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Figure-8 type optical frequency comb for spaceborne frequency reference

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ABSTRACT

Spaceborne precision frequency reference is one of the essential technologies for extensive applications in metrology, astronomy, remote sensing and global navigation satellite system, and we have researched and developed a high-precision microwave generation system which is based on an optical frequency reference. In our system, a highly-stable optical frequency is generated from an iodine-stabilized laser whose frequency is down-converted to the microwave region without degradation by using an optical frequency comb. The frequency stability of the iodine-stabilized laser would reach 10^{-15} level. In this conference, we will mainly present the development of the optical frequency comb. Nonlinear amplifying loop mirror (NALM)-type mode-locked fiber lasers have two kinds of configurations, figure-8 and figure-9. The figure-9 laser is widely used as an oscillator for the optical frequency comb due to its excellent low phase noise, and there are few reports of the figure-8 mode-locked fiber laser-based optical frequency comb. On the other hand, the operation of the figure-8 would be very stable against external perturbations because of its all polarization-maintaining fiber configurations. Therefore, we have developed low-phase-noise figure-8 lasers for our optical frequency comb because its robustness is suitable for the spaceborne system. One of the significant points of our figure-8 laser is that two types of erbium-doped fibers with different concentrations are used as the gain media of the oscillator. The repetition rate, the center wavelength and the width of the optical spectrum of our figure-8 laser are 51 MHz, 1560 nm and 58 nm, respectively. Though any NALM type mode-locked fiber laser needs initial impulse for starting mode-locking operation, our figure-8 laser can start mode-locking automatically without special procedure, which is called self-starting. We tried the operation test repeatedly for about 1600 times whose success rate reaches 99.94%. The disturbance tests and the thermal vacuum tests have been applied to our figure-8 laser, and under the conditions of both tests, our figure-8 laser shows the stable mode-locked operation without any break of mode-locking. In the radiation exposure test, we have confirmed the stable operation of our figure-8 laser till 30 krad radiation dose, and at higher radiation doses the mode-locking operation stopped.

Keywords: spaceborne frequency reference, mode-locked fiber laser, nonlinear amplifying loop mirror, optical frequency comb, highly-stable microwave generation, iodine-stabilized laser

1. INTRODUCTION

The Global Navigation Satellite System (GNSS) is an important technology as a social infrastructure. In order to further improve the positioning accuracy of the positioning system, various improvements are under planning, in progress. Improving the frequency stability of the spaceborne frequency reference is one of the key items for the high precision of the position. The current navigation satellites use the rubidium (Rb) atomic clock as the microwave frequency reference whose frequency stability is limited to the $\Delta f/f = 10^{-12}$ levels at 1 s. Higher frequency stability of the microwave frequency reference would improve the accuracy of the orbit and clock estimation.[1] In contrast, the optical frequency references have higher frequency stabilities, mainly due to

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its higher career frequency. For example, frequency stability of the optical lattice clock reaches 10^{-18} levels that uses confined cooled atoms as the frequency reference.[2] As the frequency of the optical frequency reference is too high for handling in the conventional electric circuit, the highly-stable optical frequency should be down-converted to the microwave region without degradation. The optical frequency comb is a well-known technique for down-converting the optical frequency to the microwave frequency,[3].[4] The optical frequency comb consists of equally-spaced frequency modes on the optical frequency domain, whose n-th optical frequency mode (f_n) can be described as

$$f_n = f_{\mathrm{ceo}} + n f_{\mathrm{rep}} \tag{1}$$

Where f_{rep} is the repetition frequency, and f_{ceo} is the carrier envelope offset frequency. By phase-locking f_n to the optical frequency reference, f_{opt} , and f_{ceo} to the microwave frequency reference,f_{micro} , all frequency modes are fixed, the stable microwave, f_{rep}, can be obtained from the beat notes between every adjacent optical modes. In that case, the relative frequency stability of the microwave $\Delta f_{\mathrm{rep}}/f_{\mathrm{rep}}$, is dominated by $\Delta f_{\mathrm{opt}}/f_{\mathrm{opt}}$,because the contribution of $\Delta f_{\mathrm{micro}}/f_{\mathrm{micro}}$ is $1/n$ ($n \approx 10^6$). Accordingly, the optical frequency comb converts optical frequency into microwave frequency with keeping its relative frequency stability. We have proposed and developed the spaceborne precision microwave frequency generator in which the highly-stable optical frequency from the iodine-stabilized laser is down-converted by using a mode-locked fiber laser based optical frequency comb. The spaceborne iodine-stabilized laser has been developed for the light source of the Japanese space gravitational-wave detector, DECIGO,[5] details of which have been presented in the previous ICSO.[6] In the present conference, our talk is focused on the mode-locked fiber laser. The required values for our system are summarized in Table 1.

