T.2: Interferometric gravitational wave detectors

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Abstract

Interferometers are best suited for detecting gravitational waves due to their high sensitivity and scalability. This has been borne out by the recent detection of gravitational waves by the LIGO detectors, the largest interferometers on earth. The detection of gravitational waves opens up a new window of astronomy to the universe for studying astrophysical events especially those that are electromagnetically blind such as merger of black holes. To do astronomy with gravitational waves one requires a network of detectors around the world for sky-localisation of the events. Towards this effort a LIGO detector is being setup in India in collaboration with LIGO Laboratory, U.S.A. under a project called LIGO-India. RRCAT is one of the lead institutes entrusted with the execution of the project. This article endeavours to provide a brief overview of interferometric gravitation wave detectors, the LIGO-India project and activities at RRCAT for this project.

1. Gravitational waves

Like electromagnetic waves produced by accelerating charges, the General Theory of Relativity predicts that an accelerating mass should also produce gravitational waves (GW). Unlike electromagnetism where there are both positive and negative charges, gravitational masses are only “positive” and hence gravitational waves cannot be emitted as dipole radiation (such as Electromagnetic waves). Gravitational waves are quadrupole waves and have two orthogonal states of polarization “+” (plus) polarization and “x” (cross) polarization. The best sources of gravitational waves are binary systems such as binary stars, binary neutron stars, neutron star-black hole binary or black-hole-black-hole binary, etc. A passing gravitational wave will modulate the distance between two inertial test masses. This change in distance is very very small. The signals from an astrophysical source of mass M, velocity v, at a distance R follows the Einstein quadrupole radiation formula, that describes the rate at which gravitational waves are emitted from a system of masses based on change in the quadrupole moment, according to which the strain ΔL generated on free masses on earth, separated by a distance L is:

$h = \Delta L/L = GMv^2/Rc^4$, where c is the speed of light.

Even the strongest gravitational waves from known astrophysical sources will produce a maximum strain of 10^{-22} on earth.

2. Detection of gravitational waves

Gravitational waves were predicted by Einstein's General Theory of Relativity almost a century ago, but were 'directly' detected only recently by the two Advanced Laser Interferometer Gravitational wave Observatory (LIGO) detectors in the U.S.A. Apart from putting General Theory of Relativity on a sound footing by confirming the last of its predictions, the detection of gravitational waves is of great importance to fundamental physics as it allows the testing of the General Theory of Relativity in the strong gravity regime. The detection also opens up a new window for astronomy to study astrophysical phenomena inaccessible to electromagnetic waves, such as the growth of black holes, final phase of in-spiralling and merging binary neutron stars, asymmetric supernova explosions and the stochastic gravitational wave background, the murmurs of the big-bang, etc. Gravitational waves can be detected using many techniques such as excitation of resonant bars, resonant spheres, satellite position monitoring, pulsar timing, interferometric detection, etc. A passing gravitational wave of the right frequency can excite the mechanical modes of a large bar or sphere. If a resonant mass has a very high mechanical Q-factor the strain produced by the gravitational waves is magnified by a factor of Q at the resonant frequency. The excited mechanical mode is measured by piezoelectric transducers. The initial attempts to detect gravitational waves were based on these type of detectors. Subsequently interferometer based detectors were developed and became the most promising ones to detect gravitational waves as they were scaleable in sensitivity and had a broadband response. Gravitational waves when incident on a Michelson interferometer will in one part of the wave cycle, “elongate” one arm of the interferometer while simultaneously “contracting” the other arm and vice-versa in the next part of the cycle.

This modulation of the arms of the interferometer produces fringe shifts at the output of the interferometer, encoding the gravitational wave strain as optical intensity modulation which can be detected using a photodiode. Of the various techniques for detecting gravitational wave the interferometric detector have achieved the highest sensitivity and scalability.

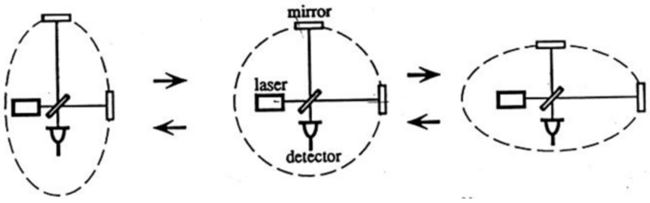

Fig. T.2.1: An exaggerated depiction of the effect of a passing gravitational wave on a Michelson interferometer. A gravitation wave of "+" polarisation moving normal to the page will result in one arm of the Michelson interferometer becoming "longer" and the other arm becoming "shorter" in one half of the wave cycle and vice versa in the next half of the wave cycle

