Compact extended-cavity diode laser for atomic spectroscopy and metrology

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We report on a compact, inexpensive, and durable extended-cavity diode laser (ECDL) of an original mechanical concept. The independent temperature control of a laser diode and an extended cavity provides a low-frequency drift. The linewidth of a few hundred kilohertz was measured by taking a beating of two identical ECDLs. The continuous tuning range of about 1 Å is achieved by the synchronous scan of two piezotransducers translating and rotating an external diffraction grating. The laser has been used in high-resolution spectroscopy, atom cooling, metrology, and precise interferometry. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2162448]

At the present time the diode lasers (DLs) occupy the principal position in the market of tunable lasers. However, to make them suitable for such applications as high-resolution spectroscopy, metrology, or precise interferometry, the linewidth of the lasers, being initially broad due to a low-quality factor of their cavity, has to be narrowed. The common mean of the linewidth narrowing and wavelength tuning is the employment of frequency-selective optical feedback.[1,2]

The optical feedback can be formed by resonant reflection from a confocal cavity[3] and by the Rayleigh backscattering which emerged in a fiber[4,5] or in a microsphere resonator.[6] In general, all these frequency-selective elements have a free spectrum range less than that of a DL cavity, and these determine the lasing wavelength at scales of up to several gigahertz. The tuning range is limited by the possibility to change wavelengths of the gain peak and an operating eigenmode. This range is typically one to two orders less than the width of the gain line. Modern technologies of integrated optics allow the growth of chip-sized resonant elements.[7,8] However, together with the above-mentioned small tuning range, the complicated method of production makes such lasers still expensive and inaccessible at wavelengths covered so far by ordinary diode lasers of the Fabry-Perot type.

That is why the cavity configuration with an external diffraction grating, which has been used since the end of the 70s,[9] remains the most widespread optical scheme of the tunable lasers put into practice. The mass of commercial lasers involved in spectroscopic experiments also uses the diffraction gratings in single-pass (Newport, Toptica, Sacher Lasertechnik, Thorlabs) or double-pass (New Focus) schemes. The commercial lasers typically have linewidth of about 1 MHz at the measuring time of 1 s, and for the lasers of the same optical scheme they have very close mechanical conceptions.

In this article we describe the design and operation of a compact, inexpensive, simple, and durable extended-cavity

diode laser. Our requirements for the tunable laser arise from the sphere of our interest and investigations—high-resolution spectroscopy, laser cooling, and metrology. All these applications need a laser linewidth below 1 MHz, a continuous tuning over a few gigahertz, and a mode-hop-free operation for a day. The experiments such as laser cooling of atoms or "deceleration" of a light pulse in atomic medium involve several independent coherent light sources. So, the price of the individual laser becomes the crucial demand of the experimental budget. The continuous frequency tuning over terahertz, which can be realized by synchronous displacement and rotation of the diffraction grating, needs precise machining and assembly of the mechanical parts and extremely low residual reflection of the laser diode facet. This sophisticated processing raises the final cost of an optical device. Besides, the wide tuning of a laser is often used only once—to tune it to the atomic line of interest. Then the great tuning abilities of the laser are frozen for a long while. Therefore, we did not concentrate on the wide continuous tuning (while the large-scale discontinuous tunability persists), paying more attention to the compactness and the mechanical rigidity of a laser cavity with a moderate tuning range of about 0.1 nm.

The top view of the laser with the open lid is shown in Fig. 1. The cavity length can have any value within the range of $1-5$ cm. The horizontal dimensions are given for the cavity length of 2.2 cm just as an example. Such length fits well for Rb spectroscopy, since it enables fast tuning from one hyperfine level of the ground state to another one separated by 6.8 GHz via modulation of laser current. We used also the shorter cavities of 1.6 cm for cesium, whose hyperfine splitting is 9.2 GHz. The height of the ECDL housing is 32 mm. A DL and a collimating objective are assembled in a single module (position 1 of Fig. 1), which is thermostabilized, keeping their mutual location insensitive to ambient temperature. The small volume of the module allows us to use it without significant power consumption at the temperatures limited by the dew point and the maximum DL temperature specified by its manufacturer.

