Analysis of Single-Mode Grating Coupled Twin Waveguide Laser Structures

N. Finger, P. O. Kellermann, W. Schrenk, and E. Gornik

Institut für Festkörperelektronik, TU-Wien, Floragasse 7, A-1040 Wien

An analysis of semiconductor laser structures with adjustable single-mode emission based on a contradirectionally grating coupled twin-waveguide structure consisting of an ITO/low-index dielectric waveguide on top of a corrugated active laser waveguide is presented. At resonance between the laser mode and the surface mode the grating-coupled radiation losses show a sharp drop with a linewidth comparable to the Fabry-Perot-mode spacing of the laser cavity, thus preferring a single longitudinal mode. Intermodal discrimination of up to 20 cm^{-1} and moderate threshold gain of ~50 cm^{-1} can be obtained. Since the resonance wavelength depends on the optical thickness of the surface waveguide, a simple post-processing adjustment of the emission wavelength with a tuning range in excess of ~15 nm can be achieved.

1. Introduction

For the realization of highly integrated wavelength division multiplexing (WDM) transmitter devices monolithic laser diode arrays are considered as a compact choice due to their capability of simultaneous transmission of several channels into a single optical fiber, thus decreasing system size and costs. Efforts on multiwavelength laser diode arrays have focussed on DFB [1] and VCSEL laser arrays. Wavelength shift in DFB laser arrays is achieved by changing the grating period of the individual elements which, however, requires a very precise definition of the grating period to achieve a well defined emission wavelength. In VCSEL arrays the wavelength shift can be achieved by generating a thickness gradient across the wafer during epitaxial growth [2]. Recently a five wavelength laser diode array [3] has been reported which utilizes the surface mode emission (SME) technique [4]. This technique provides the advantage of a simple post-processing adjustment of the emission wavelength of the individual laser diodes by adapting the surface waveguide thickness on top of the structure. A drawback of the SME technique, however, is the relatively low side mode suppression of about 20 dB. The laser structures suggested in this paper combine both the simple post-processing wavelength adjustment of the SME technique and considerable intermodal discrimination.

2. Laser Structures

The laser structures under consideration are based on a GaAs/AlGaAs DH-Laser structure utilizing an InGaAs/GaAs-MQW active region (at λ = 980 nm) embedded in highly asymmetric cladding layers in order to shift the mode field pattern towards the surface. The n-type cladding layer on top of the GaAs-substrate (refractive index $\bar{n} = 3.523$) is formed by $\mathrm{Al_{0.3}Ga_{0.7}As}$ ($\bar{n} = 3.333$, thickness 1200 nm). The active layer with a thickness of 250 nm ($\bar{n} = 3.523$) is followed by a typically 300 nm thick p-$\mathrm{Al_{0.2}Ga_{0.8}As}$ layer ($\bar{n} = 3.393$) and a p-GaAs top layer which is 250 nm thick. The top layer is corrugated by a trapezoid shaped grating with the period Λ = 192 nm, duty cycle 0.5, slope angle of 70° and a height of 80 nm. The grating is covered with a 120 nm indium tin oxide (ITO, $\bar{n}$ =1.6 + 0.04*i*) film which is needed for current injection. The SWG is made of ~200-400 nm SiO_x ($\bar{n}$ = 1.5) below a ~300 nm SiN_x layer ($\bar{n}$ =1.9). This combination of high-index and low-index dielectric is utilized in order to avoid excessive leakage losses into the high-index substrate.

3. Waveguide Modes

Since the WGS is basically a twin waveguide structure, two modes — a laser mode “a” and a surface mode “b” with the propagation constants β_a and β_b, respectively — exist. The grating causes grating coupled radiation into the substrate thus creating additional losses. In case of surface mode resonance (SMR), i.e. when the phase matching condition $\beta_a - \beta_b \approx 2\pi/\Lambda$ is satisfied, contradirectional coupling between the mode “a” and “b” occurs. (Note that $\Re\beta_b < 0$ since mode “b” is counterpropagating.) This means that energy is transferred from the LWG to the SWG and in turn back again. This energy transfer is accompanied by a resonant decrease of the grating coupled radiation loss into the substrate for both modes. Another benefit of this coupling is the effective increase of gain which a wave travelling over a certain in the active LWG experiences, since power is coupled into the SWG where it is transferred into the opposite direction and in turn coupled back into the LWG where it is amplified again.

