An Introductory Undergraduate Experiment on Second Harmonic Generation

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This project is part of a comprehensive revision of the Undergraduate Physics Laboratory Curriculum at the University of Waterloo, supported by the Dean's Undergraduate Teaching Initiative, Waterloo Science Endowment Fund (WatSEF), and the Sinclair Foundation. I have designed an introductory-level experiment on Second Harmonic Generation (SHG). SHG is a nonlinear optical process in which photons interact to produce light at twice their original frequency. The experiment is taught using inquiry-based instruction. Students investigate whether SHG depends on pulse energy, peak power, or laser intensity using a Titanium Sapphire femtosecond laser (850±50nm, 100±50fs pulses) and a Beta Barium Borate (BBO) crystal. The experiment will be implemented in the new Gee-Whiz Lab Course (GWLC), where students will conduct contemporary physics experiments without requiring prior subject mastery. This approach encourages students to revisit these beyond-introductory-level topics throughout their undergraduate education and explore how experimental investigations contribute to progress in physics in ways distinct from theoretical approaches. Preliminary work suggests the experiment is both technically feasible and pedagogically effective, providing a foundation for future introductory-level curriculum development in nonlinear optics and other topics typically reserved for upper-year or graduate study.

Acknowledgements

I would like to thank Dr. Donna Strickland and Dr. Karen Cummings. Thanks also to my lab group, especially Kyle MacRobbie for all the discussion and work that helped me develop my understanding of PER as I worked through this project while he was asking me questions like “were the other undergrads that you had in your undergrad days like my undergrads?” and also “can you show me how to make an autocorrelator again?” And reader, he was only asking because just like you and I, he could not remember what Sam and Dean had said, and Peter, Zujun, Zhiyu, Rebecca, Alissa, Xiaoyu, Joscelyn, Reza, Dr. Joe Sanderson, Dr. Stephen Rand, and all the other countless members in and out of the lab weren’t even in the lab when he asked me the question. Thank you also to Dr. Melanie Campbell, I’ll always carry the lessons you taught me forward throughout my career and do my best to pass them on to future learners. I would like to thank and acknowledge the entire laboratory staff and faculty, as well as the whole Department of Physics and Astronomy for their work. I would also especially like to thank and acknowledge Indu, Som, Lil, all of my cousins, my Love and Best-Friend-in-the-Whole-Universe-As-I-Know-It-So-Far (Cameron), and all others who supported me through this thesis. And, I would like to thank and acknowledge my old high school teacher Dave Allan, who first encouraged me to pursue physics through a funny story, Mikolas, the upper year in my undergraduate days who said physics is fun you just have to suffer through the courses first (in a good way!), my previous lab instructor Joshua Crone, who told me that it was okay to leave the lab and take a quick phone call if it came from my parents, Dr. Meg Ward, and my former professor Dr. Jim Martin. While I’m at it, shout out to John and Kaylee, and The Usual Suspects at The Office! Thank you also to Sensei Kao, Jeffrey Sax, and all those who have gone before. Thank you Optica for your support through the Women’s Scholarship! Oneigashimasu everyone and thanks for all the fish.

Dedication

For Terry Fox. And for all those who continue to cheer him on in his Marathon of Hope. Also for my (Aunt) Rathnatha, my childhood dog Mitochondrion, and for anyone who reads this sentence and smiles at the end of it. :)

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Undergraduate physics laboratory courses are designed to educate students through practical experiments covering a variety of topics. Most often, laboratory courses focus on reinforcing concepts taught in lectures rather than learning about experimentation [1]. However, curricular recommendations state that these courses should introduce and reinforce concepts and skills that are used by experimentalists to ensure students are better prepared for careers in physics and to keep students engaged and interested in pursuing physics further[1, 2, 3]. Undergraduate laboratory curricula and pedagogy vary across educational institutions, but it is recommended that each curriculum should focus on constructing student knowledge, modelling phenomena, designing experiments, developing technical and practical skills, analyzing and visualizing data, and communicating physics [3]. These curricular foci are all skills and competencies that students need to develop in order to engage in experimentation.

Several studies that assess student attitudes towards experimental physics suggest that inquiry-based learning is an instructional method that can explicitly teach students how to experiment effectively in line with curricular recommendations [3, 4, 5, 6, 7, 8]. In this thesis, I present an inquiry experiment designed for introductory undergraduate physics students that uses a mode-locked femtosecond laser to produce frequency doubled blue light from infrared light.

In this chapter, I discuss the project's motivation, the new course in which the experiment presented in this thesis takes place, a brief introduction to the experiment and its relevant concepts, previous work bringing nonlinear optics to undergraduate laboratories, and finally an outline of the remaining 5 chapters of this thesis.

1.1 Motivation to This Project

This work was motivated by the work of Dr. Natasha Holmes and Dr. Carl Wieman, who present an inquiry learning approach to reconstruct the introductory undergraduate physics laboratory [1, 2]. In this learning approach, which is explained in more detail in Chapter 2, students iteratively design and revise experiments, developing scientific reasoning and a deeper engagement with experimental practice. Our group was particularly interested in this approach because it uses inquiry to position the laboratory as more than a place to reinforce lecture content. It inspired us to begin our own laboratory revision project.

Many efforts in physics education research focus on improving the introductory laboratory to ensure that students develop the skills and competencies needed for success in upper-year coursework and eventual careers in industry or academia [2]. While experiments that align closely with introductory concepts are important, there is also a need for laboratory experiences that go beyond the introductory curriculum. These can expose students to new areas of physics and reinforce core scientific practices such as modelling, experimental design, and critical analysis [3].

In this project, I sought to incorporate inquiry learning into the undergraduate laboratory by encouraging students to see the lab as a place for generating new understanding, instead of only applying existing knowledge. To that end, we designed an experiment based on Second Harmonic Generation (SHG), a nonlinear optical phenomenon rarely encountered at the introductory level. While students may not be able to predict or explain the SHG process at the outset, the structure of the activity invites them to construct their own explanations through iterative inquiry. This kind of engagement offers a distinct learning experience compared to both lectures and traditional labs, and provides an opportunity for students to experience the laboratory as a space for authentic scientific discovery.

1.2 Research Questions

The research questions for this project are:

1. Can Second Harmonic Generation be used to develop an inquiry-based experiment at the introductory undergraduate level?
2. Can undergraduate physics students get excited about doing experimental physics as a direct result of completing this experiment?

To investigate the first research question, we have developed an inquiry-based experiment making use of Second Harmonic Generation. To investigate the second research question, the experiment constructed must be administered to introductory undergraduate students who will be further evaluated on their beliefs towards experimental physics before and after completing this experiment.

1.3 The Gee Whiz Laboratory Course (GWLC)

The Gee Whiz Laboratory Course (GWLC) presents exciting experimental physics concepts to introductory undergraduate students. Named for the phrase "Gee Whiz", this course aims to give students surprising and thought-provoking experiences through four experiments that involve contemporary physics typically not seen in first year. We encourage reflection, understanding, and enjoyment without needing subject mastery. The learning goals for this course are to reinforce inquiry-based learning processes that students are introduced to in their other laboratories and primarily, to get students excited about doing experimental physics. In groups of three over the course of a single three-hour-long session, students are to develop their own questions and perform explorations that motivate learning through inquiry. When working in groups, students are not assigned roles to avoid impacting their engagement with the phenomenon [9].

Students should take the GWLC during the second term of their first year of the undergraduate experimental physics program, known as Honours Physics, concurrently with the second introductory physics laboratory course.

The GWLC is not meant to replace introductory physics laboratory courses, but offer an additional laboratory course where students can expand their experimental physics knowledge in a space designed to promote interest in the pursuit of experimental physics. Based on findings from previous research, it is likely that focusing on getting students interested in concepts that are novel to them encourages students to return to the concepts they explore in these labs in their upper years of study with the intention of pursuing experimental physics further [3, 9, 10, 11, 12, 13, 14].

1.4 Overview of Experiment and Relevant Concepts

This section, except for Subsection 1.4.1 was developed using the 4^{th} edition of *Nonlinear Optics* by R. Boyd [15], *Lasers* by A.E. Siegman [16] as well as Lecture 8 from PHYS 714: Nonlinear Optics, offered in Winter 2024 [17].

1.4.1 Overview of Experiment

In this experiment, students will determine whether the SHG process is dependent on the pulse energy, peak power, or laser intensity. They will use a Class-IV femtosecond laser and Beta Barium Bromate (BBO) crystal to produce SHG light.

1.4.2 Nonlinear Optics

Nonlinear optics was predicted before the invention of the laser by Maria Goeppert-Mayer in 1931 [18]. Generally, light from a laser can produce nonlinear optical effects because of its high intensity compared to other light sources. Thus, it wasn't until after the laser was invented in 1960 that the field of nonlinear optics emerged. Nonlinear optics describes phenomena resulting from the optical properties in a material system that change in a nonlinear manner due to its interaction with light.

Processes that are nonlinear are those for which the dipole moment per unit volume, or polarization density, $\tilde{P}(t)$, of a material system depends non-linearly with the electric field strength, $\tilde{E}(t)$, of light applied to that material system[1]. This is different from the polarization of a wave, which is a description of its geometrical orientation. Nonlinear optical processes are characterized by the nonlinear susceptibility $\chi^{(n)}$ where (n) represents the order of nonlinearity. The relationship between the polarization density, the electric field strength, and the nonlinear susceptibility is,

$$\tilde{P}(t) = \sum_{n} \epsilon_0 \chi^{(n)} \tilde{E}^n(t). \tag{1.1}$$

The demonstration of Two-Photon Absorption, theorized by Maria Goeppert-Mayer, and demonstrated by Wolfgang Kaiser and Charles Garrett in 1961, was one of the first recognized discoveries in the field [18, 19].

1.4.3 Second Harmonic Generation (SHG)/Frequency Doubling

Second Harmonic Generation (SHG), or frequency doubling, is a nonlinear optical process that occurs when light interacts with matter (usually a birefringent crystal). Some of that light transmitted through the crystal emerges from the crystal at twice its original

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[1] The tilde, or (˜), above a term signifies that it varies with time rapidly.

frequency. SHG was first demonstrated by Peter Franken et al. in 1961, and then mathematically formulated by Nicolaas Bloembergen and Peter Pershan in 1962 [20, 21]. SHG is a second-order nonlinear process, the lowest-order wave-wave interaction, and a special case of sum-frequency generation. It is an even order nonlinearity and so can only occur in media that lack inversion symmetry. The second-order nonlinear susceptibility, $\chi^{(2)}$, of a medium is what characterizes its tendency to produce light at the second harmonic. An energy level diagram of the SHG process is shown below in Figure 1.1 along with a diagram of light travelling through a medium to produce light at the second harmonic.

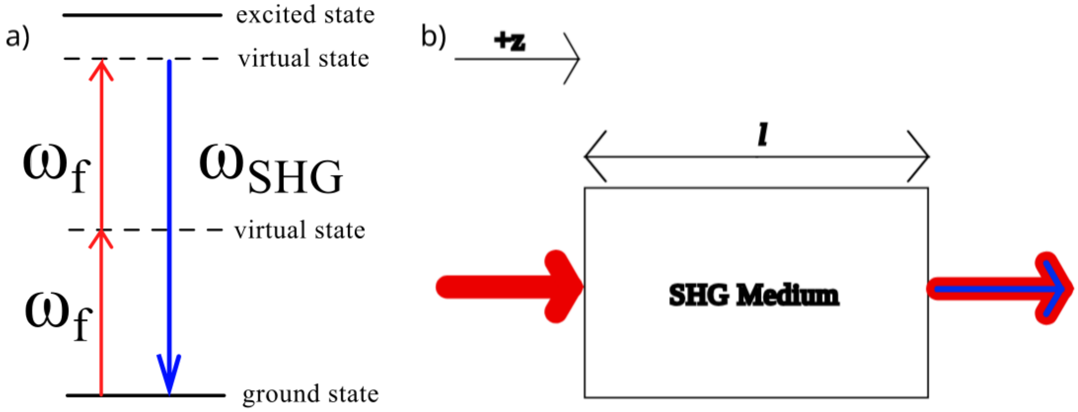

Figure 1.1: a) An energy level diagram of the SHG process. Two photons at frequency ω_f interact to produce a photon at ω_{SHG}. The two photons "combine" and are absorbed by a medium, exciting an atom and one single photon at twice the incident photons' frequency is emitted as the atom in the medium returns to the ground state.
b) A diagram showing SHG with infrared light in a medium. The length of the medium is l and the wave is travelling in the positive $z-$direction. Infrared light, represented by a thick red arrow, at about 800nm travels through a medium and SHG light is produced at 400nm, represented by a thin blue arrow over the emerging infrared light. Only a fraction of light gets converted to the second harmonic, and most of the light emerges at its fundamental frequency at $z = l$.

SHG is an intensity dependent process with the proportionality

$$I_{SHG} \alpha I_f^2, \tag{1.2}$$

where I_f is the incident intensity. A mathematical description of this proportionality is provided in Appendix A.

1.4.4 Phase Matching

When the phase relationship between the waves that interact to produce SHG light is maintained along the wave propagation direction, the phase matching condition is satisfied and efficiency is optimized. Without efficient phase matching, the power of the second harmonic light is very low as the direction of energy transfer changes periodically due to the change in the phase relationship between the interacting waves. This is presented in Figure 1.2.

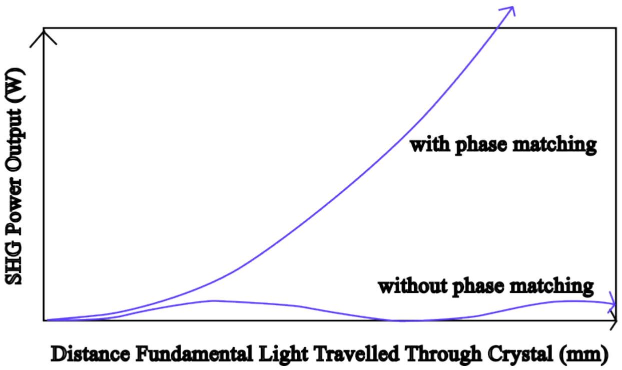

Figure 1.2: The Power Output of SHG light as the fundamental light used to generated it travels through a frequency doubling crystal. With phase matching, the power output of SHG light grows quadratically with respect to the distance travelled. Without phase matching, the power output is close to zero and oscillates due to the changing phase relationship between the interacting waves.

1.4.5 Nonlinear Optics with Gaussian Beams

Nonlinear effects are seen using lasers, whose beam profiles are Gaussian. Gaussian beams have spherical phase fronts, and the size of the beam does not vary linearly with the direction of propagation. When the medium is sufficiently small, plane waves can be used to describe behaviours of laser beam profiles, using the Plane Wave Approximation. A sufficiently small medium has a length shorter than the beam's depth of focus. The minimum value of a Gaussian beam is a radius known as the beam waist, and has a finite size which cannot be focused to a point due to diffraction. Figure 1.3 is a diagram of a Gaussian Beam.

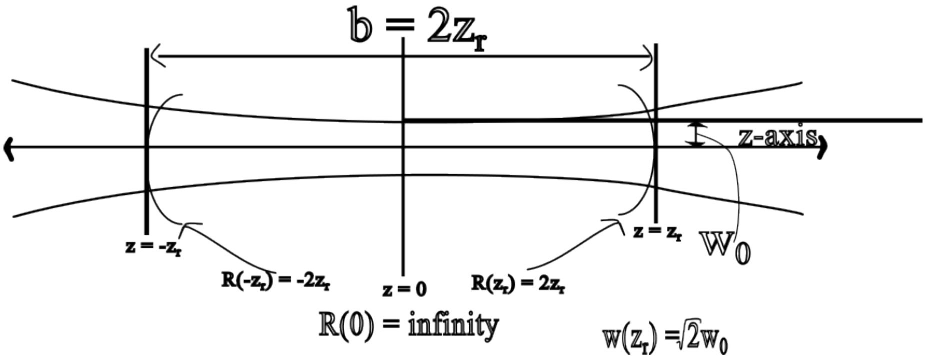

Figure 1.3: A diagram of a Gaussian beam travelling on the z-axis. The phase fronts have a radius of curvature $R(z)$, confocal parameter, b, beam waist w_0, and Rayleigh range z_r. As light travels along the z-axis, the beam size changes nonlinearly.

1.4.6 Pulse Duration and Beam Waist of the Fundamental and SHG Beams

The experiment presented in this thesis uses a laser that emits a train of light pulses each with a duration on the femtosecond scale. The beam is much more intense than a continuous wave laser, and the pulses are generated through mode-locking. The pulse duration and beam waist of the fundamental and SHG beams are interrelated, meaning changes in these properties in the fundamental beam affect those in the SHG beam accordingly.

