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LIGO-India: A Review of Technology Involved

P.M. Kokne[1], R. S. Bankar[2], R.S. Yannawar[3], A.N. Ardad[4], B. S. Kharat[5]
[1]Badrinarayan Barwale Mahavidyalaya, Jalna 431203, Maharashtra
[2]Shri. Shivaji Arts, Commerce & Science College, Motala 443103 Maharashtra
[3]Milind Science College, Aurangabad – 431001, Maharashtra
[4]Deogiri College, Aurangabad - 431005, Maharashtra
[5]Lal Bahadur Shastri College, Partur -431501 Maharashtra

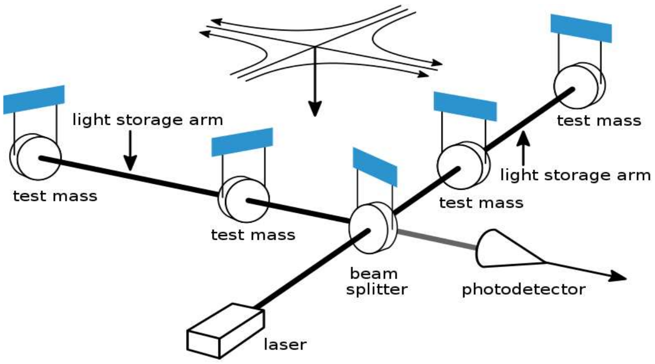
Abstract

LIGO-India is a multi-institutional mega science project which will be part of the international network of Gravitational Wave observations. The Laser Interferometer Gravitational-Wave Observatory (LIGO) - India is a planned advanced gravitational-wave observatory to be located in India as part of the worldwide network, whose concept proposal is now under active consideration in India and the USA. LIGO-India is envisaged as a collaborative project between a consortium of Indian research institutions and the LIGO Laboratory in USA, along with its international partners. LIGO-India received the Indian Government's in-principle approval in February 2016. Since then the project reached several milestones towards selecting and acquiring a site and building the observatory.LIGO-India is intrinsically a multidisciplinary mega-science project that requires expertise from a variety of fields (e.g., laser, vacuum, optics, computer, etc., and of course Physics) and provides cutting edge research opportunities.

Keywords: LIGO-India, Gravitational waves, Interferometer

Introduction:

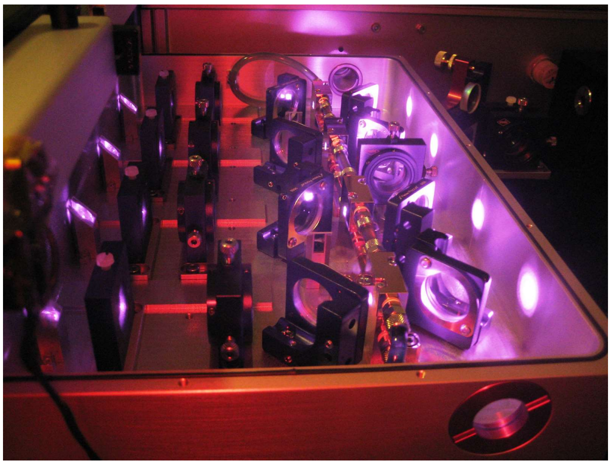
Interferometric gravitational wave detectors incorporate cutting edge technology from various fields. Glimpses of few such technological marvels that will be used in LIGO-India are provided below.



Laser

The LIGO interferometer hosts a laser at the 1064nm target wavelength. A non-planar ring oscillator (NPRO) generates a 2W ‘seed’ beam that is amplified through several stages until it can reach a desired 200W at the output. The entire system is called the pre-stabilized laser system (PSL). Power stabilization will probably be the most demanding laser stabilization task in future gravitational wave detectors.

Technical power noise on the laser can couple via many paths into the gravitational wave channel: asymmetric arms and radiation pressure noise, deviation from the dark fringe, radiation pressure noise. Advanced LIGO requires a relative intensity noise (RIN) of around 10−9/√Hz in the interferometer input beam. The accurate sensing of the needed 500 mW laser power at that location is difficult and the signal is still contaminated by pointing, polarization, and potentially even frequency noise. Ongoing research is needed to understand these couplings and reach the required stabilities.



Pre-stabilised Laser (Image: LIGO Lab/Caltech/MIT)

Optics

The LIGO core optics or test masses are currently made of ultra-high purity fused silica and coated with titania-doped tantala such that they have minimum absorption at the working wavelength of 1064nm. The mirror coatings are also dichroic in that they provide some reflectance at (1064/2) nm = 532 nm which is used for auxiliary measurements. The mirrors are specified to have absorption in the order of 3ppm and figure error in the order of 0.35nm.

This is a major challenge for materials research given the size of the mirrors at 34cm in diameter and weighing 40 kg.

Coatings research plays a major part of the upgrades that LIGO will undergo in the next few years. Reducing thermal noise of the coatings even further without losing on optical absorption will be the problem that takes center stage for the next few years. Any improvement that will reduce thermal noise by even a factor of two will contribute immensely as it would correspond to an improvement in the detection rate by a factor of 8.

