HIGHLY EFFICIENT SINGLE FREQUENCY BLUE LASER GENERATION BY SECOND HARMONIC GENERATION OF INFRARED LASERS USING QUASI PHASE MATCHING IN PERIODICALLY POLED FERROELECTRIC CRYSTALS

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Performance and reliability of solid state laser diodes in the IR region exceeds those in the visible and UV part of the light spectrum. Single frequency visible and UV laser diodes with higher than 500 mW power are not available commercially. However we successfully stabilized a multi-longitudinal mode IR laser to 860 mW single frequency. This means high efficiency harmonic generation using this laser can produce visible and UV laser light not available otherwise. In this study we examined three major leading nonlinear crystals: PPMgO:SLN, PPKTP and PPMgO:SLT to generate blue light by second harmonic generation. We achieved record high net conversion efficiencies 81.3% using PPMgO:SLT (~500 mW out), and 81.1% using PPKTP (~700 mW out). In both these cases an external resonance buildup cavity was used. We also studied a less complicated single pass waveguide configuration (guided waist size of ~ 5 um compared to ~60 um) to generate blue. With PPMgO:SLN we obtained net 40.4% and using PPKT net 6.8% (110mW and 10.1 mW respectively).
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CHAPTER 1
INTRODUCTION

The discovery of the laser in 1960 [1] has had enormous impact on science, medicine and industry. The use of visible and ultra violet (UV) lasers in fundamental science, biophotonics and nanophotonics has revolutionized our understanding of universe in the last three decades. The technology of quantum wells in laser diodes in the visible and UV is not yet able to generate single frequency light with a power of more that 500mW directly with a reasonable life time. On the other hand, laser diodes and fiber lasers in near infrared (NIR) lasers are very well developed. InGaAs fiber coupled lasers diodes in the NIR used for pumping Yterbium, Erbium and Thulium fiber lasers and amplifiers have excellent high power performance, reliability and a life time of about 100 years. These efficient, single mode and fiber coupled DFB and DBR lasers are available in almost the entire range of NIR spectrum today.

Efficient harmonic generation, like frequency doubling and quadrupling of NIR lasers, using nonlinear crystals is a viable option for generating visible and UV light. Harmonic generation was discovered by Franken et al in 1961 [2] one year after the discovery of the laser. Today optical parametric oscillators and harmonic generation using nonlinear interaction of photons in birefringent crystals have made visible, UV and deep UV light more accessible.

Among nonlinear interactions used to produce harmonic generation, quasi-phasematching (QPM) is the most attractive. In this study, I have used the three leading periodically poled crystals, PPMgO:SLN, PPKTP and PPMgO:SLT to generate blue light. All these crystals are suitable for QPM in the NIR to produce single frequency blue laser via second harmonic generation (SHG). According to this study, each one of these crystals suffer some limitations and difficulties for the task of SHG. I will introduce our newest record high result of 81.3%
conversion efficiency from NIR to blue at 486 nm via SHG, using PPMgO:SLT in resonant
enhancement cavity. Today blue lasers have large numbers of applications including
fundamental science, bioscience and industry. Our blue laser could be a more efficient and
convenient replacement for multimode Argonne ion 488 nm laser that has been used widely.
This single frequency blue source could be used for efficient generation of UV light by SHG.
Therefore results of this study could help to generate single frequency UV light which is much
more challenging than producing visible lasers. Single frequency UV light about 243 nm could
be used in precision hydrogen atomic spectroscopy, sputter-initiated resonance ionization
spectroscopy of Be, In, and Tl atoms, and also isobar suppressed accelerator mass spectrometry
that few professors in our department are interested in.
2.1 Introduction

In this chapter, I briefly recall available commercial NIR laser sources at about 972 nm which is in wavelength range of interest to us for precision hydrogen spectroscopy and our choice of laser diode because of its convenience and simplicity over other sources. Then a summary of quantum well laser diode theory and related optoelectronic parameters will discussed. Some of these parameters can be measured directly and some must be drawn indirectly. The laser diode used in this experiment is originally a PM fiber coupled diode operating in single transverse mode, but multilongitudinal modes. For efficient frequency doubling, this laser must be operating in a single frequency mode. Both of our single frequency stabilizing approaches including injection seeding and FBG stabilizing will be discussed. At the end, the modified single frequency laser behavior and its optoelectronic parameters will be modeled and determined.

2.2 Most Common Available NIR Laser Sources about 980 nm

2.2.1 Nd:Yag Laser

Neodymium-doped yttrium aluminum garnet (Nd:Y₃Al₅O₁₂) is one the most common solid state in NIR region. It was first demonstrated by Bell Laboratories in 1964[3]. Nd:Yag laser is famous for 1064 nm emission, however it has transitions near 940, 1120, 1320, and 1440 nm lines (see FIG. 2-1). The most drawback of this laser is the fact that it has to be pumped with another light in the bands between 730–760 nm or 790–820 nm. To generate about ~1W of CW single frequency, it requires tens of watts of pumping power which makes it bulky, complicated, power ineffective and costly (see the FIG. 2-2).
2.2.2 Ti:Sapphire laser

Titanium-sapphire lasers (Ti:Al₂O₃) are tunable lasers which emit red and NIR light in the range from 650 to 1100 nanometers. Ti:Sapphire laser was first demonstrated in 1982 [4]. A Ti:sapphire laser can be pumped within the absorption band of 490 to 532 nm.

Just like Nd:Yag laser, the Ti:Saphier is bulky, it needs to be pumped with another laser and has a number of optics and parts to operate. The drawbacks are the need of a visible pump, relatively complicated, high cost and cumbersome.
2.2.3 Ytterbium Doped Fiber Laser

NIR Radiation from Y_{r^{3+}} doped silicate glass was reported in 1962 [5] and first fiber laser was demonstrated in 1964 [6]. The importance of Y_{r^{3+}} fiber lasers were not realized until fiber laser communication was proposed. Fiber lasers since then have been dramatically improved.

![Absorption and emission band of Yr^{3+}](image)

**FIG. 2-5:** Absorption and emission band of Yr^{3+}.

An example of Yr^{+} laser.

**FIG. 2-6:** An example of Yr^{+} laser.

Yr^{3+} laser like the above lasers needs to be pumped by a second laser. Absorption peaks of Yr^{3+} are at about 915 nm and at 975 nm. An Yr^{3+} laser system operating at 972 nm with single frequency output power of ~1 Watt is still very costly but less cumbersome of previous laser sources.

2.2.4 Semiconductor InGaAs pump lasers

Semiconductor material InGaAs with composites of GaAs (bandgap of 1.42 eV at 300 K) to InAs (bandgap of 0.34 eV at 300 K) is a technologically important semiconductor widely exploited in optical communications, photovoltaics, sensors and laser applications [7]. InGaAs is a popular material in triple-junction photovoltaics, photodiodes and also for thermo-
photovoltaic power generation. InGaAs can be used as a laser medium too. Laser devices have been constructed operating at NIR wavelengths of 900-1300 nm.

Advanced laser diodes (LD) about 972 nm based on InGaAs quantum-well (QW) active region embedded into a thin AlGaAs optical cavity waveguides have been developed for telecom applications [8]. These efficient pump lasers with output power of ~1 Watt are designed to pump telecom co-doped Erbium and Ytterbium fiber amplifiers. The laser chip is installed in a hermetically sealed and small Butterfly package of 30 mm (L), 12 mm (W) and 8 mm (H). The laser power is coupled from chip into a polarization maintaining (PM) fiber which makes it easy to be incorporated in optical-electronic devices.

FIG. 2-7: An example of 980 nm pump laser in Butterfly package.

This laser needs only a dual controller for operation, including a laser diode current controller (max 1.5 A, 2.75 V, 4.2 W) and a TEC current controller (max 1 A, 4 V, 4 W).

2.3 Advanced Fiber Coupled 980 nm Laser Sources for SHG

Fiber coupled semiconductor quantum-well 980 nm pump lasers introduced in the section 2.2.4 and FIG. 2-7 are the most convenient sources for generating blue via SHG for us. So from now on, I will concentrate on this type of lasers. This laser is our choice of fundamental NIR source for SHG to the blue. In the remaining of the chapter, their characteristics will be altered
and studied. First I will give some information about their physical properties. Then their operation will be altered from multifrequency to single frequency by two different techniques. Also a number of optoelectronic values will be measured directly and indirectly with the aid of a Mathematica program.

2.3.1 Physical Properties and General Information

The LD in the package is welded on a thermoelectric cooler (TEC) for thermal stability. An installed miniature thermistor inside the package monitors the stabilized temperature. A photodiode detector (PD) facing the back facet of LD measures a very small power running out of the back of the laser chip and is usually calibrated and used for monitoring the output power without using an extra power meter at the fiber output.

FIG. 2-8: An example of inside the 980 nm pump laser in a cooled Butterfly package.

FIG. 2-9: Pin layout of 980 pump lasers, (laser diode: pins 9, 10), (TEC: Pins 1, 14), (thermistor: pins 2, 5) and (photodiode: pins 3, 4).
Typical 980 pump lasers with about ~1 Watt output power have a laser diode WG with cross section area of ~6 µm horizontal and ~1 µm vertical, therefore the laser beam coming out of laser chip is elliptical with larger vertical divergence, due to smaller beam size at the facet of LD (see FIG. 2-10).

![FIG. 2-10: Elliptical beam coming out of most ridge WG laser chips.](image)

Theoretically for efficiently coupling an elliptical laser beam into a circular fiber, three antireflection (AR) coated cylindrical lenses are needed, two for vertical due to high degree of divergence, and one for horizontal (see FIG. 2-11).

![FIG. 2-11: Using a set of three cylindrical lenses to couple light from chip to fiber efficiently.](image)

Experimentally the setup above is too complicated and needs a lot of alignment, therefore mass production would not be cost effective. Practically instead of lens setup above, a wedge
shaped and (AR) coated fiber tip (Fig. 2-12) is used to couple the laser chip emission to a PM fiber with efficiency of about ~80%. Therefore their original elliptical beam shape coming out of laser chip will be corrected by single mode fiber to an excellent circular TEM\textsubscript{00} Gaussian beam desirable for SHG.

![Wedge shaped fiber](image)

**FIG. 2-12:** Wedge shaped fiber used in 980 pump lasers with 80% coupling efficiency.

2.3.2 Laser Behavior and Spectrum in Free Running Regime

Commercially, these lasers are not available in single frequency and could not be used for highly efficient SHG. They operate in coherence collapse with single-transverse mode, but multi-longitudinal modes. So their spectrum bandwidth is few nanometers. The center of wavelength is determined by a feedback scheme, made of a fiber Bragg grating (FBG). The FBG provides a reflection (0.2~0.8 nm bandwidth) back to laser for multi longitudinal mode stabilizing. The FBG is placed about 1.5 meters away from the laser chip (the FIG. 2-13).

![Schematic](image)

**FIG. 2-13:** Schematic of a 980 pump laser with a FBG placed about 1.5 meter away from the laser chip (schematic is not scaled).
The tip of fiber is connectorized with 8 degree angle polished connector (FC/APC) which eliminates feedbacks from the tip of fiber up to 40dB.

Since these lasers are designed for pumping Yt\(^{3+}\) fiber amplifier for telecommunication applications, they must have very good power stability rather than short wavelength bandwidth. As it was shown in FIG. 2-5, the absorption bandwidth of Yt\(^{3+}\) is as wide as ~5 nm centered at 975 nm. The laser configuration with operation in coherence-collapse (coherence length of few cm) and cavity length of 1.5 m, make it robust against variations in optical path, mode-hops and power fluctuations [8].

For studying the free running laser behavior and spectrum, we cut off the original FBG that came with the laser (FIG. 2-14).

With no FBG attached, the laser operates in free running regime in which the center wavelength of lasing would vary by laser diode temperature and laser diode current variations. I measured these variations constants for our laser using an optical spectrum analyzer (OSA) to be:

\[
\frac{\Delta \lambda}{\Delta T} = 0.400 \frac{nm}{^\circ C} \quad (2-1)
\]

\[
\frac{\Delta \lambda}{\Delta I} = 0.008 \frac{nm}{mA} \quad (2-2)
\]

With \(\lambda\) is the laser wavelength, \(T\) is the laser chip temperature, \(I\) is the laser current. Below the lasing threshold current, the laser operates in spontaneous emission regime which a wide
florescence with a bandwidth of about 6.5 nm at the full width maximum (FWHM) of the main peak (FIG. 2-15).

![Florescence emission below threshold](image1.png)

FIG: 2-15: Florescence emission below threshold which for this laser was with bandwidth about 6.5 nm at FWHM.

Also below threshold, we can estimate the free spectra range (FSR) or mode spacing of the laser chip cavity as function length and index of refraction of laser chip:

\[
FSR(\text{Hz}) = \frac{c}{2nL} \quad (2-3)
\]

Where \( c \) is the speed of light, \( n \) is index of refraction InGaAs (active lasing media), and \( L \) is the laser chip length. Monitoring florescence below threshold with a low span of 1 nm on OSA, the Fabry-Perot sine wave modulation due to laser chip cavity will appear (FIG. 2-16).

![Florescence with a span of 1 nm](image2.png)

FIG. 2-16: Florescence with a span of 1 nm, shows the Fabry-Perot sine wave modulation due to laser chip cavity.
The laser chip cavity consists a back facet with reflectivity of ~98%, front facet with reflectivity of ~0.1% and laser media between two these two reflector (FIG. 2-17)

![Diagram of laser chip cavity configuration]

FIG. 2-17: Laser chip cavity configuration.

Using the modulation in the FIG. 2-16, we estimated the distance between two peaks (FSR) to be about 0.0329 nm which is equivalent of 10.7 GHz. Also the pattern repeat itself each 0.5 °C by varying laser chip temperature. So FSR of laser is equal to:

FSR of the laser chip = 10.695 GHz, \( \Delta \lambda \) (FSR) = 0.0328 nm, \( \Delta T \) (FSR) = 0.5 °C \hspace{1cm} (2-4)

The laser active media length \( L \) was estimated at 3.3 mm (measured by unpacking a similar laser with the same behavior), so an index of \( n = 4.25 \) is derived by using Eq. (2-3). Right at the lasing threshold current, the laser peak starts appearing at the top the florescence emission (FIG. 2-18).

![Graph of laser threshold]

FIG. 2-18: Observing threshold using OSA, by slowly increasing the laser current.
The laser threshold current could be measured using three different techniques of
(1) monitoring the laser output power at the tip of fiber, (2) monitoring the photodiode current and (3) using OSA.

![Image of Laser threshold as a function of laser current]

**FIG. 2-19:** Measured laser threshold using photodiode current.

For this laser the threshold current measured by OSA (FIG. 2-18) and monitoring the internal photodiode current (FIG. 2-19) both agreed at about 47.1 mA. The laser threshold varies as a function of temperature. At lower the temperature, the lower threshold current (FIG. 2-20).

![Image of Laser threshold as a function of current at different temperatures]

**FIG. 2-20:** Laser threshold current at 25 °C, 10 °C and 0°C.
Above the threshold current, the laser power increases with a constant slope efficiency as function of laser current. For this laser, the power increases linearly up to 1400 mA current with 981 mW of power. Above the 1400 mA current, the slope falls off (FIG. 2-21).

FIG. 2-21: Linearity of output power versus laser current in free running regime.

Above threshold, the spectrum of our laser in free running regime was measured using an OSA (See FIG. 2-22). As it could be seen, the laser has a wide bandwidth of several nm with many number of modes available.

FIG. 2-22: The spectrum of free running laser at maximum 980 mW output power.
2.3.3 Stabilizing the Laser in Coherence-Collapse Regime

Now we want to fuse back the original wide FBG that laser came with and study the laser behavior. This FBG is going to lock the wavelength of the laser. Used as a feedback element a percentage of light with a certain bandwidth is reflected back to the laser, it forces the laser for into stimulated emission (FIG. 2-23). Laser diodes are very sensitive to optical feedback. Ironically under certain circumstances this sensitivity can be used in our advantages. This feedback can provide two functions, narrowing the laser spectral width and also center wavelength stabilization [9].

![Laser chip and FBG schematic.](image)

For telecom applications, mode hop free and power stability are very important for amplifying digital data. So single frequency operation of the pump is not necessary. Therefore the FBG could be broad enough to reflect several longitudinal mode (multi-mode operation). A broad bandwidth FBG and a long distance between FBG and laser chip ($L_{EXT}$) beyond laser...
coherence (coherence-collapse) will provide conditions to avoid unstable coherent phase effects which are responsible for mode hoping and power instability [10].

To measure the bandwidth of the FBG accurately, we did not have an OSA with needed resolution of about 0.01 nm. Instead we developed a simple setup, monitoring the transmission profile of a single frequency laser through FBG as function temperature. A temperature stabilized copper groove which contains the FBG is used. The copper groove is placed on the top of TEC with a temperature controller capable of stabilizing the temperature of copper groove within 0.01°C. An accurate transmission profile measurement could be done by sending a narrow single frequency light, with wavelength of close to the FBG’s reflection center, through the FBG and recoding the transmitted values (FIG. 2-24).

FIG. 2-24: Schematic of setup for measuring the bandwidth of FBG by scanning the temperature of FBG and detecting the transmitted single frequency power.

Using the setup above, we measured the bandwidth of the original broadband FBG required for coherence-collapse for our laser at about 14°C at FWHM (see FIG. 2-25). Also we measured the wavelength shift of the FBG as a function temperature at 0.0067 nm/°C. Therefore the FBG bandwidth (∆λ) at FWHM becomes:

\[ ∆λ(FWHM) = 14 \times 0.0067 = 0.0939\text{nm} \approx 30\text{GHz} \] (2-5)

This bandwidth is about three times of FSR of laser chip that we measured to be at 10.7GHz (Eq. (2-4)). So several longitudinal modes would lase at same time if this FBG is used for mode
locking. This bandwidth is related to length of FBG, the longer FBG, the smaller the bandwidth of FBG would be [11]:

\[
\Delta \lambda (FWHM) = \frac{\lambda^2}{2n_{eff}L_{FBG}}
\]

(2-6)

Where \( \lambda \) is the center wavelength of reflectivity, \( n_{eff} \) is effective index of refraction of fused silica that fiber is made of, and \( L_{FBG} \) is equivalent uniform gating length. So the length of this FBG is:

\[
L_{FBG} = \frac{\lambda^2}{2n_{eff} \Delta \lambda (FWHM)} = 3.51 \text{mm}
\]

(2-7)

Where \( \lambda = 974 \text{nm} \), \( \Delta \lambda (FWHM) = 0.0939 \text{nm} \), and \( n_{eff} = 1.45 \) for fused silica at room temperature and operating wavelength of \( \lambda = 974 \text{nm} \).

FIG. 2-25: Transmitted power of a single frequency light through a broad FBG as function of temperature.

Also using FIG. 2-25, the peak reflectivity of this FBG can be calculated:

\[
R_{FBG} = \text{reflectivity(peak)} \approx (1 - \frac{6.5}{7}) \times 100 = 7.14\%
\]

(2-8)
While the laser is in the free running regime, we also developed a setup to measure the output facet reflectivity of the laser chip ($R_O$) in the FIG. 2-23. This value could be useful for this section of our study. Using a signal at 974 nm, a 2X2 fiber beam splitter, and a fiber coupled optical isolator we prepared the setup below:

![Schematic of the setup to measure output facet reflectivity of the testing laser.](image)

In the setup above a multimode signal laser, which isolated from the rest of setup to avoid mode hopping and power instability, will be divided to two path after 2X2 beam splitter. About 99.9% of signal power ($P_{in}$) goes into testing laser and 0.1% is being used in the monitoring power which is used to determine the actual value of $P_{in}$. There are number of losses due to fiber fuses and splitter that should be carefully considered for accurate analysis. So during the setup assembly each loss must be taken into account by careful and consistent power measurements. For our setup there were 3 fiber fuses after the splitter. The loss for each fuse was measured by measuring the power before and after fuse. We made sure that fuse losses would not exceed 2%. So after careful measurements and considering all losses, we had $P_{in} = 6.618 \, \mu W$ and $P_r = 6.9 \, nW$. Therefore the $R_O$ for this laser becomes:

$$R_O = \frac{P_r}{P_{in}} \times 100 = \frac{0.0069}{6.618} \times 100 = 0.104\% \quad (2-9)$$

Now that both $R_{FBG}$ and $R_O$ are measured, we are able to calculate the effective incoherent
reflectivity back to the laser chip when a broad FBG at a large distance beyond coherence length from laser chip is used to stabilize the laser in coherence-collapse regime [10]:

\[
R_{\text{INCOH}} = (R_O + CE^2 \frac{(1 - R_O)^2 R_{FBG}(\omega)}{1 - R_{FBG}(\omega) R_O}) \times 100 = 4.64\% \quad (2-10)
\]

Where \( R_O = 0.00104 \), \( R_{FBG} = 0.0714 \) and the chip to fiber coupling efficiency was given by manufacturer for this laser to be \( CE = 0.798 \). Now we fuse back this FBG to the laser at about 0.5 m away from laser chip.

First I will measured the threshold of laser after fusing the broad FBG. Since there is an effective \( R_{\text{INCOH}} = 4.64\% \) back to laser chip, we expect that lasing threshold be less than 47.1 mA measured in the section 2.3.2 for free running laser. The FIG. 2-28 shows the threshold of laser at 36.2 mA. So the threshold is 10.9 mA lower than free running threshold of 47.1 mA.
We also measured the output power as a function of laser current. The power is still linear up to 1400 mA with output power of 935 mW (FIG. 2-29).

