Optics and Laser Technology 105 (2018) 146–151

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

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

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ARTICLE INFO

Article history:
Received 17 October 2017
Received in revised form 8 February 2018
Accepted 21 February 2018

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 pm/$\sqrt{\text{Hz}}$ at 1 mHz and achieved 15 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.

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 5–8 pm/$\sqrt{\text{Hz}}$ [13]. The contribution from the interferometer alone should be around 1 pm/$\sqrt{\text{Hz}}$. The Taiji pathfinder will test the space laser ranging interferometer at the level of

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https://doi.org/10.1016/j.optlastec.2018.02.042

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 requirement 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).

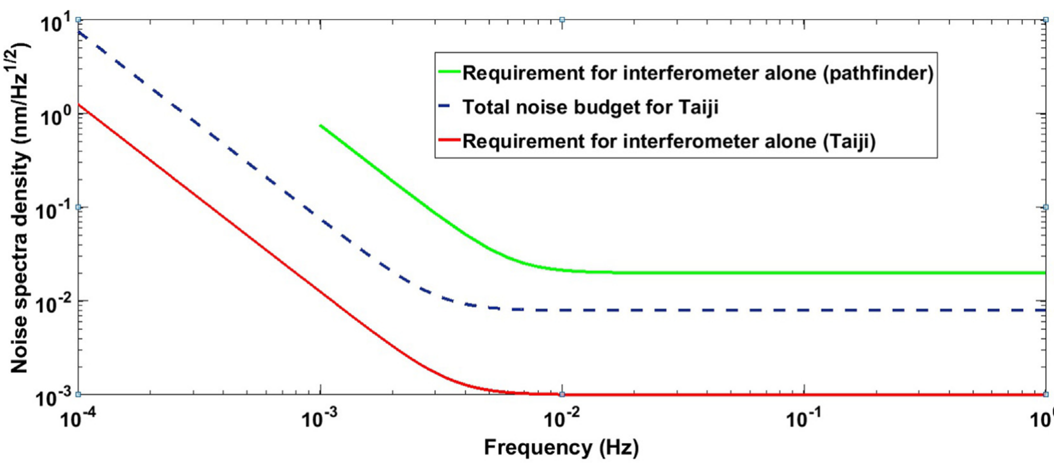

Fig. 1. The noise spectra density diagram.

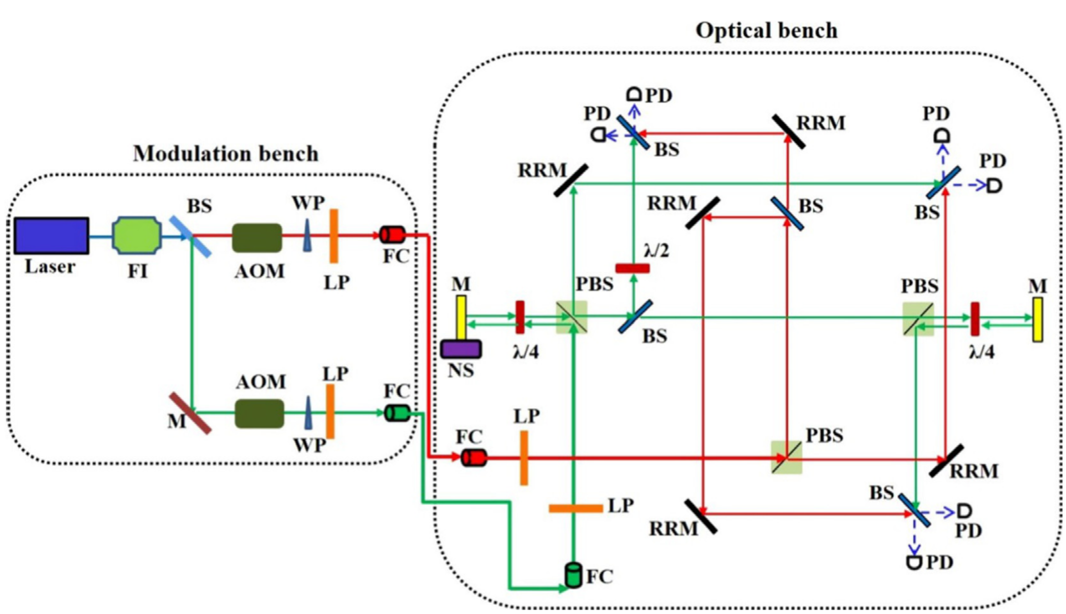

Fig. 2. The layout of the optical setups.