Measuring Scattered Light with an Integrating Sphere

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1 Introduction

Stray light is light in an optical system which was not intended in the design. The path of stray light is determined by the series of events that the beam undergoes. This includes transmission, reflection, diffraction, or scatter from a surface.

Stray light may add noise to the measured phase in an optical system if it interferes with the nominal light (light on the expected path). This could happen if the stray light reflects off enough surfaces within the gravitational wave interferometer to recombine with the main laser and the stray light carries additional phase noise from reflecting off vibrating surfaces.

In order to study stray light, or light of any kind, it is important to know how light is characterized.

The polarization of light is important, especially when you are manipulating light that comes from a beam.

Light that propagates as a plane wave is called linearly polarized. If light is propagating in the form of two plane waves differing by a phase of 90 degrees then it is called circularly polarized. Natural light is usually unpolarized.

A Gaussian beam is a beam of EM radiation that has an amplitude in the transverse plane which is given by a Gaussian function. This is useful because the beam can be focused into the most concentrated spot.

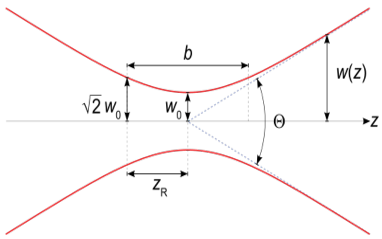
The amplitude profiles for a Gaussian beam, for a given wavelength and polarization, are determined by two parameters called the beam waist size, w_0 and beam waist position, z_0. The beam waist can be altered for a Gaussian beam by using a lens.

$$w(z) = w_0\sqrt{1 + (\frac{z - z_0}{z_R})^2}$$

Where z_R is the Rayleigh range. The Rayleigh range is the distance along the propagation direction of a beam from the waist to the place where the area of the cross section is doubled.

$$z_R = \frac{\pi w_0^2 n}{\lambda}$$

Here n represents the index of refraction and λ represents the wavelength.



Gaussian beam width w(z) as a function of the distance z along the beam.

2 Motivation

In an interferometer, the phase of the photons could be random because the stray light might bounce off other surfaces within the detector that are vibrating. These vibrations are caused by uncontrollable outside factors such as seismic or acoustic vibrations. Since the detection of gravitational waves requires measuring a phase difference corresponding to a magnitude of about 10^{12} photon wavelengths, even a few stray photons with a random phase could greatly impact gravitational wave detection.

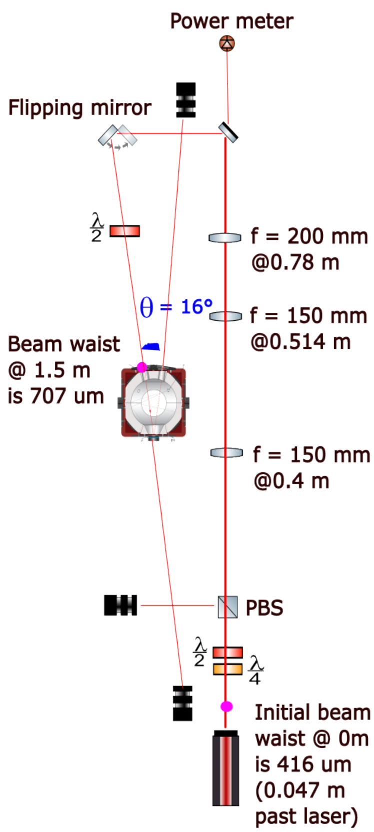
To make more accurate measurements in gravitational wave detectors, we need to understand how stray light is being induced by the optics inside detectors. One way to do this is to characterize the optics being used to estimate the amount of stray light induced. In order to do this characterization it is necessary to measure the Total Integrated Scattering (TIS). TIS is the fraction of incident light that gets scattered by the optics.

3 Methods

An integrating sphere is an optical device consisting of a hollow spherical cavity with its interior covered with a diffuse white reflective coating, with small holes for entrance and exit ports. This layout provides uniform scattering within the sphere. This makes it possible to measure TIS. The integrating sphere can be used to send light to optical components, let the specularly- reflected light leave the sphere, and trap the scattered light within the sphere so that it can reach a detector.

For this configuration, the amount of scattered light is the ratio between the photodiode current with the sample being tested and the photodiode current with a sample that is almost one hundred percent diffusive. The photodiode current is measured by connecting a photodiode amplifier to a photodiode connected to a 5mm port on the integrating sphere.

In order to optimize the use of the integrating sphere to measure scatter, it is important to control the conditions of the beam going into the integrating sphere. This is done by creating an optical line that will manipulate the beam to the desired conditions.



