Efficient surface emitting AlGaAs/GaAs laser diodes based on first-order-grating-coupled surface mode emission

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Abstract

Strongly improved surface emitting laser diodes based on surface mode emission (SME) are presented. For the first time an effective coupling mechanism utilizing first-order-grating excitation of surface modes is employed. This concept leads to an additional wavelength selection mechanism due to an efficient feedback effect, which can be used for single mode emission. A two-beam efficient surface emission with low divergency is achieved and the additional wavelength selection and feedback mechanism is demonstrated. The decisive advantage of the SME laser diodes in comparison to DFB/DBR laser diodes is their flexibility in fabrication, which makes them very suitable , for example, for wavelength division multiplexing (WDM) applications.

Introduction

Laser diodes have proven in the last two decades to be a very powerful and convenient tool in the field of telecommunication systems. Among the very broad spectrum of semiconductor laser diodes the surface emitting laser diodes (SESML) are most suitable for new optoelectronic applications, like high-power arrays, optical data storage and optically addressable short range interconnects [1]. Surface emission is achieved in most cases by beam deflectors and 45° mirrors [2,3] as well as second order grating coupling devices [4]. Surface emitting DFB/DBR laser diodes and monolithically integrated master oscillator power amplifiers (MOPA) show a narrow diffraction limited beam divergence [5-10]. Grating coupled surface emitting laser diodes with blazed grating outcouplers are also demonstrated [11]. The surface emission efficiency in these systems was further enhanced by redirecting the beam radiated into the substrate using a Bragg reflector below the waveguide [12]. Vertical cavity surface emitting laser (VCSEL) diodes are very suitable for 2D arrays and have already been employed in optical transmission systems [13-15].

Recently we have presented a new concept for surface emitting single mode laser diodes based on surface mode emission (SME) [16,17]. This concept is based on a strong coupling between the laser mode and a surface mode propagating on top of the laser diode. The first demonstration of this technique was achieved by a third order grating coupling [18]. In this letter we report for the first time on an efficient steerable surface mode emission based on first order grating coupling. Using first order grating coupling limits the surface emission to 2 peaks leading to a strongly improved surface emission. In the best case the intensity per solid angle of the surface emission is measured to be 24 times larger than the intensity emitted per solid angle at the side.

A significant narrowing in the spectral line of SME-laser diodes is observed, which is due to the additional (SME) mode selection mechanism. The effective SME feedback effect is clearly demonstrated. In addition we achieved a variation of the emission wavelength up to 4 *nm* by changing the thickness of the surface waveguide. This demonstrates the high flexibility in fabrication process of

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the SME laser diodes as compared to the DFB/DBR laser diodes. The flexible fabrication process of the SME laser diodes allows the control of radiation characteristics such as emission wavelength and emission angle only by adjusting the waveguide parameters.

Sample structure

The samples are conventional double heterostructure GaAs/Al GaAs laser diodes grown by MOCVD. An n-AlGaAs cladding layer (thickness 1300 *nm*, 35% Al) is followed by an undoped GaAs layer of 90 *nm* thickness as the active layer. The top cladding layer is a p-AlGaAs (thickness 550 *nm*, 35% Al). A grating with a period of 425 *nm* is exposed on the entire surface of the sample by laser holography and is wet chemically etched to a depth of 110 *nm* into the top cladding layer. A semitransparent Au/Zn/Au stripe (500 $\times$ 20 μm^2, thickness 30 *nm*) is evaporated on the surface of the samples defining the laser stripe. These stripes are coated with a 400 *nm* thick gold layer, which shows a 300 $\times$ 15 μm^2 window for surface emission. The top contact pads (Cr and Au) are evaporated on the sample's surface isolated by polyimide. Finally the surface waveguide (polyimide; 400 $\times$ 20 μm^2, n=1.7) is spin coated on the samples. The structure of the samples is sketched in the inset of Fig. 1.

