LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Faraday Isolator Specifications for Advanced LIGO

UF Group

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Abstract

This technical note is defines the operational requirements (physical dimensions, mechanical, optical, and vacuum compatibility) for the Advanced LIGO Input Optics Faraday Isolators. These requirements should also meet the anticipated power upgrade for initial LIGO planned to occur in the next few years.

1 Introduction

1.1 Purpose

This document lists the performance requirements for the Advanced LIGO Input Optics Faraday isolators, including physical dimensions, mechanical, optical, and vacuum compatibility requirements.

1.2 Scope

The document pertains specifically to the in-vacuum Faraday isolators in the Advanced LIGO Input Optics. In the optical layout of the IO subsystem, the FI is located after the mode cleaner and before the mode matching telescope.

The requirements for performance (power throughput, optical isolation, and laser mode quality) are sufficiently stringent that the requirements set forth here may be applicable to FIs located in other Advanced LIGO subsystems.

1.3 Definitions

1.4 Acronyms

FR – Faraday rotator

FI – Faraday isolator

IO –Input Optics

ISC – Interferometer Sensing and Control

MC- Mode cleaner

PD - photodiode

PSL – Pre-stabilized laser

TFP – Thin film polarizer

1.5 Applicable Documents

1.5.1 LIGO Documents

[1] LIGO-T020020-00-D, “Input Optics Subsystem Design Requirements Document”, G. Mueller, R. Amin, M. Rakhmanov, D. Reitze, D.B. Tanner, S. Wise

[2] LIGO-T020027-00-D, ““Input Optics Subsystem Conceptual Design Document”, G. Mueller, R. Amin, M. Rakhmanov, D. Reitze, D.B. Tanner, S. Wise

1.5.2 Non-LIGO Documents

[1] E. Khazanov, N. Andreev, A. Babin, A. Kiselev, O. Palashov, and D. H. Reitze, “Suppression of Self-Induced Depolarization of High-Power Laser Radiation in Glass-Based Faraday Isolators, J. Opt. Soc. Am B. **17**, 99-102 (2000).

[2] G. Mueller, R. Amin, D. Guagliardo, Donavan McFeron, R. Lundock, D. H. Reitze, and D. B. Tanner, “ Method for Compensation of Thermally-Induced Modal Distortions in the Input Optics Components of Gravitational Wave Interferometers”, Class. Quantum Grav. **19** 1793–1801 (2002).

[3] E. Khazanov, N. Andreev, A. Mal’shakov, O. Palashov, A. Poteomkin, A. M. Sergeev, A. Shaykin, V. Zelenogorsky, Igor Ivanov, Rupal Amin, Guido Mueller, D. B. Tanner, and D. H. Reitze, “Compensation of thermally induced modal distortions in Faraday isolators”, IEEE J. Quant. Electron. **40**, 1500-1510 (2004).

[4] Justin D. Mansell, Joseph Hennawi, Eric Gustafson, Martin Fejer, Robert L. Byer, David Clubley, S. Yoshida, and D. H. Reitze, “Evaluating the effect of transmissive optic thermal lensing on laser beam quality using a shack-hartmann wavefront sensor”, Appl. Opt. **40**, 366-374 (2001).

2 General FI description

The IO in-vacuum Faraday isolator provides optical isolation from laser light propagating back from the interferometer to the PSL. It also diverts the non-resonant light reflected back from the PRM to provide diagnostic signals for length and alignment sensing to ISC PDs located on tables outside the vacuum system.

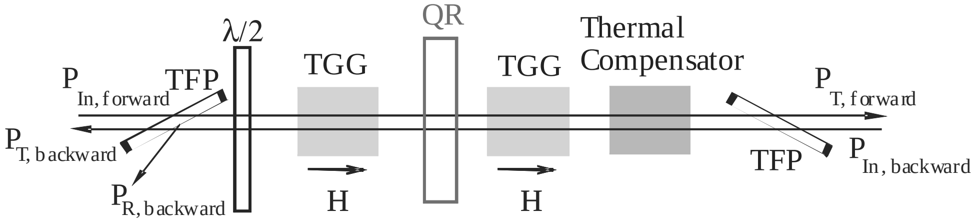
In order to perform these functions at the level specified by the Input Optics Design Requirements Document, LIGO-T020020-00-D, the FI must be designed to handle as much as 300 W average power over sustained periods and lock loss transients as much as twice that amount. The absorption of laser light in the FI components leads to thermal lensing [Mueller], thermal beam steering, and thermally induced birefringence [Khazanov,1] all of which compromise the performance of the FI.

To meet the requirements, a high power FI has been developed which compensates for both thermal birefringence and thermal lensing. [Khazanov,2] This design uses compensating elements (two TGG crystals for compensating birefringence and a -dn/dT material for compensation thermal lensing) and provides up to 45 dB optical power isolation at 100 W powers.