Suspensions and Vibration Isolation Systems

LIGO vibration isolation can be broadly classified as active damping and passive damping systems that together ensure that the detector components are isolated from any external vibration. Active damping systems probe the environment for vibrations at different frequencies using sensors and generate counter movements thereby isolating the instrument from such noise. Passive damping systems include the seismic isolation and suspension sub-systems for the optics in LIGO. It is comprised of three sub-systems: the hydraulic external pre-isolator (HEPI) for low-frequency alignment and control, a two-stage hybrid active & passive isolation platform designed to give a factor of ~ 1000 attenuation at 10 Hz, and a quadruple pendulum suspension system that provides passive isolation above a few Hz. The final stage of the suspension consists of a 40 kg silica mirror suspended on fused silica fibers to reduce suspension thermal noise.

There is ongoing R & D work to provide incremental improvements to Advanced LIGO to improve performance, enhance robustness, and improve the duty cycle of the aLIGO vibration isolation and suspension. This type of work is designed to be easily incorporated with the existing detector systems with minimal disruption of the Observatories. These upgrades include work to add additional environmental sensors and incorporate them into the controls, or adding more sophisticated control algorithms to improve performance during unusual environmental conditions, or small mechanical changes to damp vibration modes.

Control Systems

The detectors have relied mostly on classical control theory to maintain its stringent alignment requirements in order to detect gravitational waves. Control of the interferometers requires many Multiple-Input-Multiple-Output (MIMO) control loops closed both locally and globally across the 4-kilometer interferometer arm lengths. LIGO’s control and feedback systems currently operate at 16 kHz.

Several aspects of feedback and controls are already under investigation to improve the near future sensitivity of the detector by reducing the control noise. Bilinear adaptive noise cancellation has been investigated to eliminate certain noise sources from the useful gravitational wave signal. Efforts are underway to use machine learning as a tool for automatic optimization of the interferometer. Various aspects of modern control theory are looked into so that they can be incorporated into control loops in order to save time spent in tuning them by employing just the classical approach.

Ultra-high Vacuum

LIGO’s vacuum system is one of the largest sustained vacuum systems and also one of its kind. The detector is maintained at one-trillionth of the atmospheric pressure at sea level. Such ultra-high vacuum becomes necessary to eliminate noise in length changes of the interferometer arm brought by any residual air in the chambers affecting the detection of a passing gravitational wave and also avoid absorption of the laser light by any residual dust or gas molecules thereby causing unwanted scattering.

In order to maintain LIGO’s vacuum pure, everything which is placed inside the UHV, such as the seismic isolation systems, has to be rigorously qualified for outgassing. UHV materials have to be carefully chosen to start with – for example, regular steel is saturated with hydrogen, which seeps out under low pressure, so LIGO’s beam tubes were made from special low outgassing steel. Next, any components destined for the UHV has to be thoroughly cleaned with solvents, to remove most of the surface contaminants (such as machining oil). Finally, the components are sealed into a separate vacuum chamber and exposed to ultra-high vacuum.

This allows any remaining contaminants to outgas safely without contaminating LIGO’s ultra-clean vacuum. The components can be heated to temperatures as high as 300˚C while they are in vacuum to ensure any contaminants evaporate off the surface – this process is known as vacuum baking. Vacuum baking also provides a direct way to measure the contaminants that a component is outgassing. The residual atmosphere in the vacuum oven can be studied with a mass spectrometer, which provides a very good indication of the kinds of contaminants being outgassed.

Conclusion:

The interferometric gravitation wave detector pushes the limits of technology on many fronts. To meet the sensitivity requirement, the detectors must operate at the fundamental limits of physical measurement. All parts of the detector such as the laser system, optics, suspension system, control electronics etc, must meet their stringent design specification.

Each one of these components represents decades of technology development to achieve the required performance, precision engineering to make it reproducible and reliable and careful procurement management and quality assurance to ensure that the hardware delivered for the detector meets all requirements. By allying ourselves with LIGO lab, the largest and best-resourced gravitational wave detector project in the world, we are able to draw on their experience and resources to ensure the technical success of LIGO-India. By using the components shared by the LIGO Laboratory to construct the LIGO-India detector, we are assured of achieving their design sensitivity, and can take advantage of their experience in installing and commissioning the detector to complete LIGO-India much faster than could be done with an untested design.

LIGO-India can be expected to be a focal point for gravitational wave detection in the Asian-Pacific region, involving many participating scientists, engineers and students from other countries.

The LIGO-India project will be highly multi-disciplinary and will bring together scientists and engineers from different fields like optics, lasers, gravitational physics, astronomy and astrophysics, cosmology, computational science, mathematics, mechanical, electrical, electronics and civil engineering, vacuum engineering and surface physics etc.

The project is challenging, we know that it is achievable, and by partnering with LIGO, we will have access to the specialized expertise needed to achieve success. Careful management and close attention by the LIGO-India project team will ensure that all technical specifications are properly interpreted and implemented in the designs. Furthermore, hand-holding from the LIGO lab would be available to make the project a success.

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