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Frequency Stabilization of a Microsecond Pulse Sodium Guide Star Laser with a Tilt- and Temperature-Tuned Etalon *

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A frequency stabilization approach is introduced for the microsecond pulse sodium beacon laser using an intracavity tilt- and temperature-tuned etalon based on a computer-controlled feedback system connected with a fast high-precision wavelength meter. The frequency stability of the sodium beacon lasers is compared with and without feedback loop controlling. The output wavelength of the laser is locked to the sodium D_{2a} absorption line (589.159 nm) over 12 h with the feedback loop controlling technology. As a result, the sodium laser guide star is successfully observed by the telescope of National Astronomical Observatories at Xinglong. This approach can also be used for other pulses and continuous-wave lasers for the frequency stabilization.

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The resolution of the images of the astronomical objects captured by ground-based telescopes is limited by the time-varying wavefront aberrations induced by the atmospheric turbulence and by imperfections in telescope optics.[1] These aberrations can be corrected in real time using astronomical telescopes with adaptive optics systems (AOSs), which have been in applications since the early 1990s.[2] The functioning of AOS requires relatively bright stars as references for measuring and correcting the wavefront distortions.[3] This reference source of light must be as close as possible to the line of sight of the astronomical subject. However, it is impossible to find a natural guide star (NGS) bright and close enough to each astronomical observing targets. To overcome this problem, laser guide star (LGS) AOSs create an artificial reference beacon in the atmosphere and provide the wavefront distortion information below the beacon's altitude. Compared with the Rayleigh LGS (typical altitude less than 15 km), sodium LGS has a higher altitude which can offer substantially improved spatial sampling of atmospheric turbulence, thereby obtaining the full sky coverage. Current and next-generation large ground-based astronomical telescopes are using or planning to use the sodium LGS for their AOS, including the upcoming thirty meter telescope (TMT) and the European extremely large telescope (E-ELT).[4–8]

These telescopes have strict requirements on the laser format in the output power, beam quality, pulse length and duty cycle, which significantly affect the performance of AOS. However, the wavelength of the laser whether locked to D_2 resonant transition directly leads to the validity of the AOS. Therefore, the wavelength stabilization behaves as a key role in the laser parameters for AOS. Thus the telescopes require long-term wavelength stabilization of laser source to an absolute wavelength reference corresponding to the sodium D_2 resonant transition due to a narrow Doppler width of 1.2 GHz for sodium D_{2a} line.[9] To our knowledge, only a few lasers are close to meeting such a combination of requirements. Among them, the quasi-continuous wave (QCW) solid-state sodium laser[10] developed by our group, which combines 500–1000 Hz pulse repetition frequency (PRF) and 100-μs pulsed format, is a better alternative for cw lasers, which can provide a gateable pulse format to eliminate the interference of the Rayleigh scattering lights in the sodium LGS images and to achieve better AO correction effect.[11] However, the pulse sodium beacon laser has poor long-term wavelength stability, and a drift in laser wavelength can arise from temperature variations and mechanical vibrations, impeding the realization of field deployed stabilized laser systems.

To achieve laser frequency stabilization, it firstly needs a frequency standard, such as a spectral line of an atomic or molecular transition, or a cavity fringe of a stabilized Fabry–Pérot interferometer.[12,13] Secondly, it requires the techniques for frequency discrimination to provide the error signal, such as the Pound–Drever–Hall (PDH) technique or the Hänsch–Couillaud (HC) technique.[14] Nevertheless these methods cannot be applied for stabilizing the pulse laser frequency since the response time of the

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signal processor is in millisecond level to make the wavelength discrimination more difficult than that of the CW laser.[15] Recently, interferometric wavelength meters have been studied extensively and demonstrated to be a valid alternative and have been used as both wavelength standard devices and frequency discrimination tools for CW and pulse lasers.[16–18] Finally, frequency stabilization also needs approaches for tuning the laser output wavelength, such as using a piezo actuator connected to one mirror of cavity to adjust the cavity length[19] or using etalons to select output longitudinal mode,[20,21] to compensate for the frequency fluctuations. However, moving the mirror of cavity for a long time may cause resonator detuning and reduction of output power.

In this Letter, we firstly develop a frequency stabilization approach for a microsecond (μs) pulse sodium beacon laser using an intra-cavity tilt- and temperature-tuned etalon based on a computer-controlled feedback system connected to a fast high-precision wavelength meter. The frequency stability of the sodium beacon laser was compared with and without feedback loop controlling. The output wavelength of the laser was locked to the sodium D_{2a} absorption line (589.159 nm) over more than 12 h during the field experiment. As a result, the sodium LGS was observed all the time by a telescope of National Astronomical Observatory, Chinese Academy of Sciences (NAOC), at Xinglong.

