A portable sub-Hertz ultra-stable laser over 1700km

highway transportation

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Abstract: We present a sub-Hz line-width portable ultra-stable laser with the mass and volume of are 40kg and 400mm×280mm×450mm, respectively, that meets the requirements of automatic frequency locking and road transportation. A dynamic analytical model of the physical parts of ultra-stable laser is established, and the first-order resonance frequency is determined by FEA and well agrees with the experimentally measured result. To verify the transport performance of the portable ultra-stable laser, it is tested for 100 km actual road transportation and 60 min continuous vibration, corresponding to ~ 1700 km road transportation. The success of the test demonstrated that the portable ultra-stable laser was very robust. Meanwhile, the portable ultra-stable lasers shows that the median of the line-width distribution is approximately 0.78 Hz, and the fractional frequency instability is less than 3×10^{-15} at 1 to 10 s averaging time. This value approaches the total noise of 2.0×10^{-15} including thermal noise and residual amplitude modulation. The robust suggested that the portable ultra-stable laser might be a good candidate such as optical frequency transfer and metrological systems.

Keywords: Ultra-stable laser, Automatic frequency locking, road transportation, Portable

1. Introduction

Ultra-stable lasers with high frequency instability are in great demands for many fields, such as high-precision coherent phase transfer through fiber links [1-5], gravity wave detection [6-7], fundamental physics tests [8-9], and optical atomic clock [10-11]. For these attractive applications, many groups have made lots of excellent advances in the development of ultra-stable lasers by locking a laser to an optical cavity with the Pound-Drever-Hall (PDH) technique [12-16]. Nevertheless, most of them have been constrained to operate in well controlled laboratory environments. There is growing requirement in ultra-stable laser capable of operation outside the laboratory for applications, such as geodesy [17-18], hydrology [19], and low phase noise microwave synthesis [20]. Hence, a robust ultra-stable lasers operating in a non-laboratory environment were foreseen to be used as a high-precision frequency reference source.

Here, Vibration is an important factor causing damage to physical parts, including reference cavity, optical path and vacuum, which may make the ultra-stable laser unable to operate normally. In this respect, a rugged, transportable mounting design is more challenging than laboratory systems, which benefit from loose and soft mounting not applicable to transportable systems. The highly accurate ground-based time service system (HAGTSS) project in China require an ultra-stable laser that can withstand the vibration of 2 g acceleration (1 Hz to 500 Hz) [21, 22]. Such vibrations can cause resonance in physical parts of ultra-stable laser and result in the change of the optical path or vacuum leakage. Simultaneously, resonance phenomena will also lead to the deterioration of the ultra-stable laser’s
frequency noise under normal operation. To avoid the adverse effects of resonance and improve the robustness of anti-vibration, the first-order resonance frequency of physical parts of ultra-stable laser needs to be maximized for the requirements of transportation [23]. In 2012, B. Argence et al. simulated the vibration modes of the whole optical cavity vacuum system, and the first resonance frequency of ~300 Hz was obtained [24]. In 2013, D. R. Leibrandt et al. calculate the first resonance frequency of the rigid-body motional modes of the cavity using finite-element analysis to be at 280 Hz [25]. In 2021, G. Xu et al. calculated the first-order resonance frequency of the whole optical reference cavity support system by FEA to be 721 Hz, and the experimental test result is 681 Hz [26]. However, experiments on the vibration modes of the whole ultra-stable laser system have not been reported in detail. Herein, the vibration modes of the ultra-stable laser are simulated and tested to adapt to the non-lab requirements more effectively to satisfy the urgent needs of transportable lasers of HAGTSS in China.