3. Interferometers as GW detectors

The Michelson interferometer is a 'natural' detector of gravitational waves because of the differential change in the two orthogonal arms of the interferometer induced by the quadrupole field of a passing gravitational wave. Figure T.2.1 schematically illustrates the effect of a gravitational wave incident on a Michelson interferometer. The end mirrors of the two arms of the Michelson interferometer serve as the test mass and the delay due to the differential change in the two arms is determined by interference of the two beam at the beamsplitter. If the two arms are initially adjusted such that the light from the two arms destructively interfere then the output from the detector will be zero, and any differential change in the two arm lengths will result in light output from the detector. For a given strain induced by a passing gravitational wave, the differential change in the two arms of the interferometer scales with the arm length. For reliable detection from expected astrophysical processes the sensitivity for strain should be below 10^{-23} Hz$^{-1/2}$ and this translates to sensitivity to differential path length change between the two arms of $4\text{x}10^{-20}$ m-Hz$^{-1/2}$ for interferometer detector with arm length of about 4 km. This is the sensitivity target for 'Advanced-LIGO'. Since the quantum limit from photon shot noise for measuring the shift of a fringe in an interferometer operating with light at wavelength λ is at best $\lambda(N)^{-1/2}$ where N is the number of photons, even with 100 W of power, the achievable displacement sensitivity at 1064 nm wavelength is limited to $3 \text{ x } 10^{-17}$ m-Hz$^{-1/2}$. To produce a differential path length change between the two arms in the interferometer above this limit due to a strain of 10^{-23} Hz$^{-1/2}$ requires the arm lengths to be about 4 km long with Fabry-Perot enhancement (by about 300) of the arm lengths. Further sensitivity enhancements are achieved by laser 'power recycling' and 'signal recycling'. To achieve high sensitivity to the differential path length change in Michelson interferometer it is aligned to achieve almost 'zero' signal at the output port. This results in all the power being reflected towards the input port of the interferometer. This light can be reintroduced into the interferometer to increase the effective power circulating in the interferometer and thus reduce the shot noise of the detector. This is called power recycling and is achieved using a power recycling mirror of appropriate reflectivity in the input port of the interferometer. Similarly, the signal output can be reintroduced into the interferometer to accrue the differential path length change in the interferometer due to the gravitational wave. This is called signal recycling and is achieved using a signal recycling mirror at the output port of the interferometer.

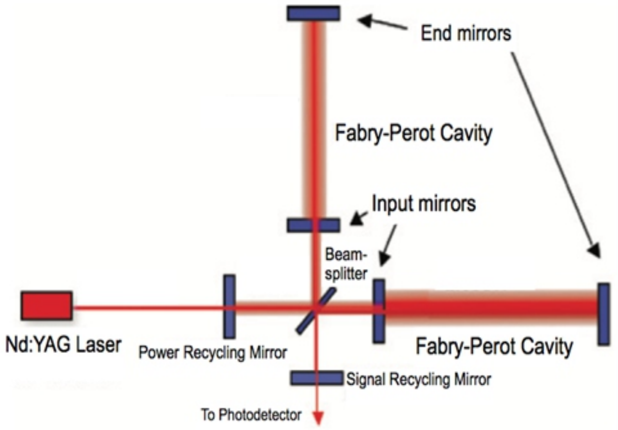

Fig. T.2.2: An oversimplified schematic of the optical layout of the LIGO interferometers. The actual interferometer detector system has many other sub-systems such as the reaction masses optics, input mode filter cavity, the output mode filter cavity, auxiliary optics sub-system, photon calibrator, etc.

The oversimplified optical configuration of the aLIGO detector is shown in Fig. T.2.2. The figure shows only the "core-optics" of the interferometer, the actual system has many other sub-systems such as the reaction masses optics, input mode filter cavity, the output mode filter cavity, auxiliary optics sub-system, photon calibrator, etc. The ultimate limit on the resolution of an interferometer comes due to the uncertainty principle and is given by the standard quantum limit. The standard quantum limit for interferometric gravitational wave detectors is obtained when the uncertainty in position due to radiation-pressure induced fluctuations is equal to the position measurement uncertainty due to fluctuations in the number of photons, or shot noise. Thus the optical readout noise is a quadrature sum of the shot noise and radiation pressure noise and the standard quantum limit for a interferometer detector at a given frequency of detection f is given by the expression below where L is the arm length and m is the mass of the mirror of of the interferometer.

$$h_{SQL}(f) = (1/\pi f L)(\hbar/m)^{1/2}$$

Before the interferometer can reach the limit set by the standard quantum limit, many other sources of “engineering noise” need to be minimised. These include isolation of the test masses from ground vibration; the micro-seismic noise, laser intensity and frequency fluctuations, noise due to thermal fluctuations from the mirror substrates and coatings, acoustic excitation of opto-mechanical components, residual gas induced phase noise, etc. The Fig. T.2.3 shows a typical sensitivity curve for the aLIGO detector during the O2 run, which is a sum of all the noise contributed by these noise sources.