Only high-quality objectives can be used for the laser beam collimation. The numerical aperture of an objective

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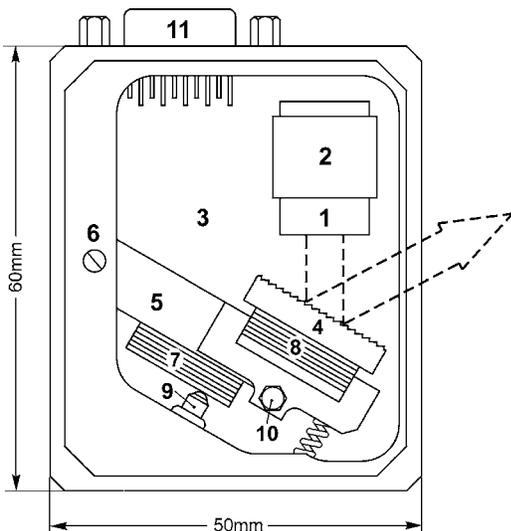
FIG. 1. The top view of the ECDL with an open lid: (1) diode laser module, (2) heatsink, (3) ECDL case, (4) diffraction grating, (5) lever, (6) pivot, [(7),(8)] piezoelements, (9) adjustment screw, (10) locking screw, and (11) connector DHS-15.
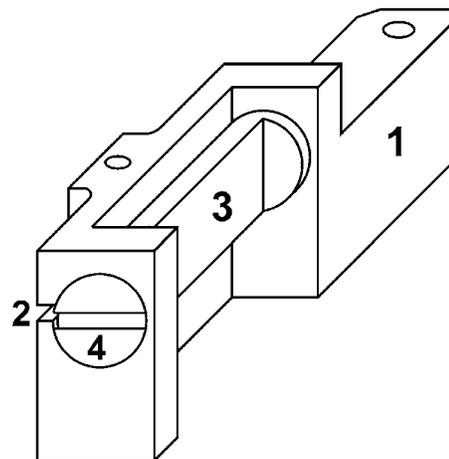

FIG. 2. The lever rotating the diffraction grating: (1) collet, (2) longitudinal cut, (3) shaft holding the grating and PZT, and (4) slot for a screwdriver.

above 0.45 is sufficient to get a stable operation of the laser. However, the collimating objectives of a higher numerical aperture provide the laser beam less distorted by the edge diffraction. As an example, the objectives Optima Precision No. 336-1027 (N_A=0.48) and Thorlabs No. C230TM (N_A =0.55) are both suited for the beam collimation and fit well in the module size. The procedure of the objective alignment is carried out on a separate assembling stage simulating the ECDL arrangement. The lowest threshold current in these conditions is a criterion of the optimum alignment.

The ECDL case (Fig. 1, position 3) is made out of a duralumin monoblock and serves as a heat dissipator of the DL thermostabilization, as a base for all mechanical components of the ECDL, and as a frame of a gimbal mount, which turns the diffraction grating (position 4). The temperature of the case is also stabilized to fix the length of the extended cavity and the angular position of the grating. The outer side of the case thermobattery has to be attached to a massive thermal conductive base (a translation stage or an optical table) for the heat dissipation. The second temperature control gave the substantial improvement of the long-term passive frequency stability of the ECDL. The time constant of the external loop of thermostabilization is greater than that of the internal one. So both loops do not interfere, while the temperatures of the DL and of the case can be kept at the optimum gain of their temperature controllers.

A wide continuous tuning range is provided when the diffraction grating is moved around a pivot, which is located near the intersection of the grating plane and the plane of the laser rear mirror.[10,11] So the length l of the lever (position 5 of Fig. 1; it is depicted separately in Fig. 2) rotating the grating (or the distance between the pivot and the point of the beam incidence on the grating) equals $l=L/\sin(\alpha)$, where L is the optical length of the laser cavity and α is the diffraction angle in a Littrow scheme. We use gratings of 1200 grooves/mm in near-infrared ECDL and 1800 grooves/mm in visible ECDL, so the angle α is about 30°. To reduce the dimensions of the device the pivot (posi-

tion 6) is shifted toward the optical axis. Hence, the tuning of the selectivity band implemented by one piezotransducer (position 7 of Fig. 1) is not optimally balanced with the tuning of the extended-cavity mode. This unbalance is corrected by means of another piezoelectric transducer (PZT) (position 8), which speeds the mode tuning. Virtually, the diffraction grating moves around the point disposed outside the ECDL housing. Such a way of synchronous motion using two independent executive elements[12] is a universal tool to expand continuous tuning range, and it may be especially acceptable for large laser cavities. The constraint of the method for the case of piezoelectric transducers is the individual variation of their technical parameters (frequency response, linearity, and voltage-to-translation constant).

