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Effect of band gap renormalization on threshold current and efficiency of a distributed Bragg reflector laser

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The threshold current and the external efficiency of a three-section distributed Bragg reflector laser are investigated as a function of a forward electrical bias applied to the passive sections. Within a well-determined range, the threshold current increases and the external efficiency decreases with increasing bias. This effect is attributed to band gap renormalization. © 2000 American Institute of Physics. [S0003-6951(00)01919-7]

High power, frequency stabilized, continuously tunable distributed Bragg reflector (DBR) lasers with a narrow spectral line are key devices for many applications in telecommunication, spectroscopy, and metrology.¹ A tunable DBR laser consists of at least three sections: An active gain section, a passive phase shift section, and a passive Bragg reflector section. The absorption in the passive, unpumped, sections is a severe problem because it can prevent lasing. Because our target laser wavelength is about 1 μm , we can neglect intervalence band absorption and thus the active layer may extend over all sections. However, in this case the interband absorption must be minimized in order to obtain low threshold currents and high external differential efficiencies. This can be achieved by (i) choosing the period of the Bragg grating such that the laser operates on the longwavelength side of the gain spectrum; (ii) using a thin compressively strained single quantum well (QW) with a low transparency current density which allows a quick saturation of the interband absorption by optical pumping; (iii) forward biasing the passive sections if they are properly contacted.

We will show in this letter, that the latter approach, i.e., the injection of electrons (and holes) into the QW of the passive sections does not necessarily result in a decreased threshold current and an increased external efficiency. Instead, the absorption increases over a certain range, which is explained by a calculation of the absorption coefficient taking into account many-body effects.

We have fabricated a three-section DBR laser emitting at a wavelength of 1.06 μm consisting of an 1000 μm long gain section, a 350 μm long phase shift section, and a 650 μm long DBR section.² The front and rear facets are anti-reflection coated (10% and 1%, respectively). The epitaxial structure is the same for all sections. The active layer contains a single compressively strained InGaAs QW embedded in tensile-strained GaAsP spacer and GaAs waveguide layers. The transparency current density is as low as 50 A/cm². The grating in the DBR section is integrated in the structure, localized in the upper GaAs waveguide layer. The period of

the grating is 312 nm and the coupling coefficient 35 cm⁻¹. The lateral mode confinement is provided by a ridge waveguide. The lasing wavelength of the cleaved gain section operated as Fabry-Perot laser is 1.047 μm , whereas the whole three-section device lases at 1.059 μm . Thus, it operates on the long-wavelength side of the gain spectrum, as desired.

The geometrical dimensions of the *p*-metallization are different in the active and passive sections. In the gain section, the metallization covers the whole surface. In the passive phase shift and DBR sections, the ridges are metallized with Ti/Pt/Au stripes with a width of 10 μm . These metal stripes can be either used as heaters (for wavelength tuning) or for injecting carriers into the QW by appropriate biasing. In the following, we investigate the influence of a forward bias applied to the DBR section between the *n*- and *p*-contacts on the light-current characteristic.

The static light-current ($L-I_G$) characteristics for five different values of the voltage U_{DBR} applied between the *n*- and *p*-contacts of the DBR section are shown in Fig. 1,

FIG. 1. Light-current characteristics of a three-section DBR laser for different voltages U_{DBR} in Volts applied to the DBR section in forward direction. I_G is the current through the gain section.

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FIG. 2. Threshold current I_{th} (top), external differential efficiency η_{ext} (middle) and current through the DBR section I_{DBR} (bottom) vs the voltage U_{DBR} applied to the DBR section in forward direction.

where I_G is the current through the gain section. The phase shift section is left unbiased. The solid curve in Fig. 1 shows the $L-I_G$ characteristic with $U_{DBR} = 0$ V. The laser threshold is reached at 30 mA. With increasing current I_G the output power rises and reaches at 150 mA a level of 30 mW. Above 150 mA, the output power saturates which can be attributed to thermal effects. The kinks in the $L-I_G$ curves are correlated with longitudinal mode hops. By applying a forward bias of $U_{DBR} = 1$ V (dashed curve) the laser threshold does not change, but the output power increases strongly above $I_G = 100$ mA and reaches at 200 mA a value of 50 mW. At larger forward voltages the threshold current increases surprisingly, as can be seen from the dotted curve in Fig. 1. This behavior will be discussed later. Above $U_{DBR} = 1.2$ V, a strong decrease of the laser threshold (dash-dotted curves) can be observed. The reason is, now the DBR section becomes transparent and provides even gain. At $U_{DBR} = 1.5$ V, which corresponds to a current of $I_{DBR} = 20$ mA through the DBR section, a maximum output power of 100 mW was measured, which is more than three times larger in comparison to that at $U_{DBR} = 0$ V.

In order to gain more insight into the unexpected increase of the threshold above $U_{DBR} = 1$ V, we have changed U_{DBR} in small steps between 0.60 and 1.24 V. In Fig. 2, the threshold current I_{th} (top), the external efficiency η_{ext} near threshold (middle) and the current I_{DBR} through the DBR section (bottom) are depicted versus the forward voltage U_{DBR} . Between 0.6 and 1.0 V, I_{th} increases slightly, but for $U_{DBR} > 1$ V a strong increase of I_{th} by about 4 mA can be observed. The maximum I_{th} , reached at $U_{DBR} = 1.12$ V, is marked with a perpendicular line in Fig. 2. A further increase of U_{DBR} leads to a strong decrease of the threshold current.