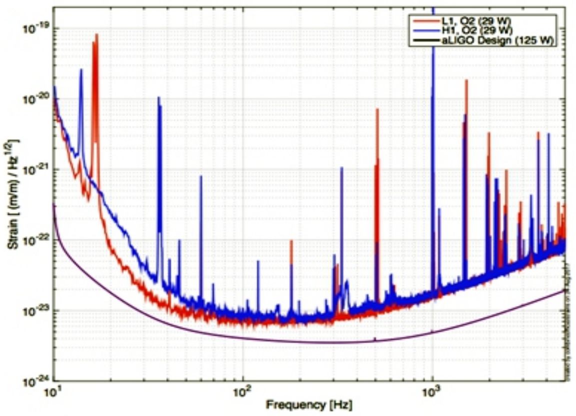

Fig. T.2.3: A typical strain sensitivity curve for the aLIGO detectors during the O2 run. The red and blue curves are the actual measured noise levels for the Livingston and Hanford detectors respectively. The purple curve is the design sensitivity the detectors have to achieve as the laser power is ramped up from the current 25W level laser power to 125W in subsequent observation runs. (Credit: Caltech/MIT/LIGO Laboratory)

4. Kilometer-class gravitational wave detectors

For detection of gravitational waves even one detector is enough but due to the very small signal at least two detectors are required for coherent detection which can eliminate a lot of 'common-mode' noise. For the detected gravitational waves to be localised in the sky for follow-up observation with optical, x-ray and radio telescopes requires a minimum of three detectors to be able to triangulate the location of the source. Larger the distances between the three detectors better is the localisation in the sky. This requires that there be a network of three or more kilometer-class detectors separated by large distances. The two Laser Interferometer Gravitational-wave Observatory (LIGO) detectors in the US, are located in Livingston, Louisiana, and Hanford, Washington, separated by about three thousand kilometers. Figure T.2.4 shows an arial photographic shot of LIGO-Livingston in Louisiana. A third detector labeled LIGO-India is being setup in India under a joint collaboration between the National Science Foundation (NSF) of U.S.A. and Department of Atomic Energy (DAE) and Department of Science and Technology (DST) of India. The National Science Foundation of U.S.A. funded the LIGO project in two phases, the first to build the facility and vacuum infrastructure and install a first generation detector called iLIGO which is short for “initial-LIGO”. Many incremental changes and upgrades

Fig. T.2.4: An arial view of the LIGO detector located in Livingston, Louisiana, United States of America.(Credit: Caltech/MIT/LIGO Laboratory)

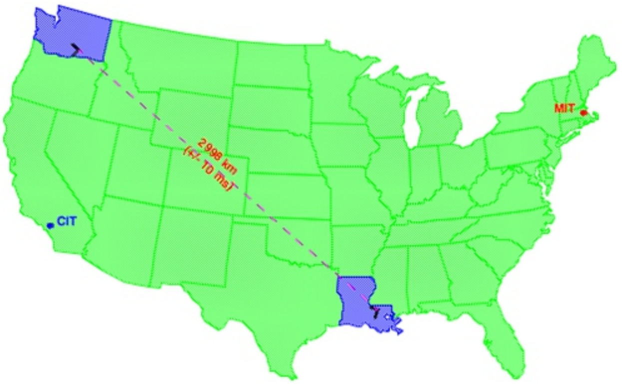

Fig. T.2.5: The two LIGO detectors currently operating are located in Livingston, Louisiana state and Hanford, Washington state, across the continental width of the United States of America (Credit: Caltech/MIT/LIGO Laboratory) were done (mainly in seismic isolation) by the time the first phase came to an end, the LIGO detector at this point had a sensitivity that was an order better than the iLIGO and the detector configuration was called eLIGO which is short for "enhanced-LIGO".

