Experiment design with Galilean beam expanders for magneto-optical traps and the advanced undergraduate laboratory

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Abstract- **This paper presents a compound lens experiment design suitable for upper-division undergraduate laboratory courses in which teams of students constructed and measured the properties of Galilean beam expanders. Skill in developing Galilean beam expanders is useful for undergraduates who will build a magneto-optical trap in a follow-on course. This laboratory experiment was performed by third-year undergraduate students in our applied optics course and provided students with the opportunity to gain knowledge about lasers, lenses, and alignment of optical components prior to their laboratory work building a magneto-optical trap.**

Index Terms – Galilean Beam Expander, Magneto-Optical Trap, Linearization, Converging Lens, Diverging Lens.

INTRODUCTION

While advanced photonics experiments, such as quantum mechanics experiments with single photons, have been incorporated into advanced physics laboratories since the early 2000s, the magneto-optical trap was selected just last year as one of ALPhA's advanced laboratory immersions which can lead to wider dissemination in undergraduate laboratory courses [1-3]. Recent work incorporating optics research skills into advanced undergraduate laboratory courses has been published by Busch (2019), Turchiello *et al.* (2017), Leung *et al.* (2017), Ashby *et al.* (2017), and Bechhoefer *et al.* (2002) [4-8]. Busch describes an experiment to incorporate spectroscopy of neon in the advanced undergraduate laboratory in which students gain technical skills in the area of optics, lasers, and radio-frequency electronics [4]. Turchiello *et al.* present a nonlinear optics experiment for the undergraduate laboratory [5]. Leung *et al.* (2017) quantify the spatial resolution of a digital camera [6]. Ashby *et al.* (2017) introduce a quantum mechanics experiment into the undergraduate laboratory [7]. Bechhoefer *et al.* introduce optical tweezers into the undergraduate laboratory [8].

This paper presents an accessible experimental design to introduce undergraduates enrolled in an applied optics course to beam expanders which they will encounter while designing and building a magneto-optical trap (MOT) in a subsequent laboratory course. Analysis of the experiment is carried out according to typical methodologies in undergraduate experiments [9]. Beam expanders have applications in a variety of areas in optical physics including materials and medical physics, interferometry, laser scanning and remote sensing, and fundamental optical physics [10-15].

BACKGROUND

As part of an experimental thread within an undergraduate physics program, students will construct a MOT as a capstone exercise. The MOT was first realized in 1987 and, as the name implies, relies on a combination of inhomogeneous magnetic fields and optical selection rules to produce a cooling effect [16-17]. The relative ease of construction and robustness of the trap has made the MOT the least expensive method for producing cold atoms (<1 mK) for further atomic physics experiments [18]. The lasers used for the MOT are tuned to the proper frequency to produce the cooling action, and their polarization is set before the beam is directed towards the trap vacuum chamber [19-20]. Prior to entering the chamber, the incoming 1-mm beam must be expanded to the final trap size, between 15-25 mm, by the use of a Galilean beam expander (also referred to as a laser beam expander) as shown in Figure I below [19-20]. The experiment detailed here provides undergraduate students with a series of learning experiences to enable their construction of the Galilean beam expanders in the follow-on course to produce differently sized beams at the trapping chamber.

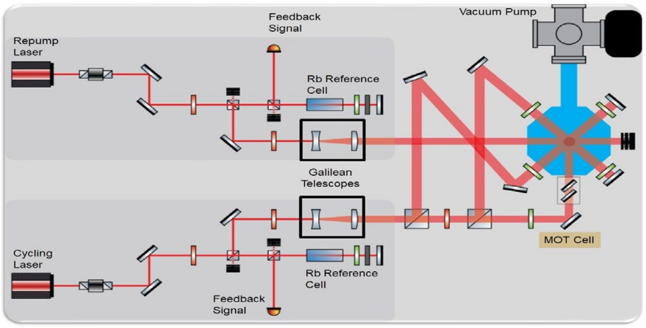

FIGURE I
DIAGRAM OF A MOT

MOTIVATION

In our applied optics course, Galilean beam expanders are used to measure the focal length f_2 of an unknown lens, and students are exposed to how to use Galilean beam expanders to expand a laser beam in a follow-on course.

In this experiment, we used Galilean beam expanders to obtain multiple trials (and multiple sizes of expanded beams). We decided for the purposes of the laboratory to do multiple trials; we gave the students opportunities to pair lenses with different values of f_1 with a lens with an unknown value of focal length (f_2) until the expanded output beam is collimated. Students then used experimental technique to extract a value of the focal length f_2 and compare it with the value provided by the manufacturer.

