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Limits of continuous frequency tuning of injection lasers with selective external cavities

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Abstract. A method for mechanical coupling of the shifts of the band of a selective element to a mode of an injection laser with an external cavity is considered. The method reduces to finding the optimal variant of plane-parallel motion of one of the cavity elements. Solutions are found for important modifications of external cavity systems (in the case of rotation about a fixed axis). Estimates are obtained of the possible width of the continuous tuning range and of the sensitivity of the tuning system to alignment errors.

1. Introduction

As a rule, a continuous tuning interval of the order of or less than 1 GHz is typical and sufficient in Doppler-free atomic spectroscopy. However, in molecular spectroscopy, in heterodyne calibration of the frequency characteristics of broadband photodetectors, and in recording the spectral characteristics of selective elements and optical amplifiers a much wider continuous tuning range is needed. This range is attained by coupled variation of the mode frequency and spectral bands of selective elements [1 – 5].

Figs 1 – 4 show some known configurations of lasers with an external selective element (a reflecting diffraction grating or a holographic grating combined with a total-internal-reflection prism used to suppress the zeroth order [6]) and a mirror. The emission wavelength of such a laser can be tuned continuously if the shift of the wavelength corresponding to the minimum of selective losses (λ_r) is coupled to the shift of the resonance wavelength (λ_q) of a longitudinal mode of an external cavity by synchronous variation of the cavity length and rotation of the selective element [1, 7].

In the case of an autocollimation configuration with a grating (Fig. 1), we have

$$\lambda_r = 2d\sin\theta, \quad \lambda_q = 2L/q .$$

Here, d is the distance between the grating lines; θ is the angle of incidence (diffraction); q is the number of wavelengths which can be fitted inside a cavity whose optical length is L. It should be pointed out that L consists of the geometric length of the external cavity and the optical length of the active region $n_d l_d$, where l_d is the physical length of the active region of the laser diode and n_d is its refractive index. Such coupling has been achieved [2] by a system of the type shown in Fig. 1 which has a mechanical drive with a connecting rod that moves the diffraction grating in such a way that $L/\sin\theta = \text{const}$. A continuous frequency tuning range of 15 nm at the wavelength of 1.26 μm is reported in Ref. [2].

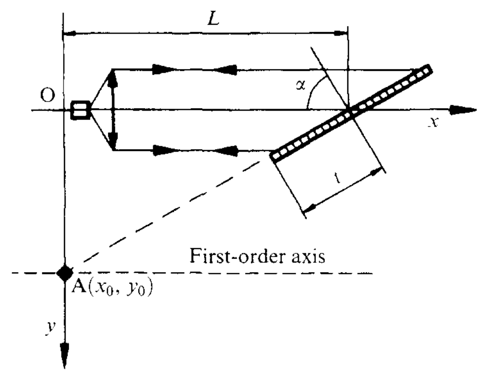

Figure 1.

Rotation of a grating about a fixed axis is used in the systems described in Refs [3, 5]. The continuous tuning range achieved in this way is reported to be 5 and 5.5 nm at the wavelengths of 830 nm and 1.3 μm, respectively. A calculation of the optimal position of the grating rotation axis, ensuring the maximum continuous (without mode hopping) tuning range is given in Ref. [5].

We shall show that the continuous tuning range in these systems is fundamentally limited by the dispersion in the active medium of the laser.

Our aim will be to find the optimal position of the rotation axis, which ensures coupled variation of the parameters of the external cavity for a number of important modifications of this cavity (Figs 1 – 4), and to analyse the limits set on the maximum continuous tuning range.

2. Formulation of the problem

The coordinate origin in Figs 1 – 3 is located at a point O at a distance $(n_d - 1)l_d$ from an external facet of a laser diode. The abscissa is assumed to be directed along the optic axis of the laser into the compound cavity. The rotation axis of one of the cavity elements is perpendicular to the plane of all the figures and intersects this plane at a point (x, y).