Reference [22] shows that the relationship between the pulse duration of the fundamental beam, δt and the SHG beam, δt_{SHG} is,

$$\delta t_{SHG} = \frac{\delta t}{\sqrt{2}}. \tag{1.3}$$

The beam waist of the SHG beam also shows a similar proportionality. The beam waist relationship between the fundamental and higher harmonic beams is,

$$w_{0,n} = \frac{w_{0,f}}{\sqrt{n}}. \tag{1.4}$$

When $n = 2$, the relationship is $w_{0,2} = \frac{w_{0,f}}{\sqrt{2}}$.

1.5 Nonlinear Optics in Advanced Undergraduate Laboratory Courses

The experiment presented in this thesis is not the first to bring nonlinear optics to the undergraduate laboratory. There are several experiments that have introduced nonlinear optics to the undergraduate laboratory environment, outlined in References [23, 24, 25, 26, 27, 28, 29, 30]. Each experiment presented in this literature review is designed for the advanced laboratory and satisfies the curricular recommendations for the upper year laboratory curriculum [3]. This work differs from these studies as the experiments will be delivered to introductory students.

1.5.1 Experiments Making Use of Nonlinear Optics in the Advanced Undergraduate Laboratory used to Develop The Introductory Undergraduate Experiment in SHG

There are 2 experiments designed for the advanced undergraduate laboratory that were studied for the development of the experiment presented in this thesis. One experiment, titled Nonlinear Optical Second Harmonic Generation, was developed by Ivan Ruddock in 1994 [23]. In this experiment, a 628.3 CW Helium Neon (He-Ne) laser was used to generate SHG light. The experiment focused on having students develop their understanding of the SHG signal's dependence on the phase-matching angle of the nonlinear crystal and the intensity of the fundamental beam.

The other experiment used to develop the experiment presented in this thesis was created by Michaela Sullivan et al. [24]. In this experiment, students were to build an intensity autocorrelator within a laboratory session and use it to approximate the pulse duration of an ultrafast laser. Students are expected to take this experiment in the final year of their undergraduate program and especially if they intend to pursue further work where intensity autocorrelation is relevant to their career.

1.5.2 Other Undergraduate Experiments Using Nonlinear Optics

There are several other experiments that were built for the undergraduate laboratory that make use of nonlinear optics. Most experiments in nonlinear optics at the advanced undergraduate level make use of a 632.8 CW He-Ne Laser, with a few exceptions as outlined in References [24, 28, 29, 30]. The equipment required for these experiments can vary in cost and make use of a mix of commercial products and industrial equipment.

One experiment is on the thermal lens effect using commercial soy sauce and a He-Ne laser operating at 632.8nm [25]. Students are to measure the radius of the laser's beam and estimate the focal length of the thermal lens induced in this experiment. In another experiment, students use Chinese tea and a He-Ne laser to explore self-defocusing and optical bistability [26]. In an experiment on photorefractive nonlinear optics at the undergraduate physics level, students can perform a set of experiments on birefringence, diffraction, and two-wave mixing with a 632.8nm He-Ne Laser [27]. There is also an experiment designed for the advanced undergraduate laboratory that uses two diode lasers operating at 780.2nm and 776.0nm to excite rubidium vapour and generate collimated blue light [28]. In another experiment, a 200fs pulsed laser was used to present an undergraduate experiment in autocorrelation and presented students with the opportunity to explore the relationship between the pulse's shape in the frequency and time domains [29]. In this experiment, students can observe the constraint on this relationship by the lower limit of the Heisenberg Uncertainty Principle.

Not all experiments are done in a physical laboratory. In the work of Dr. Tobias Brixner et al., an experiment was built on an interactive training simulator of an ultrafast laser laboratory [30]. Students are able to learn about the concepts related to femtosecond lasers, such as Gaussian beam propagation, ultrashort optical pulses, and interactions between light and crystals.

1.6 Thesis Outline and Structure

The remaining 5 chapters in this thesis discuss the construction and design of the experiment. Chapter 2 presents different inquiry based learning approaches used in undergraduate physics laboratory courses. Chapter 3 presents the workspace that I built for this experiment. Chapter 4 presents the written materials that supplement this experiment. Chapter 5 presents the proposed assessment methods that can be used to evaluate students. In Chapter 6, the project's results are presented, future work is proposed, and potential impact for this project is discussed.

Chapter 2

Inquiry Based Instruction

2.1 Chapter Introduction

This chapter provides information on a new introductory physics laboratory course at the University of Waterloo intended for undergraduate physics students in our experimental physics program, known as “Honours Physics”. Then, I present a general discussion of inquiry-based learning in undergraduate laboratories and the different methods of inquiry-based instruction that were considered for the development of this course. Finally, this chapter concludes with a discussion of different examples of educational scaffolding used in the experiment.

2.2 Inquiry in Undergraduate Laboratories

By definition, education using inquiry engages students and encourages independent thinking [1, 31, 32, 33]. Recent research has also shown that experimental physics courses designed using inquiry-based instructional strategies promote an environment where students are excited to work in a physics laboratory [1, 3, 34]. Students learning through inquiry-based courses are more engaged with the material they are learning compared to those who do not learn through inquiry [1, 34, 35]. Inquiry work enhances students’ sense of competence, autonomy, and relatedness, increasing intrinsic motivation according to Self Determination Theory [9, 10]. When students are intrinsically motivated, they are more likely to enjoy what they are working with, and the material they are learning is more likely to be interesting to them [11]. Designing inquiry experiments that encourage students to understand the role of experiment in the broader field [36, 37, 38, 39].

2.2.1 Characterizing Inquiry-Based Learning

According to the characterization of inquiry by Buck et al., there are five levels that classify inquiry-based work in the scientific undergraduate laboratory [31]. Starting with the lowest level, these are confirmation inquiry, structured inquiry, guided inquiry, open inquiry, and authentic inquiry [31]. Further, Buck discusses six characteristics that can be used to classify the level of inquiry within an undergraduate lab course. These characteristics are: Problem/Question, Theory/Background, Procedures/Design, Results Analysis, Results Communication, and Conclusions. The levels of inquiry form an independence continuum, where in the first level, confirmation inquiry, all six characteristics are *given* to students.

In confirmation inquiry work, students are evaluated on their ability to correctly obtain a pre-determined result. These labs are effective in the reinforcement of analytical methods required for experimental work in physics. "Traditional" labs often fall into this category. Often, if the purpose of a laboratory activity is to experience an unfamiliar phenomenon or learn a particular laboratory technique, confirmation inquiry methods are used.

In structured inquiry labs, the question, theory, procedures, and results analysis methods are provided, but students must communicate results and draw conclusions from their experiment independently.

In guided inquiry, the experimental question, theory, and procedures are presented to students and students are responsible for analyzing and communicating their own results and determining conclusions independently.

In open inquiry, students are only given an experimental question and theory, so that they can develop methods, and results and conclusions independently.

The final level of inquiry is authentic inquiry, which is where the student can independently develop all six characteristics of inquiry-based laboratory work. Project based courses are an example of authentic inquiry work.

2.2.2 Inquiry-Based Instructional Methods for Undergraduate Physics Laboratory Courses

Three common inquiry-based instructional methods used to develop undergraduate physics laboratory courses are the Structured Quantitative Inquiry Lab (SQILab) proposed by Dr. Natasha Holmes and Dr. Carl Wieman, the Investigative Science Learning Environment (ISLE) proposed by Dr. Eugenia Etkina, and invention activities as described by Dr. Daniel Schwartz [1, 40, 41]. These approaches mimic the process experimental physicists undergo, and encourage students to develop both inductive and hypothetico-deductive reasoning.

SQILabs are iterative, open-ended labs and serve as the basis for the development done by the University of Waterloo. Students perform preliminary measurements related to a phenomenon, develop a plan to improve the measurements, analyze their measurements, and use the results to propose a model. Then, students iterate the same experimental measurement (or measurements), but using different methods that systematically improve precision and accuracy based on the feedback of the session instructors. Finally, the students extend their model using other variables that were not tested during their previous iterations. Over time, these iterations motivate a spontaneous, repetitive inquiry process in experimental settings [1]. Despite the name, the SQILab approach can be used for guided inquiry work in addition to structured inquiry work per Buck et al.'s characterization [1, 31].

The ISLE is another instructional method which develops conceptual knowledge and scientific abilities through iteration and reflection [40, 42]. Students observe a phenomenon, devise a model to describe it, test the model, and apply the model to real world scenarios. The experiments are less open-ended compared to those taught using the SQILab approach.

Invention activities are designed so that students first invent solutions to complicated problems and then learn the expert solution [41]. In physics, the invention would require developing a mathematical model that can be used to describe an observed phenomenon [41]. These activities do not necessarily have to be iterative, the students can develop one invention before being presented with the expert solution.

2.3 Moving through different Levels of Inquiry

Increasing the level of inquiry can improve intrinsic motivation (and enjoyment) by increasing student autonomy. Generally, open inquiry is used later to build on student competence and connection to experimental physics, and to reinforce the concepts taught using structured or guided inquiry by applying these skills to the elements in an experiment that are no-longer pre-determined [9, 10, 11, 12].

The SQILab approach was chosen for the existing introductory laboratory courses to help students transition between the conventional curriculum and the GWLC because we felt that it best matched our goals. Specifically, the ISLE approach is very effective in guided inquiry work, but can limit the amount of autonomy students have when designing an experimental procedure [40, 42]. Invention activities lacked the "make improvement" aspect we valued.

While linked to lectures, the existing physics laboratory courses at the University of Waterloo cover select concepts independently. This is not the case for the GWLC. Since the GWLC experiments contain material beyond the scope of introductory physics, students need to gradually master concepts over years without expecting immediate expert solutions (which is the case for invention activities) [43].

2.4 Scaffolding in the GWLC

For this course, introductory level students will need background material that is scaffolded to prepare them to develop an appropriate procedure. Scaffolding is the process of introducing information in a manner that encourages students to self-direct their behaviour in a learning activity with some help from an instructor. Apprenticeships are classic examples of scaffolded learning. Scaffolding is also essential for fostering an engaging and question-driven laboratory environment. When students are able to independently conduct experiments in a laboratory, they will be more interested in the experiments they are conducting [12]. Scaffolding may be explicit or implicit.

Explicit scaffolding is facilitated through domain-independent and domain-dependent questions which encourage students to focus on productive paths and critically approach the subject matter to independently develop an experimental procedure. Domain-independent questions are general to most experiments in physics. They can be reused in other experiments, and repeated use will encourage students to self-scaffold when they approach new experiments. An example of a domain-independent question is "How many different experiments can you design to answer your questions?" Domain-dependent questions relate directly to an experiment. They are useful in the development of understanding a particular concept. An example of a domain-dependent question is "Why is it difficult to measure the beam area at its focus?"

Implicit scaffolding is used to organize the concepts presented throughout the experiment. The concepts are introduced in a way that encourages students to isolate one variable at a time, compare and contrast the different concepts, and use results from some of the experiments to infer relationships that cannot be measured or approximated in the laboratory. Prompts that promote thinking like an experimentalist by referring to students as "experimentalists-in-training", providing definitions for unknown terminology, and emphasize the need to understand concept are also examples of implicit scaffolding. Implicit scaffolding will also take place through peer-to-peer interactions as students develop their procedures and analysis as they conduct the experiments.

Chapter 3

Construction of the Experimental Workspace

3.1 Chapter Introduction

This chapter describes the construction of the experimental workspace which was my primary task for completion of this project. I was responsible for the following components:

1. The construction of the Class-IV laser system which involved a continuous wave (CW) pump laser connected to an external safety interlock and a mode-locked Titanium Sapphire (Ti:Sapphire) oscillator,
2. The construction of the optics apparatus where undergraduate students perform their open inquiry work, and of an intensity autocorrelator,
3. The safety considerations needed to operate this system and perform open inquiry work.

3.2 The Experimental Workspace

3.2.1 The Laser System

A diagram and a photograph of the oscillator are shown in Figure 3.1.

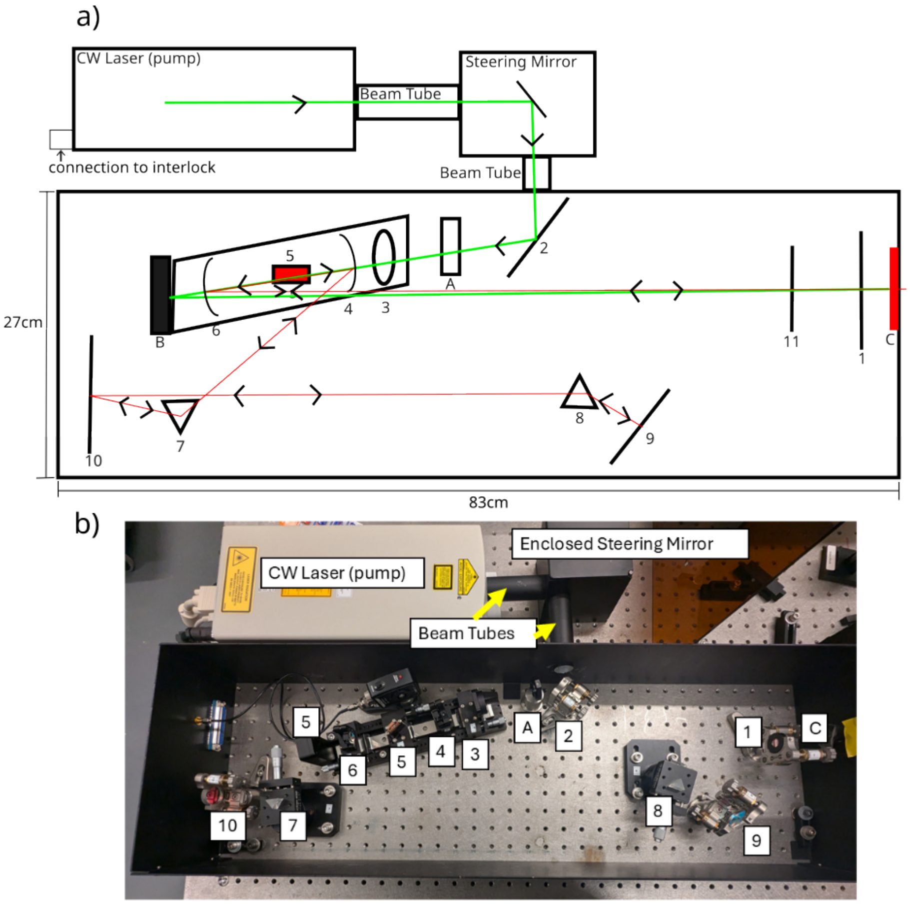

Figure 3.1: a) A diagram of the Ti:Sapphire oscillator. Beams of light are indicated by coloured lines corresponding to their wavelengths with arrows indicating the propagation direction. The numbered items are: (1) Output Coupler, (2) Alignment Mirror, (3) Collimating Lens, (4) Curved Mirror 1, (5) Titanium Sapphire (Ti:Sapphire) Crystal, (6) Curved Mirror 2, (7) Prism 1, (8) Prism 2 (mounted on a spring-loaded translation stage), (9) End Reflector Mirror, (10) Fold Mirror (minimizes the space used on the optical bench), and (11) Iris. The items labelled alphabetically are: (A) Half-Waveplate, (B) CW Beam Dump, (C) Red Light Filter. Arrows indicate the direction in which the light travels. The prisms are oriented at minimum deviation. b) A photograph of the Ti:Sapphire Oscillator. The numbered items are consistent with the labelling of (a). The oscillator is enclosed and a lid covers the components preventing dust and debris from accumulating on the components. The lid has a lock and is only able to be opened by the instructor to prevent students from being directly exposed to the Class-IV light. In this image, the iris is not placed within the cavity.

The laser system is composed of a mode-locked Ti:Sapphire oscillator pumped by a CW laser. Mode-locked Ti:Sapphire lasers were developed by Dr. David Spence et al. in 1991, but this oscillator was designed by Dr. Henry Kapteyn and Dr. Margaret Murnane and developed throughout the early 1990s [44, 45, 46]. The cavity is asymmetric, and the asymmetry of the cavity is necessary to produce high-power TEM_{00} mode-locked pulses [45]. The mode-locked oscillator was built using the Kapteyn-Murnane Labs Titanium Sapphire Collegiate Kit (TS Kit) [47, 48]. This kit was purchased because of its quality and because it was more cost effective than other Ti:Sapphire oscillators, so it fit within the project's budget. The oscillator is Kerr Lens Mode-Locked. The infrared pulsed light emitted from the mode-locked oscillator is p-polarized and has a wavelength range of 800±50nm with pulses that vary around 100±50fs. The 532nm light from the pump laser was blocked from exiting the cavity using a filter (optic (C) in Figure 3.1).

The mode-locked oscillator is pumped by the Spectra-Physics Millennia eV 5W laser that produces CW light at 532nm [49]. The CW laser is a diode pumped, Class-IV laser and produces a beam with a TEM_{00} profile [49]. This laser uses a closed-loop chiller that operates using distilled water at about 20±0.5°C [49]. To operate the laser, 120-240 VAC electrical service is required. This laser must be placed on an optical bench with enough free space around the laser to prevent overheating [49]. The light exiting the CW laser is vertically polarized, or s-polarized [49].

