CONSTRUCTION OF A 1014.8NM FIBER AMPLIFIER FOR QUADRUPLING INTO THE UV

A Thesis

by

FRANK J. GIUOCO

Submitted to the Office of Graduate Studies of Texas A&M University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Physics
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ABSTRACT

Construction of a 1014.8nm Fiber Amplifier for Quadrupling into the UV.

(December 2003)

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A fiber amplifier is constructed at 1014.8nm and then frequency doubled to produce 507.4nm radiation. This could then be frequency doubled again to produce 253.7nm radiation. The fiber amplifier consists of Ytterbium doped double-clad fiber cooled to low temperatures and incorporates a diode laser as the seed source. The amplifier is built in a two stage configuration with high power diode lasers at 980nm pumping each stage. The output of the fiber amplifier is then doubled in a PPLN crystal and redoubled in a BBO cavity. Measurements are taken throughout the system to determine output powers from the first stage and from the fiber amplifier as a whole.
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CHAPTER I

INTRODUCTION

Laser radiation at 253.7nm is critical when studying certain transitions of mercury atoms, and until recently there were few options for its production save an expensive, bulky Titanium Sapphire laser system. With the advent of fiber technology however, new approaches for the production of 253.7nm can now be studied. Beginning with a double-clad fiber doped with ytterbium and a diode laser at 1014.8nm, along with a high powered pump diode at 980nm, a fiber amplifier was constructed. With enough amplification in the fiber, efficient 1014.8nm radiation is produced to allow quadrupling to 253.7nm. First the the output will be doubled in a PPLN Crystal and then redoubled in a BBO resonator cavity. With a goal of 2W of 1014.8nm output from the fiber amplifier, several milliwatts of narrow line width 253.7nm light can be produced. This 253.7nm output is suitable for application in various experiments.

Fiber Amplifiers

Fiber amplifiers were first employed as a means to boost optical telecommunication signals which had to travel over large distances. Splices of doped fiber could be inserted directly into the optical line and pump radiation could be added from adjoining fibers. This way the signal could be amplified without the need to convert it first to an electronic signal and then back to an optical signal [1]. Fiber amplifiers operate on very simple principles. A silica fiber is drawn with a small circular inner region called the core, usually on the order of 10 microns for single mode operation. This core region is of a higher index of refraction than the surrounding medium,

This thesis follows the style of Optics Letters.
known as the cladding, so that light will be totally internally reflected down the length of the fiber. The core is doped, usually with rare-earth atoms (erbium, ytterbium thulium, etc.) which have distinctive absorption and emission spectra. The dopants act as a gain medium, and are excited to upper states with relatively long lifetimes by a pump laser source generally applied at a wavelength for which the fiber dopants have a high absorption cross section. For the laser signal being amplified, or the seed beam, the fiber should have a high emission cross section [2]. The seed can then create stimulated emission as it propagates down the fiber, resulting in gain. Problems arise due to amplified spontaneous emission (ASE), which is produced independently of the seed over a band of wavelengths and competes for gain. As pump power and fiber length increase, ASE can dominate the output, causing efficiency issues to arise for certain systems.

**Double Clad Fibers**

As a need arose for more powerful fiber amplifiers, double-clad fibers began being produced. Large amounts of pump light could not be coupled into the small diameter cores of traditional fibers, so in between the core and the cladding, a new layer was added, known as the inner-cladding. This region is generally on the order of hundreds of microns in diameter and shaped in such a way that the pump light propagating in this region will repeatedly pass though the core as it travels down the fiber. Thus, large amounts of pump light can be spread over a large area, producing considerably more gain than was previously possible [3]. In the following chapters, the theoretical and experimental methods used for constructing a fiber amplifier with these components will be examined, as well as the special procedures necessary to create a fiber amplifier at 1014.8nm.
CHAPTER II

THEORETICAL CONSIDERATIONS

Light Amplification

The construction of fiber amplifiers would not be possible without the underlying interactions between light and atoms. Atoms have levels which are separated by specific energies. When the energy difference of two levels matches the energy of a photon in the system, several interactions can take place. The atom can absorb a photon of energy $E = h\nu$, where $\nu$ is the frequency of the laser light, if $E = E_2 - E_1$ is the energy difference between levels. This is the same as exciting the atom from energy $E_1$ to $E_2$. The atom can only stay in this excited state for a short period of time, known as the *lifetime*, at which point it will drop back down into a lower state, emitting a photon with an energy corresponding to the energy difference between the upper state and the new lower state. This type of emission is known as spontaneous, because the emitted photon emerges with an energy independent of any other photons in the system. If however, the atom is in an excited state and other photons are present, the atom can emit a photon which matches the energy of these existing photons. This process is known as stimulated emission, and is the basis upon which fiber amplifiers operate. Atoms can be excited to their upper states by one laser, called the pump, and then stimulated by a second laser, known as the seed. The atoms will then emit at the seed energy. This emission adds coherently to the seed laser, amplifying it. All these processes are happening continuously when an atom interacts with laser light. Whether or not absorption, spontaneous emission, or stimulated emission takes place depends on many factors. The probability per unit time for spontaneous emission is given by:
\[ p_{sp} = \frac{c}{\sqrt{\sigma(\nu)}} \]  

(2.1)

where \( \sigma(\nu) \) is called the transition cross-section and is a function of frequency [4]. At half maximum, the spectral width of the transition cross-section is known as the linewidth and is an important spectral quantity. The narrower the linewidth, the range of frequencies that can interact with a dopant atom. Notice the probability for spontaneous emission does not depend on the photon number, since the process is incoherent. Conversely, the probability per unit time for absorption and stimulated emission,

\[ p_{a} = p_{st} = \eta \frac{c}{V} \sigma(\nu) = W \]  

