HELIUM RESONANCE FLUORESCENCE LIDAR

BY

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DISSERTATION

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ABSTRACT

Recent advancements in LiDAR for atmospheric applications have allowed measurements to reach higher altitudes and have increased temporal resolution. Increased output power, larger apertures, and higher efficiency detectors have made this possible. The helium resonance fluorescence LiDAR has the capability to probe the metastable helium content in the thermosphere and exosphere (within 250 km–750 km), where helium (2^3S) is most abundant. Strategies have been employed to increase the output power of the He LiDAR transmitter using fiber amplifier technology, increase the light gathering power of the receiver, and utilize detectors with higher quantum efficiencies at 1083 nm. A 45 W He resonance fluorescence LiDAR transmitter has been designed and fabricated, and is being tested in Urbana, IL, with plans for deployment at an astronomical observatory in the near future. The He resonance fluorescence LiDAR has the potential to further our understanding of upper atmosphere dynamics. It will provide insight into metastable helium, its temperature in the upper atmosphere, and atmospheric densities, which affect satellite drag, and possibly pave the way for new applications, such as guide star lasers. The technology may be applied from ground based, as well as satellite based, platforms for global measurement applications. This dissertation discusses the planned approach to detect the first LiDAR generated resonantly fluoresced scattered He photon, details of the He resonance fluorescence LiDAR transmitter, and the simulations for the expected signal return.
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# TABLE OF CONTENTS

CHAPTER 1  INTRODUCTION .............................................. 1
  1.1  Background and Science ........................................ 1

CHAPTER 2  CALCULATIONS: THE LIDAR EQUATION ............... 9

CHAPTER 3  FABRICATION AND CALIBRATION ..................... 11
  3.1  High-Power Transmitter ....................................... 13

CHAPTER 4  FIBER AMPLIFIER MODEL .............................. 19
  4.1  Solutions to the Helmholtz Equation ....................... 20
  4.2  Overlap Integral .............................................. 22
  4.3  Output Power .................................................. 23
  4.4  Integration of Fiber Amplifier ............................. 24

CHAPTER 5  SIMULATIONS FOR SIGNAL RETURN ................. 27

CHAPTER 6  FUTURE WORK ........................................... 34
  6.1  Slab Laser: An Alternative to the Fiber Laser Transmitter 34
  6.2  3-Frequency Technique for Temperature and Wind Measurements .................................................. 38
  6.3  Signal Return for Pulsed Monostatic System with Three-Frequency Technique .............................. 40
  6.4  Power in Fibers ................................................. 42

CHAPTER 7  POSSIBLE ALTERNATIVE APPLICATIONS ............. 47

CHAPTER 8  CONCLUSION ............................................... 50

REFERENCES .......................................................... 51
CHAPTER 1

INTRODUCTION

Resonance fluorescence LiDAR is a remote sensing technique that produces an electronic energy transition that is used to probe a specific energy state of an atom or molecule. This allows for remote measurements of density, Doppler temperature, and winds, with relatively high temporal and vertical resolution.

The thermosphere and exosphere are regions of the upper atmosphere that exist from about 90 km and above. The location of the boundary, or exopause, is not well defined but is considered to be at about 500-600 km. These neutral regions of the atmosphere have constituent densities, temperatures, and winds that are difficult to measure using remote techniques. As a result, most of what is known about these regions is from in-situ measurements made by sounding rockets and satellites. The airglow emissions such as OI (630 nm) and H (6563 Å and 4861 Å) have provided remote sensing Doppler temperature and winds of the thermosphere and exosphere. The helium resonance fluorescence LiDAR has further been developed to enable altitude resolved ground-based measurements of this region.

1.1 Background and Science

In the upper thermosphere and exosphere, the primary constituents are hydrogen, helium, atomic oxygen, and atomic nitrogen. These exist at very low densities, on the order of $10^{11} \text{ m}^{-3}$, between about 400-1000 km, as indicated by MSIS [1]. At the lower altitudes of the thermosphere, below about 100 km, the mean free path is around 10 cm, with a collision rate at about a couple thousand per second. At these altitudes, the chemical composition does not depend on molecular weight because of mixing caused by turbulence. At higher altitudes above 100 km, however, the mean free path is
about one scale height, $7.7 \times 10^4$ m [2]. This is large compared with the size of the motions that cause mixing, and as a result, the major force acting upon these particles is gravity [3]. This causes the constituents in the upper thermosphere and exosphere to separate due to gaseous diffusion [4] and become stratified with altitude, where heavier atoms such as N$_2$, O$_2$, N, and O are more dominant at lower altitudes (100-400 km) and lighter atoms, mostly H and He, exist at higher altitudes, as also shown by MSIS [1].

The neutral atmosphere of the thermosphere and exosphere is of great interest to those studying and interacting with the high altitude space environment. Variations in thermospheric and exospheric density, temperature, and winds are primarily the result of waves generated at lower altitudes, propagating upwards. Atmospheric tides are waves primarily generated in the troposphere due to thermal or gravitational excitation. Thermal tides are produced by heating primarily resulting from absorption of solar radiation by water and ozone, latent heat release in the tropics [5] and are impacted by variations in longitudinal topographical and land/sea heating contrast [6]. Gravitational tides, which tend to be much lower in amplitude, are primarily generated by the gravitational influence of the sun and the moon on the atmosphere [7]. These waves propagate upwards from the lower atmosphere into the upper atmosphere, where both the diurnal and semidiurnal tides are dominate features. Figure 1.1 shows 8 hour period waves in Na LiDAR data obtained at the Andes LiDAR Observatory in Chile, demonstrating the presence of terdiurnal tides in the lower thermosphere in the austral spring. Tides can also be generated within the thermosphere due to UV and EUV solar radiation.

Additionally, gravity waves, or buoyancy waves generated at lower altitudes, propagate upwards, where they typically break in the mesosphere and lower thermosphere. These breaking waves deposit energy in the lower thermosphere and can produce secondary waves which can vertically propagate. The variability in the thermosphere affects the ionosphere through wind transport, in such ways as dynamic heating [8], influencing the ionospheric dynamos [9], and may be a source of traveling ionospheric disturbances [10]. Consequently, changes within the thermosphere and exosphere can influence global communication, and the resulting variations in the neutral density affect the drag experienced by satellites, which has an impact on satellite orbits and re-entry trajectories, for example. Additionally, magnetosphere-
ionosphere interactions involve a dynamical response of the neutral atmosphere, as frictional forces from ion-neutral collisions transfer energy, exemplifying how the dynamics of the neutral atmosphere play an important role in magnetosphere/ionosphere interactions [11]. Due to the lack of distributed ground-based observations and/or satellite measurements in the upper atmosphere, the ability is lacking to track vertical tidal propagation into the upper atmosphere [6].

Thermospheric temperature, winds, and density variations are not well understood due to the low level populations of the constituents in that region which are difficult to probe with ground-based instruments and infrequent in-situ measurements at these altitudes. The primary methods for observation utilize spacecraft (satellites and sounding rockets) and passive ground-based or satellite-based instruments such as Fabry-Perot interferometers (FPIs) and airglow imagers. Figure 1.2 shows the regions of the atmosphere along with some of the common instruments and platforms for probing those regions. LiDAR is an optical technique used to obtain high temporal and vertical resolution with precise altitude information for measurements of density, temperature, and winds along the direction of beam propagation. Rayleigh and Mie LiDAR are commonly used for measurements at low altitudes (0-90 km) where particle sizes are larger and atmospheric composition remains relatively constant; however, recent technological advances have made it possible to increase transmission power and push Rayleigh LiDAR measurements further into the mesosphere and the lower thermosphere [12]. Resonance fluorescence LiDAR measurements have typically been made in the mesosphere region where the abundance of alkali metals exist with large scattering cross-sections. FPIs and airglow imagers are also commonly used for passive measurements of airglow volume emissions occurring in the mesosphere and middle thermosphere. The data from these instruments can be used to deduce density, temperature and winds from the total volume observed.

