



Full length article

The recent development of interferometer prototype for Chinese gravitational wave detection pathfinder mission

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ABSTRACT

A brief progress report is presented on the interferometer prototype of the Chinese gravitational wave detection pathfinder mission. After careful consideration of the temperature fluctuation induced noise and the electronic noise, the noise spectra density of the interferometer prototype reached $100 \text{ pm}/\sqrt{\text{Hz}}$ at 1 mHz and achieved $15 \text{ pm}/\sqrt{\text{Hz}}$ in high frequency region. However, in some frequency range from 3 mHz to 30 mHz, further improvement is still needed. Possible improvement is also discussed.

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1. Introduction

One hundred years after Einstein's prediction of the existence of the gravitational wave (GW), the Laser Interferometer Gravitational-wave Observatory (LIGO) has finally detected the GW signals from binary black hole mergers [1–4]. The ground-based detectors are sensitive to the mergers of binary system which contains compact objectives such as neutron stars and small black holes [5–7]. Complementary to the ground-based GW detector, space-borne antennae, such as Laser Interferometer Space Antenna (LISA) [8,9], listen to the GWs with the frequencies from 0.1 mHz to 10 Hz [8–14], which are believed to have great astrophysical and cosmological significance [15–17]. Besides LISA mission, many other space-borne interferometer GW detectors have been brought forward to explore the darkest side of the universe where the electromagnetic wave cannot access. However, the GWs are too weak that even the sensitivity of the antenna with the state of the art is barely enough to probe the most interested GW sources. It is, therefore, necessary to demonstrate and test the related technologies before the eventual launch of the space-borne GW detector. For example, time-delay interferometry (TDI), the technology for inter-satellite interferometry, has been successfully demonstrated [21]. Besides TDI, The LISA pathfinder (LPF), launched at the end of 2015, aims to demonstrate the laser interferometer, the inertial sensor, and the drag-free control for LISA mission [18,19]. After the LPF sending back the scientific data

in 2016, people, for the first time, have achieved the sub-femto-g free fall and the heterodyne interferometry has reached femtometer level [20].

China started its pursuit of GW detection in space in 2008. Inspired by Peter Bender's advanced laser interferometer antenna (ALIA) mission, an independent Chinese proposal was made in 2011 under an international collaboration between Chinese Academy of Sciences and Albert Einstein Institute [23]. In 2015, the proposal was updated as a realistic descope version [13].

As the counterpart of the LPF, a Chinese pathfinder mission was taken into consideration in 2012 and Chinese Academy of Sciences started to develop the interferometer prototype at the time [24,25]. In 2016, encouraged by the great successes of LIGO and LISA, China set up two LISA-like projects, Taiji and Tianqin [13,14,22]. While Tianqin claimed to detect GWs in the high frequency region, Taiji focused on GWs from 0.1 mHz to 1 Hz. In this paper, the recent progress in the interferometer prototype for the Chinese pathfinder mission has been presented, including the requirement, the setup, the noise and the experiment results, and further improvement is also discussed.

2. Requirement

In order to probe the GW signals from intermediate mass black hole (IMBH) binaries at high redshift descended from the heavy Pop III stars or from Intermediate Mass Ratio Inspirals (IMRIs) harbored in globular clusters, the position noise budget required by Taiji should be $5\text{--}8 \text{ pm}/\sqrt{\text{Hz}}$ [13]. The contribution from the interferometer alone should be around $1 \text{ pm}/\sqrt{\text{Hz}}$. The Taiji pathfinder will test the space laser ranging interferometer at the level of

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100–300 pm/ $\sqrt{\text{Hz}}$ (to be determined soon). The constrain of the noise contribution from the interferometer alone for Taiji pathfinder is set to be 20 pm/ $\sqrt{\text{Hz}}$ (see Fig. 1).

On the other hand, the interferometer for the Chinese pathfinder mission will also be used as a diagnostic tool to monitor the translational and angular motion of the proof masses. The proof masses will be served as the inertial references for the drag-free control and as the test particles to sense the curvature of the space-time. Similar to the LPF, the required precision for the interferometer to measure the translational and angular motion of the proof masses are 1 nm/ $\sqrt{\text{Hz}}$ @1 mHz and 100 nrad/ $\sqrt{\text{Hz}}$ @1 mHz respectively.

