

Advanced LIGO Input Optics

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Critical to the performance of the Advanced LIGO detectors is the Input Optic subsystem, charged with delivering a stable and well-shaped beam across the whole range of possible operating input powers, up to 180 W. This manuscript describes its the overall function and layout, and provides some details on the design and performance of its main components.

1 Introduction

Both Advanced LIGO gravitational wave detectors¹ have now completed the installation phase and reached the milestone of a 2-hour full lock. Commissioning activity is in full swing with the Livingston observatory (LLO) operating routinely at a range of 60+ Mpc, the Hanford observatory (LHO) catching up quickly and the first joint Observation Run planned for the fall of this year². Critical to this success has been the performance of the Input Optics (IO) subsystem, designed and built by the LIGO group at University of Florida. The IO fulfills many different functions, among which are DC power control, injection of side-bands used to control the various degrees of freedom of the interferometer, spatial filtering, frequency stabilization and mode matching of the main laser beam, and separation of the back-reflected light from the main path. Stringent requirements have to be maintained for each of these tasks over the whole range of possible input operating powers, up to 180 W.

The next section briefly describes the IO chain as seen by the laser beam that propagates from the Pre-Stabilized Laser (PSL) to the Power Recycling Cavity, while the following one provides more details on the main components of the IO subsystem, their requirements and performance.

2 Input Optics Overview

Figure 1 shows a schematic representation of the IO chain, largely based on the Enhanced LIGO design³ and upgraded to operate at even higher powers with more stringent requirements. It is located between the PSL subsystem and the Power Recycling Cavity. Most of the main components are distributed among the in-air table shared with the PSL subsystem and two in-vacuum seismically isolated tables; some diagnostics and control components are located on two dedicated in-air IO tables (named IOT2L and IOT2R).

The beam handed off by the PSL to the IO is fed into a manual power control stage and a custom built Electro-Optical Modulator (EOM), which adds phase-modulation sidebands at 9, 24 and 45 MHz. After the EOM, the beam goes through a motorized power control stage (intended for DC power control) and up a periscope that injects it into the vacuum system. Several low power beams are picked-off along the PSL table for diagnostic purposes. Upon

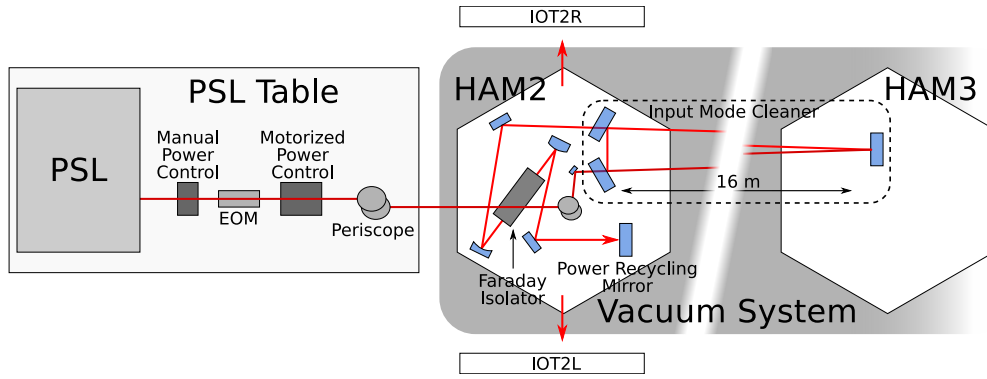


Figure 1 – A schematic layout of the Input Optic chain.

reaching the seismically isolated table inside the HAM2 (Horizontal Access Module 2) chamber, where most of the main IO components are located, the beam is brought down to table height by a periscope; two steering mirrors inject it into the 33 m round-trip length triangular Input Mode Cleaner (IMC) cavity. The beam reflected by the IMC is routed to an out-of-vacuum table where it is used for length and alignment sensing and control of the IMC. The beam transmitted through the IMC is reflected by a steering mirror, then by a mode matching optic, through the Faraday Isolator, onto another mode matching optic, and finally by the last steering mirror that injects it into the Power Recycling Cavity. Forward and backward propagating pick-off beams in transmission of the two steering mirrors are used for active power stabilization of the PSL or routed out-of-vacuum for diagnostic purposes. These four optics are suspended by the HAM Auxiliary Suspensions, single stage suspensions with vertical isolation, actuation capability and active and passive damping. The Faraday Isolator (FI) separates the beam back-reflected by the Power Recycling Mirror Cavity from the main beam path, preventing it from reaching the main laser and making it available for control and diagnostic purposes; the FI is located in vacuum so as to prevent the formation of an uncontrolled optical cavity between the IMC and the Power Recycling Mirror.