Gerard et al. [13] was the first to identify the metastable He(2^3S) state as a possible candidate for resonance fluorescence LiDAR. Although thermospheric densities are small, He(2^3S) has a backscatter cross-section of 3.8 × 10^{-16} m^{-3}, comparable to those of the alkali metals that are commonly probed at lower altitudes using resonance fluorescence LiDAR. It also has a relatively long radiative lifetime of about 7,870 seconds [14], which makes it a
Figure 1.1: Sodium LiDAR density data obtained at Andes LiDAR Observatory on 09/10/2014 (a) and 09/09/2014 (b). The high altitude (120-170 km) density has a tidal structure similar to a terdiurnal tide. The upward propagating waves have 8 hour periods and downward phase progression.
Viable candidate for resonance fluorescence. Metastable He(2^3S) is primarily produced by impact between ground state helium atoms and photoelectrons that are generated by photoionization of atmospheric constituents by extreme ultraviolet radiation [15]. The next most common source of He(2^3S) is recombination [16]. These processes are described in formulas 1.1 and 1.2.

$$\text{He}(1^1S) + e^* \rightarrow \text{He}(2^3S) \quad (1.1)$$

$$\text{He}^+ + e \rightarrow \text{He}(2^3S) \quad (1.2)$$

A transition diagram for metastable helium is shown in figure 1.3 between the He(2^3S) and He(2^3P) states. Impact between ground state helium and electrons with energies greater than or equal to 19.8 eV will generate metastable helium. At thermospheric temperatures, the temperature broadened linewidths of the $D_1$ and $D_2$ lines overlap.

The major loss mechanisms are photoionization and Penning ionization.
Figure 1.3: Transition diagram for metastable helium transitions from between the $1^1S$, $2^3S$, and the $2^3P$ states.

(continued)

Photoionization is the dominant loss mechanism at higher altitudes and Penning ionization is the dominant loss mechanism at lower altitudes, which decreases almost linearly with altitude. This works to form a layer of He($2^3S$), with densities that rapidly increase from about 200 km to 350 km or 450 km and slowly decrease from there, as demonstrated in figure 1.4. Using the METAHE model developed by Bishop [17] that incorporates the GLOW model for photoelectrons and the NRMMSISE-00 model for the neutral atmosphere, Waldrop et al. [18] simulated the loss mechanisms for metastable He($2^3S$), shown in figure 1.5.

The helium resonance fluorescence LiDAR was initially developed and tested by Carlson et al. [19] at Magdalena Ridge Observatory (MRO), with a 9.6 W output using a counter-propagating, 16 W, free-space coupled pump. Weather caused the campaign to end early after much time spent aligning.
Figure 1.4: Metastable He(2^3S) density for simulated for winter and summer at 5:30 LT using the MATAHE model developed by Bishop et al. [18].

Figure 1.5: He(2^3S) loss rates for photoionization, photodecay, and quenching loss mechanisms as a function of altitude [18].
the beam and locating it in the FOV of the MRO telescope, preventing the signal from resonant scattering with atmospheric He(2^3S) atoms that the researchers were attempting to detect.

Recently, a 45 W high-power amplifier has been built for the helium resonance fluorescence LiDAR transmitter. The transmitter has been tested at the Urbana Atmospheric Observatory (UAO) and is currently being redesigned to make the system more rugged and compact to withstand a shipment to Cerro Pachón, Chile, where it is planned to be used for an experiment to measure the first resonantly fluorescent backscattered signal from atmospheric metastable helium. During this process, however, a fiber combiner for the last stage amplifier was damaged and the replacement combiner appears to be defective with a 30% loss at high power.
CHAPTER 2

CALCULATIONS: THE LIDAR EQUATION

The LiDAR equation (eq. 2.1) is used to calculate the number of photons collected by the receiver.

\[ N_T = (\eta T_A^2) \left( \frac{P_L \tau \lambda}{hc} \right) (\sigma_{\text{eff}} n_s(z) \Delta z) \left( \frac{A_R}{4\pi z^2} \right) + N_B \tau \]  

(2.1)

The first term on the right-hand side is used to determine the number of resonantly scattered photons collected by the receiver. The second term on the right-hand side is used to determine the number of background photons collected by the receiver. The first factor in the first term is referred to as the efficiency factor. This includes \( \eta \), which is the system efficiency and takes into account all optical components and the quantum efficiency of the detector. \( T_A \) is the atmospheric transmission. Data from measurements made at the Gemini South Observatory in Chile of the atmospheric transmission are plotted in figure 2.1. As can be seen from the inset, in which a close-up of the atmospheric transmission is plotted along with the He(2\(^3\)S) linewidth, the transmission is almost 1 at 1083 nm.

The next factor is used to calculate the probability of transmitting a photon. This includes the transmitted laser energy, \( P_L \tau \), and the energy for each photon transmitted, \( hc/\lambda \). For the CW helium transmitter, \( P_L \) is 45 W, \( \lambda \) is 1083 nm, and \( \tau \) is the integration period. The next factor is the probability that a photon is resonantly scattered by a helium atom within a range bin, \( \Delta z \), along the direction of propagation. This includes the effective backscatter cross section, \( \sigma_{\text{eff}} \), and the number of scatterers, \( n_s(z) \). The last factor in the first term on the right-hand side is the probability of receiving a photon. For isotropic scattering, in the case of resonance fluorescence, \( A_r \) is the area of the receiver and \( 4\pi r^2 \) is the solid viewing angle of the receiver.
Figure 2.1: Atmospheric transmission courtesy of Lord, S. D., 1992, NASA Technical Memorandum 103957 [20], private communication with C. G. Carlson.
A 36-inch diameter, Newtonian telescope, pictured in figure 3.1, at the Urbana Atmospheric Observatory (UAO) is being used for testing the high-power helium resonance fluorescence transmitter with a Andor back-thinned Si CCD camera as the detector. The field-of-view (FOV) of the telescope is 0.43 degrees, square. The camera has a $1024 \times 1024$ array of 13 µm pixels, a dark current of 0.01 $e^-$/pixel/sec, and 2.5 $e^-$ readout noise at 60 °C.

Figure 3.1: UAO Newtonian telescope image with the hatch open above it.

Starry Night is a space and astronomy software package that simulates the star field above a specified location on Earth at a specified time. By
identifying stars, or constellations, in Starry Night that are also in images taken with the UAO telescope, the FOV can be determined and the pixel pointing towards zenith can be found. The zenith pixel is used as a reference to find the location in the image where the signal would be detected, see figure 3.2.

![He LIDAR Data (Urbana) 6–14–13 2:16 AM LT](image)

Figure 3.2: The zenith pixel is a reference for locating the area in the image where the signal is expected to be located. The altitude for each pixel is determined by the simulation described in chapter 5.

