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High stability laser source for Taiji-1 satellite

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A high stability Laser source at 1064 nm for Taiji-1 satellite is reported. The key component of the Laser source is a nonplanar ring oscillator (NPRO) solid laser with linewidth of 260 Hz. Frequency noise and power noise of Laser source are greatly improved by applying precision driving current control and temperature control. The frequency noise of 0.1 MHz/sqrt(Hz)@ 0.1 Hz and the power noise of 0.02%@0.1 Hz are obtained. Its working performances in-orbit are analyzed and compared with the ground test, showing negligible variation.

Keywords: Taiji-1; Laser source; NPRO; frequency noise; power noise; stability; in-orbit.

1. Introduction

The Chinese Space-borne gravitational waves (GWs) Detection Program "Taiji" is to detect the GW within the frequency band between 0.1 mHz and 1 Hz.[1] To achieve the final objectives, the technology road map related to "Taiji" program take three steps, "single satellite", "double satellites" and "three satellites", The "single satellite" mission, called Taiji-1 as the first step of the Taiji Program in Space has been successfully launched on 31 August 2019, and has been successfully completed its in-orbit tests, making a breakthrough in China's GW detection. It aims to test the key technologies such as high-precision and ultra-stable laser interferometer, gravitational reference sensor, ultra-high precision drag-free control and ultra-stable and ultra-static satellite platform.

One of the key devices of Taiji-1 is a high stability Laser source. Because the GW signal is very weak, the noise performance of the laser including frequency noise and

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intensity noise is demanding. The performance of the Laser source directly determines the measurement ability of the space GW.[2,3]

The most promising laser system candidate is a stand-alone high power nonplanar ring oscillator (NPRO) laser or a fiber amplifier seeded by a low power NPRO.[4–6] In this paper, we developed a high stability Laser source for the Taiji-1 satellite interferometer platform to realize high stability interferometric measurement. The core of the Laser source is a high stability NPRO laser. High stability 1064 nm single frequency output is obtained by 808 nm LD pumped Nd:YAG crystal, and the linewidth reaches sub-KHz with frequency noise of 0.1 MHz/sqrt(Hz)@0.1 Hz and the power noise of 0.02%@0.1 Hz.

2. Design of the Laser Source

The schematic diagram of Laser source is shown in Fig. 1(a). Driving current and temperature are controlled by +3.3 and ±5 V secondary power supply which are obtained by DC/DC conversion from +28 V power supply with 10 W power consumption. The core of the Laser source is a highly stable NPRO laser by 808 nm LD pumped Nd:YAG crystal. Finally, 1064 nm laser output is obtained through a single-mode polarization maintaining fiber. The schematic structure of the 2.5 kg Laser source with diameters of 240 mm × 208 mm × 58.5 mm is shown in Fig. 1(b).

2.1. *Laser design*

Figure 2 shows the working principle of Laser source. Stable single frequency operation at 1064 nm was obtained from NPRO laser by 808 nm LD pumping. An optical isolator was used to prevent laser feedback into the Laser source. Laser from isolator was divided into two laser beams (output 1 for 20% of laser output and output 2 for 80% of laser output) by beam splitter. Output 2 is the main output beam with 40 mw and output 1 is the monitoring signal with 10 mw.

The core component of Laser source is a hybrid integrated NPRO laser. An NPRO is a stable, compact and rugged laser oscillator with a special monolithic design.[4] A schematic diagram of the NPRO laser is shown in Fig. 3(a). The device is mainly comprised by pump fiber assembly, Nd:YAG NPRO crystal and coupled fiber assembly. The beam from the pump fiber is focused by lens, then injected into NPRO crystal.