Measurements and results

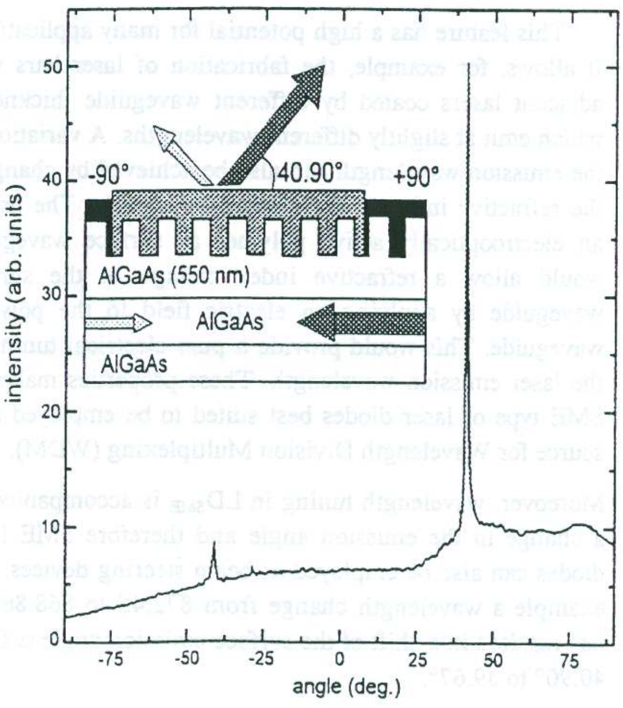

Fig. 1: Far-field pattern of the SME laser diodes. The intensity per solid angle at the surface is 24 times the intensity per solid angle at the edge. The surface emission at 40.90° corresponds to coupling of the light coming from -90°. The sample's geometry is shown in the inset.

The surface waveguide allows the existence of the transversal electric TE_0 surface mode, which can be excitedby the laser light locally in the window. A laser mode can excite the surface mode only through a surface grating, if the wave vector conservation condition is satisfied, i. e. if the vectorial sum of the laser wave vector (K_{laser}) and grating vector ($K_g=2\pi/\Lambda$: Λ: grating period) matches the wave vector of the surface mode (K_{TE_0}):

$$K_{laser} - nK_g = K_{TE_0} \tag{1}$$

The coupling via one grating vector (n=1) yields a more efficient coupling in comparison to coupling via three grating vectors and results in a two-beam surface emission. The excited TE_0 mode in turn decays radiatively via one grating vector partly in the air characterizing the surface emission and partly back into the laser structure providing an additional effective feedback and therefore a side mode suppression. This was discussed in detail in [17]. The angle α of surface radiation is then governed by

$$K_{TE_0} - 1 \times K_g = K_{light} \sin\alpha \tag{2}$$

A typical far-field pattern of the SME laser diode is shown in Fig. 1. The far-field is scanned from one cleaved facet (-90°) longitudinally over the surface of the sample to the other facet (+90°). The SME emission results in two beams emitted at 40.90°, and -41.10°. The main peak appears at 40.90° with a full width at half maximum (FWHM) of less than 1°. The measured intensity per solid angle at the peak is more than 24 times larger than the intensity emitted per solid angle at sides. As shown in the inset of fig. 1 the surface emission at 40.90° corresponds to the side emission at -90°. The asymmetric behavior of the surface emission is a consequence of the asymmetric position of the surface waveguide on the laser stripe, as indicated in Fig. 1..

The SME coupling process strongly affects the emission spectrum of the laser diode and leads to a drastic narrowing of the spectrum. The emission spectra of a reference laser diode (no grating, sample LD_R), a laser diode only with grating (but no window and no SME coupling, sample LD_G) and a SME laser diode (sample LD_{SME}) are compared at a current of 250 mA and shown in Fig. 2. The spectra of LD_R and LD_G are approximately the same and show a multimode laser oscillation with a FWHM of 5 *nm*. The effect of SME coupling on the emission characteristics is a significant decrease in the spectral width to a FWHM of 0.58 *nm*. This is due to the SME wavelength selection mechanism and feedback from the surface mode into the laser diode.

