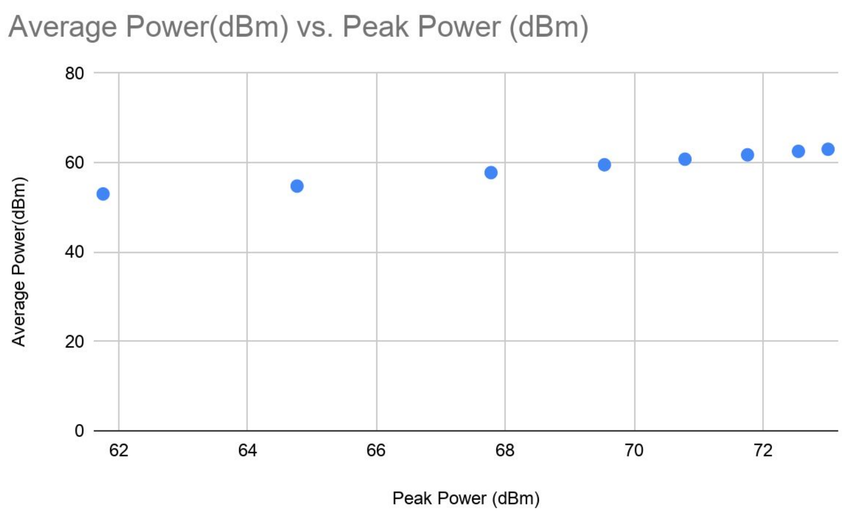

Figure 2- Power efficiency of Fiber Laser in dBm

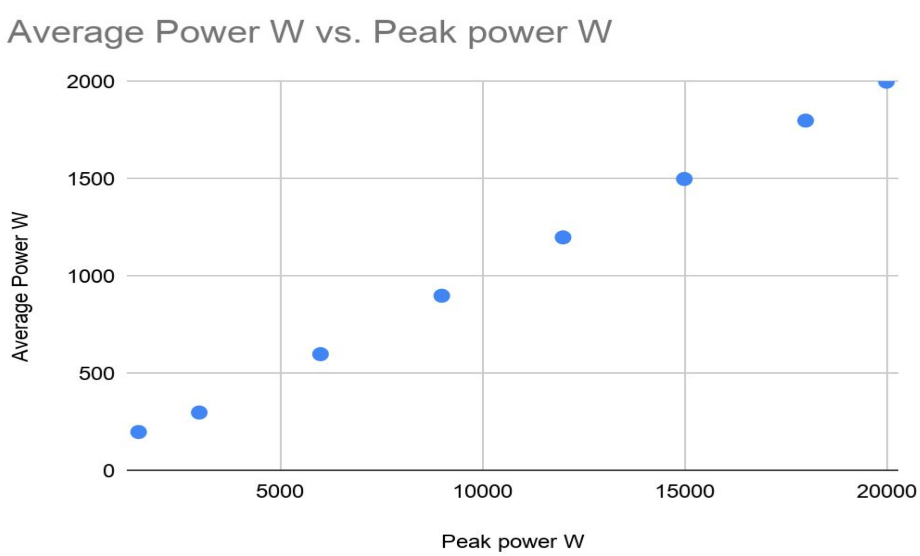

Figure 3- Power efficiency of Fiber Laser in Watts

Our Supervisor shared proposals sent to NASA by the UCSB group that integrates the Fiber Laser Technology for the allowance of scalable laser propulsion for future missions. IDEA- the Institute for Directed Energy Advancement proposed to drive radical advancements in spacecraft propulsion. Directed energy poses no "dead ends" to the first relativistic interstellar flight[6]. It allows for unlimited mission mass scaling, from grams to tons and it is the only known technology that possesses this capability[6]. DE propulsion uses a standoff system where the "launcher" is not carried on the payload, thus drastically reducing the mass. The total system consists of a DE Launch Technology Array (DELTA) and the spacecraft to be propelled[6]. Their long term plan is to incorporate the amplifier and seed source itself in the Photonic Integrated Circuit front-end[6] to increase the overall electrical-optical efficiency with respect to coherent length.

They are also investigating DE power to LEO, GEO, lunar, and other orbital assets and applications including space debris mitigation, solar system LIDAR, planetary defense, laser communication, and synthetic large aperture telescopes [UCSB 2013-18][6]. Through these proposals and research being conducted, we see a growing demand for Fiber Laser Amplifiers as they can be used in a variety of applications because of their characteristics highlighted in the report.

