Multi-Wavelength Laser Diode Array Based on Surface Mode Coupling

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Multi-wavelength emission from a visible red GaInP/AlGaInP laser diode array has been achieved with the contradirectional surface mode coupling technique. The wavelength control is attained by postgrowth adjustment of the thickness of a surface waveguide. The horizontal cavity lasers show both edge and surface emission (beam divergence 0.1° × 10°). The individual elements show single-mode emission with a spectral linewidth of less than 0.1 nm and a sidemode suppression ratio up to 30 dB. The wavelength spacing between the elements is 0.76 ± 0.08 nm yielding a total range across the array of 5.4 nm (from 681.5 nm to 686.9 nm). The thermal red-shift of the wavelength is 0.028 ± 0.002 nm/K.

1. Introduction

The *wavelength division multiplexing* (WDM) scheme is utilized to increase significantly the transmission rate of optical communication systems. Monolithic arrays of multi-wavelength laser diodes are considered as a compact choice for WDM light sources. Lasers in the visible regime are suitable to be used as emitters in optical short-range data transmission since the attenuation minimum of *polymethylmethacrylate* (PMMA) fibers lies near 650 nm.

Wavelength shift in *distributed feedback* (DFB) laser arrays is achieved by changing the grating period of the individual elements requiring a very precise definition of the grating period [1]. Also, arrays of multi-wavelength *vertical cavity surface emitting laser* (VCSEL) diodes have been attained. The optical thickness of their layers is varying in the lateral direction on the wafer. The resonance wavelength of the microcavity can be adjusted after the epitaxial growth by oxidation of an AlGaAs adjustment layer [2] or the local growth rate of all the epilayers is controlled with the help of a topographically patterned substrate [3].

2. Experimental

We have developed a multi-wavelength surface emitting laser array with horizontal cavities. The wavelength of single array elements can be adjusted after the processing by just changing the optical thickness of a *surface waveguide* (SWG). If the Fabry-Perot mirrors are etched (not cleaved) the wavelength of laser groups can be monitored and adjusted automatically on the chip. The principle of the laser diodes is based on *surface mode coupling* (SMC). Phase matching of the surface mode (propagating in the dielectric SWG) and the laser mode is achieved by a surface relief grating in the top cladding of the laser waveguide. The grating causes radiation losses of the laser mode (dominated by the emission into the substrate). The losses are reduced significantly in a narrow spectral range by the excitation and feedback process of the surface mode. The linewidth of this resonance is comparable to the longitudinal Fabry-Perot mode spacing of the laser cavity, thus providing an effective mode selection mechanism, which leads to single-mode emission. By adapting the thickness of the SWG phase matching of the surface and the laser mode is achieved at another emission wavelength. By choosing the appropriate grating period either co- (the laser and surface mode propagating in the same direction are coupled) or contradirectional (the counterpropagating modes are coupled) coupling is achieved. The surface mode couples both to the active region and into the vacuum light cone resulting in surface emission.

Recently, we have shown that a SMC laser exploiting contradirectional coupling leads to an increased SMSR [4]. This can be explained by the fact that the slopes of the intersecting dispersion curves differ much more and hence the resonance is five times narrower than for the codirectional SMC concept. The wavelength shift induced by a change of the SWG thickness is five times smaller for contradirectional SMC. This eases the wavelength adjustment and improves the insusceptibility against longitudinal variations of the SWG thickness. In this work, we realized for the first time a multi-wavelength laser array with the contradirectional SMC concept. The adjusting span was increased from 1.2 nm in Ref. 4 to 5.4 nm, the SMSR from 26 dB to 30 dB.