The oscillator was built up from noise following the procedure given in the manual [47, 48]. The Ti:Sapphire oscillator was pumped by linear, horizontally polarized light, or p-polarized light. A half-waveplate was used to rotate the s-polarized 532nm light from the CW laser into p-polarized light. P-polarization was used because the Ti:Sapphire crystal (optic (5) in Figure 3.1) and the prisms (optics (7) and (8) in Figure 3.1) were cut at Brewster angles such that there was near zero loss for p-polarized light. Light that was s-polarized could have been used to pump the oscillator, but a higher pump power would have been required (this could have over-pumped the system and led to double pulsing which would damage the optics). A system pumped with the p-polarized 532nm beam has less loss than a system pumped with an s-polarized beam, so light at p-polarization was used for a safer and more efficient system.

The pump beam was directed into the TS Kit using two mirrors, one outside the TS Kit and one inside the kit. Two mirrors are usually used together to align a beam. One mirror, usually the mirror farther from the beam's target, sets the position of the beam and the other, usually closer to the target, sets the angle. The steering mirror, which is outside the TS Kit (and labelled as such in Figure 3.1) is used to set the position of the beam as it travels through the rail sub-assembly. The sub-assembly contains a focusing lens, Curved Mirror 1, the Ti:Sapphire crystal, and Curved Mirror 2 (optics (3) to (6) in figure 3.1). The alignment mirror (optic (2) in Figure 3.1) sets the angle of the 532nm beam as it travels into the oscillator's enclosure. Moving either mirror changes both the position and the angle of the beam at the same time, but iteratively adjusting both mirrors will give proper beam alignment as long as one mirror is strictly used to set the position and the other is used to set the angle. A beam alignment tool was provided to efficiently align the pump beam. During this stage, only the minimum power of the pump was used which was about 0.2W.

Once the 532nm beam was aligned through the rail sub-assembly, it did not clip any edge of the Ti:Sapphire crystal, but did not pass through the exact centre of the crystal either. This was expected based on the information provided in the manual [47]. The 532nm pump beam was able to pass through the exact centre of Curved Mirror 1 and slightly to the side of the centre of Curved Mirror 2. The beam's position on Curved Mirror 1 and 2 were both confirmed using the provided beam alignment tool. The stability of the cavity depended on the positions of the curved mirrors and the crystal, as the radii of curvature of the mirrors and their distance from each other determined the cavity's stability parameters.

Infrared light was generated in the TS Kit when the atoms in the Ti:Sapphire crystal were excited by the 532nm CW beam. The atoms absorbed the 532nm light and emitted coherent infrared fluorescence. There were two retroreflected fluorescence beams that were emitted by the crystal used to initiate lasing. One beam was retroreflected from the Output Coupler, and the other from the End Reflector Mirror (optics (1) and (9), respectively, in Figure 3.1). To align the cavity to achieve lasing, the retroreflected fluorescence spots were overlapped. An alignment laser was not needed for the construction of the Ti:Sapphire oscillator, since it has a very high gain and produces fluorescence spots that are in the visible spectrum.

When I initially built the oscillator, the maximum output power of the oscillator was about 500±15mW, while the manual stated that a maximum output power near 1W or slightly higher is expected [47]. Mode-locking was not possible. Even though SHG can be generated from a CW source, it is much more intense when generated using a train of short pulses. For this experiment we want to ensure that students are able to clearly observe and work with the SHG beam, so a highly intense beam, which can only be generated from a train of short pulses, suits the needs of the experiment.

The largest source of loss in an oscillator is from the output coupler, which is expected as that is where the laser beam exits the cavity. The unexpected loss likely came from damaged or misaligned optics. Our first thought was that the prisms in this oscillator contributed to the loss. While they were carefully installed to be parallel with each other and at minimum deviation, their mounts had more degrees-of-freedom compared to those of the other optics which increased uncertainty in their orientation.

To eliminate other sources of the unexpected loss, the prisms were removed from the cavity. Mode-locking is not possible without the prisms in the cavity, but the cavity could be aligned to optimize the output power of the CW infrared light. If other optics in the system were causing the significant loss due to damage or misalignment, then removing the prisms would either have no change to the output power, or have a slight increase in output power (but not to the expected level). If an output power much greater than 1W is achieved, then we would be able to conclude that none of the other optics were contributing to the unexpected power loss.

It was necessary to efficiently build a stable cavity with and without the prisms in place to prevent excessive delay to the laser's construction. The cavity is changed significantly by removing or reinstalling the prisms, so keeping its total length the same in both configurations gave us the best chance to quickly rebuild a stable cavity. Without maintaining the original cavity length, a stable cavity could be built, but maintaining that stability between configurations is not possible at all which would have delayed completion further.

The positions of the output coupler and the optics on the rail sub-assembly, forming one arm of the cavity, were kept the same in both configurations. The length of the other arm of the cavity therefore needed to be increased to compensate for the distance the light travels with the prisms in the cavity to keep the total cavity length equal. The Fold Mirror was moved to reflect the fluorescence from Curved Mirror 1 along the line from that mirror to Prism 1, but not in the exact place of Prism 1. Then, to ensure that the total cavity length is the same for the alignments with and without the prisms in place, the End Reflector Mirror was moved to a position farther away from the Fold Mirror as seen in Figure 3.2, increasing the length of that arm.

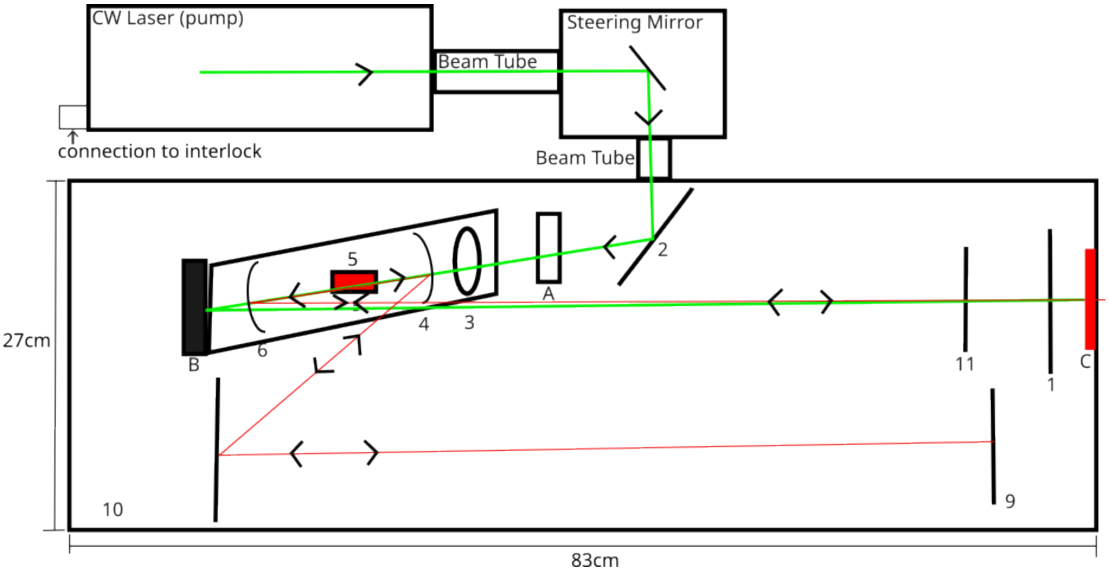

Figure 3.2: The lasing cavity without the prisms in place. Optic (10) was moved from its original position in Figure 3.1. Optic (9) was moved further back (towards the laser head or closer to the Output Coupler) to ensure that this cavity's length was the same as the alignment with the prisms in place. The distance between optics (9) and (10) is about 70cm.

When the pump laser was operating at its maximum value (about 4.9W), the laser would lase, but at about 800±10mW. This was still lower than expected, so we worked on the cavity's alignment to ensure that there was no detectable damage to the optics. The oscillator lases when the retroreflected fluorescence spots overlap. If there is some distance between the centres of each fluorescence spot, the laser is less efficient because its alignment is not optimal. For optimal alignment, the overlap must be as close as possible, so the seperation distance must be minimized. This could not be determined by solely adjusting the mirrors with their mount screws, because the detected output power of the oscillator changed minimally, even with the smallest possible incremental adjustments to the end mirrors.

Reducing the pump's power makes it possible to optimize the separation distance. As the pump power reduces, the radii of the fluorescence spots reduce, their overlap reduces, and the system ceases to lase. Increasing the overlap between the spots will achieve lasing again, which can easily be detected due to the significant change in output power. If lasing is possible at a lower pump power, the oscillator will continue to lase at higher powers. When lasing is achieved at the lowest possible pump power, the separation distance is minimized.

However, it is difficult to achieve lasing at lower pump powers since the fluorescence becomes weaker as power decreases. Incremental reductions in pump power were necessary to achieve lasing at lower power levels, with the spots overlapped after each reduction of power.

When the fluorescence spots were overlapped at a pump power of 4.2W, which was the smallest possible pump power that allowed for lasing, the pump power was increased to 4.8W and an output power of over 1W was finally recorded. The value was not much greater than 1W, indicating that there was another source of loss in addition to possible prism misalignment. With the prisms placed parallel with each other and at minimum deviation, the output power was now at 650±15mW, higher than before, but still lower than needed. We determined that since the prisms were properly aligned, there was no visible damage to the optics, and the cavity was built in a stable configuration, the beam had too much positive dispersion. This also explained why the power was not much greater than 1W in the prism-less cavity.

In addition to the excessive power loss, if there is too much positive or negative dispersion, mode-locking is not possible. This was the case when the oscillator was first constructed, and the source of unexpected loss. While the distance between the prisms introduced negative dispersion to the beam to cancel out the positive dispersion gained as it travelled through the Ti:Sapphire crystal and mirrors, but excessive positive dispersion would not be cancelled out. We believed the source of the excessive positive dispersion to be from light transmitting through either one or both of the End Reflector Mirror and Fold Mirror. The two mirrors have a highly reflective coating on only one face, and if the coating was not on the face that first interacted with the beam, most of the beam would transmit through the glass before reflecting off of the second face and its positive dispersion would increase. In the correct orientation, most of the beam should reflect off of the first face. I rotated each mirror one at a time and realigned the cavity to achieve lasing. The output power increased as each mirror was rotated, which indicated that both the mirrors were originally in the incorrect orientation.

Once a stronger output power was achieved with the prisms in the cavity and with the mirrors in the correct orientation, optimizing for the maximum possible CW output was necessary. This is because when the cavity is only slightly destabilized from the optimal CW operation, the high intensity pulses generated through mode-locking are favoured. After the infrared CW output was maximized to about 1.1±0.2W, mode-locking was initiated.

To generate a mode-locked pulse train, Curved Mirror 2 was moved about 0.6±0.25cm closer to the crystal compared to its position in the CW lasing alignment. The light had to travel within 1mm of the apex of each prism, otherwise the laser would not mode-lock as again an excessive amount of positive dispersion would be introduced to the beam. Mode-locking was achieved by quickly pushing Prism 2 out of and back into the beam path using the spring-loaded translation stage on which the prism was mounted. The sudden perturbation of the prism caused the oscillator to mode-lock.

A photodetector was placed behind the Ti:Sapphire crystal (on the side closer to the pump laser) to detect some of the fluorescence that reflected off the crystal. This way, pulses could be seen on an oscilloscope without interrupting the beam within the cavity.

3.2.2 Optics Used By Students

Due to safety requirements, students cannot interact with the beam directly. They can only work with the optics described in this subsection. Some of the optics in this workspace were placed on linear tracks with handles so that the students could move the optics in and out of the workspace without directly interacting with the beam. This ensures students can safely and easily work with the optics to modify the beam's pulse energy, peak power, and laser intensity.

It was important to design the experimental workspace to ensure the optics were always easy to realign in a quick and efficient manner. Optics were either placed on linear tracks or fixed in place in the experimental workspace to ensure that students are able to conduct the experiment within the time limit of their laboratory session. Doing so is important to keep the students interested in the work they are doing. If students are unable to complete the experiment due to the time required to align the optics, then they will not have the time they need to internalize the learning and feel positive about their accomplishments in the laboratory.

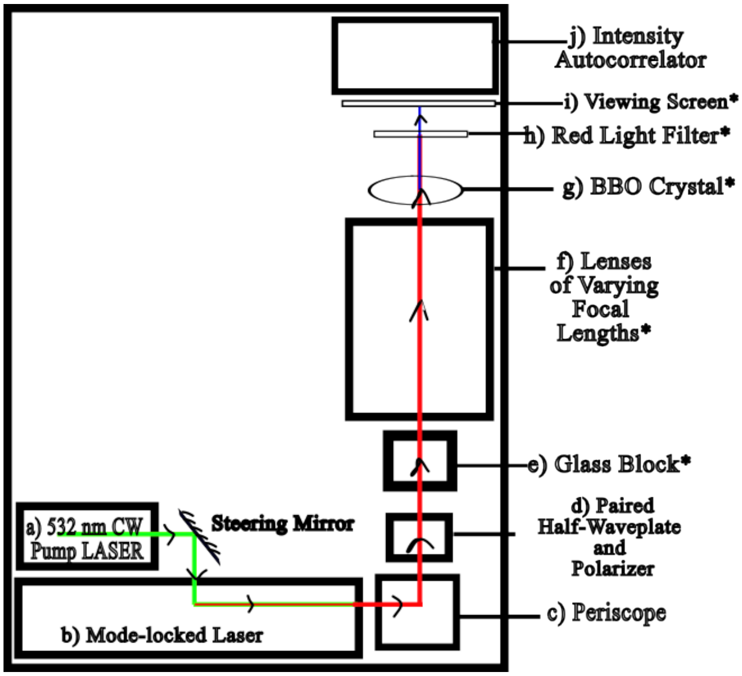

Figure 3.3: The Experimental Workspace. The optics are: (a) the 532nm Continuous Wave (CW) laser, (b) the 800±50nm mode-locked Titanium:Sapphire Oscillator, (c) the periscope used to raise the beam height, (d) the paired half-waveplate and linear polarizer, (e) the glass block, (f) lenses of varying focal lengths, (g) the BBO crystal, (h) a filter, (i) a viewing screen, and (j) an intensity autocorrelator. Power meters are placed on linear tracks between optics (e) and (f) as well as (h) and (i) to record average power measurements of red and blue light. Optics labelled with a star (*) are on a linear track and able to move in and out of the beam path as needed for the experiment. The tracks were required so that students could move optics easily and safely in a way that allows for them to successfully complete their exploration.

Figure 3.3 is a diagram of the experimental workspace. After exiting the femtosecond laser, the light first interacts with a periscope (optic (c) in Figure 3.3) which raises the beam while keeping it parallel to the optical table. Since the beam exits the TS Kit at 59mm above the optical bench and most optics in the experimental workspace were mounted higher than that, raising the beam was necessary to allow the light to interact with the rest of the optics in the workspace. The periscope can safely alter the beam height while keeping the beam parallel to the table. The periscope also rotates the polarization of the beam, so the beam became s-polarized after exiting the periscope. After the beam height is raised vertically, it passes through a paired half-waveplate and linear polarizer (optic (d) in Figure 3.3). The half-waveplate and linear polarizer are paired together so that the pulse energy of the mode-locked pulse train can be changed. The glass block (optic (e) in Figure 3.3) is made of K9 glass and is used to double the pulse duration of the infrared light emitted from the ultrafast laser. Bi-Convex Lenses with different focal lengths (optics (f) in Figure 3.3) are used to focus the beam within the centre of the BBO Crystal (optic (g) in Figure 3.3). The SHG light generated within the crystal. Since not all the infrared fundamental light converts into blue SHG light, a filter optic (h) in Figure 3.3) is placed in the beam's path to block the red light exiting the BBO crystal. The viewing screen (optic (i) in Figure 3.3) blocks all the light from exiting the experimental workspace while the intensity autocorrelator is not in use. Between optics (e) and (f), a power meter is attached on a rail to move in and out of the beam path. Another power meter is placed behind optic (h). Power meters are in place to measure the average power of both the infrared and blue beams.

Using the optics that are set up between the laser system and the intensity autocorrelator, students are able to design experiments that observe the relationship between the pulse energy, peak power, and laser intensity of the infrared fundamental and blue SHG light. Instructional materials for these experiments are presented in Chapter 4.

3.2.3 The Intensity Autocorrelator

Since optical detectors cannot measure the pulse duration of femtosecond pulses, intensity autocorrelators can be used to approximate the pulse duration by producing an autocorrelation of the pulse train. A diagram of the intensity autocorrelator I built to complete the experimental workspace is shown in Figure 3.4. Construction of the intensity autocorrelator took several months. It can only be used to approximate the pulse duration of infrared light, and not of the blue light. The SHG crystal used in the autocorrelator cannot produce SHG light with blue light as a fundamental frequency. The bi-convex lenses, BBO crystal, filter, and viewing screen were moved out of the beam path so that the infrared light could enter the intensity autocorrelator without being changed by the other optics used in the workspace. The glass block was used to approximately double the pulse duration of the infrared light and was moved in and out of the beam path as necessary for the experiment.