(2.2)

do depend on the number of photons (\( \eta \)). If there are more photons, there is a greater likelihood of the atom absorbing one, or being stimulated to emit one coherently. The probabilities of one atom absorbing or spontaneously emitting a photon are equal in a two level system, and this probability per unit time is referred to as \( W \). Also the number of photons per unit area per unit time, or the photon-flux density, defined as,

\[ \phi = \frac{I}{h\nu} \]  

(2.3)

can be used in conjunction with (2.2) to come up with a new expression for \( W \). If a cylindrical volume is taken such that the base has area \( A \) and the length is \( c \), giving \( V = cA \), then the number of photons within the cylinder in each second is simply the
number that crossed the base in that time, $\eta = \phi A$ (fig. 1) Substituting,

$$\eta = \phi \frac{V}{c}$$

(2.4)

This leads to a new expression for the probability.

$$W = \phi \sigma(\nu)$$

(2.5)

Gain

Knowing the probability for a photon to be absorbed or to stimulate emission, one can then determine the amount of gain an amplifier can produce. If the average probability is $W$ and the lower level contains $N_1$ atoms per unit volume, then the average density of absorbed photons is $N_1 W$. Similarly, if the upper level contains
$N_2$ atoms per unit volume, then the average density of photons created by stimulated emission is $N_2W$. If there are more photons being emitted coherently into your seed beam than are being absorbed, that is, if $N = N_2 - N_1$ is positive, the system is in a state of population inversion and gain can be achieved. The photon density gained would simply be $NW$ photons per unit time per unit volume. These new photons produced by stimulated emission move in the same direction as the seed beam and add to the flux ($\phi$) of the system. If the beam was propagating in the $z$ direction for example, the change in flux per unit length would simply be,

\[
\frac{d\phi}{dz} = NW \tag{2.6}
\]

Substituting (2.5) for $W$ in (2.6) and defining a new quantity called the gain coefficient $\gamma$,

\[
\gamma(\nu) = N\sigma(\nu) \tag{2.7}
\]

a differential equation in $z$ is established.

\[
\frac{d\phi}{dz} = \gamma(\nu)\phi(\nu) \tag{2.8}
\]

This can be solved by an exponential where $\phi(0)$ is a constant flux taken at $z = 0$ designated to be the beginning of the interaction region.

\[
\phi(z) = \phi(0) exp[\gamma(\nu)z] \tag{2.9}
\]
If the end of the interaction region is \( z=L \), then the total gain of an amplifier system, \( G(\nu) \) would be the ratio of flux at the beginning of the interaction region to the flux at the end of the region.

\[
G(\nu) = e^{\exp[\gamma(\nu)L]}
\]  
(2.10)

Because the gain is dependent on the population densities of each energy level, the behavior of the gain can be studied by examining the ways in which the populations change over time. This is accomplished using rate equations. These equations can accommodate all the transitions inherent in amplifiers including pumping, spontaneous and stimulated emission, and absorption. For example, in a simple two level system the rate equations take the following form:

\[
\frac{dN_2}{dt} = R_2 - \frac{N_2}{\tau_2} - N_2W + N_1W
\]  
(2.11)

\[
\frac{dN_1}{dt} = -R_1 - \frac{N_1}{\tau_1} + \frac{N_2}{\tau_2} + N_2W - N_1W
\]  
(2.12)

Where \( R_1 \) and \( R_2 \) are the pumping rates per unit volume. \( R_1 \) is defined as positive when atoms are leaving level one, and \( R_2 \) is positive when atoms are entering level two. Also, \( \tau \) is defined as the decay time for the various transitions. For example, \( \tau_{21} \) is the decay time from level two to level one. \( \tau_2 \) and \( \tau_1 \) incorporate all the decays from levels two and one respectively according to:

\[
\frac{1}{\tau_2} = \frac{1}{\tau_{21}} + \frac{1}{\tau_{20}}
\]  
(2.13)
where \( \tau_{20} \) is the decay time from level two to any levels below level one. \( N_1 W \) is the rate of absorption per unit volume, which adds population to level two and removes it from level one, while \( N_2 W \) is the rate of spontaneous emission per unit volume, which drops atoms from level 1 down to level 2. Spontaneous emission is contained in the second term on the RHS of (2.11) as well as in the third term on the RHS of (2.12). Population can leave level two through spontaneous emission, and some of it may end up contributing to the population in level one. Clearly, with these definitions, these equations make sense from a physical perspective, and solving them in the steady state by letting \( \frac{dN_2}{dt} \) and \( \frac{dN_1}{dt} \) equal zero, \( N_1 \) and \( N_2 \) can be obtained. Recall from (2.7) that the gain coefficient and subsequently the gain of an amplifier depends on 
\[ N = N_2 - N_1. \]
In this way the rate equations permit determination of the behavior of the gain for various systems. In the case of the system above, the solution becomes,

\[
N = \frac{R_2 \tau_2 (1 - \frac{N_1}{\tau_{21}}) + R_1 \tau_1}{1 + W \left[ \tau_2 + \tau_1 (1 - \frac{W}{\tau_1}) \right]} \tag{2.14}
\]

It is evident from this solution that the population difference between the levels and in turn the gain become small if the probability density \( W \) becomes large. This represents a situation in which most of the population has undergone stimulated emission and there are not enough atoms left in the excited state to maintain amplification. This condition is known as gain saturation.