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We shall follow the notation of Ref. [5] and introduce the wavelength difference

$$F(\theta, x, y) = \lambda_q(\theta, x, y) - \lambda_r(\theta) . \tag{1}$$

Here, θ is the running value of the angle of rotation about the fixed axis. We shall assume that, for some value of this angle $\theta = \theta_0$, we can obtain

$$\lambda_q(\theta_0, x, y) = \lambda_r(\theta_0) . \tag{2}$$

In general, when a selective element in the form of a grating is rotated about an axis parallel to its lines, the offset between the selective loss minimum and the resonance mode frequency increases. The condition for mode hopping can be formulated on the basis of the following model representations.

The losses experienced by the compound-cavity modes are modulated with a period equal to the intermode spacing of the laser diode cavity ('internal cavity') and the depth of modulation depends on the degree to which the coating of the laser facet facing the external cavity is made nonreflecting. We shall assume that the reflectivity of this facet is zero.

An increase in the offset given by expression (1) increases the losses and gain and, consequently, it reduces n_d. Let us assume that rotation changes the resonance wavelength λ_q faster than the selective-loss-minimum wavelength λ_r. Then, the above-mentioned reduction in the optical length of the active region will hinder mode hopping in the compound cavity when the length of the external part of the cavity is increased and will facilitate such hopping when this length is reduced. The offset given by expression (1) may represent several intermode spacings of the compound cavity at the moment of mode hopping. A similar hysteresis of the tuning characteristic has been observed [8, 9].

If the radiation power is sufficiently high, then the offset (1) can be extended greatly (to tens of intermode spacings) when the side modes are suppressed by the strong field of the dominant modes [10, 11].

We shall ignore these effects since their occurrence can only increase the continuous tuning range. Our assumptions mean that expression (2) determines the midpoint of the symmetric continuous tuning range. At the end of this range the offset (1) reaches half the intermode spacing of the compound cavity:

$$\begin{aligned}|\Delta F(\theta_0, \Delta\theta_{\max}, x, y)| = |F(\theta_0 + \Delta\theta_{\max}, x, y)| \\ - F(\theta_0, x, y)| = \lambda^2/4L ,\end{aligned} \tag{3}$$

where $\Delta\theta_{\max}$ is the maximum angle of rotation at which there is still no mode hopping. Therefore, the problem reduces to finding such a position of the rotation axis (x, y) for which equality (3) is achieved at the highest possible value of $\Delta\theta_{\max}$.

3. General solution

We shall expand the increment ΔF as a Taylor series at a point θ_0 in powers of $\Delta\theta$:

$$\begin{aligned}\Delta F(\theta_0, \Delta\theta, x, y) = c_1(\theta_0, x, y)\Delta\theta + c_2(\theta_0, x, y)\Delta\theta^2 \\ + c_3(\theta_0, x, y)\Delta\theta^3 + O(\Delta\theta^4) .\end{aligned} \tag{4}$$

Since there are two free parameters (x and y), we shall equate to zero the two leading terms of the expansion. The remaining term represents the required offset. We thus obtain the following system of equations:

$$c_1(\theta_0, x, y) = 0 , \tag{5.1}$$

$$c_2(\theta_0, x, y) = 0 , \tag{5.2}$$

$$\Delta\theta_{\max} = \left(\frac{\lambda^2}{4L|c_3(\theta_0, x, y)|} \right)^{1/3} . \tag{5.3}$$

The continuous tuning range is governed by angular dispersion of the selective element and by the doubled amplitude of rotation:

$$\Delta\lambda_{\max} = \frac{d\lambda_r}{d\theta} 2\Delta\theta_{\max} . \tag{6}$$

When the rotation axis is displaced from the optimal point (x_0, y_0), the increment of $F(\theta)$ is governed by the nonzero leading terms of the expansion. An estimate of the influence of the displacement of the axis along both directions can be obtained by solving two pairs of quadratic equations (for opposite rotations, each with their own sign on the right) with $\Delta\theta$ treated as the unknown:

$$\begin{aligned}c_1(\theta_0, x_0 + \Delta x, y_0)\Delta\theta + c_2(\theta_0, x_0 + \Delta x, y_0) \\ \times \Delta\theta^2 = \pm \frac{\lambda^2}{4L} ,\end{aligned} \tag{7.1}$$

$$\begin{aligned}c_1(\theta_0, x_0, y_0 + \Delta y)\Delta\theta + c_2(\theta_0, x_0, y_0 + \Delta y) \\ \times \Delta\theta^2 = \pm \frac{\lambda^2}{4L} .\end{aligned} \tag{7.2}$$