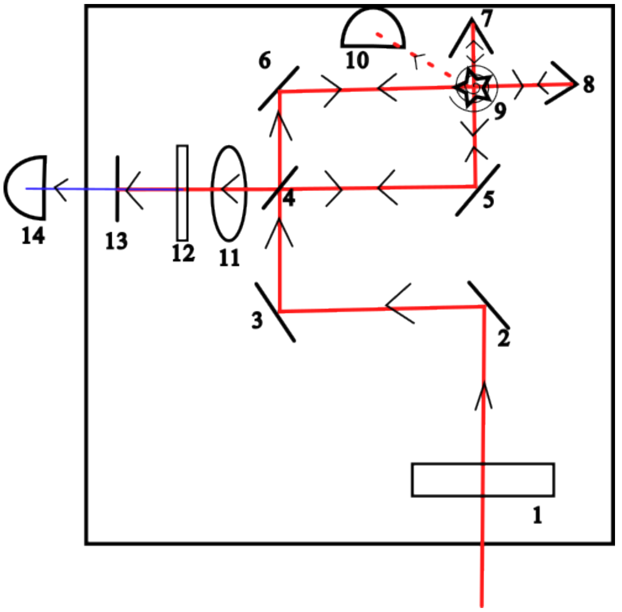

Figure 3.4: A diagram of the intensity autocorrelator built for this experiment. In numerical order, the optics are: (1) Half-Waveplate, (2) Alignment Mirror 1, (3) Alignment Mirror 2, (4) Beamsplitter, (5) Alignment Mirror 3, (6) Alignment Mirror 4, (7) Paired Mirror 1, (8) Paired Mirror 2, (9) Rotating Glass Plate, (10) Detector 1, (11) Lens, (12) BBO Crystal, (13) Iris, and (14) Detector 2 (connected to a Photomultiplier Tube before sending a signal to an oscilloscope). All mirrors are made of gold. Mirrors (2) and (3) were necessary due to the constraints of the optical bench. Both detectors are connected to the same oscilloscope. The dashed line indicates that this beam is the reflection of light from the rotating glass plate and the beam revolves as the plate rotates. Detector 1 provides a signal on an oscilloscope that can be used to stabilize the trace displayed on the oscilloscope. This signal is a reflection of the beam that interacts with the rotating glass plate. The signal obtained by Detector 2 forms the trace of the autocorrelation. Detector 2 is a fast detector and Detector 1 is a slow detector.

Since the periscope caused the polarization of the light to rotate by 90°, a half-waveplate (Optic (1) in Figure 3.4) was needed to rotate the polarization to match the phasematching angle of the BBO crystal used in the intensity autocorrelator.

The beam reflected off two gold mirrors (Optics (2) and (3) in Figure 3.4) before it interacted with the beamsplitter (optic (4) in Figure 3.4) that split the light into two beams. In each beam path, the beam reflects off a mirror, (either optics (5) or (6) in Figure 3.4 depending on the path), and the beams reflect off of paired gold mirrors, (optics

(7) and (8) in Figure 3.4). The paired mirrors are mounted perpendicularly to each other so that the beam can be raised or lowered while remaining parallel to the optical bench. They travel back towards the beamsplitter, with one path slightly higher than before and the other slightly lower. The path that travels slightly lower travels through the rotating glass plate (optic (9) in Figure 3.4) which causes a time delay between the two beams. The other beam passes over the plate to ensure that only one of the beams gets delayed in time by some delay τ, which changes as the glass rotates. The amount the delay changes is dependent on the angle by which the light is incident onto the plate. As the plate rotates, the incident angle changes and thus τ changes. This is shown in Figure 3.5.

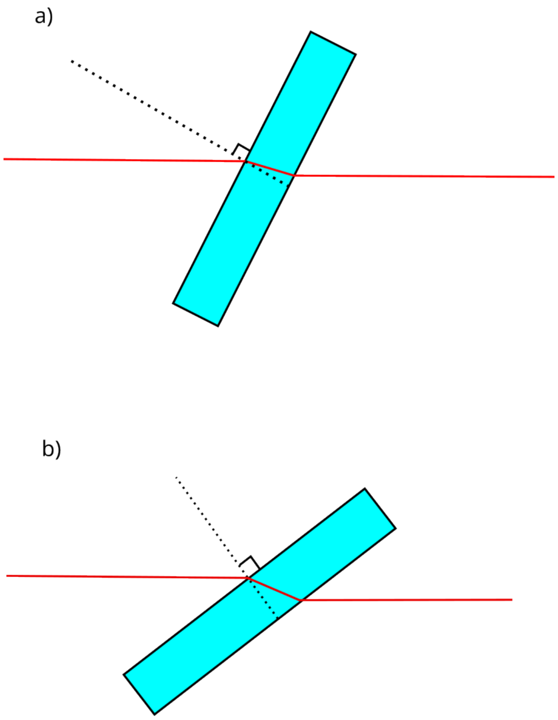

Figure 3.5: a) Light is incident by some angle on a glass plate which has some thickness. When the light transmits through the glass, its distance travelled within the glass is equal to the glass' thickness divided by the sine of the angle the light travelling through the glass makes with the normal of the glass plate. b) light is incident on the same glass plate, but at a different angle with respect to the normal, which changes the distance the light travels. Since light travels at a constant speed, the change in the distance corresponds to a change in the time taken for the light to exit the plate.

A change in τ is necessary because the autocorrelation is a function of the time delay, so a range of time delays must be used to form the autocorrelation.

After the two beams travel back and interact with the beamsplitter again, they are focused by a lens (optic (11) in Figure 3.4). When the two beams are focused through the lens, they are parallel with each other and will overlap at the focal length of the lens, where the BBO crystal (optic (12) in Figure 3.4) is positioned to produce SHG light. Since the BBO crystal cannot frequency double blue light, only infrared light can be used in this autocorrelator.

Since many highly reflective optics are used to build the autocorrelator, it is possible to produce multiple beams. In proper alignment, only three distinct beams are generated. Two beams of SHG light are generated by the individual infrared beams. In the third beam, SHG light is generated by using infrared light from both beam paths. This is shown in Figure 3.6.

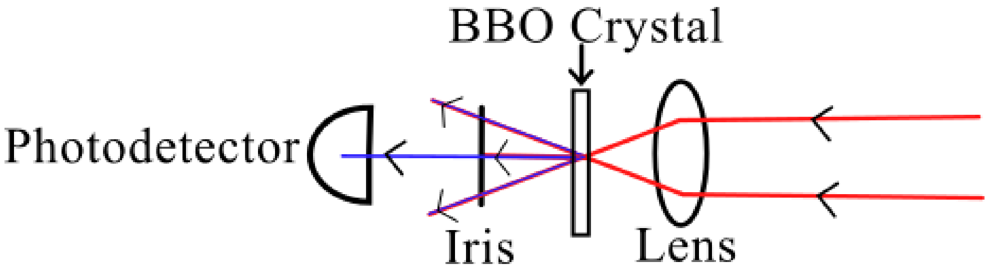

Figure 3.6: Two beams entering a lens parallel to each other. Because they are parallel, they overlap at the focal point of the lens, where a BBO crystal is placed. Within the crystal, the beams overlap and produce SHG light, with each path contributing the light generated at the second harmonic. Not all the light converts to the second harmonic. There are three paths of light emerging from the BBO crystal. Only the center path, which has SHG light produced as a result of the overlap of both beams, can generate an autocorrelation, since it is the only path that was created as a result of the interaction between the two beams. The remaining infrared light as well as the other two beams are filtered out using an iris, and the SHG light generated as a result of the overlap is detected by a photodetector. The photodetector is connected to an oscilloscope which can display the trace of the autocorrelation.

To make sure this third beam is generated using light from both paths, one of the beams can be blocked by placing a card in front of the paired mirrors. If the third blue light is generated from both beams, then blocking either beam path will cause the signal to disappear entirely and unblocking the path will cause it to reappear, along with the other spot generated by that beam.

Only the third beam is used to form the trace of the autocorrelation. The trace is used to approximate the pulse duration. To obtain the trace of the autocorrelation, two detectors are used. The first detector (optic (10) in Figure 3.4) is a slow detector which measures a reflection of the beam passing through the glass plate as the glass plate rotates. This ensures that the signal can be stabilized on the oscilloscope. The reflected beam acts as a reference for the oscilloscope which allows the signal to stabilize. Detector 2 (optic (14) in Figure 3.4) is a fast detector and it detects the signal that generates the trace. It is much more sensitive to noise than the signal measured by Detector 1. The frequency doubled light sent into Detector 2 is very weak, so the signal is also amplified by a photomultiplier tube.

To approximate the pulse duration, we start with the autocorrelation function, $\mathbf{A}(\tau)$,

$$\mathbf{A}(\tau) = \int_{-\infty}^{\infty} I(t)I(t+\tau)dt \tag{3.1}$$

$I(t)$ is the laser intensity of the original beam and $I(t+\tau)$ is the laser intensity of the delayed beam. The autocorrelation function is only dependent on the delay between the two beams due to the symmetry of the function.

The autocorrelation of a pulsed laser is Gaussian, since these pulses are assumed to be Gaussian. The width of the trace of an autocorrelation, measured at its Full Width at Half Maximum (FWHM), relates to the pulse duration through the relationship,

$$\tau_{autocorrelation} \approx \sqrt{2}\delta t_{pulse}. \tag{3.2}$$

$\sqrt{2}$ is the deconvolution factor, and this value changes depending on the shape of the pulse [50]. A pulse shape must be assumed to determine its FWHM, and we assume that the pulses emitted from the oscillator are Gaussian.

The oscilloscope can only show a trace on the microsecond scale, but the delay imposed between the two beam paths is on the femtosecond scale. A conversion factor is needed to relate the pulse delay to the trace.

To get this conversion factor, the signal on the oscilloscope needed to be translated by moving paired mirror 2 from one end of the oscilloscope display to the other. The paired mirror was placed on a translation stage. Then, the distance the mirror pair was translated (multiplied by a factor of 2) was divided by the speed of light to obtain a measurement with unit of time, and then divided by the number of microseconds the signal was translated across on the oscilloscope screen. The factor of 2 was necessary since the beam travelled over this extra distance twice.

The unitless conversion factor is used to convert the microsecond-scale FWHM value of the trace of the autocorrelation that is observed on an oscilloscope to the femtosecond scale that corresponds with the pulse duration.

Mathematically, this factor is,

$$\textbf{conversion factor} = \frac{2d}{cD}. \tag{3.3}$$

Where d is the distance that paired mirror 2 was translated to shift the autocorrelation signal on the oscilloscope display, c is the speed of light, and D is the amount the trace horizontally translated on the display. To approximate the pulse duration, Equation 3.2 becomes,

$$\tau_{autocorrelation} \approx \frac{2d}{cD}\sqrt{2}\delta t_{pulse}, \tag{3.4}$$

or as an expression of the pulse duration,

$$\delta t_{pulse} \approx \sqrt{2}\frac{cD}{4d}\tau_{autocorrelation}, \tag{3.5}$$

Pulses can be generated below 12fs with the TS kit[47, 51]. For pulses this short, we cannot assume the pulse has a Gaussian shape, its shape must also account for higher order dispersion from the prism dispersion compensation [52]. Typically, higher pulse durations are the result of imperfect dispersion compensation [45, 46]. Adjusting the separation distance between the prisms to correct the dispersion compensation could reduce the pulse duration further.

3.3 Safety Considerations

Reference [53] was used to develop guidelines for the role of the Laser Safety Officer responsible for the laboratory's operation, biological effects of laser exposure, alignment guidelines, and insight into the use of lasers in educational institutions.

Laser radiation can cause eye and skin damage upon direct exposure. To prevent harm to anyone operating the laser or performing the experiment, the beam is completely shielded using an enclosure made of acrylic and other materials. The optics presented to the students are already prearranged so that the students do not interact with the beam while working with any of the equipment. Students are only able to move optics using pre-built rails with attached handles and use cameras to observe the beam without directly looking at it. The optics are also enclosed to prevent dust and debris from building up on them, which could cause damage over time. Goggles are required to prevent exposure to laser radiation when the oscillator and pump are in operation. Everyone working with the equipment must be trained in Laser Safety, through successful completion of a course offered by the Office of Safety at the University of Waterloo [54]. Appendix B presents the documentation used to train instructors and students, as well as appropriate start up and take down procedures.

Chapter 4

Instructing the Experiment

4.1 Chapter Introduction

The following information is presented in this chapter:

1. An overview of the experiment at an introductory and advanced undergraduate level,
2. The preparatory materials used to teach the undergraduate students the concepts they will need to understand before they begin their open inquiry work,
3. Information on how the experiment can be instructed. This should be used by instructors or TAs to help facilitate students throughout their open inquiry work.

4.2 Overview of the Experiment

Students will need to determine whether the frequency doubling process is dependent on the pulse energy, peak power, or laser intensity by experimenting with the pulse energy, pulse duration, and beam area of infrared light. Students cannot work with peak power or laser intensity, but they are directly related to pulse duration and beam area, respectively. Students can use the pre-reading document to determine this relationship and use that to develop their investigation. They will not know the theory describing the frequency doubling process that was presented in Chapter 1, but they should be able to determine that the SHG process is laser intensity-dependent from their results. This is explained in Subsection 4.4.4.

Each experiment requires a student-developed method, analysis, and conclusion with instructor guidance. The procedure is not explicitly given to students, so they are not told which variables to use for their experiments. Students lack the knowledge to identify the variables spontaneously, but they can determine what the appropriate variables are using the pre-reading document presented in Section 4.3.

To help students progress through their work, the instructors will be provided with a list of comprehension questions that are listed in Appendix C. Instructors should be familiar with these questions and use them to prompt students throughout the experiment. These comprehension questions should be used on a case-by-case basis and further developed based on feedback from students who complete this experiment and instructors administering this experiment.

4.2.1 An Advanced-Level Experiment

This was the first undergraduate experiment using a Class-IV Laser within the Department of Physics and Astronomy at the University of Waterloo. Given that Class-IV laser systems are typically restricted from undergraduate use, this experiment was introduced at the upper year level. This approach aimed to engage students with prior experience in laboratory safety practices, thereby enabling them to critically evaluate and provide insights on the designed safety protocols.

This was also the first open inquiry experiment offered to undergraduate students in any of our physics programs. Since upper year students are not yet trained on moving through higher levels of inquiry, we chose to provide more information on experimental procedures and design was given to upper year students. Specifically, these students were explicitly told to design experiments changing the pulse energy, pulse duration, and beam area in the written materials and by instructors.

The written portion of the instructional materials for the upper year experiment are presented in Appendix D.

4.2.2 An Introductory-Level Experiment

In their first year, students will have experience with both structured and guided inquiry experiments in their introductory lab courses due to the newly revised introductory curriculum [55]. As mentioned in chapter 2, transitioning students to higher-level inquiry courses reinforces experimental skills that were introduced in lower-level inquiry courses.

On average, students who perform this experiment in their first year will have less knowledge on optics, energy, power, and intensity compared to upper year students. The instructional materials were written to explain some concepts related to pulsed lasers that students need to understand to determine if the frequency doubling process is pulse energy, peak power, or laser intensity dependent.

The following section presents the pre-reading document.

4.3 Pre-Reading Document for the Introductory-Level Experiment

4.3.1 Introduction

As an experimentalist-in-training, you are going to observe frequency doubling!

Frequency doubling is probably not something you have seen in your introductory classes, but, as for any new phenomena, experiments can be built to *elucidate* the underlying physics behind what is observed. When conducting this experiment, it is your task to bring what is unknown to you into *light*.

Frequency doubling is a nonlinear optical process that can happen when a laser beam is focused into a certain type of crystal. When the laser beam interacts with the crystal, new light gets produced. The light that gets generated has exactly twice the frequency of the light that was used to create it, hence the term "frequency doubling"! The phenomenon that occurs cannot be described using the optics you have learned in secondary education. It is a *nonlinear* optical process. In addition to the generated light having double the frequency of the original light, it also has half the wavelength of the original light. This is because the wavelength and frequency of light are related to each other by the expression,

$$\nu = \frac{c}{\lambda}. \tag{4.1}$$

In Equation 4.1, the Greek letter ν ('nu'), represents the frequency of light, the Greek letter λ ('lambda') represents the wavelength, and c represents the speed of light and is a constant value.

Experiment Question

For this experiment, you, the experimentalist-in-training, are going to work in a group of three to investigate the frequency doubling process. You are going to generate frequency doubled blue light from infrared light using a Beta Barium Bromate (or BBO) crystal. In this lab, you are going to answer the following question:

Is the frequency doubling process dependent on the pulse energy, the peak power, or the laser intensity?