![Output power versus laser current with the original 7.14% FBG and free running](image)

**FIG. 2-29:** Output power comparison between free running and with 7.14% FBG.

There is a decrease of output power which the FBG reflectivity is responsible for. The percentage of decreased power is comparable with the effective reflection back to laser chip calculated by Eq. (2-10).

\[
\text{Power loss with FBG} = (1 - \frac{P_{\text{With-FBG}}}{P_{\text{Free-running}}}) \times 100 = (1 - \frac{934}{981}) \times 100 = 4.79\% \tag{2-11}
\]

Spectrum of laser locked with 7.14% FBG is narrower than free running shown by FIG. 2-30.

![Spectrum of laser](image)

**FIG. 2-30:** (A) Spectrum of laser in free running. (B) in coherence-collapse with 7.14% FBG.
The spectrum in the FIG. 2-28 (B) is missing modulations due to FBG distance from laser chip which is placed at the distance of about \( L_{\text{EXT}} = 0.5 \) m. The mode spacing for this distance is equal to:

\[
\text{Mode Spacing} = \frac{C}{2nL_{\text{EXT}}} = \frac{3 \times 10^8}{2 \times 1.45 \times 0.5} = 204 \text{MHz} = 0.00068 \text{nm} \quad (2-12)
\]

But the OSA (Ando AQ-6312B) used to plot the laser spectrum in FIG. 2-31 has the maximum resolution of 0.1 nm, so it would not be able to show modulations with mode spacing of 0.00068 nm. To observe these modulations, we needed much more resolutions than 0.1 nm. So we constructed a simple fiber coupled scanning spectrum analyzer made of two curved high reflector mirror and a piezoelectric ring between two mirrors (FIG. 2-31).

![FIG. 2-31: Schematic of our homemade scanning spectrum analyzer.](image)

The setup is made of two identical concentric mirrors with curvature \( R = 20 \) mm and a distance \( L=2.638 \) mm between two mirrors. Therefore the \( g \) factor for such cavity becomes [12]:
\[
g = 1 - \frac{L}{R} = 1 - \frac{2.638}{20} = 0.8681 \quad (2-13)
\]

The FSR is equal to [12]:

\[
FSR = \frac{C}{2nL} = \frac{3 \times 10^8}{2 \times 1 \times 0.002638} = 56.86 GHz \quad (2-14)
\]

For Gaussian circular beam, the mode space between main peak TEM\(_{00}\) and the first odd mode TEM\(_{01}\) which is on top of TEM\(_{10}\) would be [12]:

\[
\text{First odd mode space} = FSR \times \frac{\cos^{-1}(g)}{\pi} = 9.406 GHz \quad (2-15)
\]

The focusing lens with focal length of 4.5 mm in the FIG. 2-32 adjusts the beam waist size of 3.3 \(\mu m\) (half of mode field diameter) at the tip of fiber to optimum Eigenmode waist sizes of [12]:

\[
\omega_o = \sqrt{\frac{L \lambda}{\pi} \frac{g + 1}{4(1 - g)}} = 39.19 \mu m \quad (2-16)
\]

\[
\omega_{1,2} = \sqrt{\frac{L \lambda}{\pi} \frac{1 - g^2}{4(1 - g)}} = 40.55 \mu m \quad (2-17)
\]

Where wavelength of light \(\lambda = 972\) nm, the distance between two mirrors \(L = 2.638\) mm, the cavity factor \(g = 0.8681\).

FIG. 2-32: Beam size adjustment from tip of fiber into the scanning spectrum analyzer.
Using this spectrum analyzer, we would be able to see the mode space of 204 MHz calculated by Eq. (2-12) for the length of 0.5 m between FBG and the laser chip, on the screen of the oscilloscope in FIG. 3-31. Coherence collapse can be seen in FIG. 2-33, which number of longitudinal modes with mode space of about 200 MHz are present. Each horizontal unit on oscilloscope is calibrated to be 486.5 MHz. So as it could be seen in the figure below, there are almost 12 mode spaces, contained in 5 horizontal units.

![FIG. 2-33: Laser in coherence-collapse regime using scanning spectrum analyzer.](image)

Now using the spectrum above, we can estimate $L_{\text{EXT}}$, the distance between FBG and laser chip more accurately using the mode space:

$$\text{Mode Spacing} = \frac{5}{12} \times 486.5 = 202.708 \text{MHz} \quad (2-18)$$

Using equation (2-12) $L_{\text{EXT}}$ becomes:

$$L_{\text{EXT}} = \frac{C}{2n \times 202.708 \text{MHz}} = 0.51033 \text{m} \quad (2-19)$$

This scanning spectrum analyzer will be very handy in the next section when we try to stabilize the laser in single frequency operation.
2.3.4 Stabilizing the Laser in Single Frequency Operation

According to our experience working with lasers from variety of manufacturers, to stabilize them in reliable single frequency operation with their maximum nominal output power, five essential requirements must be met.

1- The distance \( L_{\text{EXT}} \) between the FBG and the laser chip must be minimized and within coherence length.

2- The laser chip output facet reflectivity must be as low as possible \( R_{\text{OC}} \leq 0.1\% \).

3- The FBG bandwidth at FWHM must be less than one third of FSR of the laser chip.

4- Fiber attached to the laser must be polarization maintaining (PM) and polarization extension ratio (PER) of coupled fiber must be minimized, -20 dB or better.

5- Fiber coupling efficiency must be very good, \( \text{CE}_1 = 80\% \) or more.

By minimizing \( L_{\text{EXT}} \), the mode spacing or FSR of external cavity becomes larger, therefore mode hopping becomes less probable. Low output facet reflectivity makes the amplitude of Fabry-Prot modulations shown in the FIG. 2-16 minimized, therefore the external cavity due to FBG becomes more dominant for stabilizing the laser. This will result in less competition between internal chip modes and external cavity modes. The narrower the bandwidth of FBG is, the narrower the feedback bandwidth. Therefore the stimulated emission of laser becomes narrower. According to our results a minimum of 0.01 bandwidth at FWHM or less is required. After several years of experience with our Fujikura FSM-20PMII for splicing PM fibers and studying the settings and conditions, we are able fuse a FBG as close as 10 cm to the laser chip. The fuse loss must be minimized too. Any fuse loss contributes to output power loss, loss in the external cavity and decreasing effective reflectivity back to the chip from the FBG. We are able to make fuses with loss of as low as 0.2% with our fiber splicer, if fiber tip’s angles cleaved and prepared
for splice are less than 0.2 degrees.

PER is important too. We had lasers with PER of -10 dB that were not capable of being stabilized in single frequency at their highest power. Also a high coupling efficiency of the laser chip to fiber is desired, for maximum power delivery and minimizing feedback loss from FBG.

Prior to the year 2006, none of these conditions were met. Lasers with higher output power than 500 mW were not available. The laser chip output facet reflectivity (Roc) were high, ranging 2-8%. Lasers with PM fiber were not available commercially. A non-PM fiber could cause polarization rotation in the fiber by twisting or fiber motion, and consequently polarization rotation in feedback and laser mode hopping. The fiber coupling efficiency (Ce1) of most lasers was as poor as 50% at the time of our study. FBG with narrow bandwidth were not available commercially. The best custom made FBG we could order had ~0.02 nm (6 GHz) bandwidth at FWHM.

Late 2005, the best setup we had was a nominally 500 mW laser with PM fiber, output facet reflectivity (Roc) of ~2%, chip to fiber coupling efficiency (CE) of 65%. The custom FBG fused to this laser had the nominally length 4 cm, but our measured bandwidth was 0.04 and effective equivalent uniform length was 1 cm. Also we discovered that this FBG has a chirp along the length that causes very high bandwidth. To solve this problem we used a temperature gradient along the length of FBG, a copper groove containing FBG was placed on the top of two TECs forming temperature gradient along the length of FBG (FIG. 2-34)

![FIG. 2-34: Temperature gradient imposed on FBG to improve the bandwidth.](image-url)
The measured bandwidth with and without temperature gradient shows a significant improvement the bandwidth. Trying number of gradients in both directions with different gradient values, we found that $\Delta T = T_2 - T_1 = -15 \, ^\circ\text{C}$ (in FIG. 2-34) is an optimum condition which made the reflection spectrum uniform with minimum possible bandwidth of 0.02 nm (FIG. 2-35).

![FBG bandwidth with and without temperature gradient](image)

**FIG. 2-35**: Temperature gradient applied to FBG for improving the bandwidth.

The bandwidth of 0.02 nm was not good enough yet to stabilize the laser at highest laser output power. Then we fused this temperature gradient altered FBG to the laser with maximum power of 500 mW. The laser would stabilize in single frequency up to 100 mW power (above 100 mW was multimode). The spectrum of laser in single frequency using Ando AQ-6312B OSA and our homemade scanning spectrum analyzer confirms the single frequency operation (FIG. 2-36).

![Spectrum of single frequency](image)

**FIG. 2-36**: Spectrum of single frequency (A) using OSA, (B) using scanning analyzer

~9 GHz mode space
Unfortunately, above 100 mW of operating laser spectrum degrades to multimode operation. 100 mW was the highest single frequency power we could get out of this laser. To improve the single frequency operation, we decided to upgrade the setup to a much more complicated injection seeding one. In this setup the laser above was going to provide a single frequency seed and a second identical free running laser to amplify the seed.

![Diagram of Seed-Amplifier setup](image)

FIG. 2-37: Seed-Amplifier setup to improve 100 mW single frequency power to 500 mW.

The setup in the FIG. 2-37 was not as simple as we intended for this project. It had too many optical elements such as two lasers, one FBG, an optical isolator and a 2X2 fiber beam splitter. This was the best we could have at the given time.

By the beginning of year 2006, one of the laser manufacturers produced a significant improvement in their laser products. This new generation of telecom lasers had improvement in the output power, front facet reflectivity and also chip to fiber coupling efficiency. Our initial examination of these lasers convinced us that we should be able stabilize them in single frequency with a narrow FBG, having a bandwidth as low as 0.01 nm or 3 GHz. So we invested in a FBG phasemask to write narrow FBG at the recommendation a FBG manufacturer. This new phasemask would enable the manufacturer to write FBG with bandwidth of about 0.01 nm.
A few initial FBGs made by this phasemask showed the possibility of having a 0.01 nm bandwidth. But the manufacturer’s OSA with standard low resolution used during the FBG writing process was problematic. The reflectivity and bandwidth of the FBG measured by this manufacturer were different than what we were measuring using the setup FIG. 2-24. The spectrum collected by manufacturer showed 4 times less reflectivity and a correspondingly wider bandwidth than was actually the case. Our measurement was much more accurate than the standard OSA. After exchanging this information with the FBG manufacturer and calibrating their results with our results, they were able to write a FBG with our desired reflectivity and bandwidth.

By beginning of 2006, newly available generation of telecom lasers and narrow FBGs lead us to our first single frequency laser with maximum output power of 860 mW. This laser is the primary IR source to be used in generation of blue light for our subsequent studies of harmonic generations (FIG. 2-38).

![FIG. 2-38: Schematic of single frequency laser, including laser diode and a narrow FBG fused 15 cm away from laser chip.](image)

A number of FBGs with different reflectivities were tried on these new generation of telecom lasers. Comparing results from all, we concluded that ~9% reflective FBG is a good compromised reflectivity of FBG for laser operation stability and output power. Below 9% FBG, some instability was observed but output power was higher. Also laser operation was
studied using above 9% FBG, the maximum output power was decreased. With higher than 10% FBG, above 700 mW single frequency operation laser diode was chaotic and frequent mode hopping occurred.

The setup introduced in FIG. 2-24 was used for measuring the reflectivity and bandwidth of the FBG that experimentally gave the best results. Accurate measurement of reflectivity and bandwidth was done by 0.2 °C increments of the FBG’s temperature scanning (FIG. 2-39). The bandwidth of FBG at FWHM was measured at 1.51 °C which is equal to:

\[
\Delta \lambda (FWHM) = 1.51 \times 0.0067 = 0.0101 nm \simeq 3 GHz \tag{2-20}
\]

The reflectivity at the peak of spectrum in FIG. 2-39 is equal to:

\[
R_{FBG} = \text{reflectivity} (\text{peak}) \simeq (1 - \frac{157.8}{173}) \times 100 = 8.8\% \tag{2-21}
\]

FIG. 2-39: Spectrum of narrow FBG response as a function of temperature.

The equivalent uniform FBG length can be calculated at:

\[
L_{FBG} = \frac{\lambda^2}{2n_{eff}.\Delta\lambda (FWHM)} = 3.23 mm \tag{2-22}
\]

Where \( \lambda = 972 nm \), \( \Delta\lambda (FWHM) = 0.0101 nm \), and \( n_{eff} = 1.45 \) for fused silica at 65 °C
temperature and operating wavelength of $\lambda = 972\,nm$. Therefore our nominally 4 cm written FBG has the equivalent uniform grating of 3.23 cm instead of 4 cm.

The threshold of the laser with narrow 8.8% FBG (single frequency operation) was compared with free running (broad multimode operation) and 7.14% broad FBG (coherence collapse operation). When first we measured threshold current with the narrow 8.8% FBG, it was surprisingly close to the threshold with a 7.18% broad FBG (FIG. 2-40). But when I slightly changed the temperature of laser chip, for example by 0.1 °C, the threshold current would change by 2 mA. This was not happening when the threshold was measured while free running (FIG. 2-19), in this situation the threshold was changing maybe by about 2 mA for 10 °C laser chip temperature change.

Then we realized that with the narrow FBG and laser is in a coherent regime, which the reflection of FBG ($R_{FBG}$) and reflection of laser front facet reflectivity ($R_0$) could add to each other constructively and destructively based on the relative phase of two. Therefore, the laser threshold current as a function of laser chip temperature shows an almost uniform modulation that repeats itself with period of 0.5 °C (see FIG. 3-41). The period of modulation is exactly

![FIG. 2-40: Threshold current comparison for three different regimes.](image-url)
equal to FSR of laser chip measured by Eq. (2-4) for this laser. According to [10], the effective reflection back to laser chip due to the combination output facet reflectivity ($R_O$) and narrow FBG reflectivity ($R_{FBG}$) in coherence single frequency regime is equal to:

$$R_{COH} = \left( \sqrt{R_O} + CE \frac{(1 - R_O)}{e^{2i\phi} + \sqrt{R_{FBG}(\omega)R_O}} \right)^2 \times 100 \quad (2-23)$$

The $e^{2i\phi}$ is equal to 1 when the peak reflectivities of $R_O$ and $R_{FBG}$ are in phase and $e^{2i\phi}$ is equal to -1 when they are completely out of phase. Therefore, if $R_O = 0.00104$, $R_{FBG} = 0.088$, chip to fiber coupling efficiency $CE = 0.798$, the $R_{COH}$ has the range of (in phase and out of phase):

$$4.27\% \leq R_{COH} \leq 7.34\% \quad (2-24)$$

So when the peak reflectivity of FBG and output facet line up the effective reflectivity $R_{COH}$ is at highest value of 7.34% and threshold is at lowest value of 34.2 mA (FIG. 3-41). On the other hand, when the peak reflectivity of FBG and output facet are in the opposite phase the reflection of $R_{COH}$ is at the lowest value of 4.27% and threshold current is at highest value of 36.2 mA.
The single frequency operation was more stable when the two reflectivities were in phase and less mode hoppings would occurred. As expected, there was less output power available due to higher $R_{\text{COH}}$ at this condition. The single frequency output power when the $R_{\text{COH}}$ is maximum along with comparison to free running and coherence collapse output power is shown in FIG. 2-42.

![Output power comparison of free running, coherence collapse and single frequency.](image)

FIG. 2-42: Output power comparison of free running, coherence collapse and single frequency.

There is a sudden falloff of output power about 1180 mA, as it can be seen in FIG 2-42. This is a phenomena called coherent kink. At the kink condition, there is a slight 1–3° beam steering in the laser chip, which causes less power coupling into the fiber [13]. Also the laser operates in several lateral modes, therefore at the kink the single frequency operation collapses to multiple transverse modes. But when we increased the current above the kink current, the laser goes back to normal single frequency operation and normal power increase with normal constant slope.

The polarization extension ratio (PER) for this laser using a calcite polarizer at highest power was measured too. The polarization of lasing coming out of chip is in horizontal and
launched in the slow axis of PM fiber. The measured power after calcite in the vertical direction (fast axis of fiber) was \( \sim 8.77 \text{ mW} \) when total output power was 860 mw. So PER becomes:

\[
\text{PER} = \frac{8.77 \text{mW}}{860 \text{mW}} = 0.0102 = -19.91 \text{dB}
\]  
(2-25)

This laser has enough power (860 mW) in single frequency, with good stability, bandwidth and low PER to be used in an efficient SHG setup to generate single frequency blue light.

2.4 Modeling the Behavior of FBG stabilized 972 nm Single Frequency Laser

Semiconductor lasers work just like a p-n junction diode. In semiconductors, due to the spetial overlap of wavefunctions, each electron has a unique wavefunction and there is no two electron with same wavefunction [14]. Bloch’s theorem states that eigenfunctions of the electron wave equation in a periodical potential like semiconductors should be a product of plane wave \( e^{ikr} \) times a function of \( u_k(r) \) [15]:

\[
\psi_r(r) = u_k(r)e^{ikr}
\]  
(2-26)

The factor \( e^{ikr} \) contains the wave nature of electron and can be represented by Broglie wavelength \( \lambda \) of electron [14]:

\[
\lambda = \frac{2\pi}{k}
\]  
(2-27)

Since the \( k \) vector is quantized, the total phase shift of \( kr \) across the laser cavity with Cartesian dimensions of \( L_x, L_y \) and \( L_z \) must be multiple integer of \( 2\pi \) [14]:

\[
k_xL_x = 2n\pi \quad k_yL_y = 2n\pi \quad k_zL_z = 2n\pi \quad n = 1,2,3,\ldots
\]  
(2-28)

2.4.1 Cavity Configuration of Fiber Coupled Semiconductor Lasers

The laser structure is made of a cavity that creates and guides photons. There are multiple reflections photons back and forth, only a small fraction of photons could scape and
leave the cavity [16]. The semiconductor laser cavity has a high reflector back facet (RB) and a very low output facet reflector (RO). These two reflectors form an internal cavity in the chip. This cavity is coupled into a second reflector made by FBG. The center wavelength of laser operation is determined by the center wavelength of FBG. A lens shaped fiber tip inside package couples the laser generated in the semiconductor chip into the PM single mode fiber with coupling efficiency of CE1. The FBG written in the fiber which is at the distance of L_{EXT} from laser chip, forming a distributed Bragg reflector (DBR). This FBG with reflectivity of R_{FBG} is fused with the efficiency of CE2 to the actual fiber coming out of laser package (FIG. 2-43). A close to zero percent fuse loss or high CE2 is desirable for having maximum laser power out and also having required optimum reflectivity value back to the laser chip by FBG.

![Schematic of pump laser cavity including chip cavity and external FBG feedback (dimensions are not to the scale).](image)

**FIG. 2-43:** Schematic of pump laser cavity including chip cavity and external FBG feedback (dimensions are not to the scale).

2.4.2 Small Signal Circulation with no Loss nor Gain in the Laser Cavity

Now we want to determine the total transmission and reflection of a signal traveling from back
facet of laser chip passing through output facet of chip with reflectivity magnitude of $R_o$ and then through FBG with reflectivity magnitude of $R_{FBG}$.