By the technique of the differential wavefront sensing, the precision of the angular jitter measurement has already arrived 10 nrad/ $\sqrt{\text{Hz}}$ in our previous work [26,27]. Thus only the performance of the displacement measurement will be considered here. In our work [25], the displacement noise spectra density of the interferometer prototype achieves 100 pm/ $\sqrt{\text{Hz}}$ above 0.01 Hz. Below 0.01 Hz, the noise spectra density quickly climbs up and reaches 1 nm/ $\sqrt{\text{Hz}}$ at 1 mHz (Ref. [25] Fig. 8). To meet the require-

ment of the translational motion, the noise floor of the interferometer prototype needs to be improved by a factor of 5 or more.

3. Setups

The optical layout for this work consists of the modulation bench and the optical bench (see Fig. 2). Out of the vacuum chamber is the laser modulation bench, in which the laser is split into two parts and then the frequency is modulated by two AOMs (acousto-optic modulators, the central frequency 70 MHz). The difference of the AOMs modulation frequencies is set to be 1 MHz. The laser used here is the solid state laser and the wave length is 1064 nm. It's frequency instability is 1 MHz in two hours.

The optical measurement bench has three independent interferometers in the vacuum chamber (Fig. 3). The first is the reference interferometer (Fig. 3a), which is used to read out the optical path-length noise picked up by the two modulated beams before entering the vacuum chamber. The second interferometer is used to measure the movement of a reflector attached on a nano-positioning stage (Fig. 3b). The third one is to measure the relative displacement between the two reflectors (Fig. 3c).

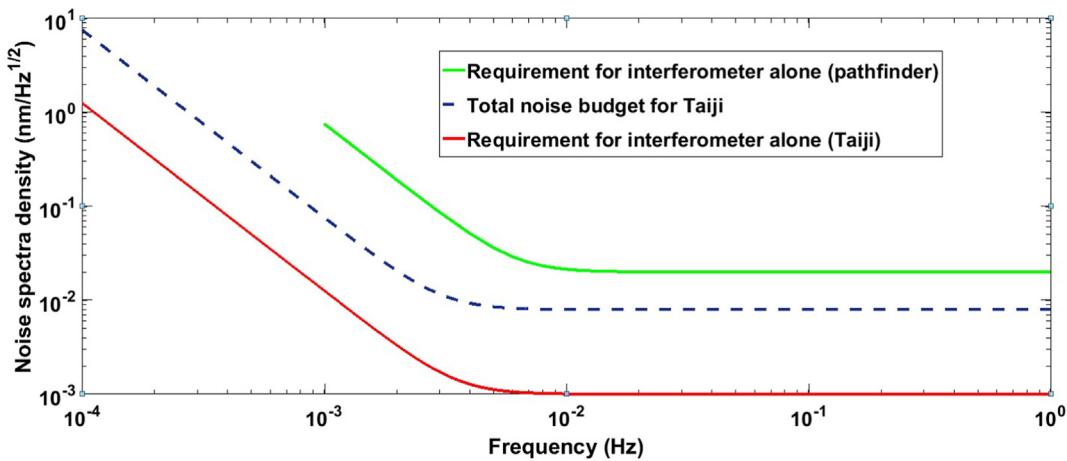


Fig. 1. The noise spectra density diagram.

