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Low Loss Faraday Isolator Preliminary Design Considerations

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1 Overview

The purpose of this document is to outline preliminary design considerations for the planned Low Loss Output Faraday Isolator (LLFI) necessary for squeezing injection in a squeezed enhanced aLIGO or future generation detectors. The document focuses on the working design at the University of Florida, which is based on the Input Faraday Isolator (IFI). An increase in optical throughput is acheived primarily through the reduction of reflective surfaces and improved antireflective coatings.

2 Introduction

Over much of the aLIGO measurement band we expect to be limited by quantum noise. With the implementation of frequency-dependent squeezing, we aim to simultaneously reduce low frequency radiation pressure noise and high frequency shot noise. The detectable level of squeezing, and hence the increase in detector sensitivity, is dependent upon the optical loss along the squeezed path.

The preliminary optical layout for squeezing injection, seen in Figure 1, requires three passes through a Faraday isolator after the filter cavity. To acheive the long term goal of 10 dB measured quantum noise supression this configuration requires $< 1\%$ loss per pass [1]. Presently, both input and output Faraday isolators installed have $2 - 3\%$ single pass optical loss (generally greater in situ), and so it is necessary to design a new isolator that can meet the throughput requirements for frequency dependent squeezing.

The working design at the University of Florida for the new LLFI is based on the current aLIGO IFI design, allowing us to draw from years of experience with the setup. Specifically, our approach is to identify sources of loss in the current IFI and modify the design to bring the total loss below the 1% threshold.

3 Prelimimary Florida Design

3.1 aLIGO Input Faraday Isolator

A cartoon of the current IFI design is given in Figure 2. The isolator consists of seven optical components: two calcite wedges, a half-wave plate, two terbium galium garnet (TGG) crystals, a quartz rotator, and a deuterated potassium phosphate (DKDP) crystal. The calcite wedges serve as polarizers, the quartz rotator is used to compensate for thermally induced birefringence in the TGG, and the DKDP acts as a negative lens to compensate for thermal lensing of the TGG.

In air, the optical throughput of this construction has been measured to be anywhere from 96% to 98%, which meets the $> 95\%$ requirement for the IFI but falls short of our goal of 99% throughput.

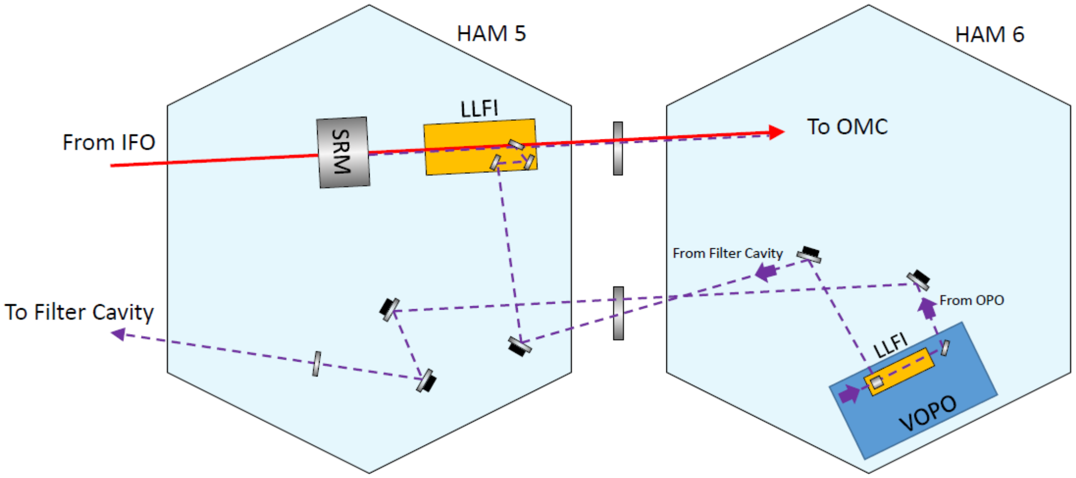

Figure 1: A bare-bones diagram of the tentative layout for squeezing injection. The squeezing optical path, shown in purple, requires three passes through a Farady isolator after the filter cavity.