![Diagram](image)

**FIG. 2-44:** Small signal reflection and transmission starting the left side of cavity.

So let's recall the following parameters in the cavity:

$L_{EXT}$ = The distance between FBG and output facet

$R_o$ = Reflectivity magnitude of output facet

$\sqrt{R_o}$ = Amplitude reflection coefficient of output facet

$\sqrt{1 - R_o}$ = Amplitude transmission coefficient of output facet

$R_{FBG}$ = Reflectivity magnitude of FBG

$\sqrt{R_{FBG}}$ = Amplitude reflection coefficient of FBG

$\sqrt{1 - R_{FBG}}$ = Amplitude transmission coefficient of FBG

$CE_1$ = Fractional chip to fiber coupling Efficiency

$CE_2$ = Fractional transmission through the fuse

$\phi = \frac{2\pi L_{ext}}{\lambda}$ = relative phase shift in the reflectivity of FBG and output facet $R_o$, is equal to zero when the peak of $R_{FBG}$ and $R_o$ are at their peak and so on.
For the small signal electric field traveling to the left and right in the (FIG. 2-44), in steady state we can write [16]:

\[
\sqrt{1 - R_O} E_{1R} - \sqrt{R_O e^{i\phi}} E_{2L} = E_{2R} \quad (2-29)
\]

\[
\sqrt{R_O} E_{1R} + \sqrt{1 - R_O e^{i\phi}} E_{2L} = E_{4L} \quad (2-30)
\]

\[
C E_1 C E_2 \sqrt{1 - R_{FBG}} E_{2R} = E_{3R} \quad (2-31)
\]

\[
C E_1 C E_2 \sqrt{R_{FBG}} E_{2R} = E_{2L} \quad (2-32)
\]

The total reflection and transmission magnitude due to RO and RFBG reflectivities would be:

\[
R(\phi) = \left( \frac{\sqrt{R_O + C E_1 C E_2 \sqrt{R_{FBG}} e^{i\phi}}}{1 + C E_1 C E_2 \sqrt{R_O \sqrt{R_{FBG}} e^{i\phi}}} \right)^2 \quad (2-33)
\]

\[
T(\phi) = \left( \frac{C E_1 \sqrt{C E_2 \sqrt{1 - R_O \sqrt{1 - R_{FBG}} e^{i\phi}}}}{1 + C E_1 C E_2 \sqrt{R_O \sqrt{R_{FBG}} e^{i\phi}}} \right)^2 \quad (2-34)
\]

2.4.3 Laser Cavity with Absorption Loss and Gain

In the FIG. 2-43, if there is an absorption loss of \( \alpha \) in the laser chip, the power of \( P_L^0 \) traveling to the left after a distance of \( x \) will decrease by [16]:

\[
P_L = P_L^0 e^{(-\alpha x)} \quad (2-35)
\]

If the length of laser chip is \( L \), the round trip loss in the power would be:

\[
P_L = P_L^0 e^{(-2\alpha L)} \quad (2-36)
\]

Also there is a gain of \( \gamma \) due to the fact that additional photons due to the inversion of semiconductor are created. After a round trip travel the power becomes [16]:

\[
P_L = P_L^0 e^{(\gamma L)} \quad (2-37)
\]

So total power returned from a round trip traveling to the right \( P_R \) would be:
\[ P_L e^{(-2\alpha L)} e^{(2\beta L)} R_B R(\varphi) = P_R \]  
(2-38)

If there is no loss and no gain \( P_L^0 = P_R \), therefore we would have

\[ P_R e^{(-2\alpha L)} e^{(2\beta L)} R_B R(\varphi) = P_R \]  
(2-39)

Consequently;

\[ e^{(-2\alpha L)} e^{(2\beta L)} R_B R(\varphi) = 1 \]  
(2-40)

By getting the natural log of each side of the above equation we would have:

\[ \ln(e^{(-2\alpha L)} e^{(2\beta L)} R_B R(\varphi)) = \ln(1) \]  
(2-41)

And then:

\[ (-2\alpha L) + (2\gamma L) + \ln(R_B R(\varphi)) = 0 \]  
(2-42)

Therefore the gain factor \( \gamma \) becomes:

\[ \gamma = \alpha - \frac{1}{2l} \ln(R_B R(\varphi)) \]  
(2-43)

2.4.4 Laser Transparency, Threshold and Output Power

The transparency condition is defined by the fact that there is no loss and no gain in the laser cavity. This is the current in which the laser becomes completely transparent. This current value is called the transparency current \( I_{Trans} \).

Lasing threshold is the condition that cavity gain \( \gamma \) overcomes the total cavity loss. Above the threshold current \( I_{th} \), the intensity of the laser increases with a constant slope. As the current increases above the threshold, the output power builds up. The threshold current is related to transparency current by [14]:

\[ I_{th} = \frac{\gamma}{B} I_{Trans} \]  
(2-44)
Which $B$ is called gain constant and is defined by [14]:

$$B = \frac{1}{\gamma} (N - N_{\text{trans}}) \quad (2-45)$$

FIG. 2-45: Laser transparency current, threshold and slope efficiency of a typical laser.

Which $N$ is the density of injected electrons into the quantum well and $N_{\text{trans}}$ is the density of electrons needed for the transparency condition. Below the threshold current, electrons and holes recombine in the absence of photons, this is called spontaneous emission. On the other hand above the threshold current, an electron and hole recombine in the presence of a photon with energy of:

$$E = h \nu \quad (2-46)$$

Where $h$ is the Planck constant and $\nu$ is the frequency of the photon emitted by recombination. If an injected carrier recombines resulting in emission of one photon with probability of $\beta$, the power emitted by stimulated emission by a current of $I_{op}$ above the threshold would be [14]:

$$P = \frac{(I_{op} - I_{\text{trans}})}{e} h \nu \quad (2-47)$$
Which \( e \) is the charge of electron. Not all of the power above leaves the laser cavity, due to absorption loss and multiple reflections discussed in the section 2.4.2, part of the power is dissipated in the laser cavity. The actual power out of laser cavity (\( P_{\text{out}} \)) would be \([14]\):

\[
P_{\text{out}} = \frac{T(\phi)}{1 - R(\phi)} \frac{(I_{\text{op}} - I_{\text{th}})}{e} \beta \frac{\ell nR(\phi)}{\ell n(R(\phi) R_g) - 2L \alpha}
\]

(2-48)

Also circulating power in the laser cavity becomes:

\[
P_{\text{cir}} = \frac{\sqrt{1 - R_{\text{bs}}}}{1 - \sqrt{R_{\text{bs}} R(\phi)}} \frac{\sqrt{1 - R(\phi)}}{e^{-2\alpha L}} \frac{I_{\text{op}} \beta \hbar \nu}{e}
\]

(4-49)

And we can write the slope efficiency (\( \text{Slope eff} \)) as:

\[
\text{Slope eff} = \frac{T(\phi)}{1 - R(\phi)} \frac{\ell nR(\phi)}{\ell n(R_{\text{bs}} R(\phi)) - 2\alpha L \beta \hbar \nu e}
\]

(4-50)

2.4.5 Analytical Optoelectronic Constants Determinations

Among introduced values in the last sections \( P_{\text{out}} \), \( I_{\text{th}} \) could be easily measured experimentally. Also another piece of information that could be measured is the power exiting the cavity on the back side. From the transmission of 1- Ra, that ends up at the internal photodiode of the laser diode, we call this \( P_{\text{back}} \) (FIG. 2-46).

FIG. 2-46: Schematic of circulation power and running out of cavity powers.
As I mentioned before, we opened a similar laser’s package and we realized that at least 99% of power running out of cavity from backside ends up at surface of the internal photodiode. So by converting the photodiode current to power, we had a good estimate of $P_{\text{back}}$. Also we learned that they are silicon detectors with efficiency of 0.64 mW/mA at 972 nm light. So at any given experimental condition, an accurate value of $P_{\text{back}}$ would be available.

Therefore if we measure $P_{\text{out}}$, $I_{\text{th}}$ and $P_{\text{back}}$ in several different condition such as different relative phase shift value of $\phi$ by slightly adjusting the temperature of laser diode accurately for a given $R_{\text{FBG}}$ value, or different value of $R_{\text{FBG}}$. By these accurate measurements, we would have enough data to determine optoelectronics constants such linear loss of $\alpha$, $B$ factor, $I_{\text{Trans}}$, $R_O$, $R_B$ analytically, using a Mathematica program and finding the best fit values. These constants cannot be measured directly.

So for a given laser, we collected following values by direct measurements:

1- $I_{\text{th}} = 45.2$ mA, free running (no FBG)

2- $P_{\text{out}} = 706.7$ mW, at 1000 mA free running (no FBG)

3- $P_{\text{back}} = 1.29$ $\mu$W, free running (no FBG)

4- $I_{\text{th}} = 34.2$ mA, with $R_{\text{FBG}} = 9.2\%$ and $\phi = 0$

5- $P_{\text{out}} = 597.7$ mW, at 1000 mA with $R_{\text{FBG}} = 9.2\%$ and $\phi = 0$

6- $P_{\text{back}} = 7.52$ $\mu$W, with $R_{\text{FBG}} = 9.2\%$ and $\phi = 0$

7- $I_{\text{th}} = 35.2$ mA, with $R_{\text{FBG}} = 9.2\%$ and $\phi = \pi/2$

8- $P_{\text{out}} = 610.1$ mW, at 1000 mA with $R_{\text{FBG}} = 9.2\%$ and $\phi = \pi/2$

9- $P_{\text{back}} = 7.04$ $\mu$W, with $R_{\text{FBG}} = 9.2\%$ and $\phi = \pi/2$

10- $I_{\text{th}} = 36.2$ mA, with $R_{\text{FBG}} = 9.2\%$ and $\phi = \pi$

11- $P_{\text{out}} = 621.6$ mW, at 1000 mA with $R_{\text{FBG}} = 9.2\%$ and $\phi = \pi$
12- \( P_{\text{back}} = 6.01 \, \mu\text{W}, \) with \( R_{\text{FBG}} = 9.2\% \) and \( \varphi = \pi \)

13- \( I_{\text{th}} = 27.3 \, \text{mA}, \) with a 99% high reflector mirror in front output fiber

14- \( P_{\text{out}} = 4.0 \, \text{mW}, \) at 1000 mA with a 99% high reflector mirror in front output fiber

15- \( P_{\text{back}} = 24.0 \, \mu\text{W}, \) with a 99% high reflector mirror in front output fiber

By plugging these measured values into our program which analytically finds the best fits possible for all of Eqs. (2-33), (2-34), (2-43), (2-44), (2-45) and (2-48), and finally estimates all constants analytically. Comparison of measured and analytically derived value for this given laser are given in the TABLE 2-1.

**TABLE 2-1: Comparison of measured and analytically derived optoelectronic variables and constants for a given laser.**

<table>
<thead>
<tr>
<th>variable</th>
<th>Experimentally Measured</th>
<th>Analytically fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{\text{th}} ) (mA), free running (no FBG)</td>
<td>45.2</td>
<td>45.192</td>
</tr>
<tr>
<td>( P_{\text{out}} ) (mW), free running (no FBG)</td>
<td>706.7</td>
<td>705.437</td>
</tr>
<tr>
<td>( P_{\text{back}} ) (\mu\text{W}), free running (no FBG)</td>
<td>1.29</td>
<td>1.271</td>
</tr>
<tr>
<td>( I_{\text{th}} ) (mA), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = 0 )</td>
<td>34.2</td>
<td>34.235</td>
</tr>
<tr>
<td>( P_{\text{out}} ) (mW), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = 0 )</td>
<td>597.7</td>
<td>590.909</td>
</tr>
<tr>
<td>( P_{\text{back}} ) (\mu\text{W}), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = 0 )</td>
<td>7.52</td>
<td>8.128</td>
</tr>
<tr>
<td>( I_{\text{th}} ) (mA), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = \pi/2 )</td>
<td>35.2</td>
<td>35.099</td>
</tr>
<tr>
<td>( P_{\text{out}} ) (mW), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = \pi/2 )</td>
<td>610.1</td>
<td>608.354</td>
</tr>
<tr>
<td>( P_{\text{back}} ) (\mu\text{W}), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = \pi/2 )</td>
<td>7.04</td>
<td>7.104</td>
</tr>
<tr>
<td>( I_{\text{th}} ) (mA), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = \pi )</td>
<td>36.2</td>
<td>36.344</td>
</tr>
<tr>
<td>( P_{\text{out}} ) (mW), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = \pi )</td>
<td>621.6</td>
<td>629.713</td>
</tr>
<tr>
<td>( P_{\text{back}} ) (\mu\text{W}), with ( R_{\text{FBG}} = 9.2% ) and ( \varphi = \pi )</td>
<td>6.01</td>
<td>5.853</td>
</tr>
<tr>
<td>( I_{\text{th}} ) (mA), with a 99% high reflector</td>
<td>27.3</td>
<td>27.383</td>
</tr>
<tr>
<td>( P_{\text{out}} ) (mW), with a 99% high reflector</td>
<td>4.0</td>
<td>5.392</td>
</tr>
<tr>
<td>( P_{\text{back}} ) (\mu\text{W}), with a 99% high reflector</td>
<td>24.0</td>
<td>24.018</td>
</tr>
<tr>
<td>Internal linear loss factor ( \alpha ) (1/m)</td>
<td>-</td>
<td>166.214</td>
</tr>
<tr>
<td>Gain constant ( B ) (1/m.A)</td>
<td>-</td>
<td>42104.001</td>
</tr>
<tr>
<td>Transparency current ( I_{\text{Trans}} ) (mA)</td>
<td>-</td>
<td>21.421</td>
</tr>
<tr>
<td>Output facet reflectivity ( R_{O} ) (%)</td>
<td>-</td>
<td>0.15801</td>
</tr>
<tr>
<td>Coupling efficiency from chip to fiber (CE1)</td>
<td>-</td>
<td>0.7478</td>
</tr>
<tr>
<td>Back facet reflectivity ( R_{B} ) (%)</td>
<td>-</td>
<td>96.586</td>
</tr>
</tbody>
</table>

Obtaining these values especially \( B, \alpha, I_{\text{Trans}}, R_{O}, \text{CE1}, R_{B} \) were exciting. This information is not available in the spec sheets that come with the laser. We have contacted most laser manufactures for getting confirmation of the accuracy of these values, but they refused to
comment due to the propriety nature of information. But finally the chief engineer of the companies who made the laser under study above confirmed the closeness of our obtained constants.

2.4.6 Stabilizing Fiber Coupled 1400-1500 nm Lasers in Single Frequency

There is another generation of pump lasers with the same concept of 980 nm, in the range 1400-1500 nm. These lasers are used to pump Erbium amplifier for telecom application. We used the same procedure from the beginning of this chapter to stabilize these laser in single frequency and also analytically programmed their behavior just as for 980 nm lasers. We were able to obtain 400 mW power single frequency at 1426 nm.

A number of these single frequency lasers at 1460 nm and 1426 nm have been produced and stabilized by us to be used at Argonne National Lab, University of Chicago and Florida State University by colleagues in the atomic and molecular spectroscopy community shown in FIG 2-47.

FIG. 2-47: Packaged single frequency laser in ranges of 960-990 or 1400-1500 nm.
3.1 Theory of Quasi-Phase-Matching (QPM)

Nonlinear interaction of two photons into one photon with twice of frequency is called SHG. In a SHG interaction, the second order nonlinear susceptibility of a nonlinear optical crystals can be used to generate a polarization with half of wavelength, or twice of frequency:

\[ P_{NL}(2\omega) = 2d_{eff} E_1(\omega)E_2(\omega) \]

(3-1)

Where \( E_1(\omega) \) and \( E_2(\omega) \) are two interacting fundamental electric fields with frequency \( \omega \), \( d_{eff} \) is effective nonlinear coefficient and \( P_{NL}(2\omega) \) is the polarization of second harmonic generated photon with frequency of \( 2\omega \). The two waves of the fundamental and second harmonic travel with two different phase velocities due to two different indexes refraction \( n_1 \) for the fundamental and \( n_2 \) for second harmonic [17]. Since the relative phase between the fundamental and the second harmonic determines the power flow from one to another, the changing phase difference between two leads to alternation in the direction power flow [17]. The distance in which the relative phase of two waves change by \( \pi \) is called coherent length \( l_c \) which is also half of the of period of the second harmonic intensity modulation [17]:

\[ l_c = \frac{\lambda}{4(n_2 - n_1)} \]

(3-2)

The phase matching between two waves could be done by using birefringence crystals which second harmonic amplitude linearly increases with the distance in the crystal, therefore the intensity of second harmonic increase quadratically. This condition is called phase matching. There is a draw back with phase matching which is a walkoff associated with this type of
interaction. Although vectors \( k_\omega \) and \( k_{2\omega} \) define the plane of constant phase for any laser beam in the crystal, directions of energy flow for the fundamental and the second harmonic are not the same. This comes from the fact that in anisotropic materials, the ordinary wave propagation \( k_\omega \) is normal to the plane of \( E_\omega \times H_\omega \) and \( S_\omega = E_\omega \times B_\omega \), but for the extraordinary wave \( k_{2\omega} \) is normal to \( E_{2\omega} \times H_{2\omega} \), but not normal to \( S_{2\omega} = E_{2\omega} \times H_{2\omega} \). The segregation of the two flows of energy for the fundamental and the second harmonic beams is called walkoff or double refraction and the angle between these two vectors is called the walkoff angle \( \rho \). This phenomenon can be seen in FIG. 3-1.

![FIG. 3-1: The walkoff angle between an ordinary and an extraordinary wave in a nonlinear crystal.](image)

This causes an asymmetric elliptical beam shape for second harmonic wave that is not desirable and introduces inefficiency for overall conversion efficiency from fundamental to second harmonic. Only under one condition does the walkoff become zero if the phasematching angle is at the critical angle equal to \( \theta_m = \pi/2 \).

\[
\rho(\theta_m) = \arctan\left(\frac{(n_o/2)\tan(\theta_m)}{n_e}\right) - \theta_m \quad (3-3)
\]
Since the phase matching is as a function wavelength, therefore there is only one wavelength that meets this requirement for each nonlinear crystal at a given temperature. There are not many nonlinear crystal developed and it is not convenient to have a crystal for each wavelength.

On the other hand, there is another method called quasi phasematching which involves repeated inversion of the relative phase between fundamental and second harmonic after an odd number of coherence length [17]. The relative phase between the two waves is reset periodically, so on average the proper phase shift for second harmonic growth is maintained [17]. Therefore the phase has to be inverted, which can be done by change the sign of nonlinear coefficient. The inverted length can be calculated by [17):

$$\Lambda = \frac{m\lambda}{2(n_2 - n_1)} \quad m = 1,3,5,.....$$  

(3-4)

Where $\lambda$ is the wavelength of fundamental light, $m$ is the order of QPM, $n_2$ is the extraordinary index of refraction for second harmonic, $n_1$ is the extraordinary index for fundamental light.

![FIG. 3-2: Nonlinear crystal with periodic inverted nonlinear coefficient.](image)

The typical value of $\Lambda$ for SHG of IR to visible light is about 4-7 µm. This thickness would be too small to make individual slabs and attached to each other. For 30 mm long crystal, 6000 of slabs have to be prepared and attached to each other which would be impossible or very costly.
For QPM applications like this, ferroelectric nonlinear crystals like Lithium Niobate (LiNbO$_3$), Potassium Titanyl Phosphate (KTiOPO$_4$) and Lithium Tantalate (LiTaO$_3$) are very useful. Due to their ferroelectric properties rearrangement of atoms and molecules can happen periodically with a strong external electric field using lithographed electrodes with period of 4-7 µm. The shorter the wavelength, the shorter the period would be and the harder for uniform poling. A lot of research and techniques have developed during last decade to have these periods be uniform and close to 50/50 duty cycle.

Beside circumventing the walkoff by QPM and also having the same polarization of fundamental and second harmonic, QPM has another superiority over ordinary phasemaching. Since QPM can happen in the Z direction using the largest nonlinear coefficient of $d_{33}$, the $d_{\text{eff}}$ in equation (3-1) for QPM has a larger value than ordinary phase matching, sometimes by a factor of 20 or so. This makes QPM very efficient for SHG [17]:

$$d_{\text{eff}}(QPM) = \frac{d_{33}}{2m\pi} \quad m = 1,3,5,\ldots \quad (3-5)$$
Where $m$ is the order of QPM. The lower the order of QPM, the higher the efficiency of SHG. The total single pass SHG conversion efficiency ($\eta$) from a fundamental light to second harmonic using Boyd and Kleinman planewave approximation [18] becomes:

$$\eta = \frac{2d_{\text{eff}}L^2\omega_1}{\pi\varepsilon_\text{r}c^3n_1^2n_2w_1w_2}$$

(3-6)

Where $L$ is the length of crystal, $\omega_1$ is angular frequency of fundamental light, $\varepsilon_\text{r}$ is permittivity constant, $c$ is speed of light, $n_1$ index of crystal for fundamental light, $n_2$ index of crystal for second harmonic light, $w_1$ waist size of the fundamental beam in crystal in $x$ direction and $w_2$ waist size of the fundamental beam in crystal $y$ direction ($\pi w_1 w_2$ is the cross section area of fundamental beam in crystal). The tighter the beam with smaller cross section area, the larger intensity and larger conversion efficiency from fundamental to second d harmonic. The power of second harmonic can be calculated by [18]:

$$P_{2\omega} = P_{\omega} \tanh^2[L\sqrt{\eta P_{\omega}}]$$

(3-7)

Where $P_{2\omega}$ is the generated second harmonic power and $P_{\omega}$ is the fundamental light power.

To summarize the superiority of QPM over ordinary phasematching:

1- The $d_{33}$ which has larger value than other constants used, so higher SHG efficiency.

2- There is no walkoff associated with QPM.

3- Fundamental and second harmonic have same polarization.

4- Due to same polarization of fundamental and second harmonic, Separating fundamental and the second harmonic is easier using angle polished facet.

3.2 Generating Blue Light Using Stoichiometric Lithium Niobate Waveguide

We wanted to generate the most blue light possible by using the largest conversion efficiency.
So we started our research with the most promising and simple configuration. The channel waveguide (WG) configuration in which IR light could couple into a small cross section area WG with large intensity was attractive. At the time only a few commercial WG fabrication companies were available, mostly making of Lithium Niobate (LN) crystal which has the largest $d_{33}$ among all ferroelectric crystals. The $d_{33}$ for common ferroelectric crystals are listed below.

<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>Nonlinearity $d_{33}$ (pm/V)</th>
<th>Photorefractive damage threshold (MW/cm$^2$)</th>
<th>Our measurement of blue absorption (%/cm)</th>
<th>Thermal conductivity W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPMgO:LN</td>
<td>27</td>
<td>50</td>
<td>-</td>
<td>5.6</td>
</tr>
<tr>
<td>PPKTP</td>
<td>14.9</td>
<td>450</td>
<td>7.5</td>
<td>3.3</td>
</tr>
<tr>
<td>PPMgO:SLT</td>
<td>13.8</td>
<td>500</td>
<td>1</td>
<td>7.7</td>
</tr>
</tbody>
</table>

There are three different common types of growth for LN:

1- Lithium rich by Vapor Transport Equilibrium [19].

2- Congruent melt LN [20].