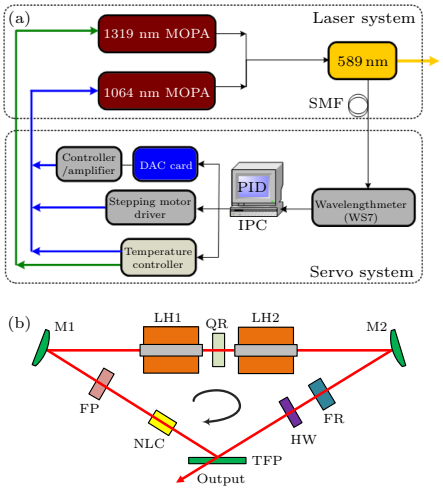

Fig. 1. (a) Schematic diagram of the sodium beacon laser system with a wavelength feedback control system. (b) Schematic diagram of the oscillator setup. LH1-LH2, laser head; QR, quartz rotator; TFP, thin film polarizer; HW, half-wave plate; FR, Faraday rotator; FP, etalon; and NLC, nonlinear crystal.

The schematic diagram of the overall sodium beacon laser system with extra-cavity single pass sum-frequency generation is shown in Fig. 1(a). The system consists of a 1064 nm laser, a 1319 nm laser, a sum frequency generation (SFG) unit to produce the 589 nm laser and a wavelength feedback control system. Both the 1064 and 1319 nm lasers have a similar structure to the diode-pumped Nd:YAG master oscillator power amplifier (MOPA). The design of both the 1319 nm and 1064 nm ring oscillators is based on a thermally near-unstable resonator with two-rod birefringence compensation to obtain a high power and high beam quality output as our previous work in Ref. [10]. As shown in Fig. 1(b), each ring laser contains two identical QCW diode-side-pumped Nd:YAG laser heads (LH), a 90° quartz rotator (QR), two reflectors, a Faraday rotator (FR), a half-wave (HW) plate, and a thin film polarizer (TFP). Unidirectional operation of the ring laser is obtained by the combination of the Faraday rotator, the half-wave plate and the polarizer, which eliminates spatial hole burning.

In the 1319 nm seed laser, the 6 mm etalon made of suprasil 3002 (Heraeus) was specially designed, with the free spectral range (FSR) of 17 GHz and the finesse of 6, to have a tunable output wavelength with narrow linewidth. For the 1064 nm seed laser, the 0.7 mm etalon with a finesse of 8.76 and an FSR of 147.8 GHz was adopted to further narrow linewidth. The etalon inside the 1064 nm seed laser was mounted on the surface of a piezoelectric translator PZT (Physik Instrumente S-316, travelling range of 1200 μrad with resolution of 0.05 μrad), which was attached to a high precision stepping motor (Sigma Koki, SHOT-204 MS, tuning resolution of 43.6 μrad). The stepping motor and PZT were used for coarse and fine adjustment of the wavelength, respectively. All etalons were placed in a temperature-controlled oven with a precision of ±0.05℃, which altered both the etalon length and refractive index by changing the temperature of the etalon. The generated 589 nm laser was guided into a wavelength meter (WS-7, High Finesse GmbH) with an accuracy of 0.002 cm^{-1} through a single-mode fiber (SMF). The values of measured wavelengths were accessed through a software dynamic link library module provided in the standard software package of this wavelength meter in combination with an industrial personal computer (IPC) in real time. With the support of the Labview VI modules, the continuous digital error signal, induced from the difference between the wavelength measured by a high-precision wavelength meter and the preset target wavelength using the National Instruments Labview^{TM} PID toolkit, was transferred to an analog voltage signal via a DAC card (National Instruments, NI 9263), then the resulting signal was fed to a high-voltage amplifier circuit to control the PZT and stepping motor module. The central wavelength of the 589 nm sum frequency laser was finally locked to the sodium D_{2a} absorption line through the servo control of the 1064 nm seed in closed loop in the wavelength feedback control system.

