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Novel Low-Frequency Vibration Isolation Technique for Interferometric Gravitational Wave Detectors

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Gravitational waves are distortion of space-time structure propagating through the universe like ripples. When a heavy object moves around, it drags around the space-time distortion caused by its mass and the resultant disturbance propagates out as a gravitational wave. This generation process of gravitational waves is fundamentally different from electro-magnetic waves. Therefore, by detecting gravitational waves from violent astronomical events such as the coalescence of binary neutron stars or black holes, supernovae, etc., we can obtain information about those events which is not available with electro-magnetic observations.

The interaction of gravitational waves with matter is extremely weak. This is, on one hand, beneficial because, unlike electro-magnetic waves, the gravitational waves are hardly attenuated by substances lying between the source and us. However, on the other hand, it makes the detection of gravitational waves extremely difficult. This is why no one has ever detected gravitational waves directly since its theoretical discovery by Albert Einstein in 1916.

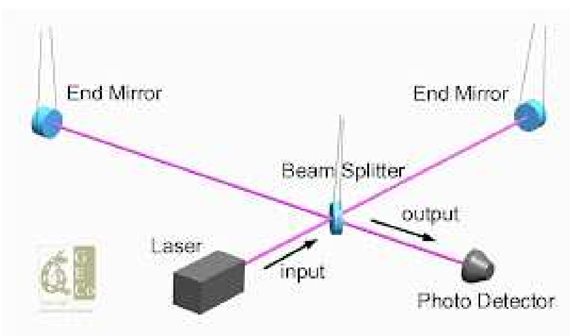

Fig 1

The most promising way to detect gravitational waves at this moment is to use laser interferometers. Fig. 1 shows the basic configuration of a Michelson interferometer. The light from the laser is divided into two orthogonal beams by a beam splitter. The two beams are reflected back to the beam splitter by the end mirrors. The interference between the two returning light beams depends on the path length difference between the two arms. In normal operation, we keep the output of the interferometer at completely destructive interference, i.e. no light coming out of the interferometer. When a gravitational wave enters the interferometer from the above, it stretches one arm while contracting the other arm. The resultant differential variation of the arm lengths changes the interference condition at the output of the interferometer and a small amount of light leaks out. By detecting this light by a photo-detector, we can detect the arrival of gravitational waves.

There are ongoing efforts to build large-scale interferometric gravitational wave detectors around the world: **LIGO**, **VIRGO**, **GEO**, **TAMA**. LIGO is currently the most sensitive detector network. LIGO detectors consists of three interferometers located at two sites in the USA. The best sensitivity reaches down to 3×10^{-23} 1/sqrt(Hz) in the unit of strain. This means you can detect the change of the 4 km arm length of LIGO by a billionth of the size of a hydrogen atom. This is a tremendous achievement and LIGO has started to set important upper limits on some astrophysical parameters. However, even with this surprising sensitivity, in order to frequently detect astrophysical gravitational wave events, we have to improve it by a factor of 10 or more.

There are plans for next generation gravitational wave detectors which are designed to have more than 10 times better sensitivities than current LIGO, such as Advanced LIGO and **LCGT**. In order to achieve the goal of those detectors, we have to reduce the noise of the interferometers. There are many noise sources for interferometers. Seismic noise is one of the most serious noises at low frequencies.

The ground is always moving even when there is no earthquake. This motion is transmitted to the mirrors through the suspension wires. The motion of the mirrors caused by the ground vibration cannot be distinguished from the displacement of the mirrors induced by gravitational waves. Therefore, we have to isolate the mirrors from ground or any vibration source as much as possible. Traditionally, the vibration isolation of the mirrors of gravitational wave detectors is achieved by a passive way: suspending the mirrors as pendulums. At frequencies higher than the resonant frequency of a pendulum, it works as an excellent vibration isolator. However, a pendulum does not attenuate the vibration below the resonant frequency. Moreover, the vibration at the resonant frequency can be amplified by a pendulum and this is why we employ a complicated damping system to suppress the motion at the resonance.

Relatively new techniques employing active vibration isolation technologies will be used in some next generation detectors in combination with pendulum suspensions. In this case, motion of the optical stage on which the pendulum suspension is mounted is monitored by sensors (seismometers, position detectors, and/or accelerometers) and signals are sent to actuators which can move the optical stage with respect to its supports. By moving the stage in the opposite direction to the sensed ground motion, we can reduce the vibration transmitted to the mirrors. In general, the performance of this technique is limited by the sensor's performance. Since accelerometers have poor sensitivity at low frequencies, the performance of the active vibration isolation is also limited at low frequencies.

