DESIGN AND ANALYSIS OF ULTRASHORT FEMTOSECOND LASER AMPLIFIERS

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Approval of the Graduate School of Natural and Applied Sciences.

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ABSTRACT

DESIGN AND ANALYSIS OF ULTRASHORT FEMTOSECOND LASER AMPLIFIERS

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This thesis presents a compact femtosecond laser amplifier design for optical preamplifiers and power amplifiers consist of theoretical perspective, simulations to analyze and optimize beam performance. The propagation through optical media is simulated for every optical component such as mirrors and nonlinear crystal separately and suggested realignment of these components required increasing amplifier performance. Finally Gaussian beam propagation and aberration compensation has been conducted.

Key Words: Lasers, Ultrashort Lasers,Amplifiers,Zemax

ÖZ

ULTRASHORT FEMTOSECOND LAZERİNİN GÜÇ YÜKSELTİCİLERİNİN TASARIM VE ANALİZLERİ

Doğan, Ersin

Yüksek Lisans, Fizik Bölümü

Tez Yöneticisi: Prof. Dr. Sinan Kadri Bilikmen

Eylül 2006, 73 sayfa

Bu tezde kısa atımlı lazerler için ön ve ana yükselticiler tasarlanmış ve sistem preformansları simulasyonlarla analiz edilmiştir.Işının ilerlemesi her bir optik eleman için ayrı ayrı simule edilerek yükselticilerin performansını artırmak için optik elemanların yerleri yeniden belirlenmiştir. Sonuç kısmında da Gauss moddaki lazer ışınının yükselticiler içerisindeki ilerlemesi listelenmiş ve optik aberasyonlar en aza indirgenmiştir.

Anahtar Kelimeler: Lazerler, Kısa atım lazerler, optik güç yükselticileri, Zemax

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LIST OF ABBREVIATIONS

CPA: Chirped Pulse Amplification

FWHM: Full Width At Half Maximum

TEC: Thermo-Electric Cooler

CHAPTER 1

INTRODUCTION

Ultrashort science is the fast evolving branch of physics promising laser pulses with power outputs in order of Tera (10^{12}) watts and pulse durations of Femto (10^{-15}) seconds. Today, even attosecond (10^{-18}) laser pulses are in progress with peak powers are in order of petawatt (10^{15})[1].

The extremely short pulse duration enables scientists to observe chemical reactions in molecular level while enormous peak powers are used in the experimental studies of thermonuclear fusion reactions and X-ray generation.

The key idea for the ultrashort pulse generation is in fact a result of Heisenberg uncertainty relation developed in 1927 by Werner Heisenberg which concludes that the more the photon uncertain in time domain, the more uncertain is the e nergy [2].

$$\Delta E \Delta t \geq \hbar \qquad (1)$$

A short pulse must have a very broadband spectrum since the forurier transform of the laser pulse in the time domain is to be short.

It was almost impossible to generate laser beams of order of femtoseconds and terawatts until the discovery of CPA(Chirped Pulse Amplification) by Gérard Mourou at the University of Rochester in the mid 1980s, that high power laser pulses can not be amplified up to terawatt levels since the damage threshold of the optical components especially the gain materials is very weak with respect to the required amplification [2]. But with CPA technique terawatt lasers are realized in the research laboratories.The evolution of pulse duration is given with respect to years in figure1.

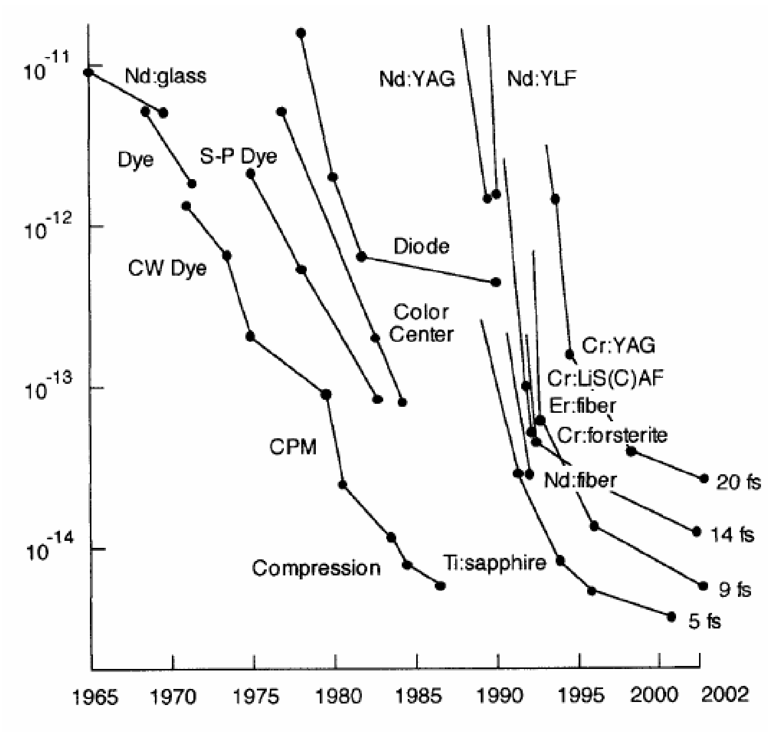


Figure 1:History of Pulse duration evolution

Chirped Pulse Amplification is a method used to amplify high power lasers with stretching the laser pulse before the amplification and compressing it after the amplification temporally and spectrally not to give any damage to gain materials like Ti:sapphire crystal. In CPA, the ultra short pulse is stretched out in time with a pair of diffraction gratings arranged antiparalle to each other in such a way that all frequencies that form the pulse follow different optical paths. Low frequencies travel a short path and high frequencies travel long path as seen in the figure 2.

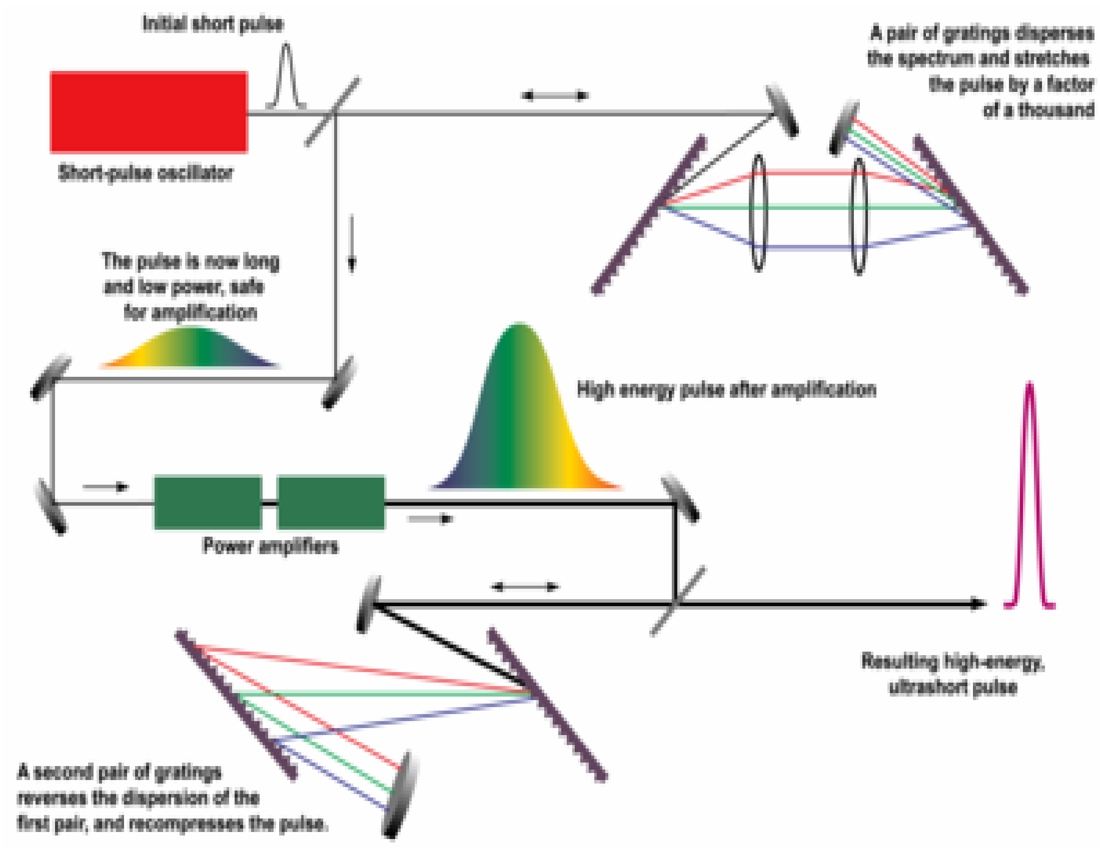


Figure 2:CPA System Overview

The laser beam is so called positively chirped and it has a longer pulse duration compared to the original one by a factor of 10^3 to 10^5 [3].

It not necessary to use diffraction grating, but also a pair of prism can be used to stretch the laser pulses as seen in the figure 3.

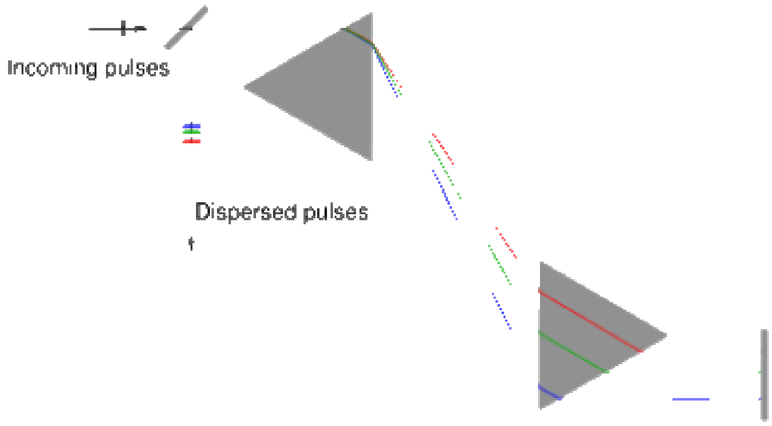


Figure 3:Prism Pair for a stretcher

Since the pulse duration is longer than the seed pulse, it has a lower power enough to amplify the pulse without damaging the optical components. The stretched pulses are sent to a regenerative or multipass preamplifier and amplify up to orders of milijoule level. For the amplified pulses,the same procedure is done at the compressor which consist of two gratings parallel to each other so that frequencies are sent to in different optical paths, lower frequencies follow a longer path to compress the pulse or negatively chirped the pulse, figure 4.

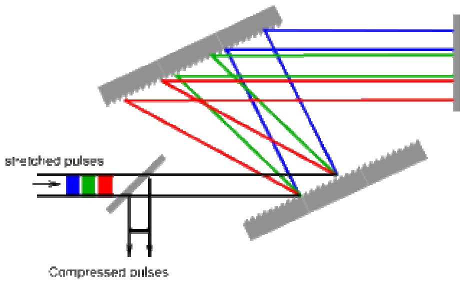


Figure 4:Diffraction Grating as a Compressor

In the design of optical multipass amplifiers, the most critical issue is the optimization of amplifier in such a way that the maximum stimulated emission must be obtained while minimizing the beam distortion due to non-normal incidence on spherical mirrors and nonlinear propagation in gain media. Also alignment of the mirrors to make laser beam propagate in the cavity can be awkward since the cavity dimensions are very large compared with the optical components, the exact number of passes must be satisfied, and the availability of space for the amplifiers are very limited.

This thesis aims to design and analyze ultrashort femtosecond optical preamplifier and power amplifier as well as a pre-work for the construction of ultrashort laser in the laboratory at METU(Middle East Technical University) Physics Department.

In this fast evolving area of physics, optical amplifier designs are different from each other due to boundaries and desired applications. In this design, our main goal is to maximize the gain and to minimize the losses due to the amplified spontaneous emission and pulse distortion and as a result a very compact 4-pass and 8-pass amplifiers are introduced with their detailed analysis. For beam tracing methods simulation programs are used to position the amplifier components and analyses are done for the designed laser cavity.

In Chapter 2, the overview of laser essentials in the literature is presented.

In Chapter 3, the design of 4-pass and 8-pass amplifier is explained with simulations and design of the system is analysed for Gaussian beam propagation.

In Chapter 4, some concluding remarks are stated on the performance of the amplifiers.

CHAPTER 2

OVERVIEW OF LASER ESSENTIALS

2.1 Pulse Characteristics

Most often lasers are formed with a pulse train instead of an isolated pulse as seen

in figure 5

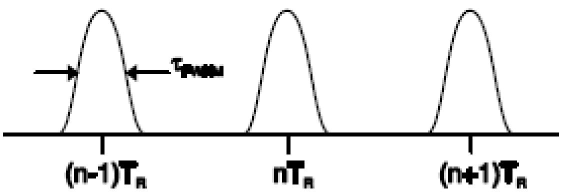


Figure 5:Pulse Train

Here T_R is the repetition rate which tells us how much pulse is generated or observed per second, W is pulse energy, τ_{FWHM} is the Full With at Half Maximum of the intensity envelope of the pulse in the time domain[4].

The peak power is given by

$$P_p = \frac{W}{\tau_{\text{FWHM}}} = P_{ave} \frac{T_R}{\tau_{\text{FWHM}}} \tag{2}$$

2.2 Ray Tracing

Ray tracing is a powerful tool to analyze the beam propagation through the optical media. In this method laser beams are treated as vectors in space with two parameters Figure 6; position and angle with respect to optical axis and every vector is represented with a 2x2 matrix depending on the optical element such as mirrors, thin lenses, etc.

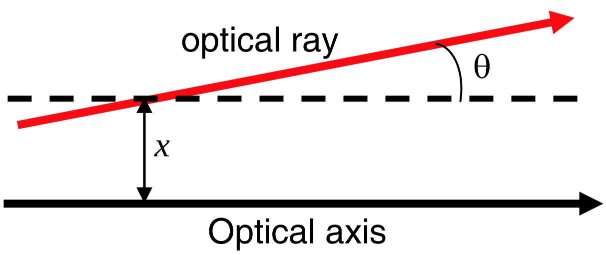


Figure 6:Ray Vector[5].

Every optical system has an optical axis and all light rays are assumed to propagate at small angles with respect to the optical axis providing paraxial ray approximation that assumes sinΘ≈Θ and tanΘ≈ Θ.

A ray does not necessarly propagate in the optical axis so all ray parameters are defined with respect to optical axis,figure 7.

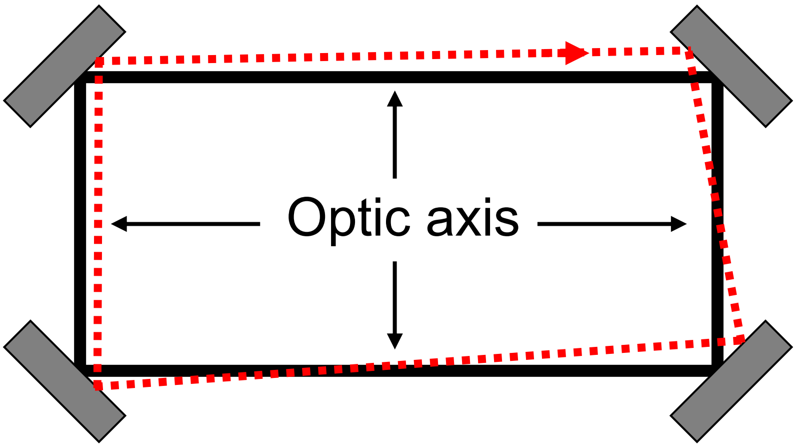


Figure 7:Optic Axis[5].

A ray vector changes its distance and angle parameters as it propagates through the optical medium. Since the amplifiers consist of only mirrors gain media, and propagation in free space,so the reflection from tilted mirrors and propagation in gain media matrices are considered.

In the amplifier system, there are off-axis incidence on the spherical mirrors which causes two different matrix calculations for sagittal and tangential plane,which is shown in figure 8 [6].

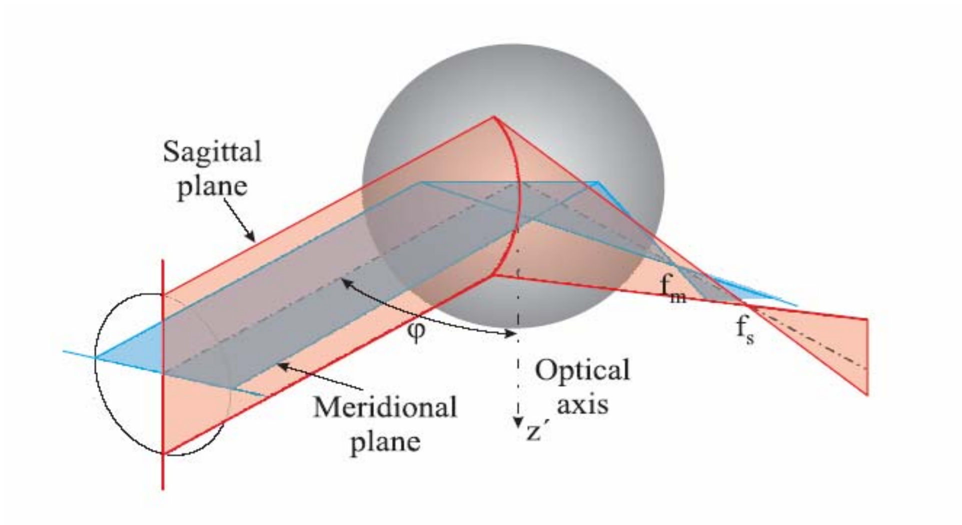


Figure 8:Tangential and meridional planes

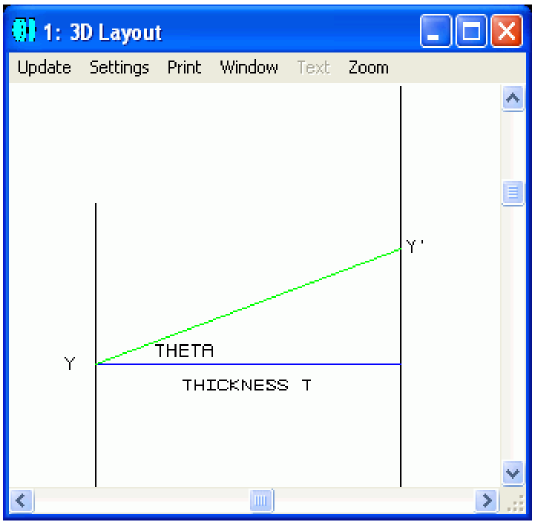
Rays that deviate from optical axis in the plane of incidence are called tangential and rays deviate from optical axis perpendicular to optical axis are called sagittal. Basic matrix elements required for paraxial ray tracing are given in table 1. The L,R,θ,d,n parameters used in the formulation of matrices are distance of the medium,radius of spherical mirrors,angle of incidence,length of the gain medium and index of refraction of the medium.

