Wavelength Adjustable Surface Emitting Single Mode Laser Diodes with Contradirectional Surface Mode Coupling

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Single-mode surface emission has been achieved from visible red GaInP/AlGaInP laser diodes by applying the contradirectional surface mode coupling technique. The emission wavelength (≈ 679.5 nm) of the laser structures was adjusted (decreased) in steps of 0.2 nm in an interval of 1.5 nm by reducing the thickness of the waveguide on top of the laser diode. The laser diodes emitted via the surface with a beam divergence of 0.10° and showed single-mode emission both in AC as well as in DC operation with a minimum spectral linewidth of 0.09 nm. The highest sidemode suppression achieved in DC operation was 26 dB.

1. Introduction

Semiconductor laser diodes in the visible regime are very suitable to be employed as powerful emitters in optical short-range data transmission (the attenuation minimum of *polymethylmethacrylate* (PMMA) fibers lies near 650 nm) and as light sources in the next generation of optical disk drives with their ability to read and write highly condensed optical information. The field of applications is widely spread, including spectroscopy, displays and optical sensing. Several red laser-diode-configurations have been successfully realized so far by using $Ga_xIn_{1-x}P/(Al_yGa_{1-y})_{0.5}In_{0.5}P$ sample structures. Excellent laser emission with low threshold current and high output power in the wavelength range between 620 and 690 nm has been reported.

Improvement of the emission characteristics and flexibility of the emission wavelength is desirable for advanced technical usage. If one achieves laser diodes with several single-mode emission spectra near the attenuation minimum of the optical fiber, the transmission bit rate of communication systems can be increased significantly by *dense wavelength division multiplexing* (DWDM) as the heart of *multiwavelength optical networking* (MONET). If surface emission (emission vertically to the epitaxially grown layers) is accomplished, the beam divergence is decreased essentially due to the expanded outcoupling window. Surface emission also eases the fabrication of two-dimensional arrays and the integration with the driving circuit on the same wafer.

Several concepts for obtaining single-mode surface emission have been presented by using second-order grating *distributed feedback* DFB lasers. They use the incorporation of a phase-shifting film [1], preferential current pumping [2], the effect of chirping the grating structure [3] or a complex-coupled grating [4]. There is no beam steering effect due to wavelength and temperature variations, since the beam direction is fixed by the DFB grating structure. Wavelength shift in DFB laser arrays is achieved by changing the grating period of the individual elements requiring a very precise definition of the grating period to achieve a well defined emission wavelength. But there have been no papers reporting about the realization of these concepts in the red wavelength regime. In contrast the red *vertical cavity surface emitting laser* (VCSEL) diodes [5], [6], with which large-signal modulation of 1.5 Gb/s has been demonstrated. A wavelength shift can be achieved by generating a thickness gradient across the wafer during epitaxial growth [7].

