Introduction of History, Current Situation And Future Development of LIGO

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***Abstract*—LIGO is a large research facility for gravitational waves' detection based on the principle of the interference of laser. Its success in detecting the gravitational wave event, GW150914, on September 14, 2015 at 09:50:45 UCT verified Einstein's prediction of the existence of gravitational wave in his General Theory of Relativity and proved the feasibility of this new method for observation of astronomical phenomena. The paper mainly discusses the basic principle and applied technology of LIGO and LIGO's history, current situation and future development.**

***Index Terms*—detection of Gravitational Wave, General Theory of Relativity, LIGO, interferometer**

I. Introduction

LASER Interferometer Gravitation Wave Observatory (LIGO) is a large research facility for the detection of gravitational wave based on the principle of interference of laser (Light Amplification of Stimulated Emission of Radiation). On February 11th, 2016, the project leader of LIGO announced their successful detection of gravitational wave on September 14, 2015 at 09:50:45 UCT[1]. This discovery shocked the public because it did not only verify Einstein's prediction in his General Theory of Relativity but also verified the feasibility of a new method for astronomical observation. This paper is going to discuss about some principle and technology applied in LIGO and introduce the history, current situation and future development of LIGO.

II. The Basic Principle and applied technology Of LIGO

LIGO is generally based on the simple model of laser interferometer and applies other technologies like damping system and vacuum ion pump.

A. Laser Interferometer

The basic principle of LIGO is the interference of light and LIGO can be seen as a large interferometer with very high accuracy. Interferometer is a device where more than one rays interfere with each other and produce the pattern of interference, from which some characters of the object studied can be figure out. Interference is one tool frequently used in engineering and scientific research and has many types. In Fig. 2, is a model of one of the simplest interferometers called Basic Michelson interferometer. When it works, the laser source radiates a ray of laser to the beam splitter, where one part of the light passes through the beam splitter and keeps going in its original direction and the rest is reflected to upside. The two rays of split light merge again after their two respective reflection and produce pattern of interference. If the relative positions of the components of the device, like laser source, mirrors, beam splitter and photodetector do not change, the distances that the two rays of light traveled will not change and the pattern they produce will not change. However, when some events, like the gravitational waves that pass by change the scale of the nearby space, the relative position of the components of the device will change, causing the change of the interference pattern. This is actually the basic structure of LIGO. As seen in Fig. 1, the two LIGOs in Livingston and Hanford are both L-shaped. The two mirrors are placed at the end of the two long arms respectively and the long distance between the two mirrors and the beam splitter is one of factors that make LIGO's high accuracy.

However, the LIGO's accuracy is $10^{-18}m$ which is a thousandth of the proton's scale[5]. The length of the arms of LIGO is still not long enough to make its accuracy to this order of magnitude if it is merely a basic Michelson Interferometer. Actually, in real LIGO project, a component called "Fabry Perot cavity" was installed between the mirrors and beam splitter as Fig. 3. The light can be reflect back and forth for about 280 times from its entering Fabry Perot cavity to its leaving[5]. This component increases the sensitivity of LIGO dramatically and also saves the space occupied by LIGO.

B. Power Boost Laser

To improve the sensitivity of LIGO, the intensity of the laser also need enhancing to produce clearer pattern of interference. The theoretic value of the power LIGO need is 750 kilo Watts[5]. However, for LIGO working at full power, the laser produced and multi-amplified is still only 200 watts and it is technically difficult to increasing the intensity produced by LIGO[5]. To fix the problem, a "power recycling" mirror was installed between the source of laser and the beam splitter (Fig. 4), which is a kind of "one-way" mirror. It means that the light can go through it from its left side to its right side easily while almost all be reflected back when coming from the right side. In this way, the part of the laser that used to return to back (travel toward the source of the laser) can be reflect back and join the light entering, which realizes the function of recycling[5]. Therefore, the intensity of the light that finally comes to the photodetector will be much higher than it when produced by the source initially.

Manuscript received June 13, 2018.