The optical line used in experiment.The laser being used has a power of 1 Watt. The black boxes correspond to beam dumps.

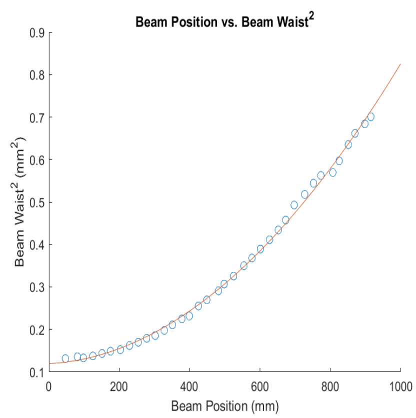
In order to find the beam waist of the laser, it was necessary to perform a beam scan with a beam profiler.

A beam profiler is a diagnostic device which measures the optical intensity profile of a laser beam coupled with an analysis software that can extract relevant parameters (radius, shape, etc.) Because this laser is 1064 nm, a beam profiler based off a CMOS camera was able to be used.

First, the laser was aligned in a straight line. Then the beam profiler was set in front of the beam at 25 mm increments. At each of these positions, the beam waist was measured and recorded.

The collected data was then analyzed using Matlab. The square of the beam width equation for a Gaussian beam was compared to position of the beam scan. Then using a quadratic fit, it was possible to find the beam waist size and position. The beam waist is $416\mu m$ at a position of $47mm$ from the laser exit pupil.

$$w^2(z) = w_0^2(1 + (\frac{z - z_0}{z_R})^2)$$



$w(z)^2 vs. z$

Using the beam waist and beam position of the laser, it was possible to design a telescope and optical line for the integrating sphere.

First, a quarter wave plate is set right outside the aperture of an infrared 1064 nm laser in order to ensure that the light is linearly polarized. Next a half wave plate is placed right before a polarizing beam splitter (PBS). Together, by manipulating the orientation of the half wave plate it is possible to change the amount of power leaving the PBS as the half wave plate shifts the polarization direction of the light and therefore shifts how much light is being reflected out of the optical line due to the PBS.

The next part of the optical line is the telescope. A telescope is a combination of lenses that bends light in order to change the waist size of the beam to be larger than it was originally. The desire of this telescope was to create a system where only one lens could be shifted in order to manipulate the beam waist from a pretty small size (about $200\mu m$) to a fairly large size (about $800\mu m$). It was important that this shift in the size of the beam stayed consistent at the locations of both entrance and exit ports of the sphere in order to keep the experiment's data consistent. The full telescope includes two lenses with a focal length of 150mm and one lens that has a focal length of 200mm.

While setting up the telescope, a beam scan is performed after each lens in order to make sure the lenses are placed correctly.

After the telescope there are two steering mirrors. These steering mirrors are placed so that the beam can enter the integrating sphere at an angle of eight degrees. The eight degree geometry was designed by the manufacturer of the integrating sphere (Thorlabs) in order for the light to bounce off of optics attached to a port on the sphere and then be reflected out again at an angle of eight degrees.

Lastly, before the beam enters the integrating sphere, it will go through one more half-wave plate. This half-wave plate allows the user to manipulate the polarization of the beam. In order for the second half-wave plate to not change the polarization set by the first half-wave plate, it must have an orientation of 25 degrees.

After everything is set up, the beam has to be aligned to have an 8 degree geometry. This means that the light entering the sphere will hit the optic (or the $4P11$ transmission port) right in the center at an angle of 8 degrees in order so that the light being reflected leaves the sphere at 8 degrees as well. This alignment is done by hand.

4 Results and Conclusions

Once the optical line was built, it was necessary to calibrate the sphere.

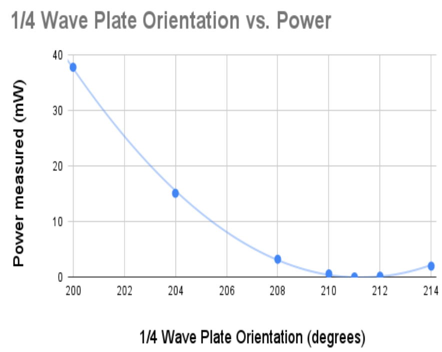
The laser has 1 W of power. Due to this, it was important to find a way to measure the power going into the sphere in a way that would not damage the sensor of a power meter. Because real mirrors are not perfect, there is a tiny bit of light that gets transmitted through them. A power meter was placed behind the first steering mirror. A series of measurements were made of the power at different points in the optical line in order to find the ratio of light measured behind the first mirror so that the real power going through the sphere could be calculated correctly in future use.