In this technique, the output wavelength of the 1064 nm oscillator is tuned by controlling the temperature and the angle of the etalon, which is given by

$$\frac{d\lambda}{dT} = n\left(\frac{dn}{ndT} + \frac{dl}{ldT}\right), \quad \frac{d\lambda}{d\theta} = -\lambda \cdot \tan\theta, \qquad (1)$$

where n is the refractive index of the etalon, l is the etalon thickness, θ is the angle of light propagation within the etalon relative to the etalon surface, λ is the wavelength of the laser, and T is the temperature

of the etalon. As shown in Fig. 2, the transmission spectrum of the etalon as a function of wavelength is calculated ($\theta = 0°$). Peaks A and B are maximum values around 1064 nm.

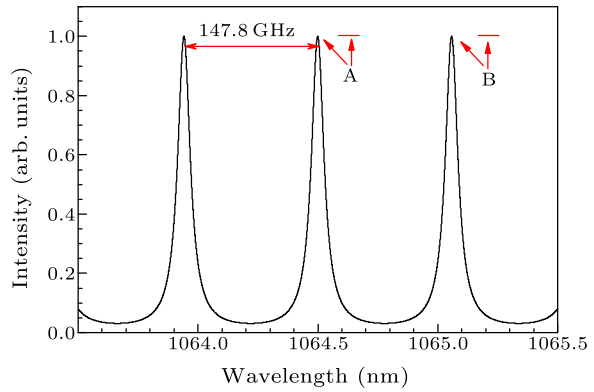

Fig. 2. Transmission spectrum of the etalon as a function of wavelength near 1064 nm.

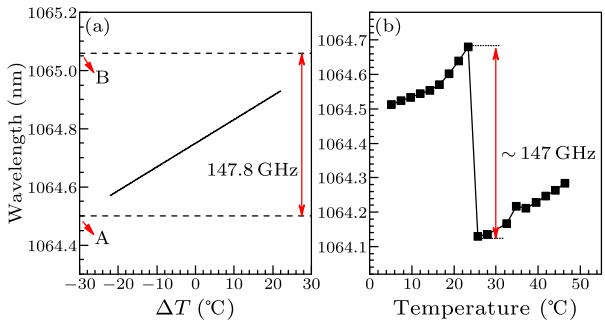

Fig. 3. (a) Calculated output wavelength, and (b) measured output wavelength as a function of the temperature for the 1064 nm Nd:YAG laser.

Here the basic requirement is that only one transmission maximum of the etalon appears within the laser gain region for the 1064 nm laser. The etalon with FSR of 147.8 GHz was employed to establish the 1064 nm laser in a single gain peak operation. According to Eq. (1), the output wavelength changing with the temperature was calculated at the initial wavelength of 1064.75 nm as shown in Fig. 3(a). The range from A to B corresponding to peaks A and B in Fig. 2 is an FSR. Obviously, it can be seen from Fig. 3(a) that the output wavelength grows monotonically with the increasing temperature of the etalon in an FSR. The slope of the curve is 8.15 pm/℃. Figure 3(b) shows the measured wavelength as a function of the temperature of the etalon inside the 1064 nm seed laser. The monotonous characteristic is consistent with the theoretical results of Fig. 3(a) in an FSR. The slope of the measured curve is about 9.13 pm/℃, which is slightly larger than the theoretical value, and the step-length of temperature during the temperature tuning was 0.05℃, corresponding to a tuning resolution of 0.45 pm. The discrepancy can be attributed to the material characteristics of the etalon and the precision of the temperature controller. Moreover, the measured mode-hopping period is 147 GHz, which is substantially close to the calculated FSR of intra-cavity etalon. Similarly, the temperature of the etalon inside the 1319 nm seed laser can also be altered, corresponding to a tuning resolution of 4.85 pm.

The 589 nm laser was generated by frequency mixing of the 1064 nm and 1319 nm lasers, which took a similar structure to MOPA. Therefore, the frequency stability of the sodium beacon laser can be obtained by controlling the frequency stability of the 1064 nm seed and seed 1319 nm lasers. In our experiment, under the repetition rate of 500 Hz, the QCW 1064 nm master oscillator provided an average output power of 50 W with the beam quality factor of $M^2 = 1.17$, and the QCW 1319 nm master oscillator emitted an average output power of 28 W with the beam quality factor of $M^2 = 1.2$. Comprehensively considering the output power and beam quality after amplification, the 1064 nm power was up to a highest value of 135 W with the beam quality factor of $M^2 = 1.48$, and the 1319 nm power was up to a highest value of 105 W with the beam quality factor of $M^2 = 1.85$.