**Amplification in Ytterbium Fiber**

The above treatment applies to an ideal two level system in which no two levels are degenerate. A ytterbium doped fiber amplifier must be treated somewhat differently. The levels of ytterbium are actually bands of levels \cite{5}, fig (2), and in order to model
Fig. 2. Ytterbium Levels. Level manifold structure in ytterbium. Energies are shown in wave number.

them correctly, the probabilities for absorption and stimulated emission in the various sublevels must be considered. Recall that in the two level system the same transition cross section, $\sigma(\nu)$ was used to describe both absorption and stimulated emission. For a fiber amplifier system with many energy levels for the dopant, separate quantities for these interactions must be introduced to model the system properly. These are the absorption cross section $\sigma_a(\nu)$ and the emission cross section $\sigma_e(\nu)$, respectively. A non-degenerate system would constitute the special case of $\sigma_a(\nu) = \sigma_a(\nu) = \sigma(\nu)$. For the fiber system, the probabilities to undergo absorption and spontaneous emission can now be written as,

$$W_a = \phi \sigma_a$$  \hspace{1cm} (2.15)
\[ W_e = \phi \sigma_e \]  

(2.16)

This leads to a gain coefficient expressed as,

\[ \gamma(\nu) = N_2 \sigma_e - N_1 \sigma_a \]  

(2.17)

In addition to the differing probabilities for absorption and stimulated emission, a ytterbium doped fiber amplifier system can be modeled as a three level system. Along with a ground state and an excited state, the three level system contains what is known as a metastable state. This state possesses a relatively long lifetime and serves to enhance population inversion. Atoms are pumped into a short lived excited state, \( E_3 \) in fig. (3b), and then fall immediately to \( E_2 \), the metastable state in the excited state complex. Atoms accumulate in this state and are readily available to undergo stimulated emission[6]. Because the lifetime of level three is so short, all atoms pumped out of level one end up in level two, meaning the pumping rates \( R_1 \) and \( R_2 \) can now be considered equal. Ytterbium is especially convenient in its level structure because it leaves no room for excited state absorption (ESA). There are no accessible levels above the upper group of bands, and therefore, no atoms excited to level three can be absorbed to even higher levels. Also the wide spacing between the two groups of bands in fig (2) preclude nonradiative transitions [7]. All the energy released when atoms relax will be in the form of photons. It is also useful to express the photon flux in terms of the intensities of the seed and pump beams \( I_s \) and \( I_p \) according to (2.3). In this way the rate equations for a general amplifier system can be rewritten to apply to a three level fiber amplifier system.
Fig. 3. Two and Three Level Systems. (a) A two level system with population inversion. (b) A three level system with the population in the metastable state.

\[
\frac{dN_1}{dt} = -\frac{\sigma_{pa}I_p}{h\nu_p}N_1 - \frac{\sigma_{sa}I_s}{h\nu_s}N_1 + \frac{\sigma_{se}I_s}{h\nu_s}N_2 + \frac{N_2}{t_{sp}} \tag{2.18}
\]

\[
\frac{dN_2}{dt} = \frac{\sigma_{pa}I_p}{h\nu_p}N_1 + \frac{\sigma_{sa}I_s}{h\nu_s}N_1 - \frac{\sigma_{se}I_s}{h\nu_s}N_2 - \frac{N_2}{t_{sp}} \tag{2.19}
\]

Here the absorption and emission cross sections for the pump and seed beams, along with the intensities of each beam have been used in place of the rates and probabilities which described the general amplifier. These equations are totally analogous with the previous rate equations, and have simply been tailored to the measurable quantities in a fiber amplifier system [8]. The steady state solution to these equations can now be obtained, and the gain (2.17) calculated.

\[
\gamma(r,z,\nu) = \frac{\sigma_s^*I_p^*(r,z) - 1}{1 + I_s^*(r,z) + I_p^*(r,z)}N_i \tag{2.20}
\]

Here the new variables are defined for notational convenience and have the following values.
\[ \sigma_s^* = \frac{\sigma_{sa}}{\sigma_{sa}} \]  \hspace{1cm} (2.21)

\[ I_p^* = \frac{I_p \sigma_{pa} t_{sp}}{h \nu_p} \]  \hspace{1cm} (2.22)

\[ I_s^* = \frac{I_s (\sigma_{sa} + \sigma_{se}) t_{sp}}{h \nu_s} \]  \hspace{1cm} (2.23)

The total number of atoms is \( N_1 \approx N_1 + N_2 \) since the decay of level three is so fast that population cannot build up there.

Dependence on \( r \) and \( z \)

As is apparent from equation (2.20), the gain coefficient is dependent not only on \( \nu \), but also on \( z \) and \( r \). This stems from the fact that the intensities of the seed and pump beams \( I_s \) and \( I_p \) are dependent on these quantities. The modes of the seed and pump beam do not evenly overlap the dopants in a cross-section of the fiber. They follow some distribution, so the intensity depends on the radial location within the fiber. This dependence is usually integrated out and can be lumped into a quantity know as the filling factor, given by \( \Gamma_s \) and \( \Gamma_p \) for the seed and pump respectively [9]. The \( z \) dependence is an obvious consequence of the absorption and emission processes constantly at work inside the fiber. The pump is generally absorbed along the length of the fiber, while the seed power can grow or shrink depending on the gain. This leads to some optimum length for any fiber amplifier, although calculating this length generally has to be done numerically. The differential equation for the length dependence of the seed or spontaneous emission wavelengths is then
\[
\pm \frac{dP^\pm(z, t, \lambda)}{dz} = \Gamma_s \left[ \sigma_{se}(\lambda) N_2(z, t) - \sigma_{sa}(\lambda) N_1 \right] P^\pm(z, t, \lambda) + \Gamma_s \sigma_{se}(\lambda) N_2(z, t) P_0(\lambda)
\]