2.3 Properties of Fiber Lasers

The key properties of fiber lasers are as follows:

- Ease of integration into a device since energy is transferred through fiber optic cables
- High wall-plug efficiency- conversion of electrical power into optical power
- A consistent focus diameter as power is changed (which is a pure gaussian at focus)
- High reliability
- Highly stable
- Low power consumption
- Higher pulse rate

2.4 Key Formulas for Reference

- Gain coefficient: Gives us amplifier characteristics such as gain bandwidth, amplification factor, and output saturation power.

  $g(w) = (g_o)/(1 + (w - w_o)^2 T_2^{\,2} + P/P_s)$;

  Where: g_o is the peak gain
  P_s is the saturation power
  w_o is the transition frequency
  T_2 is the dipole relaxation time (< 1ps)
- Gain bandwidth:

  $(\Delta w_g) = 2/T_2$

  Where: Δw_g is the gain bandwidth
- Amplifier bandwidth:

  $\Delta v_a = (\Delta w_g)(ln2/ln(G_o/2))^{1/2}$

  Where: G_o is the peak amplification given by $G_o = exp(g_o L)$
  L is the amplifier length

An important point to note is that these first order approximation formulas were only used for initial verification purposes. The simulation software, Optiwave, uses more accurate higher order equations.

2.5 Budget and Lab Allocation:

Our supervisor Professor Andrew Higgins allocated CAD 4000 for the completion of this whole project. This budget was allocated to buy components and safety equipment that is required to build a fiber optic laser. In addition, a work space was assigned in our supervisor's lab for the team which ensures McGill Rules and Regulations in handling Class 4 lasers. Furthermore, use of McGill Photonics lab was granted by Professor Odile if needed.

3. Requirements and Constraints

3.1 Requirements:

- Prior knowledge of photonics and fiber based lasers is an asset for completion of this project. DP45 consists of 4 final year electrical engineering and out of them 2 members did not have any experience in this field. So the other members helped in bridging the gaps.
- Knowledge about photonics circuit and function of a fiber laser.
- Familiarity in testing photonic devices.
- Experience in using simulation software such as OPTIWAVE.
- Completion of McGill Laser Safety Training is required in order to work with Class 4 Laser.
- A professional Lab setup with ESD proof mats over which the setup will be placed.
- Safety measures such as curtains around the laser workspace, specified wavelength goggles are required in order to work with such lasers.

3.2 Key Constraint:

- 2 out of 4 members of the team did not have any prior knowledge of photonics.
- A substantial amount of time was spent in bridging the gaps in knowledge which delayed the hardware phase.
- Budget constraints played a vital part since a lot of components were bought from third party vendors from China which delayed the deliveries.
- Delivery of components was one of the major obstacles since some components got withhold in China due to the outbreak of Coronavirus(COVID-19)
- Safety issue that relates to using Class 4 lasers.
- Closure of McGill labs due to the outbreak of COVID-19.

4. Design and Result

4.1 Design Introduction

The main schematic of the Master Oscillator Power Amplifier (MOPA) system is shown in the figure below.

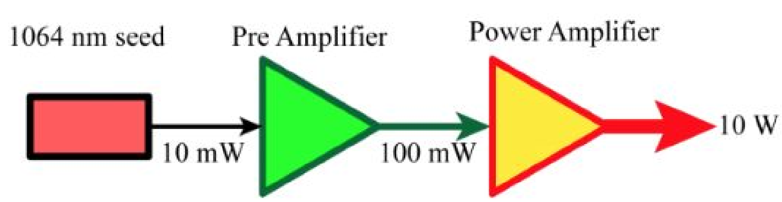

Figure 4: MOPA system schematic

In the schematic depicted above, there are 3 essential stages of the fiber laser amplifier. The first stage is the source of the laser which is the 1064nm seed laser, i.e the source laser to be amplified. The next block in the schematic is the pre amplifier which is used to maintain polarisation and to lock multiple lasers in phase. Furthermore, it serves to protect the seed laser from any back reflections by utilizing isolators. Back reflections are a source of major concern as they not only introduce unwanted noise in the system, but also damage the photonic elements in the path of the propagating reflected power. The internal components of the pre amplifier are as shown below (figure 3).