The helium LiDAR transmitter beam was launched from the UAO LiDAR building across the east field to a 6” folding mirror that is housed in a small shed. This created a 100 meter baseline between the transmitted beam and the receiver. The 6” folding mirror was used to steer the beam towards zenith by adjusting a set of two veneers on the mirror mount that are roughly aligned to steer the beam east/west and north/south. To locate the beam in the FOV of the telescope, the beam was steered westward until it pointed far enough west for the low altitude Rayleigh scattering from the 1083 nm beam to be across the FOV. It was then steered in the north and south directions until it showed up in an image with a 15 second integration period. Initially, a green beam, collinear with the IR beam, was launched in order to visually locate the beam, steer it into the telescope FOV, and roughly align the beam to center it in the FOV. Once the system was aligned, the green beam became unnecessary since changes to the beam alignment are typically small and the
IR beam is not usually far off from the FOV. Once the 1083 nm beam was found, it was steered towards zenith until the end of the beam was roughly centered in the image.

The Andor camera was pulled from the telescope and mounted outside, next to the zenith pointing folding mirror. By imaging the beam from multiple angles, the pointing direction of the beam can be determined. This was done by combining images of the beams so that the area common to each image overlaps. Once the FOV of the first image was determined with Starry Night, the star field rendering was forwarded in time to when the next image was taken and the FOV common to both camera setups became apparent. The images were stitched together and lines are drawn through each beam. The point of intersection indicates the direction in which the beam is pointed, as shown in figure 3.3. The beam can then be steered towards zenith and this process can be iterated until the beam is directed at zenith.

![Figure 3.3: Overlapping images of the He LiDAR beam used to determine the FOV.](image)

### 3.1 High-Power Transmitter

The He transmitter is a master oscillator power amplifier (MOPA) system. It has a distributed Bragg reflector (DBR) laser diode (LD) that was produced
by Prof. Jim Coleman’s group at the University of Illinois. This DBR LD has a very narrow linewidth ($\sim 100$ kHz), which enables the laser to be locked to one of the $\text{He}(2^3\text{S}) \rightarrow \text{He}(2^3\text{P})$ transitions within the laboratory and probe the Doppler broadened linewidth of the metastable $\text{He}(2^3\text{S})$ atoms in the upper atmosphere, where temperatures are typically around 1,000 K, as required by the three-frequency technique discussed in section 6.2, which is used to deduce temperatures and winds along the direction of beam propagation.

The radiative decay rate of helium $2^3\text{P}$ is $1.022 \times 10^7$ s$^{-1}$, which results in a natural linewidth of 1.62 MHz. This is illustrated in figure 3.4, where it can be seen that the natural linewidth is more than three orders of magnitude smaller than the overlapped Doppler broadened linewidths.

![Figure 3.4: Natural linewidths of He($2^3\text{S}_1$) $\rightarrow$ He($2^3\text{P}_{1,2}$) transitions and their Doppler broadened linewidths at 1,000 K.](image)

The DBR LD is mounted in a temperature controlled laser diode mount, which has an integrated thermoelectric cooler (TEC). The DBR LD is connected to an ILX Lightwave temperature controller and a LD current driver, which are controlled to adjust and maintain the wavelength of the DBR LD. Saturated absorption spectroscopy is performed with a portion ($\sim 2$-$3$ mW) of the DBR LD output to observe a stimulated transition within an inductively coupled He plasma discharge. The detector output, used to measure
the absorption caused when the laser frequency induces the transitions, is connected to lock-in amplifier. The lock-in amplifier provides an error signal to a PID controller (LABView® based) which adjusts the LD current driver to maintain lock on the He(2⁢S)→He(2⁢P) transition.

Although the DBR LD has sufficient power and linewidth characteristics for spectroscopy of He(2⁢S)→He(2⁢P), due to the 1/⁢r² nature of the received signal and transmission losses, sufficient power is required to receive backscattered signal from metastable helium in the thermosphere and exosphere, which makes amplification of the maser oscillator necessary. Figure 3.5 shows a diagram of the MOPA configuration. About 6 mW of power from the DBR LD is free space coupled into a 1064 nm, HI1060, fiber isolator. This isolator is spliced to a HI1060 Avensys® wavelength division multiplexer (WDM), which is used to couple light from a 410 mW, 973.6 nm JDS Uniphase® LD into the first stage Yb-doped single clad, single-mode fiber (SMF) amplifier. Similarly, after an additional isolator, the second stage has a 600 mW, 974 nm LD, a Hi1060 WDM, and a Yb-doped SM fiber. Between this stage and the next stage, a 5 W maximum-power isolator is used. The third stage combines the output from the 2nd stage preamp with 2- 7 W IPG® pumps using a (2 + 1) × 1 ITF Labs® fiber coupler. This stage uses a Yb-doped double clad fiber with a 15 μm core and a 130 μm outer-cladding diameter, which is spliced to a 20 W power isolator. The final, high-power amplifier stage combines 6- 7 W pumps with the output of the previous stage using a (6 + 1) × 1 combiner. This last stage of amplification has a 30 μm diameter core and a 250 μm cladding. Due to lower than expected power from the DBR coupled into the first stage preamplifier during field tests, an additional amplifier was added to the front end, which uses an SDL Optics® 130 mW, 975.3 nm pump LD, a HI1060 WDM, and Yb-doped single clad SMF.

In order to maintain the single mode behavior of the amplifier from the 15/130 μm fiber to the 30/250 μm fiber, a taper splice was made. This was done using the Vytran GPX-3000 fusion splicer by heating the 30/250 μm fiber and moving the chuck that held one of the fiber ends, thereby stretching the fiber and reducing the diameter. Once the fiber core reached the desired diameter, in this case 15 μm, the heating and pulling was discontinued and the fiber was cleaved at the taper. This end of the fiber was then spliced to the 15/130 μm fiber, as shown in figure 3.6.
Figure 3.5: MOPA for the He RF transmitter. (Not shown is the additional preamp added at the front end of the amplifier.)

Figure 3.6: The top image shows the 15/130 µm fiber (left) from (6+1)=1 combiner next to the 30/250 µm Yb-doped double clad fiber (right). The bottom image shows the two fibers spliced together after the taper is made to the 30/250 µm Yb-doped double clad fiber (right).

Pump diodes and combiners for the last two stages are mounted on a liquid cooled aluminum plate, which is connected to a Laird Technologies chiller. These are cooled to prevent damage from overheating and for pump diode wavelength stability. The last stage power-amplifier output power is about 42.5 W, with an input power of about 6.3 W, providing a gain of about 8.3 dB. Figure 3.7 shows the LI characteristics for each amplifier stage. The first stage amplifier does not show a linear behavior at lower pump input powers, which may be the result of the fiber being too long and reabsorption occurring at lower lower pump levels. (Extra care was taken during initial stages of fabrication to ensure adequate fiber was available if re-splicing was required.)

A self-heterodyne technique was used to measure the linewidth of the final
Figure 3.7: Output signal power as a function of pump current for each of the four amplifier stages.
stage by passing the fiber coupled light through a Mach-Zehnder interferometer. A small portion of the output beam from the last stage was free space coupled into an SMF fiber coupler. Light from the coupler was split between a very long segment of SMF fiber and a fiber coupled acousto-optic modulator (AOM). An additional coupler was used to recombine the separated and frequency shifted signals. The autocorrelation of the laser was retrieved by detecting the combined light with a photodiode and analyzing it with an optical spectrum analyzer (OSA). This technique indicated a linewidth narrower than 1 MHz. The linewidth at the output of the last stage, however, is further increased due to jitter from the locking mechanism, which was measured to be 5.6 MHz. This results in a linewidth of approximately 5.7 MHz, still much narrower than the Doppler broadened linewidths of the He($2^3S$) → He($2^3P_{1,2}$) transitions being measured at thermospheric and exospheric temperatures.
CHAPTER 4
FIBER AMPLIFIER MODEL

An analytical model developed by Bernard et al. [21], in combination with parameters from Digonnet [22], was used to determine the appropriate length of Yb-doped fiber for each amplifier, the result for the last stage amplifier is shown in figure 4.1. This was accomplished by first calculating the mode field diameters, the shape of the beam profiles, matching boundary conditions, and then performing overlap integrals of the fields with the Yb-density profile. An iterative approach was taken to determine the Yb-density by adjusting the density until the small signal absorption matches the loss specified by the manufacturer.