4.3.2 Conceptual Background

Frequency doubling wasn't able to be observed until after the laser was invented. So, this experiment uses a laser. Most lasers you may be familiar with are *continuous wave* lasers. They emit light as a continuous wave, and these are the kinds of lasers used to make pointers and bar-code scanners. Instead of using a continuous wave laser, we are going to use a *mode-locked* laser. A mode-locked laser emits light in short bursts called pulses, which are the shortest events in time! Since light from mode-locked lasers is emitted in pulses, it has different properties than light emitted from continuous wave lasers.

Short Pulse Trains

To get a sense of what pulses emitted from a mode-locked laser are, let's discuss the following variables:

1. Pulse Period,
2. Repetition Rate,
3. Average Power,
4. Pulse Energy,
5. Pulse Duration,
6. Peak Power,
7. Laser Intensity.

To start the discussion, we'll use a hypothetical train of short pulses, and then a train of short pulses used in one of our research labs.

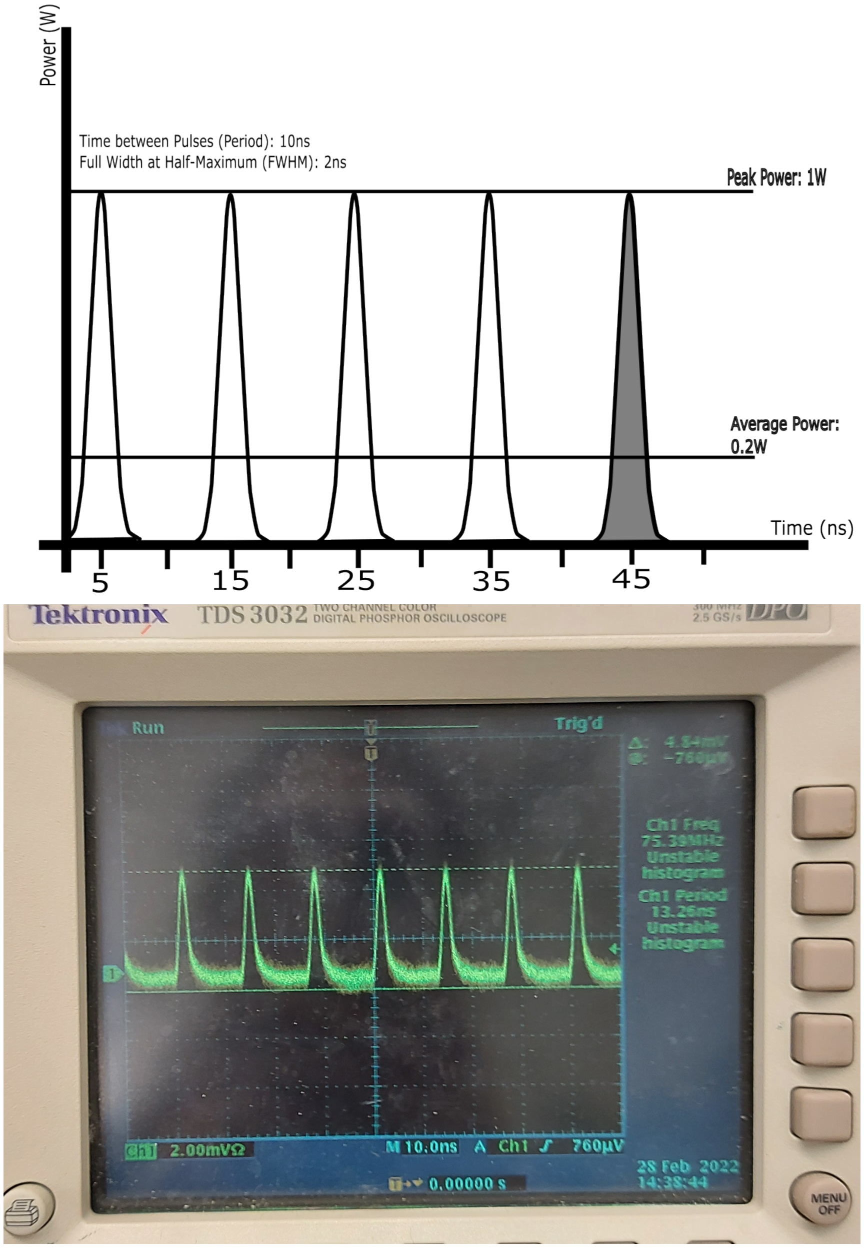

Figure 4.1: a) A plot of the power output for a short-pulse laser with a pulse period of 10ns and pulse duration of 2ns. The pulse duration of one-fifth of the pulse period was chosen so that the pulse duration and the pulse period can appear on the same plot. Each pulse has a peak power of 1W. The shaded area represents the pulse energy of a single pulse, ε. b) An oscilloscope trace of a train of short-pulses. The pulses are measured using a photodetector, so the peak power and the pulse duration cannot be seen on an oscilloscope trace. This is because the signal is electronic and is observed on a much larger time-scale (nanoseconds) than the short-pulses of laser light (femtoseconds).

In figure 4.1a, a power-time plot depicts the output power of a short-pulse laser. This plot is shows some of the parameters that cannot be seen directly on a real pulse train. Figure 4.1b shows an *oscilloscope trace* corresponding to a short pulse train measured in one of our research laboratories. The pulses were detected using an optical detector called a *photodetector*. An oscilloscope can plot electronic signals as a function of time. An oscilloscope trace is the signal seen on the screen. These pulses are not symmetric like they were in the hypothetical example. On the trace, you'll see the pulses have a sharp rise and a slower decay due to the response time of the detector.

Pulse Period and Repetition Rate

The time *between* the pulses is referred to as the **pulse period** and is associated with variable ΔT. The uppercase Greek Letter Δ ('delta') is used because this value is associated with an interval, rather than a single instant of time. In the hypothetical scenario of Figure 4.1a, there are five pulses (out of a much longer train) each with a pulse period of 10 nanoseconds (1×10^{-9}s, with symbol ns). On the oscilloscope trace in Figure 4.1b, the pulses have a period of about 13±2ns.

The reciprocal of the pulse period is referred to as the **repetition rate** and is associated with the variable R. In the case of the hypothetical scenario, $R = 100MHz$, or 100 Megahertz. The relationship between the pulse period and the repetition rate is,

$$R = \frac{1}{\Delta T}. \tag{4.2}$$

The oscilloscope trace can be used to measure the repetition rate and thus, the pulse period.

Pulse Energy and Average Power

Power is energy transferred per unit time,

$$Power = \frac{Energy}{\Delta t}, \tag{4.3}$$

where Δt is the time period over which the energy transfer occurs. From a calculus-based perspective, power is the derivative of energy with respect to time, and energy is the integral of power with respect to time.

The definite integral of a function gives the area under the curve of that function, so the **pulse energy** of a single pulse is shown in Figure 4.1a as the shaded area under the right-most pulse. The pulse energy is represented by the symbol ε, which when said verbally is spoken as "script-E". The energy of one single pulse is given by the integral of the power with the integration limits spanning one single pulse period.

The pulse energy and the average power are therefore directly related to each other. For example, if we integrate over 100 periods, we get the total energy of 100 pulses. The total time would be equal to 100 periods so the **average power** of a pulse train is given by,

$$P_{average} = \frac{100\varepsilon}{100\Delta T} = \frac{\varepsilon}{\Delta T} = \varepsilon R. \tag{4.4}$$

In other words, the average power of a pulse train is given by the pulse energy divided by the pulse period, ΔT, or the pulse energy multiplied by the repetition rate, R.

In a lab, the average power of a train of short pulses is measured using a *power meter*. Power meters have very long response times, which are on the scale of milliseconds (or a thousandth of a second).

The measurements of the pulse period from an oscilloscope's trace and the average power from a power meter can be combined to determine the pulse energy. The pulse energy is the average power divided by the repetition rate, or the average power multiplied by the pulse period. This is shown in Equation 4.5. In our lab, the infrared light has a pulse period of about 11ns.

$$\varepsilon_{pulse} = \frac{P_{average}}{R} = P_{average}\Delta T. \tag{4.5}$$

Pulse Duration

The **pulse duration** is a measurement of a pulse's length in time. It is represented by δt and the smaller size of the interval is why we use the lowercase Greek letter δ ('delta'), compared to the uppercase letter used for the pulse period. A short-pulsed, mode-locked laser can generate a train of pulses of light with durations in the picosecond (1×10^{-12}s, with symbol ps) to the femtosecond (1×10^{-15}s, with symbol fs) range. The hypothetical scenario of Figure 4.1a had pulses with a duration of 2ns. The pulse duration for the laser in our lab is about 100fs, but pulse durations from mode-locked lasers are too short to be measured by any kind of optical detector.

You may ask, why would the pulse duration be too short to measure!?

Optical detectors turn optical power into electrical power, and this takes time to do. Optical detectors have response times of about 1ns. This means that the time *between* the pulses can be measured, but not the duration of the pulses themselves. That doesn't mean we can't obtain a value for the pulse duration (considering we told you that our laser has a pulse duration of about 100fs)!

Now you may wonder, how do we quantify the pulse duration?

To solve the problem of not being able to measure the pulse duration, we need to use an *intensity autocorrelator*. This is a device that can take the beam we have and give us a signal that can be used to approximate the pulse duration. The signal we get is a function called an autocorrelation.

Figure 4.2 shows a trace from the intensity autocorrelator used in our lab, with time on the horizontal axis. The trace's width, marked by the yellow line with arrows, is measured using the time difference between the two points corresponding to the function's half maximum value. In other words, the width of the trace is the **Full Width at Half Maximum (FWHM)**.

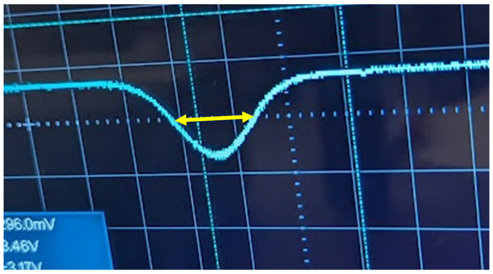

Figure 4.2: A trace from the intensity autocorrelator used in our laboratory. The horizontal axis measures time in microseconds. Each horizontal division is 500 microseconds wide, or $500\mu s$. This trace has a FWHM indicated with yellow arrows and corresponds to a pulse duration of approximately 100fs.

Pulses also have a width measured at their own FWHM, and the FWHM of a pulse is an approximate value of the pulse duration. The FWHM of a trace of a pulsed laser's autocorrelation is proportional to the FWHM of the pulse.

Peak Power

In the hypothetical scenario of Figure 4.1a, the **peak power** is the instantaneous power at the peak of the pulse, but we cannot measure the peak power this way in a lab. Instead, the peak power is defined using other parameters that we can quantify.

Being a quantity of power, the peak power is also the pulse energy divided by a time interval. Unlike the time interval used for the average power, this time interval is significantly smaller than the pulse period. The appropriate interval is the pulse duration. In other words, the pulse duration is related to the peak power.

The peak power is expressed as the pulse energy divided by the pulse duration, or,

$$P_{peak} = \frac{\varepsilon}{\delta t}. \tag{4.6}$$

Since the calculation of our pulse duration is an approximate value, the peak power is also an approximation. The peak power can be expressed as,

$$P_{peak} \approx \frac{\varepsilon}{\delta t_{FWHM}} = \frac{P_{average}\Delta T}{\delta t_{FWHM}}. \tag{4.7}$$

For experiments concerning the ratios of peak powers, the FWHM is a sufficient measurement.

Beam Area

Laser beams focus to a circle, so the beam area can be calculated at its focus using the formula for the area of a circle. The radius at the beam's focus is known as the beam waist. Due to the way our experiment is set up, it is hard to measure the radius of the beam at its focus. Instead of measuring the beam waist at the beam's focus, we are going to calculate the divergence of the beam. The divergence of the beam is related to the beam waist, w_0, with the beam area, A, then equal to πw_0^2. The divergence is the angle at which a beam expands from its focus to its outer edge at some distance. Figure 4.3 is a diagram of an infrared laser beam focused by a lens into a BBO Crystal.

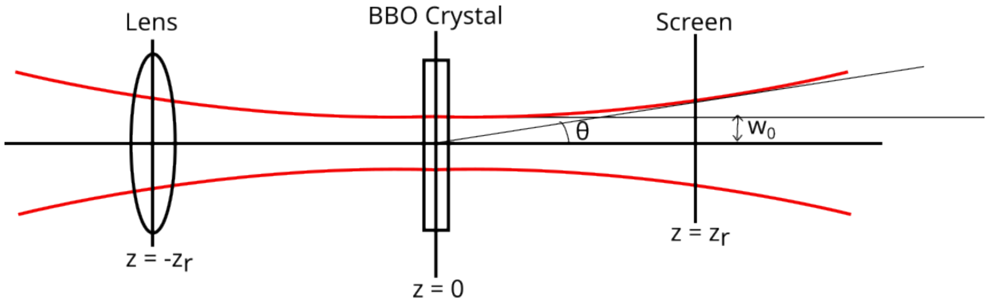

Figure 4.3: A diagram of a beam focused by a lens into a BBO, crystal. The beam waist w_0 and divergence angle θ are also depicted.

The beam waist and divergence angle are related by the expression,

$$\theta \approx \frac{\lambda}{\pi w_0}. \tag{4.8}$$

In Equation 4.8, the Greek letter θ ('theta') is the divergence angle, λ is the wavelength of the light. Equation 4.8 is an approximation but sufficient for purposes of the experiment.

If we measure the beam diameter at two different points away from the beam's focus, then we can calculate the divergence angle by using the expression,

$$\theta = \arctan(\frac{D_1 - D_2}{2d}). \tag{4.9}$$

D_1 and D_2 are each variables representing the beam diameter at two different points, 1 and 2, away from the beam's focus, and d is the distance between points 1 and 2.

Laser Intensity

Intensity, represented by I, is defined as power per unit area, or $I = \frac{P}{Area}$. Laser intensity (or irradiance) is the peak power divided by the beam area, or,

$$I = \frac{P_{peak}}{A} = \frac{\varepsilon}{\delta t A}. \tag{4.10}$$

Equation 4.10 shows that the pulse energy, the peak power, and the laser intensity are all directly related to each other. For experiments concerning the ratio of intensities, the beam area is a sufficient measurement.

4.3.3 Important Information for Your Experiment

When working in any lab, sometimes we cannot make direct measurements because of the difficulties that arise in the specific lab environment. For example, in our lab, we cannot measure the beam area within the crystal directly because of the way our experiment is set up, but you can calculate it from other measurements we are able to make. Another difficulty in our environment is that we only have an intensity autocorrelator that can approximate the infrared pulse duration. In our laboratory, we cannot approximate the pulse duration of the blue pulses.

One of the first questions we must answer is, how will we be able to determine if changing the pulse duration of the infrared beam changes the pulse duration of the blue beam? Use some findings from the other experiments to develop a solution to this challenge.

Other times when working in a lab, we cannot make direct measurements because we are physically limited by what we are able to measure. We are physically limited from being able to measure the pulse duration at all. To measure an event in time, we need a shorter event in time, and pulse durations from mode-locked lasers are the shortest events in time. There is no way to obtain a direct measurement of the pulse duration, so we have to approximate it.

4.3.4 Motivating Your Procedural Designs

To motivate your thinking, start out by working with the equipment you have available to you for a bit. Determine what you are allowed to adjust and what safety precautions you need to take when you are in the laboratory. Use the resources provided on LEARN to complete the required safety training and fully understand the regulations. These safety precautions should govern our behaviour the entire time we are in the laboratory, not just when we are working with the equipment.

Think about the variables that are pertinent to the experiment question, and then think about all the variables presented in the conceptual background. When you are comfortable with using the equipment, consider the following:

1. Which variables am I experimenting with?
2. What equipment can I use to measure or approximate each variable?
3. What equipment can I use to change each variable?

4. How many separate experiments need to be developed to answer the experiment question?
5. Pick one of the variables you are experimenting with. How are you going to measure the change in that variable?
6. How much data will you need for a sufficient experiment?

4.4 Information to Instruct this Experiment

Figure 4.4 illustrates the SHG phenomenon using a diagram of a Beta Barium Bromate crystal and infrared light.