.

	Tangential Plane	Sagital Plane
Free Space	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
Mirror Off-axis Reflections	$\begin{pmatrix} 1 & 0 \\ \frac{-2}{R\cos\theta} & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ \frac{-2\cos\theta}{R} & 1 \end{pmatrix}$
Brewster-Cut Refraction	$\begin{pmatrix} 1 & \frac{d}{n} \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & \frac{d}{n^3} \\ 0 & 1 \end{pmatrix}$

Table 1:Ray Matrices for amplifier[7].

The simulation program used to calculate the ray tracing and other beam propagation calculations uses direct cosines instead of angles in ray tracing data.



$$y' = y + \tan\theta .\, t$$
$$= y + (m/n).t$$
$$\cong y + \theta .t$$

Instead of Θ, Zemax illustrates matrix output as m and n[8]

Figure 9:Zemax ray matrix output

The program also uses real ray trace called parabasal (real ray approximation patented for Zemax coorparation) which does not assume paraxial ray approximation.

2.3 Gaussian Beam

In the femtosecond laser system, laser beam is a Gaussian type laser pulse and a short review of Gaussian beam is explained.

Gaussian beam represents the irradiance profile via frequency and it has a distribution given in figure 10.

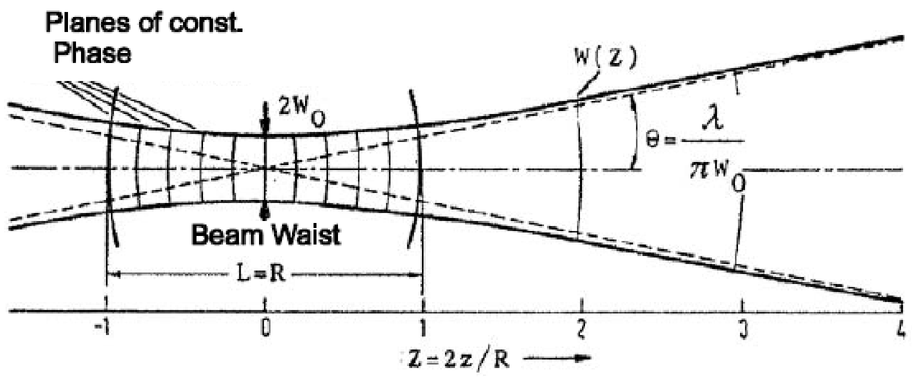


Figure 10:Gaussian Beam

Electric field for a Gaussian beam is represented by the formula

$$\underset{\sim}{E}(x,y,z) \propto \frac{\exp\left[-ikz - i\psi(z)\right]}{w(z)} \exp\left[-\frac{x^2+y^2}{w^2(z)} - i\frac{\pi}{\lambda}\frac{x^2+y^2}{R(z)}\right] \tag{3}$$

In this formula w(z) represents the spot size, R(z) is radius of curvature and ψ(z) is the phase shift. Their formulas are respectively,

$$w(z) = w_0\sqrt{1+\left(z/z_R\right)^2} \approx w_0\sqrt{\left(z/z_R\right)^2} = w_0 z/z_R \tag{4}$$

$$R(z) = z + \frac{(z_R)^2}{z} \tag{5}$$

$$\psi(z) = \arctan(\frac{z}{z_R}) \tag{6}$$

Here, z_R is the distance where the beam spot size does not change, and it is called Rayleigh Range. It has a mathematical representation as

$$z_R = \frac{\pi\omega_0^{\ 2}}{\lambda} \tag{7}$$

Here ω_0 is the beam radius and λ is the wavelength.

The beam 1/e divergence half angle $\theta_{1/e}$ is defined by $\frac{\omega(z)}{z}$ as $z \to \infty$, and describes the beam divergence for the Gaussian beam.

$$\theta_{1/e} = \lambda / (\pi w_0) \tag{8}$$

As seen from the equation (8), the smaller the waist, the larger the divergence angle is.

It is possible to write a Gaussian beam by using a q function defined as

$$\frac{1}{q(z)} \equiv \frac{1}{R(z)} - i\frac{\lambda}{\pi w^2(z)} \tag{9}$$

So the Gaussian beam become,

$$E(x,y,z) \propto \exp\left[-i\frac{\pi}{\lambda}\frac{x^2+y^2}{q(z)}\right] \tag{10}$$

The q parameter is very a useful parameter to calculate the propagation of a Gaussian beam in optical elements, and it is combined with matrix formulation to relate input and output Gaussian beam through the optical components with the formula

$$q_{out} = \frac{Aq_{in} + B}{Cq_{in} + D} \tag{11}$$

Here A, B, C, D are constants of the resultant matrix of the optical element or system, q_{in} is the initial Gaussian beam, q_{out} is the resultant Gaussian beam.

As a summary, after deciding the matrix elements of the optical components, we obtain a system matrix by multiplying the matrices opposite to the propagation direction, and then we use the result matrix to understand the propagation of a Gaussian beam through the optical system [5].

2.4 Gain Medium and Pumping

For the gain medium of multipass amplifier, Ti:sapphire laser crystal is chosen due to its large saturation and wide bandwidths that can support ultrashort pulses. Ti:sapphire crystal lazes over a continuous band from 700nm to 1100nm while supporting short pulses as short as 3fs, figure11.

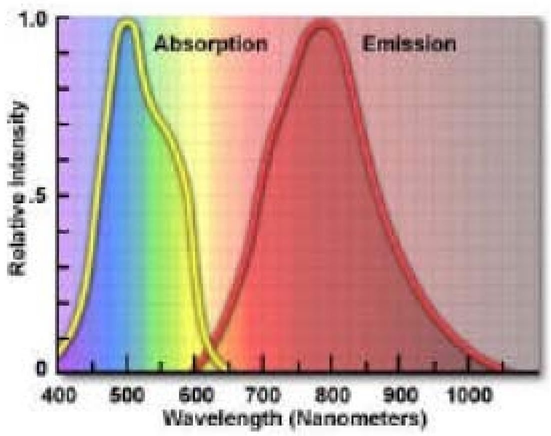


Figure 11:Absorption and Emission spectrum of Ti:sapphire Crystal

In this crystal, Ti^{3+} ions are substituted for an Al^{3+} ion in Al_2O_3, growth by the Czochralski method. The sapphire is doped with 0.1% Ti^{3+} by weight. This crystal has a hexagonal structure and energy gap of 1900 cm^{-1}, as shown in figure 12 [9].

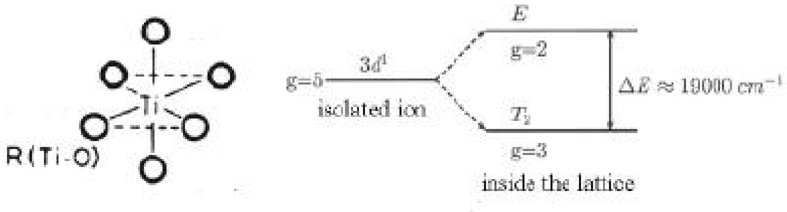


Figure 12:Ti^{3+} ion bounding with Oxygen atoms and energy bands

Active medium physical and laser properties:	
Chemical formula	Ti^{+3}:Al_2O_3
Crystal structure	Hexagonal
Lattice constants	a = 4.748 , c = 12.957
Laser action	4-Level Vibronic
Fluorescence lifetime	3.2_sec (T = 300 K)
Tuning range	660-1050 nm
Absorbtion range	400-600 nm
Emission peak	795 nm
Absorption peak	488 nm
Refractive index	1.76 @800 nm
Laser rod specification:	
Orientation	Optical axis C normal to rod axis
Size	10 mm long
End configurations	Brewster/Brewster ends
Ti_2O_3 concentration	0.25 wt %
Absorption (_ @ 532 nm)	2.5 cm^{-1}

Table 2: Active medium physical and laser properties

Moreover the crystal has a very high damage threshold of 8-10 J/cm^2, table 2. With its high thermal conductivity, Ti:sapphire crystal can be easily cooled with a chiller or a TEC (Thermo Electric Cooler) [9].

CHAPTER 3

Design of Ultra short Multi-pass Amplifiers

In designing of a multipass amplifier for ultrashort lasers, control of beam overlap, mode-matching, feedback and aberration control are important parameters to deal with. In this thesis we have a 5 mirror 8-pass amplifier design, which is pumped with a CFR 400 frequency doubled Nd:Yag laser with a repetition rate of 10Hz. The system has acapability to overcome the second order aberrations and sensitive enough to mode-match pump and input beam. Unlike regenerative amplifiers, the input and output beams are separated from each other. However it is not guaranteed that the beams of different passes will have the same size and position in the gain region. Also the off-axis angle of incidence will decrease the beam quality due to aberrations and prevents good mode-matching in the gain crystal. [4]

In this chapter, we will use a simulation to find the coordinates of the optical amplifier components which ensures exactly 8 pass within the Ti:sapphire gain crystal. Also the simulation helps us analyze the Gaussian beam propagation within the cavity. Without the help of simulation programs it is very difficult to align cavity mirrors since the cavity is so long that even any small changes in the lateral angle results in a large amount of displacement. After we decide the coordinates of cavity components, we will examine Gaussian beam propagation to see what changes affect the quality of the beam. Finally Gaussian beam propagation is introduced and beam parameters are discussed in detail.

3.1 4-Pass Amplifier

For power amplifier we have designed a four pass amplifier with a Brewster cut Ti:sapphire gain medium surrounded by nine 1 inch spherical mirrors. Gain medium has 10mm radius with 6mm length pumped longitudinally with CFR400 double frequency Nd:Yag laser. For the initial condition parameter, the laser beam spot size is taken as 0.5mm TEM_{00} Gaussian beam. A top view of the power amplifier design is given in figure 13.

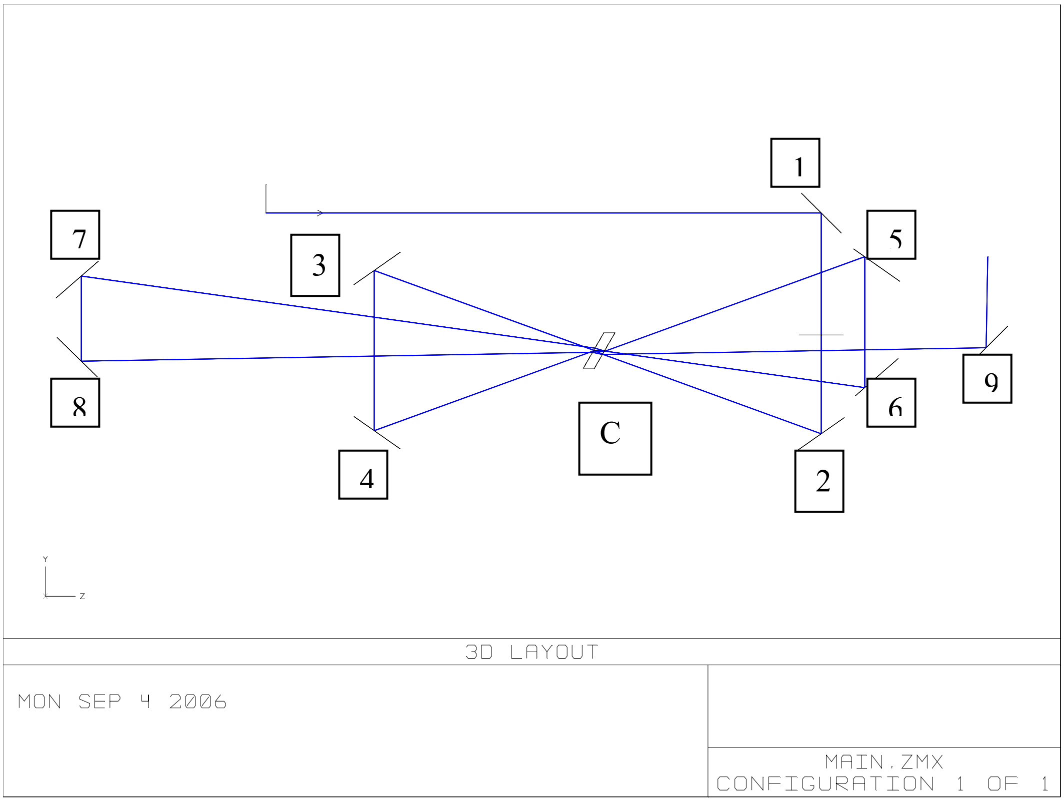


Figure 13:Two dimensional layout of Power Amplifier with its 9 mirrors.

The mirrors are aligned for exactly four passes in the gain medium. After cavity elements coordinates are decided, ray matrices are calculated for ray tracing.

Ray elements are listed in terms of optical path as 1-2 meaning propagation from mirror 1 to mirror 2 and crystal is illustrated as C. The necessary ray matrices are listed in table 3.

Path	Tangential Plane	Sagital Plane
0-1	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
1-2	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
2-3	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
3-C	$\begin{pmatrix} 1 & \frac{d}{n} \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & \frac{d}{n^3} \\ 0 & 1 \end{pmatrix}$
C-4	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
4-5	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
5-C	$\begin{pmatrix} 1 & \frac{d}{n} \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & \frac{d}{n^3} \\ 0 & 1 \end{pmatrix}$
5-6	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
6-C	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$
C-7	$\begin{pmatrix} 1 & \frac{d}{n} \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & \frac{d}{n^3} \\ 0 & 1 \end{pmatrix}$
7-8	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$

8-C	$\begin{pmatrix} 1 & \frac{d}{n} \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & \frac{d}{n^3} \\ 0 & 1 \end{pmatrix}$
C-9	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$

Table 3:Ray Matrices for power amplifier

The results of Gaussian Beam parameters are listed for every optical components in Appendix A

3.2 Analysis of Beam Profile and Gain for each Pass

For initial condition a Gaussian mode with a diameter of 0.5mm laser source is taken. All the beam profiles are arranged in such a way that the results show the spot size of the laser beam 10mm away from the crystal as seen in the figure 14.

After the first pass, figure 14, the spot size of the laser pulse increased up to 0.691mm both in x and y plane perpendicular to the propagation of direction, figure 15.

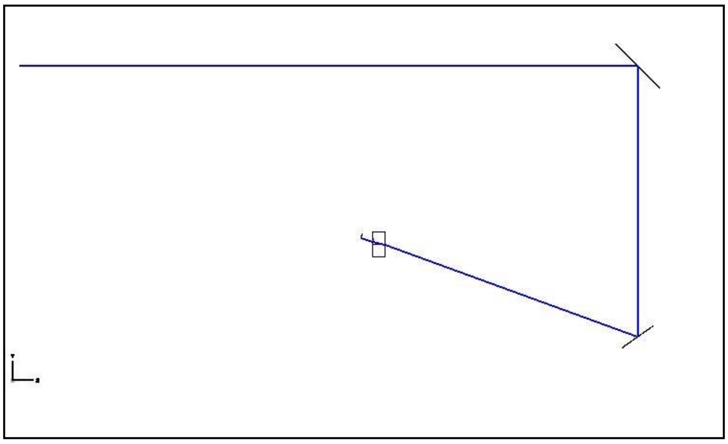


Figure 14:Gaussian Beam 10mm away after the first pass

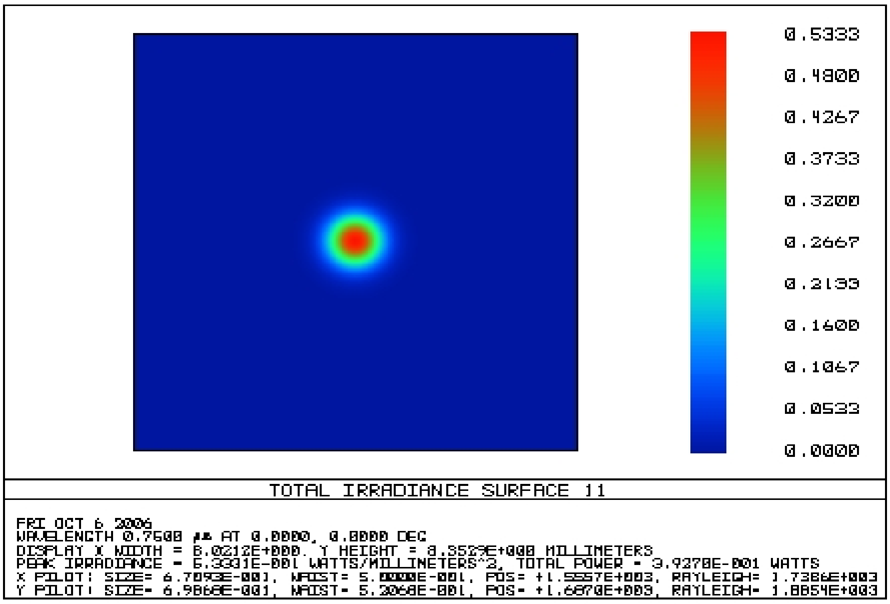


Figure 15:Beam Profile 10mm away from the gain medium

In the second pass, figure 16, the spot size of the laser beam become 0.907mm as shown in the figure 17