Figure 4.1: Output power from last stage amplifier as a function of fiber length. This is for 42 W of pump power at 975 nm and seed input power of about 6.33 W.
4.1 Solutions to the Helmholtz Equation

The electric and magnetic field components of the propagating light within the cylindrical waveguide satisfy the wave equation, for which it is assumed that the solutions are separable and must therefore also satisfy the Helmholtz equation, such that

\[ \Delta^2 U + n^2 k_0^2 = 0 \]  

(4.1)

where \( U \) represents the complex amplitudes of either the electric or magnetic fields, \( n \) is the refractive index in either the core (\( n_1 \)) or the cladding (\( n_2 \)), and \( k_0 = 2\pi/\lambda_0 \) is the wavenumber in free space with \( \lambda_0 \) being the wavelength of the pump, seed, or ASE. In cylindrical coordinates, the Helmholtz equation takes the form

\[ \frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \frac{\partial U}{\partial r} + \frac{1}{r^2} \frac{\partial^2 U}{\partial \phi^2} + \frac{\partial^2 U}{\partial z^2} + n^2 k_0^2 U = 0 \]  

(4.2)

where \( U = U(r, \phi, z) \), which is periodic in \( \phi \) and \( z \) and, as a result, takes the form

\[ U = u(r)e^{-jl\phi}e^{-j\beta z} \]  

(4.3)

Plugging equation 4.3 into equation 4.2 results in

\[ \frac{\partial^2 u(r)}{\partial r^2} + \frac{1}{r} \frac{\partial u(r)}{\partial r} + (n^2 k_0^2 - \beta^2 - l^2/r^2)u(r) = 0 \]  

(4.4)

In the core, the solutions to equation 4.2, the Helmholtz equation in cylindrical coordinates, are Bessel functions of type \( J \), while in the cladding the solutions are modified Bessel functions of type \( K \). Since most of the guided waves traveling in the fiber are paraxial and, therefore, have much larger transverse components than longitudinal components, they are approximated as TEM. The boundary conditions require continuity of the fields across the boundary between the core and cladding, \( u(a_-) = u(a_+) \), as well as their derivatives, \( du(a_-)/dr = du(a_+)/dr \), which are described by the following characteristic equation:

\[ XJ_1(X_{lm}) = YK_1(Y_{lm}) \]  

(4.5)

Here, it is assumed that LP(\( lm \))=LP(01) and \( X_{lm} \) and \( Y_{lm} \) are the normalized
Figure 4.2: Characteristic equations for determining the modal wavenumbers for the pump (a), seed (b), and ASE (c).

propagation constants satisfying

\[ X + Y = V \]  \hspace{1cm} (4.6)

where V is the fiber parameter used to describe the number of modes existing within the fiber. The right- and left-hand sides of equation 4.5 are plotted separately, as shown in figure 4.2, and the intersection(s) between them are used to determine the values for X and Y, where \( Y = \sqrt{V^2 - X^2} \). The modal wave numbers are then used to determine the propagation constants and the decay parameters,

\[ k_{T01} = \frac{X_{01}}{D_{core}/2} \]  \hspace{1cm} (4.7)

and

\[ \gamma_{01} = \frac{Y_{01}}{D_{core}/2} \]  \hspace{1cm} (4.8)

The solutions for the \( LP_{01} \) modes for the seed, pump, and ASE to the
Figure 4.3: The field intensity of the pump for the LP(01) mode.

Helmholtz equation are

\[ u_{core} = J_0(k_T01r) \]  \hfill (4.9)

\[ u_{cladding} = K_0(\gamma_01r) \]  \hfill (4.10)

The boundary condition requiring continuity between the field at the boundary between the core and cladding is applied to equations 4.9 and 4.10 and verified by plotting the intensity, as shown in figure 4.3 for the pump field intensity.

4.2 Overlap Integral

The overlap between the Yb\(^{3+}\)-density profile and the propagating modes of the pump, signal and ASE is used to determine the upper-state population that is available for stimulated and spontaneous emission. For simplicity, the doping profile of Yb is assumed to be uniform, with a doping radius equal to the core radius, \( d_{core}/2 \).

The effective area of the fundamental mode is described as

\[
A_{eff} = \int I_k(r, \phi, z)dA = \int_0^{2\pi} \int_0^{\infty} [J_0^2(k_Tr) + K_0^2(\gamma r)] r dr d\phi \]  \hfill (4.11)
whereas the effective area of the fundamental mode within the core would then be

$$A_{\text{eff}} = \int_0^{2\pi} \int_0^{d_{\text{core}}/2} J_0^2(k_T r)rdrd\phi$$ \hspace{1cm} (4.12)

If the total $Yb^{3+}$ density is $N_t(r, \phi, z)$, the overlap of the intensity of the fundamental mode with the $Yb^{3+}$-density profile within the core is

$$\Gamma_{\text{core}} = \frac{\int_0^{2\pi} \int_0^{d_{\text{core}}/2} J_0^2(k_T r) N_t(r, \phi, z)rdrd\phi}{\int_0^{2\pi} \int_0^{d_{\text{core}}/2} J_0^2(k_T r)rdrd\phi}$$ \hspace{1cm} (4.13)

The overlap of total intensity of the fundamental mode with the $Yb^{3+}$ density is determined using

$$\Gamma = \frac{A_{\text{core}}}{A_{\text{eff}}} \Gamma_{\text{core}}$$ \hspace{1cm} (4.14)

4.3 Output Power

The small-signal-absorption coefficient is determined by

$$\alpha = \Gamma \bar{N}_t \sigma_{\text{abs}}$$ \hspace{1cm} (4.15)

where $\bar{N}_t$ is the average of the total $Yb^{3+}$ concentration over the cross section of the doped fiber. The saturation power is calculated as

$$P_{\text{sat}} = \frac{A_{\text{eff}}}{\Gamma(\sigma_{\text{abs}} + \sigma_{\text{em}})\tau}$$ \hspace{1cm} (4.16)

where $\tau$ is the upper-state lifetime and $\sigma_{\text{abs}}$ and $\sigma_{\text{em}}$ are the absorption and emission cross-sections, respectively, for the pump, seed, or ASE.

Using the energy of each photon to convert the rate equations in terms of number densities into rate equations in terms of power,

$$\frac{\partial P}{\partial z} = \frac{P}{P_{\text{sat}}} \left( \frac{\partial P}{\partial z} - \alpha \right)$$ \hspace{1cm} (4.17)

which, when integrated along $z$ from 0 to $L$, has the following solution

$$P_{\text{out}} = P_{\text{in}} \exp \left\{ -\alpha L + \frac{P_{\text{in}} - P_{\text{out}}}{P_{\text{sat}}} \right\}$$ \hspace{1cm} (4.18)
An iterative approach can be taken to solve for either $L$ or $P_{out}$ in equation 4.18 to determine the proper length of fiber for optimizing the gain or the expected output power given the length of fiber. Figure 4.4 shows the results obtained when modeling the first stage fiber preamp for the helium LiDAR transmitter.