During the science run of the iLIGO and eLIGO the design and development of the sub-systems for the second generation detector termed aLIGO, short for "Advanced-LIGO" was concurrently done. The detector components of the first generation detector was decommissioned and the aLIGO was installed in the same facilities and vacuum system. Advanced-LIGO has been installed and commissioned and two science runs called O1 and O2 have been completed on aLIGO. The deign sensitivity of aLIGO is 3×10^{-24} $Hz^{-1/2}$ about ten times the sensitivity of eLIGO. When achieved, this will result in a tenfold increase in the distance to which the detector can detect gravitational waves from a binary neutron star merger. This tenfold increase should result in a thousand-fold increase in event rate as the volume of the universe covered by the detector range will scale as r^3. To achieve this high level of strain sensitivity the aLIGO detectors use a monolithic fused silica suspension for isolation of the core optics, the core optics are of 340 mm diameter fused silica optics with very high mechanical Q, the laser used is a pre-stabilised laser with 200 W output power, active seismic isolation system to provide isolation in the low frequency band (10-50 Hz), and the arm lengths are 4 km with Fabry-Perot enhancements of about 300. Advanced LIGO is designed to have a strain sensitivity of 10^{-24} $Hz^{-1/2}$ in the detection band of 10 Hz to 1 kHz. Another kilometer-class gravitational wave detector is Advanced-VIRGO, a 3 km arm length interferometer detector located at Pisa, Italy, which recently completed installation and commissioning and joined the O2 observation run in its latter part. One other kilometre class gravitational wave detector currently being built is KAGRA, (short for KAmiokaGRAvity) which is also a 3 km arm length interferometer detector but located underground in the famous Kamioka mines of Japan.

5. Recent detections by LIGO

On September 14, 2015 at 09:50:45 UTC (15:20:45 IST), the two LIGO detectors, located in Livingston, Louisiana, and Hanford, Washington, USA both measured ripples in the fabric of spacetime – gravitational waves – arriving at earth from a cataclysmic event in the distant universe. The new aLIGO detectors had just begun operation for their first observing O1 run when the very clear and strong signal was captured. The gravitational waves were produced during the final fraction of a second of the merger of two black holes to produce a single, more massive spinning black hole. This detection is labeled as GW150914 indicating the year, month and day of the detection in that order. This discovery comes at the culmination of decades of instrument research and development by LIGO laboratory, and proved a prediction made 100 years ago by Einstein that gravitational waves exist. More excitingly, it marked the beginning of a new era of Gravitational Wave Astronomy – the opening of a new window to study the Universe. During the O1 run two more 'events' from binary black-hole mergers were detected of which one was declared as 'detection'. The second detection GW141226 was on December 26, 2015 at 03:38:53 UTC. A third detection GW170104 was made on January 4, 2017 at 10 : 11:58.6 UTC, during the O2 run. Figure T.2.6 provides a pictorial summary of detections by LIGO announced till date. The event LVT151012 had a low signal-to-noise and hence was not "confirmed" as a detection. The O2 run came to a close on 25th Aug 2017 and promises to reveal more exciting events once the data analysis is completed in a couple of months.

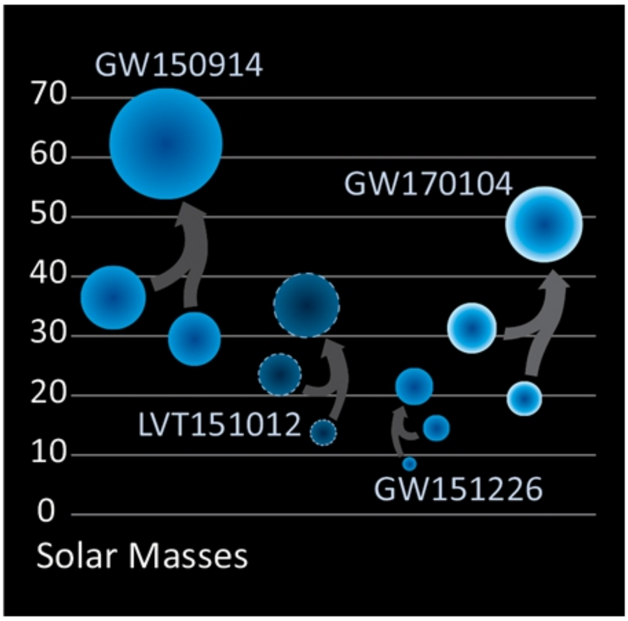

Fig. T.2.6: A pictorial summary of the various detections made to date by the two LIGO detectors. The figure depicts the estimated mass of the initial binary black-holes and the black-hole formed after merger, calculated from the detected gravitational wave waveform shape and amplitude. (Credit: Caltech/MIT/LIGO Laboratory)

6. LIGO-India

As mentioned earlier Gravitational Wave Astronomy requires independent and widely separated observatories to determine the direction of the event causing the gravitational waves, and follow up with visible, x-ray and radio telescopes. LIGO-India is a key step in this direction. LIGO Laboratory had worked closely with IndIGO, a consortium of Indian institutions interested in Gravitational Wave Astronomy, to establish a third Advanced LIGO detector on the Indian subcontinent. LIGO-India will be identical to the two LIGO detectors in operation in the US which are the aLIGO configuration. Optimal triangulation and parameter extraction from the three detector data necessitates that all three detectors LIGO-Hanford, LIGO-Livingston and LIGO-India be identical in sensitivity.