The GaInP/AlGaInP-lasers were grown by low-pressure metalorganic vapour-phase-epitaxy (MOVPE). Asymmetric cladding layers (by the aspect of thickness and refractive index) shift the electric field distribution of the laser mode towards the surface to achieve sufficient coupling. The second-order grating for the SMC is defined by holographic exposure of a spin-coated photoresist on the p-side of the laser structure. The pattern is etched into the top layers by ion milling (Λ = 270 nm, height 100 nm). The evaporation of semitransparent Au/Zn/Au stripes (5/5/20 nm, orientated perpendicularly to the surface grating) with a width of 10 μm defines the stripe-contacts of the lasers.

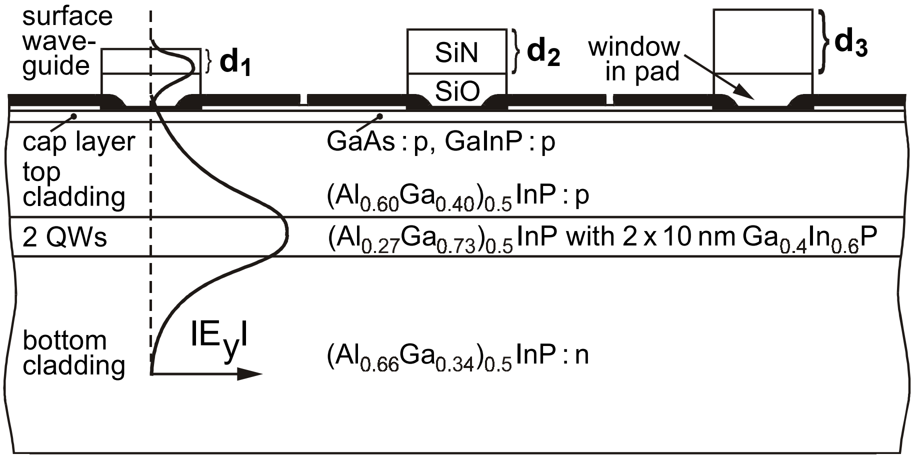

Fig. 1: Cross-sectional sample structure of three array elements. The semiconductor layers, surface waveguides (with different thicknesses), contact pads, windows, and optical mode profiles are indicated. The stripe-contacts are orientated perpendicular to the plane of the drawing. Different SiN-layer thicknesses of the surface waveguides result in different emission wavelengths.

Contact pads are evaporated on a polymid isolation and on the stripe contacts leaving a 5 µm wide window in the center of the contacts. Next the lasers are coated with ~170 nm SiO_x below ~335 nm SiN_x forming the SWG, which supports the TE_0 surface mode. The combination of one low- (SiO_x) and one high-index (SiN_x) dielectric layer avoids excessive leakage losses into the high-index substrate. The SWG thickness of individual lasers is adjusted by ion milling and photolithography. Thicknesses descending from ~505 to ~450 nm in steps of ~8 nm are realized on the finally cleaved laser bars. In Fig. 1 the cross-sectional sample structure of three array elements is sketched. The semiconductor layers, surface waveguides (with different thicknesses), contact pads, windows, and optical mode profiles are indicated. The stripe-contacts are orientated perpendicular to the plane of the drawing.

Single-mode edge emission is observed both in pulsed driven (AC) and continuos wave (CW) operation. The SMC laser diodes showed a threshold current density of 1 kA/cm^2 at a temperature of 10°C in AC and at –5 °C in CW operation. Spectra of an array with seven wavelengths due to seven different thicknesses of the SWG are shown in Fig. 2 (CW, 1.6 kA/cm^2, 0 °C). In the spectral center of the array the SMC-resonance (and thus the wavelength of the laser) falls together with the maximum of the active layer gain spectrum (~684.2 nm). This leads to a SMSR up to 30 dB as shown in the inset on the right side. With increasing distance to the gain maximum the light output intensity and the SMSR decrease. The smallest SMSR of 19 dB is depicted in the inset on the left side. The spectral linewidth achieved is <0.1 nm.

An average wavelength spacing between neighbored lasers of 0.76 ±0.08 nm is found yielding a total range across the array of 5.4 nm (from 681.5 to 686.9 nm). The SWG thickness increases in small steps of 7.9 ± 0.3 nm from 450 to 505 nm (as measured with a profilometer).