4.4 Integration of Fiber Amplifier

Figure 4.5 shows an image of the transmitter after the laser amplifier was integrated with the rest of the helium transmitter system. Since access to fibers within the power amplifier is necessary during construction and testing, the amplifier system was first built with this in mind. Although this allows changes to the system to be made with more ease, the exposed fiber makes the amplifier system very delicate, which is especially a concern during transport. Figure 4.6 shows an image of the transmitter with a new layout which is more compact for transport and shipping and has fewer parts.
Figure 4.4: Output power of signal (a), ASE (b), pump (c), the gain (d), and the efficiency (e) for varying lengths of fiber.
Figure 4.5: The He resonance fluorescence transmitter (top) is fully operational. Light escaping from the fiber amplifier can be viewed through an IR viewer (bottom) during operation.

Figure 4.6: The improved layout is more compact for shipping and has fewer parts.
Since the transmitted beam is CW, the system is in a bistatic configuration, meaning that the transmitted beam is not launched from the same position as the receiver. If the beam divergence and receiver FOV are set, a larger baseline increases the vertical resolution of the imaged beam, so that each pixel covers a small vertical range (see figure 5.1). As the baseline becomes larger, this higher resolution can be at the expense of received signal since the number of photons received is proportional to $1/r^2$, $r$ being the distance from the scatterer.

Figure 5.1: Bistatic configuration. The vertical resolution is determined by the beam divergence of the transmitted beam, the baseline between the transmitter and receiver, the FOV of the telescope, and the number of pixels across the detector array.

For the configuration being used at UAO, the 100 m baseline was not chosen for high vertical resolution, but rather to increase the signal-to-noise ratio.
(SNR) by having the resonance altitudes map to as few pixels (with minimal noise) as possible. By having poor vertical resolution, each pixel receives backscattered photons from a larger vertical range bin. If the total signal falls onto fewer pixels, this decreases the amount of dark counts and readout noise in the output signal from the detector. Figure 5.2 shows the range resolution for the configuration at UAO. Additional consideration was made for the range resolution created by the configuration so that pixels that contain signal from Rayleigh scattering will be separated by a significant number of pixels from those that could contain signal from resonant scattering. This is done to prevent ambiguity between signal from Rayleigh scattering and signal from resonant scattering. With the FOV/pixel of the receiver and the beam divergence of the transmitter set by these instruments, the 100 m baseline keeps at least 100 pixels between those pixels that will collect signal from Rayleigh scattering and those receiving signal from He(2³S) resonant scattering.

![Altitude Range for CCD Pixels](image)

Figure 5.2: Range resolution for each pixel for a 100 meter baseline, a 150 µrad beam divergence, a 0.43° FOV, with 1024 × 1024 pixels.

The SNR is simulated by calculating the expected signal using the LiDAR equation and equation 5.1, where \( N_S \) is signal only from resonance fluorescence, \( N_B \) is the background signal, \( N_D \) is the dark count signal, \( N_R \) is the signal from readout noise, \( n_{pix} \) is the number of pixels within each verti-
cal range bin, and $n_{binpix}$ is the number of pixel bins that are formed for each range bin with regard to readout noise. The result shown in figure 5.3 combines the simulated He($2^3S$) densities with the He resonance fluorescence system parameters.

$$SNR = \frac{N_s}{\sqrt{N_s + n_{pix} \times (N_B + N_D) + n_{binpix} \times N_R^2}}$$  \hspace{1cm} (5.1)

Figure 5.3: SNR simulated for the UAO He resonance fluorescence LiDAR configuration, with 45 W of CW power, for summer and winter H($2^3S$) densities.

It is important to note that there are certain times at which signal integration should take place, since the He($2^3S$) content in the thermosphere and exosphere is highest during solar and conjugate solar illumination. He($2^3S$) densities increase as solar illumination in the thermosphere and exosphere increases, which produces the photoelectrons that in turn impact ground state helium, He($1^1S$), which can resonantly fluoresce under the laser illumination. However, the critical time for observation is during twilight, when the thermosphere and exosphere are illuminated by solar radiation, while scattering from sunlight at lower atmospheric altitudes is minimal to prevent high background signal, which will reduce the SNR. The best time for He LiDAR observations would be during the winter, when the conjugate hemisphere briefly experiences solar illumination before the hemisphere in
which observations are being made. While the magnetic conjugate point to the location of observation is being illuminated, electrons get trapped in the field lines and can travel to the area above observation to generate additional metastable helium. As a result, photoelectrons generated above the location of observation and at the magnetic conjugate point will both be available simultaneously to produce metastable helium during a short period of time during the winter season. This is illustrated in figure 5.4, in which results are shown from a METEHE simulation for northern hemisphere winter around morning twilight. The time during which the shelf-like appearance

Figure 5.4: Metastable helium densities at 325 km during winter at 34° N.

in metastable helium density occurs in figure 5.4, roughly 4:30-5:30 AM local time (LT), is the time during which the solar background contamination is insignificant, but the brightness from the resonantly fluorescing metastable helium can be bright enough to detect above the other background and noise conditions.

With this in mind, one could envision chopping the CW beam to obtain a pulsed system that could be configured monostatically and integrating for longer periods of time, such as 30 minutes around 5 AM LT. This configuration has the potential added benefit of integrating signal for a given range bin only during the time for which the pulse is traversing the altitude range for that range bin, resulting in a decrease in background signal. The dissad-
vantage, however, is that the average power decreases by a factor equal to
the duty cycle of the pulsed system. The SNR for simulated return of such a
system obtained by chopping the CW laser transmitter described above with
a 8.3% duty cycle, with a 150 km long pulse, is shown in figure 5.5. This re-

![He LiDAR SNR for Chopped CW Beam](image)

Figure 5.5: SNR for a 30 minute integration period for a monostatic
configuration obtained by chopping the 45 W CW laser transmitter at an
8.3% duty cycle.

sult assumes that a detector of similar QE would be used that could provide
fast detection of photons for photon counting. Although this configuration is
preferred over a bistatic configuration, as it provides for better range resolu-
tion and reduced background noise, the result is similar to that obtained with
the CW laser transmitter in a bistatic configuration with shorter integration
periods due to the reduction in average power.

Due to the low SNR using the 45 W transmitter with the UAO receiver,
it is desirable to change the parameters in equation 5.1 to increase the prob-
ability of detecting a signal. To do this, the signal can be increased by
increasing the power-aperture product, which can be accomplished by scal-
ing the transmitter output power and/or the size of the receiver as necessary.
Additionally, the system efficiency can be increased by switching to a detec-
tor with a higher QE for the receiver. (The detector would ideally have a
lower dark count and readout noise as well.) Both of these factors can be
adjusted accordingly using an astronomical telescope that has IR imaging
capabilities, such as the SOAR telescope on Cerro Pachón in Chile. The
benefits of the SOAR telescope are that it has a 4.1 meter effective diameter and a HgCdTe detector with a QE of 55% at 1083 nm [23]. The Spartan IR imager uses a cryogenically cooled Hawaii-II detector that has readout noise of about 10 $e^-$ and a dark current of 0.3-0.9 $e^-$/pixel/s. It has a FOV of 5.12×5.12 arcminutes, which is equivalent to about 1.5×1.5 mrad, and a 2×2 mosaic of 2048×2048 arrays.

If the SOAR telescope is to be used as a receiver, the beam divergence not only needs to be as narrow as possible to achieve a high SNR, but also to fit the beam within the narrow FOV of the Spartan imager. A 20× beam expander is used to decrease the beam divergence. The beam is collimated by measuring its spot size at two different points along the beam path between the transmitter room and the zenith pointing folding mirror, and adjusting the beam expander to reduce the difference in the spot diameters. The upward pointing beam is then imaged with the telescope and the cross section is measured in the far-field (figure 5.6). The angle per pixel and the beam cross section are used to calculate the beam divergence, which is currently about 150 μrad.