2.1 Faraday Isolator Design

The schematic design of the Faraday isolator consists of two TGG magneto-optic crystals, a 62.5 degree quartz rotator QR (comprising the Faraday rotator), a thermal lensing compensation element, a λ/2 waveplate, and two thin film polarizers TFP. This design is based on extensive studies of thermo-optical effects in FIs and is presented in much greater detail in Khazanov, et al., IEEE JQE **40**, 1500-1510 (2004).

Figure 1 Architecture of the FI



3 Requirements

3.1 Introduction

The following sections list the requirements on the FI in tabular form.

3.2 Requirements on Physical Dimensions, Material Composition, Mechanical Design

The following table lists the requirements on the physical and mechanical dimensions of the FI for Advanced LIGO.

Table 1 – Physical, Mechanical, Material Requirements for the Advanced LIGO FI

Specification	*Requirement*	*Comment*
Material Composition	**All materials must meet Advanced LIGO vacuum compatibility requirements**	**See LIGO-E960050-B-E "LIGO Vacuum Compatible Materials List", D. Coyne**
Centerline beam height	**8.465 inches (215.0 mm)**	**From AdvLIGO IO layout; See Note 1**
Physical Dimension	**Approximately 24.3" long, 5.0" wide, 10.6" tall**	**Does not include diagnostic mirrors; See Note 1**
Optical Clear Aperture	**20 mm or greater**	

Note 1 – These dimensions are only for the Advanced LIGO FI; for the initial LIGO upgrade, the dimensions and centerline height are different.

3.3 Requirements on Optical Performance

The following table lists the requirements for the optical performance of the FI. **These requirements must be met for the entire range of power levels experienced by the FI: 0 – 160 W.**

Table 2 – Optical Performance Specifications for the IO Faraday Isolator

Specification	***Required Performance***	***Comment***
Power Range	**0 – 180 W**	**Range of possible Advanced LIGO powers**
Forward Going Power Throughput	**> 96%**	**Defined as $P_{T, forward}$/ $P_{in, forward}$**
Backward Going Power Throughput	**> 80%**	**Defined as $P_{R, backward}$/ $P_{in, backward}$**
Forward Going Input Polarization	**'P'**	**Polarization from the MC (after 90 deg rotation)**
Forward Going Output Polarization	**'P'**	**Polarization at the PRM**
Optical Isolation	**> 38 dB (power)**	**Defined as 10 log ($P_{in, backward}/P_{T, backward}$)**
Forward Going Output Mode Quality	**> 95% TEM00 remaining in the input mode basis; no more than 1% in non-spherical aberrations**	**See Note 1 below**
Backward Going Output Mode Quality	**> 95% TEM00 remaining in the input mode basis; no more than 1% in non-spherical aberrations**	**See Note 1 below**
Thermal Beam Steering, Forward and Backward Propagating Beams	**< 100 μrads**	**based on dynamic range of RBS system at LLO**

Note 1: In general, the amplitude coupling in the x dimension, $c_x(\psi_{aberrated}, \psi_m)$, of an aberrated beam with an electric field $\psi_{aberrated}(x)$ to a one-dimensional Hermite-Gaussian mode, $\psi_m(x)$, is determined by the overlap integral,

$$c_x(\psi_{aberrated},\psi_m) = \int_{-\infty}^{+\infty} \psi_m(x) \cdot \psi_{aberrated}^{*}(x)dx \qquad \textbf{(1)}$$

The same relationship holds for the y dimension. The two-dimensional amplitude coupling coefficient between electric fields is then the product of the two orthogonal one-dimensional coupling coefficients, or $c_x(\psi_{aberrated},\psi_m)\ c_y(\psi_{aberrated},\psi_n)$. The power coupled from an incoming beam to an outgoing TEM_{00} mode beam, κ; is the product of the two-dimensional electric field coupling coefficient to the TEM_{00} Hermite-Gaussian mode and its complex conjugate, or,

$$\kappa = \left[c_x(\psi_{aberrated},\psi_0)\cdot c_x^{*}(\psi_{aberrated},\psi_0)\right]\cdot\left[c_y(\psi_{aberrated},\psi_0)\cdot c_y^{*}(\psi_{aberrated},\psi_0)\right] = \kappa_x \cdot \kappa_y \qquad \textbf{(2)}$$

For the Advanced LIGO FI, we require $\kappa > 0.95$. See Mansell, et al. for details.

3.4 Requirements on Magnetic Field Noise Couplings

The Faraday isolator contains strong permanent magnets in a quadrupole configuration. The magnetic fields from the isolator will create forces which will push or pull on the mirrors. Changes in the distances between the isolator and the mirrors will cause fluctuations in the forces and might reduce the stability of nearby optical components.

We require that the dynamic coupling of the magnetic field to the mode cleaner suspended mirrors be less than 10% of the required frequency stability of the MC. In addition, we require that the magnetic field not compromise the in-band jitter suppression of the MC.

Complete analysis of the noise couplings can be found in “Analysis of Stray Magnetic Fields from the Advanced LIGO Faraday Isolator”, T060025-00-D, G. Mueller, et al.