(2.24)

and the differential equation for the length dependence of the pump is

\[
\pm \frac{dP_p^\pm(z, t, \lambda)}{dz} = -\Gamma_p \sigma_{pa}(\lambda_p) N_1(z, t) P_p^\pm(z, t) + \Gamma_p \sigma_{pe}(\lambda_p) N_2(z, t) P_0(\lambda_p)
\]

(2.25)

Where \( P \) and \( P_p \) are the powers of the seed (or spontaneous emission) and pump lasers, respectively [7, 9]. In addition, \( \lambda \) is now the wavelength of the lasers in question and \( P_0 \) is a constant associated with the spontaneous emission,

\[
P_0(\lambda) = \frac{2he^2}{\lambda^3}
\]

(2.26)

The plus and minus superscripts on the power terms represent a forward (+) and backward (-) propagating beam.

Amplified Spontaneous Emission

In the preceding analysis, spontaneous emission terms were taken into account only as a means to deplete the upper laser level. However, when pump powers become high, the spontaneous emission itself can promote stimulated emission, and become amplified. This is known as amplified spontaneous emission or ASE. ASE can be a severe hindrance to amplifier performance and can limit the gain of the seed. If the fiber length becomes too long and the seed becomes depleted, ASE can make up the majority of the output signal. In this way ASE must be lumped in with the seed
wavelength when calculating the population of the lasers levels, resulting in terms in the differential equation which must be integrated over all wavelengths [7, 9]. The differential equation becomes,

$$\frac{\partial N_2(z,t)}{\partial t} = \left( \frac{\Delta E \sigma_p \nu \gamma_{se}}{h \varepsilon} \right) P_p(z,t) N_1(z,t) - \frac{N_2(z,t)}{\tau_p}$$

$$= \left( \frac{\nu}{h \varepsilon} \right) N_2(z,t) \int \sigma_{se}(\lambda) \left[ P^+(z,t,\lambda) + P^-(z,t,\lambda) \right] \lambda \, d\lambda$$

$$+ \left( \frac{\nu}{h \varepsilon} \right) N_1(z,t) \int \sigma_{so}(\lambda) \left[ P^+(z,t,\lambda) + P^-(z,t,\lambda) \right] \lambda \, d\lambda$$

(2.27)

where the first two terms are very familiar. The first term is simply the population increase in the lasing level due to the pump, and the second term is a decrease in population of level two due to spontaneous emission. Now the absorption and stimulated emission terms discussed previously have been generalized to include all wavelengths of the ASE band and seed beam.

**Two-Stage Configuration**

To combat the problem of ASE a typical solution is to separate the long fiber amplifier into stages. Because ASE is spontaneous emission that is amplified as it propagates down the fiber, high seed powers and short fiber lengths are the most effective ways to curb ASE. The first stage of the amplifier is made short, amplifying the signal and producing some ASE. A narrow bandpass filter is then used to remove most of the ASE, leaving a cleanly amplified signal which is input into the second stage. This stage can now be longer without fear of ASE because the input seed is strong enough to deplete the pump leaving very little gain to go into ASE. After the overall process is completed, more seed power with less ASE is generated from a given length of fiber in two stages than would have been possible from the same length of fiber in one stage.
Spectrum of Ytterbium

The absorption and emission cross sections which determine the behavior of a fiber amplifier vary according to wavelength and dopant used. Therefore, a dopant must be chosen which can readily amplify the desired seed laser. For a fiber amplifier system at 1014.8nm, ytterbium dopant was selected [2]. Ytterbium has an absorption and emission spectrum which varies with wavelength according to figure (4). As is

![Graph of absorption and emission cross-sections](image)

Fig. 4. Spectrum of Ytterbium. The dotted curve represents the absorption spectrum and the solid curve the emission spectrum.
apparent from the figure, ytterbium has an emission and absorption peak at 980nm. This corresponds to transitions from level (a) to level (e) in figure (2). There are also secondary peaks in emission at 1030nm and in absorption at 910nm. The emission peak at 1030nm represents transition from level (e) back down to levels (b), (c), and (d), while the absorption peak at 910nm includes transitions from level (a) to (f) and (g) [5]. Since ytterbium absorbs heavily at 980nm, this was chosen for the pump wavelength. There is also sufficient emission cross section at the seed wavelength, 1014.8nm to promote gain. However, ytterbium also exhibits nontrivial absorption at 1014.8nm, caused by population in level (b) undergoing transitions [10]. This complicates the amplification process significantly. As the seed is absorbed, there is less power available to promote stimulated emission, and the gain suffers. Instead, the spontaneous emission becomes excessively amplified, and the fiber amplifier can be overtaken by noise. To reduce absorption at 1014.8nm, the fiber was cooled to liquid nitrogen temperatures, allowing sufficient stimulated emission to produce amplification. Of course, absorption can never be fully eliminated, and can still play a crucial role in limiting the efficiency of a fiber amplifier.

Cooling the Fiber

The problem of absorption is critical to the fiber amplifier at 1014.8nm. If not controlled, there is virtually no hope of achieving the gain necessary for the subsequent doubling and quadrupling to 253.7nm. In order to improve transparency to 1014.8nm radiation, the fiber was cooled to liquid nitrogen temperatures. This depletes the population in level (b) according to the Boltzmann distribution leaving less atoms to absorb the seed [5]. This process is very stressful on the fiber itself, and can destroy ordinary double-clad fibers in which the outer-cladding is a polymer. A special all
silica fiber has been obtained which can survive the cooling process. Once cooled, the levels of ytterbium which facilitate absorption are decreased in population exponentially. With less absorbers at 1014.8nm enough energy is now available to promote significant stimulated emission, and more gain can be achieved.