![He LIDAR Beam Profile (Background Removed)](image)

Figure 5.6: A cross section of the imaged beam in the far-field is used to calculate the beam divergence. Each pixel has a square FOV of 7.36 × 10^{-6} radians by 7.36 × 10^{-6} radians.

Using the parameters for the SOAR telescope, simulations were made for the vertical resolution (figure 5.7). The vertical ranges are incorporated into SNR calculations shown in figure 5.8. As can be seen from these simulations, the probability of measuring resonantly scattered signal from H(2^3S)
is greatly improved.

Figure 5.7: Simulations for range resolution with a 600 m baseline between the SOAR telescope and the He LiDAR transmitter.

Figure 5.8: The SNR is plotted with respect to altitude for the 45 W He LiDAR transmitter and the SOAR telescope Spartan IR imager.
CHAPTER 6
FUTURE WORK

6.1 Slab Laser: An Alternative to the Fiber Laser Transmitter

A CW laser transmitter for high altitude remote sensing applications has disadvantages associated with the bistatic configuration required for a CW system. This amounts to poorer range resolution than can be achieved with a pulsed transmitter in a monostatic configuration, as well increased background noise while receiving signal from a given range bin over the entire integration period as opposed to the short time span that a pulse is traversing an altitude range. A slab laser is considered as a possible alternative to the fiber amplifier developed for the helium LiDAR, in order to achieve an average output power comparable to that of the CW system currently in use and a high-peak-output power that is difficult to achieve using a standard doped fiber for amplification.

The slab laser could consist of a Yb-doped YAG glass, which is typically doped in the 0.1-3 atomic percent range for laser applications, and would be used as the power amplifier in a MOPA configuration. With a lower emission cross-section than YAG crystals typically used in slab lasers and a larger mode diameter than standard fiber lasers, a double-pass configuration would be required to achieve a significant effective length. Figure 6.1 shows the geometry of a miniature slab configuration simply for the purpose of example. The input angle sets up an angle $\gamma$ with respect to the side of the slab, which is chosen for total internal reflection (TIR) and to reduce the beam overlap. The overlap region is where extraction of stimulated emission occurs twice during the double pass. In this case, $\gamma$ is chosen to be $29^\circ$.

For the dimensions of the slab laser, the width ($w$) of the slab and the thickness ($t$) are chosen to be equal, which according to Sridharan et al.,
Figure 6.1: Slab laser amplifier diagram showing the double pass configuration. The dark red area indicates the active (pumped) region and the blue lines indicate the beam traversing the slab. The diagram in (b) shows a cross section of the slab with an extended section of undoped slab shaped to meet the necessary launch conditions. $l_{doped}$ is the length of the doped (active) region. $L_s$ and $L_p$ are used to define the overlap factor.
allows for easier operation with a $TEM_{00}$ Gaussian beam profile. Following that design methodology, $w$ and $t$ are chosen to be 1 cm. A laser with a Gaussian beam profile with a $1/e^2$ radius ($w_g$) of 500 $\mu$m is assumed to be launched into the slab. Using the “top-hat” width of a Gaussian beam as defined by [24], the area of the beam is then $A_{\text{active}} = \pi \times w_g = 1.26 \times 10^{-7}$ m$^2$ and the active width of the slab becomes $w_{th} = w_g/\sqrt{2} = 354$ $\mu$m. An overlap factor, $f$, defined by [25] as shown in equation 6.1, is used to calculate the fractional volume for which stimulated emission is extracted twice in a single pass slab laser amplifier, which also holds for the double-pass configuration described here. The angle $\gamma$ the angle between the beam and the slab surface, as shown in figure 6.1b.

$$f = \frac{L_s}{L_b} = \frac{1}{\sqrt{2}} \frac{w_g}{t \sec(\gamma)} \quad (6.1)$$

To simulate the output of the slab fiber, the approach given by Sridharan et al. is followed. The upper-state density, $N_u$, is determined by numerically integrating the following rate equation:

$$\frac{dN_u}{dt} = -\eta_{p-loss} I_{\text{in}}(t) \left( e^{\sigma_p \sigma_{abs} N_u(t)} - 1 \right) \left( R_p e^{\sigma_p \sigma_{abs} N_u(t)} + 1 \right) - \frac{N_u(t)}{\tau} \quad (6.2)$$

where $\eta_{p-loss}$ is the optical transmission of the pump, which is assumed to be 90% to account for TIR losses within the slab and reflection losses at the slab facet, $R_p$ is the reflectivity at the pump wavelength, $\sigma_p$ is the pump absorption cross-section, $\tau$ is the upper-state lifetime, and $I_{\text{in}}(t)$ is found by

$$I_{\text{in}}(t) = \frac{P_{\text{peak pump}}}{A_{\text{beam}}} \quad (6.3)$$

The gain is then calculated using

$$g_0 l_{eff} = (N_u \sigma_{em}^s + N_l \sigma_{abs}^s) \frac{l_{\text{doped}}}{\cos(\gamma)} \quad (6.4)$$

where $N_l$ is the upper-state density, and $\sigma_{em}$ and $\sigma_{abs}$ are the emission and absorption cross-sections of the signal, respectively.

The system was optimized for the gain factor by adjusting the doping concentration, which became $1.22 \times 10^{25}$/$\text{m}^2$, and the doped slab length,
which became 0.5 m. The pump power was set by available commercial devices currently on the market, which range in peak powers from 1 to 2 kW for fiber coupled diode stacks. The width and thickness of the slab have been chosen to allow the slab to be end-pumped with a diode laser stack launched through a 600 µm core diameter fiber with an NA assumed to be about 0.22. A pulse repetition rate of 150 Hz was used, which would allow for a peak altitude of 1,000 km. A pulse width of 167 µm was set to provide 50 km range bins. Assuming a 975 nm diode stack with peak pulse powers of 2 kW, figure 6.2 shows the simulated gain factor as a function of time.

![Logarithmic Gain](image)

Figure 6.2: Slab laser gain factor, $g_{0,\text{eff}}$.

The output power in the small-signal gain limit is then found by using

$$P_{\text{out}} = \eta_{s-loss} P_{\text{in}} e^{g_{0,\text{eff}}}$$

(6.5)

where $\eta_{s-loss}$ is the optical transmission of the signal and is assumed to be 98%. In order to produce a significant output power, somewhat comparable to the average power of the current CW system, from the slab amplifier a high average input power was needed. The reason for this is that the seed that would likely be available would be CW. Since the CW seed beam would only be amplified during the pump pulse, this is equivalent to chopping the CW beam. As a result, the peak power available for amplification would be approximately the average power of the CW beam and the average power of the seed would be reduced by a factor of the duty cycle of the pump. For
these reasons, it is assumed that a CW seed of 45 W average power would be available for amplification. With the pulse methodology described above for the pump, this would provide 1.13 W average power. Using equation 6.6, the output power is simulated with these parameters, with results shown in figure 6.3.

\[
P_{\text{out}} = \eta_{\text{s-loss}} I_{\text{sat}} A_{\text{active}} \cos(\gamma) f(2-f) \ln[1+(e^{E_{\text{in}}/I_{\text{sat}} A_{\text{active}} \cos(\gamma) f(2-f)}-1)e^{g_{0}l_{\text{eff}}}] 
\]

where \( I_{\text{sat}} \) is the saturation intensity. The simulated results are shown in figure 6.4, and the expected output would be somewhere around 17 W average power.