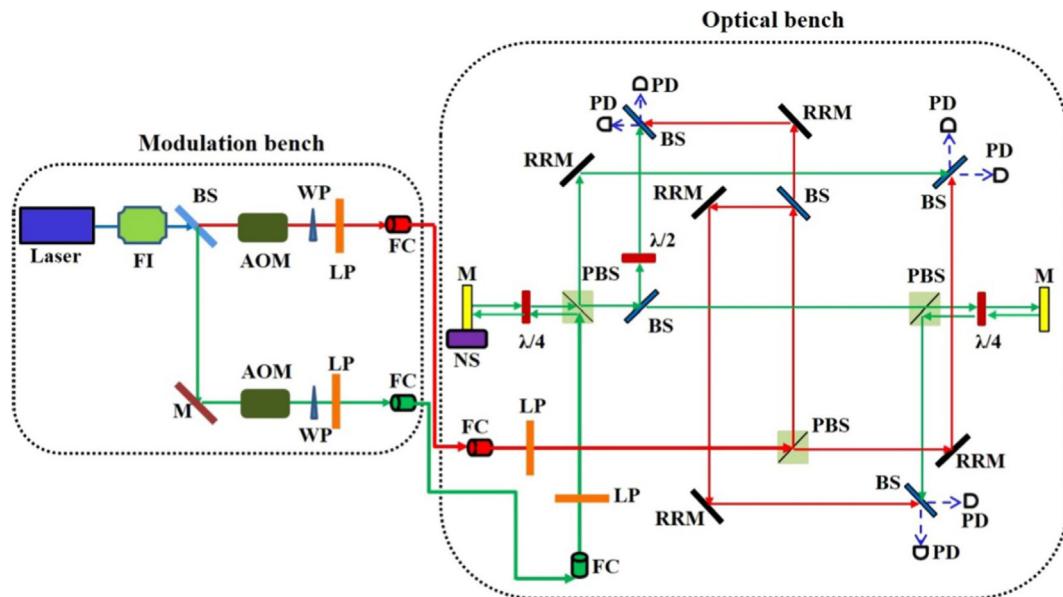


Fig. 2. The layout of the optical setups.

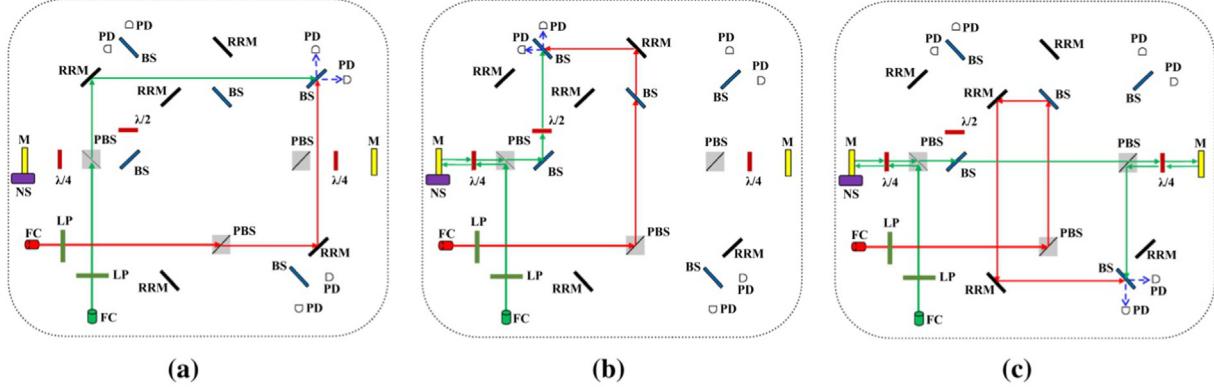


Fig. 3. The three independent interferometers.

A side view of the optical measurement bench is shown in Fig. 4. The three interferometers are all designed to be equal arm-length interferometers in which the laser frequency noise is minimized. The sensed beat signal of the interferometers is converted to the voltage by the quadrant photodiodes. The bandwidth of the diodes are from 4 kHz to 5 MHz. The phasemeter used in this work is built by ourselves [28,29] and its readout precision is $2 \mu\text{rad}/\sqrt{\text{Hz}}$.

4. Noise

In the interferometer prototype, the mirror mounts are made of aluminum with the typical thermal expansion coefficient (TEC) of $2.0 \times 10^{-5}/\text{K}$. The mirrors are made of fused silica, and its TEC is one order smaller than that of aluminum. Because of the imperfect shape matching between the mounts and the mirrors, the stress force between the mounts and the mirrors will change when temperature fluctuates. Due to the photo-elastic effect, the refractive index of the mirrors experienced by the transmitting beam will also change which further varies the light path-length of the beam (Ref. [30] chapter 15.5).