Table 1. Requirements for precision microwave generation system

Frequency stability	Microwave frequency	In-satellite operation period
$\Delta f/f < 10^{-15}$	51.2 MHz	>15 years

2. FIGURE-8 TYPE OPTICAL FREQUENCY COMB

The optical frequency comb is generated from a mode-locked laser whose longitudinal modes are stabilized to the stable frequency reference. Thus, it is important to develop robust and highly stable mode-locked lasers for the development of spaceborne optical frequency combs. We choose an erbium (Er)-doped fiber mode-locked laser around 1.5 μm as the light source of the optical frequency comb which can be configured in all-fiber components and is suitable for a spaceborne laser. For the low-noise fiber mode-lock laser, nonlinear polarization rotation (NPR) is generally used as the mode-locking mechanism. Instead of its low phase noise property, NPR mode-lock laser is not suitable for the spaceborne system because NPR is polarization-dependent process and is very sensitive to the external perturbations such as temperature change and mechanical vibrations. On the other hand, nonlinear loop mirror (NALM) process is independent of the polarization state in the fiber, and shows higher robustness than that of NPR. There are two NALM laser configurations, figure-8 and figure-9 types. In recent years, NALM-type fiber-9 lasers have been widely studied due to its relatively low phase noise.[7] Compared with figure-9 NALM laser, figure-8 NALM laser would be stronger against external perturbations and have the longer lifetime because figure-8 laser consists of all-fiber components and has no free-space optics. However figure-8 lasers are considered to have the following disadvantages that the noise characteristics of the figure-8 laser is worse than those of the NPR and figure-9 lasers, and the external trigger is necessary for start mode-locking of the figure-8 laser. Table 2 shows summarized of the property of the mode-locked configuration.

Table 2. Comparison of the mode-locked methods

		NALM	
	NPR	figure-9	figure-8
Robustness	△	○	◎
Phase noise	○	○	△
Self-start	○	○	×

After considering comparing two-type of NALM lasers, we choose the figure-8 laser and try to improve its phase noise and self-starting property for the light source of the optical frequency comb because its robustness is suitable for long-term stable operation in the satellite condition, (Figure.1).

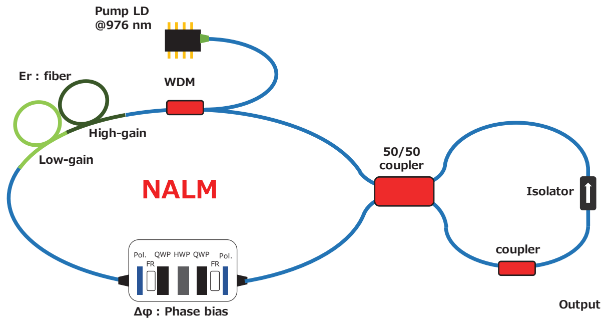

Figure 1. Configuration diagram of figure-8

3. CHARACTERISTICS OF FIGURE-8 LASER

For the spaceborne figure-8 laser, we optimized cavity parameters of the mode-locked fiber laser. First, in order to achieve low phase noise the optical cavity consists of normal and anomalous fibers in the appropriate length ratio so as to make the net-cavity dispersion zero, which is called the stretched pulse condition.[8] In addition, the length of the cavity is kept at approximately 4 meters to achieve the repetition rate of the mode-locking at 51 MHz, which is the required microwave frequency. In order to relax the condition of the self-start operation, a fiber-module-type non-reciprocal phase shifter (NRPS) is inserted into the cavity to increase the phase difference between the clockwise (CW) and counterclockwise (CCW) rotating pulses in the NALM cavity. We also try the combination of two kinds of fibers with different concentration as gain fibers. We have concluded that the different concentration of gain fibers contribute to the generation of the initial pulse by further producing stronger gains and absorption between CW and CCW, which would result in the self-starting of the mode-locking operation. In order to achieve f_{ceo} beat note, an $f - 2f$ interferometer system is also developed that includes an Er-doped fiber amplifier (EDFA), a highly nonlinear fiber (HNLF) and a nonlinear crystal whose schematic diagram of which is shown in Figure.2.

