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Design and analysis of a mode-hop-free tunable laser based on etched diffraction grating*

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Abstract: A novel semiconductor laser which can achieve mode-hop-free tuning is proposed. The device consists of an etched diffraction grating (EDG) as a dispersive element to provide the mode selection function and an active waveguide to provide optical gain for the laser. The slab waveguide region of the EDG contains a tuning section covered by an electrode to inject a tuning current, and thus changes the refractive index. Mode-hop-free tuning is achieved by specially designing the shape of the tuning section, so that the tuning rate of the central wavelength reflected by the EDG and the tuning rate of the resonant wavelength of the laser cavity are equal. An optimized tuning section shape is designed to obtain the largest tuning range within a limited current range. Numerical simulation is presented to demonstrate the mode-hop-free tuning operation.

Key words: Semiconductor laser, Integrated optics, Etched diffraction grating
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1 Introduction

A laser source which can be tuned over a wide spectral range without mode hopping is required for many applications in interferometer and spectroscopy (Levin, 2002). In the wavelength scanned interferometer, for example, mode-hopping is detrimental to spatial resolution or the position accuracy of distance measurement. To achieve mode-hop-free wavelength tuning, the tuning rate of the laser cavity and the tuning rate of the wavelength-selective element must be synchronous. For monolithically integrated lasers, two synchronous tuning electrodes and complex algorithm are usually required to achieve mode-hop-free tuning (Jayaraman *et al.*, 1993; Coldren, 2000; Kwon *et al.*, 2006). To avoid using multi-electrode simultaneous tuning architecture, which needs complicated tuning algorithms and limits the tuning speed, several laser structures tuned by a single electrode have been proposed. By using a tunable twin guide (TTG) layer structure in a distributed feed back (DFB) laser, the refractive index of the laser cavity can be changed with the gain remaining almost the same (Hayakaw *et al.*, 2006). The TTG-DFB laser requires, however, a very complex multiple regrowth and etching fabrication process. Another laser structure is based on tunable distributed amplification (TDA) DFB lasers which employ longitudinally interleaved passive and active segments, which can also be tuned by a single electrode (Nunoya *et al.*, 2008). The TDA-DFB laser also requires an etch-and-regrowth process for the active and tuning sections, in addition to the grating structure. Therefore, the fabrication process is also complicated. Single-electrode control of the lasing wavelength has also been demonstrated in a distributed Bragg reflector (DBR) laser. In this case, however, the gain section of the laser must be very short (several tens of microns) to achieve quasi-synchronous mode-hop-free tuning (Fujiwara *et al.*, 2003), which results in the laser operating under high current density with reduced long term reliability.

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Etched diffraction grating (EDG) based lasers have been investigated for many years (Soole and Poguntke, 1992), both theoretically and experimentally. The state-of-the-art fabricated devices have demonstrated their advantages, including the wide tuning range and high reliability. However, as no consideration of continuous tuning is given to this device, mode-hop occurs several times during the tuning.

In this paper, a novel EDG-based monolithically integrated mode-hop-free tunable diode laser is proposed. The laser can achieve mode-hop-free tuning without any multi-electrode synchronized tuning mechanism.

2 Laser structure and operation principle

Fig. 1 shows the schematic diagram of the EDG based mode-hop-free laser structure. It consists of a deeply etched concave echelle grating (He *et al.*, 1998), an active waveguide to provide optical gain, and a wavelength tuner within the slab waveguide region. The grating, which is designed under Rowland circle construction (Mroziewicz *et al.*, 2007), is a wavelength filter to provide mode selection function. The wavelength tuner has the same layer structure as the slab waveguide but is covered by an electrode to inject a tuning current, so that its effective refractive index can be tuned to change the spectral response of the EDG and consequently the lasing wavelength. The shape of the tuner is designed according to the principle of the mode-hop-free tuning; i.e., when the tuner is injected with a tuning current from the anode, which defines the tuner's shape, to a common ground cathode, the shift of the reflection peak of the EDG is equal to the resonant wavelength change of the laser cavity.

As shown in Fig. 1, the end point O of the active waveguide is located on a Rowland circle of radius R, while the center points of the grating facets are located on a grating circle tangent with the Rowland circle at the grating central point C. The radius of the grating circle is twice the radius of the Rowland circle. As a result, we have

$$\overline{OC} = 2R\cos\alpha, \tag{1}$$

where α is the incidence and diffraction angle with respect to the normal to the grating curve at the central point C.

