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Vibration-proof ECDL with an Intracavity Interference Filter

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Abstract—A new external cavity diode laser (ECDL) structure with an interference filter (IF) as a selective element is proposed. Key units of the developed ECDL, providing high mechanical stability, and hence, reproducible device characteristics, are the units of selective element rotation and radiation output from the laser cavity. Such ECDL is proposed to be used in onboard electro-optical systems.

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Introduction. Diode lasers (DLs) are widely used in high-resolution spectroscopy and metrology, providing tuning to almost every atomic or molecular transition in the visible and near IR spectral ranges. The detection of narrow spectral lines, especially in the case of cooled atoms, requires highly coherent radiation with a spectral width of the order of or lower than 1 MHz, which is provided for the DL by the external cavity. An increase in the cavity length results in the longitudinal mode compression and the necessity of introducing a spectrally selective element into it to maintain single-frequency lasing. The diffraction grating [1] featuring a sufficient resolution to separate one longitudinal mode is most commonly used. However, it is better to reject the reflection grating as an output mirror of the laser cavity in the devices operating under conditions of high vibration and acoustic loads. The instability of its position and angular orientation causes wavelength and radiation power fluctuations.

The optical scheme in which the laser cavity is closed by a mirror in the objective focal plane ("cat's eye") makes it possible to reduce the laser sensitivity to the angular orientation of the external mirror by more than an order of magnitude. For example [2], the spectrum width of radiation beats of two independent lasers with cavity lengths of about 1 m was lower than 100 kHz. In this case, Fabry–Perot etalons were used as intracavity selective elements.

The same role can be played by interference filters (IFs) whose application was proposed in [3]. We note that such ECDLs did not become widespread immediately after this publication due to the low spectral resolution and high losses of the filters. However, current optical fabrication technologies of multilayer variable-thickness coatings are so advanced that not only laboratory [4] but also commercial devices [5] with such filters are available.

In this paper, we describe the new ECDL design with an intracavity filter and the results of measurements of the interference filter parameters.

Design description. The optical scheme of the ECDL with an intracavity filter (ECDLF) of conventional [3, 4] design is shown in Fig. 1(a). The radiation is output from it by a half mirror that closes the cavity. Since laser radiation is focused on this mirror, an additional objective is required to obtain a low-divergence output beam. The half mirror reflectance defines the optical feedback level and the optical power fraction extracted from the cavity. It is difficult to a priori predict their optimal ratio since it depends on the degree of DL mirror bleaching, the ratio of optical lengths of active and passive cavity parts, the filter transmittance and spectral width. Therefore, a set of mirrors with different reflectances is fabricated, and the mirror most appropriate to the required conditions is experimentally selected. Half mirrors have an appreciably smaller spectral width in comparison with the total reflection

