Electrically Tunable Laser Diodes

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Abstract: The operation principles of electrically tunable laser diodes, the device structures for continuous and discontinuous tuning and the relevant device characteristics are presented. Recent progress with widely tunable devices and tunable VCSELs is emphasized.

Single longitudinal mode laser diodes with an electronically tunable wavelength are indispensable key components of advanced photonics applications such as broadband multichannel optical communications, wavelength dependent measurements and several sensing techniques. For most applications, a continuous tuning behaviour with a high spectral purity is demanded. Depending on the operation principle, the three different tuning modes shown in Figure 1 may be distinguished. Besides the continuous wavelength tuning, by which any wavelength within the covered wavelength band can be achieved, one may observe discontinuous tuning, by which discrete wavelength jumps occur, and quasicontinuous tuning, by which overlapping intervals of each continuously tunable regimes appear. The wavelength jumps in the discontinuous tuning mode stem from longitudinal mode jumps corresponding to the longitudinal mode spacing $\Delta\lambda_{\mathrm{m}}$.

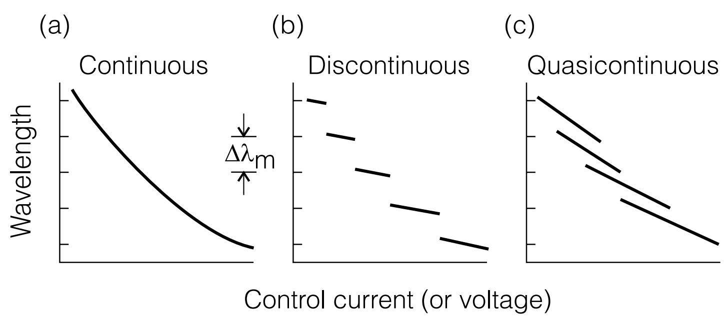

Figure 1: Tuning characteristics for the continuous (a), the discontinuous (b) and the quasicontinuous (c) tuning mode.

The electronic wavelength control requires the integration of additional controls into the laser cavity for the variation of the total wavelength-dependent cavity gain. This integration can either be performed longitudinally or transversely as shown in Figure 2. As

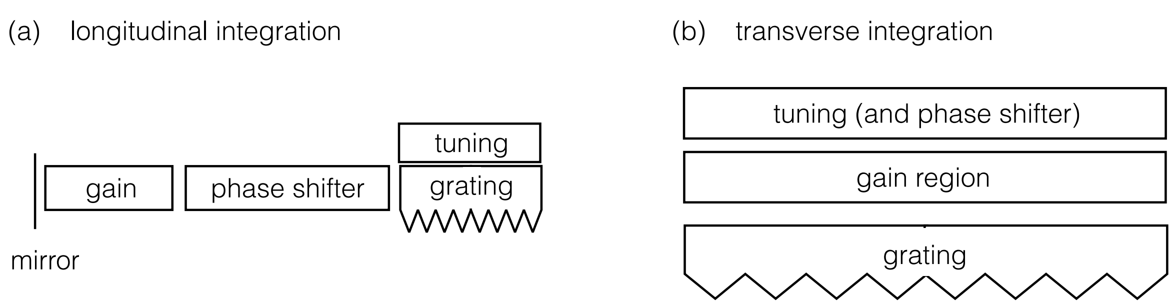

Figure 2: Longitudinally (a) and transversely (b) integrated wavelength-tunable laser diodes.

can be seen, by the longitudinal integration one replaces one (or both) of the laser mirrors, that usually are not wavelength-selective, by wavelength selective elements the center wavelength of which can be controlled electronically. Likewise, the transverse integration scheme (Figure 2 (b)) comprises a DFB laser structure, that provides the single-mode operation, and an additional electronic control mechanism for the effective refractive index of the transverse waveguide structure. In both approaches, the Bragg condition $\lambda_B = 2n_{\text{eff}}\Lambda$ yields the wavelength variation $\Delta\lambda$ due to the effective index change Δn_{eff} as

$$\Delta\lambda = \lambda_0 \frac{\Delta n_{\text{eff}}}{n_{\text{g,eff}}}, \tag{1}$$

where $n_{\text{g,eff}}$ is the group effective index. Whether the tuning performs continuously or discontinuously depends on whether the optical cavity length $n_{\text{eff}}L$ scales simultaneously with the center wavelength of the wavelength selective element.