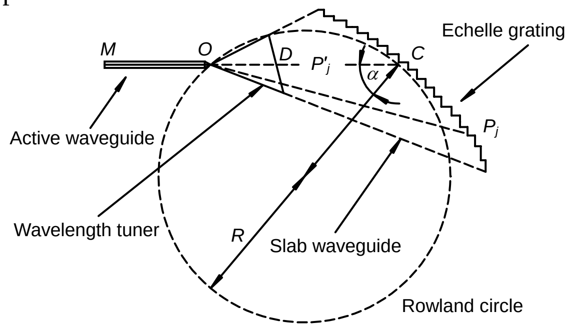

Fig. 1 Schematic diagram of the mode-hop-free continuously tunable laser

The wavelength of the light that is emitted from point O and reflected by the curved grating to the same point must satisfy the grating equation, which dictates that the phase difference between the optical paths going through two adjacent grating facets must equal an integer multiple 2π, i.e.,

$$\Delta\Phi = \frac{4\pi}{\lambda}\left[n\left(\overline{OP_j} - \overline{OC}\right) + \Delta n_\text{t}\left(\overline{OP_j'} - \overline{OD}\right)\right] = 2m_\text{g}j\pi. \tag{2}$$

Herein $\Delta\Phi$ is the phase difference between the light reflected by the grating facet at grating central point C and by the grating facet at point P_j. λ is the wavelength in vacuum, m_g the diffraction order of the grating, j the number of grating periods between the grating central point C and the grating facet at point P_j. P_j' and D are the intersections of the tuner mode-hop-free boundary and OP_j and OC, respectively. n is the effective index of the slab waveguide, and Δn_t is the effective index variation in the wavelength tuner due to current injection. The wavelength of the Fabry-Perot modes of the laser cavity constituted by the waveguide facet at M and the grating is determined by

$$\frac{4\pi}{\lambda}\left(n_\text{a}\overline{OM} + n\overline{OC} + \Delta n_\text{t}\overline{OD}\right) = 2m_\text{FP}\pi, \tag{3}$$

where n_a and OM are the refractive index and length of the active waveguide respectively, and m_FP is an integer corresponding to the Fabry-Perot mode number.

Taking the derivative of Eq. (2) and with some manipulation, we obtain the tuning rate of the EDG reflection peak:

$$\frac{\Delta\lambda}{\lambda}=\frac{\left(\overline{OP_j'}-\overline{OD}\right)\Delta n_t}{n\left(\overline{OP_j}-\overline{OC}\right)}. \quad (4)$$

Similarly, from Eq. (3), the tuning rate of the Fabry-Perot modes can be written as

$$\frac{\Delta\lambda}{\lambda}=\frac{\overline{OD}\Delta n_t}{n_a\overline{OM}+n\overline{OC}}. \quad (5)$$

By equating Eqs. (4) and (5) and with some manipulations, the synchronous wavelength tuning condition of the laser is obtained as follows:

$$\overline{OP_j'}=\overline{OD}\times\left[1+\frac{jm_g\lambda}{2(n_a\overline{OM}+n\overline{OC})}\right]. \quad (6)$$

From Eq. (5), one can see that the tuning range of the laser is determined by the lengths, *OM*, *OC*, and *OD*. By considering the requirements of providing sufficient gain and tuning range, we choose a suitable *OM* value. *OC* can be calculated from Eq. (1) after choosing the incident angle α by considering the fabrication technology and the wavelength dispersion requirement. For given dimensions of the EDG and the length of the active waveguide, i.e., when *OM* and *OC* are fixed, from Eq. (5) one can see that a larger *OD* is helpful for increasing the tuning range. For a given tuning current, however, a larger *OD* also results in an increased tuner region area and a smaller refractive index variation Δn_t, and thus reduces the tuning range. Hence, for a given injection current, there is an optimal tuner shape for achieving the largest wavelength tuning range.