The vertical beam alignment must be smooth and reproducible during preliminary adjustment only, when the optical feedback level is being optimized. At the minimum threshold current the vertical position of the diffraction grating has to be locked, and for a durable laser operation the lock should be insensitive to vibration generated by the piezoelements. The dimetric projection of the lever (Fig. 2) shows how this lock was realized. The lever (Fig. 2, position 1) represents a collet with a longitudinal cut (Fig. 2, position 2). By means of a locking screw (Fig. 1, position 10) the upper flexible part of the collet grips the horizontal shaft (Fig. 2, position 3) with the attached PZT and grating (not shown). The slot at the butt end of the shaft (Fig. 2, position 4) is designed for the screwdriver to set its initial position. The reflected laser beam moves slightly up relative to the ECDL base when the locking screw is tightened. So this screw serves to some extent as a fine adjustment. It still remains possible to control the vertical grating position with the span of about a half degree, even when the positioning of the horizontal shaft is accomplished. Nevertheless, the locked collet safely maintains the laser beam setting for months (some lasers kept their wavelengths for more than a year without readjustment).

Optimally coordinated motion of various piezoelements is possible with the individual control of tracking high-voltage amplifiers. But often it is not even necessary to control the piezoelements individually for the tuning range of a few tens. Figure 3 demonstrates continuous tuning of the ECDL with the cavity length of 2.2 cm when the same volt-
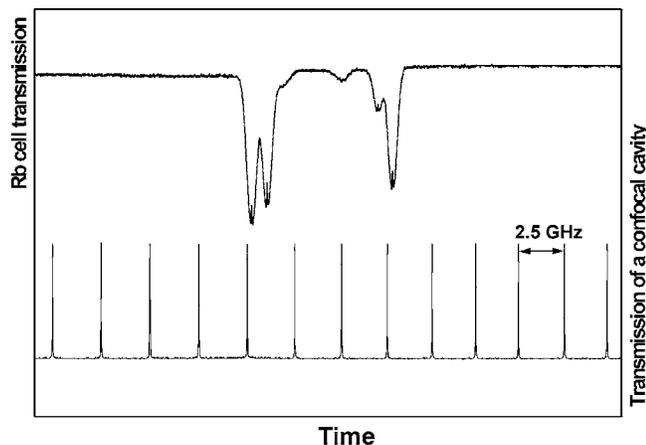
FIG. 3. Transmissions of a Rb cell (the upper trace) and a reference confocal cavity (the lower trace) at full-scale continuous frequency tuning of the ECDL.
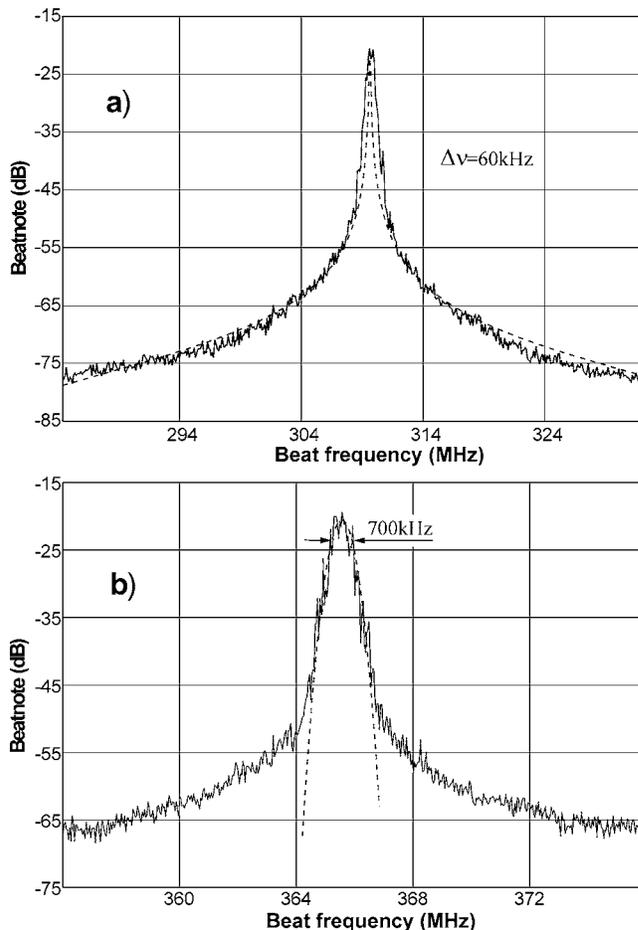

FIG. 4. A beat note of the two identical lasers operating at 795 nm (sweep time of 0.1 s, resolution bandwidth of 300 kHz, and video bandwidth of 10 kHz).

age of the maximum amplitude is applied to both PZTs. The upper oscillogram of Fig. 3 shows the light absorption in a cell filled with rubidium enriched in ^{87}Rb isotope. The laser frequency is linearly swept. Four outer Doppler profiles correspond to the $5S_{1/2}$-$5P_{1/2}$ transitions (D1 line) in ^{87}Rb; the inner two correspond to remains of ^{85}Rb isotope. The resonances of a saturated absorption are observed as narrow dips at the centers of each Doppler contour. The lower trace of Fig. 3 shows the transmission of a confocal cavity with a free spectrum range of 2.5 GHz. In the general case, the use of a single driver does not provide a coordinated displacement of two piezoelements. However, the continuous tuning over about 1 Å was always realized with the addition of a synchronous current sweep.