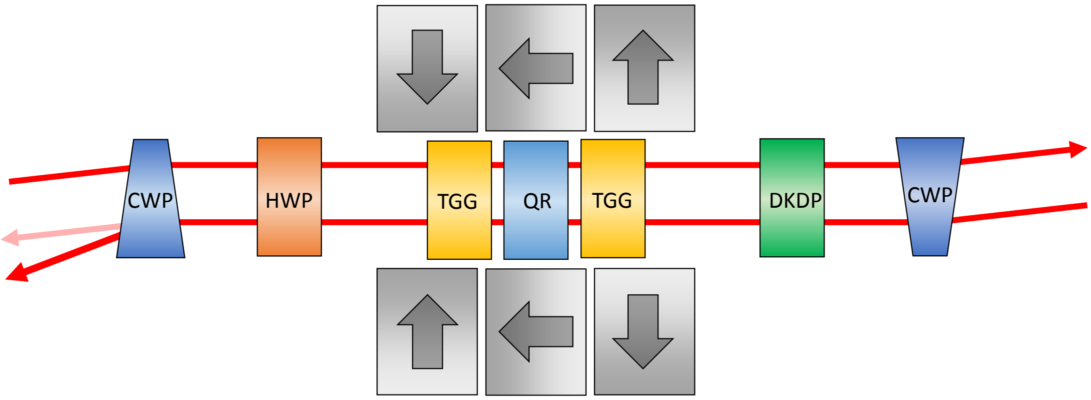

Figure 2: A conceptual drawing of the current aLIGO Input Faraday Isolator. The quartz rotator (QR) placed between the two TGG crystals compensates for the thermally induced birefringence in TGG. The DKDP is a negative lens material used to compensate for thermal lensing of the TGG.

3.2 Optical Element Redesign

We expect as much as half of the optical loss in the IFI to be from reflections on optical surfaces, and so reducing the number of elements in the Faraday path is critical to reaching our throughput goal. Because the optical power in the Signal Recyling Cavity and VOPO output path is low, we can eliminate the thermal compensation components in the IFI design. By excluding the quartz rotator, the negative lens DKDP, and making the TGG monolithic we reduce the number of reflective surfaces from fourteen to eight.

We are left with the four essential components of a Faraday isolator. The HWP is an off-the-shelf item that is not expected to be a significant source of optical loss. Similarly, TGG is currently the optimal magneto-optic material for the Faraday as it has relatively low absorption and a large Verdet constant. The calcite wedges, however, are off-the-shelf items which are not superpolished and have relatively high design reflectivities (guarantee of less than 2500 ppm per surface). Tentatively, the UF LLFI replaces the calcite polarizer wedges with potassium titanyl phosphate (KTP) wedges.

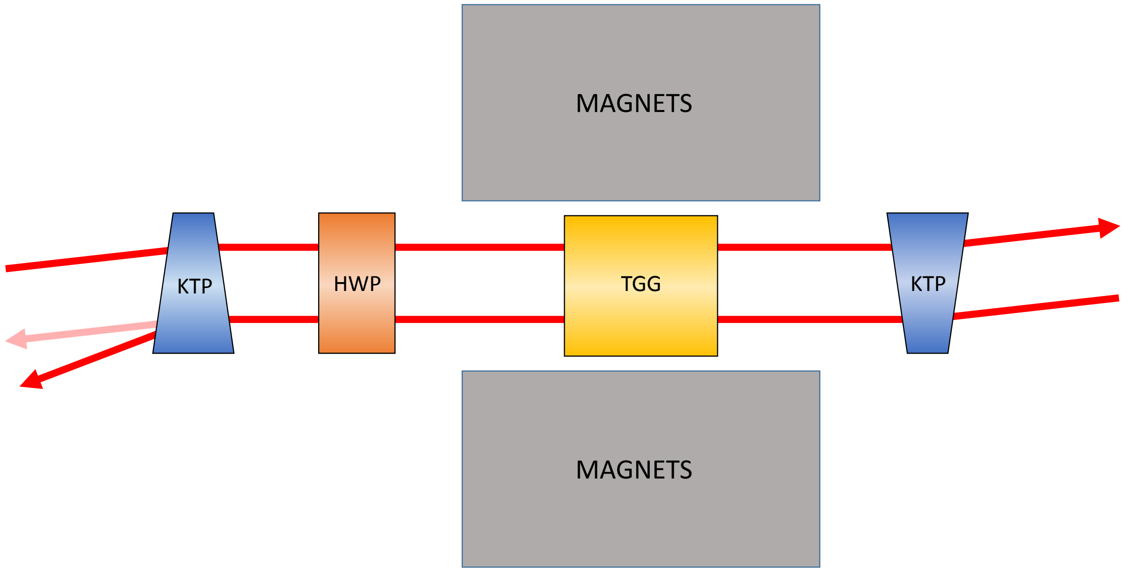

Figure 3: A conceptual drawing of the LLFI optical layout. The quartz rotator and DKDP form the current IFI have been removed, the TGG crystal is now monolithic, and the calcite wedge polarizers have been replaced with KTP wedge polarizers.