Second Harmonic Generation

Once the final output of the two stage fiber amplifier is complete, the beam must be doubled in frequency twice to achieve the desired 253.7nm radiation. Generating a doubled frequency or second harmonic takes advantage of second order non-linear terms in the polarization of various materials,

\[ P = \epsilon_0 E[\chi^{(1)} + \chi^{(2)}E + \chi^{(3)}E^2 \ldots] \]  

(2.28)

where \(E\) is the electric field, \(\chi\) is the susceptibility and \(\epsilon_0\) is the permittivity of free space. The second order non-linear susceptibility is a tensor which depends on the symmetry of the crystal medium used for doubling [11]. With the appropriate symmetries and transformations, the susceptibility tensor takes the form of a nonlinear coefficient, \(d_{\text{eff}}\) [12]. Also, the vector electric field is broken down into its components and is Fourier transformed, yielding, for the case of second harmonic generation in a lossless medium,

\[ P(2\omega) = \epsilon_0 d_{\text{eff}} E(\omega) E(\omega) \exp[i(\Delta k) \cdot r] \]  

(2.29)

\[ P(\omega) = 2\epsilon_0 d_{\text{eff}} E(2\omega) E^*(\omega) \exp[i(-\Delta k) \cdot r] \]  

(2.30)
Where $\Delta k = k_{2\omega} - 2k_\omega$ is the phase difference for second harmonic generation. When the field is propagating in the $z$ direction the differential equations for the electric fields of the fundamental an harmonic beam reduce to,

$$\frac{dE(\omega)}{dz} = i\omega \sqrt{\frac{\mu}{\epsilon}} \text{d}_{\text{eff}} E(2\omega) E(\omega) \exp[i\Delta k z] \quad (2.31)$$

$$\frac{dE(2\omega)}{dz} = i\omega \sqrt{\frac{\mu}{\epsilon}} \text{d}_{\text{eff}} E(\omega) E(\omega) \exp[-i\Delta k z] \quad (2.32)$$

Solving for the electric field of the second harmonic with the condition that the fundamental wave is constant throughout the medium, and then squaring to get the intensity, $I(2\omega)$ gives

$$I(2\omega) = \frac{\mu}{\epsilon} \omega^2 P^2 \text{d}_{\text{eff}}^2 I(\omega)^2 \frac{\sin^2(\Delta kl/2)}{\Delta kl/2} \quad (2.33)$$

Clearly, the total power of the second harmonic depends on the intensity of the fundamental beam and on the length of the interaction region, but perhaps the most crucial factor is $\sin^2(x)/x^2$ term [1, 11, 12]. This term represents the phase-matching of the fundamental and harmonic beams. From a photon perspective, second harmonic generation can be viewed as a combination of two fundamental photons to create one harmonic photon with twice the energy. Energy is conserved in this way. Momentum must also be conserved, meaning that the phase of the two incoming photons must be equal to the phase of the generated photon. With perfect phase-matching, $\Delta k = 0$ and the $\sin^2(x)/x^2$ term is maximized, leading to high powers in the harmonic. This corresponds to the condition that $2k_\omega = k_{2\omega}$. Because the index of refraction of a
material can be expressed as \( n = ck/\omega \) this phase-matching condition reduces to the condition that

\[
n_\omega = n_{2\omega}
\]  \hspace{1cm} (2.34)

Phase-Matching

Fortunately all materials possess a frequency dependent index of refraction, but fulfilling the above condition is difficult if not impossible. If the phase is mismatched, as the fundamental and harmonic wave propagate down the crystal, interference will take place. Energy will be shifted back and forth between the fundamental and the harmonic, and the harmonic beam will not be able to grow. Even in a phase mismatched system, a short distance of the crystal can still produce efficient frequency doubling before interference effects become destructive \([1, 11]\). This distance in known as the \textit{coherence length} \((l_c)\). To maintain the phase-matching condition \((2.34)\), and increase the effective coherence length materials with two different indices of refraction, or \textit{birefringent} materials are often employed. Light entering these crystals is separated into polarization components corresponding to ordinary and extraordinary rays \([13]\). The index of refraction of the extraordinary ray is dependent on the angle of incidence with respect to the optical axis. In this way it is possible to adjust the angle of the beam through the crystal so that the extraordinary ray of the harmonic beam has the same index of refraction as the ordinary ray of the fundamental beam.

This method of phase-matching is employed in the second frequency doubling stage of the experiment. The \(\beta\)-barium borate crystal which doubles the 507.4nm radiation to 253.7nm is placed in a build up cavity and situated at such an angle as to insure proper phase-matching.
Quasi-Phase-Matching

![Graph showing intensity of second harmonic versus orientation of crystal with poling period of 2\(\lambda\).]

Fig. 5. Quasi-Phase-Matching. Phase interference and crystal orientation along the crystal. Quasi-Phase-matching (solid curve) provides continued constructive interference, increasing second harmonic power, while no phase matching (dotted curve) does not allow for the second harmonic to grow.