In each case the root with the smaller absolute value is selected, since rotation by a larger angle would lead to mode hopping. The estimate described by expression (6), which gives the dependence of the continuous tuning range on the displacement Δx or Δy, should be modified by replacing $2\Delta\theta_{\max}$ with the modulus of the difference $|\Delta\theta^+ - \Delta\theta^-|$.

4. Examples of tuning systems

4.1 Diffraction grating in an autocollimation system (Fig. 1)

In this system, which makes it possible to use cavities of minimal length, a diffraction grating is rotated about a fixed axis. A parallel laser radiation beam is incident on the grating at an angle α. The diffraction into the first negative order is described by the relationship $\lambda_r(\alpha) = 2d \sin\alpha$. The section of the optic axis between the laser and the grating is denoted by $L^*(\alpha)$ and the optical length of the laser at the beginning of motion is $n_d(\alpha_0)l_d$. The increment in the cavity length because of the dispersion in the semiconductor can be described by the angle of diffraction by the grating. If the dispersion is linear, then

$$\begin{aligned}\Delta L_{\mathrm{dis}}(\alpha_0, \Delta\alpha) &= \frac{dn_d}{d\nu} \Delta\nu(\alpha_0)l_d \\ &= \Delta n l_d \sin\alpha_0 \Delta\left(\frac{1}{\sin\alpha}\right) ,\end{aligned} \tag{8}$$

where $\Delta n = \nu dn_d/d\nu$ describes the effective dispersion in the semiconductor as the frequency is varied. The length increment due to rotation is then $\Delta L(\alpha_0, \Delta\alpha) = \Delta L^*(\alpha_0, \Delta\alpha) + \Delta L_{\mathrm{dis}}(\alpha_0, \Delta\alpha)$.

When the grating is rotated, the angle of incidence of the incoming beam changes and the beam is displaced relative to the grating in a direction perpendicular to its lines. When the grating is displaced parallel to itself by an amount equal to a fraction of a grating line δt, the phase increment is $2\pi\delta t/d$. If $t(\alpha)$ is the distance in the plane of a figure from the edge of the grating to the point of intersection of the beam axis with the grating (Fig. 1), then — apart from a constant phase component — the additional phase shift caused by rotation is $2\pi t(\alpha)/d$. The mode wavelength is $\lambda_q = L(\alpha)/[q + t(\alpha)/d]$ [5]. If we use Fig. 1 to determine the dependences $L^*(\alpha)$ and $t(\alpha)$ and then apply expansion (4), we obtain (omitting the zero subscript of α_0)

$$\Delta F = \frac{\lambda}{L}\Bigg\{\sin\Delta\alpha\left[y - \frac{L^* + (n_d + \Delta n)l_d}{\tan\alpha}\right] + (1-\cos\Delta\alpha)(x + \Delta n l_d) + \Delta\alpha^2\Delta n l_d\frac{1}{\tan^2\alpha} - \Delta\alpha^3\left(\Delta n l_d\frac{\cos\alpha}{\sin^3\alpha}\right) + O(\Delta\alpha^4)\Bigg\}\,. \tag{9}$$

In this system the optimal axis position is

$$x_0 = -\Delta n l_d\left(\frac{2}{\tan^2\alpha} + 1\right), \qquad y_0 = \frac{L^* + (n_d + \Delta n)l_d}{\tan\alpha} \tag{10}$$

and it is shifted from the diffraction grating plane by a small amount. In this position we can tune continuously the laser in the range

$$\frac{\Delta\lambda_{max}}{\lambda} = \left(\frac{2\lambda}{\Delta n l_d}\cos^2\alpha\right)^{1/3}\,. \tag{11}$$

It should be noted that solution (10) implies vanishing of the terms on the right-hand side which contain the length of the external arm of the cavity and this is true in all orders of the expansion in terms of the angle $\Delta\theta$. This means that in the absence of dispersion the rotation of the grating about the axis described by expressions (10) should ensure an ideal match to the cavity parameters. Moreover, the result given by formula (11) is independent of the compound-cavity length.

