Optics Communications 421 (2018) 90–93

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Analysis of no mode-hop tuning of mirror-grating external-cavity diode laser

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ARTICLE INFO

Keywords:
Diode laser
Lasers
Tunable

ABSTRACT

The simplicity of structure and the no mode-hop tuning characteristic are of crucial importance for external-cavity diode laser applied in the field of experiment and engineering. A new and enhanced structure for mirror-grating Littrow-type external-cavity diode laser (ECDL) is proposed in this article. On the basis of this external cavity diode laser, a large mode-hop-free tuning range can be obtained and the direction of the output beam remains almost unchanged when the laser is tuned. We can tune the laser over a continuous range reaches 4.34 nm and the lateral displacement of output beam is only 0.033 mm at 805 nm when the initial length of external cavity is 12.82 mm.

1. Introduction

External cavity diode laser (ECDL) is widely used in both spectroscopy [1] and optical communication [2] and so on. Many researchers have done comprehensive and deep research on the linewidth, mode structure, tuning characteristic and applications of the ECDL [3–8] Ruhnke, N has developed a Littrow configuration extended cavity diode laser [9], the output of laser is reflected from a plane mirror fixed parallel to the tuning diffraction grating, as shown in Fig. 1a, based on the configuration, a spectral width of 20 pm at 445 nm with a side-mode suppression ratio larger than 40 dB was achieved, but the no mode-hop tuning characteristic has not been analyzed in the paper. In fact, mode-hop suppression in Ref. [9] cannot be obtained, because if the grating is rotated around the pivot point in the position at which the laser beam axis and grating plane intersect, shown in Fig. 1a as pivot point A, the length of the external cavity will not change and it means that there will be no change of wavelength until the mode hops to the next possible mode which has lower losses which has been analyzed carefully in Ref. [7].

In this paper, we develop an enhanced mirror-grating Littrow-type external-cavity diode laser which is similar to the structure in Ref. [9], namely, a plane mirror is also fixed parallel to the diffraction grating, the only difference is that the position of the mirror and grating is just opposite compared with configuration shown in Ref. [9], the incident beam is reflected by the mirror and then enters diffraction grating, as shown in Fig. 1b. This structure is unique in that when the mirror synchronously rotates with the grating, the grating-feedback wavelength and the length of external cavity will change simultaneously, which make it possible to achieve a large no mode-hop tuning range.

2. Mirror-grating structure ECDL

The mode-hop-free range can be extended by matching the grating angle tuning rate with the external cavity mode tuning rate [7], and the external cavity mode tuning rate depends on the external-cavity length. We first treat the optimum external-cavity length, the tuning characteristic is discussed in Section 2.2 and the influences of assembly errors on the no mode-hop tuning range is analyzed and discussed in Section 2.3.

2.1. The optimum external-cavity length

The geometry for the mirror-grating Littrow-type ECDL is presented in Fig. 2.

We assume that the vertical distance between the grating and mirror is L, the incident angle to the grating is θ, and the output wavelength is λ_0 before any mirror-grating rotation.

The wavelength, λ_0, is given by

$$\lambda_0 = 2d \sin\theta \tag{1}$$

where the d is grating constant.

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https://doi.org/10.1016/j.optcom.2018.03.074
Received 22 January 2018; Received in revised form 13 March 2018; Accepted 28 March 2018
Available online 11 April 2018

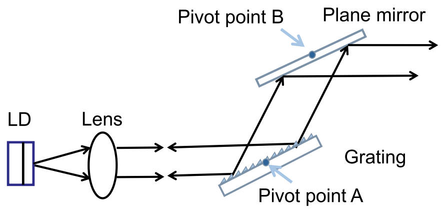

Fig. 1a. Littrow configured ECDL in Ref [9].

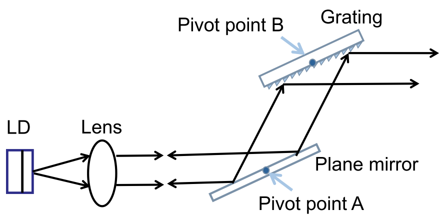

Fig. 1b. Mirror-grating structure ECDL in this paper.

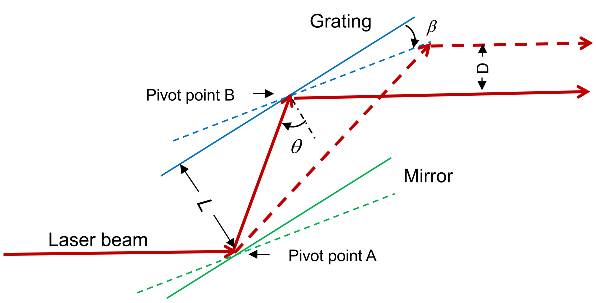

Fig. 2. Geometry for the mirror-grating external cavity diode laser. The beam that strikes the plane-mirror at pivot point A which lies in the plane of the mirror, was reflected by the mirror and then incidents upon the diffraction-grating at pivot point B which lies in the plane of the grating. The mirror and grating rotate synchronously in order to guarantee they keep parallel to each other.