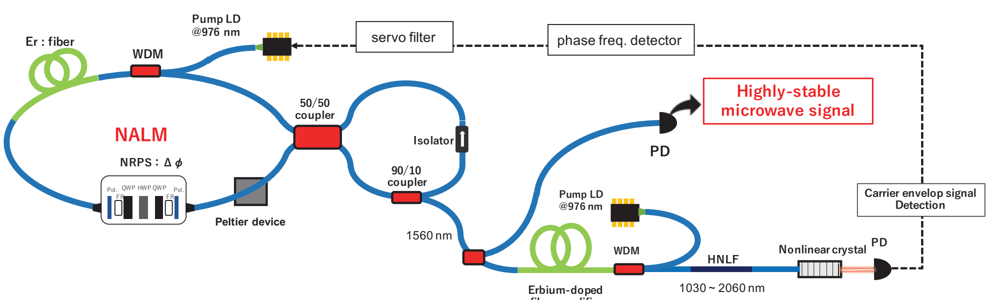

Figure 2. Optical Frequency Comb and Peripheral Configuration Diagram

The mode-locked pulse trains are amplified by a dispersion-managed EDFA and is introduced into HNLF to expand the optical spectrum to octave spanning. A nonlinear crystal (periodically-poled lithium niobate crystal) generates the second harmonic of the higher end of the expanded spectrum which is mixed with the lower end of the spectrum to make the f_{ceo} beat note.

Figure.3 shows the spectrum of our cavity-optimized figure-8 laser and the auto-correlation trace of the pulse after dispersion-managed EDFA.

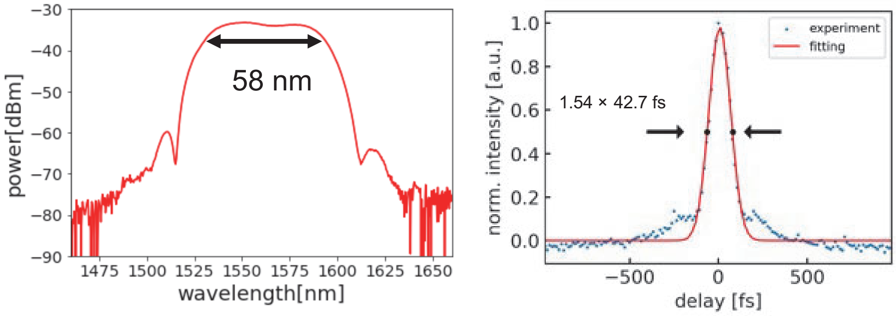

Figure 3. The stretched pulse spectrum and autocorrelation trace

The net-cavity dispersion of the figure-8 laser is optimized to be -0.01 ps^2, which is slightly in the anomalous dispersion region. The optical spectra of our figure-8 mode-locked laser is a smoothly broadened which represents typical stretched pulse. The center wavelength and the spectral width are 1560 nm and 58 nm, respectively. After amplified by a dispersion-controlled EDFA, nearly Fourier-transform-limited pulse is introduced into the HNLF to obtain octave-spanning spectra extended from 1 to 2 μm. The specifications of our mode-locked laser are described in Table. 3.

Table 3. Specifications of our figure-8 laser

output power	Rep. frequency	Center wavelength	Spectral width	amplified pulse width
2 mW	51 MHz	1560 nm	58 nm	1.54×42.7 fs (sech^2)

The $f_{\rm ceo}$ beat signal from the $f - 2f$ interference system was detected by a low-noise photodiode, and its signal-to-noise ratio was as high as 35 dB. Since the phase noise of the $f_{\rm ceo}$ represents the fundamental noise of a mode-locked laser, the phase noise characteristics of the figure-8 laser could be determined by evaluating the $f_{\rm ceo}$ signal. Figure.4 shows the beat note spectrum.