The government of India, on Feb 17, 2016 gave "in-principle" approval for the LIGO-India project. An MOU was signed between NSF, USA and DAE-DST, India for collaborating on this project. in March 2016. The LIGO-India Project is to be funded under a joint DAE-DST Consortium for Mega-Science Projects. Due to the technology intensive nature of this project it will be managed by the DAE. The lead institutes of the LIGO-India Project are; the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, the Institute for Plasma Research (IPR), Gandhinagar, Raja Ramanna Centre for Advanced Technology (RRCAT), Indore and the Directorate of Constructions and Estate Management (DCSEM), Mumbai. The key objective of the LIGO-India Project is the setting up of an Advanced LIGO detector in India in collaboration with the LIGO Laboratory and running it in a network with the existing two Advanced LIGO detectors in the United States. The Advanced LIGO, a major upgrade to the first generation LIGO detectors is mainly funded by the National Science Foundation along with funding organisations in Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council, STFC) and Australia (Australian Research Council). The addition of LIGO-India to the international network offers a very significant improvement in establishing the sky location of gravitational wave sources. Though a collaborative project with an international partner, unlike other similar collaborative projects the LIGO-India detector will be installed in India and a major part of project money will be spent in India with components sourced from Indian industries.

7. LIGO-India activities at RRCAT

As part of the IndIGO Consortium, RRCAT had contributed to the preparation of the initial proposals for LIGO-India, its presentation to the then Planning Commission of India and the National Science Foundation, of U.S.A. One of the key challenges to establishing a LIGO detector in India is the identification and selection of a suitable site. As the detector is extremely sensitive to ground noise, selection of sites with a minimum micro-seismic noise is an important step. This requirement is further compounded by the fact that the detector required an "L" shaped level area with each part of the L shape being 4 km long. The selected site is also required to have low potential for increase in the ground noise in the future due to human activities. A technical site selection team with members from various constituent institutions of IndIGO including RRCAT, with funding from IUCAA had identified 22 potential sites all over peninsular India. Of these four were shortlisted based on multiple inspection of the selected areas during site visits and experimental monitoring of seismic noise levels for two weeks, study of satellite images, and geological, seismological and topographic maps.

(a)

(b)

Fig. T.2.7: A pair of broadband seismometers installed at one of the potential sites for a two week seismic survey as a part of the site selection process. The image (a) shows the two broadband seismometers during setting up and the image (b) shows the completed installation with covers for both thermal and noise shielding

RRCAT had contributed to this effort by setting up the seismometers at various potential sites in Madhya Pradesh, Maharashtra and Rajasthan for carrying out the preliminary seismic survey. Figure T.2.7 shows a pair of seismometers installed at one of the potential sites during the preliminary seismic survey.

Concomitant to the site selection, RRCAT had also initiated development of some of the components and sub-systems that would be required for executing the LIGO-India Project. One of the crucial setups is a laser heated fused silica fiber drawing system required for fabrication of the interferometer optics suspension fibers. Figure T.2.8 shows the CO_2 laser based fiber drawing system developed for this purpose. Fused silica fibres have been drawn using this system and characterised. This system is currently being upgraded to be able to draw longer fibres and fused-silica “ribbons” for development of new suspension designs.

