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Direct Comparison of the Acoustic Stability of ECDLs with Different Types of an External Cavity

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Abstract—A method for estimating the stability of emission parameters of external cavity diode lasers to mechanical impacts in the audio frequency range is proposed and tested. Comparison results of lasers with a diffraction grating and with an intracavity interference filter are presented. Features in the response of the laser emission frequency to an external acoustic perturbation are shown.

Keywords: tunable laser, optical frequency stability, external cavity diode laser, interference filter

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1. INTRODUCTION

The availability of diode lasers for operation almost in the entire visible and near infrared ranges, their low energy consumption, compactness, and safety explain their dominance in the market of household and industrial equipment not requiring high optical powers. At the same time, the possibility of lasing in a wide wavelength range results in their active application in optical metrology, atomic and molecular spectroscopy. To achieve single-frequency lasing at a required frequency, the laser cavity should include a spectrally selective element separating the only possible mode among all others in the laser's gain line. It can be a reference optical flat etalon [1, 2], a volume diffraction grating [3], an interference filter [4], and others. The most commonly used optical schemes using the reflective diffraction gratings are autocollimation (Littrow) [5] and double-pass (Littman–Metcalf) [6] ones. This is due to both the grating availability and low price and simple practical implementation of these schemes [7–9]. However, the development of lasers for high and ultrahigh resolution spectroscopy requires the solution of a technical self-contradictory problem: the emission frequency should be tuned to a required value; as it is achieved, the frequency should become as less as possible sensitive to external perturbations. Laser frequency referencing to an atomic line solves this problem by significant complicating the optical and electronic components of a device and an increase in their cost. This suggests the necessity of using such optical and mechanical schemes of an external cavity, which would provide as much as possible rigid relation of elements between them.

To describe the radiation quality of the tunable laser, such its characteristics as the lasing linewidth and frequency drift are conventionally used. The former characterizes radiation coherence and is displayed by the spectral density of frequency noises. The latter is most often presented by the time evolution of the emission wavelength or its Allan deviation. Both characteristics partly carry information about the laser cavity sensitivity to external perturbations [4]; however, being measured under laboratory relatively quiet conditions, they do not give complete insight into the laser behavior in an acoustically aggressive environment.

In this paper, we compare two diode lasers developed by us with external cavities (ECDL) of various designs in terms of the degree of their sensitivity to acoustic effects of variable frequencies.

2. LASER DESIGNS

Lasers whose optical schemes and mechanical designs as a whole corresponded to those described in [10] and [11] were compared.

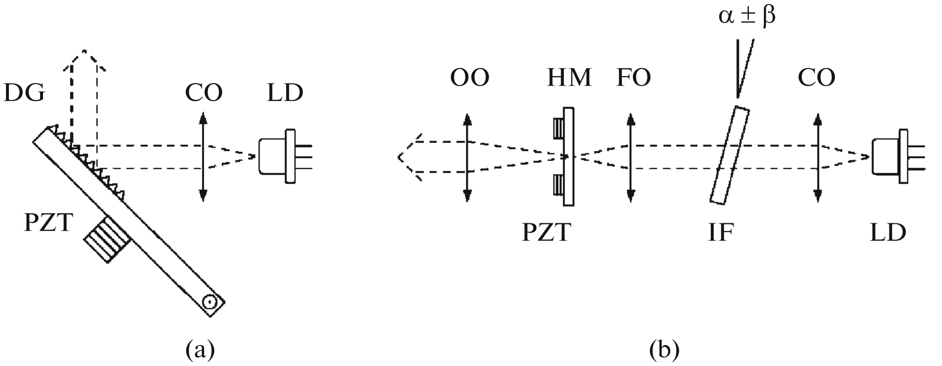

Fig. 1. Optical schemes of diode lasers with an external cavity: (a) with a diffraction grating and (b) with an intracavity interference filter. LD is the laser diode, CO is the collimating objective, PZT are piezoceramic elements, DG is the diffraction grating, IF is the interference filter, FO is the focusing objective, HM is the half-transparent mirror, and OO is the output objective.

The wavelengths of both lasers coincide with the rubidium D1 line (794.7 nm). The diodes with antireflective coated front faces were used in each, whose residual reflectance does not exceed 0.1% according to the manufacturer data. The optical schemes of the ECDLs under study are shown in Fig. 1.

The first ECDL was assembled according to the autocollimation scheme with a diffraction grating of 1800 mm^{-1} as a selective element (Fig. 1a). The grating was placed on a lever movable in the diffraction plane, which provided matched changes in the grating selectivity and the cavity length, increasing the range of continuous tuning of the emission wavelength. However, in this case, it is also an element most sensitive to vibration. Laser diode radiation was collimated by an aspherical lens with a numerical aperture of 0.6 and a focus of 4 mm. The cavity length was 20 mm. Independent temperature stabilization of the laser diode and the entire laser package was used. In contrast to [10], to simplify the design, only one piezoelectric element (Thorlabs PK2FMP2) is used, which makes it possible to tune the lasing frequency in the range to 80 GHz at synchronous scanning of the cavity length and the laser diode current. Thus, to provide the lasing linewidth less than 1 MHz, voltage fluctuation at the piezoelectric element should be no more than 10^{-5} of the maximum output voltage of its controller (75 V), i.e., less than 1 mV.