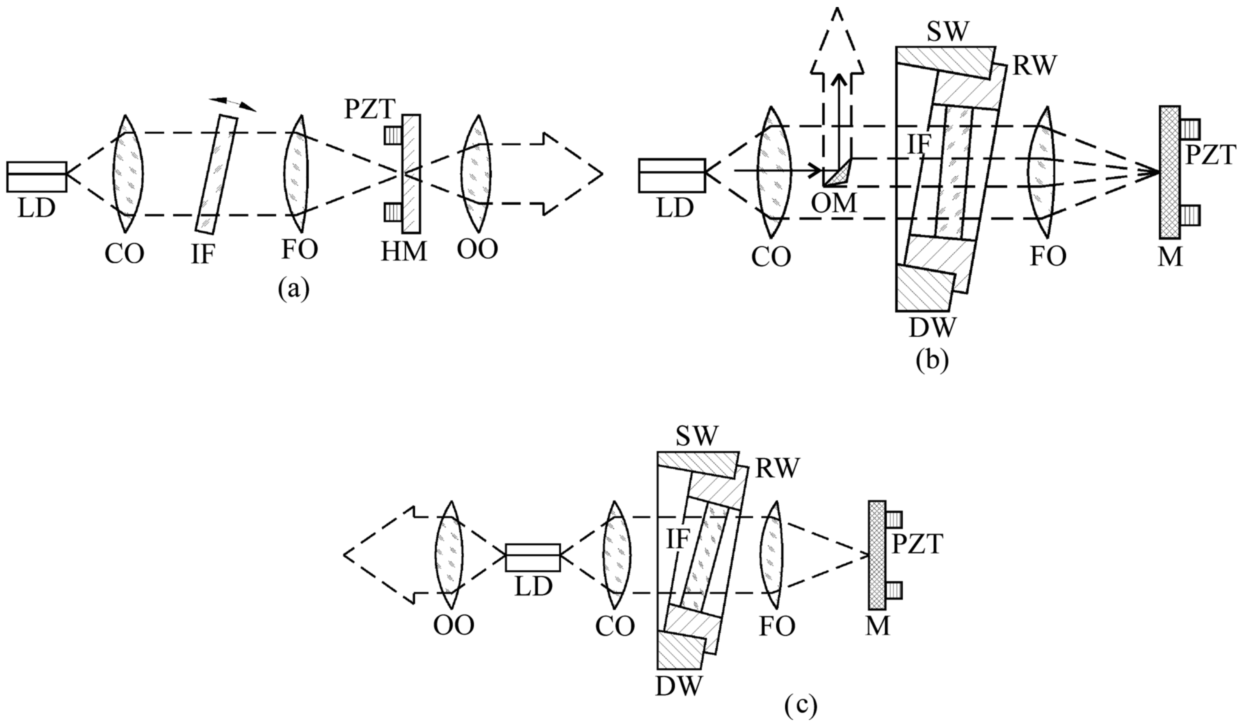

Fig. 1. Optical schemes of (a) conventional ECDLF, (b) ECDLF with radiation output by a narrow total reflection mirror, and (c) ECDLF using the second output of the diode laser. LD is the laser diode, CO is the collimating objective, IF is the interference filter, FO is the focusing objective, HM is the half mirror, OO is the output objective, PZT is the piezoceramic ring, OM is the output mirror, DW is the differential wedge, SW is the stationary wedge, RW is the rotating wedge, M is the total reflection mirror. The rotating wedge in Figs. 1(b) and 1(c) is shown in two edge positions opposite in the rotation angle.

mirrors; therefore, each new laser wavelength requires a specific set of mirrors. The second substrate side of the half mirror introduces additional losses or requires bleaching. In turn, the problem of combining the optical feedback depth and the extracted radiation fraction also arises when using gratings in the Littrow and Littman schemes. We note that the half mirror fabrication nevertheless appears simpler than the diffraction grating fabrication and selection.

The wavelength of the ECDL with an intracavity filter is tuned by its inclination. In the conventional case, the IF is placed in a rotating holder whose alignment accuracy is controlled by the screw pitch of the adjusting screw and its distance to the rotation axis. It is difficult to make this unit compact and, under conditions of strong acoustic loading, also sufficiently rigid since vibrations directly result in rotation angle fluctuations.

Figures 1(b) and 1(c) show the ECDLF optical schemes differing from the conventional one in methods for radiation output from the laser cavity and wavelength tuning. The schemes are given for two mounting types of active elements: those capsulated into a TO housing (radiation output from the LD to one side, Fig. 1(b)) and those installed into a C-mount housing (radiation output from the LD to both sides, Fig. 1(c)). In this study, the ECDLF with the C-mount housing operated at a wavelength of 852 nm (Cs resonance line), the ECDLF with the TO housing operated at a wavelength of 871 nm (clock transition subharmonic of the Yb ion). It is clear that the C-mount provides an additional port of radiation output from the LD and does not require reflectance selection for the end mirror.

In this study, it is proposed to extract radiation from the cavity by an additional narrow total-reflection mirror (Fig. 1(b)) applied on substrate prism OM with a section shaped as an isosceles triangle with an obtuse angle at the vertex, which avoids spurious shading of the laser beam. The spectral resolution of the interference filter should decrease with decreasing the beam diameter due to a divergence increase; however, it often appears higher for narrow beams due to the spatial inhomogeneities appearing during the coating deposition. Therefore, cutting a beam fraction is not so critical for the ECDLF as for the lasers with a diffraction grating, in which an increase in the spectral resolution requires an increase in the beam diameter. The DL beam divergence in the direction transverse to the p-n junction is as