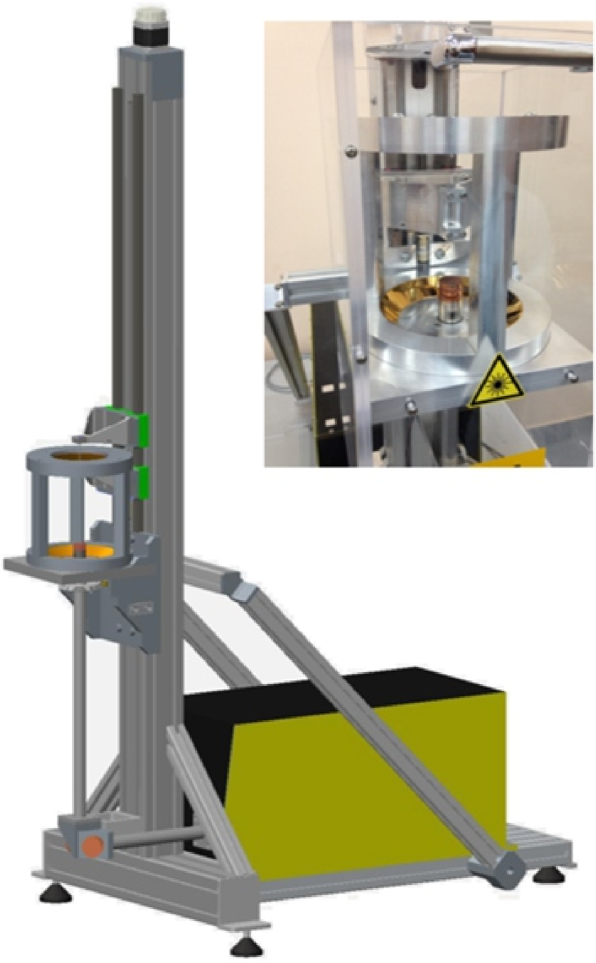

Fig. T.2.8: A CAD rendering of the suspension fiber drawing system. The inset photograph shows a close-up of the laser heated fiber drawing system showing one of the two diamond-turned axions (gold colour) used for heating the fiber preform in a radial fashion with a 75 W CO_2 laser

Development of ultra-narrow line-width lasers and ultra-precise optics have also be initiated at RRCAT. A non-planar ring oscillator (NPRO) design based Nd:YAG oscillator has been developed with sub-kHz line width. Figure T.2.9 shows a photograph of the prototype oscillator system which has an output of 100 mW at 1064 nm with a line-width of $\leq$ 600 Hz. A temperature stabilised pump diode emitting at 808 nm is used to pump the Nd:YAG NPRO crystal kept in a magnetic field which forms a monolithic oscillator with unidirectional lasing. The unidirectional lasing avoids spatial hole burning and the monolithic laser cavity reduces cavity length fluctuations due to environmental perturbations resulting in a narrow line width output. The NPRO crystal is temperature stabilised with a thermoelectric cooler and actuated by a PZT which compresses the crystal to modulate the cavity length for frequency tuning. Locking of the oscillator to a reference etalon is in progress to further reduce the line width to a value below 100 Hz. A diode pumped amplifier stage has also been designed and is under assembly for amplifying the output of the oscillator to 10 W while maintaining the narrow line width of the oscillator.

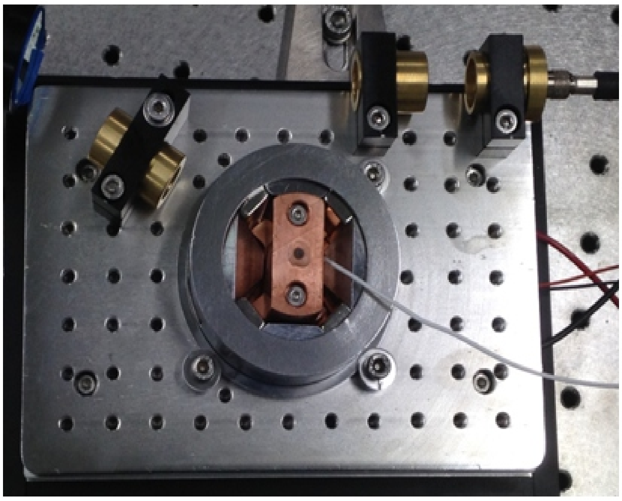

Fig. T.2.9: A close-up of the prototype Nd:YAG NPRO oscillator system which has an output of 100 mW at 1064 nm with a line-width of $\leq$ 600 Hz