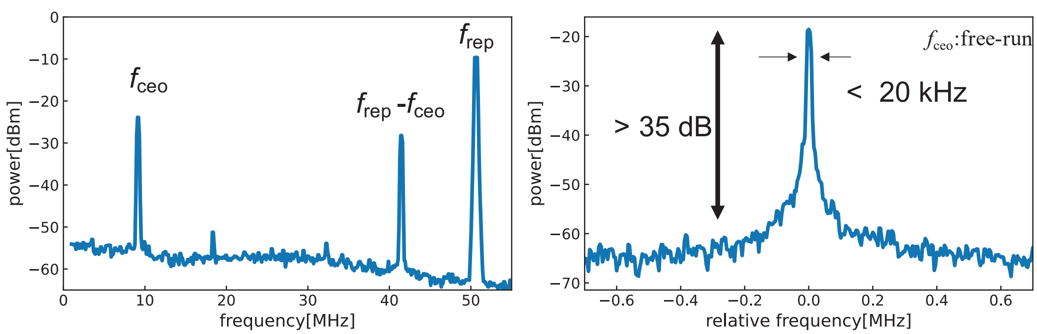

Figure 4. RF spectrum of the $f_{\rm ceo}$ signal

The linewidth of the $f_{\rm ceo}$ beat was about 20 kHz, which was comparable to that of a stretched-pulse figure-9 laser, and our figure-8 laser would be expected to low phase noise characteristics. Moreover, our figure-8 laser shows self-start operation successfully due to the optimization of two different gain fiber lengths. The self-start operation process of our figure-8 laser is very simple. First, the pump power of our figure-8 laser is increased from 0 to 500 mW. An initial pulse is generated within 100 ms under the complex multi-pulse state. Next, the pump power is smoothly decreased down to about 100 mW, and a stable single-pulse mode-locked condition is starting. This simple self-start process of the mode-locking operation would be suitable for spaceborne applications.

4. TEST FOR SPACEBORNE FIGURE-8 LASER

Several environmental tests are applied to our figure-8 mode-locked laser which simulates the satellite-environment. The results of our thermal cycle test have been already reported in the previous ICSO.[9] A constant temperature test and a thermal cycle test were confirmed in a temperature range of from 5 to 60 degrees Celsius, and stable operation of a mode-locked laser was reported. We apply the following tests to our mode-locked lasers: disturbance test, thermal vacuum test, and radiation test. In these tests, we try to evaluate the robustness of the stable operation and the repeatability of the self-starting process. First, we tested the success rate of the self-starting process in our figure-8 laser. Figure.5 shows the experimental setup for evaluation g startup repeatability.

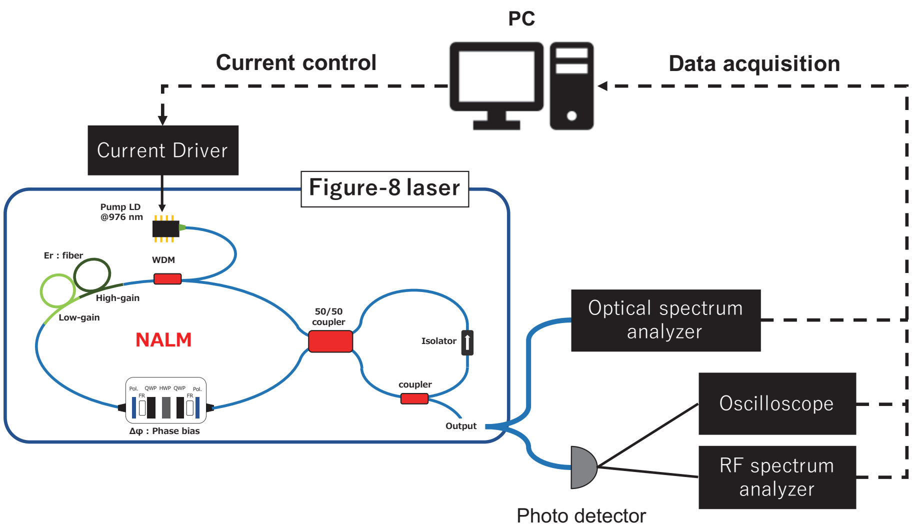

Figure 5. Repeatability experiment setup

In order to confirm the mode-locking operation, the optical spectrum, the RF spectrum and temporal waveform of the pulse train were acquired and analyzed in every trial. Before starting these environment tests, we check the start-up repeatability of our figure-8 lasers under laboratory condition (temperature fluctuations are controlled within 2 degrees around 25 degree Celsius). We tried the self-start process test to two mode-locked figure-8 lasers for about 1600 times, and success rate of 99.94% is achieved.