3- Stoichiometric LN [21]

The first few LN waveguides we used had issues with periodic poling uniformity, WG structure and uniformity, a distorted blue beam shape coming out of the WG, and also a phenomena called photorefractive. At high intensity of IR in the crystal space charges builds up in the crystal causing photorefraction, responsible for scattering of IR light out of WG and deforming of the propagating beam in the crystal. Blue generated by these WGs were a lot lower than theoretical results predicted. Also due to photorefractive damages, the lifetime of blue production was short. After several of hours of generating blue, gradually the blue power declined. Photorefractive damage was responsible for this decline. For our crystal, most of the photorefractive damages were reversible. By elevating the crystal temperature to 100 °C for few hours, evidently the space charges were discharged and the crystal would return to initial
condition. It has been shown that about 1% magnesium oxide (MgO) doping of crystal can help mobilizing charges and increase photorefractive damage threshold [22].

Finally, we ordered piece of 1% MgO doped LN waveguide with the length of 10 mm with poling period of $\Lambda \approx 6 \mu m$ for 972 nm light made by HC Photonics, Taiwan (FIG 3-4). Our best results of conversion to blue using WGs was obtained by this crystal. Also we preferred to have the SHG at an elevated temperature of 60 °C that could mobilize the charged particles and decrease the photorefractive problems [23]. The input and output facet of WG had anti-reflection (AR) coating for 972 nm light to eliminate the back reflections to laser.

Extraordinary index of refraction for 1% MgO doped Stoichiometric LN as a function wavelength $\lambda$ (µm) and temperature $T$ (°C) is given by [21]:

$$n^2_e = a_1 + b_1 f + \frac{a_2 + b_2 f}{\lambda^2 - (a_3 + b_3 f)^2} + \frac{a_4 + b_4 f}{\lambda^2 - a_5^2} - a_6 \lambda^2 \quad (3-8)$$

Where:

$a_1 = 5.078, a_2 = 0.0964, a_3 = 0.2065, a_4 = 61.16, a_5 = 10.55, a_6 = 1.59 \times 10^{-2},$

$b_1 = 4.677 \times 10^{-7}, b_2 = 7.822 \times 10^{-8}, b_3 = -2.653 \times 10^{-8}, b_4 = 1.096 \times 10^{-4}$

$f = (T - 24.5)(T - 570.82)$

For our case $\lambda_1 = 972.34 nm, \lambda_2 = 486.17 nm$ and $T = 60.0 °C$. By plugging constants and variables in into Eq. (3-8) we would have:
Theoretically, the period of poling for the first order QPM (m = 1), the equation (3-4) becomes:

\[
\Lambda = \frac{\lambda_1}{2[n_\epsilon(\lambda_2 = 486nm, T = 60^\circ C) - n_\epsilon(\lambda_1 = 972nm, T = 60^\circ C)]} = 6.044 \mu m \quad (3-11)
\]

To generate blue light at 486 nm, the FBG stabilized single frequency laser discussed in chapter two was used. Although the facets of the WG were AR coated, there was enough reflection back to laser to cause instability, so we had to use an optical isolator between the laser source and the WG. Two identical lenses with focal lengths of 2 mm were used to match the beam size from the fiber to waveguide size (see FIG. 3-5)

FIG. 3-5: Schematic of set up for generating blue via SHG in waveguide.

Also after initial results, we realized there was some heating happening at the input facet of WG at high power IR, so we solved this problem by placing the WG on a 4°C temperature gradient along the length using two TECs (see FIG. 3-6). A 10% increase in blue generation at high power was observed when 4 degree temperature gradient at high power was applied. At lower power a lower gradient needed.
Adjusting the mode matching lenses and positions of input fiber and WG we were able to couple a maximum of 70% IR power from fiber into WG.

The coupling efficiency was not constant for all input power values. As we increased the input power coupling efficiency dropped. We had a minimum of 58% coupling efficiency when 265 mW of IR power was in the WG (see FIG. 3-8). A maximum of ~110 mW of blue at 486 nm was generated using this setup. Using Equation 3-7, the single pass conversion efficiency $\eta$ shows decline from 450%/W.cm² at low power to 210%/W.cm² at high power (see FIG. 3-9).
Degradation of coupling efficiency, single pass conversion efficiency, photorefractive damages and blue induced IR absorptions (BIIRA) are responsible for the declining of the blue generation as a whole. Keeping the $\eta$ of 450% $1/W.cm^2$ constant and call it theoretical for all
input powers predict a larger blue generation than 110 mW. FIG. 3-10 shows this decline at high power.

FIG. 3-10: Blue power generation decline at high power compared to theoretical prediction.

I also measured the temperature acceptance bandwidth of SHG at high and low blue power. Theoretically the temperature and wavelength acceptance bandwidth could be calculated by [17]:

\[
\Delta T = \frac{0.4429\lambda_i}{L} \left[ \frac{\alpha}{\partial T} + \alpha \Delta n \right]^{-1} \quad (3-12)
\]

\[
\Delta \lambda = \frac{0.4429\lambda_i}{L} \left[ \frac{\Delta n}{\lambda_i} + \frac{\partial \Delta n_i}{\partial \lambda} - \frac{1}{2} \frac{\partial n_2}{\partial \lambda} \right]^{-1} \quad (3-13)
\]

Where \( \Delta n = n_2 - n_1 \) and \( \alpha \) is the linear thermal expansion of crystal. Our measurement of temperature bandwidth is smaller than. This could be directly related to nonuniform periodically poling and also thermal issues. Also as seen in the FIG. 3-12 and 3-13 the phase matching temperature of 55.8 °C at low power blue is larger than the phase matching temperature 53.4 ° at high power blue. This could be due to heating absorption of IR, blue and BIIRA.
FIG. 3-11: Temperature bandwidth and phase matching temperature at low power blue.

FIG. 3-12: Temperature bandwidth and phase matching temperature at high power blue.

I also ran the crystal for 100 hours while producing 10 mW blue. The blue power declined by 20% in about 10 hours and at the end of 100 hours only 20% of initial power remained (see FIG. 3-13). During the 100 hour examinations, I had to increase the crystal temperature to maintain maximum blue out. This is clearly an evidence of photorefractive damage building up over time (see FIG. 3-14).
3.3 Generating Blue Light Using 10 mm PPKTP Waveguide

Although the waveguide configuration using PPMgO:SLN WG seemed inconvenient due to photorefractive properties, we still did not want to give up on the WG due to high efficiency and simplicity. The next ferroelectric crystal capable of being periodically poled with short
period for blue generation was PPKTP. According to TABLE 3-1, PPKTP has 10 times higher photorefractive damage threshold than PPMgO:SLN which made it attractive to us.

The index of refraction of flux grown PPKTP is made of as a function of wavelength (μm) in the extraordinary Z direction at T=25°C is given by [24]:

\[ n_{c}^2 = A + \frac{B}{\lambda^2} - D\lambda^2 \]  \hspace{1cm} (4-1)

Where: \( A = 2.25411 \), \( B = 1.06543 \), \( C = 0.05486 \), \( D = 0.0214 \).

The temperature dependence of PPKTP’s index has been reported [25]:

\[ \Delta n_{c}(\lambda,T) = A_{1}(T - 25) + B_{1}(T - 25)^2 \]  \hspace{1cm} (4-2)

Where:

\[ A_{1} = \sum_{0}^{3} \frac{a_{m}}{\lambda^{m}} \quad \text{and} \quad B_{1} = \sum_{0}^{3} \frac{b_{m}}{\lambda^{m}} \]  \hspace{1cm} (4-3)

Where: \( a_{0} = 9.9587 \times 10^{-6} \), \( a_{1} = 9.9228 \times 10^{-6} \), \( a_{2} = -8.9603 \times 10^{-6} \), \( a_{3} = 4.101 \times 10^{-6} \),

\( a_{2} = -8.9603 \times 10^{-6} \), \( b_{0} = -1.1882 \times 10^{-8} \), \( b_{1} = 10.459 \times 10^{-8} \), \( b_{2} = -9.8136 \times 10^{-8} \),

\( b_{3} = 3.1981 \times 10^{-8} \)

For our experiment \( \lambda_{1} = 972.34\text{nm} \), \( \lambda_{2} = 486.17\text{nm} \) and \( T = 53.1 \degree C \). By plugging in into Eqs. (4-1), (4-2), and (4-3), the index of PPKTP in IR and blue becomes:

\[ n_{c}(\lambda_{1} = 972\text{nm}, T = 53\degree C) = 1.83482 \]  \hspace{1cm} (4-4)

\[ n_{c}(\lambda_{2} = 486\text{nm}, T = 53\degree C) = 1.90780 \]  \hspace{1cm} (4-5)

Theoretically, the period of poling for the first order QPM (m = 1), using (3-4) becomes:

\[ \Lambda = \frac{\lambda_{1}}{2[n_{c}(\lambda_{2} = 486\text{nm}, T = 53\degree C) - n_{c}(\lambda_{1} = 972\text{nm}, T = 53\degree C)]} = 6.66152\mu\text{m} \]  \hspace{1cm} (4-6)
3.3.1 Experimental Results Using 10 mm PPKTP WG

Our PPKTP WG was grown and prepared by ADVR, Montana, USA. The same setup as FIG. 3-6 was used for this WG too. The phase matching temperature was about 53.1 °C. We had to apply about 5.8 °C temperature gradient along the crystal length to optimize the efficiency at the highest blue power. It seems that heating problems are worse in PPKTP. It could be due to higher blue and BIIRA absorption. A maximum IR coupling efficiency of 49.4% was achieved after carefully alignment of set up at low power (in oppose to 70% for PPMgO:SLN WG of last section). A maximum of 10.1 mW with overall efficiency of 6.82% was achieved. The normalized single pass conversion efficiency was \( \eta = 0.911 \, 1/W \). Generated blue and efficiency as a function IR power in the WG is plotted in FIGs. 3-15 and 3-16.

![FIG. 3-15: Generated blue as function IR using 10 mm PPKTP WG.](image)

![FIG. 3-16: Blue conversion efficiency as a function IR power in the PPKTP WG.](image)
4.1 Introduction

Unfortunately our experience with QPM in WGs in the last chapter was not successful for a reliable, convenient and consistent blue laser source. The maximum obtained power of 110 mW with 40% conversion in the CHAPTER 3 was impressive in compared to other work of the time. Frequently spectroscopy or other single frequency experiments does not require a long time laser run. However we were still looking for higher output power and a more reliable blue source to be used in our next SHG stage for generating UV light. Generating UV by SHG has low efficiency due to number of reasons, so a blue laser source with 0.5~1 Watt output power is needed to generate 100~300 mW of UV. To minimize photorefractive damage and heating issues due to absorption of IR, blue and BIIRA, a larger beam size is the first solution comes to the mind. So we want to increase the beam size in the crystal by factor 20~25 times in comparison to WG, which causes a dramatically decrease in single pass conversion efficiency $\eta$ in the Eq. (3-6). Most experiments in bulk crystals for generating blue and green are done by research groups and large companies using Yb$^+$, Nd:Yag or Ti:Sapphier lasers that have a lot of power to spare. Remember that our IR laser source discussed in the CHAPTER 2 has only 860 mW of output power. One way to compensate for the fall of $\eta$ would be the use of efficient IR resonance buildup cavity which increases our input power by a factor 30 or more. Several results of generating blue light using efficient IR build up cavity with conversion efficiency of 75% with 243 mw of blue @ 461 nm [26], 33% with 225 mW of blue @ 423 mW [27], 40% with 200 mW of blue @ 461 nm [28] have been done.
In this chapter, I will discuss our three approaches using bulk PPKTP and PPMgO:SLT crystals in IR resonance buildup cavities. First, I discuss using 20 mm long PPKTP, generating blue at 486 nm with 680 mW power and a record high conversion efficiency of 81.1% at the time [29]. Second, using 20 mm PPMgO:SLT, generating blue at 486 nm with 456 mW power and efficiency of 52.9% [30]. Third, using 30 mm of PPMgO:SLT, generating blue at 486 nm with 466 mW power and high efficiency of 81.3% [31].

4.2 Generating Blue Using 20 mm Long PPKTP in a Semi-Monolithic Buildup Cavity

After our experience with PPMgO:LN in CHAPTR 3, in which we observed limitations due to photorefractive properties, we decided to use PPKTP that was reported to have a lot higher photorefractive damage threshold. Unfortunately, it has less $d_{33}$ value than PPMgO:LN, but we are going to compensate blue generation by IR resonance buildup.

<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>Nonlinearity $d_{33}$ (pm/V)</th>
<th>Photorefractive damage threshold (MW/cm²)</th>
<th>Our measurement of blue absorption (%/cm)</th>
<th>Thermal conductivity W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPMgO:LN</td>
<td>27</td>
<td>50</td>
<td>-</td>
<td>5.6</td>
</tr>
<tr>
<td>PPKTP</td>
<td>14.9</td>
<td>450</td>
<td>7.5</td>
<td>3.3</td>
</tr>
<tr>
<td>PPMgO:SLT</td>
<td>13.8</td>
<td>500</td>
<td>1</td>
<td>7.7</td>
</tr>
</tbody>
</table>

A better option was the use of PPMgO:SLT instead PPKTP, with higher thermal conductivity and probably less thermal instabilities, but this crystal with high stoichiometric quality was not available commercially at the time.

4.2.1 Semi-Monolithic Cavity Setup with Periodically Poled Crystal Inside

Most high efficient setups reported [26-28] before our work had the bowtie configuration (FIG. 4-1 and 4-2) including 4 mirrors, one partial reflector ($M_1$), two high reflector ($M_2$, $M_3$), and one mirror with high IR reflectivity and high transparency at blue ($M_4$).
We decided to use a much simpler configuration with two mirrors and the Brewster cut crystal at both facets to bend the beam and form the cavity. This configuration is called semi-monolithic (FIG. 4-3). The input IR coupler is a partial IR reflector (M₁). The other mirror is a high IR reflector (M₂).
To summarize the superiorities and drawbacks of semi-monolithic over bowtie cavity:

1- Only two mirrors are needed, the ring cavity completed and formed by Brewster facets.
2- There is no need for AR coating on the facets of crystal.
3- There is no need of dichroic mirror of M4 in FIG. 4-1, for exiting the generated blue out of the cavity.
4- The first drawback is the ellipticity of beam inside the crystal caused by Brewster facets.
   So the IR beam in the crystal expands in horizontal and become larger than vertical direction. The second is a less flexibility in the beam size.

4.2.2 Theoretical Analysis of Semi-Monolithic Cavity with 20 mm PPKTP

The index of refraction of flux grown that our PPKTP is made of as a function of wavelength (μm) in the extraordinary Z direction at T=25°C is given by [24]:

\[
n_e^2 = A + \frac{B}{1 - \frac{c}{\lambda^2}} - D\lambda^2
\]  \hspace{1cm} (4-1)

Where: \( A = 2.25411, \ B = 1.06543, \ C = 0.05486, \ D = 0.0214 \).

The temperature dependence of PPKTP’s index has been reported [25]:

\[
\Delta n_e(\lambda, T) = A_1(T - 25) + B_1(T - 25)^2
\]  \hspace{1cm} (4-2)

Where:

\[
A_1 = \sum_{0}^{3} \frac{a_m}{\lambda^m} \quad \text{and} \quad B_1 = \sum_{0}^{3} \frac{b_m}{\lambda^m}
\]  \hspace{1cm} (4-3)

Where: \( a_0 = 9.9587 \times 10^{-6}, \ a_1 = 9.9228 \times 10^{-6}, \ a_2 = -8.9603 \times 10^{-6}, \ a_3 = 4.101 \times 10^{-6}, \)
\( a_2 = -8.9603 \times 10^{-6}, \ b_0 = -1.1882 \times 10^{-8}, \ b_1 = 10.459 \times 10^{-8}, \ b_2 = -9.8136 \times 10^{-8}, \)
\( b_3 = 3.1981 \times 10^{-8} \)
For our experiment $\lambda_1 = 972.23\text{nm}$, $\lambda_2 = 486.17\text{nm}$ and $T = 31.0^\circ\text{C}$. By plugging in into Eqs. (4-1), (4-2), and (4-3), the index of PPKTP in IR and blue becomes:

$$n_e(\lambda_1 = 972\text{nm}, T = 31^\circ\text{C}) = 1.83447 \quad (4-4)$$

$$n_e(\lambda_2 = 486\text{nm}, T = 31^\circ\text{C}) = 1.90714 \quad (4-5)$$

Theoretically, the period of poling for the first order QPM ($m = 1$), using (3-4) becomes:

$$\Lambda = \frac{\lambda_1}{2[n_e(\lambda_2 = 486\text{nm}, T = 31^\circ\text{C}) - n_e(\lambda_1 = 972\text{nm}, T = 31^\circ\text{C})]} = 6.69011\mu\text{m} \quad (4-6)$$

Now that we have the index $n_e$ at 972.34 nm and $T=31.0^\circ\text{C}$, we can calculate the Brewster angle that PPKTP must be cut. According to the definition of Brewster angle, it is the angle in which if light enters the boundary of two mediums, the reflected and refracted beam at the boundary would be orthogonal to each other. Therefore refracted beam experience minimum loss at the boundary (FIG. 4-4).

According to Snell’s law at the boundary of two mediums we have:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (4-7)$$
Since in the Brewster condition the reflected and refracted are orthogonal, the Brewster angle $\theta_B$ becomes:

$$\theta_B = \tan^{-1}\left(\frac{n_2}{n_1}\right) \quad (4-8)$$

For traveling in the cavity from air with $n_1 = 1$ into the PPKTP with $n_c = 1.83447$ at $\lambda = 972.34$ nm and $T=31.0$ °C the Brewster angle becomes:

$$\theta_B = \tan^{-1}(n_c) = \tan^{-1}(1.83447) = 61.40447^\circ \quad (4-9)$$

We chose the geometry of internal cavity dimension corresponding to 20 mm long PPKTP, with traveling eigenmode IR waist of about 60 µm. To do so we choose the input coupler $M_1$ partial reflector with transmission of ~9.5% and radius of curvature of 25 mm and high reflector $M_2$ also with radius of 25 mm (FIG. 4-5). In this setup, the waist of IR beam inside PPKTP is increased by ~20 times larger than waist in our WG in CHAPTER 3. Therefore, probably PPKTP crystal in this setup should experience less instability and distortion than WG.

![FIG. 4-5: Geometry and dimensions of our semi-monolithic cavity with 20 mm PPKTP.](image)

By choosing $L_1 = L_2 = 15$ mm, the length $L_3$ could be determined by:

$$\theta = 2\theta_B - 90 = 2(61.4\degree) - 90 = 32.8\degree$$

$$L_3 = (L_1 + L_2)\cos\theta + L_{PPKTP} = (15 + 15)\cos(32.8\degree) + 20 = 45.217$ mm \quad (4-10)$$

The total round trip optical path length ($L_{RT}$) of the cavity would be:
\[ L_{RT} = n_rL_{PPKTP} + L_1 + L_2 + L_3 = (1.83447 \times 20) + 15 + 15 + 45.127 = 111.816mm \quad (4-11) \]

The FSR of the laser cavity becomes:

\[ FSR = C \frac{\lambda}{L_{RT}} = \frac{3 \times 10^8}{111.816mm} = 2.6829GHz \quad (4-12) \]

To couple the IR light into the cavity efficiently we had to know the cavity’s eigenmodes accurately. To do so, PARAXIA simulation software could help us finding the eigenmodes very conveniently, corresponding to cavity of FIG. 4-5 with lengths of \( L_1, L_2, L_3 \) and \( L_{PPKTP} \).

**FIG. 4-6**: Eigenmode diagram of PPKTP cavity with required waist size at any point in the cavity, blue arrows show the corresponding points in the cavity to the PARAXIA diagram.
The suggested eigenmode waists of the traveling IR beam in different positions in the cavity predicted by PARAXIA is shown in the diagram below (FIG. 4-7).

![Diagram of eigenmode mode waists of the cavity, the x direction is parallel and y direction is normal to this page.](image)

FIG. 4-7: Eigemode mode waists of the cavity, the x direction is parallel and y direction is normal to this page.

The beam ellipticity in the center of PPKTP is:

\[
\text{Ellipticity} = \frac{\text{waist(Vertical)}}{\text{waist(Horizontal)}} = \frac{52.0}{81.8} \times 100 = 63.7\% \quad (4-13)
\]

As it shows in the diagram the waist of IR beam does not change dramatically from the center of crystal to the ends of crystal. Therefore the plane wave approximation for single pass conversion given in the Eq. (3-6) is still valid. So for SHG of \( \lambda = 972.34 \text{ nm} \), \( d_{\text{eff}} = 14.9 \text{ pm/V} \) for PPKTP, \( L = 19.725 \text{ mm} \) measured carefully for the length of our crystal, \( \omega_l = 1.93 \times 10^{15} \text{ rad/s} \) for IR light, \( n_1 = 1.83477 \) at \( \lambda_1 = 972.34 \text{ nm} \) and \( n_2 = 1.90714 \) at \( \lambda_1 = 486.17 \text{ nm} \), \( w_1 = w_x = (84.7+81.8)/2 = 83.2 \mu\text{m} \) and \( w_2 = w_y = (61.3+52.0)/2 = 56.6 \mu\text{m} \) are average waists in middle and ends of PPKTP of the theoretical single pass conversion efficiency becomes:

\[
\eta_{\text{theo}}(20\text{mmPPKTP}) = \frac{2d_{\text{eff}}L^2\omega_l}{\pi \varepsilon_o C^3 n_1^2 n_2 w_1 w_2} = 1.16\% \quad (4-14)
\]
To couple the light from the tip of laser fiber into the cavity, we need to match the Gaussian beam properties including waist size $w$ and radius of curvature of the wavefront $R$ at the input coupler mirror $M_1$ in FIG. 4-7. Using Gaussian beam propagation, the waist and wavefront radius are:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{Z_R}\right)^2}$$  \hspace{1cm} (4-15)

$$R(z) = z \left(1 + \left(\frac{Z_R}{z}\right)^2\right)$$  \hspace{1cm} (4-16)

Where $w$ is the waist of beam, $R$ is the radius of front wave curvature, $z$ is an arbitrary propagation direction, $\lambda$ is the wavelength of beam and $Z_R = \frac{\pi w_0^2}{\lambda}$ is called Rayleigh range.