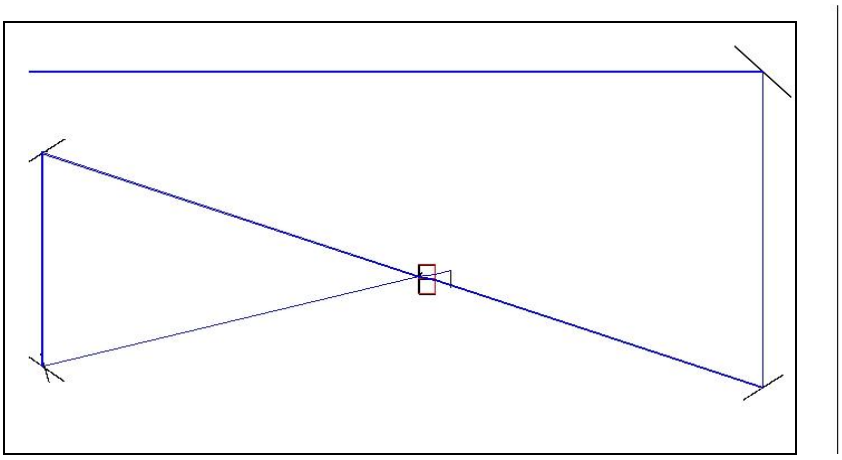


Figure 16:Gaussian Beam Parameters for Second Pass

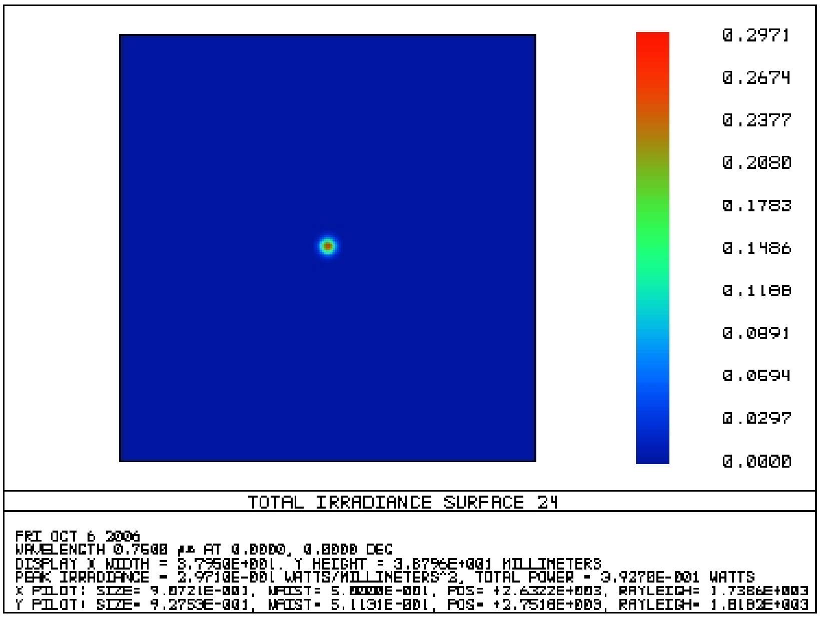


Figure 17:Beam Profile for the second pass

In the third pass, figure 18, the spot size spot size increased up to 1.210mm, figure 19.

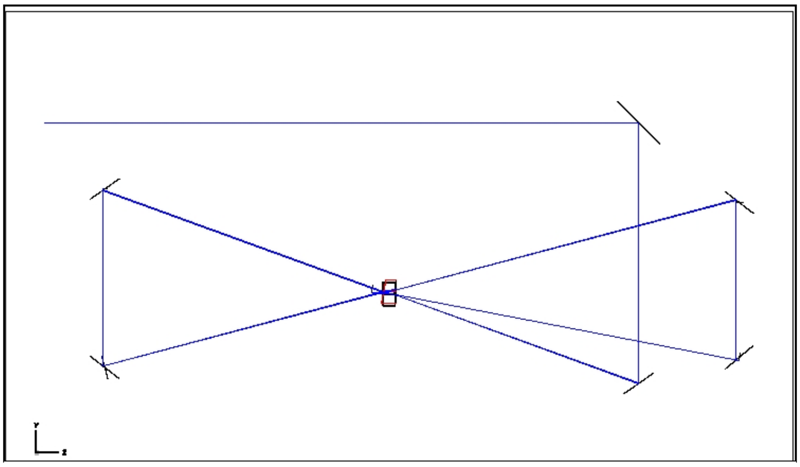


Figure 18:Gaussian Beam 10mm away from the gain medium for the third pass

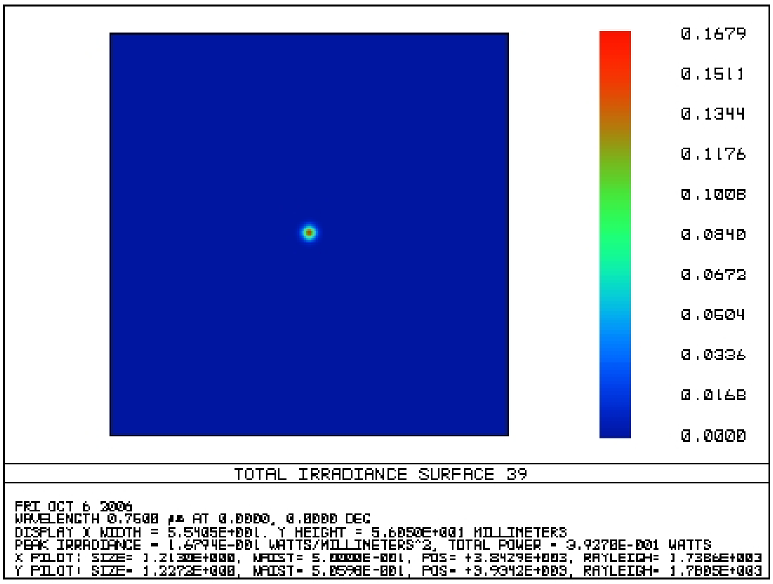


Figure 19:Beam Profile for the third pass

In the last pass, figure 20, the laser beam complete its four passes and finally the spot size become 1.570mm,figure 21.

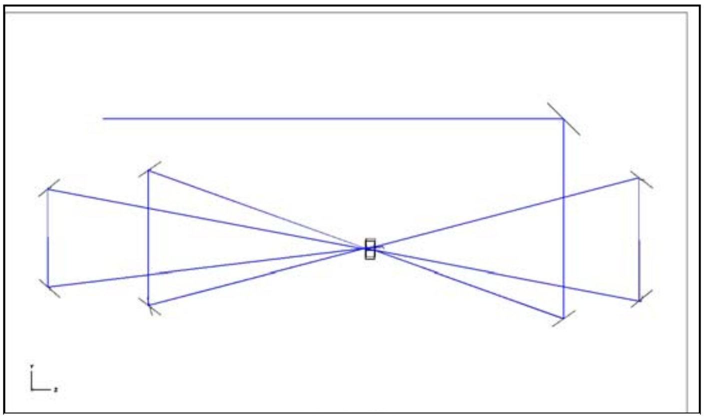


Figure 20:Gaussian Beam 10mm for the fourth pass

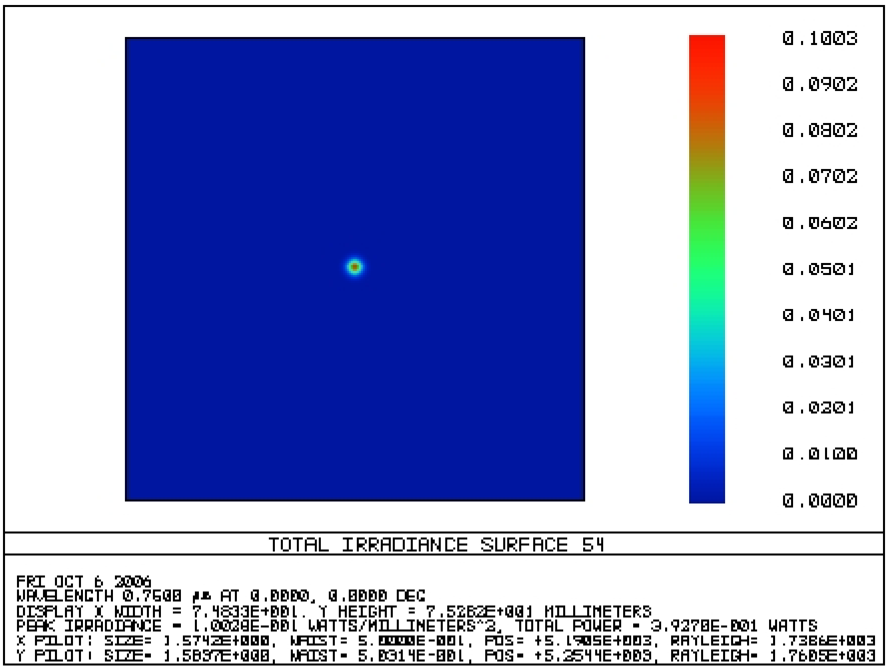


Figure 21:Beam Profile for last pass, fourth pass

The spot size evolution of the laser beam in the 4 pass cavity is given in table 4.

	Number of Passes	Spot Size(mm)	Waist(mm)	Rayleigh(rad)
X-Direction	1	0.671	0.500	$1.726x10^3$
	2	0.907	0.500	$1.738\ x10^3$
	3	1.210	0.500	$1.738\ x10^3$
	4	1.570	0.500	$1.738\ x10^3$
Y-Direction	1	0.671	0.521	$1.885\ x10^3$
	2	0.907	0.511	$1.818\ x10^3$
	3	1.210	0.505	$1.780\ x10^3$
	4	1.570	0.503	$1.760\ x10^3$

Table 4:Spot size Growth for each pass in X and Y directions

3.3 8-Pass Amplifier

The laser cavity is typical 8-pass optical amplifier consist of four 1 inch spherical mirrors with a 3x2 matrix mirror made of 6 one inch spherical mirror as shown in the figure 22. The first four passes are designed for clockwise rotation in the cavity while with the help of retro reflector, the beam propagates backwards counter clockwise to complete a total of eight pass.

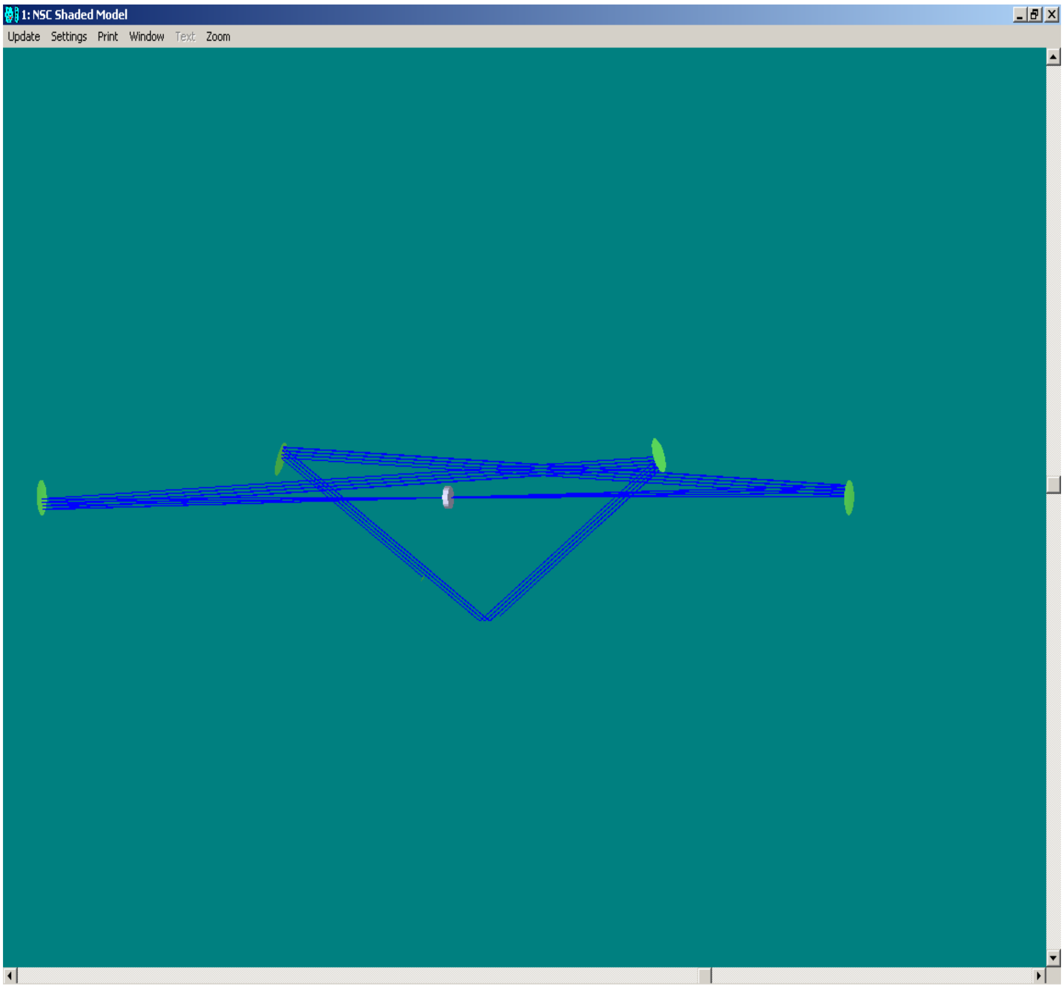


Figure 22:Two dimensional preamplifier layout.

3.4 Analysis of Beam Profile and Gain for each Pass

In the simulation we assumed a TEM_{00} Gaussian beam with diameter 0.5mm is used and beam propagation is analyzed pass by pass for each wavelengths between 532nm to 1000nm. For the gain medium, Ti:sapphire crystal is embedded in the software as a new glass with using clean transmittance and dispersion constant data given in appendix C. Two spherical mirrors are separated from each other with 1500mm centering the gain media. The two upper mirrors with 1 inch in diameter are placed for beam incidence on spherical mirrors with 1.5°, figure 23.

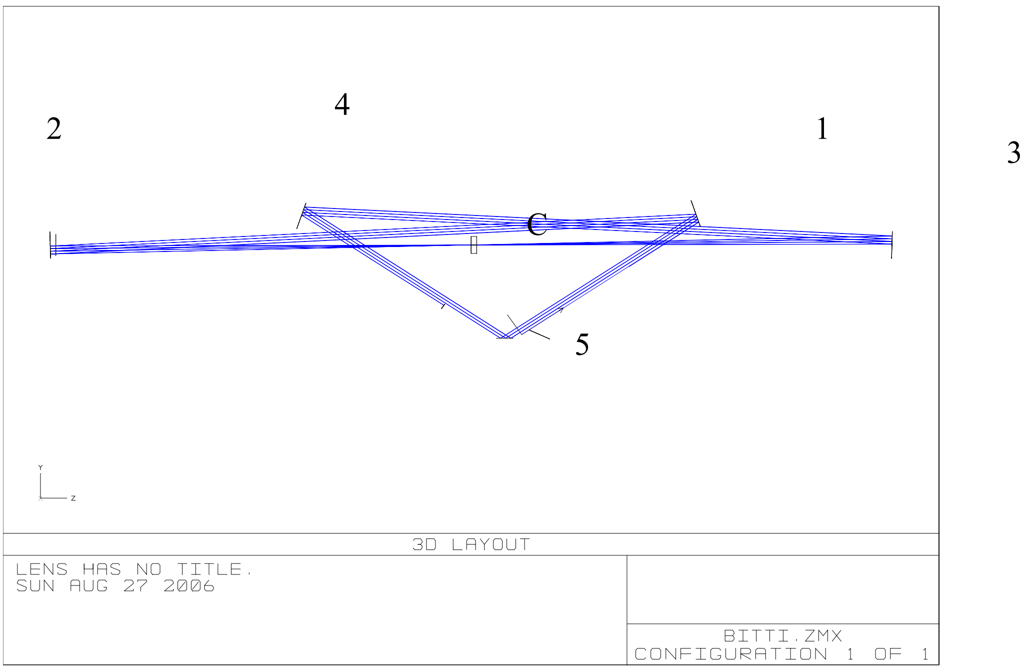


Figure 23:Two Dimensional Image of 8-pass Preamplifier.

To analyse the laser beam propagation in the cavity and beam profile in the laser cavity, a detector is put infront of the mirrors and gain crystal before 10mm with respect to beam propagation direction.

As seen in the figure 24, the beam radius increases pass by pass and spot size diagrams are given in table 5.