3.3 Magnet Redesign

In the current aLIGO IFI construction the positions of the TGG crystals within the magnet housing are manually adjusted to acheive the desired polarization rotation. While relatively simple, this process can prove to be very tedious and difficult to reproduce. Further, it is not clear whether positioning changes of the TGG during pumpdown contribute to an observed reduction in the isolation ratio.

The UF LLFI uses a fixed TGG crystal within a magnet housing. Large permanent magnets are used to approximate the field necessary for 45° rotation within the TGG, while smaller solenoid magnets are used for fine tuning of the field. This design is less susceptible to pumpdown misalignment, and allows for in vacuum adjustment of the Faraday rotation.

Two possible magnet configurations are presently under consideration, both of which are shown in Figure 4. The first is the solenoid sleeve design in which a single cynlindrical coil surrounds the stronger permanent magnets. The second is the solenoid pancake design in which two solenoid disks are spaced between permanent magnet disks. Because the sleeve design allows for tighter packing of the permanent magnets, it permits stronger magnetic fields and is more compact in the optical path dimension. However the pancake design allows for greater field tuning range for a given solenoid power.

Of significant concern is the heat dumped by the solenoid into the TGG. Initial investigations suggest that in order to obtain a tuning range of ±0.5° we require ~ 5 W for a sleeve and ~ 1.5 W for a pancake solenoids. More work must be done investigating heat sink geometries in order to prevent significant thermal loading of the TGG.

Ultimately, both designs must be experimentally tested to ensure agreement with modeling of both the fields and heat transfer.

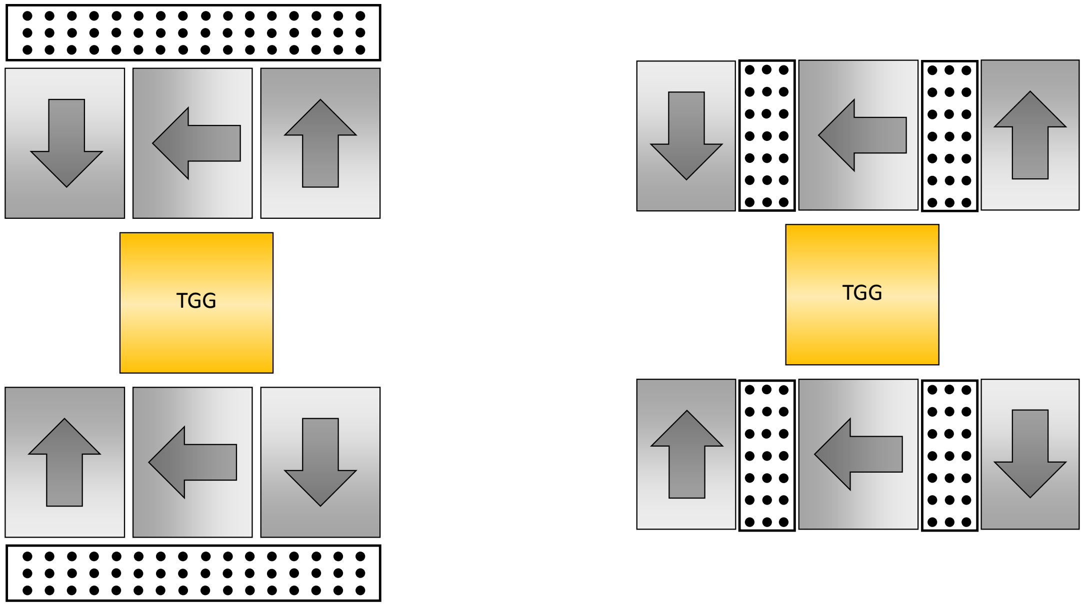

Figure 4: Two competing magnet configurations for the LLFI. On the left is the solenoid sleeve design, which has a large coil encasing strong permanent magnets. On the right is the solenoid pancake design, which has smaller solenoid disks spaced between strong permanent magnets.