FIG. 4-8: Mode matching from fiber of laser into cavity using a flat turning mirror $M_3$ and a focusing lens.

The PARAXIA suggested eigenmode waist and wavefront radius at the input facet of PPKTP crystal in two x and y direction are given in the FIG. 4-8. A flat turning mirror of $M_3$ is
added for simpler alignment by adding one more degree of freedom. Also a focusing lens very close to fiber is needed to adjust the waists.

The fiber handling the laser output power is a Nufern PM980-XP (PM fiber at 980nm) with the waist of $3.3 \pm 0.2 \, \mu m$ at $\lambda = 972$ nm. Therefore beam coming out of fiber with circular waist of $(w_x = 3.3 \, \mu m, R_x= \infty)$ and $(w_y = 3.3 \, \mu m, R_y= \infty)$ has to become $(w_x = 46.0 \, \mu m, \ R_x= -27.1 \, mm)$ and $(w_y = 61.3 \, \mu m, R_y= -19.5 \, mm)$ at the input facet of PPKTP (FIG. 4-8).

Again PARAXIA could be very useful to find a condition for maximum possible coupling, by adjusting lengths of $L_4$, $L_5$, $L_6$ and choosing the focusing lens with focal length of 4.5 mm. By reversing beam from input facet of PPKTP to the tip of fiber by PARAXIA we would have:

![Diagram](image)

**FIG. 4-9:** The best coupling was obtained by reversing beam from cavity to tip of fiber.

According to PARAXIA the closest conditions for matching waists in the FIG. 4-7 would be:

1- Focal length of lens = 4.5 mm

2- The addition of $L_3+L_4 = 34.5$ mm (the distance from lens to input coupler $M_1$)

3- The length $L_6 = 4.927$ mm (the distance from the tip of fiber to the lens)

By choosing the values above and reversing beam from cavity reached to the tip of fiber, waists
predicted by PARAXIA at the tip fiber are:

\[ (w_x = 3.326 \mu m, \ z_x = 14 \mu m) \text{ and } (w_y = 3.491 \mu m, \ z_x = -13.9 \mu m) \quad (4-17) \]

This means that beam instead of perfect condition of \( w_x = 3.3 \mu m, \ z_x = 0 \mu m \) in the x direction, it reaches to the fiber with \( w_x = 3.326 \mu m, \ z_x = 14 \mu m \). The same analogy applicable for y direction.

The total IR mode matching (MM\(_{IR} \)) due to waist size mismatch and waist position mismatch could be calculated by:

\[
MM_{IR} = \frac{4w_{x1}w_{x2}w_{y1}w_{y2}}{\sqrt{[(w_{x1})^2 + (w_{x2})^2]^2 + \left(\frac{\lambda \Delta z}{\pi}\right)^2} \sqrt{[(w_{y1})^2 + (w_{y2})^2]^2 + \left(\frac{\lambda \Delta z}{\pi}\right)^2}} \quad (4-18)
\]

For this given PPKTP cavity using \( w_{x1} = 3.3 \mu m, \ w_{x2} = 3.326 \mu m, \ w_{y1} = 3.3 \mu m, \ w_{y2} = 3.491 \mu m, \Delta z_x = 14 - 0 = 14 \mu m, \Delta z_x = -13.9 - 0 = -13.9 \mu m \) and \( \lambda = 972.34 \text{nm} \), the mode matching Eq. (4-18) becomes:

\[ MM_{IR} = 0.9812 \quad (4-19) \]

This means that about 100-98.12 = 1.88% of IR power reflects from the cavity and is not available to convert to blue.

The mirror \( M_I \) has a reflectivity of \( R_I \) and a transmission of \( T_I \) such that:

\[ T_I + R_I = 1 \quad (4-20) \]

In the cavity the input IR power \( P_{io} \) is going to be amplified by a factor of buildup of BU. The circulating power in the cavity \( P_{cir} \) is the amplified power:

\[ P_{cir} = P_{io}BU \quad (4-21) \]

Generally, the \( BU \) factor for a cavity can be defined as a function of transmission of the \( T_I \) of
input coupler and total loss $\ell$ in a cavity [12]:

$$BU = \frac{T_1}{(1 - \sqrt{1 - \ell \sqrt{1 - T_1^2}})^2} \quad (4-22)$$

For our cavity $\ell_{\omega_0}$ is losses of IR due to absorption and scattering. Also we have to add loss $\ell_{2\omega_0}$ which is a fraction circulating power that is converted to blue. So Eq. (4-22) can be rewritten as:

$$BU = \frac{T_1}{(1 - \sqrt{(1 - \ell_{\omega_0})(1 - \ell_{2\omega_0})(1 - T_1^2})^2} \quad (4-23)$$

Assuming an absorption coefficient $\alpha$ for $P_{\text{cir}}$, $P_{\text{cir}}$ is going to be an exponential equation of:

$$P_{\text{cir}}(z) = P_{\text{cir}}e^{-\alpha z} \quad (4-24)$$

As it can be assumed that $P \propto E^2$, Eq. (4-26) becomes:

$$E_{\text{cir}}^2(z) = E_{\text{cir}}^2e^{-\alpha z} \quad (4-25)$$

By differentiating over propagation direction $z$:

$$\frac{dP_{\text{cir}}(z)}{dz} = -\alpha P_{\text{cir}}e^{-\alpha z} \quad (4-26)$$

From conservation energy and power at any point in the crystal we have

$$P_{\text{cir}} + P_{2\omega_0} = \text{constant} \quad \text{or} \quad E_{\text{cir}}^2 + E_{2\omega_0}^2 = \text{constant}. \quad (4-27)$$

By differentiating both sides of the equation above we can write:

$$dE_{2\omega_0}(z) = \alpha E_{\text{cir}}^2(z)dz \quad (4-28)$$

$$dE_{\text{cir}}(z) = \alpha E_{\text{cir}}(z)E_{2\omega_0}dz \quad (4-29)$$

Using the Mathematica software, I have found two solutions for the coupled differential equations (4-28) and (4-29):

$$E_{2\omega_0}(z) = E_{\text{cir}} \tanh(\alpha z) \quad (4-30)$$
\[ E_{\text{cir}}(z) = E_{\text{cir}} \sqrt{1 - \tanh^2(\alpha z)} \]  

(4-31)

Including blue absorption loss in the crystal (\(\delta\)), the boundary conditions of

\[ P_{\text{cir}} \alpha^2 L^2 = (1+\delta)\eta P_{\text{cir}}^2 \quad \text{and} \quad BU = \frac{P_{\text{cir}}}{P_{\omega}} \] imply:

\[ \alpha = \sqrt{(1+\delta)\eta BU \omega \alpha} \]  

(4-32)

Where \(L\) is the length of crystal. Thus, \(\ell_{2\omega}\) for the total length of crystal \(z = L\) becomes:

\[ \ell_{2\omega} = \frac{P_{2\omega}}{P_{\text{cir}}} = \frac{E_{\text{cir}}^2 \tanh^2(\alpha z)}{E_{\text{cir}}^2} = \tanh^2 \sqrt{(1+\delta)\eta P_{\text{cir}}} \]  

(4-33)

Now, we can rewrite BU as:

\[ BU = \frac{T_1}{[1-\sqrt{(1-\ell_{\omega})(1-\tanh^2(\sqrt{(1+\delta)\eta BU \omega \alpha})(1-T_1))}]^2} \]   

(4-34)

So the \(P_{\text{cir}}\) becomes:

\[ P_{\text{cir}} = P_{\omega} BU = \frac{T_1 P_{\omega}}{[1-\sqrt{(1-\ell_{\omega})(1-\tanh^2(\sqrt{(1+\delta)\eta BU \omega \alpha})(1-T_1))}]^2} \]   

(4-35)

So far we know that our IR laser in the cavity circulates with the power of \(P_{\text{cir}}\), generating blue with power of \(P_{2\omega}\). A fraction of \(P_{\text{cir}}\) escapes the cavity with the power of \(P_R\) which we call it total reflected power (see FIG. 4-10).

FIG. 4-10: IR power circulating and reflected in the cavity
Also a very small fraction of $P_{cir}$ escapes the input Brewster facet that we call it $P_{Brew}$. We are not going to consider this power in our calculation due to its very small value, but this power is going to be used for mode matching alignment since it contains information about the circulating modes. Also in the FIG. 4-10, I included an input power of $P_{in}$ which is the power leaving the tip of fiber at the IR laser source. This power is going to be reduced by polarization extension ratio factor (PER) of laser and also IR mode matching $MM_{IR}$ (Eq. 4-18). So in the steady state the IR powers at mirror $M_1$ could be written as:

$$(PER) = \frac{P_{Horizontal}}{P_{in}} \quad (4.36)$$

$$P_{\omega} = (PER)(MM_{IR})P_{in} \quad (4.37)$$

$$\sqrt{P_{cir}} = \sqrt{(1-\ell_{\omega}-\ell_{2\omega})R_1P_{cir}} + \sqrt{T_1P_{\omega}} \quad (4.38)$$

$$\sqrt{P_r} = \sqrt{(1-\ell_{\omega}-\ell_{2\omega})T_1P_{cir}} - \sqrt{R_1P_{\omega}} \quad (4.39)$$

$$P_R = P_r + (1-MM_{IR})P_{in} + (PER)R_1P_{in} \quad (4.40)$$

Where $P_r$ is the reflected power due to circulating power transmission in partial reflector $M_1$. The power $P_R$ is the addition of $P_r$ and mismatched power of $(1-MM_{IR})P_{in}$ or power that is not mode matched in the cavity, and also $(PER)R_1P_{in}$ which is the power with orthogonal polarization which is not useful for SHG and reflects from the cavity. The $P_R$ is very useful for estimating the losses in the cavity. Any time during cavity operation the $P_R$ can be measured with power meter directly. If there is no loss in the cavity and no blue generated, all the power $P_{in}$ has to end up at total deflected power, so $P_R = P_{in}$. If there is loss due absorption, scattering, mode mismatched, reflection and so on, $P_R \not<P_{in}$.
Recalling Eq. (3-7), since actually now $P_{cir}$ is responsible for SHG, the second harmonic power $P_{2\omega}$ or blue power leaving the cavity becomes:

$$P_{2\omega} = P_{cir} \cdot \text{Tanh}^2 \left[ \sqrt{\eta P_{cir}} \right] \quad (4-41)$$

Over all conversion efficiency ($eff$) from IR laser’s fiber tip to blue leaving the cavity becomes:

$$eff = \frac{P_{2\omega}}{P_{in}} \quad (4-42)$$

One more factor that could be useful to know would be the impedance match of the cavity which determines how well the transmission of $T_1$ on mirror $M_1$ is chosen for given cavity conditions:

$$\text{Impedance Match} = 1 - \frac{P_R}{P_o} \quad (4-43)$$

4.2.3 Experimental Results with Semi-Monolithic Cavity with PPKTP

As I mentioned in the last section some of dimensions and parts were chosen and the rest were calculated through related equations. So our setup is going to have following elements and dimensions given in the FIG. 4-11.

1- IR laser, a 840 mW butterfly single frequency laser with tip of fiber AR coated for IR.
2- $L_6 = 4.297$ mm, the distance between laser’s fiber tip and focusing lens.
3- Lens, 4.5 mm focal length and AR coated for IR, the focusing lens for matching the IR beam into Eigemode of the cavity.
4- $L_5 = 14.5$ mm, the distance between turning mirror $M_3$ and input coupler mirror $M_1$
5- $M_5$, a flat high quality mirror with reflection of $> 99.98\%$
6- $L_4 = 20$ mm, the distance between turning mirror $M_3$ and input coupler mirror $M_1$
7- $M_1$, a 25 mm radius of curvature CVI custom made partial reflector centered at $\lambda = 972$ nm, with transmission of $T_1 = 9.5\%$ and reflection of $R_1 = 90.5\%$. The mirror came with
the diameter of one inch originally, but we cut it to 4 mirrors with the diameter 8.5 mm which made the mirror lighter for alignment stability. This way we ended up with three more partial reflector mirrors useful for future setups.

8- \( L_1 = 15 \text{ mm}, \) the lateral distance between \( M_1 \) and input facet of PPKTP crystal.

9- PPKTP crystal, with length of \( L_{PPKTP} = 19.725 \text{ mm}, 1 \text{ mm by 1 mm thick, with periodically poled with period of } \Lambda = 6.69 \mu\text{m} \) for SHG of \( \lambda = 972.34 \text{ nm} \) at 31.0°C. Both ends are cut at Brewster angle of \( \theta_B = 61.4^\circ. \)

10- \( L_2 = 15 \text{ mm}, \) the lateral distance between second facet of PPKTP and high reflector \( M_2. \)

11- \( M_2, \) a 25 mm radius of curvature CVI custom made high reflector mirror with reflectivity of 99.9% centered at 972.34 nm. Originally this mirror came with diameter of one inch. Again due to large weight load on the piezo for cavity locking purposes, first the mirror was cut into 4 pieces of 8.5 mm diameter mirrors. Then one the mirrors was sanded down to a square mirror with sides of 3 mm and 2 mm thick.

12- Piezo, high voltage piezo actuator with about 2 \( \mu\text{m} \) travel at 1000 V. The mirror \( M_2 \) is glued on the piezo for fine adjusting the length of the cavity during the locking. In the scanning mode a variable ramp voltage given to piezo can scan the cavity length for mode matching alignment purposes. In the locking mode which cavity has to be locked up at a certain length, the peizo keeps the cavity length constant for CW blue operation by voltage given from locking amplifier.

13- \( L_3 = 45.2 \text{ mm}, \) the distance between the mirror \( M_2 \) had to be adjusted in respects to \( L_1, L_2 \) and \( L_{PPKTP} \) (see Eq. (4-10)).

14- Photo detector, an InGaAs detector to convert optical information in the cavity to electric signals. In the scanning mode, this detector and oscilloscope can monitor alignments and
mode matching conditions of cavity. In the locking mode, detector gives the cavity servo information about the position of maximum peak or best locking condition.

15- Cavity servo, a locking amplifier and feedback loop to lock the cavity in CW operation.

FIG. 4-11: Schematic of experimental setup for blue generation using PPKTP.

To install optical parts and to be able to align each element individually, we designed our own miniature mirror and lens mounts capable of being aligned in two orthogonal directions (FIG. 4-12).

FIG. 4-12: Miniature mirror and lens mounts capable of tilt in two orthogonal directions.
The PPKTP mount is made of two pieces for easy crystal installation, maximum contact between crystal and mount.

![Image](image1.png)

**FIG. 4-13:** The PPKTP crystal housing and mount.

All parts are mounted on a ¼ inch thick aluminum plate for good stabilities (FIG. 4-13).

![Image](image2.png)

**FIG. 4-14:** Solid work of design for PPKTP cavity.

This plate is placed on the top a thermoelectric cooler. Therefore all optical parts including PPKTP crystal that has to be kept at constant phase matching temperature of 31.0°C are stabilized at the same temperature. The actual setup looks like the FIG. 4-15.
FIG. 4-15: The image of actual setup for PPKTP cavity.

After installing all the parts and mounts, the cavity has to be mode matched. A 100% mode matched cavity is a condition with only TEM$_{00}$ Gaussian peak repeating itself over half wavelength and no other TEM$_{nm}$ peaks are available.

FIG. 4-16: An optical cavity with 100% mode matching.

Since our Eigenmode is elliptical, the position of TEM$_{nm}$ modes for vertical and horizontal are slightly at different positions so at different frequency. The FIG. 4-16 shows the beam profile of Gaussian TEM$_{nm}$ horizontally elliptical beam which n is for horizontal and m for vertical mod numbers. If addition n+m is odd number mode is called odd mode and if n+m even, the even mode.
FIG. 4-17: Beam profile of an horizontally elliptical Gaussian TEM$_{nm}$ modes.

After lignin up the cavity carefully, all 5 optical mounts tightened at their optimum position and tilt in both horizontal and vertical direction. FIG. 4-17 shows lined up cavity in the scanning mode with two non-resolved TEM$_{20}$ and TEM$_{02}$.

FIG. 4-18: Mode structure of the lined up PPKTP cavity captured on oscilloscope with two non-resolvable TEM$_{20}$ and TEM$_{02}$ modes.
Using scanning mode we can obtain a good experimental MM\textsubscript{IR} by getting the ratio of main TEM\textsubscript{00} amplitude and addition of TEM\textsubscript{20} and TEM\textsubscript{02}. One way of experimentally confirm which peak in the FIG. 4-17 is horizontal or vertical with correct mode number n and m is to monitor directly the P\textsubscript{B} using a CCD beam profiler in slow scanning mode. You will observe in the beam profiler screen sequence of all available modes in cavity corresponding to FIG. 4-1, if they have enough power to be monitored. So experimental value of MM\textsubscript{IR} obtained by our PPKTP cavity using FIG. 4-18 is:

\[
MM_{IR}(\text{exp}) = 1 - \frac{\text{TEM}_{20} \text{amplitude} + \text{TEM}_{02} \text{amplitude}}{\text{TEM}_{00} \text{amplitude}} = 1 - \frac{0.088 + 0.088}{4.4} = 0.96
\]  

(4-44)

So the experimental mode matching MM\textsubscript{IR} is smaller than theoretical value calculated 0.981 by Eq. (4-19).

Next we measure the transmission of T\textsubscript{1} in mirror M\textsubscript{1}. Since the cavity is lined up and the optimum angle of incident of IR beam into mirror M\textsubscript{1} is stablished, we just remove the PPKTP crystal out of cavity and measure transmission T\textsubscript{1} (see FIG.4-19). We discovered that partial reflectors are sensitive to the angle incident.

FIG. 4-19: Accurate measurement of the transmission T\textsubscript{1} of mirror M\textsubscript{1}.  

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With few degrees change in the angle of incident of $P_{in}$ on the $M_1$ mirror, the value of transmitted $T_1$ could change by few 0.1%. Therefore it is more accurate to line up the cavity first, then measure $T_1$ after correct angle of incident is established. FIG 4-19 shows the schematic of $P_T$ measurement which results in $T_1$ measurement. So at the given power of $P_{in} = 500$ mW, the power $P_T = 47.45$ mW was measured. Therefore $T_1$ becomes:

$$T_1(\text{exp}) = \frac{P_T}{P_{in}} = \frac{47.45}{500} = 0.0949 \quad (4-45)$$

To measure the experimental single pass conversion efficiency $\eta$, we replaced PPKTP in the crystal and lined up the cavity. Now by blocking the circulation in the cavity, the $P_T$ only travels once in the crystal and generated blue $P_B$ could be measured with power meter (see FIG. 4-19).

At $P_{in} = 500$ mW, $P_T = 47.45$ mW, we measured $P_B = 23.87 \mu$W, when the PPKTP in phase matching crystal temperature of 31.0 °C. Therefore single pass conversion using Eq. (4-41) becomes:

![DIAGRAM]
\[
\eta(\text{exp}) = \frac{(\tanh^{-1} \sqrt{\frac{P_B}{P_T}})^2}{P_T} = 0.0106 \frac{1}{w^2} \quad (4-46)
\]

This is lower but comparable to theoretical calculated value of 0.0116 \(1/w^2\) we calculated earlier for this given cavity geometry, measured length of crystal, and waist size in PPKTP crystal (see Eq. (4-14)).

Now we want to make an accurate experimental estimation of total loss in the cavity for the IR beam \(\ell_\omega\) which includes:

1- Loss due to absorption, scattering, and front wave distortion of mirrors M1 and M2
2- Insertion loss, absorption, scattering and front wave distortion of PPKTP crystal
3- Loss due to imperfection of Brewster angle at PPKTP facets
4- Loss due to reflection and polarization rotation in PPKTP crystal.

One way of obtaining the \(\ell_\omega\) experimentally is to measure the finesse of cavity and then calculate \(\ell_\omega\) through finesse. Theoretically in our cavity configuration with partial input coupler M1 of transmission of \(T_1\), the finesse could be calculated by [10]:

\[
Finesse = \frac{\pi(1 - T_1 - \ell_\omega)^{1/4}}{1 - \sqrt{1 - T_1 - \ell_\omega}} \quad (4-47)
\]

FIG. 4-21: Measuring fineness of cavity experimentally using mode structure in scanning mode.
Experimentally, determining the finesse using mode structure in the scanning mode (FIG. 4-21) is a possibility. So the finesse would be:

\[ Finesse = \frac{FSR}{\Delta(FWHM)} \]  

(4-48)

Then by plugging Finesse obtained from Eq. (4-48) and \( T_1(\text{exp}) = 0.0949 \) measured experimentally earlier by (4-45), into the Eq. (4-47), then \( \ell_{\omega} \) could be calculated. But we found this procedure not very accurate for finding finesse, due to electronic noises, response time of “Photodiode detector” (in FIG. 4-20) and its amplifier and also nonlinear response of piezo. A more accurate way to find \( \ell_{\omega} \) is to lock the cavity at a certain power of \( P_m \), with no blue created (about 2–3 below or above phase matching temperate which no blue is generated by PPKTP), then measuring the total reflected power \( P_R \) by optical power meter as shown in the FIG. 4-22.