Commercially available diode lasers have a typical front facet reflectivity of a few percent. This is too much for a stable ECDL operation over an entire gain line. A modest antireflection coating below 1% provides a continuous tuning of 1 Å and ensures that the mechanical tuning of the grating by the adjusting screw (Fig. 1, position 9) can be accomplished without fear to miss the required wavelength.

A beat note of two identical lasers operating at 795 nm was taken to measure the linewidth of the ECDL. The result is shown in Fig. 4. Wings of the beat-note signal fit well the Lorentzian profile [Fig. 4(a)]. Leaving the amplitude of the Lorentzian fit unchanged with respect to the measured beat note, we get the "fast" linewidth of the individual ECDL (the linewidth determined by the Q factor of the laser cavity) below 60 kHz. However, the central part of the beat note reveals the broadening, which can be approximated by a Gaussian profile giving the laser linewidth of 700 kHz. At least partially this linewidth comes from the residual ripples in the voltage driving the piezoelements. The peak-to-peak amplitude of the ripples is 4 mV. Since the laser frequency is tuned over 40 GHz at the full voltage sweep of 400 V, the present ripples have to wave the lasing frequency with the span of 400 kHz. Therefore, the piezoelements of one ECDL were isolated from the high-voltage amplifier during the measurement, while the second ECDL was piezo controlled to hold the beat-note frequency in the bandwidths of a photodetector and a rf spectrum analyzer.

Large drifts of ambient temperature eventually stop the proper operation of a laser tuned to atomic line even if it is actively locked. It can be induced by a large thermal expansion of the cavity length that exceeds the maximum displacement available with a given PZT and cannot be compensated. A traditional way to improve the passive frequency stability of a laser is to use for a laser cavity the materials of a low thermal-expansion coefficient, say, zerodur or invar. However, an expansion of at least some mechanical components (copper heat sink, adjustment and locking screws, optical elements, and so on) may lead alternatively to an intolerable reduction of coupling efficiency, decreasing the side mode suppression and increasing the AM and FM noises.

The plain recipe to stabilize the temperature of the cavity is not so simple for a large cavity, complicated geometry, and poor thermal conductivity. The compact and simple housing of our ECDL is well suited for its efficient temperature stabilization. The result of the two-stage thermostabilization (individual stabilization of both the diode laser and extended-cavity temperatures) is demonstrated in Fig. 5. The wavelength evolution of a visible ECDL was measured in a day, starting from the moment of switching the laser on. Within the first hour the laser frequency changed rapidly, while the case temperature attained equilibrium. During the last 3 h of the day the drift did not exceed 100 MHz/h. This corresponds to the relative frequency stability of about 10^{-7}.
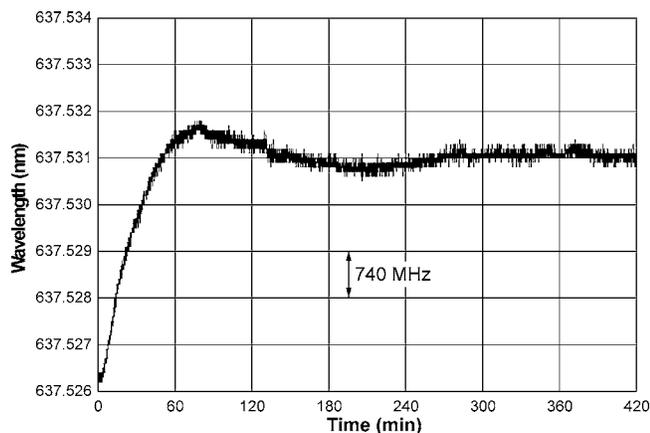
FIG. 5. The wavelength evolution of a visible ECDL measured in a working day.

It is necessary to note that the laboratory is not air conditioned and its temperature fluctuates over a day by $5-10\ ^\circ$C. The noise on the recorded trace is the noise of the wavelength meter, and the ECDL wavelength does not suffer these "digitizing" hops.

The references of the most recent experiments performed at the Texas A&M University and at the P.N. Lebedev Physics Institute with the use of our ECDL are cited in Ref. 13.

In conclusion, we have developed a compact, simple, and durable extended-cavity diode laser of an original mechanical concept. The individual temperature stabilization of both the diode laser and the extended cavity gave a high passive frequency stability. The coordinated displacement of two piezoelements provides the tuning range of several tens of gigahertz with the laser linewidth of a few hundred kilohertz.

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