Quantum Electronics **36** (5) 399 – 402 (2006)

PACS numbers: 42.55.Px; 42.60.Da; 42.60.Mi
DOI: 10.1070/QE2006v036n05ABEH013238

Low-frequency power and pointing noises of a spectrally-selective external-cavity diode laser

V.V. Bruevich, S.G. Elizarov, D.Yu. Paraschuk

***Abstract*. The spectral density of low-frequency power noise and pointing noises of an external cavity AlGaAs/GaAs laser in Littman – Metcalf configuration is studied in the frequency region up to 1 kHz. The relative level of the power and pointing noises in the laser operating on a single longitudinal mode of the external resonator was $\sim 10^{-6}$ Hz$^{-1/2}$ and did not change substantially when the feedback was switched off. Long-term intensity fluctuations caused by intermode switchings did not exceed 2 %.**

Keywords: *diode laser, external cavity, low-frequency noise.*

1. Introduction

External cavity diode lasers (ECDLs) are used in spectroscopic studies when a tunable narrowband (10^9 – 10^3 Hz) laser emitting moderate powers (1 – 100 mW) is required [1]. Their operation principle is based on the use of spectrally selective optical feedback, which affects both the spectral characteristics of the diode laser and its dynamic parameters [2]. The laser cavity is formed by AR coatings deposited on the diode laser facet and by external frequency-selective optical elements, most often – diffraction gratings.

Figure 1 shows schematically the spectra of radiation returned by means of selective optical feedback, and longitudinal modes of the main and external cavities. The locking of a longitudinal mode of the composite cavity occurs because radiation at the frequency of this mode returns to the main resonator, increasing its Q factor for the corresponding wavelength. In this case, even in the absence of a spectrally selective element (the case of a simple optical coupling), the conditions of lasing at one or several modes can be considerably improved when an external cavity mode coincides with a main cavity mode. Depending on the value of feedback and other parameters, the laser can operate in one of the several regimes. The relation between lifetimes of different laser modes is the main parameter determining its behaviour [3]. Calculations show that if the value of a simple optical coupling (from a mirror) is sufficient, the laser can emit one longitudinal mode [3]. The spectral width of radiation at this mode also decreases. However, at a certain value of feedback, the laser can operate either in a chaotic regime (in this case, the output spectrum strongly broadens) or stable operation at several longitudinal modes can be observed.

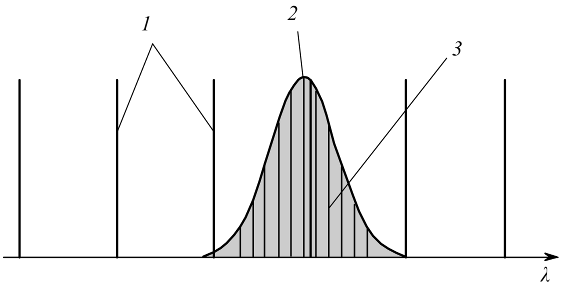

Figure 1. Spectrum of the main-cavity modes (*1*), radiation returned by means of optical feedback (*2*), and the external-cavity modes (*3*).

An ECDL can exhibit dynamic instabilities, in particular, dynamic chaos. This can lead to the deterioration of laser characteristics, for example, to the broadening of its spectral line [4]. One of the problems appearing due to the external optical feedback is an increase in the laser radiation noise [5, 6]. First, the spectrum of noise inherent in the laser itself (quantum noise) changes under the action of feedback [7]. Second, noise increases over the entire low-frequency region (less than a few hundreds of megahertz). The increase in the low-frequency noise is explained by switchings between the longitudinal modes of the ECDL [4, 6]. In this case, the noise increases due to the development of instability caused by the external feedback. Mode switchings in the main and external cavities should be distinguished. Such a noise was studied in detail experimentally [8]. It was shown that the level of fluctuations depends on the cavity temperature. At certain temperatures, the laser passes to the unstable regime, and switchings between its longitudinal modes occur.

Switchings between the longitudinal modes of the main cavity can be comparatively easily suppressed in practice. The noise behaviour in the presence of a highly spectrally selective feedback is of interest from the experimental point of view.

In nonlinear spectroscopy, the pump-probe method is widely used. Noise at the frequency of a lock-in detector in the probe channel determines the measurement sensitivity. It

V.V. Bruevich, S.G. Elizarov, D.Yu. Paraschuk Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119992 Moscow, Russia; e-mail: selizar@yandex.ru, paras@polys.phys.msu.su

Received 28 November 2005; revision received 11 April 2006
Kvantovaya Elektronika **36** (5) 399 – 402 (2006)
Translated by M.N. Sapozhnikov

is convenient to select this frequency in the sound frequency range where the $1/f$ noise is insignificant. In a number of measurements, for example, photodeflection measurements [9] the sensitivity is determined not only by power noise but also by pointing noise of the laser beam.

