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Anomalous longitudinal mode hops in GaAs/AlGaAs distributed Bragg reflector lasers

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We investigate normal and anomalous longitudinal mode hops in GaAs/AlGaAs-based distributed Bragg reflector (DBR) lasers; anomalous mode hops are defined as those which move toward shorter wavelengths with increasing temperature, which is unexpected. The two-section DBR lasers discussed in this letter, consisting of a gain section and an unpumped Bragg reflector, typically exhibit one mode hop in a 10 K temperature range. Although the longer wavelength modes are expected to start lasing when raising device temperature, occasional mode hops to a shorter wavelength are seen. We derive a model for temperature-dependent wavelength tuning, with which the overheating of the gain section is described empirically. This model allows an accurate numerical simulation of both kinds of temperature-induced longitudinal mode hops.

Semiconductor-based distributed Bragg reflector (DBR) lasers are high-performance light sources used in many applications and are particularly attractive for their spectral properties. The tuning of emission wavelength with current or temperature is often a desirable feature for the use of DBR lasers in sensor,[1,2] time standard[3] or related applications; a parameter of interest is the achievable tuning range between longitudinal mode hops. Although the tuning behavior is, in general, well understood,[4] a detailed examination of the spectral shift with temperature reveals unexpected features requiring deeper study.

In this letter, we examine the temperature wavelength tuning of GaAs/AlGaAs-based DBR lasers in detail and demonstrate the existence of both normal and anomalous mode hops. The anomalous behavior, namely mode hops to shorter wavelengths with increasing temperature, has not yet been described for DBR lasers in the near-IR spectral region. Similar results were obtained several years ago on far-IR $Pb_{1-x}Sn_xSe/Pb_{1-x-y}Eu_ySn_xSe$ DBR laser diodes.[5] We derive a simple empirical model using a non-uniform temperature distribution along the gain and the DBR section of the device to describe both the normal and anomalous behavior, using this to predict under what circumstances anomalous behavior is expected.

The DBR lasers under investigation were single quantum well (QW) devices with 800 nm thick $Al_{0.8}Ga_{0.2}As$ cladding layers and a 170 nm thick $Al_{0.3}Ga_{0.7}As$ waveguide core with a 7 nm thick GaAs QW. They employed a single-growth-step processing technology as has been described previously.[6] The pumped gain sections of these devices were either 500 or 750 μm long, with Bragg reflector lengths of 100 μm. The coupling coefficient, κ, of the DBR grating was determined by a stopband-width measurement of the subthreshold laser spectrum, yielding a value of 350 cm^{-1}. All devices were tested under cw conditions, in bar form, and at room temperature; during measurement, the bars were placed epitaxial side up on an aluminum heat sink. For the wavelength versus temperature curves shown below, the heat-sink temperature was varied in a range of 40 K.

Two different types of devices, with nominally the same structure, were examined. The first had a relatively low threshold current density (J_{th}=1.6 kA/cm^2) and an assumed uniform temperature distribution across the device whereas the second had a higher threshold current density (J_{th} =3.3 kA/cm^2) and a gain section which heated up more rapidly than the Bragg reflector. The difference in threshold current was due to a better overlap of the gain peak with the Bragg reflection peak, based on processing variations, for the former devices than for the latter. Figure 1 shows the temperature tuning characteristic of a low-J_{th} laser, exhibiting normal mode hops towards longer wavelengths with increasing temperature. Between the mode hops, a continuous tuning towards longer wavelengths at a rate of 0.058 nm/K was seen. In contrast, Fig. 2 shows the tuning behavior of a high-J_{th} laser, with mode hops towards shorter wavelengths. Between the mode hops, continuous tuning towards longer wavelengths at a rate of 0.087 nm/K was observed. The average temperature tuning rate over all mode hops was roughly the same in both devices; its value of 0.07 nm/K corresponded to the temperature tuning rate of the unpumped Bragg reflector section. In the following, we derive an expla-

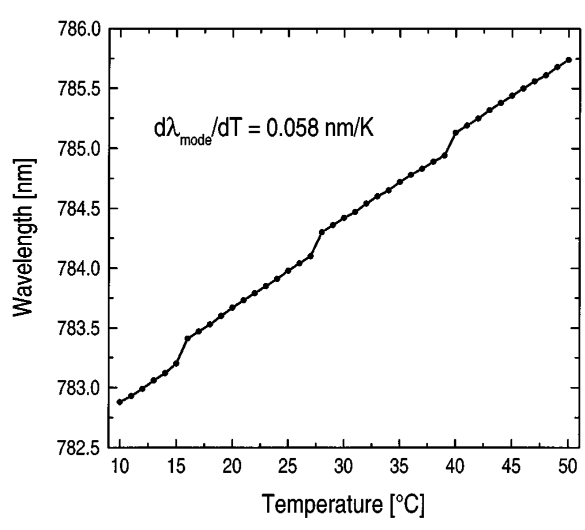

FIG. 1. Wavelength vs temperature curve of a low-J_{th} DBR laser with mode hops towards the longer wavelength side.