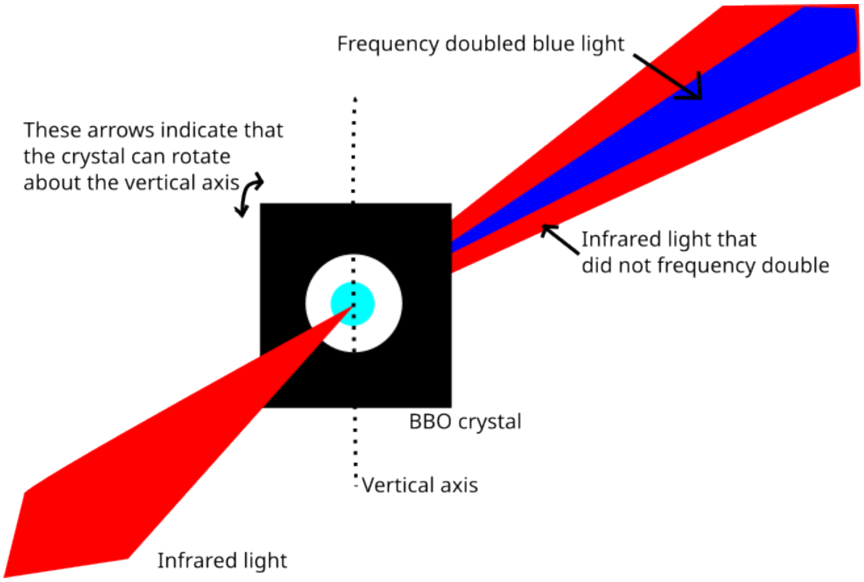

Figure 4.4: A diagram of infrared light at 800nm entering a Beta Barium Bromate crystal. The incoming infrared light interacts with the crystal and some of the red light gets converted into blue light at exactly twice the frequency of the original infrared light. The blue light has a wavelength of 400nm in this system.

As the pulse energy, pulse duration, and beam area of the infrared light are changed, the laser intensity of the blue light will change. Students should be encouraged to determine if changing one of the three variables of the infrared light changes that same variable corresponding to the blue light, and repeat the process until all three variables have been investigated. Then, based on their investigation, students should determine if the process depends on pulse energy, peak power, or laser intensity. The frequency doubling process is intensity dependent.

The experiment concerning pulse energy is presented first, and then the experiment concerning pulse duration is presented, and the experiment concerning beam area presented last. This is because the pulse energy depends on one experimental variable (the average power), the pulse duration relates to the peak power which is dependent on two experimental variables (the pulse duration and the pulse energy), and the beam area relates to the laser intensity which is dependent on three experimental variables (the beam area, pulse duration, and pulse energy). It is recommended that students conduct the pulse duration experiment last because its completion will depend on observations from the beam area experiment.

4.4.1 Experimenting with Pulse Energy

The paired half-waveplate and polarizer can change the pulse energy of the infrared light emitted from the mode-locked oscillator. First, the s-polarized light reflected off of the periscope must pass through the half-waveplate. The waveplate rotates around its optic axis, altering the s-polarized light into a mix of vertical and horizontal polarization components. Then, one component is filtered out by the polarizer. As the half-waveplate is rotated, the magnitudes of the vertical and horizontal components also change. This means the amount of light that is allowed to pass through the polarizer changes, so the measured average power of the light also changes. When the average power changes, the pulse energy also changes since they are directly related to each other. Figure 4.5 shows an illustration of the change in the average power of a beam as it passes through a paired half-waveplate and polarizer.

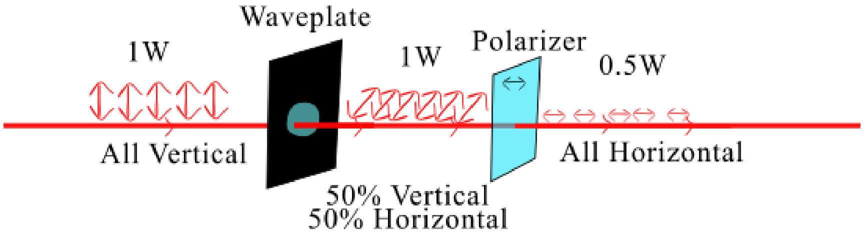

Figure 4.5: An illustration of light from a laser beam at 1W with only a vertical component, indicated by arrows, passes through a half-waveplate. After the light passes through the waveplate, both the horizontal and vertical components of the light's polarization are equal. After the light passes through the polarizer, the vertical component of the light is filtered out and the horizontal component passes through. A power meter placed after the polarizer would measure an average power of 0.5W.

A sample procedure for this experiment is below.

1. Vary the average power of the infrared beam over its full range and measure the average power of the resulting blue beam.
2. Pick two values of the average power for the infrared beam. One of the values must be twice the magnitude of the other. Record both these values.
3. Measure the corresponding average power of the blue beam for each value recorded in step 2.
4. Record the repetition rate of the short pulse train using the oscilloscope.
5. Calculate the pulse energy of the infrared light and the pulse energy of the blue light using each measured value of the average power and the repetition rate.

Any infrared light emerging from the crystal should be filtered out so that only blue light is absorbed by that power meter. If the pulse energy of the infrared light is doubled, then the pulse energy of the blue light will quadruple.

4.4.2 Experimenting with Pulse Duration

The K9 glass block can change the pulse duration of the infrared light. When the light travels through the glass, it will undergo chromatic dispersion which lengthens the pulse duration while keeping the average power constant.

The FWHM of a pulse is approximately its duration. Since the FWHM of a pulse cannot be measured, it is approximated using the FWHM of an autocorrelation of the beam and an appropriate conversion factor.

The conversion factor can be determined using the information provided in Subsection 3.2.3. The autocorrelator cannot be used to approximate the pulse duration of blue light. However, the FWHM of the infrared pulse and the FWHM of the blue pulse are related to each other. This relationship was explained in Chapter 1 and is presented below,

$$\frac{FWHM_{infrared}}{FWHM_{blue}} = \sqrt{2}. \tag{4.11}$$

Since the FWHM of a pulse is approximately its pulse duration, we also have the relationship (as seen in Chapter 1) $\delta t_{pulse,blue} = \frac{1}{\sqrt{2}}\delta t_{pulse,infrared}$, which means the pulse duration of the blue light is linearly dependent on the pulse duration of the infrared light.

The autocorrelator can only be used to approximate the pulse duration of infrared light because the frequency doubling crystal used within the autocorrelator cannot frequency double blue light. Students cannot directly observe Equation 4.11 in this experiment. They must infer the ratio from the results of the beam area experiment, which should be completed first.

In the next experiment, students will halve the beam area of the infrared light, and they should see that the beam area of the blue light also halves. Students should use this information to infer that halving the pulse duration of the infrared light should also halve the pulse duration.

A sample procedure for this experiment is below.

1. Place the glass block in the beam's path.
2. Measure the average power of the infrared and blue light. Record these values.
3. Use the autocorrelator and record the FWHM of the trace. Remember that this autocorrelator cannot measure the pulse duration of blue light. Only infrared light should be used for this.
4. Determine the FWHM of the trace of the autocorrelation.
5. Approximate the pulse duration from the FWHM of the trace of the autocorrelation.
6. Remove the glass block from the beam's path.

7. Change the average power of the infrared light so that it matches the value recorded in step 1.

8. Repeat steps 2-5 without the glass block.

As the infrared beam passes through the K9 glass block, its pulse duration approximately doubles. The sample procedure starts with the glass block in the beam path, so with this procedure the pulse duration of both wavelengths will each approximately halve. When the blue pulse duration halves, the blue light's pulse energy doubles, rather than quadruples, which was seen in the previous experiment. This may be surprising since doubling the infrared laser intensity quadruples the blue intensity, as explained in Chapter 1. However, each variable's change by a factor of two is what causes the blue laser intensity to quadruple.

4.4.3 Experimenting with Beam Area

The lenses, each with different focal lengths can be used to change the beam area (and the beam waist). The relationship betwee focal length and beam diameter is seen through Equation 4.12, where f is the focal length of the lens, λ is the wavelength of the light passing through the lens, M^2 is the beam quality factor, and d_{lens} is the beam diameter at the lens.

$$w_0 = \frac{2f\lambda M^2}{\pi d_{lens}}. \tag{4.12}$$

The beam area should be calculated at the point where the frequency doubling process is happening, which is within the crystal where the beam is focused. To calculate the beam area at its focus within the crystal, the beam divergence can be used because it is related to the beam waist. To approximate the divergence, the beam diameters at two different points away from the beams focus need to be measured.

The ratio of the beam waist of infrared light to the beam waist of the blue light is,

$$\frac{w_{0,infrared}}{w_{0,blue}} = \sqrt{2}, \tag{4.13}$$

which was the ratio presented in Chapter 1. This proportionality is also true for spot size, which is the diameter of the beam at its focus. The beam area is proportional to the square of the beam waist, given by $A = \pi w_0^2$.

The ratio of the beam area of the infrared light to the beam area of the blue light is then $A_{infrared} = 2A_{blue}$. The beam area of the blue light changes linearly with the beam area of the infrared light.

A sample procedure in order to change the beam area for this experiment is below.

1. Focus the beam through the crystal using the 100mm focal length lens.
2. Measure the beam divergence of both the infrared and blue beams using the following procedure:
   (a) Place an iris at one position away from the beam's focus.
   (b) Measure and record this position with your reference point as the focus of the beam.
   (c) Fully open the iris.
   (d) Measure and record the average power of the infrared light and blue light using the power meter.
   (e) Decrease the size of the iris' opening until the average power of both the wavelengths of light is reduced by about 15% of its value measured in step (d).
   (f) Measure the area of the iris' opening using the measurement tools provided.
   (g) Move the iris to a different position away from the focus.
   (h) Repeat steps (b) to (f).
3. Calculate the beam area at its focus using the beam divergence with the material provided in this document. Remember that the beam waist is the radius of the beam at its focus.
4. Repeat steps 1 to 5 using the 150mm focal length lens.

Students will most likely see that the average power of the blue light doubles while the beam area of the infrared and blue light both reduce by a factor of 2.

4.4.4 Understanding that Frequency Doubling is an Intensity Dependent Process

As discussed in Chapter 1, SHG efficiency scales with the square of the intensity. The laser intensity proportionality of infrared and blue light is,

$$I_{blue} \alpha I_{infrared}^2. \tag{4.14}$$

Using Equation 4.10 and Equation 4.14, we obtain,

$$\frac{\varepsilon_{pulse,blue}}{A_{blue}\delta t_{pulse,blue}} \alpha \frac{\varepsilon^2_{pulse,infrared}}{A^2_{infrared}\delta t^2_{pulse,infrared}}, \tag{4.15}$$

$$\varepsilon_{pulse,blue} \alpha \frac{\varepsilon^2_{pulse,infrared} A_{blue}\delta t_{pulse,blue}}{A^2_{infrared}\delta t^2_{pulse,infrared}}, \tag{4.16}$$

$$\varepsilon_{pulse,blue} \alpha \frac{1}{2}\frac{1}{\sqrt{2}}\frac{\varepsilon^2_{pulse,infrared}}{A_{infrared}\delta t_{pulse,infrared}}, \tag{4.17}$$

where $A_{blue} = \frac{1}{2}A_{infrared}$, and $\delta t_{pulse,blue} = \frac{1}{\sqrt{2}}\delta t_{pulse,infrared}$. Equation 4.17 demonstrates that when the pulse duration or beam area of the infrared light changes, the pulse energy of the blue light must also change, even if the pulse energy of the infrared light remains constant.

Students do not need to reproduce Equation 4.17, nor should they be assessed on their ability to do so. They should be able to conclude that frequency doubling is an intensity-dependent process based on their observations. When considering the relationship between pulse energy, peak power, and laser intensity, the changes in the blue light's pulse energy across all three experiments, even those where the infrared pulse energy remains constant, should indicate to students the intensity-dependent nature of the SHG process.

Chapter 5

Assessing Work for Epistemological and Pedagogical Effectiveness

5.1 Chapter Introduction

This chapter presents guidelines to formally assess student work in the GWLC. The chapter begins with a discussion of a questionnaire to measure the effect the experiments delivered in the GWLC have on students' excitement toward experimental physics, and then I present the first drafts of rubrics to assess student work for the experiment described in this thesis. Finally the chapter concludes with recommended next steps to effectively assess student work.

5.2 Measuring Excitement Towards Experimental Physics

To evaluate the impact the experiment has on students, we are going to use the following questionnaire, which must undergo an ethics review by the Office of Research Ethics at the University of Waterloo before being administered to students. Each question was chosen to elicit feedback that students can provide in relation to the two research questions addressed by this project and presented in Section 1.2.

Questionnaire to Obtain Student Feedback

1. Did you enjoy this experiment?

2. Do you want to be an experimental physicist?
3. Does experiment drive physics the way theory drives physics? Please explain your thoughts.
4. Did completing this lab make you want to do experimental physics?
5. Does experimental physics seem exciting to you?

5.3 Formally Evaluating Student Work

Assessment methods are not standardized in the university physics laboratory curriculum. Frameworks, such as the AAPT Recommendations for the Undergraduate Laboratory Curriculum and the VALUE rubrics, provide fundamental criteria that can be used to develop rigorous evaluations [3, 56]. A rubric ensures that specific components of assessed work are evaluated consistently throughout a given course. If student work is used for further course development, rubrics can also be used to measure significant changes in student work throughout this development. Since this evaluation may be used for further educational development, an ethics review must take place before students can be evaluated using this approach.

Formative feedback is used to provide qualitative feedback on student progress throughout a learning opportunity. This kind of feedback will be provided as students are progressing through the experiments. Summative feedback is used to formally evaluate students once an experience is completed. Grades are assigned to student work and evaluate student learning with references to pedagogical or curricular benchmarks. A summative rubric will be used to assign a grade to the work completed.

Evaluation for the advanced level experiment is presented in Appendix E.

At the introductory level, adjusting the evaluation criteria to emphasize constructive practices in the laboratory will give students feedback on skills that are not assessed in their other laboratory courses. Students will be evaluated on both their conduct in the laboratory and their written work. Given that their conduct will be evaluated, students need to be notified on how their conduct will be evaluated prior to beginning their work in accordance with ethical teaching practices.

The rubrics used to assess students focus on their ability to produce productive experimental questions and develop experiments that answer those questions. Students will be developing conclusions based on their observations, so they will be evaluated based on their ability to arrive at a conclusion solely based on the evidence they collect and interpret. The first version of the rubric to evaluate student conduct is presented in Table 5.1. These criteria align with the Inquiry and Analysis, Teamwork, and Integrative Learning VALUE Rubrics [57, 58, 59]. The presented rubrics will be further developed to add grade point levels and may be modified based on the Curriculum Map [55].

Criterion	Mark	Feedback
Did the students carefully collect data?	/1	
Did the students read the pre-reading materials?	/1	
Did they engage in constructive peer-to-peer interaction that produced an effective experimental environment?	/1	
Were the students able to infer the change in the pulse duration of the blue light when the pulse duration of the infrared light changes given what they learned when reducing the area of the red beam and observing the change in the area of the blue beam?	/1	
Were the students sharing the work equitably?	/1	
Were the students capable of answering the experimental question (does the SHG process occur through the pulse energy, peak power, or laser intensity of the beam?)	/1	

Table 5.1: The preliminary rubric to assess how students are engaging with the Gee Whiz Experiment on SHG.

Each of these criterion require an observation of student activity. For example, “careful data collection” will be evaluated based on attention to detail when recording measurements, such as ensuring the power meter is stationary when in use. To give students a mark on whether or not they read the pre-reading materials, the online learning management system will be used to track student progress. Using the learning management system, a pre-lab quiz could be used to assess comprehension and contribute towards the mark, or students may not get access to the required safety training until the document is opened and read through entirely. The method of assessment used to mark reading completion will influence student perspectives toward the experiment, so methods that keep students engaged with the material will be considered.

To evaluate their ability to engage in constructive peer-to-peer interaction and produce an effective experimental environment, the students will be assessed on their tendency to self-scaffold and the level of guidance needed to perform the experiment.

Students should be able to infer that the pulse duration of the blue light changes with the pulse duration of the infrared light when they see that the beam area of the blue light changes with the beam area of the red light. Students should expect to be evaluated on this because it was explicitly asked of them in the preparatory material.

Given that the students will work in groups of three, it is important to ensure that they are being evaluated for equitable distribution of work and constructive peer-to-peer interaction. Constructive peer-to-peer interactions will be evaluated based on the students' ability to help their group progress by brainstorming and reasoning through different elements of the experiment. Equitable work distribution will be evaluated based on the group's ability to treat group members respectfully and share tasks in a manner that allows each student to gain the most experience from this experiment.

The last criterion in this rubric focuses on the general question asked of students in the preparatory material. Students should determine that SHG is an intensity dependent process using the reasoning presented in Subsection 4.4.4.

For the written portion of this laboratory, students will work together to submit one shared document that records their observations, questions they developed, and answers to those questions. This should be an informal lab report. Written student work will be evaluated using the rubric presented in Table 5.2. These criteria align with the Teamwork VALUE Rubric [58].

Criterion	Mark	Feedback
Did all three members equitably contribute to the report?	/1	
Did the students complete and record each experiment in their lab notes?	/3	
Were the lab notes clear and concise?	/1	
Did students record their experimental questions in the lab notes?	/1	
Were students able to connect what they were physically changing in the lab to what they were expected to measure and communicate that effectively in their notes?	/1	

Table 5.2: The preliminary rubric to assess the written component the Gee Whiz Experiment on SHG.