2. Methods

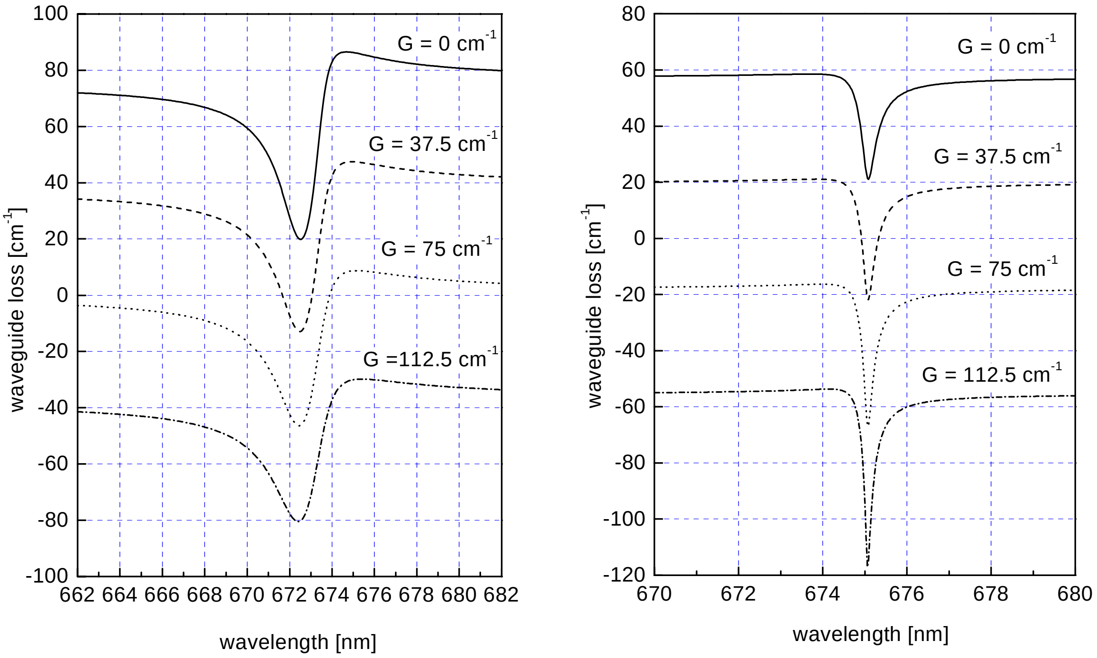
We have developed a method to achieve single-mode surface emission from horizontal cavity laser diodes, which is based on *surface mode coupling* (SMC). The laser diode characteristics (wavelength, emission-angle) can be adjusted after the processing as a laser diode by changing only the surface parameters (waveguide's optical thickness). This leads to a straight way of creating multi wavelength laser diode arrays [8]. As SMC laser diodes can be fabricated by using the established technique of the conventional stripe-contact laser the complex fabrication process of VCSEL structures and of DFB lasers is avoided. The principle of these laser diodes is based on a coupling mechanism between the laser mode and the surface mode which exists in a semitransparent metal/dielectricum waveguide structure on top of the laser diode. Phase matching of the laser mode and the surface mode is achieved by a surface relief grating in the laser diode. The grating causes radiation losses of the laser mode, which are reduced significantly only in a narrow spectral range by the excitation and feed back process of the surface mode. The effective gain mechanism of this resonance leads to single mode emission. Recently we have shown that the SMC technique with codirectional (the laser mode and the surface mode are propagating in the same direction) coupling can be applied to GaAs/AlGaAs and to GaInP/AlGaInP laser diodes to achieve both a single-mode emission as well as a surface emission with very narrow beam divergence [9], [10]. The radiation and the longitudinal mode characteristics of the waveguide grating structures have been investigated numerically with an in-depth analysis based on the Floquet-Bloch theory. The numerical analysis shows that in case of contradirectional (the laser mode and the surface mode are counterpropagating) coupling between the laser mode and the surface mode the sidemode suppression of the emission wavelength is increased compared to the codirectional coupling mechanism due to a narrower resonance. In Fig. 1 the waveguide loss with co- and contradirectional surface mode coupling is shown. In case of contradirectional coupling the depth of the resonance increases with the gain. The contradirectional surface mode coupling concept has now been realized for the first time.

The physical background of the SMC-concept with surface emission and with contradirectional coupling is the following: the laser light propagating in the active region is exciting a transverse electrically polarized (TE_0) surface mode in a waveguide structure on the top of the laser diode through a 2^{nd} order grating coupling. Therefore the phase matching condition

$$\beta_{laser} - 2 \times k_g = \beta_{TEo} + \delta \qquad (1)$$

has to be satisfied. β_{laser} is the propagation constant of the laser, $k_g = 2\pi/\Lambda$ the grating vector (Λ is the grating period), β_{TEo} the propagation constant of the TE_0-surface mode and δ is the phase mismatch. The surface mode couples both into the vacuum light cone resulting in surface emission and back to the active region leading to a gain mechanism and thus to single-mode emission. β_{TEo} can be "tuned" by changing the thickness of the surface waveguide. With β_{TEo} also β_{laser} and the emission wavelength of the laser diode is adjusted. The angle α of surface radiation is governed by the emission condition

$$\beta_{TEo} - k_g = \beta_{light} \times \sin\alpha \qquad (2).$$



(a) (b)

Fig. 1: Waveguide loss with codirectional (a) and contradirectional (b) surface mode coupling. In case (b) the numerical analysis shows a narrower resonance and the depth of the resonance increases with the gain (G).