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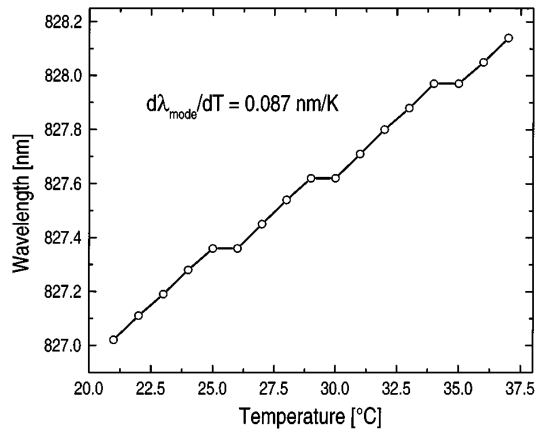

FIG. 2. Wavelength vs temperature curve of a high-J_{th} DBR laser with mode hops towards the shorter wavelength side.

nation for these two different manifestations of temperature tuning.

To qualitatively explain the occurrence of the two types of mode hops, we can use the schematic plot of Fig. 3. Shown as a function of wavelength are the three parameters which define the position of the lasing mode: the Bragg reflection peak of the DBR section (λ_{Bragg}), the material gain peak (λ_g), and longitudinal modes which satisfy the phase condition in the laser cavity (λ_{mode}). The device will lase at the wavelength at which the product of all three of these terms is maximum. All three parameters are temperature dependent, moving at rates of $d\lambda_g/dT$, $d\lambda_{\text{Bragg}}/dT$, and $d\lambda_{\text{mode}}/dT$, as will be shown below.

If, at a certain temperature, the gain peak λ_g is on the long wavelength side of the Bragg peak λ_{Bragg}, the longest-wavelength longitudinal mode λ_{mode} within the Bragg curve will lase. If the temperature is increased, the faster moving gain peak ($d\lambda_g/dT = 0.25$ nm/K) will remain on the long-wavelength side of the slower moving Bragg reflection curve ($d\lambda_{\text{Bragg}}/dT = 0.07$ nm/K). If the temperature of the device is uniform, the Bragg peak moves slightly faster than the longitudinal modes; if, on the other hand, the gain section heats more rapidly than the grating section due, for example, to a high series resistance across the device, then the longitudinal

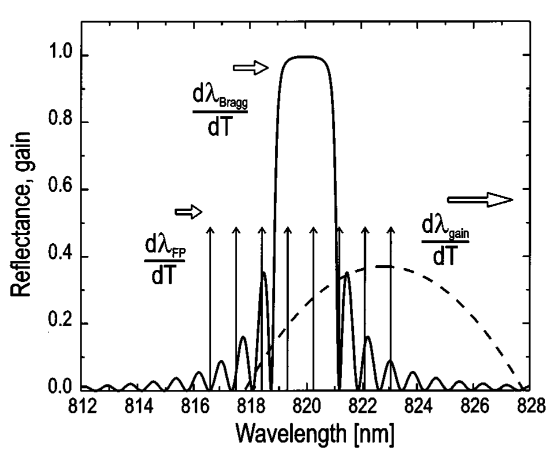

FIG. 3. Schematic representation of the temperature dependencies of semiconductor gain peak, Bragg peak, and allowed longitudinal modes in a two-section DBR laser.

modes can move faster than the Bragg peak. In the first case, a longer wavelength mode will eventually have the highest gain as temperature is increased; in the second case, a shorter wavelength mode will eventually have higher gain and lase.