After the SFG, a maximum average output power of 65 W was achieved at 589 nm with the beam quality of $M^2 = 1.38$ and the pulse width of 120 μs. The output frequency of sodium beacon laser was firstly tuned to the Na D_{2a} line via adjusting the temperature of the etalons in the 1064 nm seed and 1319 nm seed lasers. Then, a computer-controlled feedback loop on the etalon of the 1064 nm seed laser based on PZT and stepping motor with the wavelength meter was engaged to stabilize the output frequency to the Na D_{2a} line.

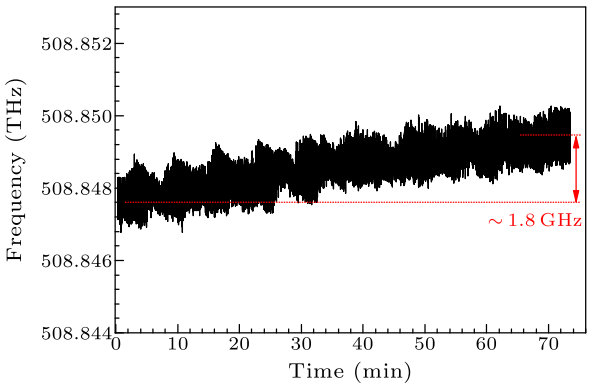

Fig. 4. Output frequency of the free-running sodium beacon laser without feedback loop controlling.

We compared the frequency stability of the sodium beacon laser near the Na D_{2a} line with and without the feedback loop controlling with an output power of 35 W. As shown in Fig. 4, a continuous frequency drift of the free-running sodium laser without feedback controlling was observed and the drift was approximately 1.8 GHz over 70 min. Moreover, the frequency of the free-running sodium laser had a random mode hopping, which can be caused by the drift of temperature and other influences such as external tiny vibrations. With feedback controlling, after adjusting the laser output beam to sodium D_{2a} absorption line through changing the temperature of the etalon, the frequency stabilized system based on a PZT was en-

gaged within an initial angle of approximately 0.5°. It can be seen from Fig. 5 that the laser output wavelength was locked to the value 589.159 nm. The system normally operated over 12 h and the frequency stability was about ±550 MHz. By the comparison of frequency stability between the free-running and locked lasers, it is found that the magnitude of frequency drift decreases from several GHz to tens of MHz. This suggests that our scheme is very effective to stabilize the sodium guide star laser.

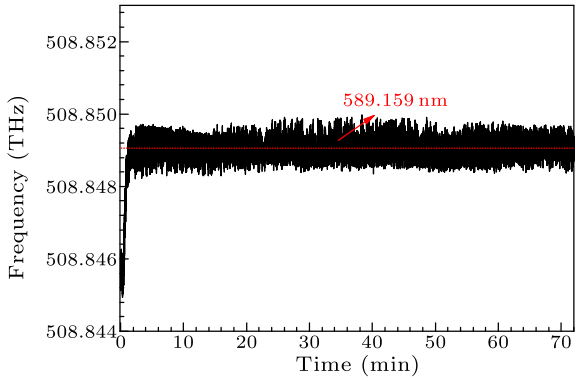

Fig. 5. Measurement of frequency stability of sodium beacon laser with feedback loop controlling.

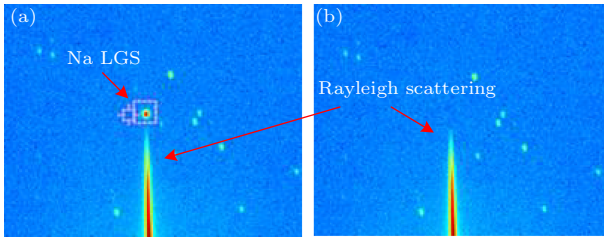

Fig. 6. (a) Image of the Na LGS spot, and (b) image of Rayleigh scattering.

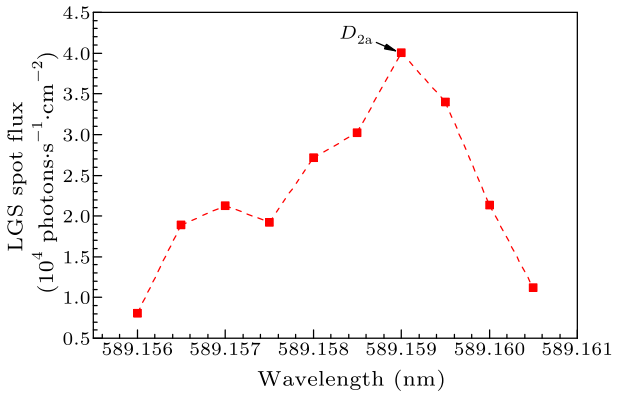

Fig. 7. LGS photon flux versus the wavelength of the sodium beacon laser.