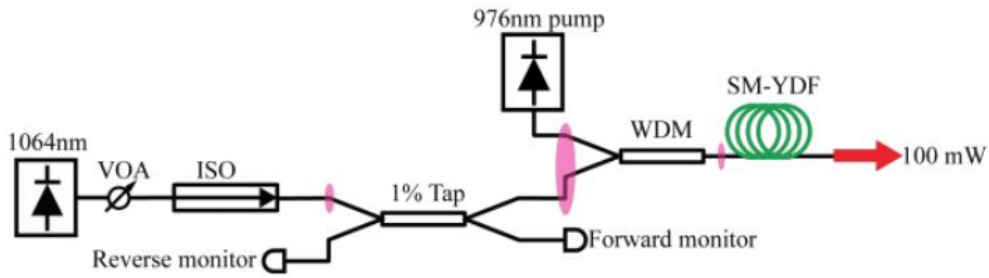

Figure 5: Pre Amplifier block diagram

With timely research and communication with peers at UCSB, we decided to omit the pre-amplifier stage as our project will not employ phase locking or polarisation maintenance.
The internal components of the power amplifier block are as shown below.

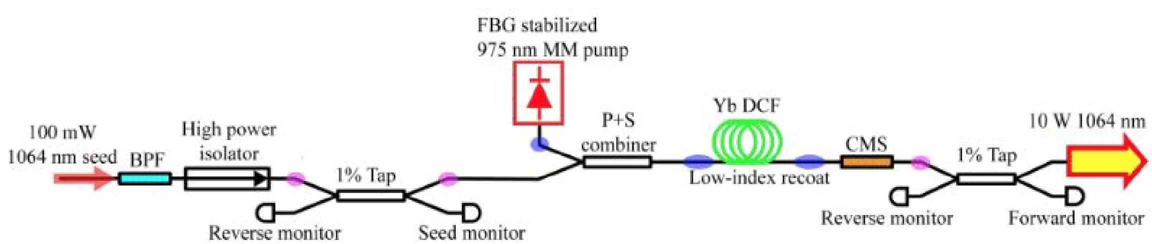

Figure 6: Power Amplifier block diagram

To reiterate, the main objective is to provide 20dB of gain at monetary restrictions, as to make the greater project at UCSB economically feasible. The power amplifier stage initially considered was to start with 100mW 1064nm seed laser as provided by the pre-amplification stage. To reduce economic cost, the seed laser is to be changed to 10mW to provide a final output of 1W. Furthermore, the 1% tap has been omitted, as it is not crucial to inspect the properties of the laser at each stage simultaneously. Employing another high power isolator after the YDCFA is added to prevent back reflections into the YDCFA and potentially the pump laser.

4.2 Power amplifier Simulation

We simulated the power amplifier using Optisystem-v16 as it is accurate. The figure below displays the schematic used to simulate our power amplification system.

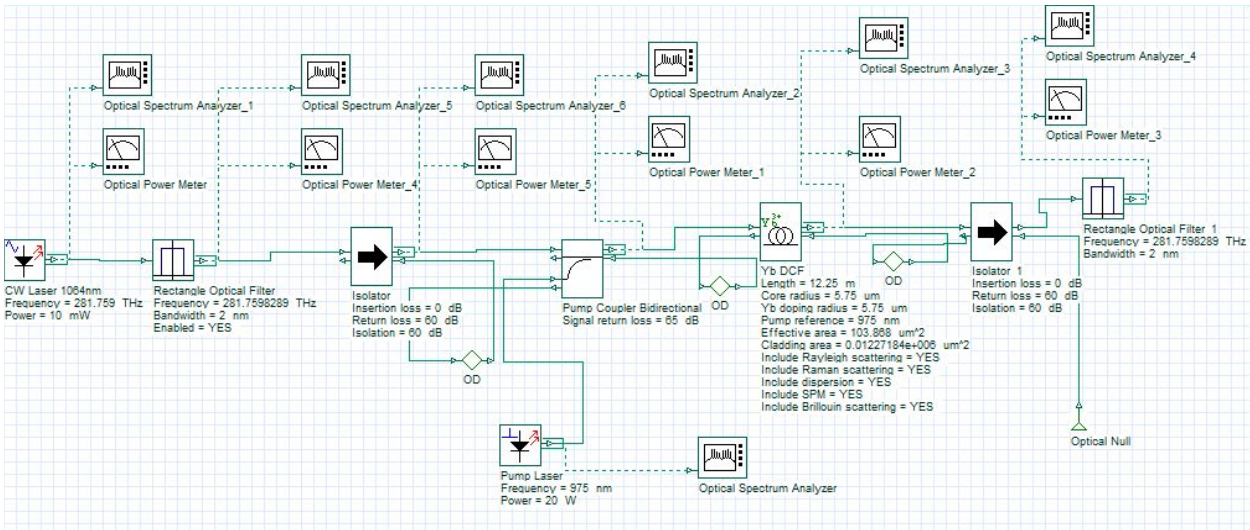

Figure 7: Power amplifier simulation schematic displaying various components and the relevant parameters.