6.2 3-Frequency Technique for Temperature and Wind Measurements

LiDAR systems, such as DIAL (differential absorption LiDAR) and Rayleigh LiDARs, use different approaches that allow for temperature measurements to be made. The narrow linewidth of the He resonance fluorescence LiDAR provides the capability to probe within the Doppler broadened linewidth of
He(\(2^3\text{S}\)) atoms in the upper atmosphere. The Doppler broadened linewidth for He(\(2^3\text{S}\)) is modeled in figure 6.5 for temperatures of 800 K, 1,000 K, and 1,200 K. By changing the wavelength of the laser, the shape of the Doppler broadened linewidth and, thus, the temperature of the atoms being probed can be inferred based on the intensity of the resonantly scattered signal that is received at each frequency. The transmitter frequency can be scanned or shifted. Additionally, the wind velocity along the direction of the beam path can be measured, since a Doppler shift will occur on the already temperature broadened linewidth, as indicated in figure 6.5, if there is a wind component along the direction of propagation. The current transmitter system can be modified by installing fiber coupled AO modulators. Two AO modulators could be used to shift off of the peak of the He(\(2^3\text{S}\))→He(\(2^3\text{P}\)) transition for the common 3-frequency technique that is applied in Na Doppler resonance fluorescence LiDARs to infer the Doppler linewidth. Assuming a thermospheric temperature of 850 K, the optimum frequencies for He(\(2^3\text{S}\)) density, wind, and temperature observations would be for the center frequency to be +784 MHz from the D1 peak and off-center shifts at ±3.66 GHz from the center frequency for nighttime observations [26].
Figure 6.5: Temperature Doppler broadened (a) and wind Doppler shifted (b) He(\(^{23}S_1 -^{23}P_{1,2}\)) linewidths.

### 6.3 Signal Return for Pulsed Monostatic System with Three-Frequency Technique

Using the results obtained in section 6.1, the expected signal can be simulated to provide a comparison to the existent helium resonance fluorescence LiDAR and understand the signal to noise. To simulate the expected signal return, the parameters describing the UAO system will be used.

As the signal propagates through the lower atmosphere, Mie and Rayleigh scattering will occur at lower altitudes. Since the signal return from Mie scattering is typically very high, it is usually chopped to protect the sensitive detectors used in upper-atmospheric LiDAR systems for photon counting, such as photomultiplier tubes, or PMTs. Assuming the Mie scattering will be blocked, the Rayleigh backscattering cross-section can be determined by [27]

\[
\sigma_{\text{Rayleigh}} = 5.45 \times 10^{-32} \times \frac{550 \times 10^{-9}}{\lambda_{\text{center}}^4}
\]  

Employing the LiDAR equation, equation 2.1, to determine the signal return for both Rayleigh scattering, with the help of equation 6.7, and resonance fluorescence scattering, the expected return for the pulsed transmitter system described in section 6.1 and the UAO receiver system is shown in figure 6.6. The densities used for determining the Rayleigh return were obtained from the MSIS00 model and the He(\(^{23}S\)) densities were obtained from
Figure 6.6: Simulated signal return for the He resonance fluorescence LiDAR using the pulsed laser system parameters, as described in section 6.1, and the UAO receiver parameters. The expected photon counts per shot are shown in (a) and the total number of photon counts for a 10 minute integration period are shown in (b). The SNR for a 10 minute integration period is shown in (c).

the METAHE model. A 50 km range bin was used for both scattering mechanisms as well as the extinction caused by absorption and scattering. Here it is assumed that a fast, photon-counting detector, with sensitivity similar to the iKon CCD, such as an InGaAs PMT or APD, would be used in the focus of the UAO telescope to measure gated returns. To account for noise, background, dark count, and shot noise are included in the results shown in figure 6.6c. Applying the three-frequency technique for temperature mea-
measurements, as described in section 6.2, the expected signal can be simulated for each frequency. The frequency selections used to obtain the results in

![He(2^3S) Return for a 90000-Shot Integration Period](image)

**Figure 6.7:** Simulated signal return for the He resonance fluorescence LiDAR using the pulsed laser system parameters, as described in section 6.1, the UAO receiver parameters, and the optimum frequencies as determined by Gardner et al. [26].

Figures 6.7 and 6.8 are the optimal frequencies for nighttime observations as determined by Gardner et al. [26]. The minimum error in temperature, in this case, would be 202 K at about 500 km.

### 6.4 Power in Fibers

Scaling the power of the transmitter to achieve a higher SNR has limitations. The major limitations of fiber amplifiers result from the high power densities guided within their small diameter cores. Thermal effects due to high power densities and inefficient thermal management can result in damage to the fiber material, resulting in melting and fracture [28]. Thermal lensing within the core can be caused by temperature induced refractive index changes. Nonlinear optical processes also occur at higher powers, the two most important being stimulated Raman scattering (SRS) and stimulated
Brillouin scattering (SBS), both of which affect the spectral characteristics of the amplified signal and can have detrimental effects on system components. Of these non-linear optical processes, SBS is the main consideration when dealing with narrow linewidth fiber amplifiers.

SBS occurs when the optical field interacts with the fiber via electrostriction, producing acoustic phonons. SBS results when the guided power becomes larger than the SBS power threshold, producing acoustic phonons which act like a grating moving at the speed of sound and causing a backward propagating Stokes signal that reduces gain for the forward propagating signal and can also reach pumps, couplers, and isolators, causing damage to them. This makes the design of high-power, narrow linewidth, pulsed fiber lasers/amplifiers difficult and, thus, poses major challenges to operating the He LiDAR transmitter in a pulsed mode, which would allow a monostatic configuration, with significant power for resonance fluorescence measurements.
SBS can be described by a set of coupled ordinary differential equations for the evolution of the pump and Stokes signals along the length of the fiber, which include a non-linear interaction term that contains a “gain factor,” the solutions to which describe the change in each field (pump or Stokes) as a result of the other [29]. In the solutions, the “gain factor” winds up in an exponential factor that is a function of length along the fiber and, as a result, is referred to as the Brillouin gain. The Brillouin gain is a function of optical frequency and, thus, has a spectrum, which is Lorentzian in shape. The peak of the Brillouin spectrum is referred to as the Brillouin gain coefficient, $g_B$.

The gain coefficient is related to the following fiber parameters as described by equation 6.8 [30]:

$$g_B = \frac{2\pi n^7 p_{12}^2}{c\lambda_s^2 \rho V_a \Delta \nu_B}$$  \hspace{1cm} (6.8)

where $n$ is the refractive index of the fiber (core), $p_{12}$ is the elasto-optic coefficient, $\lambda_s$ is the signal wavelength, $\rho$ is the material density, $V_a$ is the acoustic velocity, and $\Delta \nu_B$ is the SBS gain spectrum bandwidth. The “gain factor” can be modified to account for the bandwidth of the laser by a factor of $1/(1+\Delta \nu_L/\Delta \nu_B)$, where $\Delta \nu_L$ and $\Delta \nu_B$ are the laser and Brillouin spectrum linewidths, respectively [31]. This takes into account the finite bandwidth of the laser and results from the fact that the “gain factor” spectrum is the convolution of the laser spectrum and the intrinsic SBS spectrum. In the case of SBS, narrow linewidth typically refers to when $\Delta \nu_L \lesssim \Delta \nu_B$, at which point SBS can become the dominant nonlinear process affecting power transmission.