	Number of Passes	Spot Size(mm)	Waist(mm)	Rayleigh(rad)
X-Direction	**1**	3.645×10^{-1}	2.876×10^{-1}	3.375×10^{2}
	2	3.544×10^{-1}	1.528×10^{-1}	9.529×10^{1}
	3	3.405×10^{-1}	9.990×10^{-2}	4.072×10^{1}
	4	3.183×10^{-1}	7.435×10^{-2}	2.255×10^{1}
	5	2.946×10^{-1}	5.988×10^{-2}	1.463×10^{1}
	6	2.617×10^{-1}	5.070×10^{-2}	1.048×10^{1}
	7	2.298×10^{-1}	4.461×10^{-2}	8.122
	8	1.887×10^{-1}	4.036×10^{-2}	6.647
Y-Direction	**1**	3.644×10^{-1}	2.875×10^{-1}	3.374×10^{2}
	2	3.540×10^{-1}	1.528×10^{-1}	9.529×10^{1}
	3	3.396×10^{-1}	9.994×10^{-2}	4.075×10^{1}
	4	3.167×10^{-1}	7.443×10^{-2}	2.260×10^{1}
	5	2.922×10^{-1}	6.001×10^{-2}	1.469×10^{1}
	6	2.583×10^{-1}	5.087×10^{-2}	1.055×10^{1}
	7	2.253×10^{-1}	4.483×10^{-2}	8.200
	8	1.831×10^{-1}	4.063×10^{-2}	6.735

Table 5: Gaussian Beam parameters for every pass

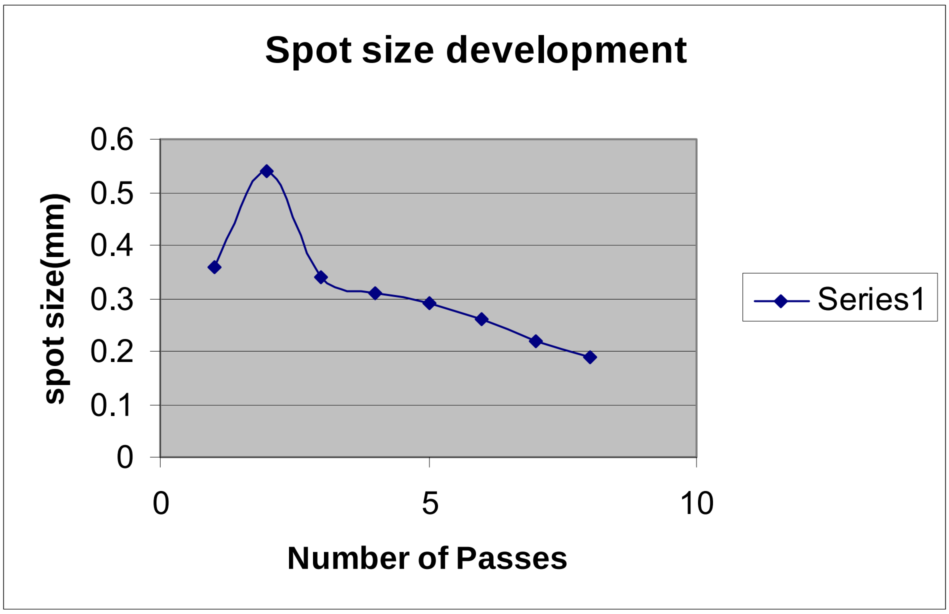


Figure 24:Beam spot size growth

After fourth pass, a retro reflector is used to convert beam propagation in the counterclockwise direction and laser beam completed its roundtrip with a total of 8 passes.

Initially the laser beam spot size was taken 0.5 mm and beam evolution for every pass are illustrated. In figure 25 the first pass results, in figure 26 second pass results, in figure 27 third pass results, in figure 28 fourth pass results, in figure 29 fifth pass results, in figure 30 sixth pass results, in figure 31 seventh pass results and finally in figure 32 eighth pass results are shown.

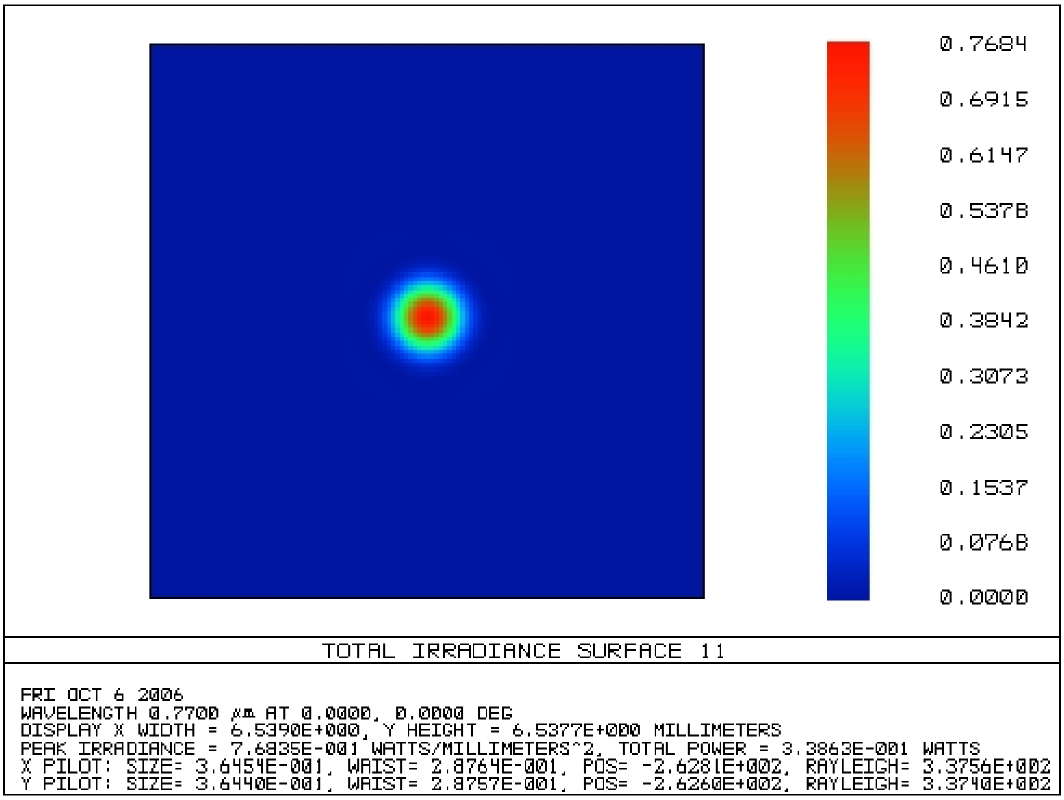


Figure 25:Beam Profile for first pass

As seen from the figure 25,the spot size of the laser beam decrased to 0.365mm after the first pass since the spherical mirrors focused the laser pulse on the gain medium..

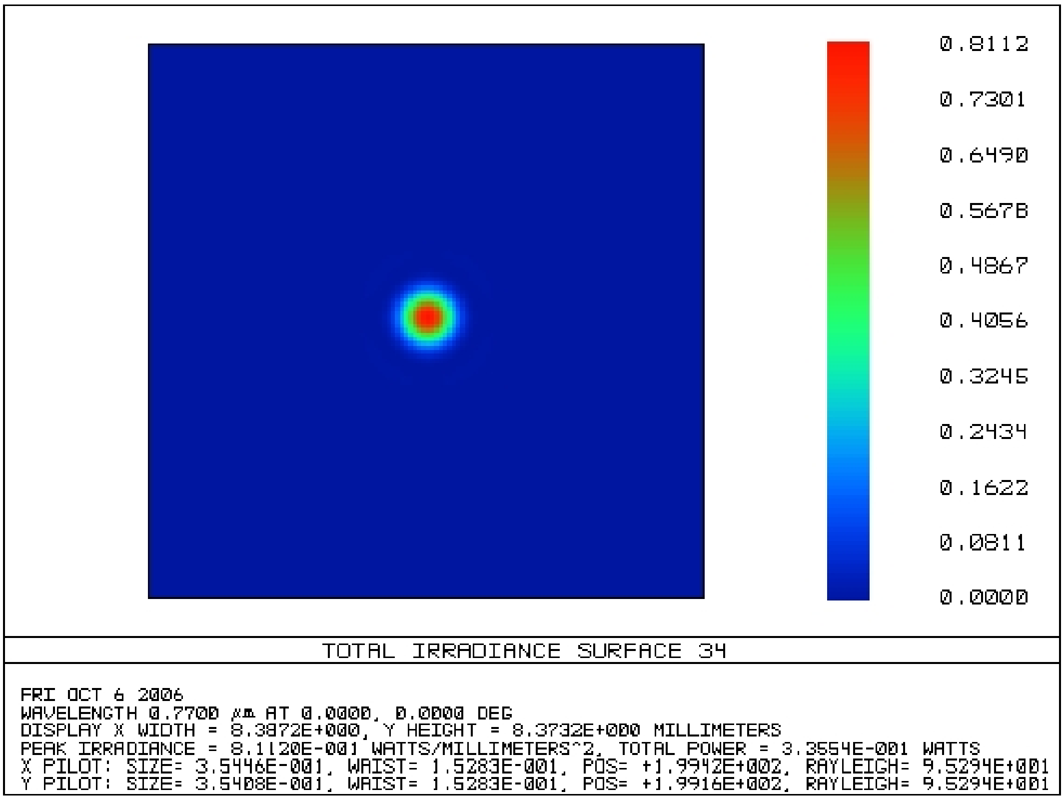


Figure 26:Beam Profile for second pass

The spot is still circular as can be understood from figure 26. The spot size continued to decrease due to beam focusing by the spherical mirrors and become 0.354mm in both directions, figure 26.

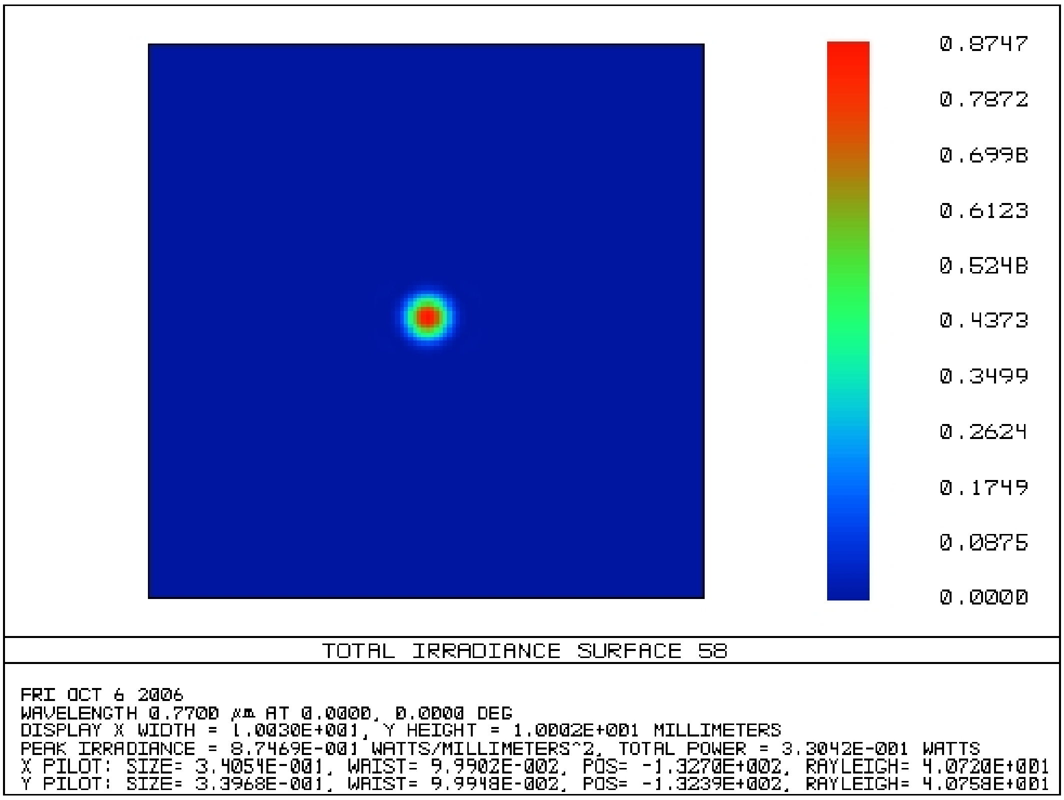


Figure 27:Beam Profile for third pass

After the third pass, spot size decreased to 0.340mm but there is slightly difference between x and y direction spot sizes, figure 27.

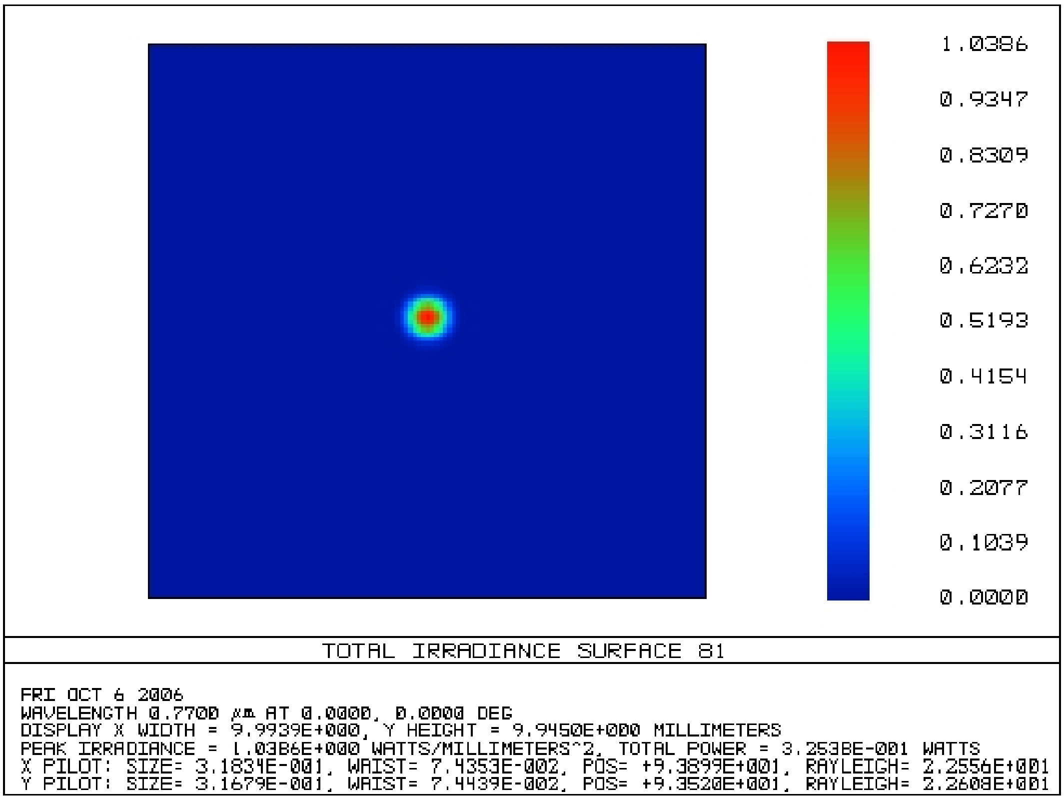


Figure 28:Beam Profile for fourth pass

After fourth pass, the spot size almost maintained its circular shaped and the spot size became 0.318mm.

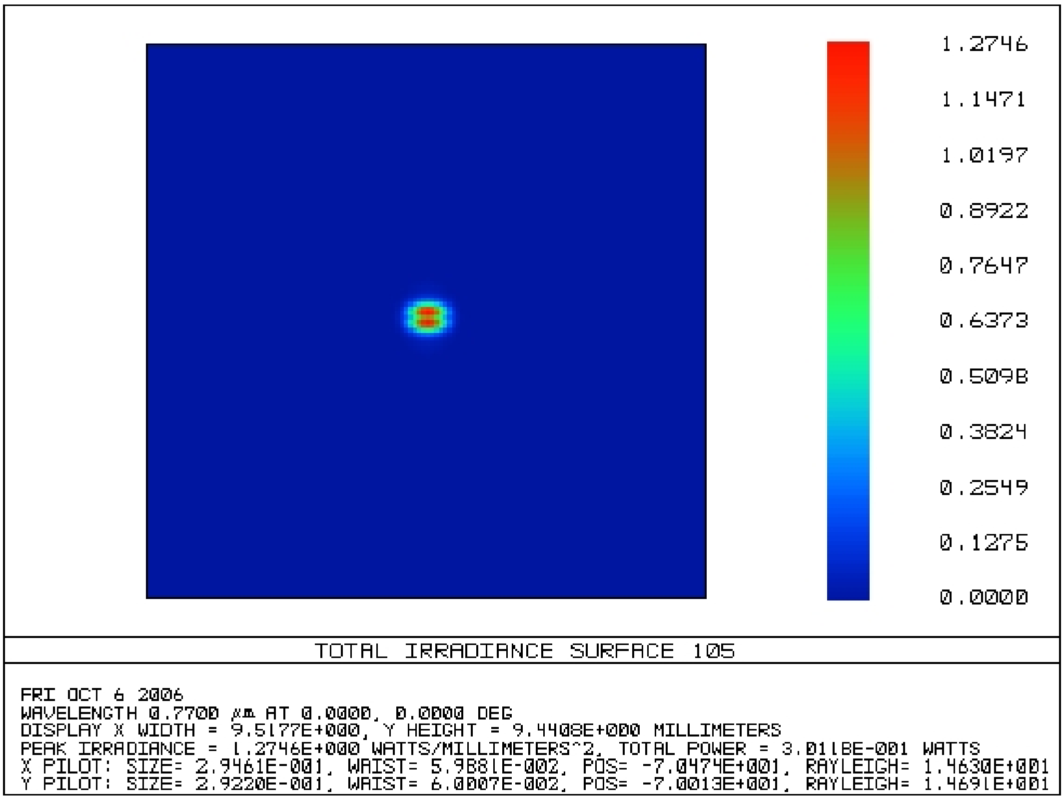


Figure 29:Beam Profile for fifth pass

After fourth pass, the direction of propagation is reversed by the retro-reflector and spot size decreased to 0.294mm in the fifth pass, figure 29.

