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Self-aligned extended-cavity diode laser stabilized by the Zeeman effect on the cesium D_2 line

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An extended-cavity diode laser at 852 nm has been built especially for the purpose of cooling and probing cesium atoms. It is a compact, self-aligned, and continuously tunable laser source having a 100-kHz linewidth and 60-mW output power. The electronic control of the laser frequency by the piezodriven external reflector covers a 4.5-kHz bandwidth, allowing full compensation of acoustic frequency noise without any adverse effect on the laser intensity noise. We locked this laser to Doppler-free resonances on the cesium D_2 line by using the Zeeman modulation technique, resulting in the frequency and the intensity of the laser beam being unmodulated. We also tuned the locked laser frequency over a span of 120 MHz by using the dc Zeeman effect to shift the $F = 4$–$F' = 5$ reference transition.

1. Introduction

To cool cesium or rubidium atoms with laser light, the simplest light source available is a diode laser. But to enhance the cooling efficiency and especially the signal-to-noise ratio in high-resolution spectroscopic applications such as cold atoms detection, the linewidth must be dramatically reduced from 10 MHz to 100 kHz or less. The simplest solution was an extended cavity structure that combines a Fabry–Perot diode and an external reflector, usually a diffraction grating. There are two well-known configurations: Littrow[1] and Littman.[2] Such an application requires some special characteristics such as a frequency-locking bandwidth of several kilohertz (to cover the range of acoustic perturbations) with low intensity noise, good insensitivity to mechanical instabilities or misalignments, and a large continuous tunability of the laser frequency without mode hops. These last two features are useful to tune the laser to an atomic reference and to keep it locked reliably over extended periods.

Unmodulated diode lasers stabilized on a spectral line, e.g., in a saturated absorption cell, are an advantage in many applications. To stabilize the laser frequency without modulating any of the laser parameters, one should either modulate the frequency of the probing beam by placing an acousto-optic modulator[3] or an electro-optic modulator in front of the reference cell or modulate the atomic resonance frequency itself by using the Zeeman[4] or Stark effects. Other methods of frequency locking without any modulation include those reported in Ref. 5 and offset locking to a reference laser as reported in Ref. 1.

Here we describe a compact and rugged Littman-type extended-cavity structure in which the retroreflector incorporates a novel combination of three features: self-alignment for mechanical stability, a low mass for high-control bandwidth without an increase of intensity noise, and a piezoactuator configuration that allows a purely electronic optimization of the continuous scanning range.

2. Extended-Cavity Diode Laser Realization

The entire extended-cavity laser (ECL) structure (Figs. 1 and 2) is contained in a single aluminum block to ensure high mechanical stability. An additional way of minimizing effects of mechanical instabilities is to use a self-aligned cavity. For practical advantages we chose a self-aligned Littman configuration with a right-angle prism as a total retroreflector.[6] The prism has a 15 mm × 3 mm hypotenuse face with an antireflection (AR) coating, a mass of 0.082 g, and a right-angle tolerance of 2 arc sec. As shown in Fig. 1, the prism ridge is mounted in the dispersive plane of the diffraction grating. The col-

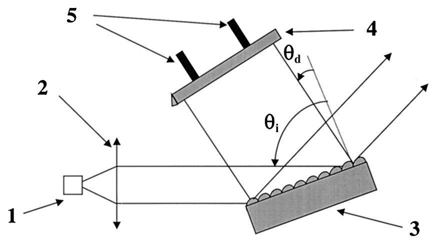

Fig. 1. Self-aligned extended-cavity diode laser in a Littman configuration: 1, laser diode chip; 2, collimating lens $f = 4.5$ mm; 3, 1400-lines/mm holographic grating; 4, right-angle prism retroreflector; 5, piezotranslators.

limating lens is an aspheric plastic lens with a focal length of $f = 4.5$ mm and an AR coating. The laser has only two mechanical degrees of freedom. The first is a fine focal adjustment of the collimator, and the second is a coarse orientation of the retroreflector to tune the wavelength [fine tuning by piezoelectric transducers (PZT's) is described below].

Our standard diffraction grating, designed for near-infrared operation, is a 1400-line/mm holographic grating on a 10 mm × 25 mm substrate. Because of the small prism dimensions, the incident angle of the laser beam on the grating is no greater than 70° and the light incident on the grating is TE polarized (**E** vector parallel to the grooves). This choice also maximizes the grating selectivity. Order zero (reflection order) of the grating provides the laser output and order one (diffraction order) the feedback. In these conditions, the diffraction efficiency is 15% and the reflection efficiency is 70%. If needed, one could simply enhance the feedback power by introducing a $\lambda/2$ plate behind the collimating lens. The resulting TM mode on the grating would have a diffraction efficiency of 80% and a reflection efficiency of 14%. In a Littman configuration the light passes across the grating twice, thereby improving its selectivity but reducing the feedback power. With a TE mode, the feedback is, however, sufficient for stable single-mode operation. The main advantage of TE mode operation is the high output power (the output power of the ECL diode is 60 mW and the solitary diode has an output power of 100 mW when the driving current value is 90 mA). In the TM mode, the same output power could not be reached because of the risk of optical damage to the laser facet.