An ideal coupling can also be achieved in the connecting-rod system described in Ref. [2]. The identity of the properties of the two systems, in spite of the obvious difference between their construction, is due to the fact that in the system considered above there is an additional phase shift because of translation of the grating parallel to itself, relative to the optic axis. The continuous tuning range of the system described in Ref. [2], like that of the system pictured in Fig. 1, is in fact limited by the dispersion in the active region of the laser. The influence of such dispersion can be reduced by introducing small corrections in the cavity described in Ref. [2]. The dispersion can be compensated in the first order if an additional angle ε is introduced between the connecting rod and the grating plane; in the second order, it is necessary to displace the support perpendicular to the optic axis by δ:

$$\varepsilon = \frac{2\Delta n l_d}{\tan^2\alpha(L + \Delta n l_d)}, \qquad \delta = -\Delta n l_d\left(\frac{2}{\tan^2\alpha} + 1\right),$$

where α is the working angle of the grating in Ref. [2].

The linearised increment ΔF at a point $(x_0 + \Delta x, y_0 + \Delta y)$ is described by the following expression in the absence of dispersion:

$$\Delta F(\alpha_0, \Delta\alpha, x_0 + \Delta x, y_0 + \Delta y) = \frac{\lambda}{L}\left[\Delta y\Delta\alpha + \left(\frac{\Delta x}{2} - \tan\alpha\Delta y\right)\Delta\alpha^2\right], \tag{12}$$

so that solution of the system of equations (7) gives

$$\Delta x = \lambda\left(\frac{\lambda}{\delta\lambda\tan\alpha}\right)^2, \qquad \Delta y = \frac{\lambda^2}{\delta\lambda\tan\alpha}, \tag{13}$$

where $\delta\lambda$ is the continuous tuning range.

Expression (12) demonstrates that at any point on the straight line parallel to the optic axis and characterised by the ordinate y_0, we find that Eqn (5.1) is satisfied so that this point is the geometric locus of the 'first-order axes' (Fig. 1).

It follows from relationships (13) that the continuous tuning range depends $\lambda/\delta\lambda$ times more strongly on the shift of the position of the rotation axis in a direction perpendicular to the first-order axis than in the case of a displacement along this axis.

We shall now consider a typical numerical example. Let the radiation wavelength be $\lambda_r = 800$ nm, the grating period $d = 1/1200$ mm, the laser diode length $l_d = 600$ μm, the refractive index of the active region $n_d = 3.5$, and the effective refractive index $n_d + v dn_d/dv = 5$. It then follows from expression (11) that $\Delta\lambda_{max}/\lambda = 0.11$, $\Delta\lambda_{max} = 88$ nm.

In an estimate of the maximum tuning range we can use expressions (13) and assume that $\delta\lambda = \Delta\lambda_{max}$: this gives $\Delta x = 236$ μm, $\Delta y = 14$ μm. If $\delta\lambda = \Delta\lambda_{max}/10 = 8.8$ nm, we have $\Delta x \approx 2000$ mm, $\Delta y = 1.4$ mm. The optimal position of the rotation axis in such a system, i.e. the point (x_0, y_0) is identified by A in Fig. 1.

