Demonstrating the Sagnac Effect Using Tabletop Optics on a Rotary Platform

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Abstract. A Sagnac interferometer splits an incident beam of light into two components which travel in opposite directions of the same path. Consequently, each beam travels an equivalent distance. However, by rotating the entire apparatus at a sufficient speed, a noticeable change in the beams' interference pattern is observed. This pattern results from one beam travelling against rotation and the other travelling with rotation, resulting in an increase or decrease in apparent path length, respectively. This is known as the Sagnac Effect. By using a traditional mirror-and-laser interferometer setup and a large turntable, we demonstrate the Sagnac Effect by showing that a given angular velocity results in a phase shift which matches what is predicted.

INTRODUCTION

When first learning about the consequences of relativity, it is useful to understand the experiments which led to its inevitable acceptance. A major cornerstone in this history is the initial hypothesis of a luminous ether with its eventual rejection. While the Michelson-Morley experiment is frequently demonstrated at the undergraduate level, the Sagnac effect also provides powerful evidence for a lack of an ether (even without addressing relativity). This paper intends to demonstrate an undergraduate experiment with a Sagnac interferometer alongside the interpretations which can be drawn from such experimentation.

In the 19th century, Maxwell's formulations of electromagnetic theory alongside Young and Fresnel's revival of Huygens' light wave propagation theory created the working assumption that there must be an ether through which electromagnetic waves propagate.[1] Experiments such as the Michelson-Morley and Sagnac interferometers were developed to measure the speed of the hypothesized ether relative to the Earth. When Michelson and Morley failed to find a nonzero speed measurement for the ether, an alternative hypothesis was proposed that the Earth drags the ether (and so the ether would appear stagnant to the Earth).[2] While Michelson and Morley found unpredicted results, Georges Sagnac successfully demonstrated his predicted "optical rotation effect" and believed it to be a "direct observation of the luminous ether."[3] One of the underlying assumptions to the Sagnac's calculations, however, is that the ether is not dragged along by the interferometer.[3,4] The Sagnac experiment together with the Michelson-Morley experiment poses a contradiction: the ether must not be dragged to produce the positive result in the Sagnac interferometer, but it simultaneously needs to be dragged to produce the null result in the Michelson-Morley interferometer.[5] These experiments alongside several others have failed to provide evidence for an ether; henceforth, the current belief is that light does not require a medium.[2]

Beyond its applicability in refuting the ether, the Sagnac effect is widely used in navigational systems and sensory technologies. Ring laser gyroscopes use a system of mirrors to create a common path for light to travel around (this is closely comparable to the Sagnac interferometer created in this experiment) while fiber optic gyroscopes control the path of light with fiber optic cables.[6] Placing three gyroscopes orthogonal to each other allows for measurements in all three degrees of freedom for a navigation system.[6] The Sagnac effect is also used in fiber optic current sensors. Optic current sensors are not influenced by electromagnetic interference, and so they are advantageous in high power systems.[7] These fiber optic sensors are also sensitive to birefringence effects from temperature and vibrations; current research is investigating how to use this birefringence for sensory applications.[8,9]

In 1921, Paul Langevin provided the first interpretation of the Sagnac effect from general relativity.[10] His derivations[10] for a rotating Sagnac interferometer find the propagation time difference between the counterpropagating waves to be:

$$\Delta t = \frac{4A\omega}{c^2} . \tag{1}$$

The area inside the beam path is given as "A", and the difference of time traveled is "Δt." In the following, let N be the number of fringes that pass by.

$$\Delta\phi = 2\pi\Delta N = 2\pi\left(f * \Delta t\right) = 2\pi * \frac{c}{\lambda} * \frac{4A\omega}{c^2} = \frac{8\pi\omega A}{c\lambda} \tag{2}$$

$$\therefore \Delta\phi = \frac{8\pi\omega A}{c\lambda} \tag{3}$$

The above relationship gives the phase difference as a function of angular velocity.