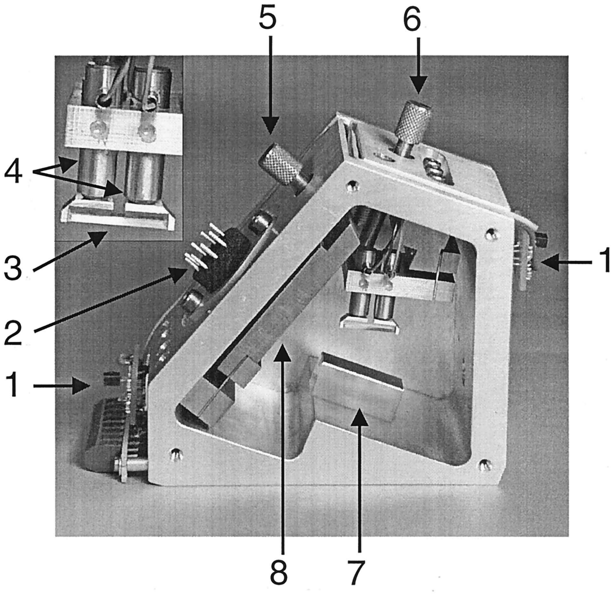

Fig. 2. Extended-cavity diode laser and enlargement of PZT's plus right-angle prism: 1, local thermostats; 2, laser diode package; 3, right-angle prism; 4, PZT's; 5, adjustment of focal point; 6, adjustment of the prism angle (more than 10-nm wavelength tuning); 7, diffraction grating; 8, lens support.

The laser diode is a commercial Spectra Diode Labs SDL-5421-H1 (the wavelength is 852 nm and the maximum output power is 150 mW) without special AR coating. The current supply is a very low-noise power supply with a white noise level of 600 pA/$\sqrt{Hz}$. By using the Peltier thermoelectric cooler included in the diode package, we stabilized the chip temperature at the 0.01 K level. The laser block was also temperature stabilized at ±1 K, which is sufficient because the remaining thermal expansion is well within the PZT range.

The main innovations in the design of this cavity concern the retroreflector and its motion. A common method of obtaining a large servo bandwidth is to apply the low-frequency part of the servo output to the PZT and the high-frequency part (above the PZT resonance frequency) to the laser current supply. However, in addition to the desired frequency corrections, current variations also induce undesired laser intensity variations. In a solitary laser, the typical sensitivities of frequency and power to current changes {typically 3 GHz/mA and $[\mathrm{d}P(I)/\mathrm{d}I] = P/(I - I_{\mathrm{threshold}})$} are such that the intrinsic laser intensity noise is virtually unaffected by a current-controlled frequency servo. An ECL, however, suffers from increased frequency noise caused by acoustical disturbances (in the kilohertz range). Because of the small ratio of laser chip optical path length to extended-cavity length, the frequency sensitivity is reduced by 2 orders of magnitude whereas the power sensitivity is comparable with that of a solitary laser. As a consequence, current control of the laser frequency, while effectively reducing frequency noise, can severely degrade the intensity noise characteristics. It is, therefore, preferable to cover the whole range of acoustic perturbations with the piezocontrolled reflector instead of the laser current. For low laser intensity noise the advantage of our relatively high bandwidth (4.5 kHz) piezocontrol over conventional current control of the laser frequency is illustrated in Fig. 3, where three patterns of the intensity noise spectrum of the laser are shown in the presence of acoustic noise (fan) near 2 kHz: free-running laser (no added intensity noise at this specific frequency), frequency-locked laser with current control (sharp increase of the intensity noise at 2 kHz), and frequency-locked laser with PZT control of the retro-

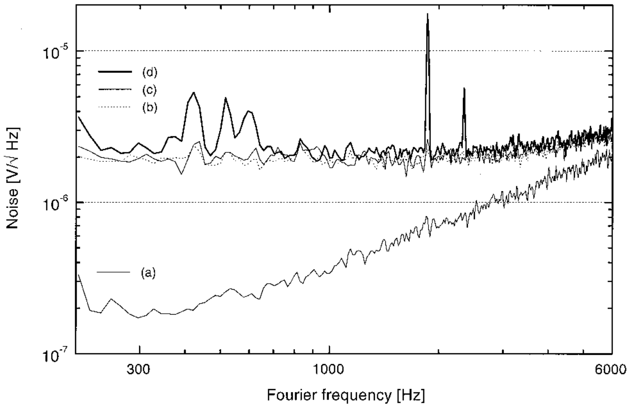

Fig. 3. Intensity noise spectra of the ECL: (a) detector noise, laser off; (b) free-running laser; (c) frequency-locked laser with piezocontrol of the reflector; (d) frequency-locked laser with current control. The direct current signal is 10 V.