4.2 Holographic selector in an autocollimation (Fig. 2) system

In this system a holographic selector is rotated about a fixed axis. The selector consists of a prism whose base angle is α and refractive index is n_p. A parallel laser beam is incident on the entry surface of the prism at a small angle $\theta\,(\leqslant 3^\circ)$ and passes through the prism at the angle of refraction $\phi(\theta)$ such that $\sin\theta = n_p\sin\phi$. Diffraction into the first negative order is described by $\lambda_r(\theta) = 2dn_p\sin(\alpha + \phi)$. That part of the optical length of the external cavity which is inside the prism is $n_p l(\theta)$. The section of the optic axis between the laser and the prism will be denoted by $L^*(\theta)$. The total cavity length is the sum of its components $L(\theta_0) = L^*(\theta_0) + n_p l(\theta_0) + n_d(\theta_0)l_d$. The length increment is $\Delta L(\theta_0, \Delta\theta) = \Delta L^*(\theta_0, \Delta\theta) + n_p\Delta l(\theta_0, \Delta\theta) + \Delta L_{dis}(\theta_0, \Delta\theta)$, where

$$\Delta L_{dis} = \frac{dn_d}{dv}\Delta v(\theta)l_d = \Delta n l_d\sin(\alpha + \phi_0)\Delta\frac{1}{\sin(\alpha + \phi)}\,. \tag{14}$$

In this system the axis of a beam incident on a phase grating is displaced relative to the grating lines perpendicular to these lines. If we use Fig. 2 to derive the dependences $L^*(\theta)$, $l(\theta)$, and $t(\theta)$, and if we utilise the Taylor's series

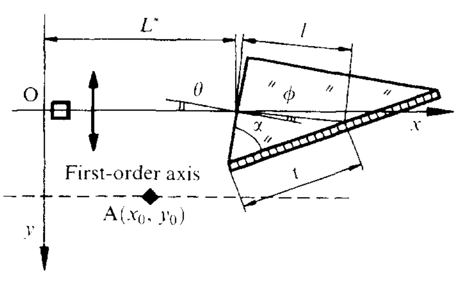

Figure 2.

expansion (4), we find that in this system the optimal position of the axis is

$$
\begin{aligned}
x_0 &= \frac{n_p^2 - 1}{n_p^2 \cos^2\phi}\left[L^* - (L + \Delta n l_d)\frac{\tan\phi}{\tan(\alpha+\phi)}\right] \\
&\quad - \frac{\Delta n l_d}{n_p^2}\left[\frac{2}{\tan^2(\alpha+\phi)} + 1\right]\frac{1 - n_p^2\sin^2\phi}{\cos^2\phi}, \\
y_0 &= \frac{(L + \Delta n l_d)}{n_p \tan(\alpha+\phi)}\,\frac{\sqrt{1 - n_p^2 \sin^2\phi}}{\cos\phi}.
\end{aligned} \tag{15}
$$

The zero index of the initial angles is omitted here.

It follows from Eqns (4), (5.3), and (6) that

$$
\frac{\Delta\lambda_{max}}{\lambda} = \frac{(1 - n_p^2\sin^2\phi)^{1/2}}{n_p\cos\phi}\left[\frac{2\lambda}{\Delta n l_d}\cos^2(\alpha+\phi)\right]^{1/3}. \tag{16}
$$

It should be noted that in this case the continuous tuning range is governed solely by the dispersion of the active region, which corresponds to the third order in the expansion. The nonideal nature of this method of matching the geometric parameters of the compound cavity is revealed in the next (fourth) order of expansion in $\Delta\theta$. The increment described by expression (12) now becomes

$$
\Delta F(\theta_0, \Delta\theta, x_0 + \Delta x, y_0 + \Delta y) = \frac{\lambda}{L}\Delta y \Delta\theta + O(\Delta\theta^2). \tag{17}
$$

The coefficient in front of the quadratic term in the above expression is then fairly cumbersome and will not be given. Nevertheless, we can see that there is a first-order axis parallel to the optic axis (Fig. 2).

In the $\theta = \phi = 0$ case, i.e. when the laser beam is incident normally on the entry surface of the prism, we have

$$
\begin{aligned}
x_0 &= \frac{n_p^2 - 1}{n_p^2}L^* - \frac{\Delta n l_d}{n_p^2}\left(\frac{2}{\tan^2\alpha} + 1\right), \\
y_0 &= \frac{L + \Delta n l_d}{n_p \tan\alpha},
\end{aligned} \tag{18}
$$

$$
\frac{\Delta\lambda_{max}}{\lambda} = \frac{1}{n_p}\left(\frac{2\lambda}{\Delta n l_d}\cos^2\alpha\right)^{1/3}. \tag{19}
$$

If, in the above typical numerical example, we assume that the refractive index of the prism is $n_p = 1.45$, we find that $\lambda_{max}/\lambda = 0.077$, $\Delta\lambda_{max} = 62$ nm.