THE EXPERIMENT

To demonstrate the Sagnac effect, this experiment uses TeachSpin's Sagnac interferometer.[11] The basic layout of the interferometer is shown in Figure 1(a). A polarizing beam-splitter cube (PBSC) separates an incident 45°-linearly polarized beam into two equal-power, orthogonal p-state beams. Each beam traverses the loop in opposing directions and rejoins at the original PBSC. These component beams are split again (not shown in figure) and sent into two separate photodetectors to allow for further analysis. The breadboard the interferometer is built upon has urethane pads at each corner to reduce ambient vibrations and stiffening beams to reduce the possibility of the breadboard deformation, both of which can distort the final images of the beams.

(a)   (b)
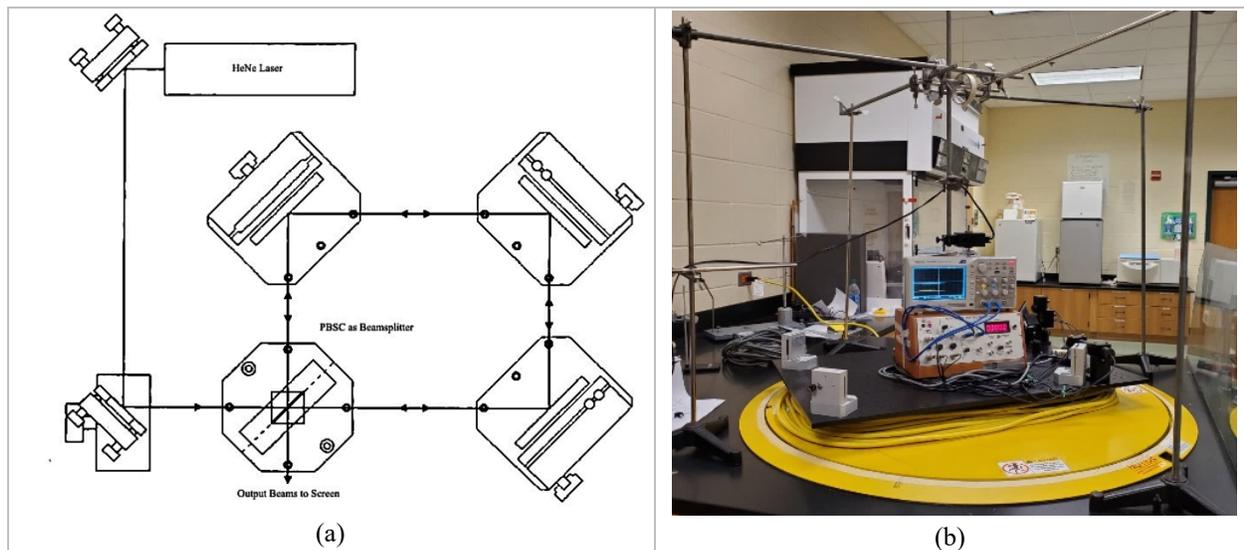
FIGURE 1: (a) Sagnac interferometer design detailed by TeachSpin.[11] (b) Apparatus utilized in experiment.

This interferometer can detect shifts in the thousandths of a fringe according to TeachSpin.[2] Introducing motion such as rotation of the apparatus results in wobbling and stray air currents which cause shifts that exceed this value; around one to two-thousandths of a fringe depending on speed. The Sagnac effect, summarized mathematically in Equation 3, will not exceed this value at lower angular velocities and smaller areas and will be indistinguishable

from it. With a small area of 0.274 m² and a wavelength of 633 nm but a high angular velocity of 2.75 rad/s the calculated shift from the Sagnac effect is one hundredth of a fringe; one magnitude higher than the shifts from other effects and enough to clearly demonstrate the Sagnac effect in action.

The combination of the interferometer's weight, size, and required angular velocity require the use of an industrial turntable. It offers the ability to rotate at high speeds and can support any weight within the scope of this experiment. A Vernier angular velocity detector which is mounted above the center of the turntable and fixed so that the turntable will turn the disk in the detector, providing for reliable measurements of ω. This detector is capable of measurements with a precision of 0.109 rad/s. Two photodetectors measure the relative intensity of the two beams after they undergo the Sagnac effect. The laser's electronics box (supplied by TeachSpin) supplies power to the laser and the photodetectors. An oscilloscope will record the signals from the photodetectors. The final apparatus is shown in Figure 1(b).