In this paper, we measured the spectral density of the low-frequency power noise and fluctuations of the radiation pattern of a single-mode AlGaAs/GaAs ECDL in Littman – Metcalf configuration in the frequency range up to 1 kHz. We also studied the influence of the spectrally selective external feedback on the noise characteristics of the laser and showed that this influence on the level of the low-frequency noise is insignificant.

2. Experimental

An external cavity was in Littman – Metcalf configuration (Fig. 2) [10]. A diffraction grating was oriented at the grazing angle with respect to laser radiation and a mirror was mounted perpendicular to radiation reflected to the first diffraction order. The output radiation frequency of such an external cavity can be controlled by rotating the mirror.

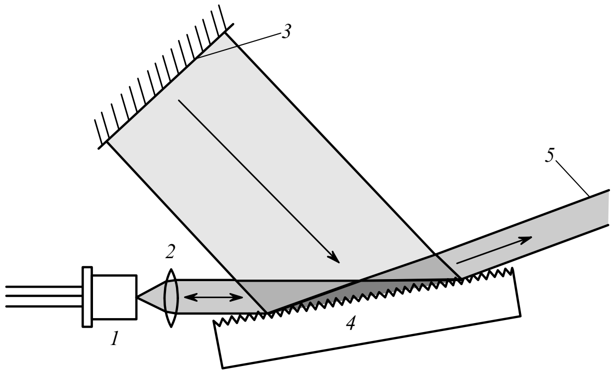

Figure 2. External-cavity diode laser in Littman – Metcalf configuration: (*1*) laser diode; (*2*) lens; (*3*) mirror; (*4*) diffraction grating; (*5*) output radiation.

We fabricated a compact external cavity intended for using with diode lasers emitting in the range 650 – 900 nm (without replacing the grating). The external cavity length was 12 cm. The cavity consisted of a 1800-lines mm^{-1} diffraction grating, an aspherical GELTECH lens with a focal distance of 8 mm and a numerical aperture of 0.5, and a movable mirror mount with an electric drive.

A laser diode was mounted so that the p – n junction plane was virtually perpendicular to the grating lines. In this position, the grating efficiency is maximal, which allows one to set the grating at a large angle to incident radiation, thereby increasing the spectral selectivity of the cavity. It is undesirable to set it strictly perpendicular because in this case the spectral selectivity considerably decreases due to a large length of the emitting region.

The external cavity was controlled with an original electronic unit. The wavelength tuning was performed by rotating the mirror with a microstep motor drive with a step ~0.001 nm. The temperature and current of the diode laser were specifies and controlled by a power supply.

We used a commercial single-mode AlGaAs/AlGaAs/GaAs laser diode with the central wavelength of 825 nm, the operating current 102 mA, the output power 50 mW, the angular aperture $30° \times 10°$, and the 1×50 μm emitting region. The optical length of the laser diode cavity was ~2.5 mm.

The ECDL spectrum was recorded with an MSDD100 (Solar TI) spectrometer equipped with a CCD linear diode array. The width of the instrumental function of the spectrometer was 0.05 nm.

The low-frequency noise of the laser was measured with an SR830 (Stanford Research) lock-in detector and a two-sectional silicon photodetector with a circuit for subtraction and addition of photocurrents based on an S4204 (Hamamatsu) photodiode. The photodetector was placed so that all radiation fall within its aperture, and the average value of the difference signal was zero. The value of $\delta I/I$ for the difference channel of the photodetector is proportional to the ratio of the standard deviation of the beam displacement to its average diameter, and $\delta I/I$ for the summation channel is the noise power density of laser radiation.

The ECDL stability was studied by using a power-calibrated silicon photodetector built in the external cavity.

3. Results

The emission spectrum of a free-running diode laser always has a pedestal containing many longitudinal modes near the spectral centre. This pedestal can be substantially reduced by introducing optical feedback. Depending on the operation conditions of the laser such as focusing affecting the feedback magnitude, the adjustment of the laser mirror and its rotation, and the laser diode current, the laser can operate in different regimes. The three characteristic ECDL operation regimes can be distinguished (Fig. 3): the first one – at a single mode of the external cavity (during the averaging time of the photodetector, the emission wavelength lies within a single mode of the external cavity), the second one – at a few modes of the external cavity within a single mode of the main cavity, and the third one, which is close to free running regime, when the emission spectrum contains one or several (depending on the laser diode temperature) intense longitudinal modes of the laser cavity