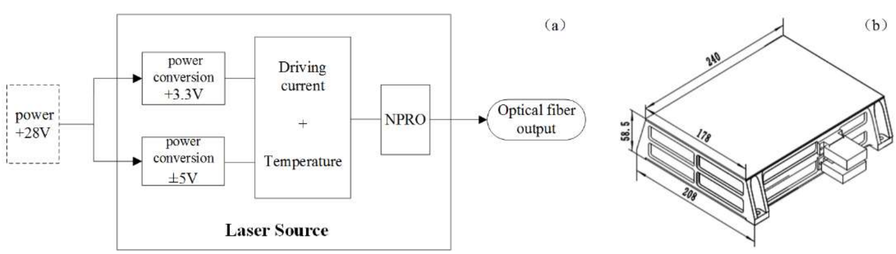

Fig. 1. (a) Schematic diagram of Laser source and (b) structure of Laser source.

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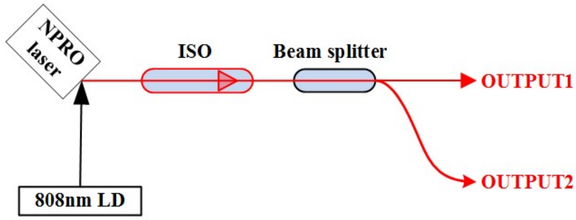

Fig. 2. Working principle diagram of Laser source.

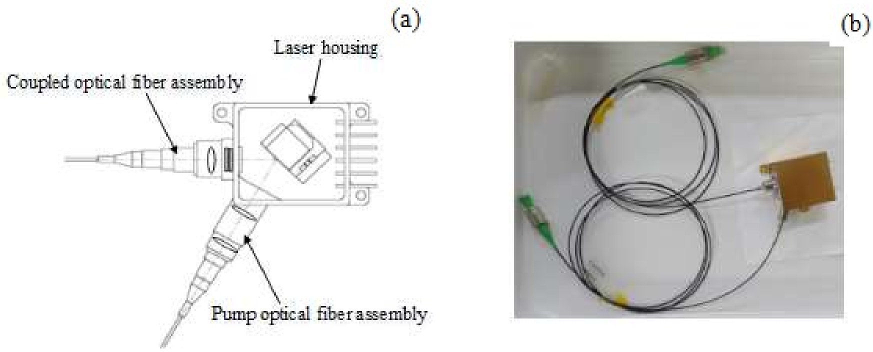

Fig. 3. (a) Schematic of NPRO laser and (b) Photograph of NPRO laser.

The beam from NPRO crystal is focused into the coupled fiber. The shape size of the NPRO crystal is 8 mm × 12 mm × 3 mm. The core diameter of the pump fiber is 105 um with numerical aperture $NA = 0.22$. The coupling fiber is a panda polarization maintaining fiber, the core diameter is 6 um with numerical aperture $NA = 0.12$.

The laser welding technology is used to hermetically seal the NPRO laser body with pure dry nitrogen in it. The photograph of the NPRO laser is shown in Fig. 3(b). The FWHM linewidth of the NPRO laser was measured by using the delayed self-heterodyne method.[7] The central peak of −20 dB bandwidth was measured to be 5.2 kHz by spectrum analyzer in Fig. 4, which corresponds to FWHM linewidth of 260 Hz.

In general, the operating temperature fluctuation will affect the frequency stability of the laser. For NPRO laser, the frequency tuning coefficient is about 3 GHz/°C, so sub mK temperature stability is needed to achieve 0.1 MHz frequency stability. In order to achieve such high temperature stability, two stage temperature regulation is used. First, a Thermo-Electric-Cooler (TEC) is used to control the temperature of the NPRO crystal. Second, another TEC is used to control the temperature of the main laser body.

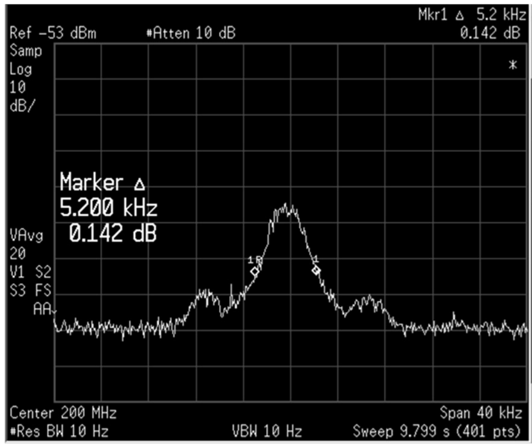

Fig. 4. Delayed self-heterodyne signal recorded by an spectral analyzer. Linewidth at −20 dB was measured to be 5.2 kHz.