In the second ECDL, an interference filter with a transmittance of 82% and a bandwidth per pass of 0.3 nm (Fig. 1b) was used as a selective element. Identical aspherical lens with a numerical aperture of 0.6 and a focal length of 4 mm are placed within the cavity. The cavity length is ~50 mm. The laser package made of D16T aluminum alloy, being a framework for all optical elements, was placed on a microcooler and thermally stabilized. In [11], optical radiation was extracted using a mirror placed within the cavity and spatially cutting a laser beam fraction. Such a scheme simplified the mechanical design: an additional objective, a piezoelectric element with an aperture for radiation output, and a dividing mirror were not required. However, diffraction losses at edges of this mirror significantly decrease the optical feedback level and lead to an increase in the threshold current. In the present study, radiation was extracted from the laser cavity by a conventional method through a half-transparent output mirror (HM in Fig. 1b) with a reflectance of 30%, which was fixed on two piezoelectric elements Thorlabs PA2JE.

The wavelength was tuned by changing the angle of the laser beam incidence on the filter. Usually, this is implemented using a mount which does become an element of increased sensitivity to the acoustical influence. The interference filter featuring axial symmetry unlike a diffraction grating allows the use of a mount in which the beam incidence angle is varied by filter rotation [11], rather than by filter inclination. To this end, the filter is fixed on the hollow shaft at a small angle β to its axis, providing the range of the incidence angle tuning for the complete shaft revolution $\pm\beta$.

The shaft is placed into a cylindrical hole whose axis is directed at the angle α of the most probable transmission of the desired wavelength by the filter with respect to the laser optical axis. The shaft rotation allows to adjust the angle of incidence of the laser beam on the filter in the range $\alpha \pm \beta$. In the device under study, the angles of 5° and 3°, respectively, were used, which allowed filter inclination tuning in the range from 2° to 8°. Such a mount with a weak response to mechanical perturbations, which lead to linear displacements of an object, showed high vibration stability in the laser cavity.

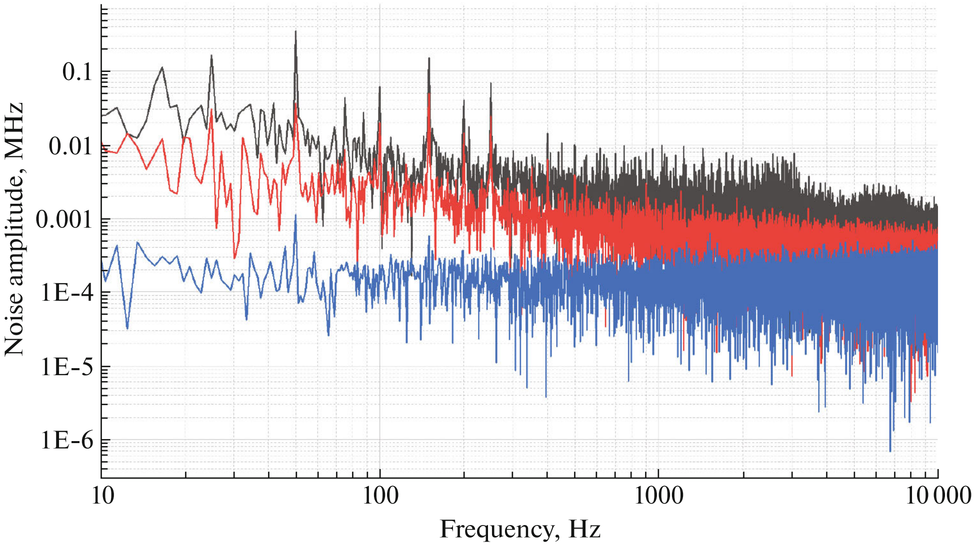

Fig. 2. Frequency noise spectrum of tested lasers under acoustically quiet laboratory conditions. The blue (lower) curve represents measurement system noise, red (medium) curve is the noise of the intracavity interference filter laser, black (upper) curve is the noise of the diffraction grating laser.