Equitable contribution to the written report will be marked based on instructor evaluation and student input. The report will be completed during the laboratory session so the instructor will be able to observe whether or not the work is being distributed equitably. Student input must be taken into consideration to account for potential conflicts that could arise during collaboration.

Evidence of each experiment's completion will be used to evaluate the second criterion. Clarity and conciseness will be evaluated based on the group's ability to effectively communicate results without over-explaining concepts or adding irrelevant information.

The record of experimental questions will be evaluated based on the relevance of each recorded question to their experiment.

Students will be evaluated on their ability to connect the measurements they make to the relevant variables in the experiment. For example, students do not directly measure the pulse energy, but instead calculate it from the measurement of average power and repetition rate. Students will be evaluated on their ability to connect the average power and repetition rate to the pulse energy using the information they were presented with in their pre-reading materials.

5.4 Next Steps for Assessing Student Work

The rubrics presented above are developed to evaluate the experiment presented in this thesis, however there will be three other experiments that require formal evaluation. These rubrics should serve as a starting point for future experiments built for this course and be regularly updated to ensure that the current best practices to evaluate student work are used. Grade point levels should be assigned to each criterion to effectively assess work and provide concrete feedback that students can use for their own improvement. Their ability to assess the intended learning goals should be evaluated using appropriate pedagogical metrics.

Chapter 6

Conclusions and Next Steps

6.1 Summary of the Project

This thesis presented the development of an inquiry-based experiment on SHG, designed for introductory undergraduate physics students. The experiment was developed for students in the second term of their first year in the Honours Physics program and assumes some foundational exposure to university-level physics. The project involved constructing a robust experimental setup, as well as designing instructional and assessment materials aligned with inquiry-based pedagogy.

Because the experiment involves a Class-IV laser system, special attention was given to ensuring both safety and durability. Unlike typical undergraduate lab environments, Class-IV lasers are usually restricted to lower-traffic areas or specialized research groups. A central challenge of the project was building a system that could operate safely and reliably for repeated use in a teaching environment.

One of the most time-intensive tasks was constructing the mode-locked oscillator. This process was delayed significantly by a single issue: the End Reflector Mirror and Fold Mirror in the TS Kit had been mounted backwards, with the reflective coating on the incorrect face. As a result, the oscillator could lase but could not achieve stable mode-locking. This misconfiguration led to excessive positive dispersion and insufficient cavity light intensity to sustain a femtosecond pulse train. Once corrected, the system successfully produced mode-locked pulses.

In addition to the oscillator, building the autocorrelator and selecting optics appropriate for student use further demonstrated that it is feasible to implement this experiment in an undergraduate teaching lab.

6.2 Reflecting on Research Questions

The two research questions this project focused on were presented in Section 1.2.

Addressing Research Question 1 began with the successful construction of the experimental setup and its initial implementation in the upper-year laboratory. This was the first step toward evaluating how the Gee Whiz experiments might influence student engagement with experimental physics. A robust experimental workspace as developed with appropriate safety protocols in place which ensured that the experiment can run safely and reliably. Additionally, extensive written materials were created for both student and instructor preparation.

Research Question 2 focuses on whether students develop a greater interest in experimental physics after participating in the experiment presented in this thesis. To answer this question directly, further investigation into students' perceptions of experimental physics is required. Chapter 5 outlines the methodology for evaluating these beliefs through a questionnaire, which will provide insight into the experiment's impact on student attitudes towards laboratory work and experimental physics more broadly.

6.3 Future Work: An Experiment on Optical Autocorrelation

Originally, the experiment designed during this project would have been on optical autocorrelation. During this project's early stages, it was determined that the frequency doubling phenomenon occurring within the intensity autocorrelator was in itself an exciting topic for inquiry work. The optical autocorrelator will now be used to develop a second experiment that builds off of the one presented in this thesis and the experiment will be held in the upper year advanced/modern physics laboratory.

6.4 Potential Impact

This thesis presented the first experiment developed for the GWLC, and provides a foundation for the development of experiments in the laboratory revision project. Beyond its local context, this work may also be valuable to educators who are interested in designing experiments using inquiry-based learning. By using inquiry-based learning in the introductory laboratory through an experiment on SHG, this project offers a basis for integrating complex physics phenomena into introductory undergraduate curricula in a pedagogically meaningful way.

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Appendices

Appendix A

More Relevant Topics in Nonlinear Optics

This appendix, just like Section 1.4, was written using the 4^{th} edition of *Nonlinear Optics* by R. Boyd [15], *Lasers* by A.E. Siegman [16] as well as Lecture 8 from PHYS 714: Nonlinear Optics offered in Winter 2024 [17].

A.1 A Mathematical Description of Nonlinear Beam Interactions

The equation for a laser beam profile can be modelled using a solution to the wave equation of the form presented in equation A.1.

$$\tilde{E}(r,z) = A(r,z)e^{ikz} \tag{A.1}$$

In equation A.1, $\tilde{E}(r,z)$ is the electric field of the beam profile, and $A(r,z)$ is the amplitude function. The wavevector is represented by k, and z is the direction of propagation for the beam. The Gaussian function is in the amplitude function,

$$A(r,z) = A_0 \frac{w_0}{w(z)} e^{\frac{-r^2}{(w(z))^2}} e^{i\frac{kr^2}{2R(z)}} e^{i\phi(z)}. \tag{A.2}$$

To get an equation for the electric field strength for any order of n, $\tilde{E}_n$, in the form of Equation A.1, we start with the wave equation,

$$\nabla^2 \tilde{E}_n - \frac{1}{(\frac{c}{n})^2} \frac{\partial E_n}{\partial t^2} = \frac{1}{\epsilon_0 c^2} \frac{\partial^2 P_n}{\partial t^2}. \tag{A.3}$$

The electric field strength, $\tilde{E}_n$ and polarization density, $\tilde{P}_n$ are

$$\tilde{E}_n(r,t) = A_n(r) e^{i(k_n z - \omega_n t)} + c.c., \tag{A.4}$$

and

$$\tilde{P}_n(r,t) = p_n(r) e^{i(k'_n - \omega_n t)} + c.c., \tag{A.5}$$

where *c.c.* is short for the complex conjugate of the previous term. A_n and p_n are complex amplitudes. If the complex amplitudes, A_n and p_n are spatially varying quantities, the electric field and polarization terms can represent non-plane waves (such as Gaussian beams). If we assume that any longitudinal variation of A_n can occur only in distances much larger than an optical wavelength, then we can assume that the envelope of a forward-travelling wave pulse varies slowly in both space and time compared to the wavelength and period and obtain equation A.6 from equation A.3. The assumption that was made is the Slowly Varying Envelope Approximation.

$$2ik_n \frac{\partial A_n}{\partial z} + \nabla_T^2 A_n = \frac{-\omega_n^2}{\epsilon_0 c^2} p_n e^{i\Delta k z}, \tag{A.6}$$

where $\Delta k = k'_n - k_n$. Equation A.6 is known as the paraxial wave equation. As long as the wave E_n is propagating primarily along the z axis, neglecting the contribution of $\frac{\partial^2 A}{\partial z^2}$ is justifiable. There are several solutions to the paraxial wave equation, each corresponding with different types of waves, such as planar, spherical, or Gaussian.

A.2 A Mathematical Description of SHG

To describe SHG mathematically, we start by working with a plane wave with amplitude $\tilde{E}(\omega_f)$ that travels in the direction of its wavevector, symbolized by k. The subscript "f" is short for fundamental. A polarization nonlinearly dependent on the electric field of the light wave is generated. The wave is generated at the second harmonic frequency and has the expression,

$$\tilde{P}^{(2)}(\omega_{SHG}) = \epsilon_0 \chi^{(2)} \tilde{E}^2(\omega_f). \tag{A.7}$$

If we introduce an effective nonlinear optical coefficient dependent on specific components of the nonlinear susceptibility, represented by $d_{eff}(\omega_{SHG};\omega_f;\omega_f) = \frac{1}{2}\chi^{(2)}$ we can rewrite the equation above as,

$$\tilde{P}(\omega_{SHG}) = 2\epsilon_0 d_{eff}(\omega_{SHG};\omega_f;\omega_f)\tilde{E}^2(\omega_f). \tag{A.8}$$

We assume the system has negligible loss at both the fundamental and second-harmonic frequency and assert the Slowly Varying Envelope Approximation, since l is small enough. The notation $d_{eff}(\omega_{SHG};\omega_f;\omega_f)$ means that the wave with frequency 2ω is the result of the interaction between the two waves with frequency ω_f. The wave equation at ω_{SHG} becomes

$$\frac{\partial E(\omega_{SHG})}{\partial z} = -\frac{i\omega_f}{m_{\omega_f} c} d_{eff} E^2(\omega_f) e^{i[k(\omega_{SHG})-2k(\omega_f)]z}, \tag{A.9}$$

where the index of refraction of the medium is m_{ω_f}. At low conversion efficiency, which is the case for many SHG systems (including the one used in this experiment), the electric field strength of the second harmonic, $E(\omega_{SHG})$, is much lower than that of the fundamental harmonic, $E(\omega_f)$. The fundamental amplitude remains constant over the length of the medium, (or the interaction length) l. The second harmonic field is zero at the left-most point of the medium, or $E(\omega_{SHG}, z = 0) = 0$. Using that boundary condition, we obtain the following equation to solve the wave equation given above:

$$E(2\omega, z = l) = -\frac{i\omega_f d_{eff}}{m_{\omega_{SHG}} c} E^2(\omega) \int_0^l e^{i[k(\omega_{SHG})-2k(\omega_f)]z} dz. \tag{A.10}$$

We can solve the integral to obtain,

$$E(\omega_{SHG}, z = l) = -\frac{i\omega d_{eff}}{m_{\omega_f} c} E^2(\omega_f) l \frac{\sin(\frac{1}{2}[k(\omega_{SHG}) - 2k(\omega_f)]l)}{\frac{1}{2}[k(\omega_{SHG}) - 2k(\omega_f)]l} e^{i[k(\omega_{SHG})-2k(\omega_f)]l}. \tag{A.11}$$

If we introduce the laser intensity, $I = \frac{m}{2}\sqrt{\frac{\epsilon_0}{\mu_0}}|E^2|$ then we see that the laser intensity of the second-harmonic wave is proportional to the square of the laser intensity of the fundamental wave,

$$I(\omega_{SHG}, l) = \frac{\omega_{SHG}^2 d_{eff} l^2}{m_{\omega_{SHG}} m_{\omega_f}^2 c^3 \epsilon_0} (\frac{\sin(\frac{1}{2}[k(\omega_{SHG}) - 2k(\omega_f)]l)}{\frac{1}{2}[k(\omega_{SHG}) - 2k(\omega_f)]l})^2 I^2(\omega_f). \tag{A.12}$$

If $[k(\omega_{SHG}) - 2k(\omega_f)] = 0$, then the process is phase-matched and the intensity of the SHG light is maximized. When the intensity of the fundamental light wave increases linearly, the intensity of light generated at the second-harmonic frequency increases quadratically. To describe SHG using Gaussian functions, we solve the paraxial wave equation using the Constant-Pump Approximation which means the pump amplitude and phase are fixed. The amplitude function of the fundamental wave in an SHG system in cylindrical coordinates is,

$$A_f(r, z) = \frac{A_{f,0}}{1 + i\frac{2z}{b}} e^{-\frac{r^2}{w_0^2(1+i\frac{2z}{b})}}, \tag{A.13}$$

and the amplitude function of the wave at any n^{th} generated harmonic is given by a solution of the form,

$$A_n(r, z) = \frac{A_n(z)}{(1 + i\frac{2z}{b})} e^{-\frac{nr^2}{w_0^2(1+i\frac{2z}{b})}}, \tag{A.14}$$

as long as $A_n(z)$ obeys the ordinary differential equation,

$$\frac{dA_n}{dz} = \frac{in\omega}{2m_n c} \chi^{(n)} A_f^n \frac{e^{i\Delta kz}}{(1 + i\frac{2z}{b})^{n-1}}. \tag{A.15}$$

The solution to the differential equation is,

$$A_n(\Delta k, z_0, z) = \frac{in\omega}{2mc} \chi^{(n)} A_{f,0}^n \int_{z_0}^{z} dz' \frac{e^{i\Delta kz'}}{(1 + i\frac{2z}{b})^{n-1}}. \tag{A.16}$$

In the case of SHG of light travelling into a medium from air ($n = 2$, $m = 1$) this relationship simplifies to show the proportionality (with $\kappa(\Delta k, z_0, z) = \frac{i2\omega}{2c}\chi^{(2)} \int_{z_0}^{z} dz' \frac{e^{i\Delta kz'}}{(1+i\frac{2z}{b})^1}$),

$$A_{SHG} \alpha \kappa A_f^2. \tag{A.17}$$

Since the laser intensity is proportional to the electric field strength, the laser intensity of the SHG light is also quadratically related to the laser intensity of the fundamental light when described using Gaussian functions,

$$I_{SHG} = I^2(\omega_f)\frac{\omega_{SHG}^2}{\pi c^2 \epsilon_0 w_0^2 m_{SHG} m_f}\chi^{(2)}\chi^{(2)}|\int_{z_0}^{z} dz' \frac{e^{i\Delta k z'}}{(1+i\frac{2z}{b})}|^2. \tag{A.18}$$

Appendix B

Safety

B.0.1 Protocols and Standard Operating Procedures for Laser Operation

Since there is laser radiation in both 532nm and a range of infrared light around 800±50nm, precautions must be made to protect all personnel from light at both wavelengths. All the 532nm light is blocked from entering the experimental workspace with a filter that allows only the infrared light to pass through the femtosecond laser head and into the experimental workspace. As the 532nm enters the TS kit, it is enclosed in beam tubes to prevent exposure.

The following safety considerations that all personnel are explicitly trained on are:

1. Ensuring that the laser is operated in a controlled apparatus and all personnel working with this laser are trained in the principles of laser safety.
2. Ensuring that no beam paths are left open, all beams must finish into a beam dump to prevent accidental exposure.
3. Ensuring that all power cords, keyswitch, shutter control, and emergency stops are accessible at all times.

Students are also required to walk through the lab with a trained instructor prior to starting their experiment and become familiar with the emergency procedures that are in place. Students are expected to:

1. Wear the protective goggles given to them at all times while the laser is operating.
2. Never look at the output beam directly at any point during their experiment.
3. Never have any physical contact with the output beam.
4. Never work with the laser outside of the designated work space and only with the equipment that allows them to make changes to the beam's properties without making contact with the beam.

This training was approved by the Safety Office as part of the requirements to complete construction in the laboratory.

B.0.2 Safety Measures for the CW Laser

Since the CW Laser is what pumps the femtosecond laser, its operation is controlled through an interlock and emergency stop. Should emergencies related to laser exposure arise in the laboratory, cutting the power used to operate the pump is the safest and most effective way to prevent harm to personnel and equipment. The beams from both the CW and the femtosecond laser are both fire and safety hazards and can cause eye and skin damage at varying levels of severity.

The CW laser is connected to an external interlock which warns personnel that the laser is in operation. This interlock is also connected to an emergency-stop button which can automatically shut the laser down should emergencies arise. The interlock and emergency stop are controlled using an Arduino, which allows for modifications such as motion sensors to activate the emergency stop, alarms, and other future functions that could both provide students the opportunity to learn about the development of safety procedures, and ensure the safety requirements of this laboratory are always kept up to date as the technology used in the laboratory changes.

The CW laser can also only be powered on through Graphical User Interface (GUI) software provided by the supplier that requires a computer and has several fail-safes in place to prevent the laser from operating unless all safety checks are cleared. If the CW laser is not warmed up, it cannot be powered on with the GUI software. It also has a keyswitch that must be enabled for operation.

In case of fire, activate the emergency stop and evacuate the room. Pull the closest fire alarm and contact the special constables (who do not get notified if a fire alarm is pulled, so they must be contacted by phone).

B.0.3 Start Up and Take Down Standard Operating Procedures

The following procedures are in effect to ensure safe start up and take down of the experiment. These procedures had to be approved by a representative from the Safety Office before the experiment could be conducted by undergraduate students.

Start Up Procedure

1. Ensure all doors are closed and locked, and windows are covered completely.
2. Turn on the chiller. Ensure that it is operating at 20°.
3. Turn on interlock light.
   (a) Check that the light is on by listening for a click as the interlock is turned on.
4. Put on the green goggles and then the orange goggles to prevent exposure to both the 532nm and the infrared light.
5. Turn on the computer and load the GUI Software to power the CW laser.
6. Power on the CW laser and ensure that it is working correctly.
   (a) The CW laser will require time to warm up. It requires anywhere between 15 to 30 minutes to completely warm up.
7. Begin mode-locking the femtosecond laser. Use the following procedure if the femtosecond laser was mode-locking reliably when last pumped:
   (a) Ensure that the femtosecond laser output is blocked.
   (b) Allow for 0.5W of CW light to enter the TS kit.
   (c) Ensure that there is no damage caused to the system and turn up the CW power to operating level. 4.5W using the GUI Software connected to the CW laser.
   (d) Do not adjust any optics for several minutes to allow for the system to warm up. This should take minimum 3 minutes and no more than 20 minutes.
   (e) Check that the CW output power is similar to what it was in previous recordings written in the logbook.
      i. If the CW power is significantly lower than previous recordings, the system may not be warmed up. Otherwise, check to make sure that the optical surfaces are clean or if the system underwent jitter or thermal drift.

        ii. If the CW power is slightly lower than previous recordings, adjust ONE of mirrors 1 and 9 in the femtosecond laser and labelled as such in Figure 3.1 to achieve maximum power.