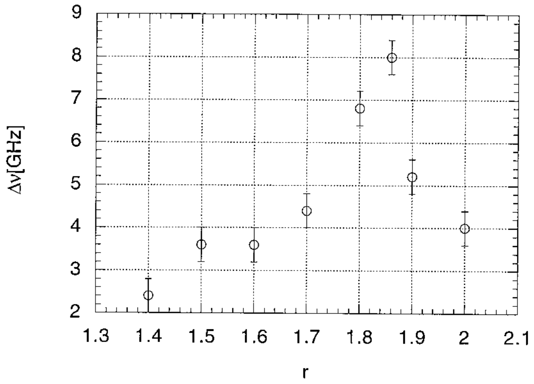

Fig. 4. Continuous tuning range versus ratio r between amplitudes of the PZT. The maximum frequency tuning without mode hop is 8 GHz.

reflector (no added intensity noise). These spectra were obtained in an otherwise quiet environment. Perturbations on the noise spectrum similar to those shown as (c) in Fig. 3 are observable in the whole range of acoustic perturbations of a normal environment when current control is used rather than PZT control.

Another aim is to construct a laser with the largest possible tuning range. In an ECL, the lasing mode is determined both by the grating angle and by the external-cavity length. The continuous tuning range without mode hop will be maximized if the following two conditions are met simultaneously:

$$\begin{aligned} &\text{cavity:} && L = k\lambda/2, \text{ where } k \text{ is an integer;} \\ &\text{grating:} && N\lambda = (\sin\theta_d + \sin\theta_i), \end{aligned}$$

where L is the total optical length of the extended cavity, λ is the light wavelength, N is the number of lines per unit length of the grating, θ_d is the angle of diffraction, and θ_i is the angle of incidence, as shown in Fig. 1. The two conditions above can be met if the retroreflector rotation satisfies the following condition:

$$R = \frac{L\cos\theta_d}{N\lambda}, \tag{1}$$

where R is the distance between the rotation center and the prism center. The line that joins the center of rotation to the prism center is parallel to the prism axis. Since R is close to the extended-cavity length, to satisfy the condition in Eq. (1) by mechanical means involves bulky or complicated adjustments. One can avoid complicated adjustments by mounting the retroreflector through elastic braces on two PZT's (Fig. 2), which is possible because R is much larger than the PZT's displacement amplitude. One can obtain the required combination of translational and rotational motion of the prism by adjusting the ratio between the voltages applied to the two PZT's. We have built two small aluminum L-shaped braces weakened at the edge. The prism is glued to the braces and the braces are glued to the PZT's (Fig. 2). Figure 4 shows the continuous tunability range versus amplitude ratio r between PZT's. The highest continuous tunability range is 8 GHz without current or temperature tuning of the diode. A theoretical prediction gives a maximum range of 24 GHz limited by amplitude of PZT. We attribute the discrepancy to the subcavity created by the laser diode output facet. The solution would be to apply a more efficient AR coating on the diode output facet to eliminate the subcavity.

The extended-cavity dimensions are approximately 120 mm × 90 mm × 60 mm and the cavity length is 57 mm. Figure 2 shows a picture of the complete laser.

Three 126-MHz beat notes between three extended-cavity diode lasers of different designs locked to two different saturated absorption lines of a cesium cell ($F = 4$–$F' = 4/F = 4$–$F' = 5$ crossover and $F = 4$–$F' = 5$ transition) have allowed us to determine the absolute linewidth of the new laser. We obtained a linewidth of 100 kHz (see Fig. 5). In these beat notes, the other two lasers have a linewidth of 80 kHz (low output power, TM-polarized Littman cavity) and 370 kHz (Littrow cavity). The 100-kHz linewidth could appear to be much larger than the 10–15 kHz reported in Refs. 7 and 8. The difference, however, is largely a result of different measurement approaches and methods: the spectrum of Fig. 5 was accumulated during 20 s and the combined linewidth was measured between actual −3-dB points. In contrast, the beat spectrum detailed in Refs. 7 and 8 was sampled during 2 ms only, which removed a 200-kHz pedestal,[8] and the reported 15-kHz linewidth[7] was indirectly inferred from that at −30-dB points under the assumption of a Lorentzian line shape.