For fabrication of the ultra-precise optical components of peak-to-valley (PV) variation of $\lambda/100$ or smaller requires development of expertise in deterministic optical figuring techniques such as liquid jet polishing, ion beam figuring, magnetorheological polishing, etc. A liquid jet polishing machine is being developed at RRCAT for this purpose. Figure T.2.10 shows a close-up of the liquid jet polishing prototype head developed for trials on fused silica. In this technique a polishing fluid consisting of cerium oxide suspended in de-ionised water is used under high pressure to impinge on the optics in a narrow jet. The material removed by the jet of polishing fluid is characterised by interferometric measurements and is used for calculating the dwell time at each point for figuring an optical surface. The liquid jet is moved over the optics in a raster fashion to remove material from the high points of the optics to reduce the PV value. Liquid jet polishing technique is best suited for figuring optics up to a PV of $\lambda/500$. Due to fluctuations in pressure of the liquid jet, wear-out of the jet orifice, variations in temperature of the fluid jet, etc., the technique does not converge very well for PV values below $\lambda/500$. To handle figuring of optics below $\lambda/500$ an ion beam figuring technique is better suited due to its high process stability. In ion beam figuring a stable ion beam, usually of argon is used to atomically “sandblast" the material away from the high point on the optics. As the process is extremely stable and repeatable the level of figuring is limited only by the number iterations and the spatial frequency limit from the ion beam footprint. To develop expertise in ion beam figuring and fabricate the required optics for a 10 m prototype interferometer being setup at RRCAT, an ion beam figuring system is being procured. The system has recently been qualified at the manufacturer's facility and will be installed at RRCAT in the coming months. In this system the interferometric surface profile data of the optics to be figured is used to calculate the ion beam dwell time at each point on the optic to remove material from the high points. The technique as such is stable enough to produce optics with PV lower than $\lambda/1000$ and is only limited by measurement accuracy, registration errors of the optic with the co-ordinate system of the ion beam figuring system, and other such systematic errors. The expertise to produce optics with PV better than $\lambda/1000$ using the ion beam figuring system will be generated in the coming year for fabrication of the optics required for the 10 m prototype interferometer.

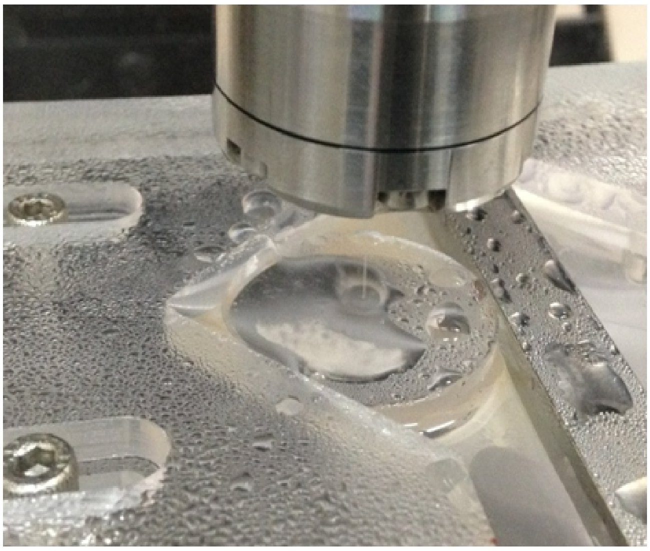

Fig. T.2.10: Initial liquid jet polishing trails on 30 mm diameter fused silica using the liquid jet polishing prototype head developed at RRCAT

In the LIGO-India project RRCAT is the lead institute responsible for the laser interferometer part of the project and also responsible for the technology development for detector upgrades and the for the next generation of gravitational wave detectors. This involves collaborating with the LIGO Laboratory to re-design the optical configuration of the third interferometer optics to make it similar to the other two aLIGO detectors, development of some of the components and spares, installation and commissioning of the interferometer to achieve the design sensitivity and carry out research and development for future detector upgrades and subsequently for 3rd generation detector technology. The key optical and laser components of the interferometer will be contributed by the LIGO Lab U.S.A. as part of their contribution to the collaboration. RRCAT will use these components to build an Advanced LIGO interferometer in India under this project. The optics and the laser system used in the interferometer represent the state-of-art in ultra-high precision optics and ultra-narrow line-width laser systems. Expertise and facilities for these do not currently exist in the country. In the near term the development of these specialised optical components and its metrology is being pursued at RRCAT under a project titled “Technology Development & Capacity Building for Gravitational Wave Detection” to serve the dual purpose of expertise building for the LIGO-India Project and technology assimilation from this international collaboration. As part of this project for capacity building a 10 m prototype interferometer is being constructed along with the development of its laser system, optics, vacuum components and multi-input-multi-output control system. The 10 m prototype interferometer will be setup at RRCAT and will be used for developing expertise in interferometer optics suspension assembly, alignment and commissioning.

As part of the capacity building expertise two prototype vacuum chambers one each of the two types used in the LIGO vacuum system will be fabricated by IPR. These chambers will then be provided to RRCAT to setup a training program for "in-vacuum" installation of the interferometer components. A quad-suspension used for the isolation of the interferometer mirrors in aLIGO will be fabricated from drawings and used for assembly and installation training in the vacuum chamber provided by IPR. The quad-suspension is one of the most delicate and complex assemblies that would be required to be carried out for the LIGO-India detector. Figure T.2.11 shows a typical quad assembly used in the aLIGO detectors. It consists of 188 fabricated parts unique to each quad-suspension, 1569 fabricated parts in total and 3575 total parts including machined part and fastening hardware.