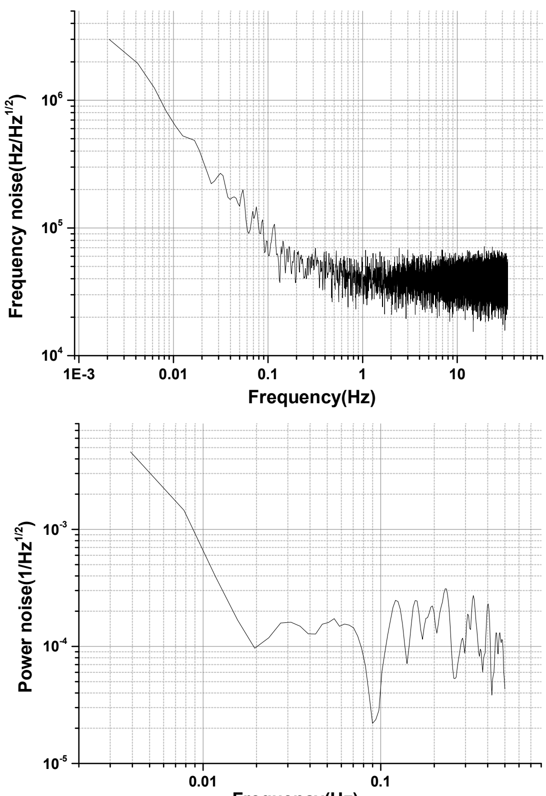

Fig. 5. Frequency and power noise spectral density of Laser source.

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3. Frequency Noise and Power Noise with Laser Source

The frequency noise of Laser source is measured by a highfinesse WS7 wavemeter. The result of the frequency noise is shown in Fig. 5. The frequency noise is about 0.1 MHz/sqrt (Hz) @0.1 Hz. The power noise measured by an optical power meter is about 0.02%@0.1 Hz.

4. Environmental Test on the Ground

Compared with the laser on the ground, the technical challenge of space laser is very complex. The space laser need to have high reliability and meet the requirements of space environment. Space laser will mainly face the following problems brought by space environment: to withstand the huge impact of rocket launch, to work in vacuum environment and to face severe high temperature and low temperature changes. In addition, the laser can work stably and reliably in the complex space environment for a long time. Therefore, it is very necessary to carry out mechanical vibration test, thermal vacuum test and temperature cycling test for the Laser source.

Mechanical vibration tests include Sinusoidal vibration, random vibration and mechanical shock are carried out for our Laser source where the test conditions are shown in Table 1.

Table 1. Mechanical vibration test conditions.

Frequency	100–400 Hz	400–5000 Hz
Shock	+6 dB/oct	1000 g
Axis	X（±），Y（±），Z（±）	
Time	Each axis 3 times	

Frequency（Hz）	PSD
10	0.0062 g^2/Hz
80	0.048 g^2/Hz
400	0.048 g^2/Hz
500	0.066 g^2/Hz
1500	0.066 g^2/Hz
2000	0.038 g^2/Hz
Total（g）	10.69 g
Axis	X, Y, Z
Time	Each axis 1.5 min

Frequency（Hz）	PSD
5–15	11.11 mm
15–100	10 g
Axis	X, Y, Z
Scan rate	4 oct/min

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Table 2. Thermal vacuum test conditions.

Pressure	1.3×10^{-3} Pa
Maximum temperature	+28°C
Minimum temperature	+16°C
Cycle times	5.5
Rate of temperature change	≥1°C/min
Storage time	4 h

Table 3. Thermal cycle test conditions.