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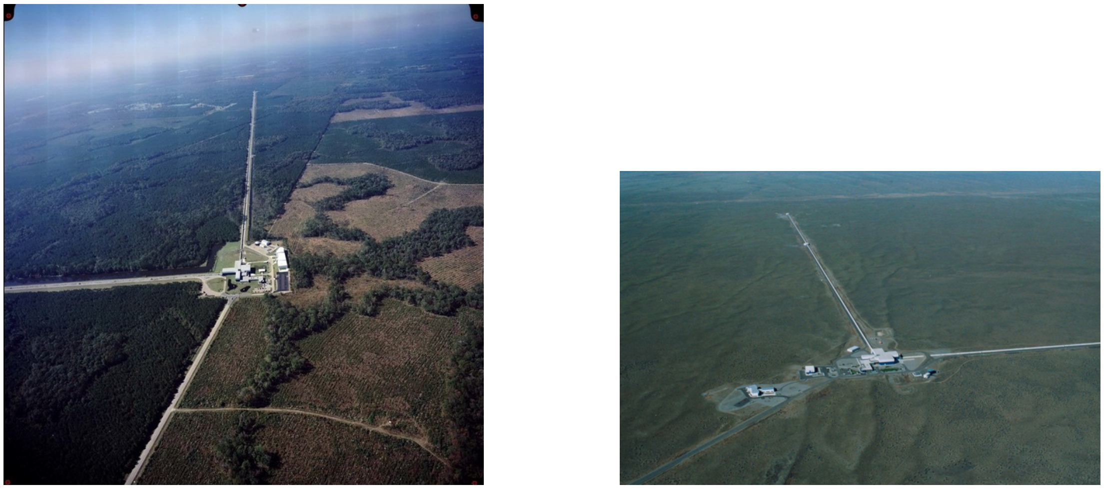

(a) (b)

Fig. 1: Aerial pictures of LIGO.[3][4]

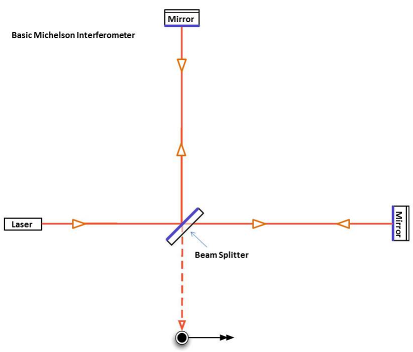

Fig. 2: Model of basic Michelson interferometer. The one ray of light is separated into two by the beam splitter and the two split ray of light merge again into one after two reflection and produce pattern of interference.[2]

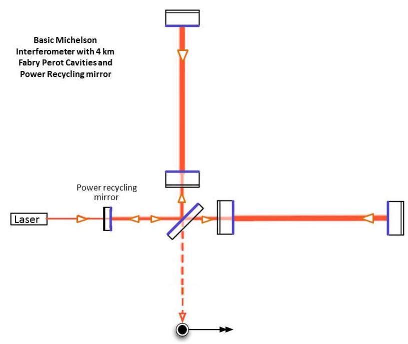

Fig. 4: Model of interferometer with "power recycling" mirror. The "power recycling" mirror can enhance the intensity of the laser produced by LIGO to get clearer pattern of interference.[7]

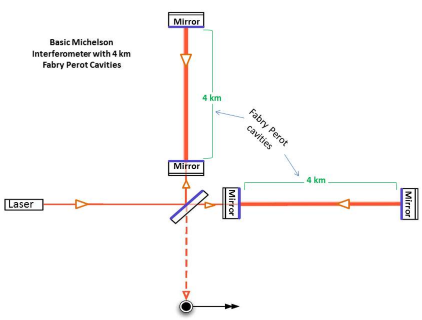

Fig. 3: Model of interferometer with Fabry Perot cavity. Fabry Perot cavity allows the light travel between the mirrors repeatedly and increases the distance that the light travels to make the device more sensitive.[6]

C. Seismic Isolation

Because LIGO is so sensitive that any slight disturbance from the outside can affect the detection result. To overcome this potential disadvantage, the system that eliminates outside vibration is essential for LIGO to avoid noises to cover the the signal produced by the gravitational waves, which includes the positive damping system and passive damping system (Fig. 5), which work together to keep the components stable[9].

1) Active Damping System: The Internal Seismic Isolation (ISI) system can sense the motion of the outside environment and perform inversely to keep the components of LIGO stable[9].

2) Passive Damping System: The passive damping system of LIGO suspends the mirrors with "quad", which is a 4-staged pendulum including four 0.4mm thick fused-silica fibers[9]. This passive damping system helps eliminate the noises further and the heavy wight (40 kilograms each) of the mirrors also restrains the vibration of the mirrors at the same time[9].