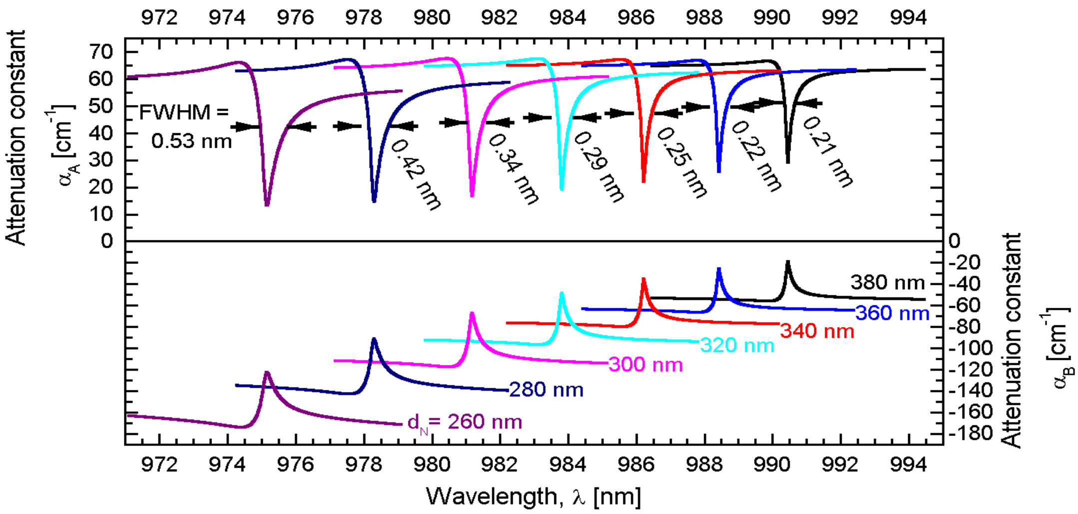

Fig. 1: Attenuation curves for a WGS with a 120 nm ITO/350 nm SiO/SiN SWG for different SiN thicknesses ranging from 260 to 380 nm. α_A and α_B are the attenuation constants of the laser mode and the surface mode, respectively.

The analysis used for the calculation of the waveguide properties follows the numerical approach presented in [5]. It is a coupled mode theory which is based on a rigorous Floquet-Bloch analysis of the grating waveguide problem yielding accurate results even for strong gratings. The governing equations relating the slowly varying amplitudes of the waves propagating in the LWG and the SWG $a(z)$ and $b(z)$, respectively, are obtained as $da/dz = (i\kappa_{11} + G)a + i\kappa_{12}\exp(-i\delta z)b$ and $db/dz = i\kappa_{21}\exp(i\delta z)a + i\kappa_{22}b$, where the coupling coefficients κ_{ij} (i, j = 1, 2) provide information about absorption loss, radiation loss and coupling between mode “a” and “b”. The influence of gain is described by G; $\delta = \beta_a - \beta_b - 2\pi/\Lambda$ is the phase mismatch between modes “a” and “b”.

Figure 1 shows the (power) attenuation curves of a WGS with a 250 nm p-$Al_{0.2}Ga_{0.8}As$ layer and a 120 nm ITO/350 nm SiO/SiN SWG with SiN-layer thicknesses varying from 380 to 260 nm. Since the dispersion of the SWG depends on the SWG thickness the resonance wavelengths range from 990.4 to 975.2 nm. The linewidth of the SMR increases from 0.21 nm to 0.53 nm due to increasing leakage losses of the SWG. However, due to the stronger penetration of the SWG field into the grating region a moderate increase of the mutual coupling coefficient from 27 + 8.4i cm^{-1} to 45.1 + 21.3i cm^{-1} is observed.

4. Finite Length Resonators

The finite length resonators are formed by the WGS terminated by as cleaved facets located at $z = \pm L/2$ (cavity length L) with amplitude reflection coefficients $r_a = \sqrt{0.3}$ and $r_b = \sqrt{0.05}$ for the LWG and the SWG. The laser structures are basically Fabry-Perot (FP) cavities with an intrinsic narrow-band wavelength filter favoring to lase just one FP mode coinciding with the resonance wavelength. In order to obtain single mode operation two requirements must be met: 1) The linewidth of the SMR has to be comparable or yet better smaller than the FP mode spacing and 2) a proper matching of the SMR and the FP mode spectrum must be achieved. The former requirement is fulfilled since both the SMR and the FP mode spacing are in the sub-nm regime. The latter requirement, however, needs to be discussed in detail: An effective mode selection only occurs if one of the FP resonances is near the wavelength with minimum losses. If the wavelength of minimum loss is between two FP modes, single mode emission cannot be expected since both FP modes suffer almost equal losses. The relative position of the FP modes and the SMR, however, can be adjusted thermally since the FP modes shift with a rate of $\Delta\lambda_{FP}/\Delta T \approx \lambda/n_a \cdot \Delta n_a/\Delta T = 0.067\,\text{nm/K}$, whereas the SMR shifts more slowly ($\Delta\lambda_{res}/\Delta T \approx \lambda/(n_a + n_b)\cdot \Delta n_a/\Delta T = 0.045\,\text{nm/K}$). This is a consequence of the much smaller temperature dependence of the effective index of the SWG (n_b) than that one of the LWG (n_a). For a cavity length L= 600 µm a temperature deviation of 10 K shifts the FP mode spectrum from one optimum position with respect to the SMR to the next one. Thus in order to avoid mode hopping a temperature stabilization allowing maximum deviations of ~1 K is necessary.