In this paper, we report in details of a portable ultra-stable laser at 1550nm that is stabilized to a home-made cubic cavity of length 50 mm at room temperature, and it meets the requirements of the road transportation. The mass and volume of this portable ultra-stable laser are 40kg and 400mm×280mm×450mm, respectively. A dynamic analytical model of the physical parts of ultra-stable laser is established. The vibrational modes are studied utilizing experiments and FEA simulation, and the first-order resonance frequency is determined by FEA and well agrees with the experimentally measured result. To verify the transport performance of the portable ultra-stable laser, it is tested for 1700 km of road transportation, which includes about 100 km actual road transportation followed by continuous vibration for 60 min in the shake table, equal to approximately 1600 km of road transportation. The success of the test demonstrated that the portable ultra-stable laser was very robust. Meanwhile, the portable ultra-stable lasers shows that the median of the line-width distribution is approximately 0.78 Hz, and the fractional frequency instability is less than $3 \times 10^{-15}$ at 1 to 10 s averaging time. This value approaches the total noise of $2.0 \times 10^{-15}$ including thermal noise and residual amplitude modulation. The robust suggested that the portable ultra-stable laser might be a good candidate such as optical frequency transfer and metrological systems. And it is also of great significance for researching the space ultra-stable laser

2. Ultrastable laser system

Since the optical cavity is used as the reference source, it directly determines the performance of the ultra-stable laser. To adapt to a non-laboratory environment with large vibrations and impacts, the optical cavity needs to be fixed and protected by the support system to avoid damage or motion of the optical cavity. The schematic of the optical cavity with its support system is shown in Fig. 1. Referring to the design of NPL, the length of this home-made cubic cavity are 50mm. The detailed design of the cavity spacer is shown in Fig. 1(a), and its optical cavity is along the X-axis. Both the spacer and mirror substrates are made from standard grade ULE glass (7972). The radius of curvature of the mirrors are infinity and 500 mm, respectively. The two mirrors with a 25.4 mm diameter have a thickness of 6.3 mm and are high-reflectivity-coated for 1550nm. The line-width of the optical cavity are 5.9 kHz, corresponding to finesse values of 508000. Fig. 1 (b) shows the optical cavity's support system, including thermal shields, a bracket, and a vacuum flange, all of which are fixed to each other by four stainless steel screws. Gaskets made by PEEK are installed between the bracket, the two thermal shields, the vacuum flange, and the screws to isolate vibrations and heat. The optical cavity is fixed to the bracket with four screws made by PEEK (381G), and the squeeze force of every vertex is 100N. The vibration sensitivity of less than $1 \times 10^{-11} \text{g}^{-1}$ are calculated through Finite element software (FEA), when the cut-
off depth of approximately 4.5 mm for the eight vertices of cubic optical cavity towards to the center. The cavity and its supports system were placed in a vacuum chamber with a vacuum of less than 1×10⁻⁵ Pa to reduce the impact of the external environment such as temperature and sound.

Fig. 1. Diagram of an optical cavity with a support system. (a) Three dimensional diagram of cavity. (b) Photograph of the cavity mounted on the support system.

A structure diagram of the complete system is shown in Fig. 2 (a). A commercial fiber laser (NKT Photonics Koheras Basik E15) operating at 1550.12 nm was used as the laser source, which is fixed on the side of the vacuum chamber next to the electronics module with four spare stainless steel screws. An output beam of ~20 mW was sent to the fiber optical module, which includes a fiber-optic isolator (FIO), a fiber acousto-optic modulator (AOM), a single-mode coupler, an optical fiber polarization beam splitter (FPBS), and a fiber electro-optic modulator (EOM). After a FIO, the laser beam is coupled to an AOM (50 MHz), which was also used as the executor of the fast frequency servo for stabilization of the laser frequency. Then the first-order diffraction laser from AOM was split into two parts using a single-mode optical fiber coupler (90:10). The laser power of 90% was sent to the fiber noise cancellation (FNC) system to reduce the influence of the optical fiber noise on the measurement results [OC 论文]. The other portion was sent to an FPBS with an extinction ratio of approximately 50 dB, which was used to minimize residual amplitude modulation (RAM) of the EOM by matching the main axis of the EO-crystal. The laser was subsequently phase-modulated using the EOM with a modulation frequency of 20 MHz. After the EOM, a beam of ~100 μW was sent to the space optical module. The laser beam is adjusted by a homemade spatial modulator to match the Hermite-Gaussian 00 (HG₀₀) mode of optical cavity, and the coupling efficiency is more than 20%. And then, the appropriate optical power was adjusted by a combination of a half-wave plate (HWP) and a polarization beam splitter (PBS) before the beam entered the optical reference cavity. The laser reflected from the surface of the cavity mirror was steered to a photo-detector (PD) using a combination of a quarter-wave plate (QWP) and a PBS, which was also used to prevent the laser from returning along the original path. The beam signal between the laser carrier and modulation sidebands was detected using PD, and it was sent to electronics module. This beat signal and the signal used to drive EOM was mixed with a double balanced mixer (DBM) to obtain a discrimination signal, which was sent to Servo1 to control the voltage of the laser piezoelectric transducer (PZT), and to the Servo2 system to control the driving frequency of AOM. The total delay time of the AOM driver and photo-detector was less than 2 μs, which corresponds to a servo bandwidth of 500 kHz.