3.4 Loss Budget

3.4.1 Loss to Optical Elements

We anticipate the greatest source of loss in the Faraday to be reflection at the surface of and absorption within the bulk of the optics themselves. For this reason, both the KTP wedges and TGG crystals will be superpolished by Photon LaserOptik and AR coated by ATFilms. The coatings are deposited with an ion-beam sputtering technique (IBS), which provides for the best absorption, surface roughness, and reproducibility of the conventional coating methods. The design goal is 200 ppm reflectivity per surface, with < 500 ppm guaranteed. Table 1 gives a conservative estimate of losses due to each optical component.

Isolator element	*Optical loss (ppm)*
KTP reflection (per face/total)	500/2000
KTP absorption (per crystal/total)	25/50
HWP reflection (per face/total)	300/600
HWP absorption	50
TGG reflection (per face/total)	500/1000
TGG absorption (20 mm crystal)	3000

Table 1: Approximate optical loss of each component in the current UF LLFI design. Altogether, these specifications lead to roughly 0.6% single pass loss.

3.4.2 Misalignment Losses

Beyond loss to reflections, absorption, and scattering, a misalignment of the optics (the wedge polarizers with respect to one another, for example) will manifest as a reduced power throughput. In general, the precision of optical alignment is dependent upon our ability to measure the power in alignment beams.

Suppose we are working with a 200 mW input alignment beam. For alignment of the polarizers and the HWP, we need to minimize the power in the rejected polarization; that is, we must attempt measure 0 mW. For the TGG adjustment, we need to evenly split the power in both polarizations and so we must attempt to measure 100 mW. Assume a 3% uncertainty in power measurement and a power floor of 100 μW (not uncommon for off-the-shelf power meters), and let us make a naive and pessimistic estimation of our resulting losses. For our 0 mW measurements, we are insensitive to losses below:

$$\frac{100\ \mu\text{W}}{200\ \text{mW} \pm 3\%} \approx 5 \times 10^{-4}$$

which corresponds to a maximum misalignment of 1.3° in the polarizers and 0.7° in the HWP. For our 100 mW measurements, supposing we measure both beams simultaneously, we are unable to guarantee that the two beams within less than ~ 2 mW of one another.

This corresponds to a maximum misrotation of 0.6° in the TGG. With these bounds, we find that we can pessimistically expect $\sim 0.4\%$ loss from optical misalignments. Note that we did not consider misalignment of the beam through the optics at all.

3.4.3 Inhomogeneity Losses

An inhomogeniety in the magnetic field over the profile of the beam (as seen in Figure 5 within the TGG results in inhomogeneous polarization rotation, and will thus result in a loss in optical throughput.

We can approximate this loss by calculating the induced rotation as a function of the radius, r, about the central axis and then projecting the resultant field onto the plane of desired rotation. From that, we can compare the integral of the resultant field amplitude squared to that of the incoming beam.

For the particular magnet configuration with field distribution given in Figure 5 we can expect a power loss of 1.5 ppm for a beam with $w_0 = 2$ mm and 0.6 ppm for a beam with $w_0 = 1$ mm. We conclude that inhomogeneous rotation should never be a limiting loss mechanism in the LLFI.