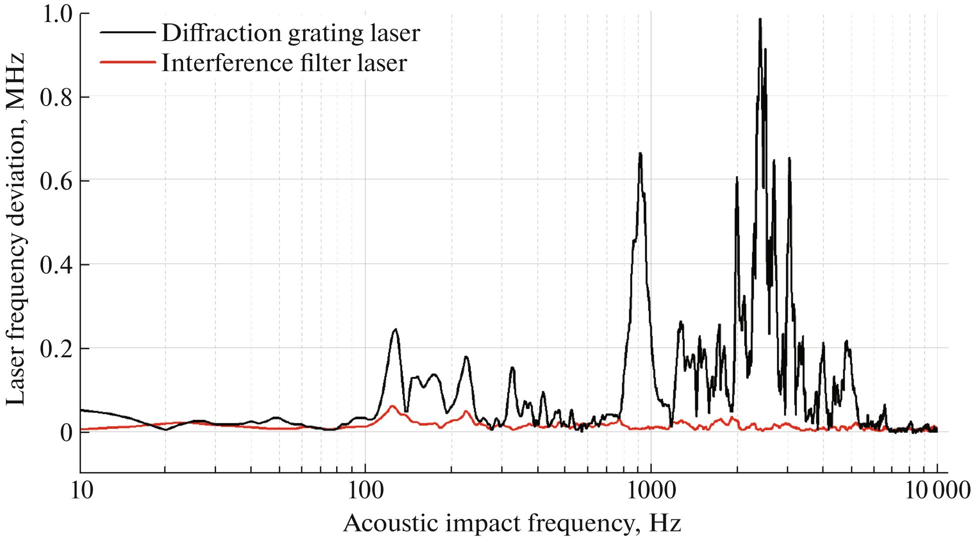

Fig. 3. Frequency deviation of the diffraction grating laser (black curve) and the interference filter laser (red curve) under acoustic perturbation conditions.

3. TECHNIQUE AND COMPARISON RESULTS

Lasers were compared using the emission frequency noise (Fig. 2) and laser frequency deviation (Fig. 3) spectra under conditions of the acoustical perturbation of variable frequency.

As a frequency discriminator, the resonance of saturated absorption (sub-Doppler resonance) [12] corresponding to the $F_g = 2 \rightarrow F_e = 1$ transition of the ^{87}Rb D1 line was used. Its width was 10 MHz.

Both lasers demonstrated good passive frequency stability and did not leave the resonance slope during measurements; therefore, additional referencing was not used. The atomic cell transmission signal was recorded for 1 s with a time resolution of 10 μs providing a measured signal bandwidth of 50 kHz. Figure 2 shows the frequency noise spectra in the bandwidth of 10 kHz with a resolution of 1 Hz, obtained by the Fourier transform of recorded signals. Itrinsic noises of the measurement system are presented by the lower curve.

Measurements were performed alternately using the same diode current, temperature, and piezoelectric element voltage controller for both lasers to avoid the effect of electronics on the comparison results. Noises of the diffraction grating laser are several times higher than those of the interference filter laser. This is explained by the smaller cavity length and a ten times higher sensitivity to voltage fluctuations of the Thorlabs PK2FMP2 piezoelectric element. Narrow peaks at frequencies multiple of 25 Hz in the noise spectra are associated with the power line frequency, its harmonics, and subharmonics.

As a whole the behavior of lasers under acoustically quiet laboratory conditions is comparable: both demonstrate high passive frequency stability and close generation linewidths which were compared by noise amplitudes on the saturated absorption resonance slope and were determined mostly by current and voltage fluctuations in piezoelectric elements. A certain excess noise in the vicinity of frequencies of 1–3 kHz is shown by the diffraction grating laser, but without some resonant properties.

To compare the behavior of lasers under acoustic perturbation conditions, a dynamic head was attached to the optical plate on which ECDLs were placed. Lasers were equally spaced from the perturbation source and the sub-Doppler resonance formation scheme. A sinusoidal fixed-amplitude signal with a frequency scanned in the range from 10 Hz to 10 kHz for 80 s was fed to the head. As the discriminator converting frequency fluctuations to amplitude ones, the saturated absorption resonance in rubidium atoms was also used. To eliminate drift at measurement times, the emission frequency was stabilized on the resonance slope by a slow feedback loop with a bandwidth of 5 Hz and the control signal was applied to the piezoelectric element. The amplitude of the oscillating component caused by the sound was measured, rather than the spectrum of the measured signal. To this end, a Stanford Research SR830 synchronous detector was used; the signal of the generator setting the perturbation frequency was used as the reference one. The perturbation amplitude was chosen so that the response in the optical signal at any frequency would remain within the discriminator linear conversion. The measurement result is shown in Fig. 3.

The data obtained clearly show the difference of two ECDL in the response to an acoustic perturbation. For example, in the frequency range from 800 Hz to 5 kHz, the frequency deviation of the grating laser is 20—30 times higher that the deviation of the filter laser. Such a significant quantitative difference was not expected based on the data of Fig. 2; therefore, the described method for estimating the acoustic stability of lasers can be an efficient complement to a set of calibration tests in fabricating prototypes and commercial devices. Instead of the atomic line, a stabilized interferometer with a resonance width of ~1 MHz can be used as a frequency discriminator. Accurate information on intrinsic mechanical resonances of the laser system can facilitate the calculation and fabrication of damping systems necessary during operation of a tunable laser outside a scientific laboratory in an acoustically aggressive environment.

4. CONCLUSIONS

A direct comparison of the acoustic stability of two ECDLs differing by external cavity designs: the autocollimation laser and the intracavity interference filter ("cat's eye") laser was performed. It was shown that the lasers can feature different susceptibility of the emission spectrum to mechanical perturbations in the acoustic frequency range at comparable spectra of intrinsic frequency noises at rest. This was clearly demonstrated by the dependence of the laser frequency deviation on the frequency of the external acoustic perturbation in the frequency range of 0.1–10 kHz.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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