The internal structure of the portable ultra-stable laser is shown in Fig. (b), the space optical module and the fiber optical module are fixed on the outer wall of the vacuum chamber with M4 screws and reinforced with thread fastening glue. The vacuum chamber and electronics module are fixed on an aluminum base plate with a thickness of about 8mm. The all other components are connected with M3 screws and reinforced with solid glue, only the two mirrors frames in front of the optical cavity can be adjusted to prevent the temperature change from affecting the direction of
the optical path, but the bottom of the mirror frames and the mirrors are also reinforced with solid glue. The overview of the portable ultra-stable laser system is shown in Fig. 5(c). The outer dimensions of the system is approximately 400mm × 200mm × 300 mm (length×width×height). The total mass is approximately 40 kg.

Fig. 2. Schematic diagram and physical diagram of ultra-stable laser. (a) Schematic diagram. (b) Internal structure diagram. (c) Physical object.

3. Test of vibration

To avoid damage caused by complex mechanical vibration frequencies in the working environment for ultra-stable laser, the ultra-stable laser should have high first-order resonance frequencies, and better robustness to the strong vibrations. Thus, experiments and FEA simulations are conducted to provide guidelines for designing the structure of ultra-stable laser with high first-order resonance frequencies. To understand the vibration of the physical part of the ultra-stable laser, we established a simple model to calculate the natural resonance frequency by finite element analysis (FEA). We originally intended to design the structure of the ultra-stable laser by referring to reference 26, but the result of the FEA shows that its resonance frequency is mainly limited by the ion pump. The first-order resonance frequency is 147.8 Hz, and the first five order resonance frequencies are shown in Table 1. Such a low first-order resonance frequency is easy to encounter in the actual working environment, and it is likely to lead to vacuum leakage. Therefore, to improve the first-order resonance frequency of the physical part of the ultra-stable laser, the fixed mode of the ion pump is redesigned. The first order resonance FEA model of the physical part of the ultra-stable laser is shown in figure 3 (a), the result show that the first-order resonance frequency is still limited by the ion pump. Nevertheless, it can be seen from the table 1 that the value of the first-order resonance frequency is raised to 317.8 Hz, which is approximately twice that of the model in reference 26. To understand the distribution of vibration intensity at the ion pump, the vibration acceleration power spectral density (PSD) is simulated by FEA refereeing to the vibration test standard of highway transportation [23]. The simulation results of vibration acceleration PSD in three directions are shown by the green solid line (Z axis) and red break line (X axis) and blue dotted line (Y axis), respectively in figure 3 (b), and the black line represents the excitation source. It can be seen from
the figure that only the intensity of the first-order resonance frequency in the Z-axis direction is obvious, and it is also the weakest compared with the other two directions. Among them, the first-order and second-order resonance intensities in the x-axis direction are the largest, and the two resonance intensities are 20.4 $g^2$/Hz and 9.7 $g^2$/Hz, respectively. The first-order and second-order resonance intensities in the y-axis direction reach 6.25 $g^2$/Hz and 1.67 $g^2$/Hz, respectively. The black line is the acceleration power spectral density of excitation source on shake table which is measured by the accelerometer 1, the frequency-domain of the test sweep is 10 to 500 Hz. The power spectral density of acceleration amplitude is 0.015 g within 40 Hz, and it decreases gradually with the variation coefficient of 3 dB/oct from 40 Hz to 500 Hz.