3 Numerical simulations and discussions

From Eqs. (1), (5), and (6), one can see that reducing the Rowland circle radius *R* results in a decrease of the tuner area and consequently an increase of the injection current density. A smaller radius *R* results in, however, a broader spectral response of the grating and lower threshold margin, and thus a lower single-mode selectivity. In addition, from Eq. (5), a shorter length *OM* of the active waveguide is helpful for obtaining a larger tuning range. For practical considerations, however, the length of the active waveguide cannot be too short in order to provide sufficient optical gain without a high injection current density. Under these considerations, the parameters of EDG are set as: Rowland circle radius *R*=1500 μm, *OM*=300 μm. Since the bandwidth of the material gain is about 60 nm, we chose the diffraction order *m*=15, which produces a suitable free spectral range (FSR) in relation to the bandwidth of the material gain.

Fig. 2 shows the spectral response of the EDG calculated by using the Kirchhoff-Huygens diffraction formula and overlap integral formula (Sheng *et al.*, 2001; Shi and He, 2005). The incident field is assumed to be a Gaussian beam with a waist of 1.25 μm. The peak of the reflection spectrum is located at 1550 nm, and its 3 dB bandwidth is about 0.4 nm. The threshold gain of the lasing modes is determined by $r_1r_2e^{gL_a}e^{2ik_0(n_aL_a+nL+\Delta nl)}=1$, where r_1 is the reflection coefficient of the cleaved facet on the left of the active waveguide, r_2 is the amplitude reflection coefficient of the EDG, k_0 is the wave number in vacuum, *L*=*OC*, *l*=*OD*, and L_a=*OM* is the length of the active waveguide. The threshold gain of different longitude modes is plotted as a function of wavelength (Fig. 3). The threshold margin between the main lasing mode and the adjacent mode is about 12 cm^{-1}, which is high enough for single-mode operation.

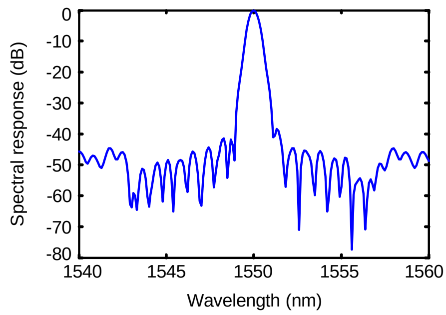

Fig. 2 Spectral response of etched diffraction grating

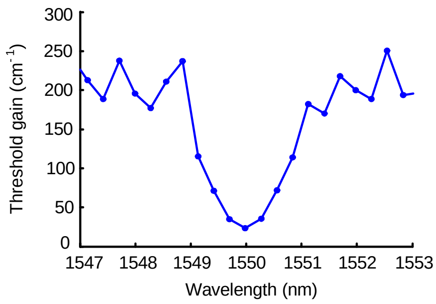

Fig. 3 Threshold gains of the longitudinal modes

As we have mentioned in Section 2, for a given grating geometry, there is an optimal value of the tuner length *OD* for obtaining the largest tuning range. Fig. 4 shows the tuning range as a function of the tuner length *OD* with different incidence angles of 70°, 60°, and 50° within a tuning current range of 300 mA. The effective refractive index change in the tuner area is calculated by the following method. In InGaAsP waveguide, the effective refractive index n_t can be written as: $n_t=\Gamma n_2+(1-\Gamma)n_1$, $n_1=3.1$, $n_2=3.4$, $\Gamma=0.5$ is the confinement factor. We assume that the effective refractive index change in the tuner area is proportional to carrier density *N*, i.e., $\Delta n_t=\chi N$, with $\chi=1.5\times10^{-26}$ m^3. The carrier density is determined by the rate equation $I/(eV)=AN+BN^2+CN^3$, where *I* is the injected current, *V* is the volume of the injection region, $A=10^8$ s^{-1}, $B=5\times10^{-11}$ cm^3/s, and $C=7.5\times10^{-29}$ cm^6/s are constants associated with the material (Weber, 1994). For a given injected current *I*, the effective refractive index change can be calculated precisely. Based on this, the tuning range with all the parameter given can be calculated. Fig. 4 shows that for every value of the incidence angle, an optimal length *OD* exists to obtain the largest tuning range. The existence of the optimal value is due to the fact that the increase of *OD* increases the tuner area, and thus reduces the refractive index change for a given injection current. On the other hand, a larger *OD* increases the proportion of the tuner length over the total cavity length, which helps to increase the tuning range. The tuning range also increases with the incidence angle α. A larger α also results in a larger wavelength dispersion and consequently a higher single-mode selectivity (Fig. 5). However, a larger α also results in smaller grating facets, which increases the loss due to the limitation of fabrication technology. We chose α=70° in our design, which produces a threshold margin of about 12 cm^{-1}, sufficient for achieving a good single-mode selectivity. In this case, the optimal tuner length is *OD*=380 μm and the tuning range is about 3.6 nm.

