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Two-hertz- linewidth Nd:YAG lasers at 1064 nm stabilized to vertically mounted ultra-stable cavities*

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Two Nd:YAG lasers operating at 1064 nm are separately servo-locked to two vertically mounted ultra-stable cavities. The optical heterodyne beat between two cavity-stabilized lasers shows that the linewidth of each laser reaches 2 Hz and the average frequency drift reduces to less than 1 Hz/s.

Keywords: narrow linewidth laser, laser frequency stabilization, high finesse cavity, optical clock
PACC: 4262E, 4272, 4230

1. Introduction

Narrow linewidth lasers are necessities for optical clock configuration, measurements of fundamental constants and expriments of fundamental physics.[1−5] To achieve superior narrow linewidth, the laser frequency is servo-locked to a highly isolated, passive optical cavity with high finesse by using the Pound–Drever–Hall (PDH) technique.[6−10] The laser linewidth is narrowed by keeping the laser frequency tightly in resonance with the reference cavity. Therefore the linewidth of such cavity-stabilized lasers is mainly determined by the length stability of the reference cavity. To minimize the length sensitivity of the cavity to thermal fluctuation, both the spacer and the mirror substrates of the reference cavity are made of ultra-low expansion (ULE) glass. Since environmental noise sources, especially acoustic noise and seismic noise dominated from 1 to several hundreds Hz, modulate the length of the reference cavity, thus broaden the laser linewidth, special shapes of cavities are carefully designed for reducing the vibration sensitivity of the cavity length.[11−14] Locking to these specially designed cavities, laser systems with hertz or sub-hertz linewidth have been realized in several laboratories.[7−10]

In the preent paper, we report two Nd:YAG lasers separately servo-locked to vertically mounted cavities using the PDH technique. By optical heterodyne beating between two cavity-stabilized lasers, the linewidth of each stabilized laser reaches 2 Hz and the average frequency drift of the laser reduces to less than 1 Hz/s.

2. Experimental setup

The experimental set-up is shown in Fig.1. The laser to be stabilized is an Nd:YAG laser operating at 1064 nm (Innolight OEM 200NE) with a power output of about 200 mW. The laser frequency can be tuned within 100 MHz by a piezo element (PZT, which is short for lead zirconate titanate) bonded on the monolithic Nd:YAG crystal. A beam splitter (BS) splits the laser beam into two parts. Ont is the transmission beam that is coupled into a fiber for optical heterodyne beating with a second Nd:YAG frequency-stabilized laser system, which has the same design as the first set-up, and the other is the reflection light with a power of about 10 mW for laser stabilization. An acousto–optic modulator (AOM), used as an isolator, shifts the laser frequency by 80 MHz. A combination of a half-wave plate ($\lambda/2_1$) and a polarization

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beam splitter (PBS_1) is used to adjust the laser power coupled into a high finesse reference cavity. Then the laser passes through an electro–optic modulator (EOM) for phase modulation to generate symmetric sidebands beside the laser carrier frequency. A second half-wave plate ($\lambda/2_2$) before the EOM is used to adjust the laser beam polarization to match the principal axis of the EOM for reducing residual amplitude modulation (RAM) effect.[15] Mode matching between the laser beam and the high finesse reference cavity is achieved by carefully adjusting the positions of lenses ($Lens_1$ and $Lens_2$). The contrast of the reflected beam from the reference cavity can be larger than 60% in a perfect mode-matching condition. When the laser passes through a quarter-wave plate ($\lambda/4$) twice, its polarization rotates through 90 degrees relative to the polarization of the input light. Thus the reflected light from the reference cavity is steered onto a photo-detector (DET) after passing through a second PBS_2. The DET detects optical heterodyne beat signal between the carrier and sidebands unbalanced-phase-shifted by the reference cavity. The beat signal from DET and the phase-shifted reference signal from an EOM driver are sent to a double balanced mixer (DBM) to demodulate frequency discrimination signal relative to the dispersion of the reference cavity. After servo, the cavity-based frequency discrimination signal is used to control the PZT to accomplish laser frequency stabilization to the high finesse reference cavity. The servo bandwidth is less than 100 kHz limited by the response bandwidth of the PZT in the Nd:YAG laser.

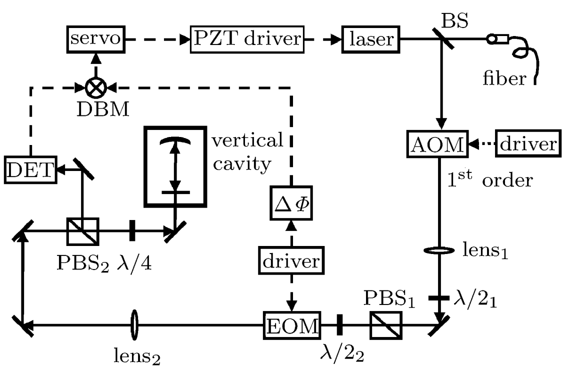

Fig.1. Schematic diagram of the experimental set-up, in which BS stands for beam splitter, AOM for acousto-optic modulator, PBS for polarization beam splitter, EOM for electro–optic modulator, and DBM for double balance mixer, $\lambda/2$ denotes half-wave plate, $\lambda/4$ quarter-wave plate, DET photo-detector, and $\Delta\Phi$, phase shifter.