Table 1. First five vibrational modal shapes. Unit: Hz

| Mode          | First | Second | Third | Fourth | Fifth |
|---------------|-------|--------|-------|--------|-------|
| Reference…    | 147.8 | 159.4  | 306.6 | 318.6  | 377.2 |
| This paper    | 317.8 | 346.1  | 383.7 | 400.2  | 456.0 |

Fig. 3. Modal simulation of physical part of ultra-stable laser. (a) The diagram of FEA. (B) The results of FEA.

As shown in Fig. 4 (a), to verify the vibration reliability of this ultra-stable laser, it is transported 100km roundtrip by a car from the National Time Service Center (NTSC) of the Chinese Academy of Sciences to AVIC Aircraft Strength Research Institute (ASRI), and then vibrated continuously for 60 min on the vibration table in the AVIC-ASRI equaling to about 1600 km road transportation. The block diagram and site of the test system are shown in Fig. 4 (a) and (b). This ultra-stable laser system is fixed to the vibration table through two clamps and four long screw rods. There are three accelerometers, one for the excitation and the other for the response. Accelerometer 1 is located on the top of the vibration table and fixed with screws to measure the excitation. The second one is located on the top of the vacuum chamber with a strong adhesive and yellow adhesive tape, which facilitates the removal of the accelerometer. The last one is pasted on the top of the ion pump. The signal wires of the accelerometer 2 and accelerometer 3 are transmitted to the outside through the small hole on the shell of ultra-stable laser. All signal wires is fixed by anti-static sticker to reduce the influence of vibrations on the accelerometers. The acceleration power spectral densities of the accelerometer 3 are shown in figure 4 (c). Since the measurement results of accelerometer 2 are similar to those of excitation source, there is no detailed discussion. The red line represents the acceleration spectral PSD measured in the Z axis, the results show that there is only the first-order resonance frequency, the value of the frequency is 342 Hz and the intensity is 0.49 $g^2$/Hz. The acceleration spectral PSD of the X axis is shown by the blue line, the
resonance frequencies are 342 Hz and 356 Hz, respectively, and the corresponding intensities are 3.0 \( \text{g}^2/\text{Hz} \) and 0.54 \( \text{g}^2/\text{Hz} \), respectively. The black line shows the acceleration spectral PSD of the Y axis, the results reveals that the first-order resonance frequency is 340 Hz and its intensity is 32.0 \( \text{g}^2/\text{Hz} \) which is the largest among all resonance frequency. It can be seen from the table 2 that the frequency and intensity of resonance points measured in the three directions are consistent with the simulation results. For the first-order resonance peaks and the second-order resonance peaks, there is also a deficiency between the FEA simulation and measured results in three directions: the frequency has an approximate difference of 8% and 3%, respectively, the difference of intensity are less than 3 dB and 16 dB, respectively. The above results show that in the vibration range of 500Hz we should be careful to prevent resonance from damaging the ion pump, especially horizontal vibration, resulting in vacuum leakage.

Table 2. The comparison of experimental and simulation results of modal simulation. (Unit. Frequency: Hz, Intensity: \( \text{g}^2/\text{Hz} \))

|            | Z axis          | X axis          | Y axis          |
|------------|-----------------|-----------------|-----------------|
|            | First order     | First order     | Second order    | First order     | Second order    |
|            | Frequency       | Intensity       | Frequency       | Intensity       | Frequency       | Intensity       |
| FEA        | 317.9           | 0.42            | 317.9           | 6.4            | 346.1           | 1.7            |
| Experiment | 342.0           | 0.49            | 342.0           | 3.0            | 356.0           | 0.54           |

Due to slight variations in the optical path will change the amplitude of the discrimination signal resulting in the inability of the ultra-stable laser to lock, to verify the transportable performance of the
 ultra-stable laser its discrimination signals before and after vibration are measured. The two signals are represents by black line and blue line in figure 4 (d), respectively. As can be seen from the figure, the discrimination signal after the vibration test is consistent with that before the vibration test, it indicates that this portable ultra-stable laser has extremely high reliability for holding transportation. Note that the discrimination signal (blue line) is measured without any adjustment of the ultra-stable laser system after the vibration test.