To see this explicitly, we will calculate the different temperature tuning rates of Bragg peak, gain peak, and longitudinal modes using simple models for the wavelength-dependent shape of these parameters. The Bragg reflectance curve, $R(\lambda,T)$, can be represented as[7]

$$R(\lambda,T)=\left|\frac{-i\kappa\cdot\sinh(SL)}{S\cdot\cosh(SL)+i\Delta\beta\cdot\sinh(SL)}\right|^2 \tag{1}$$

with L being the grating length, $S=\sqrt{\kappa^2-(\Delta\beta)^2}$ and

$$\Delta\beta=2\pi n_{\text{eff}}\left(\frac{1}{\lambda}-\frac{1}{\lambda_{\text{Bragg}}+\dfrac{d\lambda_{\text{Bragg}}}{dT}\cdot T}\right). \tag{2}$$

In these expressions, typical numerical values are $n_{\text{eff}}=3.4$, $\lambda_{\text{Bragg}}=820$ nm, $d\lambda_{\text{Bragg}}/dT=0.07$ nm/K, $L=100$ μm, and $\kappa=350$ cm^{-1}.

The tuning rate of the Bragg peak can then be expressed as

$$\frac{d\lambda_{\text{Bragg}}}{dT}=\frac{\lambda_{\text{Bragg}}}{n_{\text{eff}}(\lambda)}\cdot\frac{\partial n_{\text{eff}}}{\partial T}, \tag{3}$$

which uses the wavelength-dependent effective modal index, $n_{\text{eff}}(\lambda)$, including the dispersion term, given by

$$n_{\text{eff}}(\lambda)=n_{\text{eff}}-\lambda\cdot\frac{\partial n_{\text{eff}}}{\partial\lambda} \tag{4}$$

where n_{eff} is the effective modal, or group, index at the Bragg resonance wavelength. Using the measured temperature dependence of the Bragg wavelength, $d\lambda_{\text{Bragg}}/dT=0.07$ nm/K, the Bragg wavelength, $\lambda_{\text{Bragg}}=820$ nm, and the wavelength derivative of the effective modal index, $\partial n_{\text{eff}}(\lambda)/\partial\lambda=-7.5\times10^{-4}$ nm^{-1}, we can calculate the temperature dependence of the effective modal index in the Bragg section to be $\partial n_{\text{eff}}/\partial T=-3.4\times10^{-4}$ K^{-1} (Ref. [8]).

In agreement with measured gain spectra,[9] we assume a simple parabolic wavelength dependence for the dimensionless gain spectrum

$$g(\lambda,T)=g_0+g_1\cdot\left(\lambda-\lambda_g-\frac{d\lambda_g}{dT}\cdot T\right)^2 \tag{5}$$

using $g_0=1.5$, $g_1=-5\times10^{-3}$ nm^{-1}, $\lambda_g=827$ nm, and $d\lambda_g/dT=0.25$ nm/K.

Finally, the wavelength of the lasing longitudinal mode, λ_{mode}, is defined by the satisfied phase condition in the laser cavity and is qualitatively analogous to a Fabry-Perot mode in a cavity with one wavelength-selective mirror. To model the distribution of allowed longitudinal modes, we define a series of 30 evenly spaced delta functions, whose wavelength positions fulfill the phase conditions within the laser cavity, namely

$$\phi(\lambda,T)=\sum_{m=-15}^{15}\delta\left(\lambda-\lambda_{FP}-m\cdot\Delta\lambda_{FP}-\frac{d\lambda_{FP}}{dT}\cdot T\right). \tag{6}$$

For Eq. (6), we used $\lambda_{FP}=820$ nm, $\Delta\lambda_{FP}=0.17$ nm, and $d\lambda_{FP}/dT=0.057$ nm/K for low-J_{th} DBR lasers with a 500 μm long gain section, and $\Delta\lambda_{FP}=0.13$ nm and $d\lambda_{FP}/dT=0.088$ nm/K for high-J_{th} DBR laser with a 750 μm long gain section.

The position of each λ_{mode} shifts due to carrier injection, usually at a slightly lower rate than the Bragg peak. According to Suematsu,[10] the temperature dependence of the lasing wavelength is described by

$$\frac{d\lambda_{mode}}{dT}=\lambda_{mode} \cdot \frac{\varepsilon\cdot \ell \cdot\left(\frac{\partial \overline{n}_{eff}}{\partial T}+\Gamma\cdot\frac{\partial \overline{n}_{active}}{\partial N}\cdot\frac{dN_{th}}{dT}\right)+L_{eff}\cdot\frac{\partial n_{eff}}{\partial T}}{\ell\cdot \overline{n}_{eff}(\lambda)+L_{eff}\cdot n_{eff}(\lambda)}. \quad (7)$$