Figure 2 shows the longitudinal mode spectrum of a laser structure (length 600 µm) with an ITO/SiO/SiN SWG (layer thicknesses 120, 350 and 300 nm; the p-$Al_{0.2}Ga_{0.8}As$ layer thickness is 300 nm). Additional losses of 10 cm^{-1} were assumed for both sub-waveguides. The lowest threshold mode has a mode gain $2G$ =45.2 cm^{-1} and a threshold gain difference of about 14 cm^{-1} which is suitable for single mode operation with a side mode suppression of more than 30 dB. A clear resonant decrease of the power radiated into the substrate is observed whereas the power emitted via the facets peaks. However, due the resonant increase of optical power in the absorbing ITO layer, also the absorbed power peaks at the SMR.

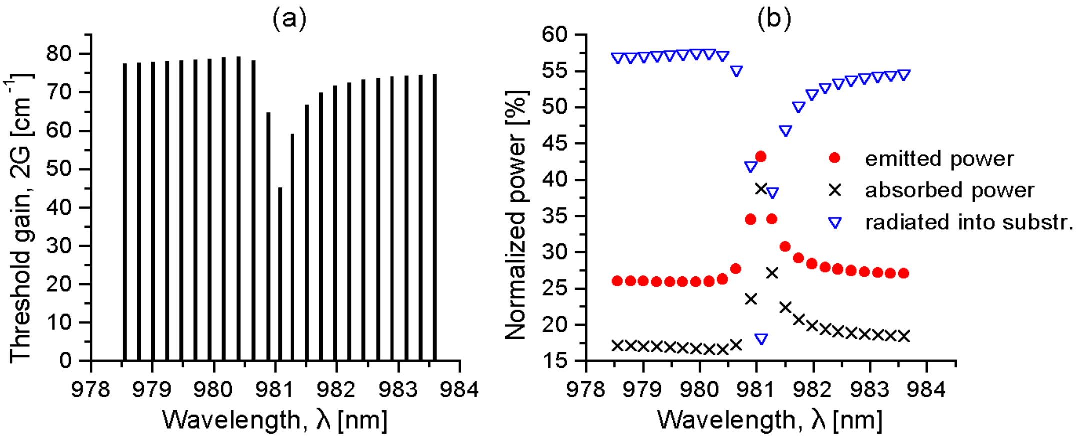

Fig. 2: Longitudinal mode spectrum (a) and normalized powers (b) for a 600 µm long device with an ITO/SiO/SiN SWG. The powers are normalized with respect to the stimulated emission power.

5. Conclusion

We have suggested a novel design for single-mode laser diodes with adjustable emission wavelength. The mode selection mechanism is based on a narrow-band suppression of radiation loss of an active/passive twin-waveguide structure. Intermodal discrimination can be as high as 20 cm^{-1} while maintaining relative low threshold gain (~50 cm^{-1}) and moderate differential output efficiency (~40 %). Simple and precise post-processing wavelength adjustment with a range in excess of ~15 nm is feasible, since changing the SWG thickness yields a shift of the SMR at a rate of $\Delta\lambda_{res}/\Delta d_{SWG} \approx 0.12$.

Acknowledgements

This work is partly supported by the Volkswagen-Stiftung (Germany).

References

[1] L. Davis, M. Mazed, S. Keo, J. Singletary, T. Wang, S. Fourouhar: *Proc. SPIE*, vol. 2690, p. 304, 1996.

[2] C.J. Chang-Hasnain, J.P. Harbinson, C.E. Zah, M.W. Maeda, L.T. Florez, N.G. Stoffel, T.P. Lee: *IEEE J. Quantum Electron.*, vol. QE-27, p. 1368, 1991.

[3] A. Golshani, P.O. Kellermann, A. Köck, E. Gornik, L. Korte: “Five-wavelength surface emitting laser diode array based on postgrowth wavelength adjustment”, *Appl. Phys. Lett.*, vol. 71, pp. 762-764, 1997.

[4] A. Köck, A. Golshani, R. Hainberger, E. Gornik, L. Korte: “Single-mode and single beam emission from surface-emitting laser diodes based on surface mode emission”, *Appl. Phys. Lett.*, vol. 69, pp. 3638-3640, 1996.

[5] N. Finger, E. Gornik: “Analysis of metallized-grating coupled twin-waveguide structures”, *IEEE J. Quantum Electron.*, submitted for publication, 1998.