    (f) Initiate mode-locking and record the bandwidth. Adjust prisms 1 and 2 (seen in Figure 3.1 as optics (7) and (8)) if needed.

    (g) Unblock the light and ensure that there are no leaks through the shielding to prevent exposure of any radiation.

8. Close the cover for the femtosecond laser and record the output infrared average power from the laser in the logbook kept at the experimental workstation. Record the time and date.

Take Down Procedure

1. Block the light exiting the femtosecond laser.
2. Use the GUI Software to stop the emission from the CW laser.
3. Turn off the CW laser using the switch on the back of the laser
4. Turn off the interlock light.
    (a) Check that the light is turned off by listening for a click.
5. Turn off the chiller.

All these procedures are reviewed termly to ensure that the current conditions of the lab are recorded and records are kept up to date.

Appendix C

Comprehension Questions

C.1 Information on Comprehension Questions

Within this document are questions that can be used to check for comprehension of any new or reinforced concepts presented. These questions are not mandatory but are beneficial to help break down the concepts that are introduced. It is also recommended that students write down their own questions that develop while reading this document. Neither the development of or answers to these questions are evaluated on a numeric grading scale.

C.2 Comprehension Questions on Experimentation in Lab

1. In any experiment, why would it be important to distinguish the relationship between what variable is being measured and what variables are changing?
2. Even with every single piece of equipment in the world available in a laboratory space, some variables cannot be directly measured. Can you think of an example where the previous statement could be the case?

C.2.1 Comprehension Questions related to Prereading Material

1. Why would electrons travel slower than photons?

2. Why can't the average power of a train of short pulses be directly measured from an oscilloscope trace?
3. Why is it difficult to measure the beam area at its focus?

Comprehension Questions to Help Students Design Experiments

1. Does the pulse energy of the blue beam depend on the pulse energy of the infrared beam? If so, how?
2. Does the pulse duration of the blue beam depend on the pulse duration of the infrared beam?
   (a) If so, how?
   (b) Does that mean the peak power of the blue beam depends on the peak power of the infrared beam? If so, how?
3. Does the beam area of the blue beam depend on the beam area of the infrared beam?
   (a) If so, how?
   (b) Does that mean the laser intensity of the blue beam depends on the laser intensity of the infrared beam? If so, how?
4. How many different experiments can you design to answer your questions?
5. What are some of the measurement devices you have available to you and what do they measure?
6. Are you able to directly measure the pulse energy, pulse duration, and laser intensity?
7. What is an experiment you can conduct to observe if the pulse energy of the blue beam depends on the pulse energy of the infrared beam?
8. How can you change the pulse duration of the infrared beam?
   (a) What happens to light as it travels through different media?
   (b) If light travels through glass from air, what happens to its speed?
   (c) If the light's speed changes, but it travels through the same distance, what happens to the time taken for the light to travel that distance?

9. Are you measuring every important variable that is relevant to the experiment?
10. How can you change the laser intensity of a beam?
    (a) What factors have you already changed that related to the laser intensity of the beam?
11. Why would we need to measure the area to determine the laser intensity instead of the other variables used in the experiment?

Appendix D

Upper Year Experiment Instructions

D.1 Instructional Materials at the Advanced Undergraduate Level

D.1.1 Outline

Frequency doubling is a technique in ultrafast optics. When a laser beam interacts with a nonlinear crystal, some of the light gets frequency doubled. As an example, some red light emanating from a beam will double to blue light. The concepts used to explore frequency doubling must be studied in higher level optics courses, but the use of frequency doubling in the lab will help us to understand the properties of the laser, and that is exactly what this experiment intends to do. Using a frequency doubling optical set up, the purpose of this inquiry-based lab is to understand the relationship of energy, power, and intensity of light. In this lab, you will design a set of experiments to determine whether or not the conversion efficiency of frequency doubled light produced in this system is dependent on the three variables: energy, power, and intensity.

D.1.2 Prerequisites to Entering the Lab

Students are required to complete the Laser Safety Course on LEARN and bring a picture of their certificate at the start of the session. If they fail to do so, they are prohibited from completing the experiment as instructed by the Office of Safety and will need to coordinate for a new lab. Students must try to bring a USB key to the lab.

D.1.3 Background Material

You may notice there is very little preparatory material. That is because:

1. Your time preparing for the lab should go towards finishing your training.
2. This is an inquiry-based lab that revolves around your learning taking place in the lab environment. A brief lesson will take place during your in-person training during the first half hour of your experiment.

The laser we are using in this lab is a pulsed laser. This differs from your average laser pointer because it uses a concept called "mode-locking" that is used to generate short, intense pulses. These pulses can be observed using an oscilloscope by connecting the oscilloscope to a photodetector and placing the photodetector in the path of a short-pulse laser. The image below presents a train of short pulses on an oscilloscope.

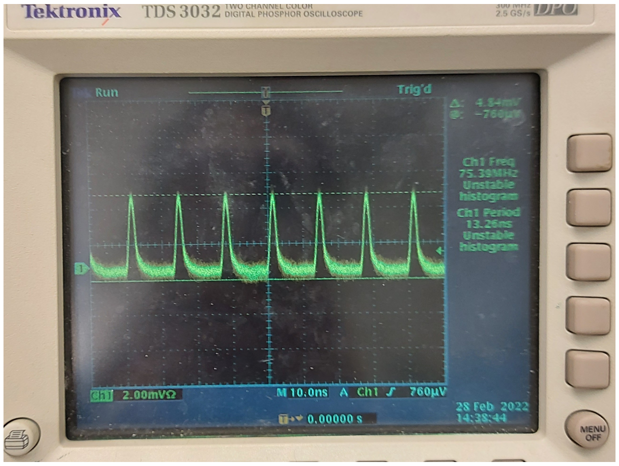

Figure D.1: An oscilloscope trace of a mode-locked short pulse train.

We will also be using the following definitions during this experiment.

1. Pulse Duration: The measured time of a pulse, determined by obtaining the full width at half max (FWHM) of a spectrum.
2. Beam Area: The cross-sectional area of the beam.
3. Energy: A measure of the emission of the laser beam.

4. Peak Power: The highest instantaneous optical power emitted, estimated by

$$P_{peak} = \frac{E}{\tau} \tag{D.1}$$

where τ is the pulse duration.

5. Average Power: The energy of the beam multiplied by the repetiton rate of the laser,

$$P_{avg} = ER. \tag{D.2}$$

6. Intensity: The energy per unit time per unit area, or the power divided by the area

$$I = \frac{E}{\tau A}. \tag{D.3}$$

D.1.4 Learning Objectives

By the end of this experiment, learners will:

1. Design a series of experiments that determines relationships between the frequency doubling process and potential variables that influence this process.
2. Develop skills related to use and applications of an ultrafast laser.

D.1.5 First Half Hour of the Lab

For the first half hour of the lab, you will be going through training to be familiar with the safety protocols and risks associated with a Class IV laser. This training is part of your requirements in order to be able to safely use the laser. Everyone who chooses to take part in this experiment will need to complete this safety training which is accessible through the LEARN page for this experiment. This involves an in-person orientation and is mandatory to complete the experiment.

D.1.6 Relationships between Factors Influencing the Second Harmonic Generation of Infrared Light

Part 0: Pilot Measurements (45 Minutes)

For this part of the lab, you are going to work with the instructor to develop the relationship between the power of the red light of the laser and the power of the blue light of the laser. Ensure that you write down questions as they are discussed and make note of experimental choices and decisions.

Part 1: Planning (15 minutes)

Answer the following questions and then discuss with the instructor.

1. How do you determine whether or not energy, power, and intensity of a source laser beam is a variable that determines the conversion efficiency of frequency doubled light produced by that source?
2. How will you measure the conversion efficiency of frequency doubled light produced?
3. How will you design an experiment to test the relationship of energy of a laser source and the conversion efficiency of frequency doubled light produced?
   (a) What are you directly measuring in the lab?
   (b) What is the relationship between what you are directly measuring and the energy?

Part 2: Execution and Analysis (1 hour)

Execute your plan to observe the behaviour of frequency doubled light when the energy of the source laser is changed. Record your method and observations. Show these to your instructor and make note of any modifications. Then, analyze this data using methods discussed with the instructor.

Part 3: Modification (10 Minutes)

Make note of any limitations in your current analysis and develop a modified plan. Feel free to reuse any question as presented above.

Part 4: Repetition and Iteration (20 Minutes)

Iterate your plan following the steps in Parts 2 and 3 until you've collected satisfactory data.

Part 5: Extension (1 hour)

1. How will you design an experiment to test the relationship of intensity of a laser source and the conversion efficiency of frequency doubled light produced?
    (a) What are you directly measuring in the lab?
    (b) What is the relationship between what you are directly measuring and the intensity?
2. Conduct the modified experiment to determine the relationship between intensity of the source laser beam and the conversion efficiency of frequency doubled light produced. Record your method and observations. Show these to your instructor and make note of any modifications.

Notes for your report

You will notice here that in contrast to many other preparatory material for experiments in this course, these instructions do not outline the method. That is because the purpose of your work is to determine the method that you will use to conduct this experiment, and justify what you are doing. The marking rubric focuses on the explanations of the lab skills you used and concepts based on ***undergraduate*** physics concepts (don't go researching frequency doubling and write 50 pages on phase matching. That wasn't relevant to what you did! What was?) The main purpose of this report is to determine: does the conversion efficiency of frequency doubled light depend on the energy, power, intensity, or a combination of the 3 variables? Regarding questions in the analysis, you will actually be discovering them along side the TA! Since this is an inquiry-based lab, you will be developing the questions with the TA/Instructor based on your own inquiry. We will be responsible for ensuring you leave with an appropriate level of questions, but we are happy to take any questions you have regarding this delivery method!

Appendix E

Upper Year Assessment Rubric

E.1 Assessment Rubric for Undergraduate Experiment at the Advanced Level

The advanced level experiment is delivered through the advanced undergraduate laboratory course, where students are given the option to choose experiments they wish to perform. As part of their course requirements, students select one experiment that they completed as a topic for a 10-minute presentation outlining the methods, results, and conclusions they obtained. Students are also required to write formal reports for all the experiments they completed. Table E.1 presents the rubric used to assess the frequency doubling experiment in the upper-year advanced modern physics laboratory course. This rubric was in use during the 2023-2024 Academic Year at the University of Waterloo.

Table E.1: Rubric used to assess the advanced level frequency doubling experiment.

Criteria	Level 4 (2 Grade Points)	Level 3 (1 Grade Point)	Level 2 (0.5 Grade Points)	Level 1 (0 Grade Points)	Criterion Score (Grade Points)
1. Development of Experimental Mindset (understanding link between experiment and theory)	Demonstrates high level understanding of the unique uses of a laser.	Demonstrates sufficient understanding of the properties of the laser and its role in this experiment.	Demonstrates partial understanding of the properties of a laser and its differences between other sources of light	Does not demonstrate an understanding of the properties of the laser.	/2

					Continuation of Table E.1
Criteria	Level 4 (2 Grade Points)	Level 3 (1 Grade Point)	Level 2 (0.5 Grade Points)	Level 1 (0 Grade Points)	Criterion Score (Grade Points)
2. Development of Experimental Mindset (ability to develop productive experimental questions during the first round of iteration)	Asked, answered and recorded several productive questions related to the experiment	Asked, answered and recorded some questions related to the experiment	Asked and answered questions related to the experiment in the session, but recorded a few	Asked and answered questions related to the experiment in the session, but recorded none	/2
3. Development of Experimental Mindset (ability to engage in productive independent experimental design)	Designed an effective plan based on results from their pilot measurements, and clearly recorded the process systematically in the report, where anyone reading the report can clearly understand what they intended to accomplish, and clearly recorded their definition of all variables such as conversion efficiency and the relationship between what they measure and what needs to be interpreted	Designed an effective plan based on results from their pilot measurements, and recorded the process sufficiently enough to explain to the grader what they did and clearly recorded their definition of most variables such as conversion efficiency and the relationship between what they measure and what needs to be	Designed an effective plan based on results from their pilot measurements, and recorded the process sufficiently enough to demonstrate an understanding of what they did, but the grader had to press for clarification but only clearly recorded their definition of one variable such as conversion efficiency and the relationship between what they measure and what needs to be	Designed an effective plan based on results from their pilot measurements, and recorded the process but work needs revision to understand what this plan was, and no definition of vague variables were provided	/2

Continuation of Table E.1

Criteria	Level 4 (2 Grade Points)	Level 3 (1 Grade Point)	Level 2 (0.5 Grade Points)	Level 1 (0 Grade Points)	Criterion Score (Grade Points)
4. Developing skills in data collection, analysis, and interpretation (ability to use data to support or refute physical models)	Used their data to determine whether or not there was a relationship between energy of the red laser and conversion efficiency, and provided suggestions as to what this relationship was based on correct use of statistical analysis techniques	Used their data to determine whether or not there was a relationship between energy of the red laser and conversion efficiency, and provided suggestions as to what this relationship was based on statistical analysis techniques, but minor corrections are required	Used their data to determine whether or not there was a relationship between energy of the red laser and conversion efficiency, and provided suggestions as to what this relationship was based on qualitative discussion	Did not determine or state whether or not there was a relationship between energy of the red laser and conversion efficiency of frequency doubled light.	/2
5. Developing skills in data collection, analysis, and interpretation (ability to understand best practices in data collection and how to make good measurements in specific domains)	Correctly determined the measurement range and increment range of their experiment based on pilot measurements, as well as recorded it clearly in the method. Demonstrated and recorded proper technique in demo 1.	Determined the measurement range and increment range of their experiment based on pilot measurements, as well as recorded it clearly in the report demonstrated and recorded proper technique in demo 1 but needed minor improvements	Determined the measurement range and increment range of their experiment based on pilot measurements, but did not clearly record it in the report did not adequately demonstrate or record proper technique in demo 1	Insufficient demonstration of recording of measurement range and increment range of their experiment based on pilot measurements or demonstration 1.	/2

Continuation of Table E.1

Criteria	Level 4 (2 Grade Points)	Level 3 (1 Grade Point)	Level 2 (0.5 Grade Points)	Level 1 (0 Grade Points)	Criterion Score (Grade Points)
6. Developing skills in data collection (ability to correctly analyze data by choosing appropriate techniques) (energy)	All included graphs were justified effectively and any necessary statistical comparisons were made correctly with good sample calculations	All included graphs were justified effectively and any necessary statistical comparisons were made	Some elements of the graphs were missing and few statistical comparisons were made	Graphs were missing or incorrect and no statistical comparisons were made	/2
7. Developing skills in data collection (ability to correctly analyze data by choosing appropriate techniques) (power)	All included graphs were justified effectively and any necessary statistical comparisons were made correctly with good sample calculations	All included graphs were justified effectively and any necessary statistical comparisons were made	Some elements of the graphs were missing and few statistical comparisons were made	Graphs were missing or incorrect and no statistical comparisons were made	/2
8. Developing skills in data collection (ability to correctly analyze data by choosing appropriate techniques) (intensity)	All included graphs were justified effectively and any necessary statistical comparisons were made correctly with good sample calculations	All included graphs were justified effectively and any necessary statistical comparisons were made	Some elements of the graphs were missing and few statistical comparisons were made	Graphs were missing or incorrect and no statistical comparisons were made	/2
9. Developing knowledge of, and confidence using scientific equipment	Were able to correctly describe the apparatus used and how each optic was significant to the system	Were able to describe the apparatus used and how most optics were significant to the system with minor corrections	Were able to describe the apparatus used and how most optics were significant to the system with major corrections	Several descriptions were missing and required significant corrections	/2

					Continuation of Table E.1
Criteria	Level 4 (2 Grade Points)	Level 3 (1 Grade Point)	Level 2 (0.5 Grade Points)	Level 1 (0 Grade Points)	Criterion Score (Grade Points)
10. Developing scientific communication skills	Effectively communicate their results (using words, figures, tables and graphs), as well as their interpretation of results, and their experimental processes clearly and concisely in written form.	communicated their results (using words, figures, tables and graphs), as well as their interpretation of results, and their experimental processes with some minor adjustments and corrections	Several elements are missing or incomplete but the general purpose of the report is accomplished	Report is incomplete and significant communication gaps are present. Overall the report does not meet the expectations of a formal report written at the upper year undergraduate level.	/2
					End of Rubric