The problem of rotation of a holographic selector reduces to that of rotation of a diffraction grating in the autocollimation system (Fig. 1), if we assume that

$$
n_p = 1, \quad \theta = \phi, \quad \alpha + \phi = \alpha_g. \tag{20}
$$

where α_g is the angle of incidence of the beam on the grating.

In the next two examples of the tuning systems (Figs 3 and 4) a moving part is a mirror which may be much lighter than in the case of a diffraction grating or a holographic selector, so that it should be possible to increase the frequency of modulation of an external-cavity laser.

4.3 Littman system (Fig. 3)

An external cavity shown in Fig. 3 can be more selective than the autocollimation system. Another advantage of that cavity is that radiation can be coupled out from the zeroth grating order. The radiation remains immobile when the laser frequency is tuned. A laser beam is incident at a point O on a grating and the angle of incidence is α. The radiation diffracted at an angle β is reflected by a mirror and

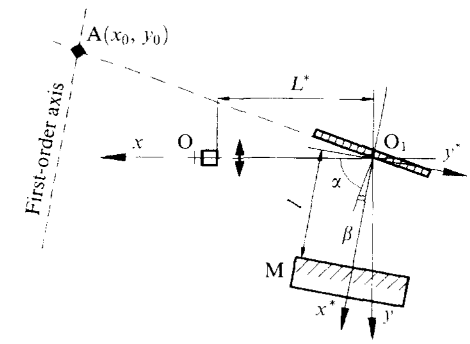

Figure 3.

it is diffracted again by the grating, returning finally to the laser diode (the angles α and β are measured in opposite directions from the normal to the grating). These diffraction conditions are described by $\lambda_r = d(\sin\alpha - \sin\beta)$. Mirror tuning does not alter the position of the beam axis on the grating. There is no additional phase shift associated with displacement of the grating parallel to itself. The length of the external cavity includes a constant part L^* (from the laser to the grating) as well as variable parts $l(\beta)$ and $n_d l_d$: $L(\beta) = L^* + l(\beta) + n_d l_d$. The length increment is $\Delta L(\beta_0, \Delta\beta) = \Delta l(\beta_0, \Delta\beta) + \Delta n l_d(\sin\alpha - \sin\beta_0)\Delta[1/(\sin\alpha - \sin\beta)]$.

The orientations of the coordinates are shown in Fig. 3. The optimal position of the mirror rotation axis is given by

$$
\begin{aligned}
x_0 &= \frac{L\sin\alpha}{\sin\alpha - \sin\beta} + 2\Delta n l_d \frac{\cos^2\beta\cos(\alpha+\beta)}{(\sin\alpha - \sin\beta)^2}, \\
y_0 &= \frac{L\cos\alpha}{\sin\alpha - \sin\beta} + 2\Delta n l_d \frac{\cos^2\beta\sin(\alpha+\beta)}{(\sin\alpha - \sin\beta)^2}
\end{aligned} \tag{21}
$$

and it is displaced by a small amount from the grating plane. The zero indices are omitted above. The solution described by expression (21) also specifies the ideal position of the mirror rotation axis in the absence of dispersion. The continuous tuning range is then

$$
\frac{\Delta\lambda_{max}}{\lambda} = \left(\frac{\lambda}{\Delta n l_d}\,\frac{2\cos^2\beta}{1 - \sin\alpha\sin\beta}\right)^{1/3}. \tag{22}
$$

The linearised increment in the function F, expressed in terms of coordinates rotated about the point O by an angle $\alpha + \beta$ (Figs 1–4), is

$$
\Delta F(\beta_0, \Delta\beta, x_0^* + \Delta x^*, y_0^* + \Delta y^*) = \frac{\lambda}{L}\left(\Delta y^*\Delta\beta - \Delta x^*\frac{\Delta\beta^2}{2}\right).
$$