Multiple trials enabled the students to gain hands-on experience that complemented the knowledge they gained in the classroom. Multiple trials also provided several opportunities for the students to engage with the concepts and gain a deeper understanding of lenses and alignment of optical components.

In this laboratory, the linearization process is used to determine the value of f_2 of the lens. Multiple trials are used; we assume that the value of f_1 is known and is provided to the students. Students can see multiple diameters of the output expanded beam.

GALILEAN BEAM EXPANDERS

The Galilean beam expander is a simple optical system that consists of two lenses, a negative lens and a positive lens separated by distance $L = f_1 + f_2$ with magnification $M = \frac{D}{d}$ [12-13]. Figure II and Figure III offer a visual depiction of the Galilean Beam Expander.

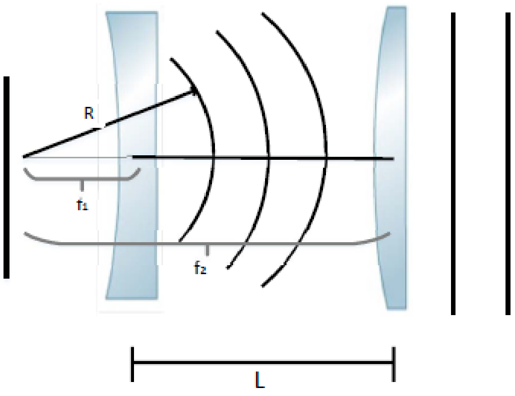

FIGURE II
SIDE VIEW OF GALILEAN BEAM EXPANDER

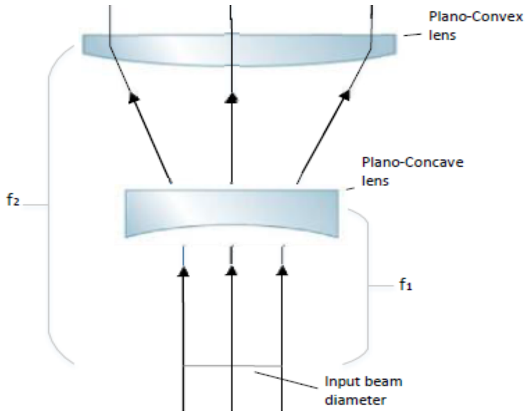

FIGURE III
TOP VIEW OF GALILEAN BEAM EXPANDER

The beam expander takes an input collimated beam with diameter d and produces an output beam with diameter, D, as given by (1).

$$D(f_1, f_2) = f_1\left(\frac{d}{f_2}\right) \tag{1}$$

where the terms f_1 and f_2 represent the focal lengths of the plano-convex lens and plano-concave lens, respectively. In this experiment design, the slope of the linearized graph is given by (2).

$$Slope = \frac{d}{f_2} \tag{2}$$

The independent quantity is f_1, and the dependent quantity is D. The objective quantity is f_2 and is given by (3).

$$f_2 = \frac{d}{slope} \tag{3}$$

The absolute uncertainty in the magnification, δM, is given by (4).

$$\delta M = \sqrt{\left(\frac{1}{d}\delta D\right)^2 + \left(-\frac{D}{d^2}\delta d\right)^2} \tag{4}$$

The assumption in this experiment was that the input beam had negligible divergence, which is approximated well for the CrystaLaser diode lasers used in the experiment.

EXPERIMENTAL DESIGN: DETERMINING THE FOCAL LENGTH, f_2 OF A NEGATIVE LENS

In this experiment, students measured the focal length, f_2 of a negative lens from properties of several Galilean beam expanders [12-13].

For each of four Galilean beam expanders, the output beam diameter D is measured, and the values are plotted as a function of the value of the focal length f_1 of the positive lens. Regression performed on the data provides a value for the slope as a confidence interval. A value of the focal length and the uncertainty of the plano-concave lens is obtained with (3) and compared with the manufacturer's value.

In this activity, both lenses were aligned so that light passing through will pass orthogonally through both lenses. The lenses were carefully aligned, and the separation between the lenses was adjusted, so that the output beam was collimated over a distance of approximately one meter. Both the diameter of the input beam (between f_1 and f_2) and the output beam (after f_2) were measured while wearing laser safety goggles. The track length distance, L, between f_1 and f_2, was measured using markings on the track.