The seed was modeled by a continuous wave (CW) laser at 1064nm with power of 10mW. The optical bandpass filter is modeled by a rectangular filter at a center wavelength of 1064nm and a bandwidth of 2nm. The pump used is at a wavelength of 975nm and power of 20W. The pump and the isolated output of the optical bandpass filter are coupled with a bidirectional pump coupler. The YDCFA's geometrical parameters displayed in the figure were calculated from the PLM-YDF-10/125-HI-8 [8] datasheet of the YDCFA used by the UCSB team. Furthermore, the simulation takes into account all forms of YDCFA losses including brillouin scattering. As a cladding mode stripper (CMS) is not available in the software to absorb the pump power, another bandpass filter of the same characteristics was used as a pseudo-CMS. The table below displays different lengths of fiber and different output powers.

Simulation number	Length (meters)	Output power (Watts)	Gain (dB)
1	8.00	213.285e-3	13.289
2	10.00	457.927e-3	16.607
3	12.00	981.785e-3	19.920
4	12.25	1.079	20.330
5	12.30	1.100	20.413
6	12.50	1.187	20.744
7	13.50	1.763	22.462

Table 2: Simulations results displaying power output of the power amplifier at various fiber lengths along with the total gain achieved.

Table 2 shows that the desired 1W output is achieved at a fiber length of 12.25m. These values of gain are plotted in the figure below.

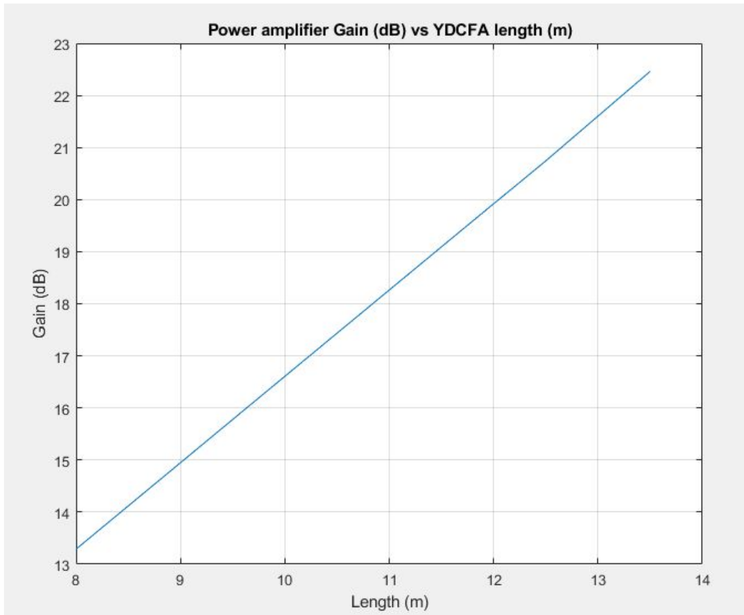

Figure 8: Plot displaying the total gain achieved at various fiber lengths.

The gain at this range of lengths shows a linear trend. At the length of 12.25m, the spectral characteristics of the YDCFA are shown in the figure below.