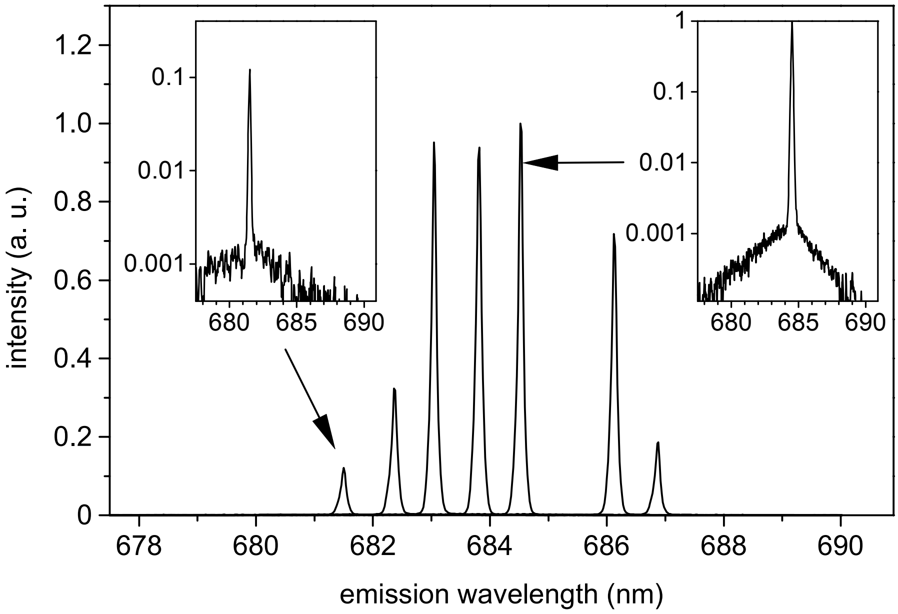

Fig. 2: Emission spectra of seven SMC lasers with seven different thicknesses of the SWG all joining the same array (CW, 1.6 kA/cm^2, 0 °C). Spectra with the smallest (19 dB) and highest (30 dB) SMSR are shown with a logarithmic scale in the insets.

The far-field pattern of the lasers was measured by scanning from one cleaved facet along the stripe contact to the other facet. The surface emission for a laser that emits at 683.7 nm is observed at $\alpha = \pm 47.5°$ with a beam divergence of 0.12°. The divergence in the azimuthal direction is 10°. The other array elements show a shift in α due to their different wavelengths. The shift in α between neighbored lasers is ~0.25°. The intensity emitted per solid angle via the surface beam is five times larger than the one at the edges. Presently a fraction of 2% of the whole light output power (7 mW at 1.6 kA/cm^2, 0 °C, CW) is emitted via the surface.

The thermal behavior $\partial\lambda/\partial T$ of an SMC-laser was compared with a Fabry-Perot laser, which was prepared on the same array. The wavelength of the SMC-laser increases with 0.028 ± 0.002 nm/K. The Fabry-Perot laser shifts with 0.12 ± 0.01 nm/K according to the bandgap shift. The small red-shift of the SMC-lasers is due to the fact that the wavelength is "locked" to the SMC resonance.

3. Conclusion

In conclusion, the contradirectional SMC technique for obtaining a multi-wavelength surface emitting single-mode laser array has been demonstrated with visible red GaInP/AlGaInP lasers. The wavelength control is achieved by postgrowth adjustment of the thickness of a surface waveguide. The wavelength spacing between the individual lasers is 0.76 ± 0.08 nm yielding a total range across the array of 5.4 nm. A SMSR up to 30 dB is reached.

An optimization of the red SMC laser array with the help of index- instead of gain-guiding is under progress. Increased surface emitted power, increased SMSR and a wider wavelength span are expected.

Acknowledgements

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

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