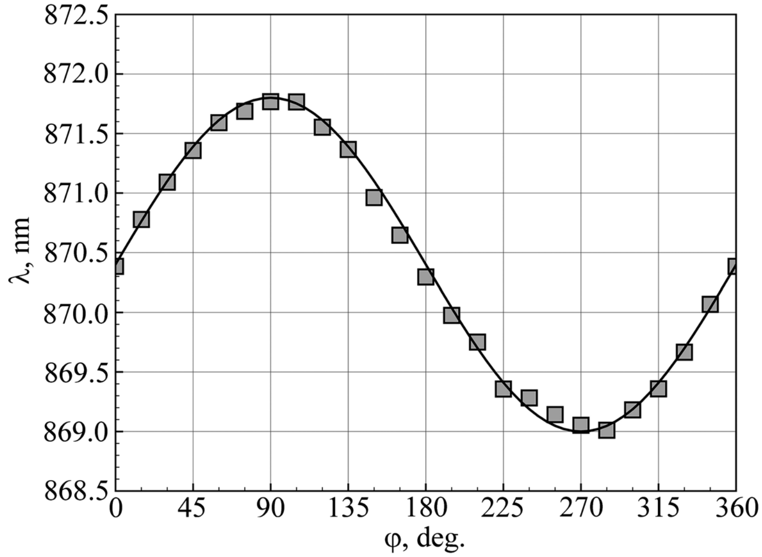

Fig. 2. Dependence of the ECDLF lasing wavelength λ on the mobile wedge rotation angle φ.

a rule larger than along the junction. As a result, the collimated beam has an elliptic shape in the cross section, which complicates its matching with axisymmetric optical systems. The light intensity distribution in the direction transverse to the p-n junction is well described by the Gaussian curve. An output mirror displacement in this direction makes it possible to find the balance between the feedback and the output power. Being at the beam center, the mirror extracts maximum power from the laser cavity with maximum axial symmetry. As the mirror is displaced to the beam periphery, the optical feedback level increases at a certain beam symmetry loss.

To vary the angle of laser radiation incidence on the interference filter, a rotation device (Differential Wedge) was developed, consisting of an immobile wedge-shaped (Static Wedge) slab with the angle α most probable for tuning to the required lasing wavelength, and a Rotary Wedge whose angle β was chosen corresponding to the filter fabrication accuracy tolerance. As the mobile wedge rotates with respect to the immobile one, the angle γ of the laser beam incidence on the filter varies from $\alpha-\beta$ to $\alpha+\beta$ (from 2° to 8° in this study). The angle β defines the range and accuracy of the incidence angle γ tuning. The lasing wavelength tuning precision is provided by that the tuning coefficient $d\lambda/d\varphi$, where φ is the mobile wedge rotation angle, becomes smaller by a factor of $\beta/90$. The dependence of the lasing wavelength on the rotation angle of the mobile wedge is shown in Fig. 2. Small deviations of the experimental data from the theoretical curve are due to the fact that laser mode frequencies and the IR transmission peak cannot be identical.

During vibrations, the optomechanical device is subjected to linear accelerations of different amplitudes, frequencies, and directions. Under these conditions, relative displacements of individual device components are most probable, rather than their relative rotation. Therefore, the proposed method for tuning the lasing wavelength also provides a higher vibration resistance of the ECDLF characteristics in comparison with the conventional cases.

Interference filter. The IR transmittance controls the loss, lasing threshold, and attainable ECDLF output power, and the filter spectral bandpass affects the degree of selection of cavity modes. An insufficiently narrow-band IF does not allow reliable separation of a single laser cavity mode among a set of longitudinal modes. This results in excess amplitude and frequency noises, mode switching, and multifrequency regime. An increase in the frequency range between neighboring cavity modes by decreasing its length to improve mode selection has a limit and increases both technical and fundamental contributions to the lasing linewidth. Thus, it is desirable to know accurate IF characteristics at the ECDLF development stage.

Several IFs whose characteristics are given below were fabricated by specialists of the Open Company "Albedo Optics" and "Vacuum Technique Laboratory" (VTL) in production areas of the Lebedev Physical Institute. The "Albedo Optics" filter consists of two mirrors and seven pairs of