For narrow linewidth operation, if the depletion of the incident wave is ignored, the SBS power threshold can be approximated with the following equation [32]:

$$P_{th} \approx \frac{21 A_{eff}}{g_B L_{eff}}$$  \hspace{1cm} (6.9)

where $P_{th}$ is the threshold power at which SBS occurs, $g_B$ is the Brillouin gain coefficient, $A_{eff}$ is the effective mode area, and $L_{eff}$ is the effective fiber length. Steps can be taken in the design of high-power amplifiers to mitigate the risks of SBS, such as using a wider core diameter, as was done for the last stage fiber amplifier in the He LiDAR. These considerations were made when designing the fiber amplifiers for the He LiDAR transmitter, and SBS was not a concern in the current application. However, to reduce the risk of
damage from backward propagating signal caused by reflections, SBS, and other processes, isolators are in place in front of each stage. An additional consideration is the higher backward insertion loss on the last stage coupler. In the case of considerable SBS, this might cause damage to the coupler before enough power is transmitted back to other devices that can damage them. Depending on the value of the pumps and other components, this can be beneficial.

The power threshold for stimulated Brillouin scattering is inversely proportional to $g_B$ and, as a result, some fiber designs have benefited from increased SBS power thresholds by reducing $g_B$. Some of the common techniques applied to alter the Brillouin gain coefficient focus on fiber structure variations to alter the acoustic velocity in the transverse direction and material selection to modify the elasto-optic coefficient. Since the SBS gain coefficient is inversely proportional to the SBS gain bandwidth, this has become another parameter that fiber designers commonly desire to change. One such example is a spinel-derived fiber reported by [33] which showed the largest (ever reported to date) SBS gain bandwidth of over 200 MHz.

6.4.1 Pulsed Fiber Amplifier

As an additional consideration for an alternative laser source for the He LiDAR, currently available technology can be considered for use in a pulsed laser fiber amplifier. Although increasing the core size of the fiber can have the benefit of increasing the power threshold for SBS, one of the challenges faced with increased core sizes is the beam quality. Larger core sizes allow for higher order modes to be guided within the core, thus decreasing the beam quality and increasing the divergence, which for LiDAR applications has the disadvantage of lower spatial resolution and can potentially reduce SNR. The power threshold for SBS, however, is proportional to the effective area, which can be related to the square of the mode field diameter by a correction factor [34]. It is possible to increase the mode field diameter of the core while maintaining single mode operation. As compared to the effective mode areas for standard single mode fibers, large mode area (LMA) fibers, such as some photonic crystal fibers, can achieve single mode operation by suppressing higher order modes while maintaining a large mode field diameter.
One example is the NKT fiber DC-200/40-PZ-Yb, which is a Yb-doped fiber with a 40 µm core diameter and a 760 µm² mode field area. The Brillouin gain factor in an aluminosilicate fiber using a pump wavelength of 975 nm and signal wavelength of 1083 nm is approximately $2.68 \times 10^{-11}$ m/W. This leads to an SBS power threshold of 305 W, when approximating the effective length for SBS as 2 m. Assuming a pulsed pump input of 300 W with an 6.3 W narrow linewidth input seed at 1083 nm, figure 6.9 shows the potential peak pulse power output as a function of length along the photonic crystal fiber. The result shows a peak power of 272 W with a fiber length of about 3.26 m. If used in a similar fashion as the slab laser for pulse widths on the order of 167 µs at a repetition rate of 150 Hz, the average available power output could be on the order of 6.8 W with pulse energies of about 0.045 mJ in an idealized scenario.
CHAPTER 7
POSSIBLE ALTERNATIVE APPLICATIONS

Besides using the He LiDAR to understand more about the physics of the upper atmosphere, the system could have other potential applications once it has progressed in its development to the point at which significant returns can be achieved. One possible application is relating the density of He($^2\text{S}$) to the effects that the neutral atmosphere has on satellites.

Low earth orbit (LEO) satellites experience atmospheric drag, which is a major component of orbital decay. Orbital decay is proportional to the atmospheric density by the following equation:

$$d = \frac{1}{2} C_d A \rho v^2$$  \hspace{1cm} (7.1)

where $C_d$ is the drag coefficient, $A$ is the cross section of the space craft, $\rho$ is atmospheric density, and $v$ is the velocity of the space craft. For many orbital decay models, which use a simple exponential decay model, variations in thermospheric density are related to temperature variations, which are considered to be directly related to solar activity. These models relate the solar radio flux F10.7 measurements and magnetic activity, using the $K_p$ and $A_p$ indices, respectively, to temperature in order to account for heating caused X-ray radiation and particle precipitation, respectively. The relationships are empirically derived and measurements, such as those made by the GRACE and CHAMP satellites, to update these models are costly. Helium is one of the major contributors at LEO altitudes that causes satellite drag [35]. One consideration for further work is to understand the errors that would arise from working backward in the model for the He($^2\text{S}$) content to calculate the neutral density, since the photoelectron flux that produces metastable helium is produced by photoionization of the neutral atmosphere. Errors in He($^2\text{S}$) density could be related to errors in photoelectron fluxes.

Another possible alternative application is the use of the He LiDAR trans-
mitter for laser guide star applications. Adaptive optic systems typically use natural guide stars to measure wavefront distortions caused by turbulence. However, suitable natural guide stars are not always in the FOV when measurements are being made. Laser guide stars are used to create an “artificial star” that is bright and remains within the FOV during measurements. Sodium guide star lasers have a major advantage over Rayleigh guide star lasers in that the altitude from which the scattering occurs is much higher. Whereas Rayleigh guide stars are typically focused at about 10-20 km, the majority of resonance scattering from sodium occurs between 85 and 95 km in altitude. This scattering from higher altitudes creates a more planar wavefront that will pass through the turbulent layers, which reduces the error caused from wavefront sensors detecting the non-planar wavefronts as effects of turbulence [36].

Figure 7.1: Wavefronts from a higher altitude guidestar would be more planar before passing through turbulent layers than wavefronts from guidestar at lower altitudes. The curvature in the wavefront at the wavefront sensor is measured as a perturbation caused by turbulence and results in correction errors. A helium guidestar would have the potential to reduce these errors.

The peak He(2^3S) density occurs between 250 and 450 km in altitude and
would provide for a much more planar wavefront. Figure 7.1 illustrates the effects of higher altitude guide star lasers on wavefront sensors. The major drawback is the brightness that could be produced with a He(2^3S) guide star. The column abundance of metastable helium from 250 km to 750 km is 2 orders of magnitude lower than that of sodium.
CHAPTER 8

CONCLUSION

The helium resonance fluorescence LiDAR has the potential to make ground-breaking measurements in the thermosphere and exosphere, furthering our understanding of the physical processes that occur within this region. This current work builds upon the work done by Gerrard et al. [13] and C. G. Carlson et al. [19], who made major contributions and developments to advance the He resonance fluorescence LiDAR. Recent progress has been made in calibrating the system and increasing the power output to increase the probability of measuring signal from He(2^3S). A defective pump and signal combiner has halted progress and operations of He LiDAR operations. The goal for the future would be to relocate the transmitter to be used with a large aperture telescope and a high-efficiency detector, or utilize the existing telescope at UAO and replace the Andor Camera with a detector with higher quantum efficiency, in an attempt to make the first resonance fluorescence ground based measurement in the thermosphere and exosphere. This challenge to make the system more compact and rugged to withstand shipment owes to the fact that components within the system become difficult to access when something is damaged during shipping. Additionally, this requires sophisticated equipment to be on hand in remote locations to repair damaged components within the fiber amplifier system. The more reliable approach would require an efficient detector to be on site for the initial experiments to detect a single photon. When signal is finally detected, further advancements to the system can be considered so as to have wind/temperature capabilities, a higher SNR, and better vertical resolution.
REFERENCES