When the mirror-grating is clockwise rotated by angle β, the grating-feedback wavelength, λ_g, is given by

$$\lambda_g = 2d\sin(\theta+\beta) \tag{2}$$

And the external-cavity modal wavelength is

$$\lambda_{ec} = \frac{2(L_{ec}+L_e)}{q} \tag{3}$$

where L_{ec} is the external-cavity length which is the beam path between the back front of the diode laser and the surface of the grating. L_e is the external-cavity length variation caused by mirror-grating rotation.

$$L_e = \frac{\cos(\theta-\beta)L}{\cos(\theta+\beta)\cos\theta} - \frac{L}{\cos\theta} \tag{4}$$

q is the longitudinal mode number, and $q = 2L_{ec}/\lambda_0$, by taking into account the phase shift of the feedback optical field caused by the relative displacement between the incident beam and grating plane, q needs to be revised as follow.

$$q = \frac{2L_{ec}}{\lambda_0} - \frac{L_d}{d} \tag{5}$$

where L_d is the relative displacement.

$$L_d = \frac{L\sin(2\beta)}{\cos(\theta+\beta)\cos\theta} \tag{6}$$

The mode-hop suppression can be obtained by rotating the mirror-grating while scanning the cavity length simultaneously. We expand the expression λ_{ec} and λ_g in a Taylor's series about β,

$$\lambda_{ec} = \lambda_0 + \left(\frac{L\lambda_0^2}{L_{ec}d\cos^2\theta} + \frac{2L\lambda_0}{L_{ec}\cos^2\theta}\right)\beta + o(\beta) \tag{7}$$

$$\lambda_g = 2d\sin\theta + (2d\cos\theta)\beta + o(\beta) \tag{8}$$

The condition of matching the mirror-grating angle tuning rate with the external cavity mode tuning rate can be found by equating the first term in these expressions Eqs. (7) and (8).

Then we can find that the optimum external-cavity length is

$$L_{ec} = \frac{2\lambda_0\sin\theta}{d\cos^3\theta}L \tag{9}$$

L_{ec} has been derived as the same as Eq. (9) for the mirror-grating anticlockwise rotation. In this paper, we assume $\lambda_0 = 805$ mm, $d = 1/1800$ mm, then we can calculate

$$L_{ec} = 6.41L \tag{10}$$

2.2. The mode-hop free characteristic

When the difference between the modal and grating-feedback wavelength does not exceed half the cavity-mode spacing, the mode-hop will not occur while the wavelength is tuned, i.e.,

$$\left|\frac{1}{\lambda_{ec}} - \frac{1}{\lambda_g}\right| \le \frac{1}{4L_{ec}} \tag{11}$$

The mode-hop-free tuning range is defined by Eq. (12)

$$\Delta\lambda = \lambda_g(+) - \lambda_g(-) \tag{12}$$

where

$\lambda_g(+) = 2d\sin(\theta+\beta(+))$, $\lambda_g(-) = 2d\sin(\theta-\beta(-))$.

$\beta(+)$ and $\beta(-)$ are the maximum clockwise and counterclockwise angles which prevent mode hops, respectively.

And the lateral shift of output beam can be derived as Eq. (13)

$$D = D(+) + D(-) \tag{13}$$

where $D(+)$ and $D(-)$ are the lateral shift when the mirror-grating clockwise and counterclockwise rotation, respectively

$$D(+) = \frac{\sin(\beta(+)-\theta)+\sin(3\beta(+)+\theta)}{\cos\beta(+)+\cos(\beta(+)+2\theta)}L,$$

$$D(-) = \frac{\sin(2\beta(-))}{\cos(2\beta(-)-\theta)}L.$$

Simulation of the external length on the maximum counter-clockwise and clockwise angles is shown in Fig. 3.

From the Fig. 3 it clearly shows that the maximum counterclockwise and clockwise angles $\beta(+)$, $\beta(-)$ decreases with the increase of L_{ec}. Given that the tuning range $\Delta\lambda$ and lateral shift of the output beam D are related directly to the counterclockwise and clockwise angles, then we will analyze the effect of the optimum external-cavity length L_{ec} on the tuning range and lateral displacement of output beam.

The effect of the external length L_{ec} on the continuous tuning-range $\Delta\lambda$ and lateral shift of output beam D is illustrated in Fig. 4. It can be seen from the figure that $\Delta\lambda$ decreases and D increases with increasing L_{ec}. When L_{ec} is 9.62 mm, $\Delta\lambda$ is 5.01 nm and D is 0.028 mm. When the L_{ec} increases to 19.23 mm, $\Delta\lambda$ decreases to 3.55 nm and D increases to 0.041 mm. So a large tuning range and small displacement can be obtained by decreasing L_{ec}, however, L_{ec} should not be too small in the practical application because of restriction by assembly accuracy. On the premise to ensure the assembly accuracy, the initial distance L between the mirror and grating should be decreased as much as possible because L_{ec} is proportional to L as shown in Eq. (10). We consider that $L = 2$ mm