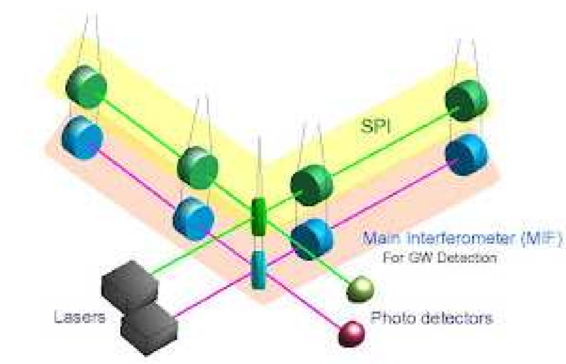

Fig. 2

A suspension point interferometer (SPI) is a different kind of active vibration isolation scheme, which makes use of auxiliary interferometers as sensors. It was first proposed by Ron Drever of California Institute of Technologies [1]. As is shown in Fig. 2, the mirrors of the main interferometer, which is used for gravitational wave detection, are suspended from an auxiliary interferometer. This auxiliary interferometer is called an SPI. Any ground motion transmitted through the suspension wires is first sensed by the SPI. Then feedback forces are applied to the mirrors of SPI to cancel out the motion. In this way, the seismic vibration is not transmitted to the final stages.

Compared to accelerometers, an SPI is a displacement sensor, which has a good sensitivity even at very low frequencies. This makes the SPI especially useful at low frequencies, where other traditional vibration isolation schemes do not work well. The noise of an SPI can also be very small and, in principle, we should be able to achieve the same sensitivity as the main interferometer.

Reduction of low frequency seismic noise has significant impacts on the performance of an interferometer in many ways. First of all, expansion of our observation frequency band toward lower frequency would give us more chance of detecting massive black hole collisions which emit strong signals but only at low frequencies.

Low frequency seismic disturbances are the main culprit for the instability of interferometers. During the operation, an interferometer has to be kept in a very delicate state (in terms of mirror positions and orientations) to maintain a good sensitivity. This state can be easily broken by a large seismic disturbance. An SPI can block seismic disturbances to reach the main interferometer. This would improve the duty cycle of the interferometer, which is very important because the detector always has to keep its eyes on the sky to catch rare astrophysical events.

Finally, the reduction of low frequency noise can actually mitigate many technical noises at higher frequencies, because those noises appear at the output of an interferometer coupled with the overall fluctuation of interferometer mirrors, which is dominated by low frequency motions. Examples of those high frequency noises are laser noises, up-conversion noises by the non-linearity of detection system, actuation noises, etc.

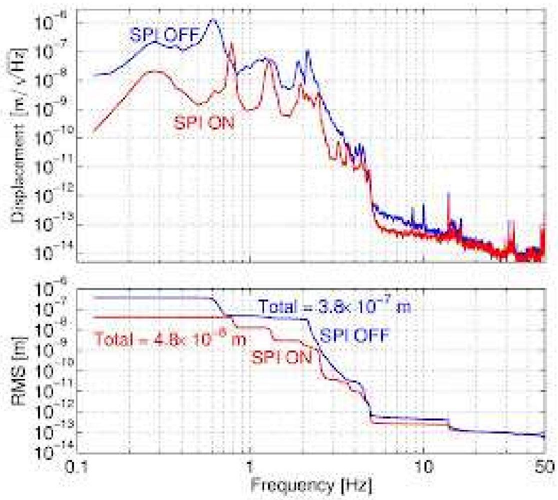

Fig. 3

In order to demonstrate and study the practical performance of this scheme, we have built a prototype Fabry-Perot interferometer equipped with an SPI at University of Tokyo [2][3]. The apparatus consists of a 200mW laser with a laser stabilization system and triple pendulum suspended Fabry-Perot cavities. Care has been taken to reduce all noises below the horizontal seismic noise level to clearly see the effect of SPI. The results are shown in Fig. 3 [3]. The blue curve shows the noise spectrum of the interferometer without the SPI. When we turned on the SPI, the noise was reduced as shown by the red curve. We achieved the reduction of noise by a factor 100 at maximum below 10Hz. This is a clear demonstration of the usefulness of this scheme.

From this study we have also learned practical limitations to the performance of an SPI, such as couplings from rotational and vertical seismic vibration, the difficulty in aligning the two interferometers and so on. With the help of this knowledge, next generation detector projects like Advanced **LIGO** and **LCGT** are exploring the possibility of including this technique in their design. In the case of **LCGT**, the mirrors are cooled down to reduce the thermal vibration. In order to do this, we have to attach heat conducting wires to the penultimate masses of the mirror suspension system to extract heat from the mirrors. However, extra vibration is introduced to the mirrors from those wires. SPI is considered as a way to suppress this extra vibration. In this case, the low noise nature of an SPI is critical because it is installed very close to the main interferometer.

There are many ongoing R&D efforts for developing advanced techniques, such as SPI, for next generation gravitational wave detectors. With those techniques combined with the knowledge and experience accumulated by the construction and operation of current large scale detectors, we are expecting to open a new era of gravitational wave astronomy in the near future. So stay tuned !

References
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