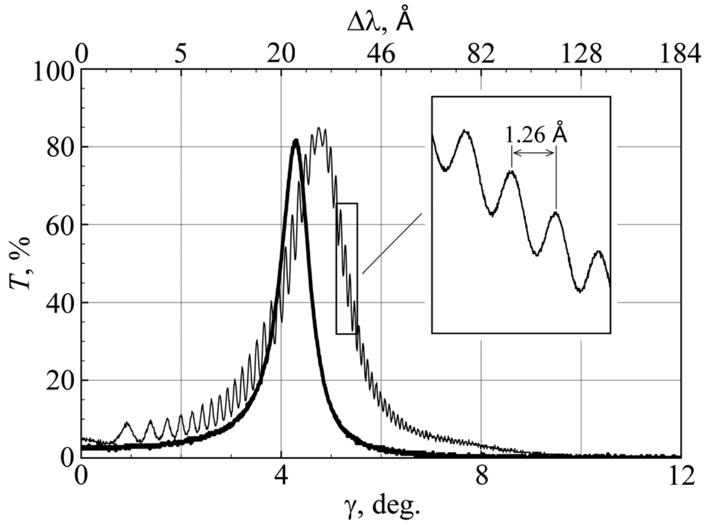

Fig. 3. Dependences of the transmittance of two interference filters with a transmittance maximum at 871 nm on the incidence angle of the laser radiation. Filters differ in the coating design; the narrower-band one was fabricated at the LVT; the other one was fabricated at the "Albedo Optics". The filter fabricated on the wedge-shaped substrate has no transmission oscillations. The upper scale shows the correspondence between the incidence angle and the wavelength detuning in Å.

quarter-wave TiO_2/SiO_2 layers separated by a SiO_2 spacer with an optical thickness of 871 nm (four wavelengths). The resonance position is controlled by the spacer thickness. The coating was deposited using an ORTUS 700 (Izovak LLC, Belarus). The LVT filter structure contains 41 layers of alternating TiO_2/SiO_2 layers of various thicknesses. It was fabricated using a Spector Veeco-IonTech (USA) ion-beam sputtering setup, whose software and optical control provide necessary IR fabrication precision.

As a rule, the resolution of ordinary spectrophotometers (Perkin Elmer, Lamda 35, and others) is several Ångströms which allows measurements of the central wavelength of the IF transmission peak and its locking bandwidth. However, such resolution is insufficient to measure the transmission peak amplitude and width.

IF characteristics can be measured using a continuously and widely tunable single-frequency laser. The results of the filter measurements for a wavelength of 852 nm using a vertical-cavity surface-emitting laser (VCSEL) are given in [6]. These lasers are no longer exotic, but they are still unavailable in many spectral regions. Therefore, the filter designed for the 871-nm ECDLF was characterized in another way with a laser [1] tuned to the filter transmission line but not providing the continuous tuning range sufficient to estimate the spectral line width. In this case, the width was estimated by transmission modulation during filter rotation (at constant λ), arising due to radiation interference on two IF substrate surfaces. The filter was rotated by a galvo driver.

Figure 3 shows the dependences of the transmittance of two filters at 871 nm on the angle γ of laser radiation incidence. Interference maxima are determined from the condition $2Ln\cos\gamma = N\lambda$, where λ is the emission wavelength, L and n are the substrate thickness and refractive index, and N is the maximum order. It is possible to switch from one maximum to the other by changing the IF tilt angle at a constant wavelength or by changing λ at a constant incidence angle. The range of such change in the incidence angle corresponds to the wavelength tuning by $\Delta\lambda = \lambda^2/(2Ln\cos\gamma)$. Since the IF tilt angle is small, and its change for a narrow-band filter is also small when measuring the angular dependence of the transmittance, the difference of $\cos\gamma$ from unity can be neglected. Thus, the IF spectral transmission bandwidth is estimated by the number of intervals between interference maxima per the envelope width (FWHM, Fig. 3). It is 15 Å for one IF and 7 Å for the other. For the filter for the wavelength of 852 nm, the estimation according to the presented method was confirmed with good accuracy by recording the IF spectral profile using a tunable laser (VCSEL). This simple method is inapplicable to substrates of filters with high wedging or with a well-bleached surface of the IF backside. However, it is easy to show that the wavelength scale obtained for one filter (Fig. 3) can be used for the other if they are fabricated for the same wavelength.

Conclusions. An original ECDL scheme with an intracavity interference filter was proposed, which provides high mechanical stability of the cavity and offers the possibility of using ECDLs in onboard systems. A high-resolution technique for measuring the intracavity IF parameters, which does not require widely and continuously tunable lasers is proposed. Measurements can be performed using a laser tuned to the IF transmission resonance to within its two–three widths. Filters with a bandpass less than 1 nm and amplitudes higher than 80% were implemented. It is expected that the band will be narrowed to fractions of a nanometer, and the transmittance will be higher than 90% in the nearest experiments.

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