3. Frequency Locking by the Zeeman Modulation Technique

The laser output was frequency stabilized on a saturated absorption cesium line whose frequency was modulated with the Zeeman effect.[4,7] The experi-

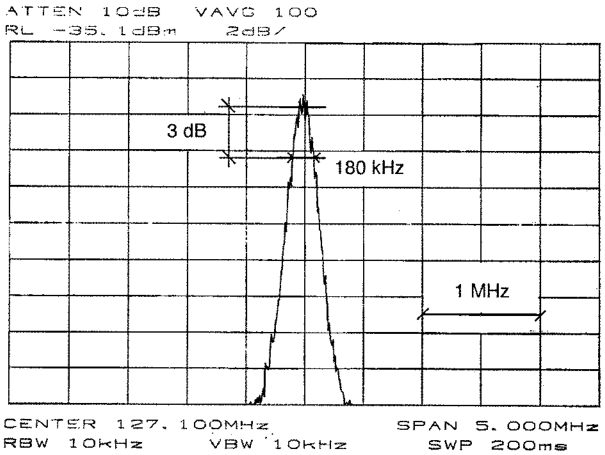

Fig. 5. Beat-note signal between two different extended-cavity diode lasers with an accumulation time of 20 s (100 scans). The linewidths measured between the −3-dB points of the two lasers are 80 and 100 kHz, respectively, as calculated from two other beat notes with a third laser.

mental setup is simple and requires only a coil around the usual saturated absorption sealed cell. The coil and the cell are surrounded by a magnetic shield to reduce the locked laser frequency sensitivity to uncontrolled magnetic field fluctuations in the laboratory. The modulation frequency is 50 kHz. It is also possible to apply dc to the coil to shift the frequency of the atomic transition. The laser frequency is locked to the cycling transition $F = 4$–$F' = 5$ or to the neighboring crossover resonance between $F = 4$–$F' = 4/F = 4$–$F' = 5$. We also conducted tests on transition $F = 4$–$F' = 4$ by using elliptically polarized light. Linear polarization results in zero sensitivity of the transition frequency to a magnetic field, whereas circular polarization would pump the $F = 4$ level into the dark $F = 4$, $m_F = 4$ state. It is possible to lock the laser to this last transition, but the error signal would remain weak even in optimal conditions.

A laser locked to the $F = 4$–$F' = 5$ transition was Zeeman tuned by an amount of ±60 MHz as measured by the shift of the beat note with a reference laser frequency locked to the crossover resonance in a zero magnetic field (Fig. 6). The tuning range is limited to 120 MHz by the distortion of the resonance curve at high fields.[5] The measured stability of the beat-note frequency was less than 10 kHz over a 1-s interval. The peak-to-peak variation over a 30-min interval amounted to less than 10 kHz.

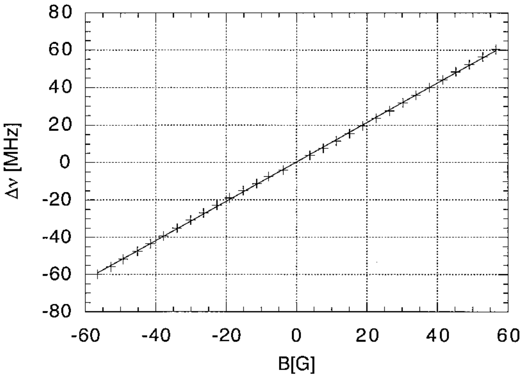

Fig. 6. Frequency shift of a laser locked to the $F = 4$–$F' = 5$ transition as a function of the applied magnetic field. The tuning factor (1.05 MHz/G) is smaller than the value for the ($F = 4$, $m_F = 4$–$F' = 5$, $m_{F'} = 5$) transition (1.4 MHz/G) because of incomplete Zeeman pumping.

4. Conclusion

A new self-aligned extended-cavity diode laser with a continuous tuning range of 8 GHz, a locking bandwidth of 4.5 kHz limited by the PZT's, and a linewidth of 100 kHz has been successfully constructed. We locked the frequencies of three extended-cavity diode lasers to Doppler-free resonances on the cesium D_2 line by using Zeeman modulation techniques. The relative stability of two such lasers locked by the Zeeman modulation technique to saturated absorption lines of cesium is better than 10 kHz between 1 s and 30 min. The high bandwidth of the PZT control allows efficient stabilization of the laser frequency against acoustic perturbations without resorting to current control, which entails, as we have demonstrated, a degradation of the relative intensity noise. A frequency shift of ±60 MHz on the $F = 4$–$F' = 5$ transition by the dc Zeeman effect has been obtained. This kind of laser is useful for many applications and especially in the field of atomic physics, spectroscopy, laser cooling of atoms, and metrology.

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