3 Main components

3.1 Electro-Optical Modulator

The EOM uses a design already adopted in Enhanced LIGO⁴, with three independent pairs of electrodes installed on a single $4 \times 4 \times 40 \text{ mm}^3$ electro-optical Rubidium Titanyl Phosphate (RTP) crystal. Each pair of electrodes is part of its own RLC circuit tuned to resonate at a specific sideband frequency. RTP was chosen for its low optical absorption, and the single-crystal design reduces the number of interfaces and thus scattering losses. The end faces of the crystal are AR-coated and wedged so as to eliminate the risk of a parasitic interferometer and to help reduce residual unwanted amplitude modulation by separating the two orthogonal polarizations passing through it; the extinction ratio is about 10^5 . Well before the main interferometer control scheme details were worked out, the requirement for the modulation depth of the 9 and 45 MHz sidebands was set at 0.4 to account for ample margins; the 24 MHz sideband has to be adequate to control the IMC. The currently installed EOMs (at the two sites) meet requirement for all but the 45 MHz sidebands, for which the modulation depth is a factor 2-3 too low (see Figure 2). The problem could be solved by employing more powerful drivers and improving the resonant circuit, but the commissioning effort has thus far indicated that the current modulation depth is probably sufficient. The measured residual amplitude modulation to phase modulation ratio is right at the specification level of 10^4 . Although long term observation have shown that thermal drift can slightly compromise this performance, it is not anticipated to be an issue and can be easily mitigated if needed with a dedicated thermal enclosure.

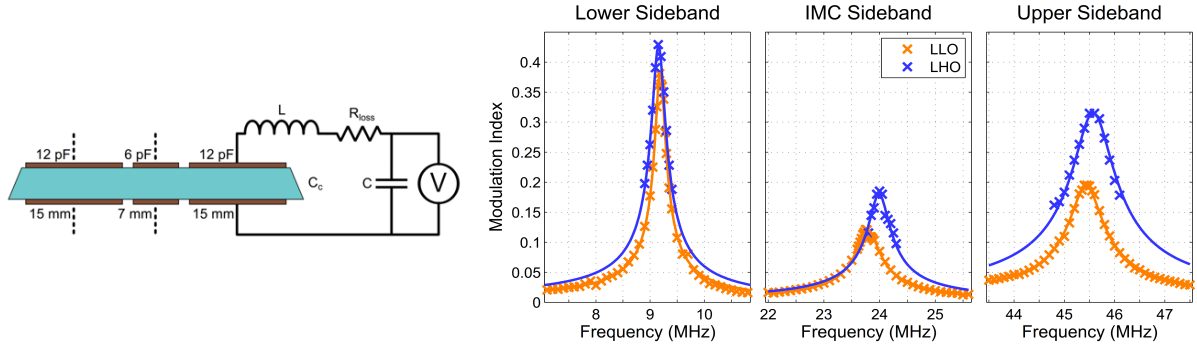


Figure 2 – Left: a schematic representation of the EOM arrangement. Right: the modulation depths for the three sidebands measured at both the Livingston and Hanford observatories.

3.2 Input Mode Cleaner

The IMC (dashed area of Figure 1) is a ~ 33 m round-trip length triangular cavity comprised of 6" diameter mirrors suspended by triple suspensions which are the responsibility of the aLIGO Suspension subsystem. The input and output mirrors are located in HAM2; the third optic is located in HAM3, about 16 m away. The main laser is locked to the IMC using the Pound-Drever-Hall technique; wavefront sensors are employed to control the alignment. Besides filtering and stabilizing the spatial mode and the polarization of the laser, the IMC serves as an intermediate frequency reference for the laser above ~ 15 Hz; the arm cavities are eventually used when the full interferometer is locked. Below 15 Hz, where the seismic isolation performance starts to degrade, the error signal of the locking loop is instead used to control the IMC length actively.

The measured geometrical and optical properties of the two installed IMC satisfy the requirements. As an example, at LHO the cavity pole and finesse have been measured to be 8.72 kHz and 515 respectively, in agreement with the design values (see Figure 3; assuming the transmissivities provided by the vendor, this results in an estimated round trip loss of about 150 ppm. Total and per-mirror absorptions, of particular concern because of possible thermal deformations induced by the absorbed heat, have been measured using a combination of two techniques: cavity Gouy phase tracking⁵ and shift of the individual optics' mechanical resonant modes⁶. The result is a per-mirror absorption between 2 and 4 ppm; the estimated corresponding thermal deformations induce a mode mismatch of less than 0.3% at full power, negligible compared to the 5% maximum higher order mode content required.

An attempt has also been made towards compiling a complete IMC length noise budget, although the final performance depends on many other components and effects in the scope of other subsystems. The budget is reported in Figure 3 and shows that there is an unexplained excess between about 3 and 100 Hz. While at present the excess doesn't represent a limiting factor for the performance of the interferometer, its cause is under ongoing investigation.

3.3 Faraday Isolator

The Faraday Isolator is located after the Input Mode Cleaner and, in addition to the 5% maximum higher order mode content in the transmitted beam, has to satisfy a requirement of at least 30 dB of isolation at all laser powers up to 130 W. To this purpose the Faraday Isolator is based on a special design with particular attention to thermal effects, as shown in Figure 4.