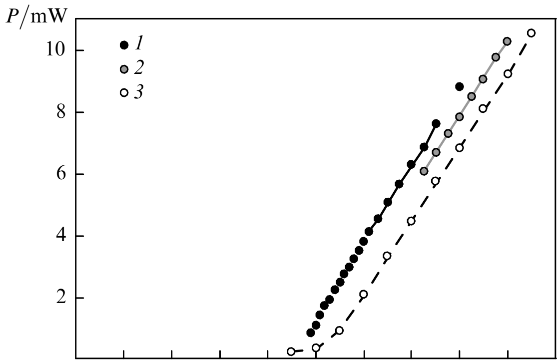

Figure 3. Dependences of the output power on current for the external-cavity diode laser operating at a single longitudinal mode of the external cavity (*1*), a single mode of the main cavity (*2*), and in the free-running regime (*3*).

and a pedestal consisting of comparatively weak longitudinal modes.

When feedback is not strong enough, the laser operates in the third regime, and no noticeable variations in its emission spectra occur. In the first and second regimes, the laser operates at a wavelength close to that of the external cavity. Although we could not measure laser linewidths (less than 0.05 nm) in these regimes, we found that the output powers and lasing stability were substantially different (Fig. 3). We assume that in the second regime the laser emits a few longitudinal external-cavity modes of close intensities (which can rapidly switch from one to another), while in the first regime the laser tends to operate at a single longitudinal mode of the external cavity. The lasing efficiency in the second regime decreases due to switching between the longitudinal modes.

In the first regime, the lasing threshold is decreased because radiation losses per round trip in the composite cavity at the selected wavelength are lower than losses in the main cavity in the third regime. Thus, it is possible to control the lasing regime and the output power.

The ECDL can operate at a single stable mode of the main cavity within the tuning range of 20 nm near the gain line centre. The output linewidth of the diode laser is smaller than 0.05 nm. The output power weakly depends on the tuned wavelength (for a specified current of the laser diode).

4. Output radiation stability

Figure 4 presents the time dependences of the output power in the first regime, when the laser emits a single longitudinal mode of the external cavity [curve (*1*), Fig. 3]. One can see that the amplitude of power fluctuations is much smaller than a change in the radiation power in passing between regimes of lasing at a single longitudinal mode of the main or external cavities. Thus, we can assume that fluctuations of the laser wavelength are much smaller than the distance between the two longitudinal modes of the main cavity. The root-mean-square deviation in the 0 – 5-Hz band is 0.4 %, while the maximum deviation of the intensity caused by switching between the external-cavity modes does not exceed 2 %.

The plot in Fig. 4b suggests that switching between the longitudinal modes of the external cavity can occur for several seconds. For this reason, the measurements of the low-frequency intensity noise and radiation pattern (see below) were averaged over a few tens of seconds.

Because the external cavity was not thermally stabilised, it is most likely that switching between longitudinal modes was caused by thermal fluctuations of the optical length of the external cavity. It is known that several switching scenarios are possible [6], and low-frequency noise can increase in the regions of changes in the cavity parameters (where switching occurs).

5. Low-frequency noise of the laser

Figure 5 shows the low-frequency noise spectra of the laser operating in the first and third regimes. The output power was 12 mW. The noise did not increase within the experimental accuracy when feedback was switched on. In the frequency region below 1 kHz, the noise was of the $1/f$ type and its level did not exceed 10^{-6} Hz$^{-1/2}$ in the region of 1 kHz, which is approximately an order of magnitude higher than the shot noise of the photocurrent equal to 65 μA.

Figure 5 also presents the pointing noise spectrum. The fluctuations were measured in the p – n junction plane. The pointing noise spectrum, as the power noise, monotonically decreases with increasing the frequency. We found that the direction of output radiation changed jumpwise when the temperature of the active medium was changed.

As pointed out in Introduction, the increase in the noise intensity in the low-frequency region is mainly caused by

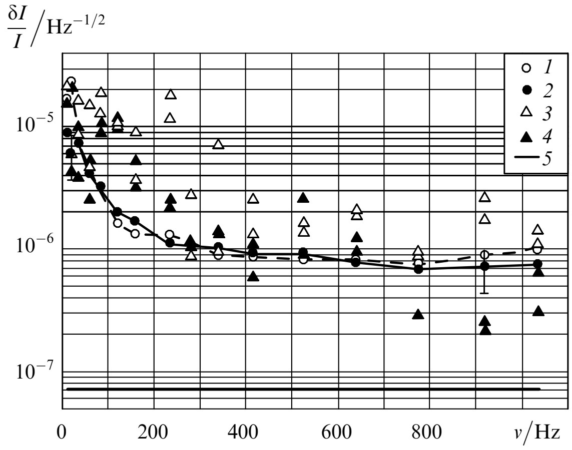

Figure 5. Spectral noise power density normalised to the total radiation power density. The output radiation noise in the first (*1*) and third (*2*) regimes and the noise of the output radiation direction drift in the first (*3*) and third (*4*) regimes; (*5*) shot noise level.