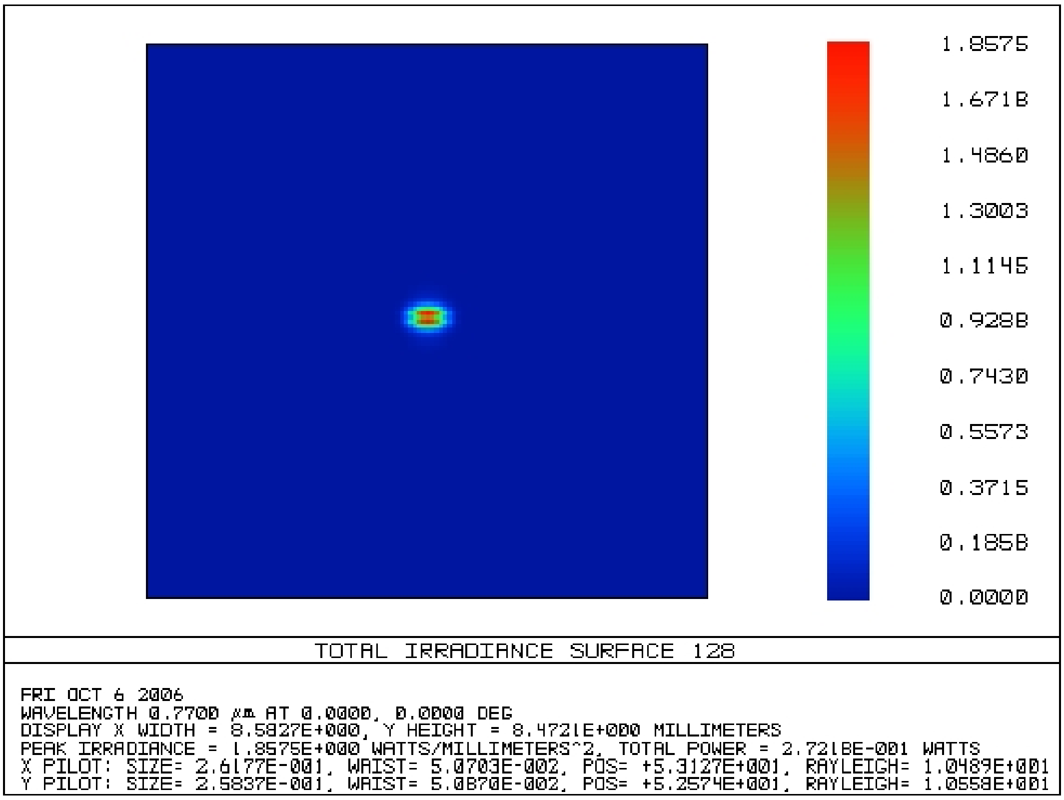


Figure 30:Beam Profile for sixth pass

As seen from the figure 30, after six pass the spot size did not change its shape which means the aberration due to spherical mirrors is compensated. But there is still difference between x and y direction spot sizes.

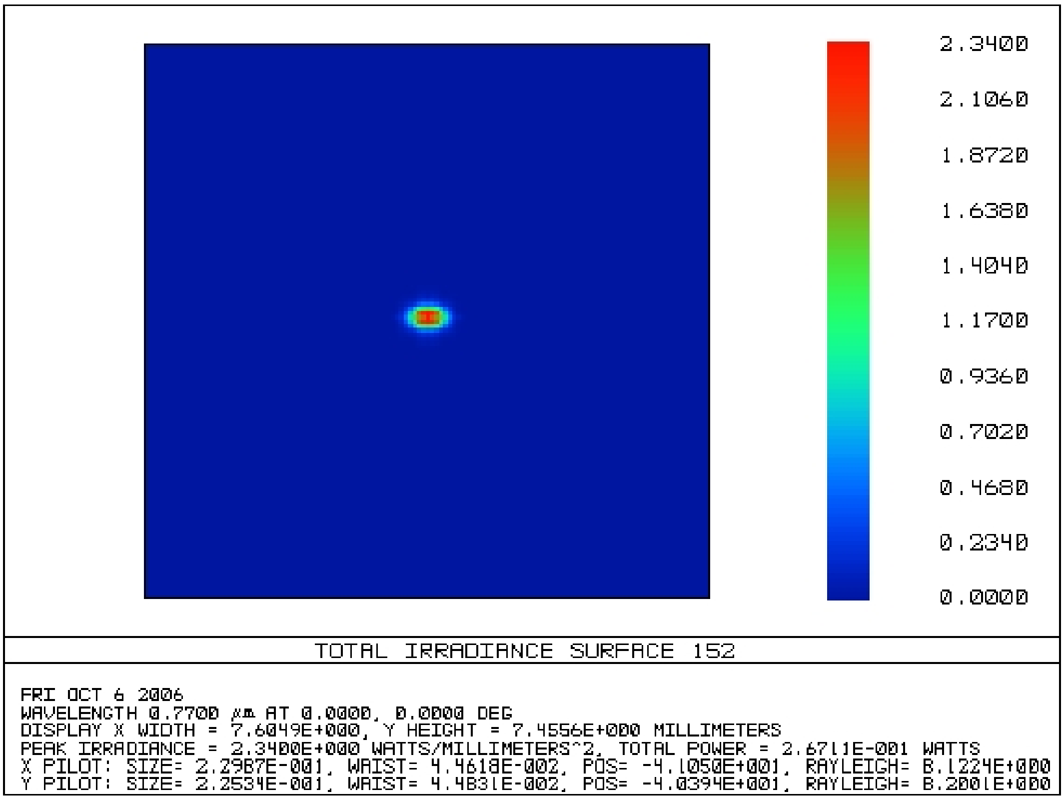


Figure 31:Beam Profile for seventh pass

In figure 31 and 32 it is seen that the beam spot size decreased for seventh and eighth passes up to 0.229mm and 0.118mm respectively.

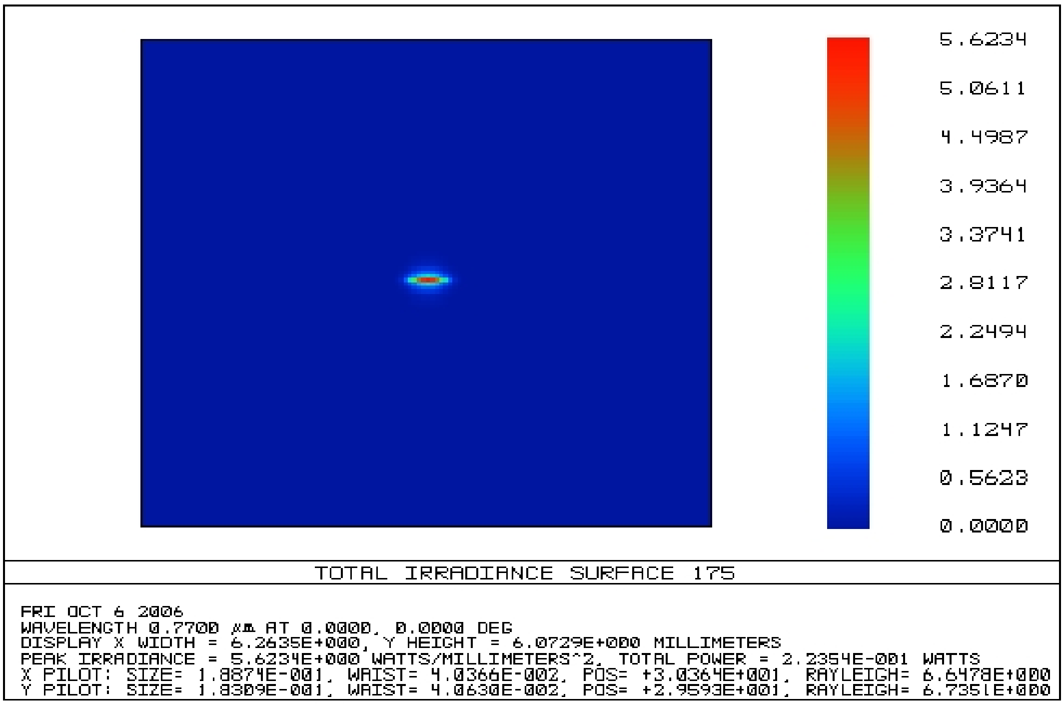


Figure 32:Beam Profile for eight pass

We can also see the beam positions for every passes on any optical components. For example, if we put our detector infront of the mirror that is in the most left in the cavity, we see inrease in the pulse height for each passes, figure33.

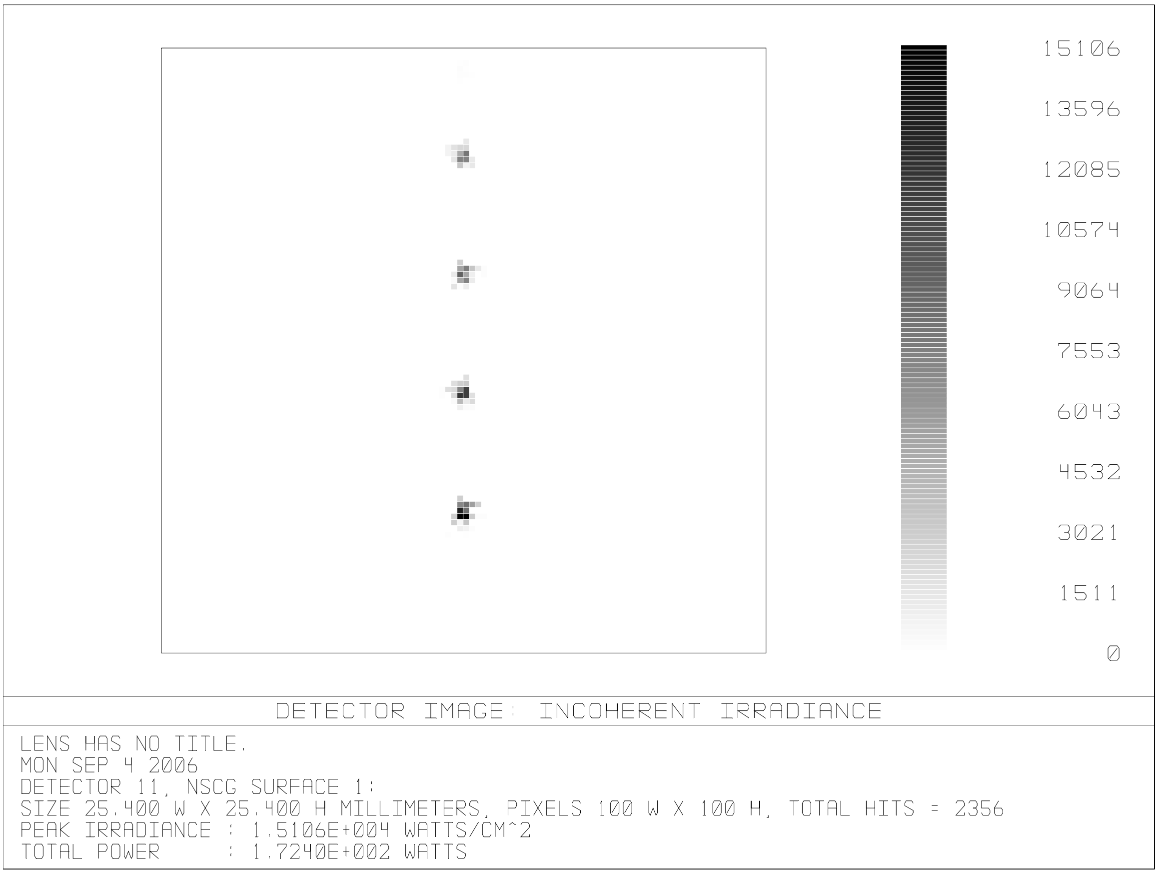


Figure 33:Beam Positions at the left spherical mirror

Same way beam positions can be seen by replacing the detector 1mm away from the gain medium with respect to crystal surface. So the same procedures can be done for any point of the amplifier depend on the desired analyses required for any applications.

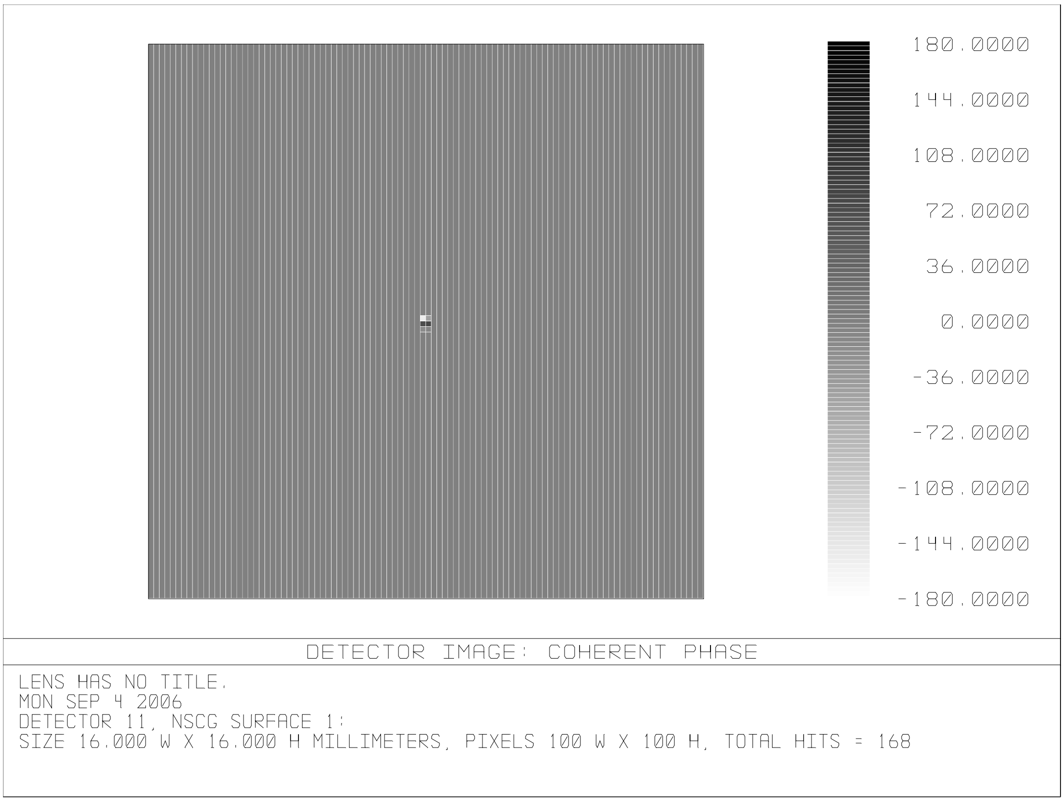


Figure 34:Beam Profile 1mm away from the gain medium

From figure 35 , it is seen that gain medium is actually 6mm away from the focus point of the beams. So for beam overlapping of multipasses, we have to shift Ti:sapphire crystal 6mm in the negative z-direction, figure 36.

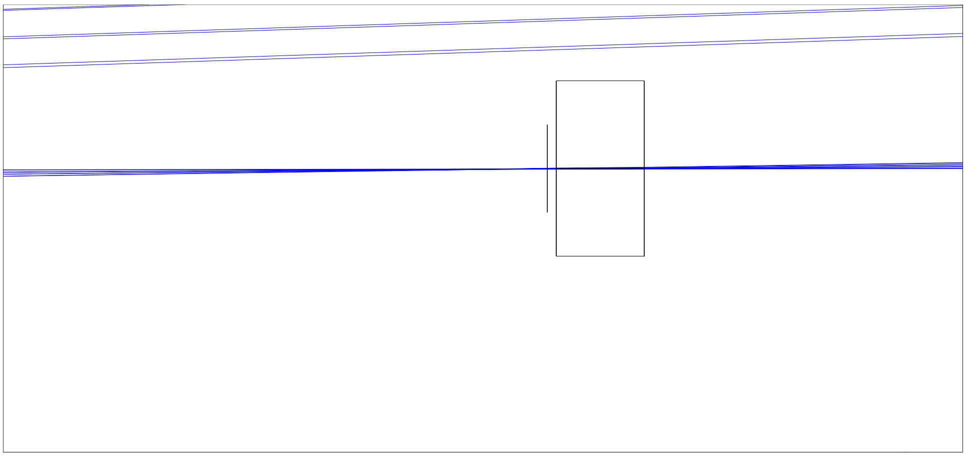


Figure 35:Crystal 6 mm away from the focal point

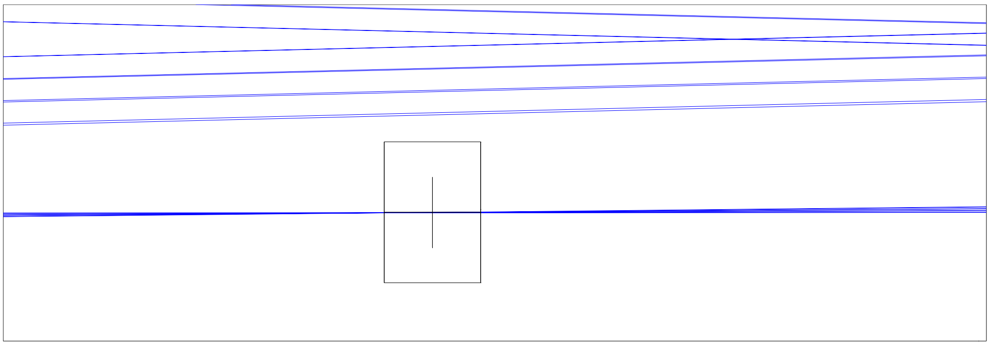


Figure 36:Crystal at Focus

3.5 Cooling of Gain Medium

For the multi pass preamplifier, a chiller serially connected to the femtosecond oscillator will be used as a cooling mechanism. A cylindrical shaped copper holder is designed and indium sheet is rolled around gain media to increase thermal conductivity.The design of the cooler and built coolers are represented in figure 37 and 38.

