Widely tunable single-longitudinal-mode pulsed dye laser

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Received May 22, 1989; accepted July 20, 1989

We have developed a simple cavity-length-stabilization method appropriate for single-longitudinal-mode pulsed lasers that use grazing-incidence gratings. Our technique relies on the detection of a minute (<0.5-mrad) angular variation in the output beam direction caused by a detuning between the cavity-mode frequency and the center frequency of the grating passband. In a prototype system implementing this stabilization scheme we have generated single-longitudinal-mode scans of up to 290 cm^{-1}.

In this Letter we describe a simple active cavity-stabilization technique that significantly enhances the performance of grazing-incidence-grating, single-longitudinal-mode (SLM) lasers.[1-3] By actively stabilizing the cavity longitudinal-mode frequency to the grating maximum, the mechanical and alignment tolerances are relaxed. In addition, cavity-length changes owing to external perturbations and dispersion are automatically and continuously eliminated.

Our cavity-stabilization technique relies on the presence of a small, but detectable, angular variation in the output of the resonator that is indicative of the detuning between the cavity-mode frequency and the grating passband. This deviation of the laser's output beam is a direct consequence of the dispersion of the grating. For the specific resonator configuration of this laser[2] (see Fig. 1) the center wavelength of the grating passband, λ, is determined by

$$\lambda = d(\sin\alpha + \sin\beta), \tag{1}$$

where d is the grating spacing and the grating is used in first order. For wavelengths given by Eq. (1) the rays will follow a closed path in the cavity. For a cavity mode that is detuned by an amount $\Delta\lambda$ from λ there is an angular deviation, $\Delta\Theta$, of the output beam. One can show that after a round trip in the cavity, in which a ray is diffracted twice by the grating, $\Delta\Theta$ is given by

$$\Delta\Theta \simeq 2\Delta\lambda/(d\cos\beta). \tag{2}$$

This calculation is approximate because it ignores diffraction effects that are due to the finite beam size. The angular deviation between longitudinal cavity modes for a laser with a total cavity length L operating at a nominal wavelength λ is therefore

$$\Delta\Theta_{\text{mode}} \simeq \lambda^2/(Ld\cos\beta). \tag{3}$$

For a cavity length of 4 cm, a nominal wavelength of 570 nm, a 2400-groove/mm grating, and an angle of incidence of 89°, the angular deviation between longitudinal modes is approximately 1.1 mrad. As we show below, angular deviations of this magnitude are easily detected.

Relation (3) suggests that the divergence of the laser beam within the cavity should be less than $\Delta\Theta_{\text{mode}}$ for reliable SLM operation; this implies the existence of a minimum beam diameter within the laser below which SLM operation will be more difficult. This limit may be estimated[4] by assuming that the laser operates in a Gaussian TEM_{00} mode of minimum diameter $2w_0$. The half-angle of divergence at a distance L from the waist[5] is

$$\Delta\Theta_{\text{ha}} = w(L)/R(L) = w_0[1 + (L/z_r)^2/(L + z_r^2/L)]^{1/2}, \tag{4}$$

where $z_r = \pi w_0^2/\lambda$ and $2w(L)$ and $R(L)$ are the beam diameter and the wave-front radius of curvature, respectively, at L. By requiring that $\Delta\Theta_{\text{ha}} \le \Delta\Theta_{\text{mode}}$ and assuming that $z_r/L \ll 1$, we find that

$$w_0 \ge dL\cos\beta/\pi\lambda. \tag{5}$$

For the conditions of our laser, this requires that $w_0 \ge 150\ \mu\text{m}$.

The experimental resonator layout follows the description by Littman,[1] with the addition of a piezoelectric transducer (PZT) on the rear mirror (M1 in Fig. 1) to permit fine adjustment of the cavity length. The optical components include a 2400- or 1800-groove/mm holographic grating (PTR GI-2400 or GI-1800), a

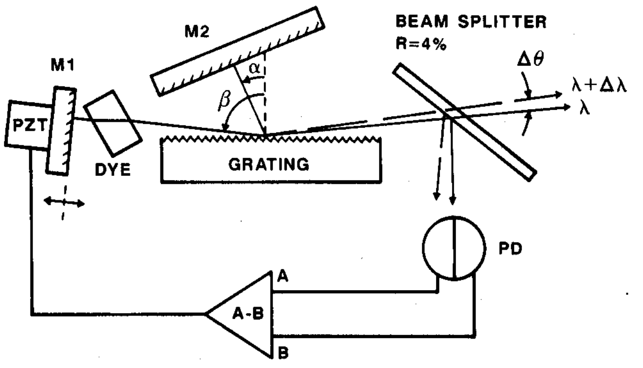

Fig. 1. Laser used, of the Littman variety,[1] with a PZT-translated rear mirror (M1). Cavity-length errors result in a deviation in the output beam direction ($\Delta\Theta$), which is sensed by the two-element photodiode (PD). The laser is tuned by rotating mirror M2 in nominal accordance with the prescription of Liu and Littman.[2]