D. Vacuum

In order to avoid the air particles in Brownian movement to impact the mirrors irregularly and to affect the way that the laser ray travels to produce noises, all the components of LIGO

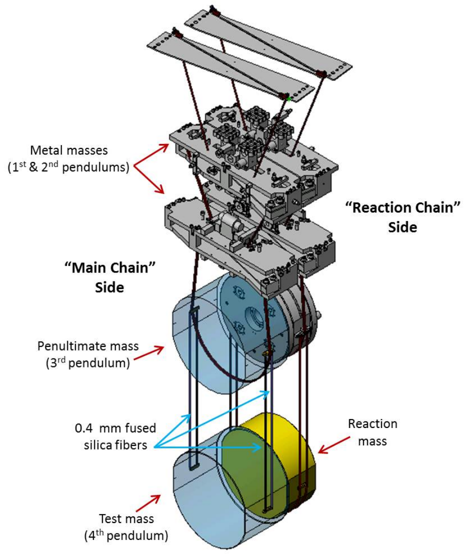

Fig. 5: Passive damping system. The "Main Chain" side was faced with the rays of laser while the "Reaction Chain" side is responsible for keeping the mirror stable.[8]

system need placing in the nearly absolute vacuum. This strict condition is realized by the following measures. (1)Keep the tubes' temperature between 150°C and 170°C for a month to drive out the air; (2)Use Turbo-pump vacuums to pump out the air further; (3)Use the ion pump to first charge and then extract the single air molecules contained in the metal with electric field[9]. These measures enable the space inside LIGO reach the stage that the air pressure inside is only one-trillionth of it at sea level.

E. Mirrors

The high-intensitied laser requires high quality of the mirrors because slight absorption of the light by the mirrors can produce lots of heat during the about 280 reflection of the light in the Fabry Perot cavity, which will dramatically increase the temperature of the mirror, changing its physical properties and causing inaccuracy of the result and danger. Therefore, the mirrors of LIGO was made of very pure fused silica glass, which only absorb 1 photon out of 3×10^6 that meet the mirrors[9]. Furthermore, the mirrors are polished sophisticatedly to the order of magnitude of atom[9], which assures that the light will not travel out of its track during its about 280 reflection in Fabry Perot cavity.

F. Dual Detector

The LIGO was composed of two detectors, which are located in Livingston, Louisiana and Hanford Washington. The detector in different place are separated by 3002 kilometers. The reason to separate the two devices so far is that the impact of irrelevant vibrations on the earth like earthquake on the device at different place is different. Therefore, if the two devices get same or similar signals, conclusion can be derived that the signal was not cause by the irrelevant vibrations[10]. Furthermore, same or similar results from two devices at different places can be more convincible than it from one.

III. The Revolution History Of LIGO

A. Weber bar

Actually, LIGO is not the first device designed for the detection of gravitational waves. The first person that proposed idea and tried detecting gravitational waves is Joseph Weber, who invented a device called Weber bar as his tool[11]. At that time, Weber's Weber bar was mainly composed by two large aluminium bars suspended by thin lines, each of whose length measured 2 meters and diameter measured 1 meter. The quality factor of the two bar is very high, which means it cost very little energy when oscillating. Therefore, when gravitational waves passes the device, squeezing and stretching the space around, resonance can be generated, which will be amplified by piezoelectric sensors installed on the two bars to be the signal that can be detect. In1969, Weber claimed that the signal of gravitational wave was detected by his device[12]. However, his experiment result was found unable to be repeated by other research group and was seen as a mistake[16].

Although Weber bars had not produce any valid results and have flaws like inadequate accuracy and instability and its principle was different from today's LIGO, his efforts showed the possibility to detect gravitational waves and arose other researchers' interest in this field. The laser interferometer was invented by his student Robert Forward and his efforts for early try of detecting gravitational waves are universally acknowledged by the researchers who participated in the project of LIGO. One of the founder of LIGO, Kip S. Thorne, praised Weber as the "founding father of this field" after their news conference about their first detecting gravitational wave on February 11th, 2016[16].

B. Early Theoretic Works and Construction of LIGO

In 1962 two Soviet Physicists, Mikhail Gertsenshtein and Vladislav Pustovoit, formally proposed the idea of detecting gravitational waves using the interference of laser but did not conduct it[13]. Later in 1969, Rainer Weiss, who is specialized at laser, was inspired by a paper of Pirani Felix[14]. He could not understand Weber's experiment and had not heard the theoretic works accomplished by the two Russian Physicist at that time. Therefore, he designed a method of detecting gravitational waves with a interferometer on his own[15]. His idea was published on the internal periodical of Massachusetts Institute of Technology[15] but did not arose too much repercussions or convince many people. Later, he also made a real mini prototype which was 1.5 meter long using military fund, but was terminated before the device could work successfully[16].