When standard phase-matching is impractical a technique known as *quasi-phase-matching* may be employed. As stated above, after one coherence length in a crystal, the phases of the fundamental and harmonic beams begin to interfere destructively, preventing energy from building up in the harmonic beam [14]. If however, the orientation of the medium itself is reversed after one coherence length, the phases of the beams can be made to converge, thereby interfering constructively again. This is the essence of quasi-phase-matching and the method at work in the first doubling stage of the experiment in which the 1014.8nm radiation is converted to 507.4nm. The crystal used was periodically poled lithium niobate (PPLN). It contains a grating of alternating, oppositely oriented sections. By reversing the orientation in each section
the phases of the fundamental and harmonic beams are pushed back together (fig. 5), greatly increasing the effective coherence length and in turn the frequency doubling efficiency. Since the index of refraction of the crystal is also dependent on temperature, the PPLN is temperature tuned to index match for the desired wavelength. With appropriate temperature setting and stabilization, and with appropriate poling period, PPLN can be used for second harmonic generation at many wavelengths.
CHAPTER III

EXPERIMENTAL SETUP AND PROCEDURE

Double-Clad Fiber

The two stage fiber amplifier at 1014.8nm consists of an all silica, double-clad, ytterbium doped fiber pumped at 980nm. Optical fiber is essentially a glass waveguide. Laser light is introduced at one end of the fiber, and through total internal reflection, can be made to propagate down the length of the fiber. In order to achieve amplification, the fiber must contain dopants that the laser light can excite, causing stimulated emission in the manner described in chapter two. Generally, many modes of the laser can propagate down the fiber, but if the waveguide is made with a small enough diameter, only one mode can be totally internally reflected down the fiber [8]. This is known as a single-mode fiber. The area where the single-mode propagates is known as the core of the fiber. Surrounding the core is a larger area known as the cladding where light does not travel. This area has a lower index of refraction than the core and is designed to keep light in the core by ensuring that light is always reflecting at an angle less than the critical angle. The cladding also provides an optically clean interface to ensure total internal reflection throughout the length of the fiber. Because the diameter of a single mode core is typically on the order of 10\(\mu\)m, it is difficult to couple large amounts of pump radiation into them from relatively large aperture pump lasers. Pump beams of several watts generally have large spot sizes, and fiber coupled pumps are typically on the order of 200\(\mu\)m in diameter. Therefore, in high power applications, double-clad fiber is typically used [3]. Double clad fiber has an extra layer of silica cladding, around the core, designed to transmit pump radiation. This is referred to as the inner-cladding. The inner-cladding is much larger than
the core, on the order of hundreds of microns, and large amounts of pump light can be coupled into it easily. The pump light then repeatedly passes through the core while it travels down the inner-cladding, exciting the dopants almost as efficiently as if it was traveling down the core itself. While the fiber core is generally circular, the inner-cladding usually is not. With the core located in the center of the fiber, a circular inner-cladding would create modes of pump that spiral down the fiber without ever passing through the core. Instead, inner-claddings are shaped in various ways to maximize the amount of pump that passes though the core. The double-clad fiber used here possesses a hexagonally shaped inner-cladding, as indicated in figure (6). In traditional double-clad fiber, pump light is confined to the inner-cladding with another layer called the *outer-cladding*. This layer is made of a polymer material with a low index of refraction, making sure the conditions for total internal reflection are upheld. However, it was discovered experimentally that the polymer used in most double-clad fiber could not withstand the shock of exposure to a liquid nitrogen
bath. The polymer would degenerate after a few treatments and the fiber would no longer support light in the inner-cladding. Because of this deficiency, a new fiber was obtained made entirely of silica. With a glass outer-cladding, the fiber survived the nitrogen baths and experiments at low temperature could proceed.

**Setup of the Fiber Amplifier**

The seed beam is produced by a 60mw external cavity laser source at 1014.8nm, figure (7). This beam is then coupled into a polarization maintaining fiber and output to a fiber bench. Because the ytterbium absorbs heavily at 1014.8nm when the fiber is at room temperature, coupling is difficult. Therefore, an alignment laser beam at 1064nm is also coupled into the polarization maintaining fiber. Ytterbium is relatively transparent to 1064nm, having a much lower absorption cross section at this wavelength. The alignment of the core can easily be accomplished at room temperature at 1064nm even if the pump is not running, whereas the 1014.8nm light in the core cannot reach the end of the fiber for detection at room temperature. When the experiment is ready to operate a simple mirror can be flipped and the 1014.8nm beam will automatically be aligned, since fiber coupling ensures output at a specific location. The fiber bench assembly provides stability and reproducibility to the first stage, and allows for simple insertion of optical components. Part of the assembly is a 2mm focal length micro-lens which collimates the divergent output of the polarization maintaining fiber for coupling into the doped fiber. On the fiber bench, the beam passes through a half-wave retarder plate and then through a Faraday isolator. The Faraday isolator allows only polarization in the horizontal direction to enter, and then rotates the polarization of the output by 45 degrees. In this way a beam passing though the isolator and bouncing back will be rotated through a total angle of 90
degrees. This ensures that backwards traveling beams do not propagate beyond the isolator and damage the sensitive diode laser in the seed laser system. After the isolator, the beam enters the first stage of the amplifier. This stage is approximately 2 meters long and coiled into a pan. Liquid nitrogen can then be poured directly on the fiber, cooling it to 77K. At the input of the first stage is another 2mm focal length micro-lens, which focuses the incident light onto the fiber. With proper alignment, the light can be guided into the single mode core of the fiber. When the beam emerges from the first stage, it passes through a 2mm focal length micro-lens which acts not only to collimate the output of the first stage, but also to focus the pump light from the first 980nm diode into the fiber. The output of the first stage will then pass through a dichroic mirror coated to allow transmission at 1014.8nm while reflecting the 980nm pump beam backward through the double-clad fiber. The 15W pump source is also fiber coupled and affixed to a fiber bench. The pump is collimated with an 11mm focal length micro-lens to allow good coupling into the inner cladding of the doped fiber. After the dichroic mirror the amplified first stage travels through a narrow band filter centered at 1014.8nm to eliminate ASE and through another half-wave plate, isolator combination before being coupled into the second stage of the fiber amplifier via a 2mm focal length micro-lens. This fiber is longer, about 3.5m, and also cooled to liquid nitrogen temperatures. The output of this stage passes through a dichroic mirror which serves to reflect the second stage pump produced by another fiber coupled, 15W source and 11mm focal length collimating lens.
Fig. 7. Experimental Setup.
Seed: External cavity diode laser at 1014.8nm, 60mW
M2: "Flipper" mirror
Alignment laser: Diode laser at 1064nm, 1mw
I2, I3, I4, I6: Micro-lens 2mm focal length
Pump 1,2: Fiber pigtailed pump at 980nm 15W
I4, I7: Micro-lens 5mm focal length
PPLN: Periodically Poled Lithium Niobate crystal at 150°C
I5, I8: Micro-lens 11mm focal length
BBO cavity: WAVETRAIN\textsuperscript{TM} model resonator cavity
FI: Faraday isolator
Patch fiber: Polarization maintaining single mode fiber
\(\lambda/2\): Half-wave retarder plate
Stage 1: Preamplifier, double-clad Yb fiber 1.8m
BPF: Band Pass Filter at 1014.8nm bandwidth 2nm
Stage 2: Amplifier, double-clad Yb fiber 4.8m
HPF: High pass filter cutoff at 800nm
D1, D2: Dichroic mirrors reflect 980nm transmit 1015nm
M2, M3, M4: Bending mirrors
L1: Focusing lens, focal length 15cm
L9: Mode Matching lens, focal length