Fig. T.2.11: A photograph of one of the quad-suspensions used in aLIGO taken during assembly. (Credit: Caltech/MIT/LIGO Laboratory)

Subsequent to building of the 10 m prototype interferometer at RRCAT, development of optics with low loss coatings and squeezed light sources will be taken up. These would be required to keep pace with the planned upgrades to the two aLIGO detectors in the U.S.A. Development of the low loss optics and squeezed laser sources will allow us to upgrade the optics and laser system of the LIGO-India detector to match the sensitivities of all three detectors which is required to maintain the sky-localisation accuracy. The 10 m interferometer will also serve as a test and validation system for new techniques in gravitational wave detection using interferometers. Development of new interferometer detector configurations which incorporate novel components such as cryogenically cooled (123 K) mirrors made of silicon to reduce thermal noise, high power frequency dependent squeezed light sources to go below the standard quantum limit, optical coatings (possibly crystalline coatings) with ultra-low loss, etc., will be pursued using the 10 m interferometer as the test bench for developing techniques for the next generation of interferometers for gravitational wave detection.

8. New fields of science

Gravitational wave detection is a multidisciplinary field of high resolution measurements where laser systems, optics (substrates & coatings), vibration isolation, low noise sensing electronics are pushed to the limits of technology. The LIGO Project has been responsible for pushing the envelope of these technologies and have been responsible for the development of various technologies such as low loss coatings, ultra-precise optics and ultra-stable laser systems. The GW detectors work at the limits of the standard quantum limits and technologies such as squeezed light are being developed for operating these detectors below the standard quantum limit. The technologies being pursued for gravitational wave detectors have implications for other related fields of science and also for the exploration of quantum mechanical properties at macroscopic scales. Techniques developed for gravitational wave detection has engendered the field of Quantum Metrology. Quantum Metrology is the field of high resolution measurements where principles of quantum mechanics dictate the limits of measurement. For a long time, this had been limited to cold atoms, but recently with advances in micro-machining, low loss coatings, ultra-stable lasers and squeezed light sources, quantum influences in macroscopic systems such as in Micro-Opto-Electro-Mechanical-Systems (MOEMS) are being explored. These measurements have implications for a variety of related fields such as quantum optics, quantum computing, quantum encryption, coherent communication, standards development, ultra-precise sensing, quantum engineering, etc. Quantum Metrology is currently limited by engineering limitations such as stability of laser sources, low loss coatings, fabrication of micro-resonators with high Q, low noise electronics, isolation from environmental perturbations, etc. Various groups all over the world are addressing these problems to be able to put macroscopic system in quantum states ("cooling" of macroscopic objects to their quantum ground states). Progress in this direction has led to new areas of work such as cavity opto-mechanics or quantum opto-mechanics in which one seeks to achieve control over mechanical quantum states. This has implications for achieving unprecedented levels of force sensitivity in quantum limited mechanical devices and also for experiments on opto-mechanical quantum entanglement. The radiation pressure in a high Q cavity can also be used to cool mechanical devices to a near zero average phonon occupancy and would allow measurement of quantum phenomena in MOEMS devices and macroscopic systems.

9. Technology spin-offs

Gravitational wave Detectors are currently limited by the thermal noise in the coatings of the test mass optics and limitation of optics fabrication errors of these optics. Crystalline coatings and optics of ultra-pure silicon are being explored to address these issues. Various groups all over the world are working on these problems to be able to develop detector upgrades to the Advanced LIGO and possible applications in the next generation of gravitational wave detectors. The ultra-narrow line width lasers with high powers, squeezed state lasers, etc. developed for the aLIGO detectors find ready application in narrow line-width spectroscopy, Doppler LIDAR, differential LIDAR, precision calibration and measurement, quantum cryptography for secure communication, etc. For the gravitational wave sensing interferometers mirrors to be truly inertial, the mirror mass has to be isolated from the ambient and ground motion by 14 order of magnitude to keep the final perturbations low enough for the displacement due to the gravitational waves to be detected. This kind of isolation technology is also required for high resolution TEM and SEM microscopes in material science, precision metrology for standards calibration, laser tweezers, cold atom metrology, accelerometer and gyroscope calibration for defence applications, etc. Hence technology developed for LIGO have become a driver of growth for future developments in high end technology.

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