Another noise driven by the temperature fluctuation is the dependence of the refractive index upon the temperature [31,32]. The refractive index of mirror will not be a constant with respect to temperature changing. If the fluctuation of the temperature is small the first order approximation could apply,

$$\left| \frac{dn}{dT} \right| = C, \quad (1)$$

where dn is the change of refractive index, dT is the change of temperature, C is constant called temperature coefficient of refractive index. For typical glasses, C will be 10^{-6} to $10^{-5}/\text{K}$ at room temperature. If the temperature fluctuation reaches $0.01 \text{ K} \sqrt{\text{Hz}}$, for a 1 cm thick mirror, the changing of light path-length will be 100 pm to $1 \text{ nm}/\sqrt{\text{Hz}}$.

The third low-frequency noise comes from the optical fiber. The single mode fiber for 1064 nm is usually made of silica which has the TEC of $5.0 \sim 6.0 \times 10^{-7}/\text{K}$. A small temperature fluctuation of 1 K acts on a 1-m long fiber could convert into 500–600 nm path-length change. Another problem is the small variation in the polarization of the laser coming out of the fiber. When the two beams interfere, the variation of polarization induces amplitude modulation on the beat signal which will give rise to unwanted noises.

In order to reduce the noises induced by the temperature fluctuation, a thermal shield is built around the vacuum chamber. The temperature drifting is improved by a factor of 6 inside the thermal shield (see Fig. 5). The amplitude spectra density of the temperature fluctuations are also plotted in Fig. 6.

The noises mentioned above mainly contribute to the low frequency part (0.1 Hz–1 mHz) of the noise spectra density. The noise dominate the high frequency part (above 0.1 Hz) is believed from electronics and relatively easy to suppress. The problems related to the inter-satellite interferometry such as the suppressions of the laser frequency noise and the ultra stable oscillator jitter noise will not be addressed here. To solve these problems the TDI technology has to be employed. A comprehensible introduction and the first ever experimental demonstration of TDI could be referred to [21].

5. Experiment and results

Then the experiment is carried out as follows. By running the three interferometers on the optical measurement bench, three phase measurement data can be obtained. ϕ_1 is the data from the reference interferometer and ϕ_2 (or ϕ_3) is from the second (or the third) interferometer. Usually the optical phase noise from the laser modulation bench and the optical fibers could be hundreds of nanometers (see Fig. 7 and discussion above). This noise will be readout by the reference interferometer and then subtracted from ϕ_2 (or ϕ_3). The difference between ϕ_1 and ϕ_2 (or ϕ_1 and ϕ_3) will be used as the representative of the residue noise in the interferometers.



Fig. 4. The side view of the optical measurement bench.

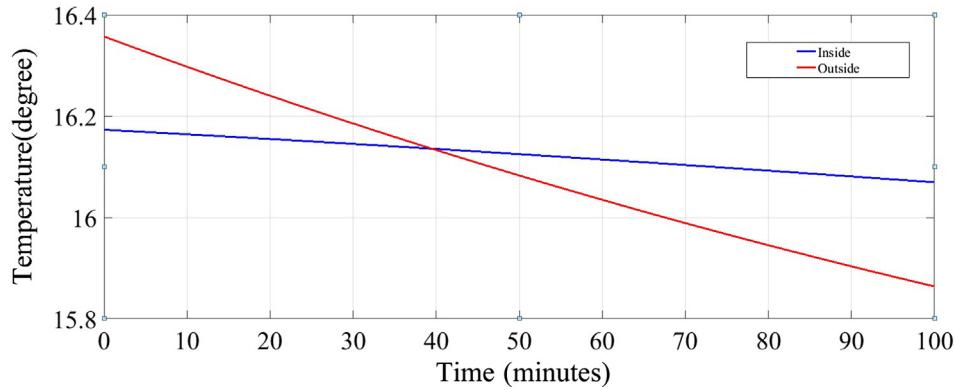


Fig. 5. The temperature fluctuation inside (blue line) and outside (red line) the thermal shield. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