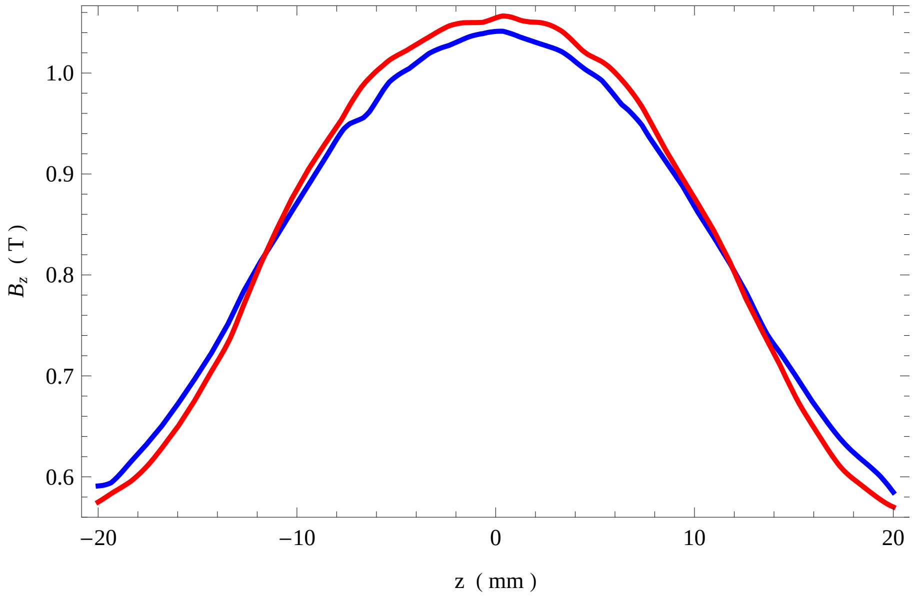

Figure 5: The axial field magnitude within the magnet housing as a function of distance along the optical axis for a potential magnet configuration. The blue curve corresponds to $r = 0$ mm and the red curve to $r = 5$ mm. Though the fields are visibly different at this scale, the consequent power loss to inhomogeneous polarization rotation is negligible.

3.4.4 Uninvestigated Losses

There are some sources of loss, or effective sources of loss, that have yet to be researched. Without adequate investigation, it is difficult to determine what is likely to limit the LLFI performance, though such a list might include:

- birefringence induced ellipticity of TGG output
- second harmonic generation in KTP wedges
- astigmatism of LLFI output
- heating/cooling of the TGG
- etalon effects within LLFI optical components
- misalignments from desired optical axis

All of these are worthy of further study, especially in the event that the LLFI design does not meet specifications.

4 Additional and Alternative Improvements

4.1 Prism Polarizers

Because the polarizers comprise half the potential reflective surfaces in the LLFI, a reduced loss in the polarizers could significantly improve total loss in the Faraday. A different polarizer design based on Brewster's angle manufactured by LEYSOP has been investigated by Skeldon et. al. at the University of Glasgow [2]. The single pass loss of each polarizer was measured to be around 250 ppm, a significant improvement over the expected KTP polarizer performance. Additionally, the prism design of the LEYSOP polarizers creates greater spatial separation of the s and p polarizations which allows us to make the LLFI more compact.

Further tests of these polarizers (not at Florida) are ongoing or in the works.

4.2 Stronger Fields

Regardless of improvements to antireflective coatings or polarizer topologies, absorption loss in the bulk of the TGG crystal is the single greatest contributor to optical loss in the Faraday isolator. In the current aLIGO IFI this corresponds to approximately 3000 ppm loss to absorption. Short of discovering a better magneto-optic material, the only way to mitigate this loss is to reduce crystal length. To do so while maintaining 45 degrees of rotation at 1064 nm we can:

1. reduce the temperature of the TGG crystal to increase the Verdet constant
2. increase the static magnetic field within the TGG crystal

The second option is far simpler to implement, as it requires only a limited redesign of the magnet configuration and housing. With magnets currently available from K&J Magnetics, field models predict that we could (in principle) reduce the TGG crystal length from 20 mm to 10.5 mm. Further reduction is likely not possible with available magnetic materials without significant redesign of the Faraday.

4.3 Loss Budget

By replacing the wedge polarizers with prism polarizers, and reducing the TGG crystal length to 12 mm, we see in Table 2 that we may hope to reduce the single pass loss from optical elements from 0.6% to 0.4%.

Isolator element	*Optical loss (ppm)*
Prism polarizer (per element/total)	250/500
HWP reflection (per face/total)	300/600
HWP absorption	50
TGG reflection (per face/total)	500/1000
TGG absorption (12 mm crystal)	1800

Table 2: Approximate optical loss of each component in an improved low loss Output Faraday Isolator design. Altogether, these specifications lead to roughly 0.4% single pass loss.

References

[1] LSC Instrument Science White Paper for 2014-2015, `T1400316`

[2] K. D. Skeldon et. al., "Measurements of an ultra-low loss polarizer for $\lambda = 1064$ nm using a high finesse optical cavity", Journal of Modern Optics, Vol. 48, No. 4, 2001

Component	**Manufacture**	**Polishing**	**Coating**	**AR**	**Absorption**	**Status**
KTP wedge	Raicol	Photon LaserOptik	ATFilms	< 500 ppm	< 50 ppm cm^{-1}	ordered
HWP	CVI Laser Optics	N/A	N/A	~ 300 ppm	~ 30 ppm cm^{-1}	not ordered
TGG	Northrup Grumman	Photon LaserOptik	ATFilms	< 500 ppm	1500 ppm cm^{-1}	ordered
Prism polarizer	LEYSOP	N/A	N/A	250 ppm total loss		not ordered