FIG. 4-22: Schematic of set up for measuring the total reflected power off blue resonance.
If there were

1. \( \ell_{\omega} = 0 \), loss of IR in the cavity
2. \( \ell_{2\omega} = 0 \) due to off resonance condition (\( \eta = 0 \)),
3. \( \text{MMIR} = 1 \) (no loss due to mode matching)
4. \( \text{(PER)} = 1 \) (perfect laser polarization extension ratio)

there would be no power loss and \( P_R = P_{in} \). But otherwise, less power than the input power \( P_{in} \) ends up in the \( P_R \) (\( P_R < P_{in} \)). When we locked the cavity at \( P_{in} = 500 \text{ mW} \), the measured power \( P_T = 445.79 \text{ mW} \) was observed. Using Eqs. (4-34) through (4-40), with the following conditions:

1. \( P_{in} = 500 \text{ mW} \)
2. \( \text{(PER)} = 0.99 \)
3. \( \text{MMIR} = 0.96 \)
4. \( T_1 = 0.0949 \)
5. \( P_T = 445.79 \text{ mW} \)

One can calculate the buildup of BU using (4-34):

\[
BU = 37.83 \tag{4-49}
\]

the circulating power using (4-35):

\[
P_{circ} = 17.97 \text{ W} \tag{4-50}
\]

and finally \( \ell_\omega \) using (4-36) through (4-40):

\[
\ell_\omega = 0.003 \tag{4-51}
\]

Therefore our IR beam inside cavity experiences a total loss of 0.3%. I have to mention, we must make sure that all mirror surfaces, and facets of the PPKTP crystal are absolutely clean. To reach \( \ell_\omega = 0.003 \), we had clean each optical element in the cavity and make sure no higher power of \( P_R \) is achieved by any more cleaning of the surfaces. There were times that we thought
the surfaces were cleaned even under microscopic observation before cavity assembly. But we realized there were often very thin invisible films causing losses in the cavity. So cleaning surfaces part by part then measuring $P_R$ in locking mode to see if any improvement is accomplished would be recommended to achieve absolute minimum loss of $\ell_{\omega}$.

The PPKTP’s blue absorption insertion loss of $\delta$ introduced in the Eq. (4-32) was measured experimentally using the schematic below:

![FIG. 4-23: Schematic of blue insertion loss $\delta$ measurement.](image)

Using the blue at $\lambda = 486$ nm generated by PPMgO:SLN waveguide setup discussed in the CHAPTER 3 with $P_{B1} = 1.00$ mW focused into the PPKTP with the waist of very close to the Eigenmode of cavity. Then we measured the transmitted blue power of $P_{B2} = 0.15$ mW after PPKTP by power meter. So blue absorption by $\sim 20$ mm long PPKYP became:

$$\delta = \frac{P_{B2}}{P_{B1}} = \frac{0.15}{1.00} = 0.15 \quad (4-52)$$

This means PPKTP absorbs about 7.5% 1/cm which was considerable and alarming for thermal stability of PPKTP in high power blue generation condition. But later on, considering plane wave approximation and ignoring IR single pass depletion, we realized the most blue is generated in the last 1/3 length of PPKTP. Therefore effective $\delta$ for our setup was:
\[
\delta^{\text{(eff)}} = \frac{0.15}{3} = 0.05 \quad \text{(4-53)}
\]

So although single pass blue absorption for our 20 mm PPKTP was 15%, but effective \( \delta \) is actually 0.05.

Now all the constants needed to describe our PPKTP cavity is experimentally measured:

1- \((\text{PER}) = 0.99\)

2- \(T_1 = 0.0949\)

3- \(\text{MMIR} = 0.96\)

4- \(\eta = 0.0106 \text{ \, l/W}\)

5- \(\ell_{\omega} = 0.003\)

6- \(\delta = 0.05\)

By varying the input power \(P_{in}\) into the cavity using the constants above and Eqs. (4-34) through (4-40) calculated and observed \(P_R\) and \(P_{2\omega}\) (the two useful immediate direct measurable values outside the cavity) are listed in the table below [29].

**TABLE 4-2: Comparison of calculated \(P_R\) and \(P_{2\omega}\) using constants above and observed \(P_R\) and \(P_{2\omega}\) using power meter.**

<table>
<thead>
<tr>
<th>Pin (mW)</th>
<th>Calculated (P_R) (mW)</th>
<th>Observed (P_R) (mW)</th>
<th>Calculated (P_{2\omega}) (mW)</th>
<th>Observed (P_{2\omega}) (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>79</td>
<td>31</td>
<td>28</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>149</td>
<td>37</td>
<td>34</td>
<td>98</td>
<td>92</td>
</tr>
<tr>
<td>602</td>
<td>35</td>
<td>49</td>
<td>522</td>
<td>480</td>
</tr>
<tr>
<td>715</td>
<td>37</td>
<td>60</td>
<td>626</td>
<td>575</td>
</tr>
<tr>
<td>840</td>
<td>41</td>
<td>70</td>
<td>740</td>
<td>681</td>
</tr>
</tbody>
</table>
A maximum blue power of 681 mW with overall efficiency of $\text{eff} = 81.1\%$ was generated.

FIG. 4-24 shows the generated blue power $P_{2\omega}$ as a function input IR power of $P_{in}$.

FIG. 4-24: Generated blue power $P_{2\omega}$ as a function input IR power $P_{in}$.

Also overall conversion efficiency in percentage showing maximum 81.1% versus calculated 88.1% is plotted in FIG. 4-25.

FIG. 4-25: Overall conversion efficiency comparison of experimental and calculated values.

4.2.4 Discussion on Generated Blue Using PPKTP

It seems that PPKTP is capable of being efficiently periodically polled. Our observed single pass
conversion efficiency 1.06% is comparable to theoretical value of 1.16%. Also our measured temperature bandwidth of 1.1 °C at FWHM which would be consistent with uniform poling was observed. PPKTP was found to have no significant IR absorption. In fact when the cavity was locked off the blue resonance (off the phase matching temperature of 31.0 °C) with maximum power input power of $P_{in} = 860$ mW and very high circulating power of $P_{cir} = 31$ W, no significant heating or crystal temperature rise was observed. The reflected power $P_R$ was very close to calculated power of $P_R = 749$ mW. But when the cavity was locked on blue resonance temperature, heating problems occurred. We had to decrease the crystal temperate at higher than 400 mW blue to compensate for heating and keep the crystal in phase matching temperature. As it was shown in FIGs. 4-23 and 4-24, there is blue power and efficiency fall off when the generated blue power was increased. It seems our measured single pass blue absorption of 15% could be one of the causes. Also blue induced IR absorption (BIIRA) plays a role in our heating problem. As it was mentioned earlier without blue in the cavity, it was found the calculated and observed values agreed very well. Also after several 10–20 hours of high power blue generation, the conversion start declining. Unlike PPMgO:LN, this pattern was not reversible by heat treatment. In fact we baked the crystal at 500°C for a few hours and no improvement or reversal of damage was observed. This permanent photochromic damage caused by a phenomena call grey tracking in PPKTP at high intensity has been studied [32]. According to this study grey tracking causes changes in index profile of crystal which makes phase matching condition less optimized than usual.

4.3 Generating Blue Using 20 mm Long PPMgO:SLT in a Semi-Monolithic Buildup Cavity

4.3.1 Introduction

The limitation of PPKTP for generating reliable single frequency blue with moderate power of
about ~500 mW forced us to move on to the next viable nonlinear crystal, PPMgO:SLT. The
superiority of PPMgO:SLT over PPKTP comes from much less blue abortion, higher
photorefractive damage threshold and larger thermal conductivity given in TABLE 4-1. This
made it very attractive to try. The cavity configuration will be still semi-monolithic. All
pervious theoretical calculations are still viable, so I will not repeat them in this section, but I
refer to equation numbers given in the section 4-2. Unfortunately PPMgO:SLT has the index of
about ~2.1 in compare to index of ~1.8 for PPKTP. Larger index plus slightly lower d33 of
PPMgO:SLT than PPKTP results in declining the single pass conversion η by half for 20 mm in
compare to 20 mm PPKTP.

We made several following improvements on PPMgO:SLT cavity in compare to PPKTP one:

1- The tip of fiber, handling the IR power, was polished at Brewster angle of 55.8 ° to
deliver the maximum power possible with no use of costly AR fiber tip. This also
makes the beam elliptical in horizontal direction and more suitable to be coupled into
semi-monolithic cavity with elliptical eigenmode. About 2.3 % more power was
available at the Brewster cut fiber.

2- We replaced the focusing lens in the FIG. 4-22 with a different one with less beam
distortion. We realized that the GelTech aspheric glass molded lens used previously
is designed for collimating a light beam at λ = 980 nm. It causes distortion on the
beam when it is used for focusing to the waist ~60 μm in the PPKTP cavity. After
trying different lenses from different manufacturer we found a lens with a 4.0 mm
focal length lens, AR coated for IR and designed for λ = 685 nm but caused the least
amount of distortion on our IR light to be coupled into the cavity. Both of these 980
and 685 nm lenses would focus the beam in infinity with no distortion, but for
focusing beam about 40 mm away, the 685 nm lens had much less imposed front wave distortions (see FIGs. 4-25 and 4-26 taken by CCD beam profiler)

![FIG. 4-26: Wave front beam quality, when (A) collimated (B) focused by 980 lens.](image)

![FIG. 4-27: Wave front beam quality, when (A) collimated (B) focused by 685 lens.](image)

Recall the calculated $\text{MM}_{\text{IR}} = 98.1\%$ in compare to observed $\text{MM}_{\text{IR}}= 96\%$ in PPKTP setup. The distortion made by the 980 nm lens might have been one of the sources of discrepancy of $\text{M}_{\text{IR}}$. In our upcoming PPMgO:SLT cavity using 685 nm lens, discrepancy of $\text{MM}_{\text{IR}}$ was less.
3- The high voltage (1000 V), 1 mm thick piezo actuator on mirror M2 in FIG 4-22 was replaced by an efficient low voltage (60 V) and 2 mm thick multilayer piezo.

4- The crystal was thermally isolated from cavity plates and optical mounts. We decided to order the PPMgO:SLT to be phase matched at $\lambda=972.34$ nm at an elevated temperature of $\sim 80$ °C to be safe with respect to the possibilities of photorefracton. Elevated temperate could cause more mobility for charges that are responsible for photorefractive. So elevating the whole cavity to $80$ °C was not convenient. Only the PPMgO:SLT crystal was at elevated temperature, isolated by a second housing made of very a good thermal isolator material called Peek (figure below).

4.3.2 Theoretical Analysis of Semi-Monolithic Cavity with 20 mm PPMgO:SLT

The index of refraction of our Stoichiometric PPMgO:SLT (with 1% mole doped MgO) as function of wavelength ($\mu$m) and temperature (°C) in the extraordinary Z direction is given by [15]:

$$n^2(\lambda, T) = A_1 + \left( \frac{B_1 + B(T)}{\lambda^2 - (C_1 + C(T))^2} \right) + \left( \frac{E_1}{\lambda^2 - F_1} \right) + \left( \frac{G_1}{\lambda^2 - H_1} \right) + D_1 \lambda^2$$

(4-54)

Where:

$$B(T) = (3.483933 \times 10^{-8})(T + 273.15)^2, \quad C(T) = (1.607839 \times 10^{-8})(T + 273.15)^2,$$

$$A_1 = 4.502483, \quad B_1 = 0.007294, \quad C_1 = 0.185087, \quad D_1 = -0.02357, \quad E_1 = 0.073423, \quad F_1 = 0.199595, \quad G_1 = 0.001, \quad H_1 = 7.99724.$$
For our experiment $\lambda_1 = 972.23\text{nm}$, $\lambda_2 = 486.17\text{nm}$ and $T = 83.3\ ^\circ\text{C}$. By plugging in Eq. (4-54), the index of PPMgO:TP in IR and blue becomes:

$$n_e(\lambda_1 = 972\text{nm}, T = 83^\circ\text{C}) = 2.13872 \quad (4-55)$$

$$n_e(\lambda_2 = 486\text{nm}, T = 83^\circ\text{C}) = 2.22007 \quad (4-56)$$

Theoretically, the period of poling of PPMgO:SLT for the first order QPM ($m = 1$), using (3-4) becomes:

$$\Lambda = \frac{\lambda_1}{2[n_e(\lambda_2 = 486\text{nm}, T = 83^\circ\text{C}) - n_e(\lambda_1 = 972\text{nm}, T = 81^\circ\text{C})]} = 5.976\mu\text{m} \quad (4-57)$$

Recall the section 4.1.2, for traveling in the cavity from air with $n_1 = 1$ into the PPMgo:SLT with $n_e = 2.13872$ at $\lambda = 972.34\ \text{nm}$ and $T = 83.3\ ^\circ\text{C}$ the Brewster angle becomes:

$$\theta_B = \tan^{-1}(n_e) = \tan^{-1}(2.13872) = 64.9736^\circ \quad (4-58)$$

Our accurate measurement of angles on our actual PPMgO:SLT crystal were 65.41° on one facet, and 64.24° on the other facet. We wish they were closer to theoretical values.

$$\theta = 2\theta_B - 90 = 2(64.9736) - 90 = 39.95^\circ \quad (4-59)$$

We choose again the lateral $L_1 = L_2 = 15\ \text{mm}$. Our accurate measurement of PPMgO:SLT dimensions resulted in length of $L_{PPMgO:SLT} = 20.1\ \text{mm}$ and sides of 1×1 mm. The $L_3$ becomes:

$$L_3 = (L_1 + L_2) \cos \theta + L_{PPMgO:SLT} = (15 + 15) \cos(39.95) + 20.1 = 43.098\text{mm} \quad (4-60)$$

The total optical round trip path length $L_{RT}$ is equal to:

$$L_{RT} = L_1 + L_2 + L_3 + n_e(\lambda = 972\text{nm}, T = 83^\circ\text{C})L_{PPMgO:SLT} = 116.086\text{mm} \quad (4-61)$$

The free spectra range (FSR) of the cavity becomes:

$$\text{FSR} = \frac{C}{L_{RT}} = \frac{3 \times 10^8}{116.086\text{mm}} = 2.5843\text{GHz} \quad (4-62)$$

The schematic of our semi-monolithic cavity with 20 mm PPMgO:SLT using parameters
calculated by Eqs.(4-54) through (4-61) is shown in FIG. 4-27.

FIG. 4-28: Schematic of semi-monolithic cavity with 20 mm PPMgO:SLT crystal inside.

FIG. 4-29: Eigenmode diagram of 20 mm PPMgO:SLT cavity with required waist size at any point in the cavity, blue arrows show the corresponding different points in the cavity to the PARAXIA two dimensional waist diagram.
As it could be seen if FIG. 4-30, the beam is more elliptical in the center crystal of PPMgO:SLT than PPKTP cavity (was 63.7%).

\[
\text{Ellipticity} = \frac{\text{waist(Vertical)}}{\text{waist(Horizontal)}} = \frac{55.2}{95.8} \times 100 = 57.6\% \quad (4-63)
\]

FIG. 4-30: Eigemode mode waists of the 20 mm PPMgO:SLT cavity, the x direction is parallel and y direction is normal to this page.

With \( \lambda = 972.34 \) nm, \( d_{\text{eff}} = 13.8 \) pm/V for PPMgO:SLT, \( L = 20.1 \) mm measured carefully for the length of our crystal, \( \omega_1 = 1.93 \times 10^{15} \) rad/s for IR light, \( n_1 = 2.13872 \) at \( \lambda_1 = 972.34 \) nm and \( n_2 = 2.22007 \) at \( \lambda_1 = 486.17 \) nm, \( w_1 = w_x = (95.8+97.1)/2 = 96.5 \) \( \mu \)m and \( w_2 = w_y = (61.1+55.2)/2 = 58.2 \) \( \mu \)m are average waists in middle and ends of PPMgO:SLT, the theoretical single pass conversion efficiency becomes:

\[
\eta_{\text{theo}}(20\text{mmPPMgO:SLT}) = \frac{2d_{\text{eff}}L^2\omega_1}{\pi\varepsilon_0 C^3 n_1^2 n_2 w_1 w_2} = 0.00542 \quad (4-64)
\]

Again PARAXIA could be very useful to find a condition for maximum coupling possible by adjusting length of \( L_4, L_5, L_6 \) in the FIG. 4-27, by choosing the focusing lens with focal length of 4.0 mm. By reversing beam from input facet of PPKTP to the tip of fiber we have:
FIG. 4-31: The best coupling was obtained by reversing beam from cavity to tip of fiber

According to PARAXIA the closest conditions of waists in the FIG. 4-30 would be:

1- Focal length of lens = 4.0 mm
2- The addition of $L_3 + L_4 = 47.8$ mm (the distance from lens to input coupler $M_1$)
3- The length $L_6 = 4.263$ mm (the distance from the tip of fiber to the lens)

By choosing the values above the reversing beam from cavity to the fiber reached to the tip of fiber with waist $w$ and position of the waist $z$ predicted by PARAXIA are:

$$\left( w_x = 3.341 \mu m, \ z_x = +9.1 \mu m \right) \ \text{and} \ \left( w_y = 2.573 \mu m, \ z_y = -9.1 \mu m \right)$$

(4-65)

Positive $z$ means that waist position is in the front of fiber tip and negative $z$ means waist position inside the fiber. So the beam instead of perfect condition of $w_x = 3.3 \mu m, \ z_x = 0 \mu m$ in the x direction, it reaches to the fiber with $w_x = 3.326 \mu m, \ z_x = 14 \mu m$. The same analogy applicable for y direction.

The total IR mode matching (MMIR) due to waist size mismatch and waist position mismatch using Eq. (4-19) was calculated. For this given 20 mm PPMgO:SLT cavity
using \( w_{x_1} = 3.3 \mu m \), \( w_{x_2} = 3.341 \mu m \), \( w_{y_1} = 2.573 \mu m \), \( w_{y_2} = 3.491 \mu m \), \( \Delta z_x = 9.1 - 0 = 14 \mu m \),
\( \Delta z_x = -9.1 - 0 = -9.1 \mu m \) and \( \lambda = 972.34 nm \), the mode matching Eq. (4-18) becomes:

\[
MM_{IR} = 0.9601 \quad (4-66)
\]

This means that about 100-96.01= 3.99% of IR power reflects from the cavity without converting to blue and ends up in the PR.

4.3.3 Experimental Results of Semi-Monolithic Cavity with 20 mm PPMgO:SLT

After lignin up the cavity carefully, all 5 optical mounts tightened at their optimum position and tilt in both horizontal and vertical direction. FIG. 4-32 shows the lined up cavity in the scanning mode with two unresolved TEM\(_{20}\) and TEM\(_{02}\) modes.

![Mode structure of the lined up 20 mm PPMgO:SLT cavity captured on oscilloscope with two non-resolvable TEM\(_{20}\) and TEM\(_{02}\) modes.](image)

FIG. 4-32: Mode structure of the lined up 20 mm PPMgO:SLT cavity captured on oscilloscope with two non-resolvable TEM\(_{20}\) and TEM\(_{02}\) modes.

So experimental value of MM\(_{IR}\) obtained by our PPKTP cavity using FIG. 4-32 is:

\[
MM_{IR}(exp) = 1 - \frac{TEM_{20}amplitude + TEM_{02}amplitude}{TEM_{00}amplitude} = 1 - \frac{0.165 + 0.165}{6.6} = 0.95 \quad (4-67)
\]

So the experimental mode matching MM\(_{IR}\) is still smaller than theoretical value calculated at 0.96 by equation (4-66), but closer to theoretical than the case of PPKTP (96.0% versus 98.1%). The less beam distortion due to new focusing lens could be responsible for this improvement.
Now that cavity is lined up, next we want to measure accurate transmission of $T_1$ the mirror $M_1$, after removing the PPMgO:SLT crystal out of cavity (as discussed by schematic of FIG. 4-19). So at the given power of $P_{in} = 43.6$ mW, the power $P_T = 4.27$ mW was measured. Therefore $T_1$ becomes:

$$T_1(\text{exp}) = \frac{P_T}{P_{in}} = \frac{4.27}{43.6} = 0.095$$  \hspace{1cm} (4-68)

Single pass conversion efficiency was also measured using the schematic of FIG. 4-20. At $P_{in} = 516.2$ mW, $P_T = 49.04$ mW, we measured blue power of $P_B = 3.99$ μW at the PPMgO:SLT’s phase matching temperature of 83.3 °C. Therefore single pass conversion using Eq. (4-41) becomes:

$$\eta(\text{exp}) = \frac{(\text{Tanh}^{-1}\sqrt{\frac{P_B}{P_T}})^2}{P_T} = 0.00166 \frac{1}{W^2}$$ \hspace{1cm} (4-69)

Unfortunately this is almost one third of expected theoretical value of for 20 mm PPMgO:SLT with discussed intended eigenmode waists calculated by Eq. (4-64).