Fig. 6 depicts the lasing wavelength as a function of the injection current. When the tuner is designed according to the mode-hop-free condition with the optimal *OD* value of 380 μm at α=70°, no mode-hop occurs within the tuning range of 3.6 nm. The corresponding effective refractive index change is 0.017 over the tuner area of 5.7×10^4 μm^2. However, if the mode-hop-free condition is not met, for example, if the second term in Eq. (6) is reduced by a factor of 1/2, mode-hop occurs several times during the tuning.

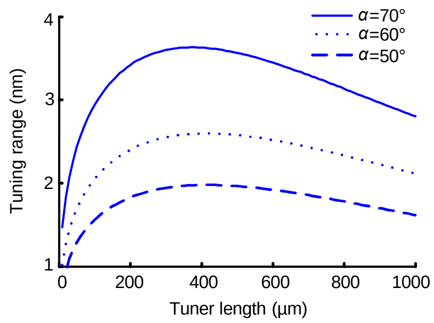

Fig. 4 Tuning range vs. tuner length for different incidence angles

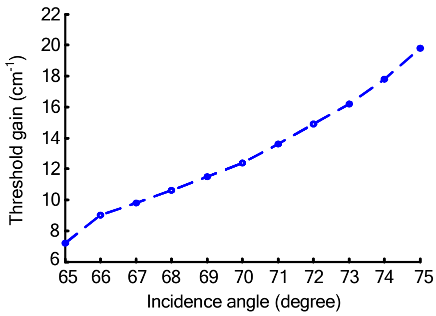

Fig. 5 Threshold gain difference vs. the incidence angle

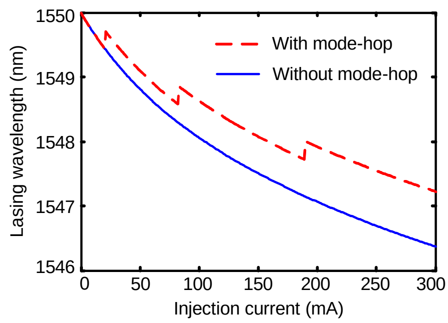

Fig. 6 Lasing wavelength vs. injection current, showing the tuning operations with and without mode-hop

Fig. 7 depicts the tuning range as a function of the maximum injection current. A larger tuning current will increase the tuning range, because it causes a larger refractive index change. The increase, however, is not linear. The refractive index, and consequently the tuning range, increase more slowly as the tuning current increases. This results from the nonlinear relation between the carrier density and the injected current in the rate equation. In addition to the change of the focal point of EDG, which leads to the tuning of the lasing wavelength, the injection of the tuning current into the tuning section also causes a loss increment due to the plasma effect. As confirmed by our calculation, however, the loss increment increases only slightly the lasing threshold but does not affect the tuning characteristics.

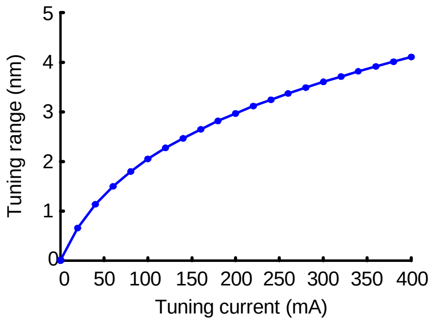

Fig. 7 Tuning range vs. maximum tuning current

4 Conclusions

A waveguide echelle grating based diode laser which is capable of mode-hop-free tuning has been proposed. This laser can be tuned by a single electrode without a complex algorithm. The shape of the tuner is optimized to obtain the maximal continuous tuning range for a given injection current. A mode-hop-free tuning range of 3.6 nm can be achieved, and it can cover multiple wavelength bands simultaneously by using multiple waveguide channels. The monolithic integrated laser can be tuned at high speed and widely used in lidar sensing and the interferometer.

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