4.1 DISTURBANCE TEST

The purpose of the disturbance test is to confirm the stable mode-locking operation of our figure-8 lasers in the satellite-like vibration environment. In the disturbance test, our mode-locked laser is mounted on a 400×300×15 mm aluminum plate with the mass of about 5 kg. The driving forces are applied to the test block along each 3 axes (x,y,z) to generate mechanical vibrations with the frequency range from 20 to 200 Hz. (Figure. 6).

We confirmed that the continuous stable mode-locked operation is kept under all test frequency conditions. The successful rate of the self-starting process shows 100% in almost all the frequency range except at around 170 Hz. The reason for the reduced successful rate would be the coupling of the mechanical resonance to the laser resonator which changes the operating condition of the mode-locked laser. We plan further vibration test at around 170 Hz to confirm the detail mechanism of the self-starting.

4.2 THERMAL VACUUM TEST

The thermal vacuum test was conducted by using JAXA's 1-meterϕ space chamber, where our mode-locked laser operates under the temperature range from 5 to 65 degrees Celsius. We wonder that the cooling efficiency of the fiber laser would be decreased under the vacuum condition because generated heat of the fiber laser is evacuated from the fiber surface, which would suffer the mode-locking condition. The figure-8 laser tested in the vacuum

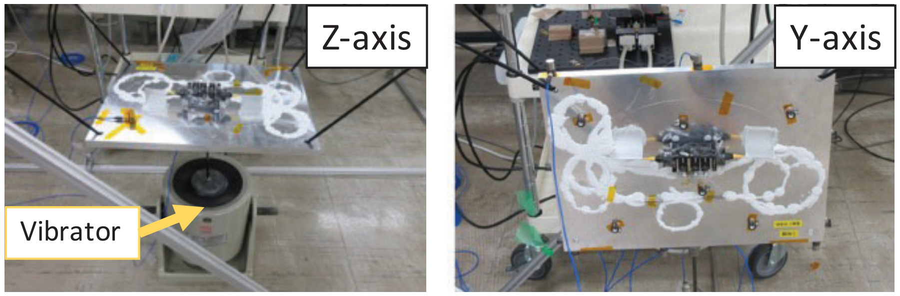

Figure 6. Disturbance test experiment

chamber is integrated in a 200 x 150 x 50 mm aluminum box housing (Figure.7). A part of the fiber oscillator can be remotely temperature-controlled by a Peltier element.

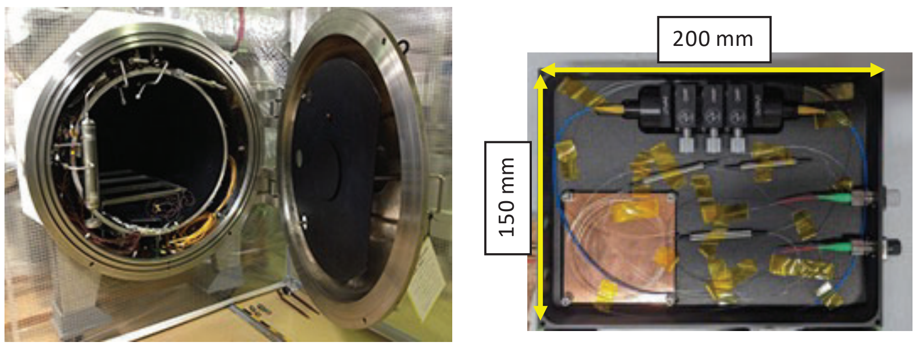

Figure 7. Photograph of the 1mϕ space chamber, compact figure-8 laser for the vacuum test

Ribbon heaters are wound around the test fuselage to control its temperature from the outside of the vacuum chamber. During the vacuum test, the degree of vacuum inside the chamber is kept at around 10^{-5} Pa. The thermal vacuum test was performed according to the following procedure: First, the figure-8 lasers were installed in a chamber in an atmospheric environment. After the chamber is evacuated to the target vacuum level, the lasers start operating, and the continuous stable operation was tested. We confirm that The mode-locked laser successfully maintained a stable continuous mode-locked operation under the vacuum condition at the requirement temperature range between 5-65 degrees Celsius, and the startup success rate was also kept high. After that we try the extra test for further decreasing temperature. When the temperature of the test fuselage was decreased down to about -20 degrees Celsius, the mode-locked operation is lost and even was never recovered.