Pressure	Atmospheric pressure
Maximum temperature	+28°C
Minimum temperature	+16°C
Cycle times	18.5
Rate of temperature change	5°C/min
Storage time	4 h

Thermal vacuum test is carried out for Laser source to verify the working ability in thermal vacuum stress environment. The test condition is shown in Table 2.

Thermal cycle test on Laser source is carried out to check the performance change under the condition of high and low temperature change. The test condition is shown in Table 3.

The test data before and after the mechanical vibration, thermal vacuum and thermal cycle test are compared. The variation of LD power and LD current telemetry signals is all less than 5%. The variation of output optical power is also less than 5%. The variation of wavelength is less than 0.001 nm. The optical and electronic properties of the Laser source have successfully passed those environmental tests.

5. Stability of Laser Source In-Orbit

The performances of Laser source in Taiji-1 are tested in-orbit. According to the telemetry data, the laser data are processed and the changes of LD power and NPRO crystal temperature are compared with the ground test. The telemetry average value of LD power is about 0.900 V in-orbit, as shown in Fig. 6(a), and 0.886 V on the ground test as shown in Fig. 6(b) which shows little variations.

The telemetry average value of NPRO crystal temperature is about 0.639 V in-orbit as shown in Fig. 7(a), and 0.630 V on the ground test, as shown in Fig. 7(b). The variations are very small for LD power and NPRO crystal temperature in-orbit compared with on the ground test.

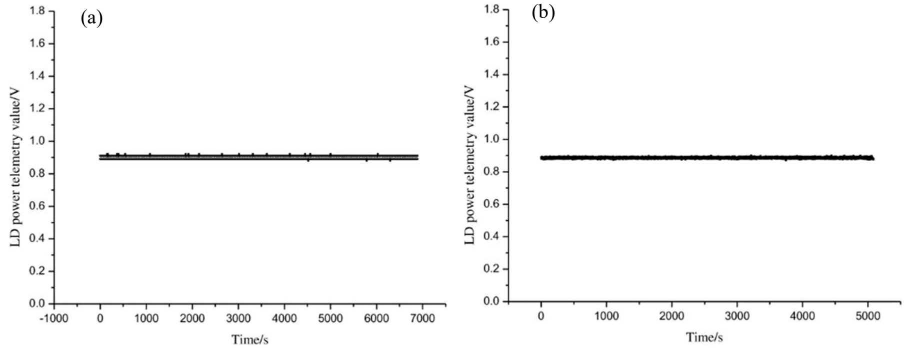

Fig. 6. The telemetry value of LD power: (a) in-orbit and (b) on the ground test.

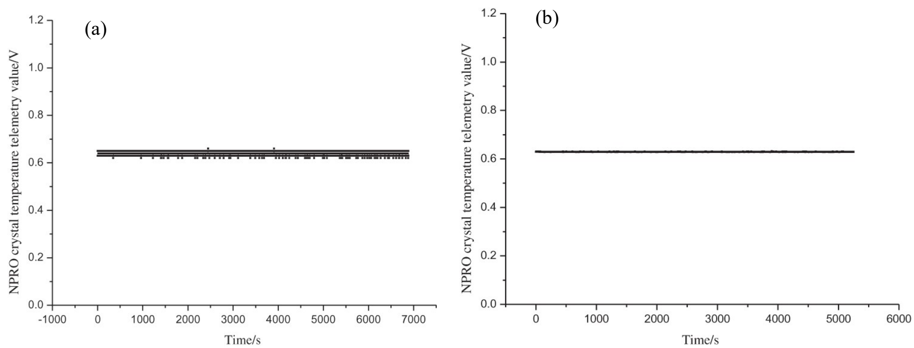

Fig. 7. The telemetry value of NPRO crystal temperature: (a) in-orbit and (b) on the ground test.

6. Conclusions

A high stability Laser source for the Taiji-1 satellite is presented in this paper. The frequency noise is about 0.1 MHz/sqrt (Hz) @ 0.1 Hz and the power noise is about 0. 02%@0.1 Hz. The optical and electronic properties of the Laser source have been passed various environmental routine tests. Compared with the ground test, the performance variations are very small in-orbit.

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