Position	Before First Mirror	Behind First Mirror	Before Sphere Entrance
Power (mW)	156	0.389	143

From this data it was discovered that the ratio between the amount of power measured behind the first mirror and the power actually entering the integrating sphere is 0.0027. Therefore this ratio can be used for calculating actual power entering the sphere for large power levels when the power meter is placed behind the first mirror.

Additionally this data tells us that 0.92 of the power leaving the laser is entering the sphere. This number makes sense as power gets lost when it is hits the mirrors as some light gets transmitted and some light gets reflected back to create a second tiny beam. In order to deal with the problem of the second tiny beam, an adjustable iris was placed right before the integrating sphere entrance in order to block it's path. These measurements were made after the iris was placed.

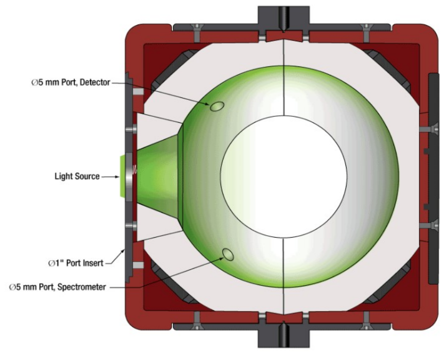
Next, the quarter-wave plate orientation versus the power going in to the sphere was measured in order to find the orientation that allowed the least amount of circularly-polarized light. The orientation that allowed the least amount of circularly-polarized light is the one that correlates to the smallest power. This is because linearly polarized light is confined to a single plane and more light will be interacting (and therefore reflected out) of the PBS. By measuring the power while the quarter-wave plate was in different orientations, it was found that the desired orientation of the quarter-wave plate is 211°.



The Quarter-Wave Plate Orientation vs. Power

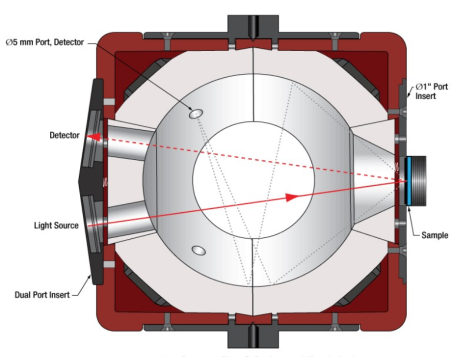
The integrating sphere is a Modular Port 4P4 Integrating Sphere designed by Thorlabs. This integrating sphere was designed to have different port inserts that could be used for different experimental purposes. The two ports that we are most interested in studying are the 4P10 and 4P11 ports.

The 4P10 port insert is designed to complete the the full circle inside the integrating sphere in order to produce uniform scattering for an light that enters the sphere.



The 4P10 Port insert attached to the Integrating Sphere.

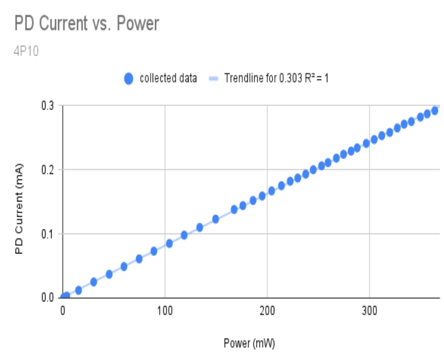
The 4P11 port insert was designed so that optics could be attached to it's transmission port. This makes it possible to characterize how light, specifically scattered light is produced by these optics. Set up correctly, light from the beam will enter the sphere, hit the optic at an angle of 8 degrees which will make the reflected light bounce off the optic at another 8 degrees. A photodiode can be connected to the 5 mm port at the top of the sphere in order to measure scattered light.



The 4P11 Port insert attached to the Integrating Sphere.

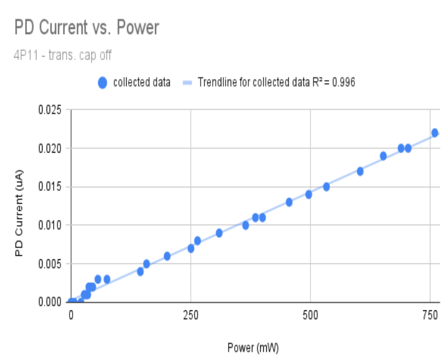
In order to calibrate the sphere it was important to understand how much scattered light the photo-diode attached to a 5 mm port on the sphere measured as power changed. These calculations were done for three different integrating sphere configurations.