RESULTS

Figures IV and V show the graphs of the beam diameter D at the output of four Galilean beam expanders as functions of the focal length f_1 in each beam expander. The data collected by one lab group is shown in Figure IV, and the data collected by a second lab group is shown in Figure V. Linear regression is performed on the data, and the best fit is indicated in the red line passing through the data values. From the values of the slope obtained from linear regression, a confidence interval for f_2 can be obtained from each of the graphs. The greater scatter in the data in Figure V produces a larger uncertainty in the value for f_2, as discussed below.

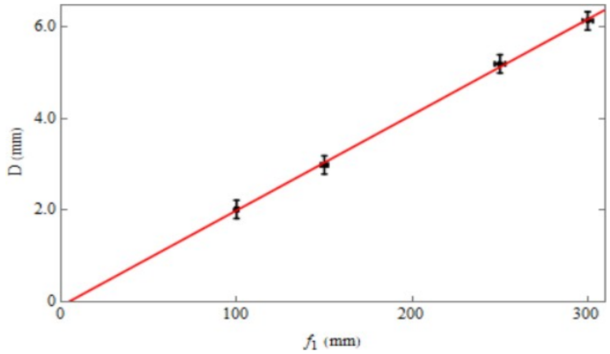

FIGURE IV
DIAMETER *D* OF EXPANDED BEAM AS A FUNCTION OF POSITIVE LENS FOCAL LENGTH PROVIDED BY LAB GROUP 1

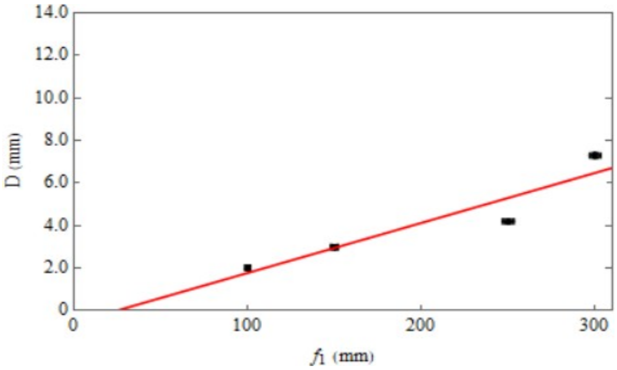

FIGURE V
DIAMETER *D* OF EXPANDED BEAM AS A FUNCTION OF POSITIVE LENS FOCAL LENGTH PROVIDED BY LAB GROUP 2

The confidence interval for f_2 from data in Figure IV is 48 ± 5mm, and the confidence interval for f_2 from data in Figure V is 50 ± 10 mm, where the absolute uncertainty is reported with one significant figure [9].

A number line analysis and comparison with the manufacturer's value for the lens with $f_2 = 50$ mm shows that the students' measurements of f_2 in Figure IV and Figure V overlap with the manufacturer's value of f_2 but have less precision, so that the students' experimental values are accurate but not precise; the source of error is random for both lab groups.

STUDENT REFLECTIONS

From the perspective of an undergraduate physics student, this experiment provided the class with a level of hands-on learning with the Galilean Beam Expander not seen in many other undergraduate physics programs. Conducting this experiment, therefore, gave the students an appreciation for how the theory of the beam expander is supported by real-world experimentation. One student reflects, "I like that a problem we ran into with systematic error was identified and an alternative solution to mitigate this problem was offered for future execution of this lab". Another student reflects, "If this experiment [were] to run again, we would be sure to measure the output diameter with greater accuracy, which would solve a large portion of our systematic error."

FUTURE WORK

Follow-on activities that could stem from this laboratory include an activity with another Galilean beam expander to measure the focal length of an unknown plano-convex lens (using the value of the focal length of the plano-concave lens from the previous activity).

A more collimated beam might have resulted in a better- defined output diameter. Future labs could benefit from use of a beam profiler to measure beam diameter input to, and output from, the beam expander. For reference and potential future work in the realm of Galilean beam expanders, Figure VI below depicts the equipment used throughout the experiment.

FIGURE VI
EQUIPMENT USED FOR GALILEAN BEAM EXPANDER EXPERIMENT

ACKNOWLEDGMENTS

The authors thank Benjamin Hoffman for assistance with graphing Figures IV and V, and thank A. Chung, J. Dancer, J. Anthis, D. Charleton, D. Lynch, K. Seaward, W. Addy, T.