The first-order axis is parallel to the variable arm $l(\beta_0)$ of the external cavity. We then have

$$
\Delta\lambda_{max}/\lambda = 0.12, \quad \Delta\lambda_{max} = 96 \text{ nm}.
$$

4.4 Holographic selector with an intermediate (Fig. 4) mirror

An external cavity with a fixed holographic selector is more usable (and convenient). Such a cavity is aligned with the aid of an additional mirror. We shall denote the angle of incidence of the beam on the mirror (and of the reflection from the mirror) by β. The optical length of the cavity then consists of the following parts: $L_1(\beta)$ (from the laser to the mirror $+ n_d l_d$), $L_2(\beta)$ (from the mirror to the entry surface of the selector prism), and $n_p l(\beta)$ (the section of the optical path inside the prism). The total cavity length is

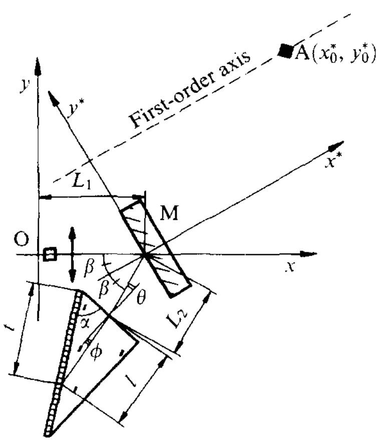

Figure 4.

$L(\beta) = L_1\beta + L_2(\beta) + n_p l(\beta)$. The other parameters of the system are similar to those of the system shown in Fig. 2.

When the mirror is rotated about the z axis, the increment in the angle β is equal to the increment in the angle of rotation and the increment in the angle θ is twice as large as the rotation.

Our calculation was carried out in terms of coordinates x^* and y^* rotated, about the point O, by the angle β with the origin shifted to the point of incidence of the beam on the mirror (Fig. 4):

$$x_0^* = \frac{2}{\cos\beta}\left[L_1 - (L + \Delta n l_d)\frac{(1 - n_p^2\sin^2\phi)^{1/2}}{n_p\cos\phi}\right.$$
$$\left.\times\frac{\tan\beta}{\tan(\alpha+\phi)}\right] - \frac{n^2-1}{n^2\cos^2\phi}\,\frac{2}{\cos\beta}\left[L_1 + L_2 - (L + \Delta n l_d)\right.$$
$$\left.\times\frac{\tan\phi}{\tan(\alpha+\phi)}\right] + \frac{4\Delta n l_d}{\cos\beta}\,\frac{1 - n_p^2\sin^2\phi}{n_p^2\cos^2\phi}\,, \tag{23}$$
$$y_0 = \frac{L + \Delta n l_d}{n_p\tan(\alpha+\phi)\cos\beta}\,\frac{(1 - n_p^2\sin^2\phi)^{1/2}}{\cos\phi}\,.$$

Displacement of the axis from the optimal point gives the following, linearised in respect of x^* and y^* (Fig. 4), expression for the offset:

$$\Delta F(\beta_0, \Delta\beta, x_0^* + \Delta x^*, y_0^* + \Delta y^*) = \frac{\lambda}{L}\cos\beta\Delta y^* 2\Delta\beta + O(\Delta\beta^2)\,.$$

The first-order axis is perpendicular to the mirror plane.