Elements in Experimental Setup
Quadrupling

The output of the fiber amplifier at 1014.8nm must be doubled to produce 507.4nm light. This was accomplished using a PPLN crystal. A diagram of the heating box and crystal configuration is given in figure (8). Because of the polarization dependence of the PPLN, the amplifier output first passes through another half-wave retarder plate. Then the beam passes through a lens to ensure sufficient mode matching within the crystal. The PPLN has an index of refraction which is temperature tuned. To most efficiently frequency double the 1014.8nm, the PPLN must be maintained at 150°C. This is done by a heating box and temperature controller unit. The PPLN itself is 5cm long with a period of 5.66μm. This corresponds to a coherence length of 2.83μm. The enlarged portion of figure (8) shows the grated structure of PPLN, with each coherence length corresponding to an opposite orientation of the crystal structure. The beam passes through the PPLN, leaving an output which contains both 1014.8nm radiation as well as 507.4nm radiation. Before being doubled again, the 1014.8nm light is eliminated using an optical filter, allowing the 507.8nm to proceed into the BBO cavity [15] for doubling to 253.7nm. An overview of the BBO cavity is illustrated in figure (9).
Fig. 8. PPLN Crystal Setup
Fig. 9. WAVETRAIN\textsuperscript{TM} Buildup Cavity.

PM: Phase Modulator  L1, L2: Mode matching lenses
M3, M4, M5, M6: Bending mirrors  FC: Fiber connector
BS: Beam Shifter  BW: Brewster window
BT: Beam Shaper  M1: Cavity Input Mirror
M2: Cavity Output mirror  BBO: Doubling crystal
P: Prism  PZT: Piezoelectric transducer
FD: Fundamental detector  HD: Harmonic detector
CHAPTER IV

DATA

Fiber Data

As previously stated the fiber used in the construction of the fiber amplifier is a special all silica double-clad fiber. The fiber has the following specifications, and a cross section is shown in figure (10):

- Core diameter: 6.6 μm
- Inner-cladding diameter: 225 μm
- Outer-cladding diameter: 250 μm
- Coating diameter: 386 μm
- Core numerical aperture: .12
- Inner-cladding numerical aperture: .248
- Composition of outer-cladding: Fluorine doped silica
- Peak absorption at 976 nm: .9 dB/m

Coupling

All interfaces between fiber and laser radiation are subject to coupling losses. Coupling from the initial 60mW seed source to the patch fiber was approximately 30%. The optical components such as the retarder plates and Faraday isolator had little effect on the beam, offering approximately 90% transmission. The net power incident on the first stage of the fiber was approximately 18mW. To compute the coupling into the first stage, it was necessary to use the alignment laser at 1064nm. At room temperature, the 1014.8nm radiation is completely absorbed, leaving no way to measure output. Since the 1064nm radiation transmits with very little absorption and is coincident with the 1014.8nm, it was used for the calculation of coupling. Coupling
into the first and second stage cores was then found to be approximately 30%.