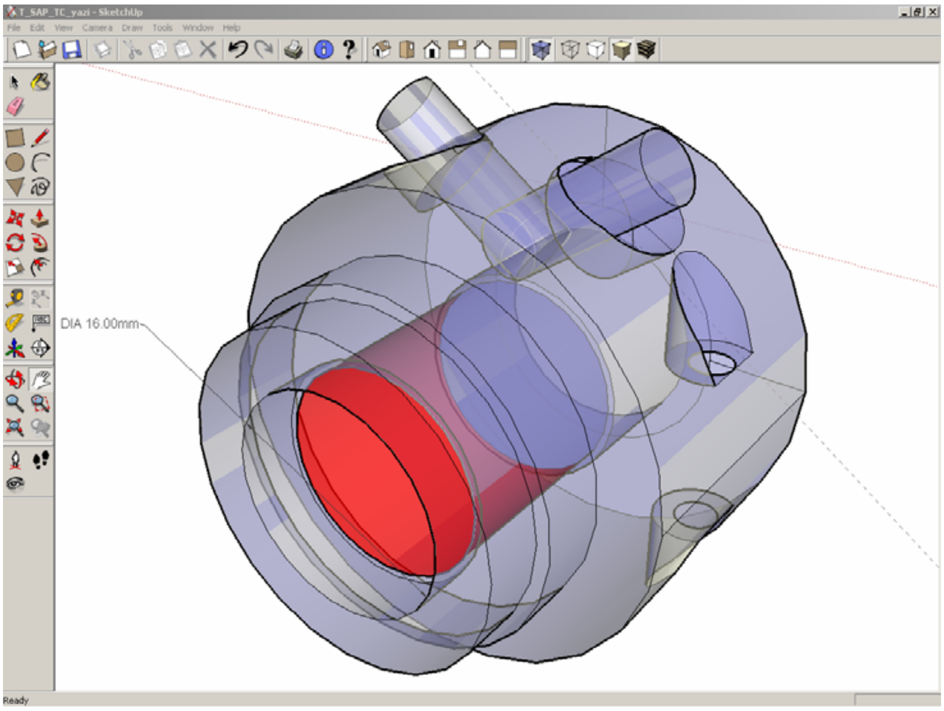


Figure 37:Cooler Design

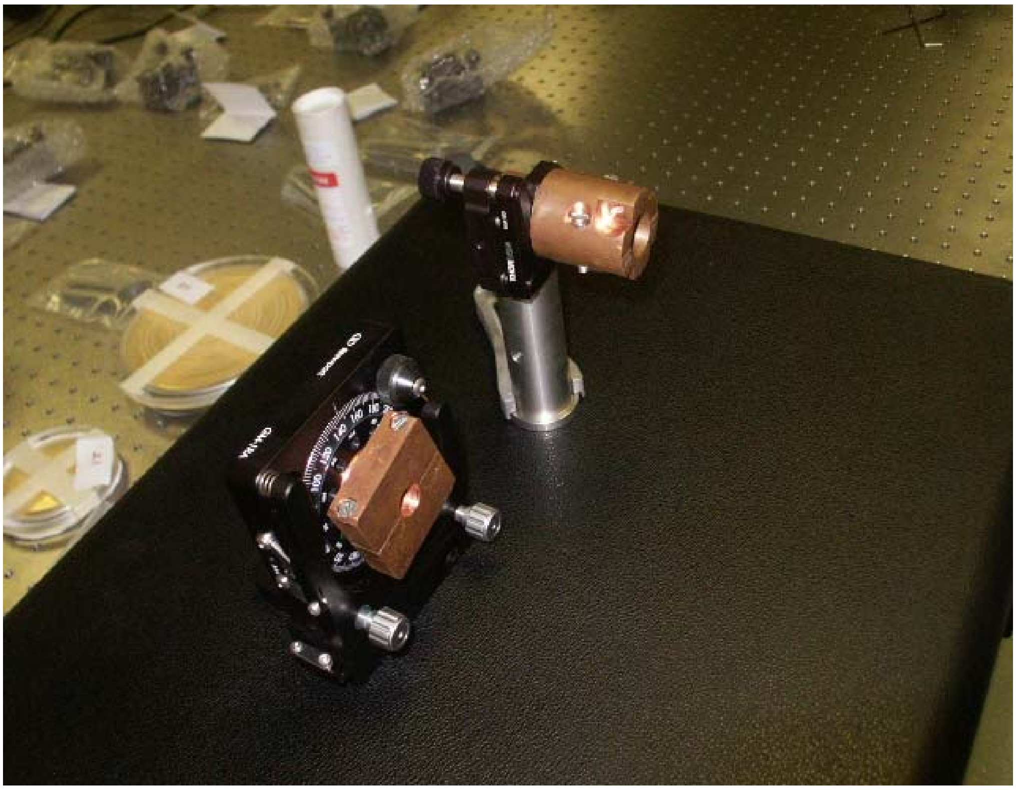


Figure 38: Cooler built for 4-pass and 8-pass optical amplifiers

CHAPTER 4

CONCLUSIONS

For 8-pass amplifier, It is necessary to squeeze all the passes at the same point in the crystal where pump pulse is incident. First of all we decided the optical components coordinates for exactly 8 passes and then by matrix formulation, the Gaussian Beam propagation is simulated. Finally we saw that the focal point of the system was actually 6 mm away from the crystal, which will cause bad mode matching. There were two ways of solving this problem, first realignment of the cavity which was a long way of solving the problem, second replace only the crystal to the focal point while the rest of the components remain at same coordinate.

For 4-pass amplifier, the cavity geometry was relatively simpler with respect to eight pass and easier to align the optical components. In doing the simulation we first decide the coordinates of the components and then we used matrix method to analyze the propagating beam. It is seen that the crystal is in the right position where the four passing beams waist are almost confocal.

APPENDIX A: GAUSSIAN BEAM ANALYSES FOR 4 PASS

Paraxial Gaussian Beam Parameters
Data for 0.5500 µm.
Input Beam Parameters:
Waist size : 5.00000E-001
Surf 1 to waist distance: 0.00
M Squared : 1.00000E+000
Y-Direction:
Fundamental mode results:

Optical Component	Sur	Size(mm)	Waist(mm)	Radius(mm)	Divergence (mm)	Rayleigh(rad)
	STO	5.00E-01	5.00E-01	Infinity	4.77E-04	1.05E+03
	2	5.54E-01	5.00E-01	2.69E+03	4.77E-04	1.05E+03
	3	5.54E-01	5.00E-01	-2.69E+03	4.77E-04	1.05E+03
	4	5.54E-01	5.00E-01	-2.69E+03	4.77E-04	1.05E+03
Mirror 1	5	5.54E-01	5.00E-01	-2.69E+03	4.77E-04	1.05E+03
	6	6.07E-01	5.00E-01	-2.24E+03	4.77E-04	1.05E+03
Mirror 2	7	6.07E-01	5.00E-01	2.24E+03	4.77E-04	1.05E+03
	8	6.07E-01	5.00E-01	2.24E+03	4.77E-04	1.05E+03
	9	6.07E-01	5.00E-01	2.24E+03	4.77E-04	1.05E+03
	10	6.71E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
Crystal	11	6.71E-01	5.00E-01	3.50E+03	2.88E-04	1.74E+03
	12	6.73E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
	13	6.70E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
	14	6.73E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
	15	7.58E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
Mirror 3	16	7.58E-01	5.00E-01	-2.11E+03	4.77E-04	1.05E+03
	17	7.58E-01	5.00E-01	-2.11E+03	4.77E-04	1.05E+03
	18	7.58E-01	5.00E-01	-2.11E+03	4.77E-04	1.05E+03
	19	8.13E-01	5.00E-01	-2.16E+03	4.77E-04	1.05E+03
Mirror 4	20	8.13E-01	5.00E-01	2.16E+03	4.77E-04	1.05E+03
	21	8.13E-01	5.00E-01	2.16E+03	4.77E-04	1.05E+03
	22	8.13E-01	5.00E-01	2.16E+03	4.77E-04	1.05E+03
	23	9.07E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
Crystal	24	9.07E-01	5.00E-01	3.78E+03	2.88E-04	1.74E+03
	25	9.09E-01	5.00E-01	3.79E+03	2.88E-04	1.74E+03
	26	9.09E-01	5.00E-01	3.79E+03	2.88E-04	1.74E+03
	27	9.09E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
	28	9.09E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
	29	9.09E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
	30	1.03E+00	5.00E-01	2.47E+03	4.77E-04	1.05E+03

Mirror 5	31	1.03E+00	5.00E-01	-2.47E+03	4.77E-04	1.05E+03
	32	1.03E+00	5.00E-01	-2.47E+03	4.77E-04	1.05E+03
	33	1.03E+00	5.00E-01	-2.47E+03	4.77E-04	1.05E+03
	34	1.09E+00	5.00E-01	-2.56E+03	4.77E-04	1.05E+03
	35	1.09E+00	5.00E-01	2.56E+03	4.77E-04	1.05E+03
	36	1.09E+00	5.00E-01	2.56E+03	4.77E-04	1.05E+03
Mirror 6	37	1.09E+00	5.00E-01	2.56E+03	4.77E-04	1.05E+03
	38	1.21E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
Crystal	39	1.21E+00	5.00E-01	4.63E+03	2.88E-04	1.74E+03
	40	1.22E+00	5.00E-01	4.64E+03	2.88E-04	1.74E+03
	41	1.22E+00	5.00E-01	4.64E+03	2.88E-04	1.74E+03
	42	1.22E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
	43	1.22E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
	44	1.22E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
	45	1.37E+00	5.00E-01	3.08E+03	4.77E-04	1.05E+03
Mirror 7	46	1.37E+00	5.00E-01	-3.08E+03	4.77E-04	1.05E+03
	47	1.37E+00	5.00E-01	-3.08E+03	4.77E-04	1.05E+03
	48	1.37E+00	5.00E-01	-3.08E+03	4.77E-04	1.05E+03
	49	1.42E+00	5.00E-01	-3.18E+03	4.77E-04	1.05E+03
Mirror 8	50	1.42E+00	5.00E-01	3.18E+03	4.77E-04	1.05E+03
	51	1.42E+00	5.00E-01	3.18E+03	4.77E-04	1.05E+03
	52	1.42E+00	5.00E-01	3.18E+03	4.77E-04	1.05E+03
	53	1.57E+00	5.00E-01	3.48E+03	4.77E-04	1.05E+03
Crystal	54	1.57E+00	5.00E-01	5.77E+03	2.88E-04	1.74E+03
	55	1.58E+00	5.00E-01	3.48E+03	4.77E-04	1.05E+03
	56	1.57E+00	5.00E-01	3.47E+03	4.77E-04	1.05E+03
	57	1.58E+00	5.00E-01	3.48E+03	4.77E-04	1.05E+03
	58	1.71E+00	5.00E-01	3.75E+03	4.77E-04	1.05E+03
	59	1.71E+00	5.00E-01	3.75E+03	4.77E-04	1.05E+03
	60	1.71E+00	5.00E-01	3.75E+03	4.77E-04	1.05E+03
X-Direction:						
Optical Component	Sur	Size(mm)	Waist(mm)	Radius(mm)	Divergence (mm)	Rayleigh(mm)
	STO	5.00E-01	5.00E-01	Infinity	4.77E-04	1.05E+03
	2	5.54E-01	5.00E-01	2.69E+03	4.77E-04	1.05E+03
	3	5.54E-01	5.00E-01	-2.69E+03	4.77E-04	1.05E+03
	4	5.54E-01	5.00E-01	-2.69E+03	4.77E-04	1.05E+03
Mirror 1	5	5.54E-01	5.00E-01	-2.69E+03	4.77E-04	1.05E+03
	6	6.07E-01	5.00E-01	-2.24E+03	4.77E-04	1.05E+03
Mirror 2	7	6.07E-01	5.00E-01	2.24E+03	4.77E-04	1.05E+03
	8	6.07E-01	5.00E-01	2.24E+03	4.77E-04	1.05E+03
	9	6.07E-01	5.00E-01	2.24E+03	4.77E-04	1.05E+03
	10	6.71E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
Crystal	11	6.71E-01	5.00E-01	3.50E+03	2.88E-04	1.74E+03
	12	6.73E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
	13	6.70E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
	14	6.73E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03
	15	7.58E-01	5.00E-01	2.11E+03	4.77E-04	1.05E+03

Mirror 3	16	7.58E-01	5.00E-01	-2.11E+03	4.77E-04	1.05E+03
	17	7.58E-01	5.00E-01	-2.11E+03	4.77E-04	1.05E+03
	18	7.58E-01	5.00E-01	-2.11E+03	4.77E-04	1.05E+03
	19	8.13E-01	5.00E-01	-2.16E+03	4.77E-04	1.05E+03
Mirror 4	20	8.13E-01	5.00E-01	2.16E+03	4.77E-04	1.05E+03
	21	8.13E-01	5.00E-01	2.16E+03	4.77E-04	1.05E+03
	22	8.13E-01	5.00E-01	2.16E+03	4.77E-04	1.05E+03
	23	9.07E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
Crystal	24	9.07E-01	5.00E-01	3.78E+03	2.88E-04	1.74E+03
	25	9.09E-01	5.00E-01	3.79E+03	2.88E-04	1.74E+03
	26	9.09E-01	5.00E-01	3.79E+03	2.88E-04	1.74E+03
	27	9.09E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
	28	9.09E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
	29	9.09E-01	5.00E-01	2.28E+03	4.77E-04	1.05E+03
	30	1.03E+00	5.00E-01	2.47E+03	4.77E-04	1.05E+03
Mirror 5	31	1.03E+00	5.00E-01	-2.47E+03	4.77E-04	1.05E+03
	32	1.03E+00	5.00E-01	-2.47E+03	4.77E-04	1.05E+03
	33	1.03E+00	5.00E-01	-2.47E+03	4.77E-04	1.05E+03
	34	1.09E+00	5.00E-01	-2.56E+03	4.77E-04	1.05E+03
	35	1.09E+00	5.00E-01	2.56E+03	4.77E-04	1.05E+03
	36	1.09E+00	5.00E-01	2.56E+03	4.77E-04	1.05E+03
Mirror 6	37	1.09E+00	5.00E-01	2.56E+03	4.77E-04	1.05E+03
	38	1.21E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
Crystal	39	1.21E+00	5.00E-01	4.63E+03	2.88E-04	1.74E+03
	40	1.22E+00	5.00E-01	4.64E+03	2.88E-04	1.74E+03
	41	1.22E+00	5.00E-01	4.64E+03	2.88E-04	1.74E+03
	42	1.22E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
	43	1.22E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
	44	1.22E+00	5.00E-01	2.79E+03	4.77E-04	1.05E+03
	45	1.37E+00	5.00E-01	3.08E+03	4.77E-04	1.05E+03
Mirror 7	46	1.37E+00	5.00E-01	-3.08E+03	4.77E-04	1.05E+03
	47	1.37E+00	5.00E-01	-3.08E+03	4.77E-04	1.05E+03
	48	1.37E+00	5.00E-01	-3.08E+03	4.77E-04	1.05E+03
	49	1.42E+00	5.00E-01	-3.18E+03	4.77E-04	1.05E+03
Mirror 8	50	1.42E+00	5.00E-01	3.18E+03	4.77E-04	1.05E+03
	51	1.42E+00	5.00E-01	3.18E+03	4.77E-04	1.05E+03
	52	1.42E+00	5.00E-01	3.18E+03	4.77E-04	1.05E+03
	53	1.57E+00	5.00E-01	3.48E+03	4.77E-04	1.05E+03
Crystal	54	1.57E+00	5.00E-01	5.77E+03	2.88E-04	1.74E+03
	55	1.58E+00	5.00E-01	3.48E+03	4.77E-04	1.05E+03
	56	1.57E+00	5.00E-01	3.47E+03	4.77E-04	1.05E+03
	57	1.58E+00	5.00E-01	3.48E+03	4.77E-04	1.05E+03
	58	1.71E+00	5.00E-01	3.75E+03	4.77E-04	1.05E+03
	59	1.71E+00	5.00E-01	3.75E+03	4.77E-04	1.05E+03
	60	1.71E+00	5.00E-01	3.75E+03	4.77E-04	1.05E+03

APPENDIX B: GAUSSIAN BEAM ANALYSES FOR 8-PASS

Input Beam Parameter:
Waist size: 5.0000E-01
Surf1 to waist distance: 0.0000
Y-Direction:
Fundamental mode results:

Optical Component	Sur	Size(mm)	Waist(mm)	Radius(mm)	Divergence(mm)	Rayleigh(rad)
	STO	5.00E-01	5.00E-01	Infinity	4.90E-04	1.02E+03
	2	5.39E-01	5.00E-01	2.94E+03	4.90E-04	1.02E+03
Mirror:1	3	5.44E-01	5.00E-01	-2.94E+03	4.90E-04	1.02E+03
	4	5.44E-01	5.00E-01	-2.94E+03	4.90E-04	1.02E+03
	5	5.39E-01	5.00E-01	-2.94E+03	4.90E-04	1.02E+03
	6	9.15E-01	5.00E-01	-2.23E+03	4.90E-04	1.02E+03
Mirror:2	7	9.15E-01	2.88E-01	-1.13E+03	8.52E-04	3.37E+02
	8	9.15E-01	2.88E-01	-1.13E+03	8.52E-04	3.37E+02
	9	9.15E-01	2.88E-01	-1.13E+03	8.52E-04	3.37E+02
Crystal	10	3.68E-01	2.88E-01	-1.15E+03	5.14E-04	5.60E+02
Detector	11	3.64E-01	2.88E-01	-6.96E+02	8.52E-04	3.37E+02
	12	3.59E-01	2.88E-01	-7.03E+02	8.52E-04	3.37E+02
	13	5.05E-01	2.88E-01	7.21E+02	8.52E-04	3.37E+02
Mirror:3	14	5.05E-01	5.04E-01	-1.87E+04	4.86E-04	1.04E+03
	15	5.05E-01	5.04E-01	-1.87E+04	4.86E-04	1.04E+03
	16	5.05E-01	5.04E-01	-1.87E+04	4.86E-04	1.04E+03
	17	7.39E-01	5.04E-01	-2.08E+03	4.86E-04	1.04E+03
Mirror:4	18	7.51E-01	5.04E-01	2.08E+03	4.86E-04	1.04E+03
	19	7.51E-01	5.04E-01	2.08E+03	4.86E-04	1.04E+03
	20	7.39E-01	5.04E-01	2.08E+03	4.86E-04	1.04E+03
	21	8.61E-01	5.04E-01	2.19E+03	4.86E-04	1.04E+03
Mirror:5	22	2.61E+00	5.04E-01	-2.19E+03	4.86E-04	1.04E+03
	23	2.61E+00	5.04E-01	-2.19E+03	4.86E-04	1.04E+03
	24	8.61E-01	5.04E-01	-2.19E+03	4.86E-04	1.04E+03
	25	1.03E+00	5.04E-01	-2.43E+03	4.86E-04	1.04E+03
Mirror:1	26	1.04E+00	5.04E-01	2.43E+03	4.86E-04	1.04E+03
	27	1.04E+00	5.04E-01	2.43E+03	4.86E-04	1.04E+03
	28	1.03E+00	5.04E-01	2.43E+03	4.86E-04	1.04E+03
	29	1.54E+00	5.04E-01	3.36E+03	4.86E-04	1.04E+03
Mirror:2	30	1.54E+00	1.53E-01	9.66E+02	1.60E-03	9.53E+01
	31	1.54E+00	1.53E-01	9.66E+02	1.60E-03	9.53E+01
	32	1.54E+00	1.53E-01	9.66E+02	1.60E-03	9.53E+01
Crystal	33	3.63E-01	1.53E-01	4.14E+02	9.67E-04	1.58E+02