For measuring the IR cavity loss of $\ell_{\omega}$ we locked the cavity at $P_{in} = 43.6$ mW, the measured power $P_{TR} = 32.35$ mW was achieved. Using Eqs. (4-34) through (4-41), with following conditions:

1- $P_{in} = 43.6$ mW
2- (PER) = 0.99
3- $\text{MM}_{IR} = 0.95$
4- $T_1 = 0.098$
5- $P_R = 32.35$ mW

One can calculate buildup of BU using (4-34):

95
\[ BU = 33.5 \quad (4-70) \]

the circulating power using (4-35):
\[ P_{\text{cir}} = 1.369 \text{ W} \quad (4-71) \]

and finally \( \ell_{\omega} \) using (4-36) through (4-41):
\[ \ell_{\omega} = 0.0082 \quad (4-72) \]

The 20 mm PPMgO:SLT’s blue absorption insertion loss of \( \delta \) introduced in the Eq. (4-34) was measured experimentally using the schematic shown in FIG. 4-23. Using our WG made blue power of \( P_{B1} = 1.0 \text{ mW} \) going into crystal, we measured the transmitted blue power of \( P_{B2} = 0.9915 \text{ mW} \) after PPMgO:SLT by power meter. So blue absorption by ~20 mm long PPMgO:SLT became:
\[ \delta = \frac{P_{B2}}{P_{B1}} = 1 - \frac{0.9915}{1.0} = 0.0085 \quad (4-73) \]

As it was predicated by [12, 16], the blue absorption \( \delta \) in 20 mm PPMgO:SLT is substantially lower than PPKTP by a factor 18 (\( \delta = 0.15 \) for 20 mm PPKTP). This will make a huge difference in our locking stability and crystal heating management.

Now all constant deciding factors in our 20 mm PPMgO:SLT cavity is experimentally measured:

1- (PER) = 0.99
2- \( T_1 = 0.098 \)
3- \( \text{MM}_{\text{IR}} = 0.95 \)
4- \( \eta = 0.00166 \text{ 1/W} \)
5- \( \ell_{\omega} = 0.0082 \)
6- \( \delta = 0.0085 \)

By varying the input power \( P_m \) into the cavity using constant above and Eqs. (4-34)
through (4-41) calculated and observed $P_R$ and $P_{2\omega}$ (the two immediate direct measurable values outside the cavity), in the locked mode and on blue resonance are listed in the table below.

**TABLE 4-3: Comparison of calculated $P_R$ and $P_{2\omega}$ using constants above and observed $P_R$ and $P_{2\omega}$ using power meter in 20 mm PPMgO:SLT cavity.**

<table>
<thead>
<tr>
<th>Pin [mW]</th>
<th>Calculated $P_R$ [mW]</th>
<th>Observed $P_R$ [mW]</th>
<th>Calculated $P_{2\omega}$ [mW]</th>
<th>Observed $P_{2\omega}$ [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.6</td>
<td>29.14</td>
<td>29.20</td>
<td>2.88</td>
<td>2.88</td>
</tr>
<tr>
<td>111.2</td>
<td>68.04</td>
<td>65.7</td>
<td>16.80</td>
<td>16.01</td>
</tr>
<tr>
<td>206.7</td>
<td>109.7</td>
<td>107.5</td>
<td>50.83</td>
<td>48.3</td>
</tr>
<tr>
<td>300.0</td>
<td>140.7</td>
<td>136.6</td>
<td>95.65</td>
<td>91.5</td>
</tr>
<tr>
<td>400.0</td>
<td>161.1</td>
<td>164.4</td>
<td>152.8</td>
<td>138.5</td>
</tr>
<tr>
<td>529.0</td>
<td>191.2</td>
<td>194.1</td>
<td>236.6</td>
<td>226.5</td>
</tr>
<tr>
<td>633.0</td>
<td>206.2</td>
<td>210.7</td>
<td>310.3</td>
<td>296.5</td>
</tr>
<tr>
<td>713.0</td>
<td>215.6</td>
<td>220.7</td>
<td>369.9</td>
<td>352.0</td>
</tr>
<tr>
<td>798.0</td>
<td>223.8</td>
<td>235.0</td>
<td>435.5</td>
<td>414.0</td>
</tr>
<tr>
<td>862.0</td>
<td>228.9</td>
<td>237.1</td>
<td>486.2</td>
<td>456.0</td>
</tr>
</tbody>
</table>

**FIG. 4-33: Image of 20 mm PPMgO:SLT cavity with generated 456 mW blue.**
A maximum of $P_{2o} = 465$ mW of blue at $\lambda = 486.17$ nm with maximum over all conversion efficiency of $\eta = 52.9\%$ was achieved. A maximum build up factor $BU = 33.4$ and IR circulating power of $P_{cir} = 27.1$ W was obtained. The calculated and observed blue power and efficiency are plotted in FIGs. 4-33 and 4-34.

**FIG. 4-34:** Comparison of generated and calculated blue power as a function IR input power.

**FIG. 4-35:** Comparison of generated and calculated over all conversion efficiency $\eta$ as function IR input power.
4.3.4 Discussion on Generated Blue Using 20 mm PPMgO:SLT

It seems our calculated and experimental single pass conversion of $\eta$ for our 20 mm PPMgO:SLT are not close. Our observed single pass conversion efficiency 0.166% is not comparable to theoretical value of 0.549% for 20 mm PPMgO:SLT. The only speculation for the large cause of discrepancy would be that this specific sample has a $d_{33}$ of lower than 13.8 pm/V suggested for PPMgO:SLT. The round trip IR loss of $\ell_{\omega} = 0.0082$ was much higher than PPKTP setup (with $\ell_{\omega} = 0.003$). On the other hand no significant IR and blue absorption was detected. The stability of locking on and off the blue were similar. In fact when the cavity was locked off the blue resonance (off the phase matching temperature of 83.3 °C) with maximum power input power of $P_{in} = 860$ mW and very high circulating power of $P_{cir} = 27$ W, no significant heating or crystal temperature rise was observed. The reflected power $P_R$ was very close to calculated power of $P_R = 639$ mW. When the cavity was locked on the blue resonance temperature, no heating problems was occurred. The phase matching temperature was the same when operating in low power or the maximum power of 465 mW. Although 465 mW stable single frequency blue power would seem impressive but, but 52.9% conversion efficiency was not matching our previous work with 20 mm PPKPT with obtained 81.1% efficiency. Also it was shown in FIGs. 4-33 and 4-34, there is a gradual blue power and efficiency fall off when the generated blue power was increased. For this given crystal since the value of $\eta$ was not close to theoretical value, it is very hard to speculate about sources discrepancy. We observed some intensity fluctuation of TEM00 mode in the scanning mode when piezo was under slow ramp. We did not take it very seriously at the time. But later on in the next section that I will discuss thoroughly, we will confirm that our 30 mm PPMgO:SLT from different vendor had the same behavior. After our diagnosis we confirmed that there is fractional polarization rotation per single pass in
PPMgO:SLT crystal. We did not observe any degradation for several hour of operation. We cut our investigation on this sample and moved on a new cavity with 30 mm PPMgO:SLT. Very low blue absorption of 0.41% 1/cm confirmed by our own experiment for PPMgO:SLT made the consideration of longer crystal very tempting. So in the next section I will introduce 81.3% efficiency (our best results ever) using 30 mm PPMgO:SLT from a vendor (Oxide Corp. Japan), with their better handle on SLT products.

4.4 Generating Blue Using 30 mm Long PPMgO:SLT in a Semi-Monolithic Buildup Cavity

4.4.1 Introduction

Large difference between theoretical and experimental single pass conversion of $\eta$ in our previous section with 20 mm PPMgO:SLT crystal was a little bit troubling. Also high IR round trip cavity loss of $\ell_{\text{IR}} = 0.0082$ was a deciding factor for low efficiency. The efficiency of 52.9% for generating blue was also so far away from 81.1% in case of PPKTP. We really wanted to have progress in our efficiency and this was backward. So we decided to give PPMgO:SLT one more shot. In this new setup following improvements over last section were done:

1- Due to low IR and blue absorption of PPMgO:SLT, we decided to use 30 mm long crystal. Since single pass conversion related by $\eta \propto L^2$ (L the length of crystal), a 30% increase in the length would give us a factor 1.67 times increase in $\eta$. After consulting with Oxide Corp. (Japan), they recommended 30 mm too. Also after exchanging our experience with our 20 mm PPMgO:SLT’s poor $\eta$ value. They recommended 0.5 mm thick crystal in oppose to previous one (with 1 mm thickness). They mentioned that SLT is harder than KTP to be uniformly periodically polled. The IR mode field diameter in the crystal is in the order of $\sim 200 \mu m$, so 0.5 mm thickness works but not much room left for alignment slop. Since we were eager to know if we could improve the $\eta$ we accepted
the 0.5 mm thick crystal idea. It seems the thinner the crystal substrate, the more uniform electric field penetration for uniform poling would be. They also recommended a 2 mm height of crystal in oppose of 1 mm for previous crystal. This way, they could place the periodically poled section in only 1 mm center of height, leaving two sections of 0.5 mm non-poled SLT substrate at the top and bottom of crystal which could be used for comparison of some behaviors in poled and non-poled sections of crystal.

FIG. 4-36: Side view of 30 mm PPMgO:SLT crystal with periodically poled section between of two non-poled MgO:SLT substrate.

The top view still look like previous crystals with the following image:

FIG. 4-37: Top view of 30 mm PPMgO:SLT crystal with Brewster polished facets.

Since we did not observe any photorefractive at 83°C with our 20 mm PPMgO:SLT in the last setup, we decided to have the phase matching at lower temperature of ~70 for less power usage and more electric power efficiency.

2- The 2 mm long, low voltage piezo was replaced by a 6 mm one (FIG. 4-38), with three time more travel at a given voltage. In the cavity to be built in this section, the free
spectra range (FSR) is as low as about 5.0 V on piezo. So we could replace a complicated and costly Stanford Research locking amplifier with a C++ programmable TTL microprocessor for locking the cavity in the CW blue operation. At least one FSR flexibility is needed for resonance peak search by any locking skim.

![Image](image_url)

**FIG. 4-38:** The installed 6 mm long piezo with 5 V needed for 0.5 μm travel.

4.4.2 Theoretical Analysis of Semi-Monolithic Cavity with 30 mm PPMgO:SLT

The index of refraction of our Stoichiometric PPMgO:SLT (with 1% mole doped MgO) for IR with λ = 972.34 nm and second harmonic blue with λ = 486.17 nm at phase matching temperature of 67.5 °C using Eq. 4-54 would be:

\[
n_e(\lambda_1 = 972nm, T = 67^\circ C) = 2.13862 \quad (4-74)
\]

\[
n_e(\lambda_2 = 486nm, T = 67^\circ C) = 2.21964 \quad (4-75)
\]

Theoretically, the period of poling of PPMgO:SLT for the first order QPM (m = 1), using (3-4) becomes:

\[
\Lambda = \frac{\lambda_1}{2[n_e(\lambda_2 = 486nm, T = 67^\circ C) - n_e(\lambda_1 = 972nm, T = 67^\circ C)]} = 6.001 \mu m \quad (4-76)
\]
For traveling in the cavity from air with \( n_1 = 1 \) into the PPMgo:SLT with \( n_e = 2.13872 \) at 
\( \lambda = 972.34 \text{ nm} \) and \( T = 67.5 \text{ °C} \) the Brewster angle becomes:

\[
\theta_B = \tan^{-1}(n_e) = \tan^{-1}(2.13862) = 64.9726°
\]  \( \text{(4-77)} \)

The required angle \( \theta \) in FIG. 4-39 becomes;

\[
\theta = 2\theta_B - 90 = 2(64.9726) - 90 = 39.95°
\]  \( \text{(4-78)} \)

For better mode matching factor of MMIR we had to lengths had to decreased the lateral lengths in FIG. 4-36 to \( L_1 = L_2 = 12.5 \text{ mm} \) in oppose to 15 mm in last two cavities. Our accurate measurement of PPMgO:SLT dimensions resulted in length of \( L_{PPMgO:SLT} = 30.0 \text{ mm} \) and sides of 2×1 mm. The \( L_3 \) becomes:

\[
L_3 = (L_1 + L_2)\cos\theta + L_{PPMgO:SLT} = (12.5 + 12.5)\cos(39.95) + 30.0 = 49.165mm
\]  \( \text{(4-79)} \)

The total optical round trip optical path length \( L_{RT} \) is equal to:

\[
L_{RT} = L_1 + L_2 + L_3 + n_e(\lambda = 972nm, T = 83°C)L_{PPMgO:SLT} = 138.324mm
\]  \( \text{(4-80)} \)

The schematic of our semi-monolithic cavity with 30 mm PPMgO:SLT using parameters calculated by Eqs.(4-74) through (4-80) is shown in FIG. 4-39.

![Schematic of semi-monolithic cavity with 30 mm PPMgO:SLT crystal inside.](image)

FIG. 4-39: Schematic of semi-monolithic cavity with 30 mm PPMgO:SLT crystal inside.

The FSR of the cavity becomes:
The eigenmode of this cavity using PARAXIA is given in the following figure:

![Eigenmode diagram of 30 mm PPMgO:SLT cavity with required waist size at any point in the cavity, blue arrows show the corresponding different points in the cavity to the PARAXIA two dimensional waist diagram.](image)

FIG. 4-40: Eigenmode diagram of 30 mm PPMgO:SLT cavity with required waist size at any point in the cavity, blue arrows show the corresponding different points in the cavity to the PARAXIA two dimensional waist diagram.

As it could be seen if FIG. 4-40, the beam ellipticity in the center crystal of 30 mm long PPMgO:SLT is:
Ellipticity = \frac{\text{waist(Vertical)}}{\text{waist(Horizontal)}} = \frac{48.7}{78.9} \times 100 = 61.7\% \quad (4-82)

FIG. 4-41: Eigemode mode waists of the 30 mm PPMgO:SLT cavity, the x direction is parallel and y direction is normal to this page.

With \( \lambda = 972.34 \text{ nm} \), \( d_{\text{eff}} = 13.8 \text{ pm/V} \) for PPMgO:SLT, \( L = 30.0 \text{ mm} \) measured carefully for the length of our crystal, \( \omega_1 = 1.93 \times 10^{15} \text{ rad/s} \) for IR light, \( n_1 = 2.13862 \) at \( \lambda_1 = 972.34 \text{ nm} \) and \( n_2 = 2.21964 \) at \( \lambda_1 = 486.17 \text{ nm} \), \( w_1 = w_x = (78.9 + 83.6)/2 = 81.3 \mu\text{m} \) and \( w_2 = w_y = (66.0 + 48.7)/2 = 57.4 \mu\text{m} \) are average waists in middle and ends of PPMgO:SLT, the theoretical single pass conversion efficiency becomes:

\[
\eta_{\text{theo}}(20\text{mmPPMgO:SLT}) = \frac{2d_{\text{eff}}L^2\omega_1}{\pi\varepsilon_0 C^3 n_1^2 n_2^2 w_1 w_2} = 0.014688 \quad (4-83)
\]

Using PARAXIA for finding the maximum coupling possible by adjusting length of \( L_4, L_5, L_6 \) in the FIG. 4-39, by choosing the focusing lens with focal length of 4.0 mm. By reversing beam from input facet of 30 mm PPMgO:SLT to the Brewster cut fiber tip we would have:
FIG. 4-42: The best coupling was obtained by reversing beam from 30 mm PPMgO:SLT cavity to the Brewster cut fiber tip.

According to PARAXIA the closest conditions of waists in the FIG. 4-41 would be:

4- Focal length of lens = 4.0 mm
5- The addition of $L_3 + L_4 = 39.1$ mm (the distance from lens to input coupler $M_1$)
6- The length $L_6 = 4.35$ mm (the distance from the tip of fiber to the lens)

By choosing the values above, the reversing beam from cavity to the fiber reached to the tip of fiber with waist $w$ and position of the waist $z$ predicted by PARAXIA are:

$$\begin{align*}
(w_x = 3.46 \mu m, z_x = +18.9 \mu m) \quad \text{and} \quad (w_y = 2.71 \mu m, z_x = -18.9 \mu m)
\end{align*}$$

Positive $z$ means that waist position is in the front of fiber tip and negative $z$ means waist position inside the fiber. The total IR mode matching (MMIR) due to waist size mismatch and waist position mismatch using Eq. (4-18) for this given 30 mm PPMgO:SLT cavity with,

$$\begin{align*}
w_{x1} = 3.3 \mu m, w_{x2} = 3.461 \mu m, w_{y1} = 3.3 \mu m, w_{y2} = 2.72 \mu m, \Delta z_x = 18.9 - 0 = 18.9 \mu m,
\end{align*}$$
\[ \Delta z_2 = -18.9 - 0 = -18.9 \mu m \text{ and } \lambda = 972.34 \text{ nm} \]

becomes:

\[ MM_{IR} = 0.942 \quad (4-85) \]

This means that about \( 100 - 94.2 = 5.8\% \) of IR power leaves the cavity without converting to blue and ends up in the \( P_R \).

4.4.3 Experimental Results of Semi-Monolithic Cavity with 30 mm PPMgO:SLT

After assembling the cavity just like the schematic of FIG. 22 that two previous cavities was made, we started lining up the cavity. But when we were getting close to complete alignment, a strong feedback to laser would be accruing. The laser in this condition was not single frequency anymore. To isolate the feedback, we used an OFR optical isolator designed for about \( \lambda = 975 \text{ nm} \) which was very close to our wavelength. The isolator was PM fiber coupled by ourselves efficiently in the lab to the improve the manufacturer spec of 1.2dB insertion loss to 1dB (\( \sim 23\% \)). So FIG. 22 was modified to FIG. 4-43 with an added isolator.

![Schematic of 30 mm PPMgO:SLT cavity with optical isolator to minimize feedback.](image)
FIG. 4-44: Actual image of 30 mm PPMgO:SLT cavity with isolator.

For this given isolator we measured 32dB isolation. After placing the isolator in the cavity the laser was stable. After lining up the cavity carefully, all 5 optical mounts tightened at their optimum position and tilt in both horizontal and vertical direction. FIG. 4-45 shows the lined up cavity in the scanning mode with two unresolved TEM$_{20}$ and TEM$_{02}$.

FIG. 4-45: Mode structure of the lined up 30 mm PPMgO:SLT cavity captured on oscilloscope with two non-resolvable TEM$_{20}$ and TEM$_{02}$ modes and FSR of ~ 5V.
So experimental value of MMIR obtained by our 30 mm PPMgO:SLT cavity using FIG. 4-45 is:

\[
MM_{IR}^{\exp} = 1 - \frac{TEM_{20}^{\text{amplitude}} + TEM_{02}^{\text{amplitude}}}{TEM_{00}^{\text{amplitude}}} = 1 - \frac{0.66 + 0.66}{26.4} = 0.95
\] (4-86)

In this cavity just like 20 mm PPMgO:SLT, we were observing the intensity fluctuation of TEM\(_{00}\) mode in scanning by varying the crystal temperature.

Now that cavity is lined up, next we want to measure accurate transmission of T\(_1\) the mirror M\(_1\), after removing the PPMgO:SLT crystal out of cavity. So at the given power of P\(_{in}\) = 43.6 mW, the power P\(_T\) = 4.27 mW was measured. Therefore T\(_1\) becomes:

\[
T_1^{\exp} = \frac{P_T}{P_{in}} = \frac{3.989}{43.6} = 0.0915
\] (4-87)

Single pass conversion efficiency was also measured using the schematic of FIG. 4-20.

At P\(_{in}\) = 534.0 mW, P\(_T\) = 48.86 mW, we measured the blue power of P\(_B\) = 30.54 μW at the PPMgO:SLT’s phase matching temperature of 67.51 °C. Therefore single pass conversion using Eq. (4-41) becomes:

\[
\eta^{\exp} = \frac{(\text{Tanh}^{-1} \sqrt{\frac{P_B}{P_T}})^2}{P_T} = 0.0128 \cdot \frac{1}{W^2}
\] (4-88)

This η is comparable with theoretical value η = 0.0147 calculated by Eq. (4-83).

For measuring the round trip IR cavity loss of ω\(_\omega\) we locked the cavity at Pin = 43.6 mW, but we realized when we change the frequency laser and adjusting the crystal temperature the different P\(_R\) values were observed, which were corresponding to different values loss of ω\(_\omega\). So the ω\(_\omega\) was not constant as a function phase matching temperature of crystal. Something that we did not observed in PPKTP cavity setup. So we decided to monitor the single reflection back from crystal as a function of crystal temperature. The instability of laser without isolator was an
evident of feedback from crystal poling intersections. Using the schematic of FIG 4-46 and optical power meter, we measured the reflection power \( P_{\text{ref}} \) by varying the crystal temperature:

**FIG. 4-46:** Schematic of setup to measure reflection back from crystal.

**FIG. 4-47:** Reflection of IR power from crystal as a function of crystal temperature.
The reflection back from crystal had a maximum of 0.15% and a minimum 0.057% shown in the FIG 4-47. But it is not periodical nor uniform.

Also observing the TEM$_{00}$ peak fluctuation in scanning mode as a function of temperature was an evident of fractional IR polarization rotation by crystal [XX]. So using the schematic of shown in FIG. 4-48, we monitor the vertical polarization after IR passing through crystal once as a function of crystal temperature using two cross polarizers.