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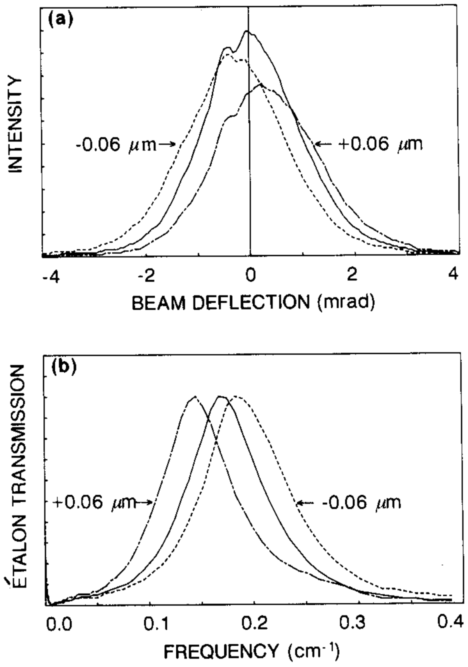

Fig. 2. Effect of cavity-length changes on (a) the beam deflection and (b) the laser frequency. The solid curves are taken with the laser adjusted for optimal SLM operation. The cavity was shortened (lengthened) by 60 nm for the dashed (dashed–dotted) curves.

2-mm path-length dye cell (Precision Cells no. 48), and λ/20 high-reflectivity mirrors (NRC BD.1). The grating and mirrors are mounted with a flexible silicone adhesive to minimize distortion to the optical surfaces. Note that the net round-trip optical distortion in the cavity should be less than λ/4 for proper SLM operation. The wavelength scanning mechanism comprises a precision rotation stage (Control Technics Corporation model 571-100) with a motorized micrometer and a digital length gauge having a 0.1-μm resolution (Heidenhain MT-12).

The laser's rigid Invar base is mounted with rubber pads in an aluminum enclosure to reduce air currents and vibration. To minimize frequency jitter due to thermally induced variations in the index of refraction of the methanol, we pass the dye through a tube filled with stainless-steel ball bearings before flowing it through the dye cell.

The pump laser is a spatially filtered, frequency-doubled, injection-seeded[6] Nd:YAG laser (DCR-2A) operating at 10 Hz. Up to 1.1 mJ of pump radiation is imaged to a spot of 0.3 mm diameter at the dye cell. We have demonstrated SLM operation with laser dyes (Exciton Chemical Company) R610, R640, DCM, and LDS 698, 750, 751, and 821 dissolved in methanol at concentrations of 32, 40, 50, 80, 160, 160, and 133 mg/L, respectively. Typically 1–10 μJ of SLM output energy is generated. Proper dye concentration is critical to stable SLM operation. The amplitude and frequency stability of the laser are best when pumped by the SLM output from the pump laser but are adequate when pumped by a multimode pump laser.

The effect of cavity detuning on the output beam is shown in Fig. 2. A photodiode array is used to monitor simultaneously the longitudinal-mode structure, through a 1-cm^{-1} free-spectral-range étalon, and the output beam profile of the laser. Figure 2(a) illustrates the near-diffraction-limited beam profile obtained when the cavity length is tuned for optimal SLM operation and when changed by ±60 nm. Note that the output beam deviates to a larger output angle (i.e., to a more grazing angle) for a shortened cavity as predicted. Figure 2(b) shows the corresponding frequency shifts determined from étalon fringe positions.

To sense the angular deviation we use a two-element photodiode (EGG UV-140BQ-2) located approximately 30 cm from the dye cell. The photodiode signals are subtracted in a differential amplifier to produce a signed error signal that is integrated, amplified, and applied to the PZT to control the cavity length. With the feedback loop open and the cavity length adjusted for optimal SLM operation, the output beam is centered on the photodiode to produce a null error signal. The loop can then be closed to correct the cavity length continuously.