Kip Thorne, who used to be suspicious of the method proposed by Weiss, reconsidered the method and was convinced of its feasibility after his communication with Weiss[16]. He persuaded California Institute of Technology to fund him with the project and invited Ronald Drever to help to create a lager prototype in 1983, whose length is 40 meters[16]. This project verified the feasibility of the interferometer whose length order of magnitudes is kilometer.

At that time, MIT and Caltech conducted their detection for gravitational waves separately. When the two group both applied fund from NSF (National Science Foundation), they had to merge their project under the pressure from NSF that refused to fund two large project with same aim[16].

The LIGO project suffered a period of difficult time because of conflict between the members and funding issue between 1984 and 1994 and made little progress on research[16]. This project was restarted in 1994 in Hanford, Waston State and 1995 in Livingston, Louisiana and roughly completed in 1997[16].

The initial LIGO (iLIGO) worked between 2002 and 2010[16]. However, it did not discover any signal of gravitational wave during its service because of its inadequate accuracy[16]. Even though, as a pathfinder, iLIGO developed basic technologies for LIGO. The LIGO device began its updating, which ended in 2015[16].

C. Successful Observation

From February, 2015, aLIGO (advanced LIGO) entered its "engineering mode" (test mode), and began its formal observation in September. It was not many days after its formal observation that LIGO first detected the signal of gravitational wave in human's history. The finding was verified carefully before the conference on February 11th, 2017[1], which testified Einstein's prediction in his General Theory of Relative and the feasibility of gravitational wave detection.

Till now, LIGO has detected gravitational wave of more five astronomical events, GW151226[17], GW170104[18], GW170608[19], GW170814[20] and GW170817[21], named after the date they were found.

IV. The Future Development Of LIGO

A. "A+"

"A+" proposal provides a guideline for modest-cost upgrade on the base of aLIGO during 2017 and 2026. In "A+", squeezed light injection reduces the quantum noise, application of better coating with lower absorption rate reduces the thermal noise caused by the photon absorbed by the mirrors and the adoption of high stress fiber that used in quad can reduce suspension thermal noise by restrain the vibration of the mirrors[22]. According to theoretic estimation, these measures combined together can double the sensitivity of LIGO[23].

B. LIGO Voyager

LIGO voyager (LV) is another more important upgrade based on existing aLIGO, which is planned to come to use during 2027 and 2028[22]. LIGO voyager will also double sensitivity of original LIGO and make its minimum frequency that can be detected half of its original value[22]. LV will apply a laser of higher energy (300-700W) and higher frequency (wavelength at 1550 nm) to reduce the scattering of the laser[22]. To neutralize the extra thermal noise and improve its sensitivity, LV is going to work in a temperature lower than $123K$. Besides, LV also will use the mirror with bigger weight (160 kilograms) to restrain noises caused by vibration[22].

C. LIGO Cosmic Explorer

LIGO cosmic explorer is a proposal for building a new observatory at a new place to detect the binary neutron star beyond one red-shift[22]. The proposal has not been mature yet. However, it is considered to have arms of much longer length (40kilometers) and work with other existing LIGO facilities[22].

D. Scientific Plans And Facilities Of The Same Series As LIGO in Other Country

There are also many facilities for gravitational wave detection in other countries. Some of them have cooperation with LIGO, like VIRGO and GEO600 in Europe while others are still under construction like KAGRA in Japan. China also raised its proposal of gravitational wave observatory called Taiji Plan and Tianqin Plan, which, however, are different from LIGO because it is not based on the ground but detects the gravitational waves with the facilities in the space. The space-based facility will avoid the noises from the ground and, therefore, more sensitive.[24][25] Facilities like LIGO can work together not just for reverifying Einstein's prediction for this mission has been generally completed by aLIGO but to develop a new method for astro-observation for human being because compared with the traditional observatory detecting electromagnetic wave, LIGO observes astronomy phenomena with gravitational wave. Besides, the cooperation and data sharing between the facilities can reduce the negative effect of noises on the results and make the results more convincible.

V. Conclusion

The development of LIGO and gravitational waves detection have gone through a long, difficult time and have improved its accuracy and stability with its repeated iteration. Through the first successful detection of gravitational wave, LIGO did not only verify Einstein's prediction in his General Theory of Relative but also introduced a brand new method for astronomical observation. That is, detecting the gravitational waves rather than the traditional way, detecting the electromagnetic waves. In the future, as the further updating of LIGO, the completion of similar facility and increasing of the corporation between the researchers of similar facilities, the accuracy of the detection of gravitational waves will be improved further and it will make possible for more specific data of gravitational waves detection, which may make gravitational detection one of the mainstream observation methods and promote people's knowledge about the space.

Acknowledgment

The author would like to thank everyone and everything.

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