Surprisingly the polarization rotation by crystal was considerable. IR power in the cavity with vertical polarization does not generate any blue, so it would be a source of round trip loss which results in less buildup, $P_{cir}$ and consequently less generated blue. Our few time repeating the polarization rotation measurements confirm that as a function of temperature, there would be between 0.2~0.45% of polarization rotation loss (see FIG. 4-49).
To make sure if reflection and polarization rotation is due to poled intersections in the crystal or not. We shifted the PPMgO:SLT crystal a about 0.75 mm up and realigned the cavity in the non-poled section of crystal. In fact no reflection was observed. So we got convinced that poled intersections are cause of reflection. But unfortunately the polarization rotation was behaving same as the FIG. 4-49. Also we locked the cavity in the non-poled region at highest IR circulating power of $P_{cir}=17.5$ W in the absence of blue at room temperature. We observed a $\sim 1.3$ °C temperature rise of crystal in compare to case of $P_{cir}= 0.05$ W. Since the resistance of our heater strip was $R=29.5$ $\Omega$ and we needed a current of $I =25$ mA to cool the temperature of crystal by 1.3 °C, we concluded that there is a loss of:

$$\ell_{scat} = \frac{RI^2}{P_{cir}} = \frac{29.5(0.025)^2}{17.5} = 0.00105 \quad (4-89)$$

We are calling this loss due to scattering not the heating absorption. Since our own measurement of loss for IR and blue in PPMgO:SLT was very low. We speculate that his loss could only be
caused by scattering which scattered IR power reaches the aluminum housing of crystal and warming up the housing sensed by the close by thermistor.

After collecting above information in non-poled section of crystal, we switched back to poled section and lined up the cavity again. To avoid the retro reflection in poled section, this time we lined up the cavity in a slight angle of 0.5° inside the crystal.

**FIG. 4-50:** Cavity lined up with 0.5° off the strait line in the crystal.

Due a large index of $n_e = 2.138$ for PPMgO:SLT the beam leaving the Brewster facet ($P_{Brew}$) would make an angle $\theta_{out} = 2.0°$. The reflection was substantially lower. But when locked the cavity off the blue, we had a total round trip IR loss of $\ell_\omega = 1.1\%$. So far we have speculated that sources of $\ell_\omega$ are:

1- Scattering and absorption in mirrors ($\ell_m = 0.2\%$)

2- Reflection back in the crystal ($\ell_R = 0.05 \sim 0.15\%$)

3- Polarization rotation in the crystal ($\ell_{pol} = 0.2 \sim 0.45\%$)

4- Scattering in the crystal ($\ell_{scat} = 0.1\%$)

Where:

$$\ell_\omega = \ell_m + \ell_R + \ell_{pol} + \ell_{scat} \quad (4-90)$$
But observed $\ell_{\alpha} = 1.1\%$ was too high.

So we went back to straight alignment and let isolator to take care of retro reflection. The cavity was lined up again using original FIG. 4-43. But this time we carefully scanned the frequency of the laser (by varying the FBG temperature) against the crystal temperature and looked for maximum reflected $P_R$ in FIG 4-43, which would correspond to minimum loss of $\ell_{\alpha}$. So finally at the FBG temperature of $T_{FBG} = 35.8 \, ^\circ\text{C}$ which increased the IR wavelength by $\Delta \lambda = 0.0068 \times 10.8 = 0.073\, \text{nm}$ in compare to $T_{FBG} = 25.0 \, ^\circ\text{C}$, and crystal phase matching temperature of $67.5 \, ^\circ\text{C}$ on blue resonance we had a maximum $P_R = 28.99 \, \text{mW}$ when IR input power was $P_{in} = 37.4 \, \text{mW}$. Using Eqs. (4-34) through (4-41), with following conditions:

1- $P_{in} = 37.4 \, \text{mW}$
2- $(\text{PER}) = 0.99$
3- $\text{MMIR} = 0.95$
4- $T_1 = 0.0915$
5- $P_R = 28.99 \, \text{mW}$

One can calculate buildup of BU using (4-35):

$$BU = 36.7 \quad (4-91)$$

the circulating power using (4-36):

$$P_{circ} = 1.289 \, \text{W} \quad (4-92)$$

and finally $\ell_{\alpha}$ using (4-37) through (4-41):

$$\ell_{\alpha} = 0.0065 \quad (4-93)$$

The 30 mm PPMgO:SLT’s blue absorption insertion loss of $\delta$ introduced in the Eq. (4-34) was measured experimentally using the schematic shown in FIG. 4-22. Using our WG made
blue power of \( P_{B1} = 1.0 \) mW going into crystal, we measured the transmitted blue power of 
\( P_{B2} = 0.9992 \) mW after 30 mm PPMgO:SLT by power meter. So blue absorption became:
\[
\delta = \frac{P_{2B}}{P_{1B}} = 1 - \frac{0.9901}{1.0} = 0.0099 \quad (4-94)
\]
Now all constant deciding factors in our 30 mm PPMgO:SLT cavity is experimentally measured:

1- (PER) = 0.99
2- \( T_1 = 0.0915 \)
3- MMIR = 0.95
4- \( \eta = 0.0128 \) I/W
5- \( \ell_{ao} = 0.0065 \)
6- \( \delta = 0.0099 \)

By keeping the constants above and varying the input power \( P_{in} \) into the cavity using constant 
above and Eqs. (4-34) through (4-41) calculated and observed \( P_R \) and \( P_{2\omega} \) (the two immediate 
direct measurable values outside the cavity), in the locked mode and on blue resonance are listed 
in the table below.

**TABLE 4-4:** Comparison of calculated \( P_R \) and \( P_{2\omega} \) using 6 constants above and observed \( P_R \) and 
\( P_{2\omega} \) using power meter in 30 mm PPMgO:SLT cavity.

<table>
<thead>
<tr>
<th>( P_{in} ) mW</th>
<th>Calculated ( P_R ) mW</th>
<th>Observed ( P_R ) mW</th>
<th>Calculated ( P_{2\omega} ) mW</th>
<th>Observed ( P_{2\omega} ) mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.4</td>
<td>17.47</td>
<td>17.42</td>
<td>13.16</td>
<td>13.10</td>
</tr>
<tr>
<td>119.6</td>
<td>27.9</td>
<td>29.1</td>
<td>75.0</td>
<td>73.6</td>
</tr>
<tr>
<td>223.0</td>
<td>29.6</td>
<td>34.0</td>
<td>167.8</td>
<td>164.4</td>
</tr>
<tr>
<td>335.0</td>
<td>29.7</td>
<td>44.5</td>
<td>272.0</td>
<td>258.4</td>
</tr>
<tr>
<td>449.0</td>
<td>30.1</td>
<td>52.9</td>
<td>378.1</td>
<td>358.0</td>
</tr>
<tr>
<td>572</td>
<td>34.7</td>
<td>63.0</td>
<td>491.0</td>
<td>466.0</td>
</tr>
</tbody>
</table>
Using TABLE 4-4, blue power and efficiency is plotted by FIGs. 4-51 and 4-52.

**FIG 4-51:** Observe and calculated conversion efficiency.

**FIG. 4-52:** Observed and calculated blue power as a function of input power.

After looking carefully the data in the TABLE 4-4, we realized that observed $P_R$ is larger than calculated one. But the addition of calculated $P_R + P_{2\omega}$ is very close to observed $P_R + P_{2\omega}$. This means that conservation energy is met. Larger observed $P_R$ means that the extra power ending out of cavity but not actually absorbed in the cavity. This is a good news, otherwise if it
was absorbed, it would create much more problem than declining efficiency. We speculated that this could be due to declining of the mode matching as we increase the $P_{\text{cir}}$. Front wave distortion, polarization rotation and feedback in the cavity could be responsible for this decline. Therefore we could not consider $\text{MMIR} = 0.95$ as a constant value from low power to high power anymore. By varying the $\text{MMIR}$ in Eqs. (4-34) through (4-41), we came up with the TABLE 4-5 that calculated and observed $P_{2\omega}$ values are much closer.

### TABLE 4-5: Comparison of calculated and observed $P_R$ and $P_{2\omega}$ using constants: (PER), $T_1$, $\eta$, $\ell$, $\delta$ above and variable $\text{MMIR}$ in 30 mm PPMgO:SLT cavity.

<table>
<thead>
<tr>
<th>Pin (mW)</th>
<th>$\text{MMIR}$</th>
<th>Calculated $P_R$ (mW)</th>
<th>Observed $P_R$ (mW)</th>
<th>Calculated $P_{2\omega}$ (mW)</th>
<th>Observed $P_{2\omega}$ (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.4</td>
<td>0.95</td>
<td>17.47</td>
<td>17.42</td>
<td>13.16</td>
<td>13.10</td>
</tr>
<tr>
<td>119.6</td>
<td>0.94</td>
<td>29.1</td>
<td>29.1</td>
<td>73.9</td>
<td>73.6</td>
</tr>
<tr>
<td>223.0</td>
<td>0.935</td>
<td>33.1</td>
<td>34.0</td>
<td>164.5</td>
<td>164.4</td>
</tr>
<tr>
<td>335.0</td>
<td>0.91</td>
<td>43.8</td>
<td>44.5</td>
<td>258.8</td>
<td>258.4</td>
</tr>
<tr>
<td>449.0</td>
<td>0.903</td>
<td>52.3</td>
<td>52.9</td>
<td>357.5</td>
<td>358.0</td>
</tr>
<tr>
<td>572</td>
<td>0.903</td>
<td>62.2</td>
<td>63.0</td>
<td>465.1</td>
<td>466.0</td>
</tr>
</tbody>
</table>

So the $\text{MMIR} = 0.95$ observed in Eq. (4-86) was good at low power, but gradually decline to 0.903 at the highest power. The mode matching $\text{MMIR}$ as a function of circulating power is plotted in FIG. 4-47.

**FIG. 4-53:** $\text{MMIR}$ as a function of circulating power on blue resonance.
The blue comes out of the cavity with ellipticity of 62%. The blue beam profile quality did not degrade from low power to high power (see FIG. 4-54)

FIG. 4-54 Generated blue beam profile (A) with 10 mW blue (B) with 466 mW blue.
CHAPTER 5

SUMMARY AND FUTURE WORK

The goal of this work was to generate CW single frequency (SF) blue light at a moderate output of about >500 mW. Currently few SF blue from leading laser companies like Sapphire 488 (by Coherent Inc, with max of 200 mW power) and Cyan 488 (by Newport, with max of 150 mW) are commercially available. But none of these match our proposed power of ~500 mW. Our blue is going to be used as a fundamental laser source for a second SHG stage to generate UV. The single pass conversion efficiency from blue to UV using BBO or CLBO crystals is as low as 0.01% 1/W. Therefore, for generating about ~200 mW of UV there is a need of more than 500 mW blue. All three leading crystals PPMgO:SLN, PPKTP and PPMgo:SLT suitable for efficient SHG using QPM in this study have shown capability of generating blue at our power goal with some different limitations for each.

5.1 Generating Blue in WG Configuration

In the case PPMgO:SLT WG, we reported about 110 mW of blue with efficiency of 41% [33]. Our WG was implanted by technique called Proton-Exchange (PE) [34]. Our achieved power, efficiency and simplicity of setup was comparable or superior over several other work at the time. There are reports of 80 mW blue with conversion efficiency of 26% [35], 159 mW with conversion of 52% [36]. All these researches had a lot more complicated IR sources than ours.

We observed photorefractive properties in this crystal. The single pass conversion efficiency dropped from 4.5 1/W in low power to 2.1 1/W at high power. After few hours of operation the power drops down. This effect was reversible by few hours of heat treatment about 100 °C, but it makes very inconvenient. Photorefractive damages due to formed space charges,
BIIRA and IR absorption are this source of decline. It has been shown the Proton-Exchange actually intensify the photorefractive properties [37]. Due to this correlation between Proton-Exchange and photorefractive properties, several work have been reported higher conversions and less photorefractive using pure crystal ridge WG made of PPMgO:LN substrate. This type of WGs are actually formed by micro machining and sawing a of PPMgO:LN substrate or by etching. Reports of 190 mW of blue with conversion of 49% using machined WG [38] and 40 mW with conversion of 59% etched ridge WG [39] have been reported, both with less difficulty than Proton-Exchange WG. These WGs never became commercially available and were used only research facilities at NGK and Sony for high definition TV and screen applications.

In fact PPMgO:SLN never become utilized for actual products to generate blue due to high BIIRA and blue absorption. Today, several green laser sources about 10 mW using PPMgO:SLN WG are available commercially. It seems green absorption and green induced IR absorption (GIIRA) are less than blue

In the case of PPKTP WG, we generated about 7 mW with conversion of 10%. The blue power after several hours dropped substantially. Heat treatment and annealing did not improve the degradation. As we observed in our buildup cavity, PPKTP has grey tracking property that changes the index while exposed to high intensity blue. This caused permanent index profile change and drop of conversion efficiency.

5.2 Generating Blue in Resonant Buildup Configuration

Due to large photorefractive properties observed with PPMgO:SLN, we never tired this crystal in a buildup cavity. Our next available choice of crystal was PPKTP with substantially larger photorefractive damage threshold than PPMgO:SLN (see TABLE 3-1). We reported 681 mW of blue with record high conversion of 81.1% [29]. In this work we also coupled the
generated blue into PM fiber with coupling efficiency of 87.5%. Our semi-monolithic cavity configuration was simpler and convenient than other works. Our blue conversion was higher than all reported works for generating blue using QPM. Also our free air blue to fiber coupling was very efficient too. There are reports of 320 mW blue with conversion of 51% [40], 400 mW with conversion of 60% [27], 200 mW with conversion 40% [28], 234 mW with conversion 75% [26], using PPKTP in resonant cavity. Simplicity and convenient of IR source of our setup was superior over above works. PPKTP was a better choice than PPMgO:SLN in respect to feedback. In fact no feedback to IR laser was detected at highest power of 840 mW going into the cavity. Therefore the setup was very simple with no need of optical isolator. But in respect to absorption and degradations, PPKTP has highest blue absorption among all three leading crystals. Also permanent degradation due to grey tracking and index change make it not very unconformable setup to generate high power blue. Excessive heat due to large 7.5% 1/cm blue absorption makes the locking of the cavity very hard.

After achieving very good results with PPKTP with high power and high conversion at the beginning, locking instability due to large absorptions and degradation at the end, our next choice was PPMgO:SLT. This crystal has much less blue absorptions, large damage threshold and higher conductivity than PPKTP (see TABLE 3-1). Our first attempt with 20 mm PPMgO:SLT resulted in 456 mW blue with conversion of 53%. Locking was smooth and no thermal difficulty was observed. But single pass conversion was one third of theoretical calculations. It seems that poled domain were not uniform and similar, therefore poor conversion was observed. No feedback was detected from crystal to IR laser. But I wish we would experience some feedback with this crystal. Due to the fact that we did not run into feedback problem with 20 mm PPMgO:SLT, we did not correct our next order for 30 mm one.
A slight angle of ~1 degree tilt of periodically domains could minimize the reflection substantially and there would be no need of bulky and expensive optical isolator.

After obtaining poor results with 20 mm and also observed low blue absorption of 0.4% 1/cm, we decided to increase the length by 33% which increases the single pass blue conversion by an order of 1.6. Single pass conversion in 30 mm crystal was a lot closer to theoretical value than 20 mm one. But unfortunately, we had enough feedback from crystal to laser that had use an isolator. Also polarization rotation and some scattering in the crystal was observed that was troubling. In fact largest source of round trip loss in the cavity was polarization rotation. Despite of all difficulties above, we obtained 466 mW of blue with another record high conversion of 81.3%. There are reports of 500 mW blue with conversion 30% [41], 55 mW with conversion 10% [42], and 4 W of blue with conversion of 27% [43], all using PPMgO:SLT in single pass configuration.

5.3 Future Work

5.3.1 Generating Blue Via SHG

According to our results from all three crystals of PPMgO:SLN, PPKTP and PPMgO:SLT, it seems PPMgO:SLT might be the best choice for generating blue. This crystal also has shown very high power green generation capacity via SHG by several authors. There are successful reports of watts level green using PPMgO:SLT such as 19 W of green with efficiency of 27% [44], 18 W green with conversion 17.6% [45], 10 W green with conversion of 35% [46], 7 W green with conversion of 24% [47]. All these report are in single pass configuration. In fact, I have not run into publications regarding PPMgO:SLT in buildup cavity configuration.

In regard to our setup with 30 mm PPMgO:SLT, initial results with ~500 mW and conversion of 81.6% are very exciting and rewarding. But we have to complete this study
further. The life time of crystal with maximum CW blue must be tested. Also effects of feedback and polarization rotation detected on our crystal worthwhile to be taken in accounts.

For the feedback problems, we are negotiating with crystal manufacturer to order 30 mm long with slight angle in periodically poled geometry while keeping the same Brewster angle at the crystal facets to minimize the feedback. Using isolator in the setup is cumbersome, it has insertion loss of 23% and also it is very costly. There should be a way to eliminate the use of isolator.

As I mentioned, in CHAPTER 4, we tired about 0.5° tilt in the IR beam in crystal which results in 2° off Brewster angle incident to facet. This 2° of angle would cause about 0.13% loss on each crystal’ facet, a total of 0.26% of round trip IR loss which is substantial. That was why with an angle going into crystal, the best round trip loss we got was $\ell_{\omega} = 1.1\%$ in oppose to $\ell_{\omega} = 0.65\%$ with strait beam. With an angle of 0.5° inside crystal, the feedback was a lot less, so if manufacturer induce an angle 2° in poled section shown in FIG. 5-1, we might get rid of feedback completely.

Also in the case of success after testing long hour of CW high power blue, we would like to couple the generated blue into PM fiber for convenience in power delivery. In the case of our PPKTP setup, we coupled 516 mW of blue into PM fiber with efficiency of 87.5%. But as I
mentioned before, some of lenses used for coupling and focusing were introducing front wave distortion on the beam. Actually the lens that was used to couple blue into fiber was one of them. So by using correct lens or using two lenses (collimating beam coming out of crystal with first lens, then focusing it into the fiber by a second lens) we might get more coupling efficiently than 87.5% for our PPMgO:SLT setup.

In regards with locking schematic, to lineup or run the setup in CW blue, we use several instruments such as ramp generator and locking amplifier (FIG. 5-2). We have been able to program a single TTL micro programmer capable of both acting as ramp generator for lining up and also cavity locker (FIG. 5-3). We have tested this programmable IC for locking several times and it has shown reliability so far. Very soon the IC is going to be installed on the cavity plate capable of doing three tasks of, ramp generator mode for alignment, locking mode for CW blue operation, and also due to the fact this IC has internal integrated thermistor, by installing the IC directly on the plate it could stabilized the plates temperature which results in more cavity stability.

![FIG. 5-2: PPMgO:SLT cavity with various controller, locker and ramp generator.](image-url)
5.3.2 Generating UV Via SHG

In the case of success with our 30 mm PPMgO:SLT for generating ~500 mW blue, this setup could be an excellent fundamental source for SHG from blue to UV. Currently three crystals are available for generating UV.

1- BBO, with excellent transmission at about 243 nm light (our desired wavelength)

2- CLBO, with three time single pass conversion efficiency than BBO at 243 nm

3- PP-LBGO, capable of QPM for generating UV.

BBO has been used widely for generating UV. It has low UV absorption, but cannot be periodically poled. So it has to be phase matched ordinary with walkoff. The single pass conversion efficiency to generate 243 nm light using 10 mm BBO is only 0.01%. BBO could be phase matched at room temperature. On the other hand, CLBO has higher conversion of 0.03% for 10 mm crystal. But it is strongly hygroscopic, absorbing water from exposed air which makes it hard to handle. To keep it away from hygroscopic properties it has to be phase matched
at ~200 °C. So with this difficulties, CLBO might not be a good option. So our choices would be BBO or PP-LBGO.

In the case of BBO, the phase matching in BBO would be an general SHG with two ordinary (o) IR photons, creating an extraordinary (e) blue photon \((o + o \rightarrow e)\), or wise versa \((e + e \rightarrow o)\). So polarization of UV would be orthogonal to polarization of blue light. Therefore the semi-monolithic cavity does not separate blue from IR. There would be the need of dichroic beam splitter in the cavity. Instead of the dichroic splitter, we have proposed use of a \(\pi/2\) waveplate at UV which also acts as a \(\pi\) wave plate. A correct thickness of plate made of quartz attached the output facet of BBO could do this task. The only difficulty would be efficiency of the contact between BBO and quartz that has to be evaluated yet. It has to have very low loss for blue transmission at the intersection of BBO and quartz to obtain high conversion to UV. Necessary optical parts like high and partial mirrors have been tested and cut to small sizes to be placed in the assembly already. So two proposed schematic for BBO would be any schematics of in FIGs. 5-4, 5-5.

**FIG. 5-4:** BBO semi-monolithic cavity using quartz waveplate (ordinary phasematching).
In the case PP-LBGO, since UV could be generated by QPM, we can use our semi-monolithic setup used for generating blue (FIG. 5-6).

This set would be very desirable due to simplicity over BBO setup. So the total setup for frequency quadrupling of IR 972 nm to 243 nm UV would be as simple as of schematic of FIG. 5-7.
FIG. 5-7: Frequency quadrupling of IR light to UV using two semi-monolithic cavities in series.

This would be an efficient setup with minimized number of optics. One the most respected recent publications on quadrupling IR to UV had more complicated setup than ours [48]. In this work, 6 W of 808 nm to 700 mW of blue at 488. Then the blue was converted 215 mW at 244 nm. Therefore, the overall conversion efficiency from 808 nm to 244 nm was 3.6% or 31% conversion from 976 nm to 244 nm. We are hoping that we could match up their results with much less complicated setup.
REFERENCES