To compensate for thermal depolarization, an arrangement proposed by Snetkov et. al.⁷ has been employed: two Terbium Gallium Garnet (TGG) crystals, each providing 22.5° of rotation in a ≈ 1 T magnetic field, are placed in series, with a 67.5° quartz rotator in between. This allows for thermal induced birefringence effects to be largely compensated between the two crystals. Calcite wedge polarizers with extinction ratio in excess of 10^5 and optical efficiency greater than 99% are used to separate polarization in the input and output beams. A half wave plate placed

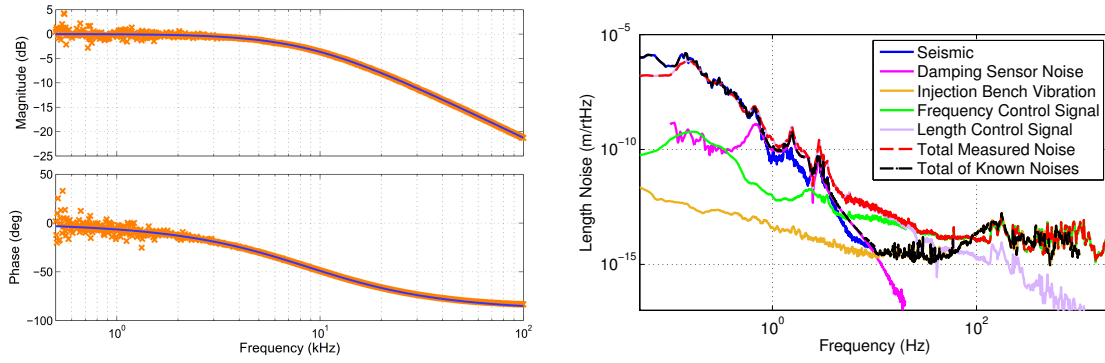


Figure 3 – Left: The measured and fitted cavity pole of the Input Mode Cleaner. Right: noise budget of the IMC sensed length noise (or, equivalently, frequency noise of the locked laser).

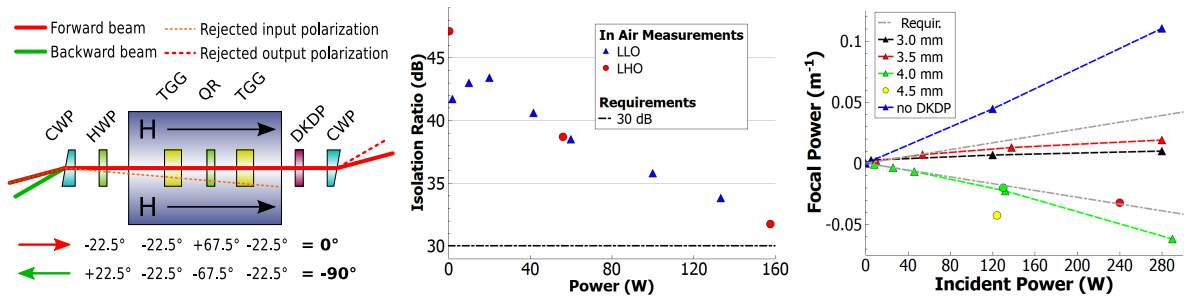


Figure 4 – Left: a schematic representation of the Faraday Isolator. Center: measured in-air isolation ratio of the FI as a function of power traversing the crystal. Right: measured total thermal lensing of the FI as a function of the length of the DKDP crystal. Hanford data is represented by triangles, Livingston data by circles.

before the Faraday rotator sets the total rotation to 0° and 90° for the forward and backward beams respectively; it is installed on a motorized rotational stage for in-vacuum optimization.

Absorption of laser power creates a thermal gradient inside the TGG crystal. Because of the temperature-dependent index of refraction ($dn/dT > 0$), this translates in a focusing of the beam referred to as “thermal lensing”; to mitigate the effect, a DKDP crystal with negative dn/dT is located right after the Faraday rotator, and its thickness is tuned so that its own thermal lens mostly cancels out that arising inside the TGG crystals.

While the observatories haven’t employed full laser power yet, both isolation ratio and thermal lensing have been successfully tested in air, and the results are shown in Figure 4.

Acknowledgments

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References

1. The LIGO Scientific Collaboration, *Classical and Quantum Gravity* **32**, 074001 (2015)
2. A. N. Staley, *Proceedings of the 50th Rencontres de Moriond Conference*, (2015)
3. K. L. Dooley et al., *Review of Scientific Instruments* **83**, 033109 (2012)
4. V. Quetschke, *Coherent Optical Technologies and Applications*, CMCI (2008).
5. C. L. Mueller et al., *arXiv:1502.02284* (2015)
6. C. L. Mueller, *PhD thesis, University of Florida* (August 2014)
7. I. Snetkov et al., *Opt. Express* **19**, 6366-6376 (2011)