Amison and J. Broussard for assistance with data collection. M. Lanzerotti thanks Z. Lachance for assistance with the lab and D. Kashinski for assistance scheduling the labs.

REFERENCES

[1] Waruel, John; Liwag, F, and Kees. Introduction of advanced photonic physics at the undergraduate level: an example from the Philippines, 2002. Online. Available: https://www.researchgate.net.

[2] Theresa Lynn and Jason Gallichio. ALPhA Advanced Laboratories. Quantum Mechanics Experiments with Single Photons and Entangled Photons. Harvey Mudd College, May 29-31, 2019. Online. Available: https://advlab.org/Imm2019HMQuantum.

[3] ALPhA Advanced Laboratories. ALPhA's Laboratory Immersions. Michaela Kleinert, Magneto-Optiical Trap. Willamette University, Salem, OR. Aug. 8-10, 2018. Online. Available. https://advlab.org/Imm2018WillametteMOT.

[4] H. C. Busch, "Spectroscopy of neon for the advanced undergraduate laboratory", *Am. Jnl. Phys.*, vol. 87, pp. 223-229, 2019. DOI: https://doi.org/10.1119/1.5088806.

[5] R. de F. Turchiello, Luiz A. A. Pereira and S. L. Gomez, "Low-cost nonlinear optics experiment for undergraduate instructional laboratory and lecture", *Am. Jnl. Phys.*, vol. 85, pp. 522-528, 2017. DOI: https://doi.org/10.1119/1.4984808.

[6] C. Leung and T. D. Donnelly, "Measuring the spatial resolution of an optical system in an undergraduate optics laboratory", *Am. Jnl. Phys.*, vol. 85, pp. 429-438, 2017. DOI: https://doi.org/10.1119/1.4979539.

[7] J Ashby, P. D. Schwarz, M. Schlosshauer, "Delayed-choice quantum eraser for the undergraduate laboratory", *Am. Jnl. Phys.*, vol. 84, pp. 95-105, 2017. DOI: https://doi.org/10.1119/1.4938151.

[8] J. Bechhoefer and S. Wilson, "Faster, cheaper, safer optical tweezers for the undergraduate laboratory", *Am. Jnl. Phys.*, vol. 70, pp. 393-400, 2002. DOI: https://doi.org/10.1119/1.445403.

[9] *Laboratory Analysis Manual* (SLAM). Revised AY 18-1. Online. Available: http://readtheslam.com.

[10] Newport Corporation. Laser Beam Expander. Online. Available: https://www.newport.com/f/laser-beam-expanders.

[11] EO. Laser Optics Lab: Beam Expander Configurations and Designs. Online. Available: https://www.edmundoptics.com/resources/industry-expertise/laser-optics/.

[12] Laser Beam Expanders,Edmund Optics. Online. Available: https://www.edmundoptics.com/resources/application-notes/lasers/beam- expanders/.

[13] How to Design your own Beam Expander Using Stock Optics, Edmund Optics. Online.

[14] Optical surfaces. Beam Expanders Help Deliver World's Most Powerful Laser System. Online. Available: https://www.optisurf.com/index.php/beam-expanders-help-deliver-worlds- most-powerful-laser-system/.

[15] Beam Expanders. Online. Available: https://www.ulooptics.com/beam-expanders/.

[16] Raab E. L.; Prentiss M.; Cable A.; Chu S.; Pritchard D.E. (1987). "Trapping of neutral sodium atoms with radiation pressure". Physical Review Letters. 59 (23): 2631–2634.

[17] Metcalf, Harold J. Magneto-Optical Trapping and Its Application to Helium Metastables, J. Opt. Soc Am. B 6,2206-2210 (1989).

[18] Metcalf, Harold J. Straten, Peter van der (1999). Laser Cooling and Trap- ping. Springer-Verlag New York, Inc.

[19] Lee E. Harrell, Mary Clare Cassidy, Kirk A. Ingold, David O. Kashinski, Corey SS. Gerving, "An advanced laboratory course based on the construction and modeling of a magneto-optic atom trap", Proc. American Physical Society Annual Meeting, Boston, MA, March 2019.

[20] Kashinski, D.O, Harrell, L.E., Gerving, C.S., Cassidy, M.C., and Ingold, K.A. Using a Magneto-Optical Trap (MOT) to Teach Experimental and Computational Methods in Undergraduate Physics, DAMOP 2019.

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