4.3 RADIATION TEST

The radiation test was performed, with the γ-ray radiation from cobalt-60. The dose rate was 5 krad/h, and the total dose time was 32 hours. The radiation test is applied to not only the mode-locked fiber laser but also each optical components such as a semiconductor laser, active fiber and HNLF, and the γ-ray directly illuminate them with out any radiation shield. All the optical components under test consists of ordinary, non-radiation-harded elements. During the radiation tests, several optical and electrical data are recorded in real-time detection. For example, the optical spectrum of a mode-locked laser and the optical power of a semiconductor laser. Figure. 8 shows the temporal evolutions of the mode-locked laser spectra during dose exposure. The horizontal axis indicates the amount of radiation dose, and the vertical axis indicates the wavelength. At the radiation dose below 3 krad, no spectral change was observed, and the mode-locked laser was operated in stable, and self-start process is successfully performed. This amount of dose is comparable to those at one-year operation on the International Space Station orbit. After further dose exposure, however, a spectral change of the mode-locked laser was observed at about 10 krad, and the mode-locked operation was stopped at 30 krad radiation dose. The

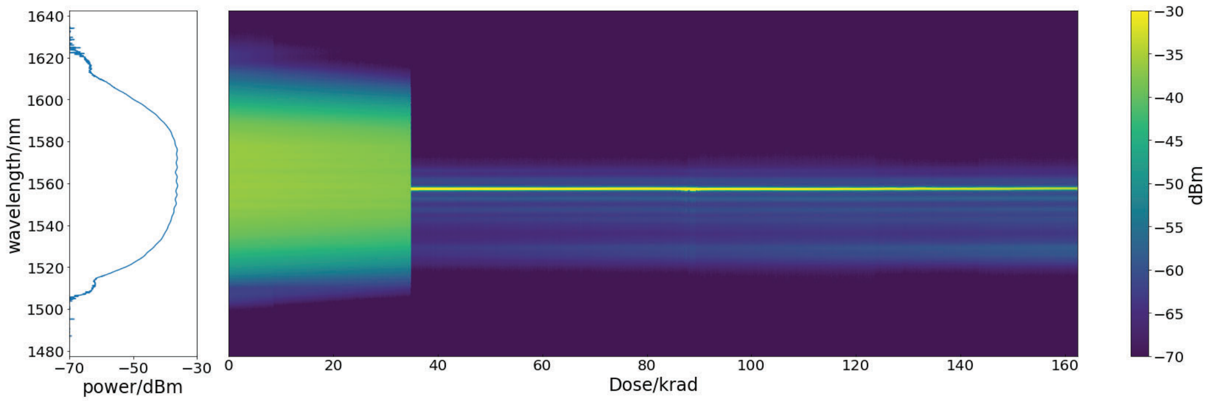

Figure 8. The spectrum of the temporal evolutions

temporal variations of the output power of the semiconductor lasers and the Er-doped fiber lasers are shown in the figure below. These light sources showed the decreasing of the output power of about 20% at 30 krad. The output power of these light sources are decreasing (20 % loss at 30 krad), and the loss rate is saturated at 70% after 100 krad radiation dose. From these results, we speculate that the loss of gain in Er-doped fibers is the main factor in the effect of mode-locked lasers. When our mode-locked laser operates in hard radiation condition such as more than ten-years operation in quasi-zenith orbit, the active fiber should be replaced with radiation-harded fiber and the all the component should be protected by using radiation shields.

5. CONCLUSION

For spaceborne optical frequency combs, we have developed a robust and highly stable figure-8 mode-locked laser. We have successfully solved the problems of figure-8 laser (worse phase noise, difficulty of self mode-locking) by optimizing the gain fiber concentration and the net-cavity dispersion to the figure-8 mode-locked laser cavity. The f_{ceo} linewidth of the figure-8 laser is less than 20 kHz in the free-running state, which indicates the possibility of low phase noise. Our figure-8 fiber laser can easily start mode-locked operation in the simple startup process (only up and down the pumping LD current), whose self-start operation rate reaches 99.94%. Additionally, by integrating the mode-locked laser into a small aluminum housing, we have developed a robust and compact light source. Our mode-locked lasers shows their robustness in the environment tests for the space borne system. In the radiation test, the stable mode-locked operation was confirmed at the total dose up to 30 krad, and further doses of exposure caused the mode-locked operation to be broken. In the future, we plan to conduct additional radiation test of the mode-locked laser and develop a radiation-hard system in order to achieve further long-term operation.

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