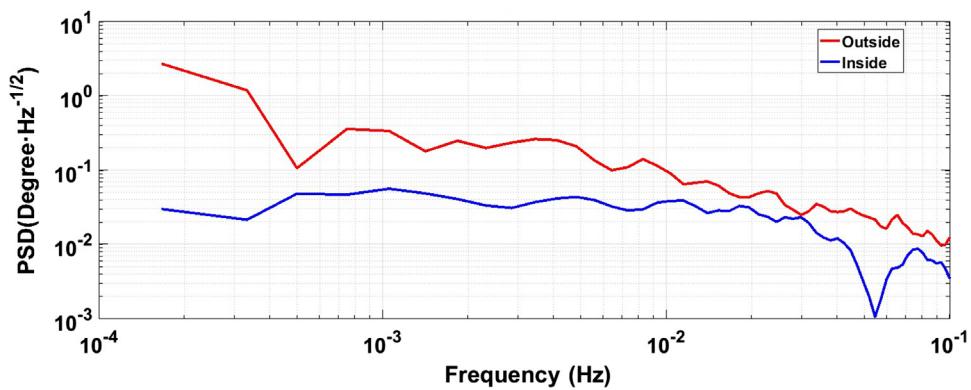


Fig. 6. The amplitude spectra density of the temperature fluctuations.

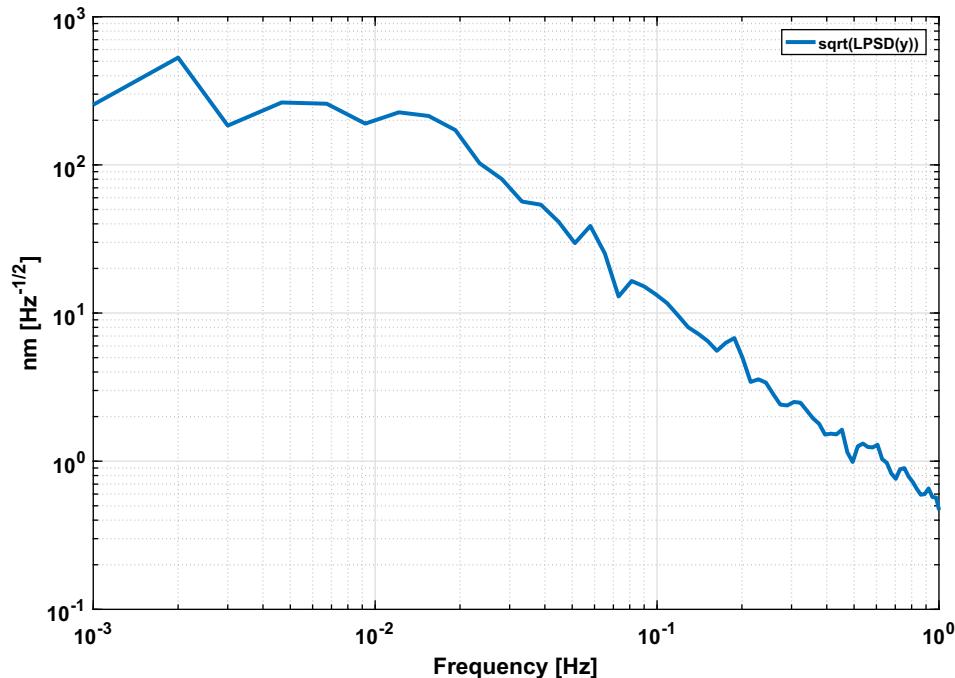


Fig. 7. The fiber noise amplitude spectra density.