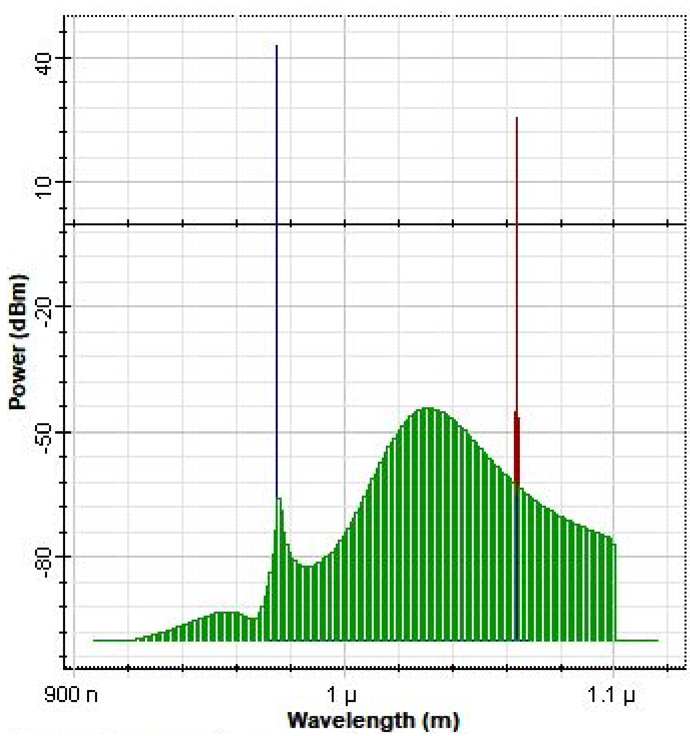

Figure 9: Spectral characteristics at the YDCFA output. The pump is in blue, ASE noise is in green and the amplified seed is in red.

The spectrum displays a few critical pieces of information. Firstly, the power meter at this stage displays a total output power of 19.255W. The spectrum shows the need for a CMS at the output as the power at this stage is dominated by the excess pump power. Furthermore, the ASE noise of the YDCFA also contributes to this power. The ASE noise pollutes the output spectrum and poses an issue if polarization and phase locking was to be taken into account. For these reasons, the CMS is a necessity. The figure below displays the spectral characteristics at the output of the pseudo-CMS (BPF).

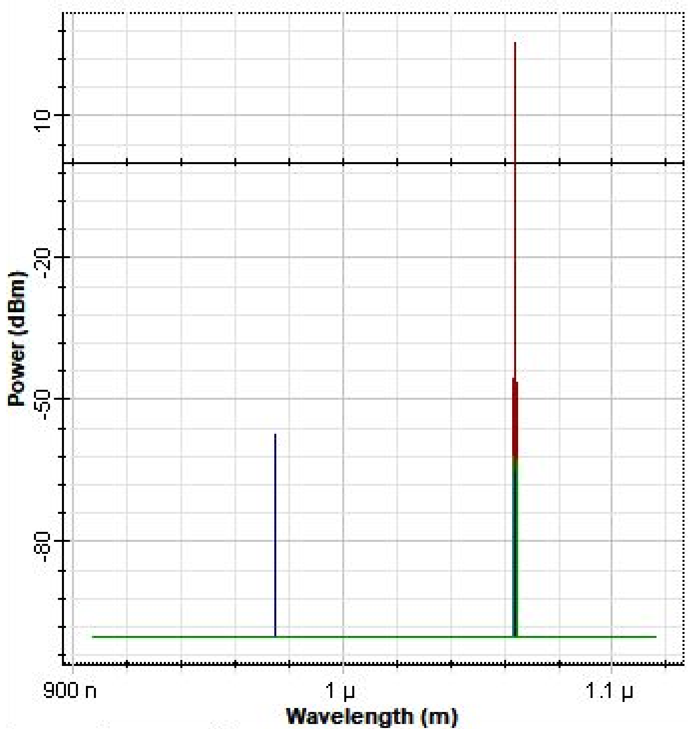

Figure 10: Spectral characteristics at the pseudo-CMS output. The pump is in blue, ASE noise is in green and the amplified seed is in red.

The power at this stage is 1.79W, signifying the power of the amplified seed laser. The ASE noise is eliminated, except for at the seed wavelength making it insignificant. The pump power is approximately -56.5 dBm, which is also insignificant. Thus the assumption can be made that the total power at this stage is purely the power of the amplified seed laser.

The total gain obtained is the desired 20.33dB. This is achieved at a YDCFA length of 12.25m, input seed laser power of 10mW, pump power of 20W.

5. Semester Update

Semester 1(Fall 2019):

The total length of the project was about 8 month or two semesters. After our preliminary meeting with our supervisor we outlined our plans to handle this project. So for the first semester, the team mainly worked on the theory. Since the project idea was fairly new to the team, so all the members spent time on researching published papers from UCSB. The first half was dedicated in bridging our gaps in knowledge and coming up with a design that fits our limited budget and end goal. Thus we successfully simulated a design with OPTIWAVE Software.

Semester 2(Winter 2020):
For the second semester, we concentrated on vendors for components purchase. A lot of research had to be done to find an economical source to purchase our components. After a lot of market research we were able to order our hardware mostly from China to reduce the cost. Our main suppliers were Lightel and CorActive. Other than that, a secure lab space was arranged and as soon as a hardware got delivered, we began to do rigorous testing. We commenced with the seed laser to figure out the power source. However, the delay in deliveries disrupted our assembly process which pushed the timeline further. Later closure of McGill labs stopped our assembly for the laser which brought an abrupt end to the project.