The laser is run for thirty minutes before running trials to minimize power fluctuations resulting from increasing temperatures. Each trial runs for twenty seconds. The first five seconds are for measuring the voltages of each photodetector's signal while the interferometer is stationary. The remaining fifteen seconds involve measuring these voltages while the interferometer rotates at various velocities. Each run is then analyzed by the methodology below.

The rotational phase difference is the difference of each photodetector's output voltage while the system rotates. Note that this value changes as rotational velocity changes. The sum of these two voltages is the total output voltage of the original beam. The rotational phase difference divided by the total original output voltage determines the phase shift. These values are then averaged across all trials at each increment of velocity. The results of this are summarized in Table 1 (only a limited range is shown). Figure 2 shows all the velocity data compared to the predicted change.

TABLE 1: Angular Velocity vs Phase Shift (Range 1.4180 rad/s to 2.9450 rad/s).			
Velocity	Measured Change	Theoretical Change	Percent Error
1.4180	0.0538	0.0515	-4.5099
1.5270	0.0569	0.0555	-2.5968
1.6360	0.0616	0.0594	-3.7406
1.7450	0.0586	0.0634	7.4958
1.8540	0.0625	0.0673	7.1763
1.9630	0.0660	0.0713	7.4747
2.0730	0.0698	0.0753	7.2578
2.1820	0.0739	0.0792	6.7110
2.2910	0.0752	0.0832	9.6687
2.4000	0.0838	0.0872	3.8539
2.5090	0.0833	0.0911	8.6061
2.6180	0.0872	0.0951	8.3249
2.7270	0.0899	0.0990	9.2450
2.8360	0.0931	0.1030	9.6303
2.9450	0.0976	0.1069	8.7086
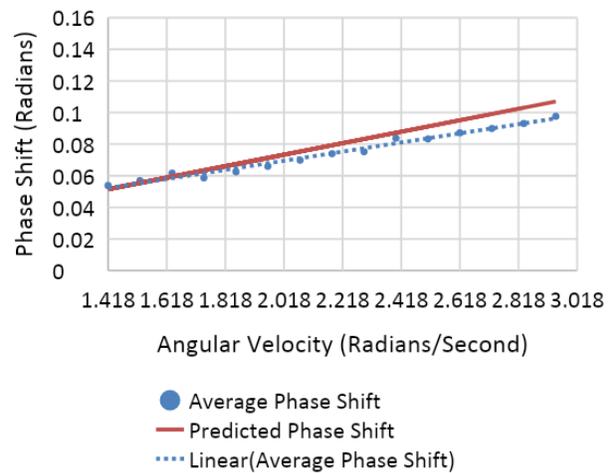
FIGURE 2: Predicted Change vs Measured Change vs Angular Velocity.

This data is correlated with predicted values in ranges 1 rad/s to 3 rad/s due to the relatively low effect of signal disturbance compared to the Sagnac effect. An angular velocity above or below these bounds results in a Sagnac effect that is too low to be meaningfully distinguished from experimental sources of distortion such as vibration or air currents, particularly at higher velocities. Therefore, for regions where the angular velocity is between 1 rad/s and 3 rad/s the correlation with the predicted effect offers strong evidence for the Sagnac effect.

CONCLUSION

A noticeable correlation of the measured phase shift to the Sagnac effect is observed. Individual data points and tests varied from expected values due to experimental errors, but more data points mitigated these deviations. Due to the nature of interferometry, reducing outside and systematic interference is the largest challenge of this experiment;

things as small as vibrations from a refrigerator across the room created noticeable shifts in data. In future experiments of this type, it is recommended to consider alternative setups that would reduce the effect of outside interference as well as mitigate risk to the equipment if higher rotational speeds are desired. Despite these limitations, this experiment adequately shows the lack of an ether through the no-ether Sagnac effect applying to the data. We encourage the use of this experiment in undergraduate laboratories to deepen each student's understanding of the historical breakthrough that shaped how physics is today.

ACKNOWLEDGMENTS

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