To demonstrate the stabilized laser's usefulness in spectroscopy, we took a laser-induced-fluorescence (LIF) spectrum of I_2. The laser light was passed through a room-temperature I_2 cell; the LIF was detected at 90° from the beam direction with an appropriately filtered photomultiplier tube. A portion of the laser beam was directed through a 0.5-cm^{-1} free-spectral-range étalon to serve as a frequency marker. While the low finesse of this étalon (15) is insufficient to resolve the 300-MHz bandwidth of the laser, it is adequate to resolve its 5-GHz longitudinal-mode spacing. The LIF, frequency-marker, linear-transducer, and cavity-control signals were acquired at 10 Hz on a shot-by-shot basis with a computer while the laser frequency was stepped at approximately 275 MHz/shot from 659 to 647 nm. This scan rate is consistent with the 300-MHz linewidth of this laser and resulted in an ~1-h, 290-cm^{-1} scan containing over 32,000 resolution elements. A representative 10-cm^{-1} segment of this scan is shown in Fig. 3 [curve (a)]. In Fig. 3, curve

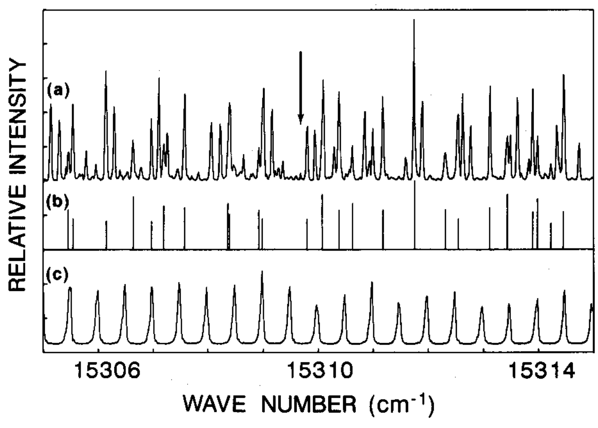

Fig. 3. Curve (a), 10-cm^{-1} portion of a room-temperature I_2 fluorescence excitation spectrum. Curve (b), the tabulated positions and relative absorption strengths from Ref. 7. Curve (c), transmission through the 0.5-cm^{-1} marker étalon. The arrow indicates the point at which the stabilization circuit was intentionally reset.

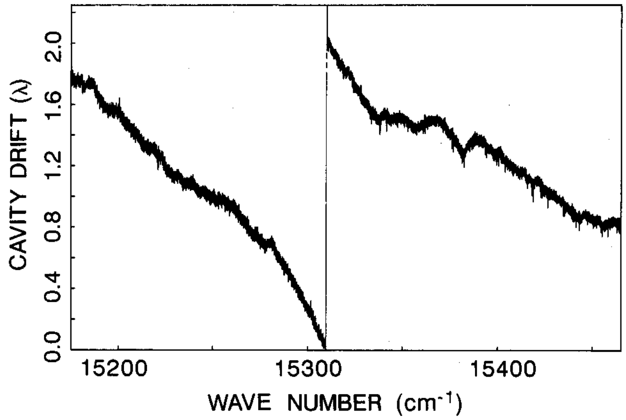

Fig. 4. Cavity-length correction required for the 290-cm^{-1} scan. The abrupt change at 15 309.7 cm^{-1} is an intentional reset of the stabilization circuit.

(b), we have also plotted the positions and absorption strengths of all tabulated[7] I_2 lines in this region. The frequency-marker signal over this region [Fig. 3, curve (c)] verifies SLM operation of the laser.

The quality of the wavelength scan of this laser is evaluated by first calibrating the êtalon frequency marks to the tabulated positions of 503 of the I_2 peaks across the spectrum. By linearly interpolating peak positions between êtalon fringes we are able to fit the I_2 peaks with an rms deviation of 330 MHz. This clearly demonstrates the continuous SLM operation of the laser. The Heidenhain gauge, once calibrated to the marker êtalon, is accurate to 0.1 cm^{-1}.

The cavity-stabilization signal for the 290-cm^{-1} scan plotted in Fig. 4 illustrates the magnitude of cavity-length correction required. Only 35 cm^{-1} into the scan the cavity length was already corrected by $\lambda/2$; without this correction, a mode hop would certainly have occurred by this point. At 15 309.7 cm^{-1} the integrated error signal was intentionally reset because the excursion range of the PZT had been exhausted. Figure 3, which covers the 10-cm^{-1} range where this reset occurred, shows that the cavity-control electronics can be reset without significantly perturbing the laser frequency.

We have demonstrated a simple means of significantly improving the SLM tuning range and mode stability of SLM grazing-incidence-grating pulsed lasers. These compact, narrow-bandwidth laser sources should be useful in moderate-resolution laser spectroscopy and in nonlinear-optical studies.

This research was performed at Sandia National Laboratories and is supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.

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