The practically relevant physical mechanisms for the electronic refractive index control are: the free-carrier plasma effect, the quantum-confined Stark-effect (QCSE), and the temperature dependence of the refractive index. The maximum *continuous* tuning range reported so far in the 1.55 μm wavelength range is around 13 nm (1.6 THz) and has been achieved with transversely integrated tunable twin guide (TTG) DFB lasers exploiting both the free-carrier plasma effect and thermal tuning [1] as displayed in Figure 3. Owing

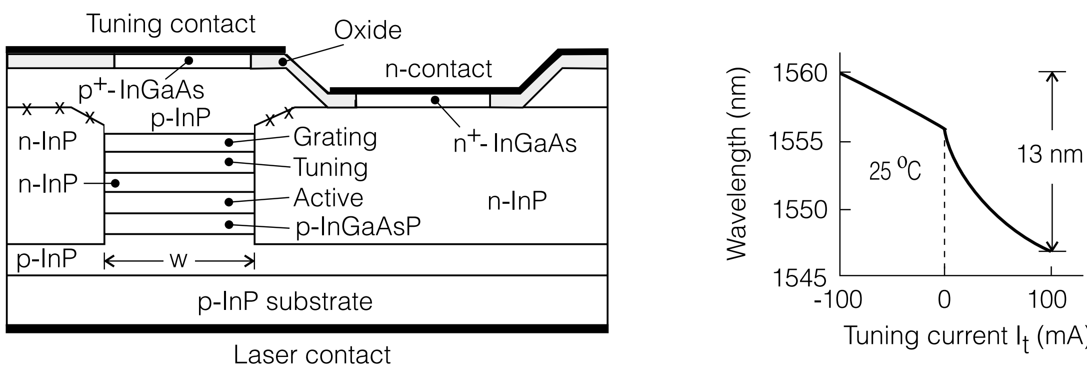

Figure 3: Schematic cross-section and wavelength versus tuning current characteristic of a TTG DFB laser.

to the limited magnitude of the electronically inducable effective refractive index changes (< 1 %), the maximum continuous tuning range (excluding thermal heating) of conventional DFB and DBR type tunable lasers is restricted to values below about 15 nm at 1.5 μm wavelength.

The continuous electronic wavelength tuning is ultimately limited by the maximal achievable effective refractive index change. With maximum refractive index changes of the order 1 % and maximum confinement factors of the tuning regions around 50 %, therefore, the continuous tuning range is limited to about $0.5 - 1$ % of the wavelength. Significantly larger tuning ranges can be achieved if discontinuous or quasicontinuous tuning can be accepted. In this case the tuning range is enhanced by mode jumps from one longitudinal mode to the next one. Again, the electronic tuning is induced by refractive index changes exploiting the physical mechanisms discussed in the preceding section. Thereby, largest discontinuous and/or quasicontinuous tuning range around 22 nm was achieved by combining the free-carrier plasma effect and thermal heating [2].

In order to obtain the large tuning effect one exploits the vernier effect, by which small relative refractive index changes can be used to yield large relative wavelength changes. The application of the vernier effect in tunable laser diodes is illustrated in Figure 4 for the case of the longitudinal integration technique. The essential device components are

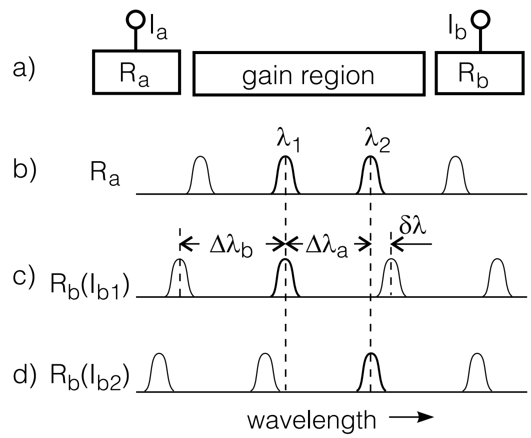

Figure 4: Schematic illustration of widely tunable laser diodes exploiting the vernier effect.