3. Materials

The devices realized in this work are double-quantumwell $Ga_xIn_{1-x}P/(Al_yGa_{1-y})_{0.5}In_{0.5}P$ laser diodes grown by low-pressure metallorganic vapor-phase-epitaxy (MOVPE). Se-doped (n-doped) GaAs and $Ga_{0.51}In_{0.49}P$ buffer layers, followed by a Se-doped $(Al_{0.66}Ga_{0.34})_{0.5}In_{0.5}P$ cladding layer (1000 nm) and an undoped $(Al_{0.27}Ga_{0.73})_{0.5}In_{0.5}P$ waveguide layer (65 nm) are grown successively on a n-GaAs substrate, which is tilted 6° off towards the [111]-plane. Two compressively strained $Ga_{0.4}In_{0.6}P$ quantum wells (2×10 nm) with an $(Al_{0.27}Ga_{0.73})_{0.5}In_{0.5}P$ barrier (4 nm) form the active region. Next are a $(Al_{0.27}Ga_{0.73})_{0.5}In_{0.5}P$ waveguide layer (55 nm), a Zn-doped $(Al_{0.60}Ga_{0.40})_{0.5}In_{0.5}P$ cladding layer (400 nm), a Zn-doped $Ga_{0.51}In_{0.49}P$ layer (30 nm) and finally a Zn-doped GaAs cap layer (20 nm). Asymmetric cladding layers (by the aspect of thickness and refractive index) are designed to shift the electric field distribution of the laser mode towards the surface to achieve a sufficient coupling between the laser light and the TE_0 surface-mode.

The second-order grating (duty cycle 0.67) for surface mode coupling is defined by holographic exposure of a spin-coated photoresist (Hoechst AZ 5214) on the p-side of the laser structure. The pattern is etched into the top layers by ion milling (period Λ =

270 nm, height H = 100 nm). The evaporation of semitransparent Au/Zn/Au metal stripes (thickness 5 nm/5 nm/20 nm) with a width of 12.4 µm defines the stripe contacts of the lasers. Ti/Au contact pads (50 nm/250 nm), which overlap the laser stripe contact by 3.7 µm from both sides leaving a 5 µm wide window in the center of the laser stripe contact, are evaporated on a polymid isolation in between the single stripe contacts. Next the laser stripe is coated with two dielectric layers (~150 nm SiO_x ($\bar{n} = 1.5$) below ~250 nm SiN_x ($\bar{n} = 1.9$)) forming a slab waveguide on the top of the laser diode, which supports the TE_0-surface-mode. The combination of low-index and high-index dielectric is utilized in order to avoid excessive leakage losses into the high-index substrate. Finally, the laser bars are cleaved to a length between 350 µm and 500 µm and mounted on a Peltier element.

4. Results

The SMC laser diodes showed a threshold current density (j_{th}) of 1 kA/cm^2 at a temperature of 10°C in pulsed driven (AC) and at –5°C in continuos wave (DC) operation. The series resistance of the laser diodes was near 9 Ω.

The farfield pattern of the laser diodes was measured by scanning from one cleaved facet along the laser stripe-contact to the other facet. The surface emission was observed at ±50° with a beam divergence of 0.10°. The divergence in the perpendicular direction was 10°. The intensity emitted per solid angle into the single surface beam was three times larger than the emitted intensity per solid angle at the edges.

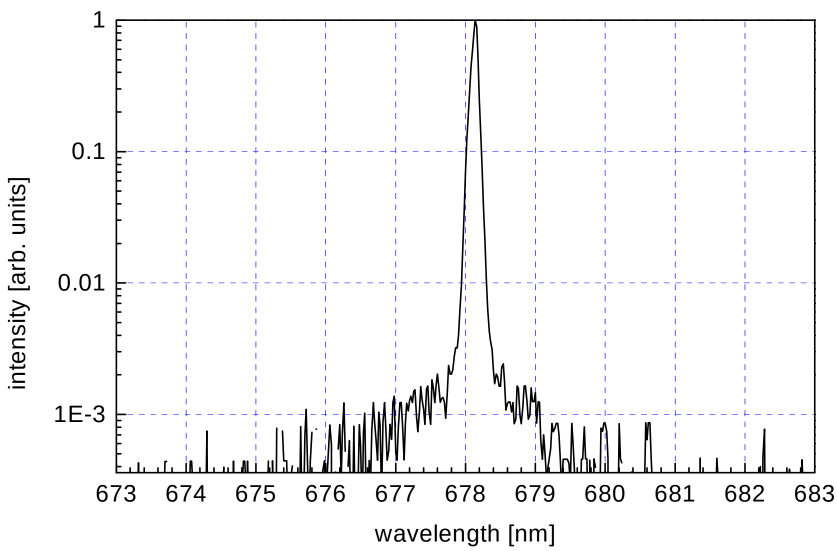


Fig. 2: Wavelength emission spectrum in DC operation. The laser diode emitted at 678.1 nm with a sidemode suppression of 26 dB.