The first configuration is the 4P10 port insert on the integrating sphere.



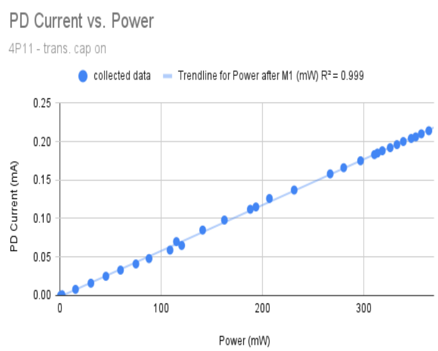
PD Current represents scattered light measured by the photo-diode.

The second configuration is the 4P11 port insert with the transmission cap off.



PD Current represents scattered light measured by the photo-diode.

The last configuration is the 4P11 port insert with the transmission cap on.

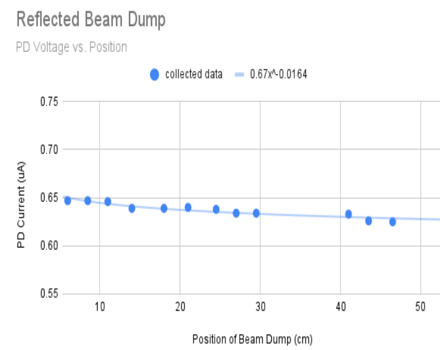


PD Current represents scattered light measured by the photo-diode.

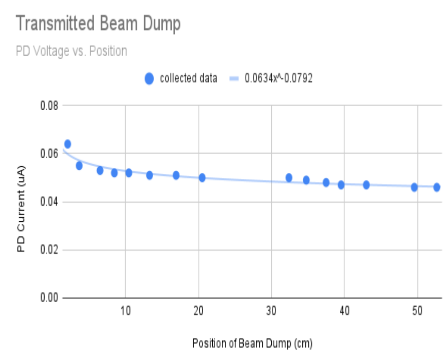
For all of these measurements, the relationship between the amount of current measured by the photo-diode and power is linear. This is what was expected.

The last measurements that were taken were to analyze how much the beam dumps back scattered into the integrating sphere. These measurements were also done with beam traps in order to see the difference between beam dumps and beam traps on back-scattering into the sphere.

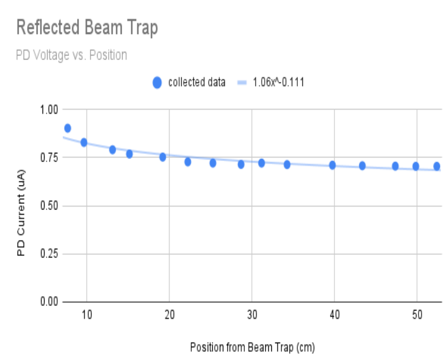
The best way to do this was to measure the amount of scattered light measured by the photo-diode while the beam dump or beam trap was place at different positions. These measurements were done for both the reflected and transmitted beams exiting the integrating sphere.



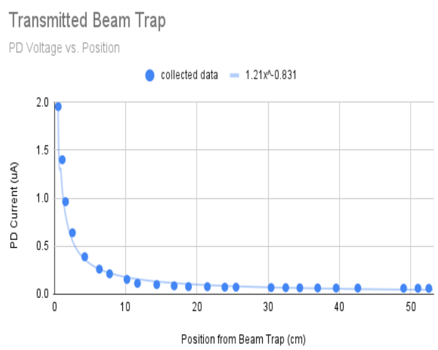
PD current vs. Power for Reflected Beam Dump



PD Current vs. Power for Transmitted Beam Dump



PD Current vs. Power for Reflected Beam Trap



PD Current vs. Power for Transmitted Beam Trap

For all of these measurements it was expected to see a trend of inverse-square with distance. None of these plots ended up having and inverse-square relationship with distance, but they each clearly have an inverse relationship with distance still at different exponential levels.

5 Future Work

The set-up for the integrating sphere will be used to measure scattering from different optical devices used in gravitational wave detectors.

These measurements will also be compared to the same measurements made with a similar system called a scatterometer.

Additionally, the system may be used to measure scattering from samples in dust monitoring.

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7 References

D'Angelo, B. 2022. 'Numerical Simulations of Stray Light in Virgo'. PhD. Universit'a degli Studi di Genova. Padova.

Pizella, A. 2018. 'A Homodyne Quadrature Interferometer for the study of Thermal Noise in Non-Equilibrium Steady States'. Masters. Universit'a degli Studi di Genova. Padova.