The reason is that the excess carrier density in the QW of the DBR section is now large enough to provide gain. This is related to a corresponding rise of I_{DBR} as can be seen in the bottom of Fig. 2.

The behavior of η_{ext} is somewhat different. It decreases already for $U_{DBR} < 1$ V and reaches a minimum at $U_{DBR} = 1.06$ V. The rise of η_{ext} for $U_{DBR} > 1.06$ V is again due to the gain in the DBR section. Both the maximum of I_{th} and the minimum of η_{ext} around $U_{DBR} = 1$ V can be caused only by an increase of the absorption in the DBR section.

In order to prove this, we have calculated the absorption coefficient α_{mod} for the fundamental TE_{00} mode on which I_{th} and η_{ext} directly depend. The calculation has been performed in two steps: First, the local absorption coefficient α_{loc} of the QW is calculated by means of a Keldysh Green's functions approach, details of which can be found in Ref. 3. Second, the modal absorption coefficient is calculated by solving a scalar complex waveguide equation and a diffusion equation for the laterally varying carrier density profile in the QW. As outlined in Ref. 4, the injected current density is proportional to the difference between the voltage applied to the device and the spacing of the electron and hole quasi-Fermi levels.

In what follows, we briefly outline the main points of the calculation of α_{loc} . Nonparabolic valence band structure, strain, and quantum-confinement effects are described by the Luttinger Hamiltonian, whose solutions are used as input for the many-body corrections. Included here are plasma screening of the Coulomb interaction, Pauli blocking, which combine to give rise to band gap renormalization (BGR), and furthermore, a T -matrix-like structure for the polarization function, responsible for the optical response. Part of the Coulomb corrections are incorporated in the theory through the carriers self energy. In the random phase approximation (RPA) the real part of it gives rise to the band gap renormalization discussed in this letter and the imaginary part gives rise to carrier-carrier scattering. In this letter we do not present the full RPA formula, but rather a frequency-dependent fit to it, which is sufficient for our purposes. In the Green's functions approach used here, the optical response of the medium is obtained by a polarization function which satisfies a sum rule, called Kubo-Martin-Schwinger relation that guarantees that the crossover from absorption to gain takes place exactly at the chemical potential. It embodies the essence of Einstein's relations between light emission and absorption. It further eliminates artifacts in the low energy side of the spectrum.

In Fig. 3, the calculated modal absorption coefficient is depicted versus the applied voltage. The wavelength is selected as the peak gain wavelength plus 12 nm. Using a simple free carrier theory (i.e., with many-body effects "switched off") for the local absorption coefficient of the QW (dashed line), there is a monotonous decrease of α_{mod} with increasing bias. On the other hand, taking into account many-body effects as outlined above, notably BGR (solid line), the behavior of α_{mod} versus bias reproduces that of the measured I_{th} : For $U < 1$ V, α_{mod} increases slightly, there is a pronounced maximum at 1.1 V, and for $U > 1.1$ V, α_{mod} drops rapidly. The maximum of α_{mod} versus the applied voltage is due to the shift of the absorption edge towards larger wavelengths λ , caused by BGR, as shown in Fig. 4: For a

FIG. 3. Modal absorption coefficient α_{mod} for TE₀₀ mode vs the voltage U_{DBR} applied to the DBR section calculated with many-body effects (solid) and without (dashed) at the peak gain wavelength plus 12 nm.

fixed wavelength $\lambda > 1.046 \mu\text{m}$, the QW absorption increases by changing the carrier density N from 10^{14} to $5 \times 10^{17} \text{ cm}^{-3}$. The gain spectrum for $N = 1.5 \times 10^{18} \text{ cm}^{-3}$ is shown dotted in Fig. 4.

The shift of the minimum of η_{ext} to a smaller value of U_{DBR} in Fig. 2 compared to the maximum of I_{th} can also be understood: Above threshold, additional excess carriers are created by the absorption of the laser light in the passive sections, thus shifting the minimum of η_{ext} (corresponding to maximum absorption) to smaller U_{DBR} values.

In summary, we have investigated a three-section DBR laser emitting at $1.06 \mu\text{m}$ where the active layer extends over all sections. The threshold current and the external differen-

FIG. 4. Local absorption coefficient α_{loc} of the InGaAs QW vs wavelength for different carrier densities N in cubic centimeters. At $N = 1.5 \times 10^{18} \text{ cm}^{-3}$, there is gain instead of absorption.

tial efficiency go, respectively, through a maximum and a minimum, as the applied bias to the DBR section is scanned around $U_{\text{DBR}} = 1.1 \text{ V}$. The reason is a nonmonotonous dependence of the interband absorption on the excess carrier density for a fixed wavelength, caused by band gap renormalization. Thus, the observed behavior of threshold current and efficiency is a direct evidence for band gap renormalization taking place in semiconductor lasers.

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