Detector	34	3.54E-01	1.53E-01	2.45E+02	1.60E-03	9.53E+01
	35	3.40E-01	1.53E-01	2.37E+02	1.60E-03	9.53E+01
	36	8.97E-01	1.53E-01	-5.67E+02	1.60E-03	9.53E+01
Mirror:3	37	8.97E-01	5.19E-01	2.33E+03	4.72E-04	1.10E+03
	38	8.97E-01	5.19E-01	2.33E+03	4.72E-04	1.10E+03
	39	8.97E-01	5.19E-01	2.33E+03	4.72E-04	1.10E+03
	40	1.33E+00	5.19E-01	3.07E+03	4.72E-04	1.10E+03
Mirror:4	41	1.35E+00	5.19E-01	-3.07E+03	4.72E-04	1.10E+03
	42	1.35E+00	5.19E-01	-3.07E+03	4.72E-04	1.10E+03
	43	1.33E+00	5.19E-01	-3.07E+03	4.72E-04	1.10E+03
	44	1.48E+00	5.19E-01	-3.34E+03	4.72E-04	1.10E+03
Mirror:5	45	4.47E+00	5.19E-01	3.34E+03	4.72E-04	1.10E+03
	46	4.47E+00	5.19E-01	3.34E+03	4.72E-04	1.10E+03
	47	1.48E+00	5.19E-01	3.34E+03	4.72E-04	1.10E+03
	48	1.48E+00	5.19E-01	3.34E+03	4.72E-04	1.10E+03
Mirror:1	49	1.66E+00	5.19E-01	3.70E+03	4.72E-04	1.10E+03
	50	1.67E+00	5.19E-01	-3.70E+03	4.72E-04	1.10E+03
	51	1.67E+00	5.19E-01	-3.70E+03	4.72E-04	1.10E+03
	52	1.66E+00	5.19E-01	-3.70E+03	4.72E-04	1.10E+03
Mirror: 2	53	2.18E+00	5.19E-01	-4.76E+03	4.72E-04	1.10E+03
	54	2.18E+00	9.99E-02	-8.90E+02	2.45E-03	4.08E+01
	55	2.18E+00	9.99E-02	-8.90E+02	2.45E-03	4.08E+01
	56	2.18E+00	9.99E-02	-8.90E+02	2.45E-03	4.08E+01
	57	3.54E-01	9.99E-02	-2.50E+02	1.48E-03	6.76E+01
Detector	58	3.40E-01	9.99E-02	-1.45E+02	2.45E-03	4.08E+01
	59	3.16E-01	9.99E-02	-1.36E+02	2.45E-03	4.08E+01
Mirror: 3	60	1.52E+00	9.99E-02	6.20E+02	2.45E-03	4.08E+01
	61	1.52E+00	5.41E-01	-3.59E+03	4.53E-04	1.20E+03
	62	1.52E+00	5.41E-01	-3.59E+03	4.53E-04	1.20E+03
	63	1.52E+00	5.41E-01	-3.59E+03	4.53E-04	1.20E+03
Mirror:4	64	1.97E+00	5.41E-01	-4.53E+03	4.53E-04	1.20E+03
	65	2.00E+00	5.41E-01	4.53E+03	4.53E-04	1.20E+03
	66	2.00E+00	5.41E-01	4.53E+03	4.53E-04	1.20E+03
	67	1.97E+00	5.41E-01	4.53E+03	4.53E-04	1.20E+03
Mirror:5	68	2.11E+00	5.41E-01	4.83E+03	4.53E-04	1.20E+03
	69	6.40E+00	5.41E-01	-4.83E+03	4.53E-04	1.20E+03
	70	6.40E+00	5.41E-01	-4.83E+03	4.53E-04	1.20E+03
	71	2.11E+00	5.41E-01	-4.83E+03	4.53E-04	1.20E+03
Mirror:1	72	2.29E+00	5.41E-01	-5.21E+03	4.53E-04	1.20E+03
	73	2.31E+00	5.41E-01	5.21E+03	4.53E-04	1.20E+03
	74	2.31E+00	5.41E-01	5.21E+03	4.53E-04	1.20E+03
	75	2.29E+00	5.41E-01	5.21E+03	4.53E-04	1.20E+03
Mirror:2	76	2.80E+00	5.41E-01	6.31E+03	4.53E-04	1.20E+03
	77	2.80E+00	7.44E-02	8.51E+02	3.29E-03	2.26E+01
	78	2.80E+00	7.44E-02	8.51E+02	3.29E-03	2.26E+01
	79	2.80E+00	7.44E-02	8.51E+02	3.29E-03	2.26E+01
	80	3.36E-01	7.44E-02	1.74E+02	1.98E-03	3.75E+01
Detector	81	3.17E-01	7.44E-02	9.90E+01	3.29E-03	2.26E+01

	82	2.85E-01	7.44E-02	8.96E+01	3.29E-03	2.26E+01
Mirror:3	83	2.16E+00	7.44E-02	-6.57E+02	3.29E-03	2.26E+01
	84	2.16E+00	5.81E-01	5.32E+03	4.22E-04	1.38E+03
	85	2.16E+00	5.81E-01	5.32E+03	4.22E-04	1.38E+03
	86	2.16E+00	5.81E-01	5.32E+03	4.22E-04	1.38E+03
Mirror:4	87	2.59E+00	5.81E-01	6.30E+03	4.22E-04	1.38E+03
	88	2.63E+00	5.81E-01	-6.30E+03	4.22E-04	1.38E+03
	89	2.63E+00	5.81E-01	-6.30E+03	4.22E-04	1.38E+03
	90	2.59E+00	5.81E-01	-6.30E+03	4.22E-04	1.38E+03
Mirror:5	91	2.73E+00	5.81E-01	-6.61E+03	4.22E-04	1.38E+03
	92	8.26E+00	5.81E-01	6.61E+03	4.22E-04	1.38E+03
	93	8.26E+00	5.81E-01	6.61E+03	4.22E-04	1.38E+03
	94	2.73E+00	5.81E-01	6.61E+03	4.22E-04	1.38E+03
Mirror:1	95	2.73E+00	5.81E-01	6.61E+03	4.22E-04	1.38E+03
	96	2.90E+00	5.81E-01	7.00E+03	4.22E-04	1.38E+03
	97	2.92E+00	5.81E-01	-7.00E+03	4.22E-04	1.38E+03
	98	2.92E+00	5.81E-01	-7.00E+03	4.22E-04	1.38E+03
Mirror:2	99	2.90E+00	5.81E-01	-7.00E+03	4.22E-04	1.38E+03
	100	3.37E+00	5.81E-01	-8.11E+03	4.22E-04	1.38E+03
	101	3.37E+00	6.00E-02	-8.26E+02	4.08E-03	1.47E+01
Crystal	102	3.37E+00	6.00E-02	-8.26E+02	4.08E-03	1.47E+01
	103	3.37E+00	6.00E-02	-8.26E+02	4.08E-03	1.47E+01
	104	3.16E-01	6.00E-02	-1.31E+02	2.46E-03	2.44E+01
Detector	105	2.92E-01	6.00E-02	-7.31E+01	4.08E-03	1.47E+01
Mirror:3	106	2.52E-01	6.00E-02	-6.36E+01	4.08E-03	1.47E+01
	107	2.78E+00	6.00E-02	6.80E+02	4.08E-03	1.47E+01
	108	2.78E+00	6.30E-01	-7.33E+03	3.89E-04	1.62E+03
	109	2.78E+00	6.30E-01	-7.33E+03	3.89E-04	1.62E+03
Mirror:4	110	2.78E+00	6.30E-01	-7.33E+03	3.89E-04	1.62E+03
	111	3.18E+00	6.30E-01	-8.33E+03	3.89E-04	1.62E+03
	112	3.23E+00	6.30E-01	8.33E+03	3.89E-04	1.62E+03
	113	3.23E+00	6.30E-01	8.33E+03	3.89E-04	1.62E+03
Mirror:5	114	3.18E+00	6.30E-01	8.33E+03	3.89E-04	1.62E+03
	115	3.30E+00	6.30E-01	8.64E+03	3.89E-04	1.62E+03
	116	1.00E+01	6.30E-01	-8.64E+03	3.89E-04	1.62E+03
	117	1.00E+01	6.30E-01	-8.64E+03	3.89E-04	1.62E+03
Mirror:1	118	3.30E+00	6.30E-01	-8.64E+03	3.89E-04	1.62E+03
	119	3.46E+00	6.30E-01	-9.04E+03	3.89E-04	1.62E+03
	120	3.49E+00	6.30E-01	9.04E+03	3.89E-04	1.62E+03
	121	3.49E+00	6.30E-01	9.04E+03	3.89E-04	1.62E+03
Mirror:2	122	3.46E+00	6.30E-01	9.04E+03	3.89E-04	1.62E+03
	123	3.90E+00	6.30E-01	1.02E+04	3.89E-04	1.62E+03
	124	3.90E+00	5.09E-02	8.10E+02	4.82E-03	1.06E+01
Crystal	125	3.90E+00	5.09E-02	8.10E+02	4.82E-03	1.06E+01
	126	3.90E+00	5.09E-02	8.10E+02	4.82E-03	1.06E+01
	127	2.87E-01	5.09E-02	1.00E+02	2.90E-03	1.75E+01
Detector	128	2.58E-01	5.09E-02	5.47E+01	4.82E-03	1.06E+01
Mirror:3	129	2.11E-01	5.09E-02	4.52E+01	4.82E-03	1.06E+01

	130	3.36E+00	5.09E-02	-6.98E+02	4.82E-03	1.06E+01
	131	3.36E+00	7.12E-01	9.99E+03	3.44E-04	2.07E+03
	132	3.36E+00	7.12E-01	9.99E+03	3.44E-04	2.07E+03
Mirror:4	133	3.36E+00	7.12E-01	9.99E+03	3.44E-04	2.07E+03
	134	3.72E+00	7.12E-01	1.10E+04	3.44E-04	2.07E+03
	135	3.77E+00	7.12E-01	-1.10E+04	3.44E-04	2.07E+03
	136	3.77E+00	7.12E-01	-1.10E+04	3.44E-04	2.07E+03
Mirror:5	137	3.72E+00	7.12E-01	-1.10E+04	3.44E-04	2.07E+03
	138	3.83E+00	7.12E-01	-1.13E+04	3.44E-04	2.07E+03
	139	1.16E+01	7.12E-01	1.13E+04	3.44E-04	2.07E+03
	140	1.16E+01	7.12E-01	1.13E+04	3.44E-04	2.07E+03
Mirror:1	141	3.83E+00	7.12E-01	1.13E+04	3.44E-04	2.07E+03
	142	3.83E+00	7.12E-01	1.13E+04	3.44E-04	2.07E+03
	143	3.96E+00	7.12E-01	1.17E+04	3.44E-04	2.07E+03
	144	4.00E+00	7.12E-01	-1.17E+04	3.44E-04	2.07E+03
Mirror:2	145	4.00E+00	7.12E-01	-1.17E+04	3.44E-04	2.07E+03
	146	3.96E+00	7.12E-01	-1.17E+04	3.44E-04	2.07E+03
	147	4.35E+00	7.12E-01	-1.28E+04	3.44E-04	2.07E+03
Crystal	148	4.35E+00	4.48E-02	-7.97E+02	5.47E-03	8.20E+00
	149	4.35E+00	4.48E-02	-7.97E+02	5.47E-03	8.20E+00
	150	4.35E+00	4.48E-02	-7.97E+02	5.47E-03	8.20E+00
	151	2.58E-01	4.48E-02	-7.94E+01	3.30E-03	1.36E+01
Detector	152	2.25E-01	4.48E-02	-4.21E+01	5.47E-03	8.20E+00
	153	1.72E-01	4.48E-02	-3.26E+01	5.47E-03	8.20E+00
	154	3.88E+00	4.48E-02	7.10E+02	5.47E-03	8.20E+00
	155	3.88E+00	8.17E-01	-1.32E+04	3.00E-04	2.72E+03
Mirror:4	156	3.88E+00	8.17E-01	-1.32E+04	3.00E-04	2.72E+03
	157	3.88E+00	8.17E-01	-1.32E+04	3.00E-04	2.72E+03
	158	4.19E+00	8.17E-01	-1.42E+04	3.00E-04	2.72E+03
	159	4.25E+00	8.17E-01	1.42E+04	3.00E-04	2.72E+03
Mirror:5	160	4.25E+00	8.17E-01	1.42E+04	3.00E-04	2.72E+03
	161	4.19E+00	8.17E-01	1.42E+04	3.00E-04	2.72E+03
	162	4.28E+00	8.17E-01	1.45E+04	3.00E-04	2.72E+03
	163	1.30E+01	8.17E-01	-1.45E+04	3.00E-04	2.72E+03
Mirror:1	164	1.30E+01	8.17E-01	-1.45E+04	3.00E-04	2.72E+03
	165	4.28E+00	8.17E-01	-1.45E+04	3.00E-04	2.72E+03
	166	4.41E+00	8.17E-01	-1.49E+04	3.00E-04	2.72E+03
	167	4.45E+00	8.17E-01	1.49E+04	3.00E-04	2.72E+03
Mirror:2	168	4.45E+00	8.17E-01	1.49E+04	3.00E-04	2.72E+03
	169	4.41E+00	8.17E-01	1.49E+04	3.00E-04	2.72E+03
	170	4.75E+00	8.17E-01	1.61E+04	3.00E-04	2.72E+03
Crystal	171	4.75E+00	4.06E-02	7.87E+02	6.03E-03	6.74E+00
	172	4.75E+00	4.06E-02	7.87E+02	6.03E-03	6.74E+00
	173	4.75E+00	4.06E-02	7.87E+02	6.03E-03	6.74E+00
	174	2.19E-01	4.06E-02	6.12E+01	3.64E-03	1.12E+01
Detector	175	1.83E-01	4.06E-02	3.11E+01	6.03E-03	6.74E+00
	176	1.25E-01	4.06E-02	2.19E+01	6.03E-03	6.74E+00
	177	4.35E+00	4.06E-02	-7.20E+02	6.03E-03	6.74E+00

	178	4.35E+00	1.01E+00	1.83E+04	2.44E-04	4.13E+03
Mirror:4	179	4.35E+00	1.01E+00	1.83E+04	2.44E-04	4.13E+03
	180	4.35E+00	1.01E+00	1.83E+04	2.44E-04	4.13E+03
	181	4.60E+00	1.01E+00	1.93E+04	2.44E-04	4.13E+03
	182	4.67E+00	1.01E+00	-1.93E+04	2.44E-04	4.13E+03
Mirror:5	183	4.67E+00	1.01E+00	-1.93E+04	2.44E-04	4.13E+03
	184	4.60E+00	1.01E+00	-1.93E+04	2.44E-04	4.13E+03
	185	4.67E+00	1.01E+00	-1.96E+04	2.44E-04	4.13E+03
	186	1.42E+01	1.01E+00	1.96E+04	2.44E-04	4.13E+03
Mirror:1	187	1.42E+01	1.01E+00	1.96E+04	2.44E-04	4.13E+03
	188	4.67E+00	1.01E+00	1.96E+04	2.44E-04	4.13E+03
	IMA	4.67E+00	1.01E+00	1.96E+04	2.44E-04	4.13E+03
X-Direction						
Optical Component	Sur	Size(mm)	Waist(mm)	Radius(mm)	Divergence(mm)	Rayleigh(rad)
	STO	5.00E-01	5.00E-01	Infinity	4.90E-04	1.02E+03
	2	5.39E-01	5.00E-01	2.94E+03	4.90E-04	1.02E+03
Mirror:1	3	5.39E-01	5.00E-01	-2.94E+03	4.90E-04	1.02E+03
	4	5.39E-01	5.00E-01	-2.94E+03	4.90E-04	1.02E+03
	5	5.39E-01	5.00E-01	-2.94E+03	4.90E-04	1.02E+03
	6	9.15E-01	5.00E-01	-2.23E+03	4.90E-04	1.02E+03
Mirror:2	7	9.15E-01	2.88E-01	-1.13E+03	8.52E-04	3.38E+02
	8	9.15E-01	2.88E-01	-1.13E+03	8.52E-04	3.38E+02
	9	9.15E-01	2.88E-01	-1.13E+03	8.52E-04	3.38E+02
Crystal	10	3.68E-01	2.88E-01	-1.15E+03	5.14E-04	5.60E+02
	11	3.65E-01	2.88E-01	-6.96E+02	8.52E-04	3.38E+02
	12	3.59E-01	2.88E-01	-7.04E+02	8.52E-04	3.38E+02
	13	5.05E-01	2.88E-01	7.21E+02	8.52E-04	3.38E+02
Mirror:3	14	5.05E-01	5.04E-01	-1.87E+04	4.86E-04	1.04E+03
	15	5.05E-01	5.04E-01	-1.87E+04	4.86E-04	1.04E+03
	16	5.05E-01	5.04E-01	-1.87E+04	4.86E-04	1.04E+03
	17	7.39E-01	5.04E-01	-2.08E+03	4.86E-04	1.04E+03
Mirror:4	18	7.39E-01	5.04E-01	2.08E+03	4.86E-04	1.04E+03
	19	7.39E-01	5.04E-01	2.08E+03	4.86E-04	1.04E+03
	20	7.39E-01	5.04E-01	2.08E+03	4.86E-04	1.04E+03
	21	8.61E-01	5.04E-01	2.18E+03	4.86E-04	1.04E+03
Mirror:5	22	8.61E-01	5.04E-01	-2.18E+03	4.86E-04	1.04E+03
	23	8.61E-01	5.04E-01	-2.18E+03	4.86E-04	1.04E+03
	24	8.61E-01	5.04E-01	-2.18E+03	4.86E-04	1.04E+03
	25	1.03E+00	5.04E-01	-2.43E+03	4.86E-04	1.04E+03
Mirror:1	26	1.03E+00	5.04E-01	2.43E+03	4.86E-04	1.04E+03
	27	1.03E+00	5.04E-01	2.43E+03	4.86E-04	1.04E+03
	28	1.03E+00	5.04E-01	2.43E+03	4.86E-04	1.04E+03
	29	1.54E+00	5.04E-01	3.36E+03	4.86E-04	1.04E+03