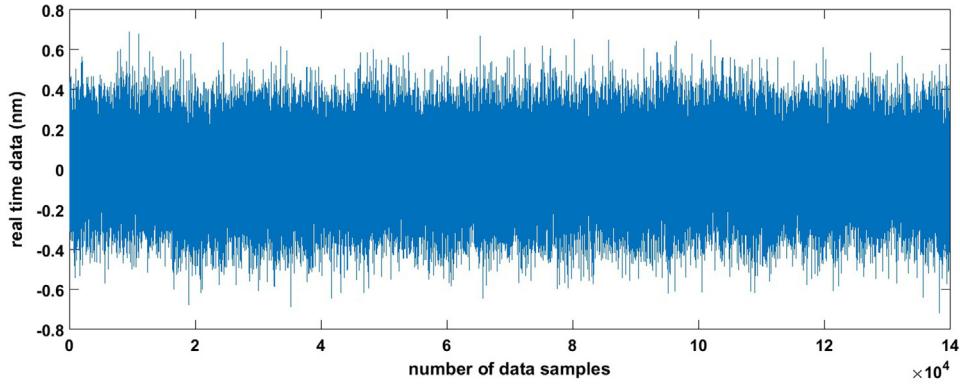


Fig. 8. The experimental data.

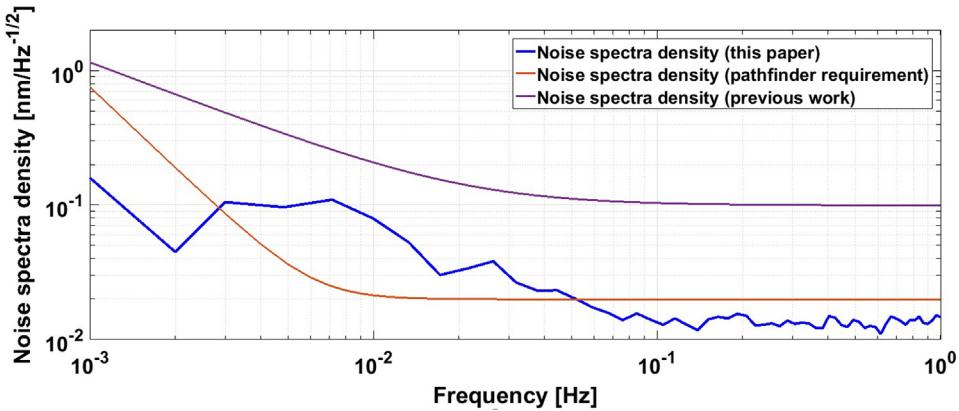


Fig. 9. The noise spectra density of this experiment, the requirement of Chinese pathfinder mission and the fitting curve of previous result.

An example of the phase difference $\phi_2 - \phi_1$ is in Fig. 8. The data sampling frequency is 140 Hz. The noise spectra density is calculate via **LTPDA** toolbox, a software developed by Albert Einstein Institute (Hannover) [33].

The result of this experiment is plotted in bold blue line in Fig. 9. Compared to the result of our previous work, the noise spectra density of the interferometer is improved in all the frequency band. In the frequency region higher than 30 mHz, 15 pm/ $\sqrt{\text{Hz}}$ has been achieved. At 1 mHz the noise level is brought down to 100 pm/ $\sqrt{\text{Hz}}$. However, from 3 mHz and 30 mHz, the new results still fail to meet the requirement of Taiji pathfinder.

6. Discussion

Based on the optical setup of our previous work, a thermal shield is constructed and the thermal stability of the experimental system improved by a factor of 6. Thus the noises induced by the temperature fluctuation have been suppressed. Unfortunately the major part of the optical fiber cannot be inclosed in the thermal shield, which gives rise to a significant path-length noise. To solve this problem, the fiber noise is measured by a reference interferometer and subtracted from the data from the scientific interferometer. Meanwhile, all the electronic components are carefully analyzed and the noisy units has been replaced. The imperfect matching of the impedance and the attenuation of the transmitting wires have also been solved. The result improves significantly compared with the previous result. In the frequency below 3 mHz and above 30 mHz, the interferometer prototype has reached requirement of the Taiji pathfinder. However, it is still need to improve the response by 2 or 3 times from 3 mHz to 30 mHz.

We hypothesize that the noise from 3 mHz to 30 mHz still comes from photo-elastic effect (or stress birefringence) mentioned above. In the next step, the so called "low stress optical bonding" technique [34,35] will be employed to improve the performance of the interferometer in the lower frequency band.

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