In the experiment, both the spacer and the mirror substrates of the reference cavity are made of ULE glass. Moreover, the structure of the cavity is symmetrically wider in the middle and tapered at the ends, specially designed so as to be immune from environmental perturbations. The cavity is mounted vertically by three Teflon rods at its mid-plane to reduce vertical vibration sensitivity.[8,10] The reference cavity is 7.75 cm long, equipped with a plane and a concave mirror at each end of the cavity, and its finesse is measured as about 300,000 by cavity-ring-down spectroscopy of the reflected field.[16] The ultra-stable cavity is enclosed by a polished, gold coated copper heat shield inside a vacuum chamber that is evacuated by a 20 l/s ion pump down to 2.7×10^{-5} Pa. The vacuum chamber is made of aluminum for better temperature control (< 1.5 mK over 12 hours).

3. Results and discussion

To explore linewidth and frequency stability of the Nd:YAG laser, two cavity-stabilized laser systems with the same design are separately constructed on independent vibration isolation platforms. The outputs of two lasers are separately transmitted via optical fibers enclosed in foam for passive noise elimination, and the optical heterodyne beat between two lasers is detected.

To make a comparison between the linewidth of free running lasers (un-stabilized lasers) and that of cavity-stabilized lasers (stabilized lasers), two heterodyne beat signals are recorded by a spectrum analyzer. Figure 2 shows the heterodyne beat signals (the crossing markers) and their Lorentz fittings (the solid lines). In Fig.2(a), the linewidth (FWHM, which stands fro full width at half maximum) of the beat signal between the free running lasers is about 5.8 kHz with a resolution bandwidth (RBW) of 3 kHz. In Fig.2(b), at an RBW of 1 Hz the beat signal linewidth is about 2.4 Hz, which is contributed by two cavity-stabilized lasers. Therefore the linewidth of each laser reaches 1.7 Hz on the assumption that the stabilized lasers have the same linewidths.

In order to characterize the long-term frequency stability, the heterodyne beat signals of both free running lasers and stabilized lasers are recorded by a counter. In Fig.3(a), the relative frequency change of the heterodyne beat between free running lasers is about 5 MHz in 1000 s and correspondingly its relative Allan standard deviation is about 2×10^{-10} in 1 s. Without any laser frequency drift correction, the relative frequency drift of the beat signal between stabilized lasers is recorded in Fig.3(b). In 1000 s, the frequency drift is about 80 Hz (< 1 Hz/s on average), and in 1 s integration time the relative Allan standard deviation is 3×10^{-15}.

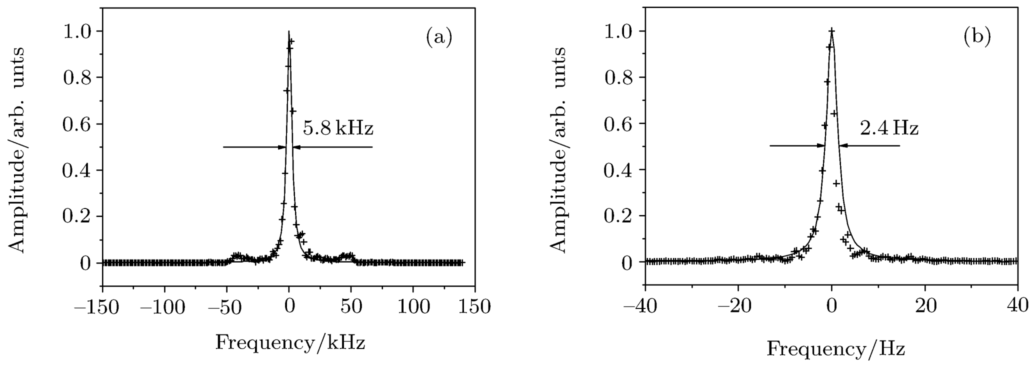

Fig.2. Heterodyne beat signals between the free running lasers (RBW: 3 kHz) (a) and between the cavity-stabilized lasers (RBW: 1 Hz) (b) (crossing markers) and their Lorentz fittings (solid lines).