4. Performance evaluation

We also directly measure the line-width of the portable ultra-stable laser by comparing with another one in the laboratory. The beat note is down-converted to 50 kHz from 726 MHz and recorded using a fast Fourier transformer (FFT). A single measurement time is 2 s allowing for sufficiently high frequency resolution bandwidth (RBW) of 0.5 Hz. Each group of spectra was fitted with the Lorentz function to obtain the line-width of the beat note. 100 groups of the spectra taken 1 hours are measured, and the results is shown in figure 5 (a). The top half shows the probability for line-width of less than 1 Hz is 85% by integrating the line-width. The bottom half reveals that the median of the line-width distribution is about 0.78 Hz, and the line-width from 0.6 Hz to 1.0 Hz has a probability of about 82%. The possibility line-width of the beat note for the portable ultra-stable laser is 0.72 Hz. The Figure 5(b) shows a typical full width at half-maximum (FWHM) of 0.57 Hz (red line), which is the narrowest beat note spectrum we observed.

![Fig. 5. Measurements of linewidth of the transportable ultra-stable laser.](image)

The frequency drift of about 50 kHz with 12 hours between two ultra-stable lasers is measured by a frequency counter working on Λ-mode (Agilent 53230a), as seen in figure 6 (a). The frequency linear drift of 1.5 Hz/s is presented in the first 9 hours, and it about 1.8Hz from the 9th hour to the 12th hour. The fractional frequency instability of the portable ultra-stable laser is shown in figure 6 (b) by blue line. After removing a linear drift of approximately 1.5 Hz/s, a typical frequency instability of the stabilized laser from the 2th hour to the 3th hour is shown by the blue line, and it is around $2.6 \times 10^{-15}$ at an averaging time from 1 to 10 s, which is very close to the total noise of approximately $2.0 \times 10^{-15}$ including the thermal noise limit (Break red line) of approximately $1.6 \times 10^{-15}$ and the residual amplitude noise (Solid pink line) of approximately $1.2 \times 10^{-15}$ at an averaging time from 0.1 to 10 s. For short averaging times, the vibration and acoustic noise have a significant effect on the instability. For longer averaging times, temperature fluctuations are the primary contributors to fractional frequency instability.
5. Conclusion

We present a sub-Hz line-width portable ultra-stable laser with the mass and volume of are 40kg and 400mm×280mm×450mm, respectively, that meets the requirements of automatic frequency locking and road transportation. A dynamic analytical model of the physical parts of ultra-stable laser is established. The vibrational modes are studied utilizing experiments and FEA simulation, and the first-order resonance frequency is determined by FEA and well agrees with the experimentally measured result. To verify the transport performance of the portable ultra-stable laser, it is tested for 100 km actual road transportation and 60 min continuous vibration, corresponding to ~ 1700 km road transportation. The success of the test demonstrated that the portable ultra-stable laser was very robust. Meanwhile, the portable ultra-stable lasers shows that the median of the line-width distribution is approximately 0.78 Hz, and the fractional frequency instability is less than 3.0×10^{-15} at 1 to 10 s averaging time. This value approaches the noise limit (2.0×10^{-15}) of thermal noise and residual amplitude modulation. The robust suggested that the portable ultra-stable laser might be a good candidate such as optical frequency transfer and metrological systems.

Acknowledgments

This work is supported by National Natural Science Foundation of China (NSFC) (11803041, 61127901, 91636101, 12103059)

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