In this expression, $\lambda_{mode}=820$ nm is the wavelength of the lasing longitudinal mode, $l=500$ μm defines the gain section length, $L_{eff}=100$ μm is the effective grating section length, $\partial\overline{n}_{eff}/\partial T=\partial n_{eff}/\partial T=3.4\times10^{-4}$ K^{-1} are the temperature dependencies of the effective modal indices in the pumped and the DBR section, respectively, and in addition, $\partial\overline{n}_{active}/\partial N=-0.6\times10^{-20}$ cm^{-3} (Ref. 11) stands for the carrier dependence of the active region refractive index, $dN_{th}/dT=3\times10^{16}$ cm^{-3} K^{-1} (Ref. 10) is the temperature dependence of the threshold carrier density, $\Gamma=0.4$ represents the confinement factor of the waveguide core, and $\overline{n}_{eff}(\lambda)=4.05$ and $n_{eff}(\lambda)=4$ are the dispersion-corrected effective modal indices of the gain and the Bragg section, respectively.

Central to our model is the parameter ϵ, which represents an empirical overheat factor for the pumped region. This factor is defined as the ratio between the temperature increases of the gain and DBR sections, hence $\epsilon=\Delta T_{gain}/\Delta T_{Bragg}$. Using values of $\epsilon=1$ for a low-J_{th} DBR laser and $\epsilon=1.6$ for a high-J_{th} device, we can calculate two different temperature tuning rates for low-J_{th} lasers ($d\lambda_{mode}/dT=0.057$ nm/K) and high-J_{th} lasers ($d\lambda_{mode}/dT=0.088$ nm/K).

Using these three models, we can now calculate the lasing wavelength of the DBR laser as a function of temperature for the two types of devices. The laser emission wavelength is given by the maximum of the function $G(\lambda,T)=g(\lambda,T)\cdot R(\lambda,T)\cdot\phi(\lambda,T)$, which is the product of gain curve, $g(\lambda,T)$, DBR reflectance, $R(\lambda,T)$, and the phase condition, $\phi(\lambda,T)$. The different temperature tuning rates were taken from Eqs. (3) to (7). The resultant temperature tuning characteristics are shown in Fig. 4 for both kinds of DBR lasers. The low J_{th} device exhibits mode hops to the longer wavelength side every 11 K, whereas the high J_{th} device shows hops towards shorter wavelengths every 9 K, in good agreement with the experiments.

Further corroboration for the presented explanation was given by the low T_0 values measured for devices with anomalous mode hops ($T_0=100$ K), but higher T_0 values for lasers showing only normal modal behavior ($T_0=160$ K); we recall that the difference between the two devices was based on a better overlap of the gain peak with the Bragg reflection peak for the latter devices than for the former.

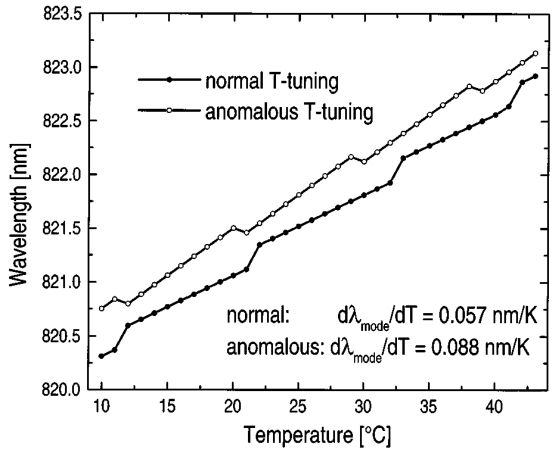

FIG. 4. Calculated wavelength vs temperature curves of low-J_{th} and high-J_{th} DBR lasers.

Since the emission wavelength of a two section DBR laser is determined by the Bragg resonance, a misplaced gain peak on the long wavelength side results in an increasing wavelength mismatch under temperature increase and therefore substantially decreasing gain for the lasing mode. This decaying gain has to be overcome by harder pumping and hence more heating of the gain section. Consequently, the described overheating ($\epsilon>1$) typically occurs in DBR lasers with $\lambda_g-\lambda_{Bragg}>$ 5 nm. Due to this mismatch, we also measured much higher threshold current densities on these lasers than on those with $\lambda_g=\lambda_{Bragg}$ and normal heating ($\epsilon=1$).

In conclusion, we have presented a model explaining mode hops to both longer and shorter wavelengths with increasing temperature for DBR lasers. The central parameter in this model is the empirical overheat factor, ϵ, of the gain section. Anomalous mode hops, to shorter wavelengths, are possibly due to nonuniform heating of the gain and reflector sections.

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