6. Project Final Update

Due to the outbreak of coronavirus (COVID-19) the project could not be completed. Components such as the CMS were held in China and did not get delivered to us. Moreover due to the sudden closure of McGill campus for the pandemic we could not complete our test or assemble the components to build our fiber optic laser. So after a team discussion with the supervisor, an outline will be set for the next team and for our supervisor's lab members so that they can carry on with the project.

7. Impact on Society and Environment

Research in Interstellar Flight with directed energy is a major breakthrough in science. The world is divided and is in constant threat of climate change and global warming. The fight with the non-renewable energy industry has reached its peak. Scientific proofs have been published where the world needs to utilize a greener source of energy and hence a success of interstellar flight projects will have a major shift in paradigm from non-renewable chemical energy to photon based energy. Thus seeing major breakthroughs in the energy sector and most importantly in space travels.

7.1 Non Renewable Resource
Throughout this project the only hazardous material used was the Yb Db. dope medium. Since the laser will be only used for research, so there won't be any issue of unauthorized usage. Also if needed, the components should be disposed of according to the rules of McGill Hazardous Materials.

7.2 Environmental Benefits:
Directed energy for propulsion can be the next breakthrough in the energy industry. Since the use of environmental friendly resources is encouraged, directed energy propulsion can play a vital part for an ease of transition from non-renewable to environmentally friendly energy.

7.3 Safety and Risk:
Risk associated with class 4 lasers is that it can cause skin burn and over exposure to the beam can have health issues. So to avoid such issues, a safe workspace needs to be assigned for the laser and a mandatory training to any personnel who will deal with the laser. Other than that, basic safety features need to be incorporated such as curtains around the laser and safety goggles and lab coat for the personnel's. Since this laser will be part of our supervisor lab so all the lab members will be getting training and updates on the laser use.

7.4 Benefits to Society

The main goal of the project was to build an economical feasible fiber optic laser. Thus successful completion of this project will play a vital part in reducing the cost of fibre optic laser. This could lay a framework for the future which will enable researchers and students to build a laser at a cheaper cost. Other than the financial factor, this laser will be part of the research of the Interstellar Flight Team in McGill which will free their budget from buying an expensive laser and can be used for the Interstellar Flight Research.

8. Teamwork

For this project, we spent our first semester time in research and brainstorming. Our main focus in our first semester was to gather enough information and clear any gaps in our knowledge. Therefore, we have worked on past research papers and experiments to gain tips and ideas so that we can incorporate it in our project. Later,we began to order components that we needed to build the laser. In order to move ahead with this project each team member worked according to their own strength. Everyone was assigned tasks according to their skills and strengths. Also our clear communication and the responsibility taken by each team member helped us to achieve our set goals. Each team member pulled through their responsibility and communicated with the team and the supervisor. Thus, this created a healthy dependability among the members which helped us to create a chain process with fewer obstacles.

In order to highlight individual contribution, Roshan and Ameer dealt with the photonics aspect of this project. They are the primary contact to Professor Odile who is lending us a helping hand with a few tricky concepts in the field of photonics. For this project they worked on past research papers to grasp better understanding. Also they played a vital role to pinpoint questions and confusions to discuss with Prashanth at UC Berkeley. In addition, Roshan was the main point of contact with vendors and to purchase components. Hajera, being a minor student in Aerospace Engineering, brings forward her research to see the implementation of this project in the aerospace industry. She helped our supervisor to find the obstacles and limitations that the team can face during the course of this project. Lastly, Ruptanu helped the team in the documentation and hardware aspect of the project. He is assigned to maintain track of the research and to keep documentation of the project for the course and future purposes.

Altogether the team members provided support to each other for any tasks regarding the project. There was always an additional member who provided support to the primary in his/her tasks. So this made the research and ordering of components a smooth sail. However due to the later outbreak of coronavirus all work was brought to halt and the project had to end abruptly due to the closure of McGill labs.

9. Conclusion

Design Group 45 had a great start to the year long project to build a 1W Fiber Optic Laser. Although due to unforeseen reasons we could not finish the hardware phase, we still had a successful year. Other than gaining an extensive knowledge about photonics and interstellar flights, we also managed to gain a professional relationship with amazing researchers. In addition our simulated design and the guidelines of components will provide a clear pathway for future teams to pick up the work and complete the hardware phase. Overall, with the year long work, McGill is one step closer in contributing in research for the world’s first interstellar flight with directed energy.

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