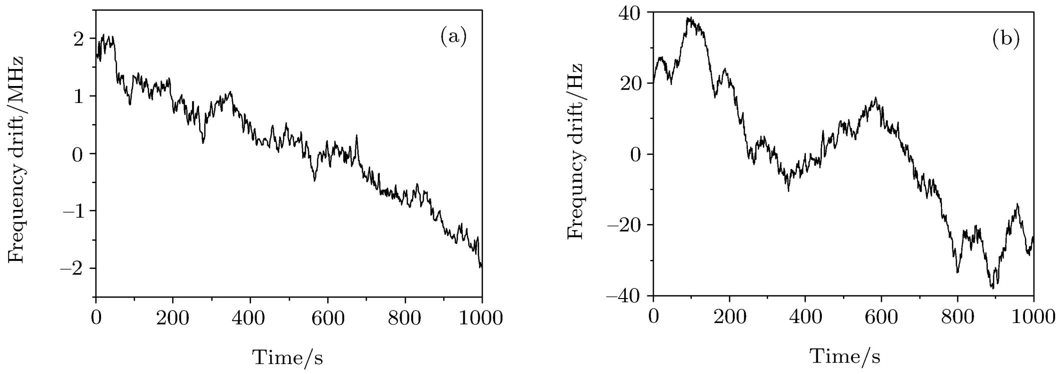

Fig.3. Relative frequency drift of the heterodyne beat between free running lasers (a) and cavity-stabilized lasers (b).

For the sake of the shot-noise-limited performance of the systems, the modulation frequencies of the EOMs are carefully chosen in the experiment. As is known, in laser frequency stabilization the wide bandwidth with high frequency modulation enable rapid signal recovery and servo response. Since in the experiment the servo bandwidth is less than 100 kHz determined by the response bandwidth of the PZT, the modulation frequencies might be larger than 100 kHz. Moreover most noises, particularly the laser intensity noise, is dominant in a low frequency region. As shown in Fig. 4, the intensity noise spectra of the Nd:YAG laser are recorded with a photodiode and a spectrum analyzer (RBW=30 kHz). Dot line and dashed line separately show the laser intensity noise spectra when a noise eater option is off and on. The noise eater suppresses the intensity noise at a frequency of 0.3 MHz by 2 orders of magnitude, but above 0.5 MHz the laser noise remains. Detection noise (dash and dot line) and shot noise limit (solid line) are also indicated in Fig.4. As is shown, the laser intensity noise is close to the shot noise limit when frequency is larger than 2 MHz. Therefore, in order to achieve lower noise and rapid servo response in the experiment, the laser beams are phase modulated at frequencies of 2.14 MHz and 2.69 MHz respectively.

It is obvious that the length stability of the reference cavity determines both the linewidth and the frequency stability of the cavity-stabilized lasers. Since environmental noise modulates the cavity length, the high-finesse cavity has to be well protected from environmental perturbations. Two experimental set-ups, including their ultra-stable cavities, are passively isolated from low-frequency vibrations with BM-4 bench top vibration isolation platforms from Minus K technology. Nevertheless, small part of acoustic noise fluctuates the length of the cavities through cables and air. In the measurements all the cables are suspended with springs and rubbers. But some cables, especially the cables of the lasers and the ion pumps, are too stiff to be totally isolated from vibration. To further reduce environmental noise, the laser heads have to be located outside the platforms and so the laser light is transmitted via optical fibers employing fiber-phase-noise cancellation.[17,18] Moreover, the whole set-ups may be shielded from acoustic noise as well.

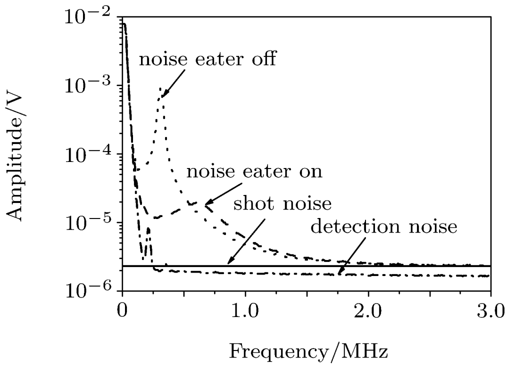

Fig.4. Laser intensity noise spectra with a resolution of 30 kHz. The dot line and the dashed line respectively show the laser intensity noise spectra when a noise eater option is off and on. Detection noise (dash and dot line) and shot noise limit (solid line) are also indicated.

Besides the length stability of the reference cavities, residual amplitude modulation (RAM) in the EOMs ruins the linewidth and the frequency stability of the lasers as well.[15] The RAM in EOM arises from that variation of temperature-dependent birefringence of the phase-modulator crystal, etalon effects, vibration, etc, when the sidebands produced by the EOM are not exactly equal in magnitude and opposite in phase, resulting in the deviation of stabilized laser frequency from resonance frequency of the reference cavity. The RAM can be minimized by various optical or electronics means, either passively or actively.[19−21] Passive temperature control of the EOM can effectively eliminate the temperature-dependent RAM. To precisely eliminate the RAM, an active feedback control strategy has to be adopted.

4. Conclusions

Two Nd:YAG lasers operating at 1064 nm are servo-locked with a linewidth of 2 Hz and an average laser frequency drift of less than 1 Hz/s. Further vibration isolation, better temperature control of the reference cavities, fiber phase noise cancellation and elimination of the RAM as well are believed to be able to improve these results.

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