The laser diodes showed a single mode emission in AC condition as well as in DC operation. A wavelength emission spectrum in DC operation is shown in Fig. 2 ($j_{th} \times 1.3$ = 1.3 kA/cm^2, -5°C). The laser diode emitted at 678.1 nm with a sidemode suppression of 26 dB. The minimum spectral linewidth achieved was 0.09 nm (spectrometer resolution 0.07 nm). The longitudinal mode separation of the Fabry-Perot cavity was measured to be 0.11 nm.

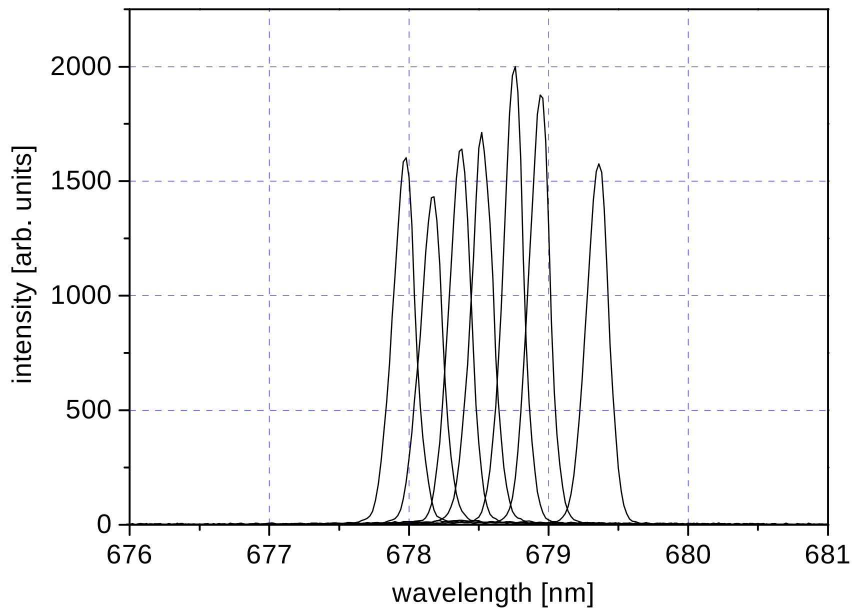


Fig. 3: The emission wavelength of the laser structures was adjusted (decreased) in steps of ≈0.2 nm in an interval of ≈679.5 nm to 678 nm by reducing the thickness of the waveguide on top of the laser diode.

As shown in Fig. 3 the emission wavelength of the laser structures was adjusted (decreased) in steps of ≈0.2 nm in an interval of ≈679.5 nm to 678 nm by reducing the thickness of the waveguide on top of the laser diode. (The surface waveguide was sequentially etched with HF 0.25%.) The temperature of the Peltier element was held constant at 25 °C. The resonance of the surface and the laser modes (and with it the emission wavelength of the laser diode) was shifted to the maximum of the laser gain spectrum (≈678.8 nm) and then to smaller wavelengths. This led to an increase and then decrease of the sidemode-suppression and of the light output intensity.

5. Conclusion

The contradirectional surface mode coupling concept has now been realized for the first time. Single-mode surface emission has been achieved from visible red GaInP/AlGaInP laser diodes by applying this technique. The emission wavelength (≈679.5 nm) of the laser structures was adjusted (decreased) in steps of 0.2 nm in an interval of 1.5 nm by reducing the thickness of the waveguide on top of the laser diode. The laser diodes emitted via the surface with a beam divergence of 0.10° and showed single-mode emission both in AC as well as in DC operation with a minimum spectral linewidth of 0.09 nm. The highest sidemode suppression achieved in DC operation was 26 dB.

Acknowledgements

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