Then, a long-term frequency stabilized μs pulse sodium beacon laser prototype was developed to generate a sodium LGS. A 200 mm diameter laser launch telescope provided by the Institute of Optics and Electronics (IOE) was used to expand the laser beam and project it to the sky, and the LGS was observed with a 400 mm photometry telescope. A standard astronomical Johnson photometric V-band filter was used to carry out the photometry of the sodium beacon. With the feedback loop controlling, while the laser wavelength was locked to the Na D_{2a} line at 589.159 nm the sodium LGS was observed all the time by the telescope of NAOC at Xinglong site, where the angle of the earth's geomagnetic field is 64.7° and the laser propagation direction is along 89.8° with respect to the horizontal plane. Figure 6(a) exhibits a clear sodium LGS. When the wavelength detuned away from 589.159 nm, only Rayleigh scattering was exhibited as shown in Fig. 6(b).

Finally, we investigate the dependence of the LGS photon flux on the wavelength. The wavelength of the laser was adjusted by changing the tilt angle of the etalon through the stepper motor and the PZT as mentioned above. The wavelength was scanned from 589.1560 nm up to 589.1605 nm in steps of 0.5 pm. Figure 7 shows the mean values of the photon flux versus the wavelength of the sodium beacon laser. The maximum photon flux return was obtained when the laser operates at a wavelength of 589.1590 nm, which coincides well with the Na D_{2a} line.

In summary, we have demonstrated a frequency stabilization approach for a μs pulse sodium beacon laser using a tilt- and temperature-tuned etalon based on a computer-controlled feedback system with a fast high-precision wavelength meter. With the frequency stabilization, the output wavelength of the laser can be locked to the sodium D_{2a} line (589.159 nm) precisely over 12 h. It is found that the magnitude of frequency drift decreases from several GHz to tens of MHz. As a result, the sodium LGS is successfully observed all the time by the telescope of NAOC at Xinglong. This approach can be used in other pulse and cw lasers for frequency stabilization.

References

[1] Clare R M and Dam M A 2007 *Opt. Express* **15** 4711
[2] Jin K et al 2015 *Publ. Astron. Soc. Pac.* **127** 749
[3] Moyssaoui N et al 2010 *Astron. Astrophys.* **511** A31
[4] d'Orgeville C et al 1999 *Proc. SPIE* **3762** 150
[5] Wizinowich P L et al 2006 *Publ. Astron. Soc. Pacific* **118** 297
[6] Hayano Y et al 2006 *Proc. SPIE* **6272** 627247
[7] Joyce R et al 2006 *Proc. SPIE* **6272** 62721H
[8] Diolaiti E et al 2010 *Proc. SPIE* **7736** 77360R
[9] Peter W M et al 1999 *J. Opt. Soc. Am.* A **16** 2555
[10] Wang P Y, Xie S Y, Bo Y, Wang B S, Zuo J W, Wang Z C, Shen Y, Zhang F F, Wei K, Jin K, Xu Y T, Xu J L, Peng Q J, Zhang J Y, Lei W Q, Cui D F, Zhang Y D and Xu Z Y 2014 *Chin. Phys.* B **23** 094208
[11] Brakley L C 1992 *J. Opt. Soc. Am.* B **9** 1931
[12] Jiang Y Y et al 2011 *Nat. Photon.* **5** 158
[13] Bohlouli-Zanjani P, Afrousheh K and Martin J D D 2006 *Rev. Sci. Instrum.* **77** 093105
[14] Beck T et al 2016 *Opt. Lett.* **41** 4186
[15] Xia Y et al 2015 *Opt. Commun.* **354** 52
[16] Trickl T and Vogelmann H 2004 *22ND International Laser Radar Conference*, vols 1 and 2 **561** 175
[17] Kobtsev S et al 2007 *Appl. Opt.* **46** 5840
[18] Mahakud R et al 2012 *Opt. Laser Technol.* **44** 412
[19] Bienfang J C et al 2003 *Opt. Lett.* **28** 2219
[20] Cabaret L et al 2001 *Opt. Lett.* **26** 983
[21] Gibson B M and Mccall B J 2015 *Opt. Lett.* **40** 2696