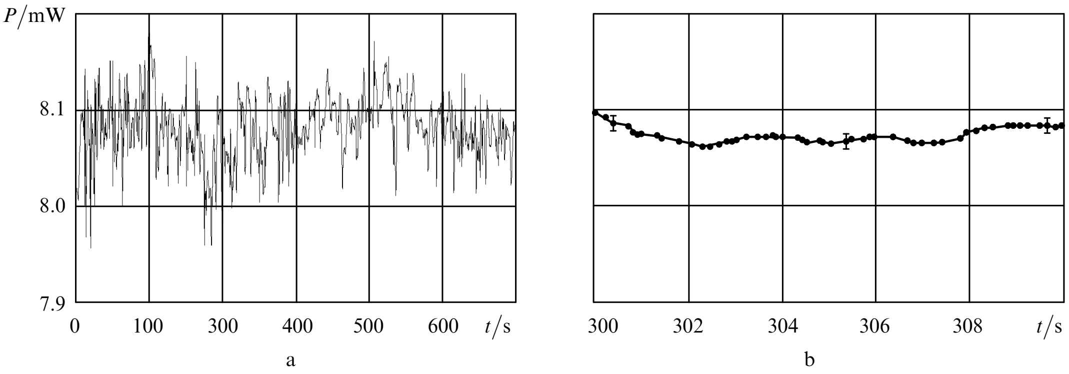

Figure 4. Time dependences of the laser output power in the single-frequency regime during 10 min (a) and 10 s (b).

switchings between the longitudinal modes of the cavity. The mode spectrum of a composite cavity is determined by the lengths of the main and external cavities. Because the external-cavity length is much greater than that of the main cavity, the intermode distance for the external cavity is much smaller than that for the main cavity. Therefore, the introduction of the external cavity with a low spectral selectivity gives rise to a number of modes for which the lasing conditions are fulfilled. Switchings between these modes can result in the noise increase. If the spectral selectivity of the external cavity is sufficient to provide the conditions for lasing at a single longitudinal mode of the composite cavity, such a switching will be unlikely. It seems that for this reason no noticeable increase occurs in the intensity and pointing noise of the ECDL upon switching feedback.

6. Conclusions

We have studied the spectral power density of the low-frequency intensity and pointing noise in the frequency region up to 1 kHz for external-cavity AlGaAs/GaAs diode lasers. The measurements were performed for lasing at a single longitudinal mode of the external cavity. It was shown that the relative power and pointing noise of the laser was 10^{-6} $\mathrm{Hz}^{-1/2}$. It was found that the noise level in this region is independent of the presence or absence of feedback (within the experimental accuracy). The long-term fluctuations of the laser power caused by switchings between the external-cavity modes do not exceed 2 %.

References

1. Wieman C.E., Hollberg L. *Rev. Sci. Instrum.*, **62**, 1 (1991).
2. Salathe R.P. *Appl. Phys.*, **20**, 1 (1979).
3. Pierce I., Rees P., Spencer P.S. *Phys. Rev. A*, **61**, 053801 (2000).
4. Buldu J.M., Trull J., Torrent M.C., Garcia-Ojalvo J., Mirasso C.R. *J. Opt. B: Quantum Semiclass. Opt.*, **4**, L1 (2002).
5. Nilsson B.O. *IEEE Transactions on Electron Devices*, **41**, 2139 (1994).
6. Kamiya T., Ozu M., Yamamoto V., et al. *Fizika poluprovodnikovykh lazerov* (Physics of Semiconductor Lasers) (Moscow: Mir, 1989).
7. Hjelme D.R., Mickelson A.R., Beausoleil R.G. *IEEE J. Quantum Electron.*, **27**, 352 (1991).
8. Bogatov A.P., Drakin A.E., Plisyuk S.A., Stratonnikov A.A., Kobyakova M.Sh., Zubanov A.V., Marmalyuk A.A., Padalitsa A.A. *Kvantovaya Elektron.*, **32**, 809 (2002) [*Quantum Electron.*, **32**, 809 (2002)].
9. Olmstead M.A., Amer N.M., Kohn S., Fournier D., Boccara A.C. *Appl. Phys. A*, **32**, 141 (1983).
10. McNicholl P., Metcalf H. *J. Appl. Opt.*, **24**, 2757 (1985).