the two mirrors with comb reflection spectra exhibiting different pitch $\Delta\lambda_a$ and $\Delta\lambda_b$, respectively. Typically, $\Delta\lambda_a$ and $\Delta\lambda_b$ differ only by $3-10$ %. The comb reflection spectra may be achieved, for instance, by spatially modulated Bragg gratings (sampled gratings, super structure gratings, chirped gratings). As shown in Figure 4 b and Figure 4 c, lasing can occur only at wavelength λ_1, where both mirrors exhibit nonvanishing reflection. By a small shift $\delta\lambda$ of the comb reflection spectrum of mirror B, using e. g. the free carrier plasma effect, the 'resonance' at λ_1 breaks and lasing can now take place at wavelength λ_2. Consequently, the wavelength tuning by $\Delta\lambda_a$ from λ_1 to λ_2 is much larger than $\delta\lambda$ because of the vernier effect provided by the two comb reflection spectra with slightly different pitch.

Practically, the amplification factor due to the vernier effect can be of the order $10-100$, so that the maximum discontinuous tuning range is now finally limited by the gain bandwidth of the laser gain region. The latter is of the order 10 % of the laser wavelength for usual III/V laser diodes and discontinuous and quasi-continuous tuning ranges around 100 nm were achieved in InGaAsP/InP laser diodes at 1.55 μm wavelength [3].

The vernier effect can also be applied onto transversely integrated structures such that the small differences in optical path length of the interfering modes of a twin-waveguide are tuned. The tuning ranges achievable with the transversely integrated devices is also of the order 50-100 nm for 1.55 μm lasers [4]. Particular performance with tuning ranges exceeding 100 nm at 1.55 μm wavelength [5] and spectral linewidth below 4 MHz [6] can be obtained by combining the longitudinal integration scheme with the transverse one.

Wavelength tuning can also be accomplished with the vertical-cavity surface-emitting lasers (VCSELs). The longitudinal single mode operation and the efficient suppression of other longitudinal modes because of the short cavity length eases the mode control considerably so that continuous tuning is usually possible. Tuning of VCSELs may either be performed externally by using a piezoelectric transducer actuator [7] or with an integrated micromechanically moveable top mirror [8]. Tuning ranges around 40 nm have been reported for the wavelength ranges 950 nm [9] and 1.3 μm [7]. After the successful realization of monolithic InP-based VCSELs for 1.55 μm wavelength [10] with threshold currents around 1 mA at cw RT operation, we are now developing a tunable VCSEL for this wavelength. As shown in Figure 5 the tuning shall be performed by a micromechanically moveable mirror.

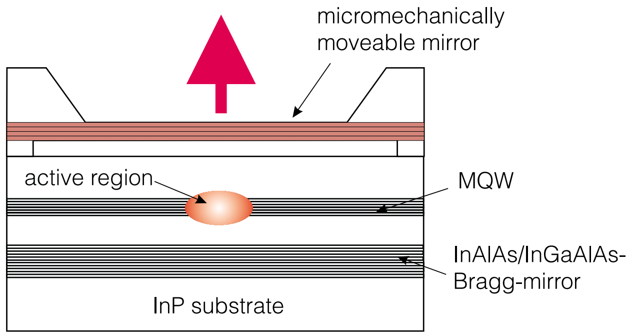

Figure 5: Schematic cross-section of micromechanically tunable VCSEL for 1.55 μm wavelength.

While continuous tuning over several ten nanometers appears feasible for the long-wavelength VCSELs, the major challenge for the widely tunable lasers still remains the poor wavelength selectivity of the tunable filter, so that a sufficiently strong side mode suppression is difficult to achieve over the entire tuning range. Consequently the wavelength access is also poor and the present research therefore focuses on improved methods to address the majority of the longitudinal modes of the composite laser cavity.

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