**Absorption**

Because the fiber absorbs the pump wavelength, the loss from absorption must be taken into account to calculate the coupling from the pump. Similarly, since the coupling is known for the seed, the absorption of the seed at low temperature can also be determined. From the above fiber data, the absorption at the pump wavelength is approximately .9db/m, and using the relation,

\[ 10 \log \frac{I_{\text{out}}}{I_{\text{in}}} = G(\text{dB}) \]  

(4.1)
Fig. 11. Temperature Dependence. Plot of seed transmittance as temperature is increased. At room temperature, there is no transmittance through the core.

the pump coupling can be determined. With 10mW of incident pump light, a calculated value of 6.8mW of is expected with 100% coupling through a fiber of 1.8m. The measured value of output was approximately 5mW. This leads to a first stage pump coupling of approximately 70%. Such high values are expected for double-clad fibers due to their large area and numerical apertures. Using a similar technique for the second stage, a value of 70% was again calculated for the second stage pump coupling. As for the seed, values cannot be obtained experimentally unless the fiber is cooled. The data for transmittance with temperature is given in figure (11).
Knowing the initial value of 18mW, and that the coupling of the seed is 30%, an assessment of the core absorption at low temperatures can be calculated. At low temperatures, enough 1014.8nm radiation is transmitted to be measured experimentally. A value of 1.8mW of core radiation is measured, where the value after 30% coupling should have been 5.4mW. This means that 3.6mW of seed, or 67% is still absorbed even at liquid nitrogen temperatures. This may have negative affects on the overall fiber amplifier performance.

**Amplifier Performance**

The spectrum of the output is shown in figure (12). The output of the first stage of the amplifier (fig. 13) as well as the overall output (fig. 14) is plotted as a function of pump power input. Two different lengths of fiber where used for each stage to illustrate the dependence on fiber length. In both cases, points were plotted only up to maximum seed output. Any further pump increases only serve to increase ASE and lower the overall output of the seed. In this way it is apparent from the data that the system is operating in a strong ASE regime, where longer fiber lengths actually show worse performance than shorter lengths due to less competition from ASE.
Fig. 12. Single Scope Trace. Peaks obtained in a Fabry-Perot etalon. A linewidth of 7.5MHz was measured
Fig. 13. First Stage Output. Plot of seed power versus pump input for two different lengths of fiber. The 1.8m segment (top) shows better performance than the 1.93m segment (bottom).
Fig. 14. Total Output. Plot of total seed output for both stages versus pump input. Again the shorter segment (top) performs better than the longer segment (bottom) when the system is run at full power.
As is apparent from the figures, the filtered output displays good spectral quality with a linewidth of 7.5MHz. The output of the first stage is approximately 250mW at full pump power, while the total output is 800mW for the whole system. With an input of approximately 5.4mW, using equation (4.1) the gain is 16.7dB for the first stage, and 21.7dB overall. However the efficiency of the amplifier is still rather low. This 800mW of output was aligned with the PPLN crystal and produced only 2mW of frequency doubled output. This is far below expectations. The PPLN should be one to five percent efficient per watt of input and with 800mW of fundamental more than 10mW of 507.4nm was expected. With only 2mW of output at 507.4nm, the threshold of the WAVETRAIN cavity, which is approximately 10mW, cannot be reached. Data was not obtained for the final doubling stage due to this lack of intensity in the second harmonic.
CHAPTER V

SUMMARY AND CONCLUSIONS
A fiber amplifier was constructed at 1014.8nm. A two stage configuration with double-clad ytterbium fiber was implemented in hopes of producing as much 1014.8nm radiation as possible. To counteract absorption and in turn improve amplification, the fiber was cooled to liquid nitrogen temperatures. With enough radiation at 1014.8nm, frequency quadrupling of the signal was expected to occur and a 253.7nm beam could be produced to examine the structure of mercury atoms. Despite these efforts and expectations, the efficiency of the system was not as high as expected. Also the frequency doubling efficiency of the PPLN crystal was well below nominal. Because of these shortcomings, insufficient 507.4nm radiation was produced to frequency double in the WAVETRAIN buildup cavity, and no 253.7nm radiation was observed. Several routes remain for further investigation into the creation of 257.3nm radiation. Perhaps the most readily available future avenue involves investigation of the PPLN crystal itself. Although the 1014.8nm system exhibited low output power, the 800mW it produced should have been enough to warrant tens of milliwatts of 507.4nm. The fact that only 2mW was observed leaves the PPLN suspect. If the PPLN can be brought up to factory specified operation, with a doubling efficiency of 5% per watt, the threshold for operation of the BBO cavity can be reached, and 253.7nm radiation can be observed. More complicated issues arise when attempting to improve on the fiber amplifier itself. Because liquid nitrogen cooling was implemented, only one fiber was commercially available at the time of the project which could survive the temperature exposure. The fiber used had relatively low absorption at the pump wavelength (.9dB/m) and much of the pump power was left unabsorbed. If a suitable fiber could be found with a higher dopant concentration, more pump could be
absorbed. Of course more of the seed wavelength would also be absorbed, especially if the fiber remained at room temperature during the experiment. Although not discussed here, there is some evidence to suggest that pumping at 980nm may not be the most efficient pump wavelength for high power applications. At the time of the project, a high power diode at 910nm, the other absorption peak of ytterbium, was not available. Perhaps an investigation into pumping at this wavelength could be mounted if resources became available.

With the rise of fiber lasers, very high power single mode systems are being developed at various wavelengths using fused fiber technology and a system of gratings etched into the fiber itself. It is conceivable that the technology may soon be available to create such a system at 1014.8nm. This system might be more efficient than the one described here, even on coupling considerations alone. All in all, there are no fiber systems producing 1014.8nm currently available, let alone systems which can produce the kinds of power necessary for quadrupling. For an initial foray into fiber systems at 1014.8nm, these results can serve as a useful learning tool to guide our future expectations.
REFERENCES


VITA

Frank J. Giuoco was born on April 22, 1978 in McAllen, Texas to Sam E. Giuoco and Kathy Giuoco. He graduated from Sharyland high school in Mission, Texas and received his undergraduate degree in physics from Texas A&M University in College Station, Texas. His permanent address is 2508 Brentwood Dr. Mission, Texas.

The typist for this thesis was Frank Giuoco.