Mirror:2	30	1.54E+00	1.53E-01	9.66E+02	1.60E-03	9.53E+01
	31	1.54E+00	1.53E-01	9.66E+02	1.60E-03	9.53E+01
	32	1.54E+00	1.53E-01	9.66E+02	1.60E-03	9.53E+01
Crystal	33	3.63E-01	1.53E-01	4.14E+02	9.67E-04	1.58E+02
	34	3.54E-01	1.53E-01	2.45E+02	1.60E-03	9.53E+01
	35	3.40E-01	1.53E-01	2.37E+02	1.60E-03	9.53E+01
	36	8.96E-01	1.53E-01	-5.67E+02	1.60E-03	9.53E+01
Mirror:3	37	8.96E-01	5.19E-01	2.32E+03	4.73E-04	1.10E+03
	38	8.96E-01	5.19E-01	2.32E+03	4.73E-04	1.10E+03
	39	8.96E-01	5.19E-01	2.32E+03	4.73E-04	1.10E+03
	40	1.33E+00	5.19E-01	3.06E+03	4.73E-04	1.10E+03
Mirror:4	41	1.33E+00	5.19E-01	-3.06E+03	4.73E-04	1.10E+03
	42	1.33E+00	5.19E-01	-3.06E+03	4.73E-04	1.10E+03
	43	1.33E+00	5.19E-01	-3.06E+03	4.73E-04	1.10E+03
	44	1.48E+00	5.19E-01	-3.33E+03	4.73E-04	1.10E+03
Mirror:5	45	1.48E+00	5.19E-01	3.33E+03	4.73E-04	1.10E+03
	46	1.48E+00	5.19E-01	3.33E+03	4.73E-04	1.10E+03
	47	1.48E+00	5.19E-01	3.33E+03	4.73E-04	1.10E+03
	48	1.48E+00	5.19E-01	3.33E+03	4.73E-04	1.10E+03
Mirror:1	49	1.66E+00	5.19E-01	3.69E+03	4.73E-04	1.10E+03
	50	1.66E+00	5.19E-01	-3.69E+03	4.73E-04	1.10E+03
	51	1.66E+00	5.19E-01	-3.69E+03	4.73E-04	1.10E+03
	52	1.66E+00	5.19E-01	-3.69E+03	4.73E-04	1.10E+03
Mirror: 2	53	2.18E+00	5.19E-01	-4.75E+03	4.73E-04	1.10E+03
	54	2.18E+00	9.99E-02	-8.91E+02	2.45E-03	4.07E+01
	55	2.18E+00	9.99E-02	-8.91E+02	2.45E-03	4.07E+01
	56	2.18E+00	9.99E-02	-8.91E+02	2.45E-03	4.07E+01
	57	3.55E-01	9.99E-02	-2.50E+02	1.48E-03	6.76E+01
	58	3.41E-01	9.99E-02	-1.45E+02	2.45E-03	4.07E+01
	59	3.17E-01	9.99E-02	-1.36E+02	2.45E-03	4.07E+01
Mirror: 3	60	1.52E+00	9.99E-02	6.20E+02	2.45E-03	4.07E+01
	61	1.52E+00	5.40E-01	-3.58E+03	4.54E-04	1.19E+03
	62	1.52E+00	5.40E-01	-3.58E+03	4.54E-04	1.19E+03
	63	1.52E+00	5.40E-01	-3.58E+03	4.54E-04	1.19E+03
Mirror:4	64	1.97E+00	5.40E-01	-4.51E+03	4.54E-04	1.19E+03
	65	1.97E+00	5.40E-01	4.51E+03	4.54E-04	1.19E+03
	66	1.97E+00	5.40E-01	4.51E+03	4.54E-04	1.19E+03
	67	1.97E+00	5.40E-01	4.51E+03	4.54E-04	1.19E+03
Mirror:5	68	2.11E+00	5.40E-01	4.81E+03	4.54E-04	1.19E+03
	69	2.11E+00	5.40E-01	-4.81E+03	4.54E-04	1.19E+03
	70	2.11E+00	5.40E-01	-4.81E+03	4.54E-04	1.19E+03
	71	2.11E+00	5.40E-01	-4.81E+03	4.54E-04	1.19E+03
Mirror:1	72	2.29E+00	5.40E-01	-5.20E+03	4.54E-04	1.19E+03
	73	2.29E+00	5.40E-01	5.20E+03	4.54E-04	1.19E+03
	74	2.29E+00	5.40E-01	5.20E+03	4.54E-04	1.19E+03
	75	2.29E+00	5.40E-01	5.20E+03	4.54E-04	1.19E+03
Mirror:2	76	2.81E+00	5.40E-01	6.30E+03	4.54E-04	1.19E+03
	77	2.81E+00	7.44E-02	8.52E+02	3.30E-03	2.26E+01

	78	2.81E+00	7.44E-02	8.52E+02	3.30E-03	2.26E+01
	79	2.81E+00	7.44E-02	8.52E+02	3.30E-03	2.26E+01
	80	3.38E-01	7.44E-02	1.74E+02	1.99E-03	3.74E+01
	81	3.18E-01	7.44E-02	9.93E+01	3.30E-03	2.26E+01
	82	2.86E-01	7.44E-02	9.00E+01	3.30E-03	2.26E+01
Mirror:3	83	2.16E+00	7.44E-02	-6.57E+02	3.30E-03	2.26E+01
	84	2.16E+00	5.77E-01	5.29E+03	4.25E-04	1.36E+03
	85	2.16E+00	5.77E-01	5.29E+03	4.25E-04	1.36E+03
	86	2.16E+00	5.77E-01	5.29E+03	4.25E-04	1.36E+03
Mirror:4	87	2.60E+00	5.77E-01	6.27E+03	4.25E-04	1.36E+03
	88	2.60E+00	5.77E-01	-6.27E+03	4.25E-04	1.36E+03
	89	2.60E+00	5.77E-01	-6.27E+03	4.25E-04	1.36E+03
	90	2.60E+00	5.77E-01	-6.27E+03	4.25E-04	1.36E+03
Mirror:5	91	2.73E+00	5.77E-01	-6.58E+03	4.25E-04	1.36E+03
	92	2.73E+00	5.77E-01	6.58E+03	4.25E-04	1.36E+03
	93	2.73E+00	5.77E-01	6.58E+03	4.25E-04	1.36E+03
	94	2.73E+00	5.77E-01	6.58E+03	4.25E-04	1.36E+03
Mirror:1	95	2.73E+00	5.77E-01	6.58E+03	4.25E-04	1.36E+03
	96	2.90E+00	5.77E-01	6.97E+03	4.25E-04	1.36E+03
	97	2.90E+00	5.77E-01	-6.97E+03	4.25E-04	1.36E+03
	98	2.90E+00	5.77E-01	-6.97E+03	4.25E-04	1.36E+03
Mirror:2	99	2.90E+00	5.77E-01	-6.97E+03	4.25E-04	1.36E+03
	100	3.38E+00	5.77E-01	-8.09E+03	4.25E-04	1.36E+03
	101	3.38E+00	5.99E-02	-8.27E+02	4.09E-03	1.46E+01
Crystal	102	3.38E+00	5.99E-02	-8.27E+02	4.09E-03	1.46E+01
	103	3.38E+00	5.99E-02	-8.27E+02	4.09E-03	1.46E+01
	104	3.19E-01	5.99E-02	-1.32E+02	2.47E-03	2.43E+01
	105	2.95E-01	5.99E-02	-7.35E+01	4.09E-03	1.46E+01
Mirror:3	106	2.55E-01	5.99E-02	-6.40E+01	4.09E-03	1.46E+01
	107	2.78E+00	5.99E-02	6.80E+02	4.09E-03	1.46E+01
	108	2.78E+00	6.23E-01	-7.26E+03	3.93E-04	1.59E+03
	109	2.78E+00	6.23E-01	-7.26E+03	3.93E-04	1.59E+03
Mirror:4	110	2.78E+00	6.23E-01	-7.26E+03	3.93E-04	1.59E+03
	111	3.19E+00	6.23E-01	-8.27E+03	3.93E-04	1.59E+03
	112	3.19E+00	6.23E-01	8.27E+03	3.93E-04	1.59E+03
	113	3.19E+00	6.23E-01	8.27E+03	3.93E-04	1.59E+03
Mirror:5	114	3.19E+00	6.23E-01	8.27E+03	3.93E-04	1.59E+03
	115	3.31E+00	6.23E-01	8.58E+03	3.93E-04	1.59E+03
	116	3.31E+00	6.23E-01	-8.58E+03	3.93E-04	1.59E+03
	117	3.31E+00	6.23E-01	-8.58E+03	3.93E-04	1.59E+03
Mirror:1	118	3.31E+00	6.23E-01	-8.58E+03	3.93E-04	1.59E+03
	119	3.47E+00	6.23E-01	-8.97E+03	3.93E-04	1.59E+03
	120	3.47E+00	6.23E-01	8.97E+03	3.93E-04	1.59E+03
	121	3.47E+00	6.23E-01	8.97E+03	3.93E-04	1.59E+03
Mirror:2	122	3.47E+00	6.23E-01	8.97E+03	3.93E-04	1.59E+03
	123	3.92E+00	6.23E-01	1.01E+04	3.93E-04	1.59E+03
	124	3.92E+00	5.07E-02	8.10E+02	4.83E-03	1.05E+01
Crystal	125	3.92E+00	5.07E-02	8.10E+02	4.83E-03	1.05E+01

	126	3.92E+00	5.07E-02	8.10E+02	4.83E-03	1.05E+01
	127	2.90E-01	5.07E-02	1.01E+02	2.91E-03	1.74E+01
	128	2.62E-01	5.07E-02	5.52E+01	4.83E-03	1.05E+01
Mirror:3	129	2.15E-01	5.07E-02	4.57E+01	4.83E-03	1.05E+01
	130	3.37E+00	5.07E-02	-6.97E+02	4.83E-03	1.05E+01
	131	3.37E+00	7.01E-01	9.86E+03	3.49E-04	2.01E+03
	132	3.37E+00	7.01E-01	9.86E+03	3.49E-04	2.01E+03
Mirror:4	133	3.37E+00	7.01E-01	9.86E+03	3.49E-04	2.01E+03
	134	3.73E+00	7.01E-01	1.09E+04	3.49E-04	2.01E+03
	135	3.73E+00	7.01E-01	-1.09E+04	3.49E-04	2.01E+03
	136	3.73E+00	7.01E-01	-1.09E+04	3.49E-04	2.01E+03
Mirror:5	137	3.73E+00	7.01E-01	-1.09E+04	3.49E-04	2.01E+03
	138	3.84E+00	7.01E-01	-1.12E+04	3.49E-04	2.01E+03
	139	3.84E+00	7.01E-01	1.12E+04	3.49E-04	2.01E+03
	140	3.84E+00	7.01E-01	1.12E+04	3.49E-04	2.01E+03
Mirror:1	141	3.84E+00	7.01E-01	1.12E+04	3.49E-04	2.01E+03
	142	3.84E+00	7.01E-01	1.12E+04	3.49E-04	2.01E+03
	143	3.98E+00	7.01E-01	1.16E+04	3.49E-04	2.01E+03
	144	3.98E+00	7.01E-01	-1.16E+04	3.49E-04	2.01E+03
Mirror:2	145	3.98E+00	7.01E-01	-1.16E+04	3.49E-04	2.01E+03
	146	3.98E+00	7.01E-01	-1.16E+04	3.49E-04	2.01E+03
	147	4.38E+00	7.01E-01	-1.27E+04	3.49E-04	2.01E+03
Crystal	148	4.38E+00	4.46E-02	-7.97E+02	5.49E-03	8.12E+00
	149	4.38E+00	4.46E-02	-7.97E+02	5.49E-03	8.12E+00
	150	4.38E+00	4.46E-02	-7.97E+02	5.49E-03	8.12E+00
	151	2.62E-01	4.46E-02	-8.04E+01	3.31E-03	1.35E+01
Mirror:3	152	2.30E-01	4.46E-02	-4.27E+01	5.49E-03	8.12E+00
	153	1.76E-01	4.46E-02	-3.32E+01	5.49E-03	8.12E+00
	154	3.89E+00	4.46E-02	7.09E+02	5.49E-03	8.12E+00
	155	3.89E+00	7.99E-01	-1.30E+04	3.07E-04	2.60E+03
Mirror:4	156	3.89E+00	7.99E-01	-1.30E+04	3.07E-04	2.60E+03
	157	3.89E+00	7.99E-01	-1.30E+04	3.07E-04	2.60E+03
	158	4.21E+00	7.99E-01	-1.40E+04	3.07E-04	2.60E+03
	159	4.21E+00	7.99E-01	1.40E+04	3.07E-04	2.60E+03
Mirror:5	160	4.21E+00	7.99E-01	1.40E+04	3.07E-04	2.60E+03
	161	4.21E+00	7.99E-01	1.40E+04	3.07E-04	2.60E+03
	162	4.31E+00	7.99E-01	1.43E+04	3.07E-04	2.60E+03
	163	4.31E+00	7.99E-01	-1.43E+04	3.07E-04	2.60E+03
Mirror:1	164	4.31E+00	7.99E-01	-1.43E+04	3.07E-04	2.60E+03
	165	4.31E+00	7.99E-01	-1.43E+04	3.07E-04	2.60E+03
	166	4.43E+00	7.99E-01	-1.47E+04	3.07E-04	2.60E+03
	167	4.43E+00	7.99E-01	1.47E+04	3.07E-04	2.60E+03
Mirror:2	168	4.43E+00	7.99E-01	1.47E+04	3.07E-04	2.60E+03
	169	4.43E+00	7.99E-01	1.47E+04	3.07E-04	2.60E+03
	170	4.78E+00	7.99E-01	1.58E+04	3.07E-04	2.60E+03
Crystal	171	4.78E+00	4.04E-02	7.87E+02	6.07E-03	6.65E+00
Detector	172	4.78E+00	4.04E-02	7.87E+02	6.07E-03	6.65E+00
	173	4.78E+00	4.04E-02	7.87E+02	6.07E-03	6.65E+00

	174	2.25E-01	4.04E-02	6.24E+01	3.66E-03	1.10E+01
Mirror:3	175	1.89E-01	4.04E-02	3.18E+01	6.07E-03	6.65E+00
	176	1.30E-01	4.04E-02	2.25E+01	6.07E-03	6.65E+00
	177	4.37E+00	4.04E-02	-7.20E+02	6.07E-03	6.65E+00
	178	4.37E+00	9.72E-01	1.78E+04	2.52E-04	3.86E+03
Mirror:4	179	4.37E+00	9.72E-01	1.78E+04	2.52E-04	3.86E+03
	180	4.37E+00	9.72E-01	1.78E+04	2.52E-04	3.86E+03
	181	4.63E+00	9.72E-01	1.88E+04	2.52E-04	3.86E+03
	182	4.63E+00	9.72E-01	-1.88E+04	2.52E-04	3.86E+03
Mirror:5	183	4.63E+00	9.72E-01	-1.88E+04	2.52E-04	3.86E+03
	184	4.63E+00	9.72E-01	-1.88E+04	2.52E-04	3.86E+03
	185	4.71E+00	9.72E-01	-1.91E+04	2.52E-04	3.86E+03
	186	4.71E+00	9.72E-01	1.91E+04	2.52E-04	3.86E+03
Mirror:1	187	4.71E+00	9.72E-01	1.91E+04	2.52E-04	3.86E+03
	188	4.71E+00	9.72E-01	1.91E+04	2.52E-04	3.86E+03
	IMA	4.71E+00	9.72E-01	1.91E+04	2.52E-04	3.86E+03

APPENDIX C: TI:SAPPHIRE OPTICAL PROPERTIES

Refractive Indices			Clean Transmittance			Dispersion Constant	
	λ[nm]		λ[nm]	T_i (5 mm)	T_i (25mm)	A_0	2.7091574
$n_{2325.4}$	2325.4		2325.4			A_1	-1.2750242
$n_{1970.1}$	1970.1		1970.1			A_2	2.7097845
$n_{1529.6}$	1529.6		1529.6			A_3	2.4436836
$n_{1060.0}$	1060.0	1.64947	1060.0			A_4	-2.1244237
n_t	1014.0	1.65062	700	0.999	0.995	A_5	2.3518172
n_s	852.1	1.65571	660	0.998	0.991		
n_r	706.5	1.66300	620	0.998	0.991		
n_C	656.3	1.66667	580	0.998	0.991		
$n_{C'}$	643.8	1.66772	546.1	0.998	0.988		
$n_{632.8}$	632.8	1.66870	500	0.995	0.975		
n_D	589.3	1.67319	460	0.990	0.950		
n_d	587.6	1.67339	435.8	0.983	0.92		
n_e	546.1	1.67889	420	0.977	0.89		
n_F	486.1	1.68997	404.7	0.963	0.83		
$n_{F'}$	480.0	1.69141	400	0.954	0.79		
n_g	435.8	1.70417	390	0.92	0.66		
n_h	404.7	1.71698	380	0.83	0.4		

Refractive Indices			Clean Transmittance			Dispersion Constant
n_i	365.0	1.74164	370	0.62	0.09	
			365.0	0.40		
			350	0.01		
			334.1			
			320			
			310			
			300			
			290			
			280			

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