4.5 Grating with an intermediate mirror

In the special case described by expression (20), i.e. when the grating is used in the system shown in Fig. 4, we have

$$x_0^* = \frac{2}{\cos\beta}\left[L_1 - (L + \Delta n l_d)\frac{\tan\beta}{\tan\alpha^*}\right] + \frac{4\Delta n l_d}{\cos\beta}\,,$$
$$y_0 = \frac{L + \Delta n l_d}{n_p\tan\alpha^*\cos\beta}\,. \tag{24}$$

In this case the continuous tuning range is

$$\frac{\Delta\lambda_{\max}}{\lambda} = \left|\left(\lambda\left\{\left[L_1\tan\alpha^* - (L + \Delta n l_d)\frac{\tan\beta}{\tan^2\alpha^*}\right]\right.\right.\right.$$
$$\left.\left.\left.\times\tan\beta\tan^2\alpha^* + 4\Delta n l_d(\tan^2\alpha^* + 1)\right\}^{-1}\right)^{1/3}\right|\,.$$

The external-cavity geometry is selected to ensure that the first term in the denominator of the radicand vanishes. If the other parameters of the system are the same as in a typical numerical example given above, then $\Delta\lambda_{\max}/\lambda = 0.056$, $\Delta\lambda_{\max} = 44$ nm.

5. Conclusions

The above calculations show that the limits imposed by the dispersion in the active region of the laser make it possible, provided the position of a fixed rotation axis is selected correctly, to tune continuously an external-cavity injection laser within practically the whole of the gain profile. Since the limits are related to the width of the gain profile, other limiting factors become of primary importance. The first of them is the residual reflectivity of a laser diode facet, particularly if its spectral dependence is taken into account. Another limit is imposed specifically by the wider frequency tuning range. A mechanical element which displaces a selector or a mirror by a distance much less than the wavelength should ensure that the grating lines remain parallel to the rotation axis and to the active region of the laser throughout the displacement process. The image of the diffracted beam formed on the antireflection-coated facet of a laser diode should not exceed the dimensions of the active region, which implies that the grating lines are parallel to the rotation axis within the limits

$$\delta\gamma \approx \frac{a}{f}\,\frac{\lambda}{\Delta\lambda_{\max}}\,,$$

where a is the width of the active region and f is the focal length of a lens. It follows from the above estimates (on the assumption that $a = 5$ μm and $f = 7$ mm) that $\delta\gamma \approx 0°30'$.

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References

1. Anokhov S P, Marusiĭ T Ya, Soskin M S *Perestraivaemye Lazery* (Tunable Lasers) (Moscow: Radio i Svyaz', 1982)
2. Favre F, le Guen D, Simon J C, Landousies B *Electron. Lett.* **22** 795 (1986)
3. Schremer A T, Tang C L *Photonics Technol. Lett.* **2** 3 (1990)
4. Nilsson O, Goobar E, Vilhelmson K, in *Proceedings of Sixteenth European Conference on Optical Communication (ECOC'90) Amsterdam, 1990* (Eindhoven, Netherlands: Eindhoven University of Technology, 1990) Vol. 1, pp 373–376
5. de Labachelerie M, Passedat G *Appl. Opt.* **32** 269 (1993)
6. Soskin M S, Taranenko V B *Kvantovaya Elektron. (Moscow)* **4** 536 (1977) [*Sov. J. Quantum Electron.* **7** 298 (1977)]
7. Demtröder W *Laser Spectroscopy: Basic Concepts and Instrumentation* (Berlin: Springer, 1981)
8. Lang R, Kobayashi K *IEEE J. Quantum Electron.* **QE-16** 347 (1980)
9. Bykovskiĭ Yu A, Velichanskiĭ V L, Goncharov I G, Grachev A P, Zibrov A S, Koval' S I, Pak G T *Kvantovaya Elektron. (Moscow)* **16** 1128 1989) [*Sov. J. Quantum Electron.* **19** 730 (1989)]
10. Bogatov A P, Eliseev P G, Okhotnikov O G, Rakhval'skiĭ M P, Khaĭretdinov K A *Kvantovaya Elektron. (Moscow)* **10** 1851 (1983) [*Sov. J. Quantum Electron.* **13** 1221 (1983)]
11. Akul'shin A M, Bazhenov V Yu, Velichanskiĭ V L, Zverkov M V, Zibrov A S, Nikitin V V, Okhotnikov O G, Sautenkov V A, Senkov N V, Yurkin E K *Kvantovaya Elektron. (Moscow)* **13** 1391 (1986) [*Sov. J. Quantum Electron.* **16** 912 (1986)]