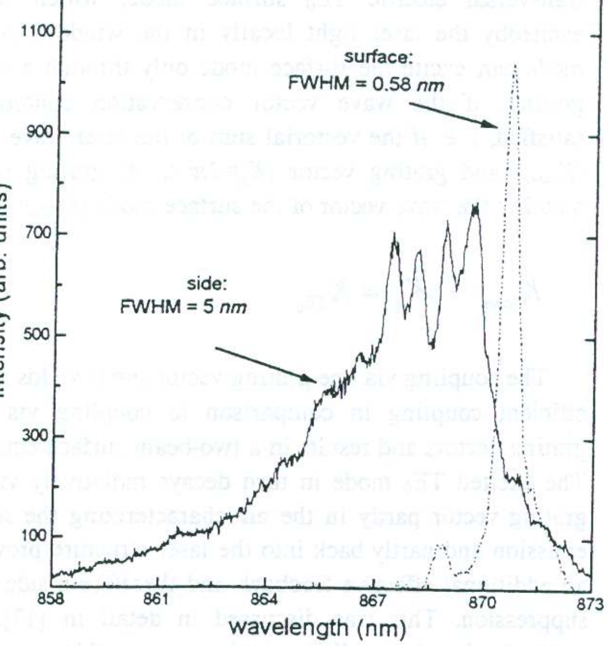

Fig. 2: Spectra of the reference laser and SME laser. The FWHM of the reference laser is reduced from 5 *nm* to 0.58 *nm* due to the additional wavelength selection mechanism and feedback effect provided by the SME coupling process.

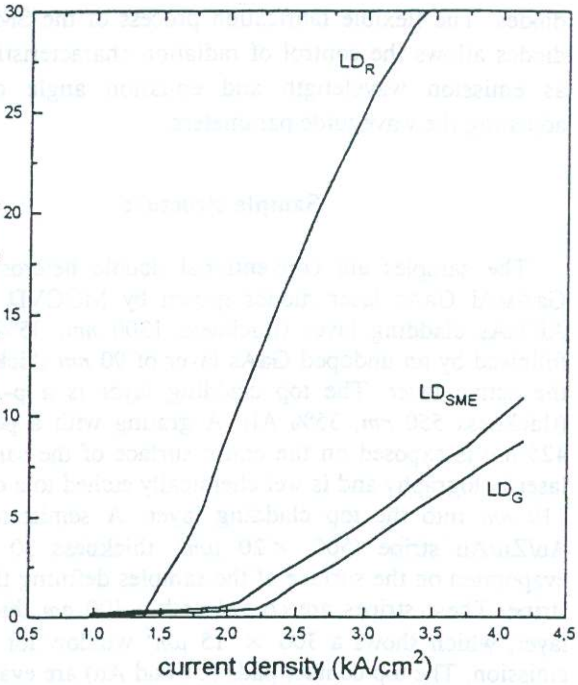

Fig. 3: Threshold current densities for reference laser diode, Laser diode with a surface grating and SME laser diode. J_{th} *is 1.41 kA/cm²* for LD_R, 2.14 kA/cm² for LD_G and 1.90 kA/cm² for LD_{SME}. The smaller value of J_{th} for LD_{SME} as compared to LD_G is due to the additional feedback from SME mechanism.

The L-I curves of the samples LD_R, LD_G and LD_{SME} supplies an obvious proof for this active feedback processin SME laser diodes. The L-I curves of LD_R, LD_G and LD_{SME} are given in Fig. 3. The threshold current density (J_{th}) of LD_R is measured to be 1.41 kA/cm^2, while the LD_G has a J_{th} of 2.14 kA/cm^2. J_{th} of LD_{SME} is measured to be 1.90 kA/cm^2. The threshold current density for LD_G and LD_{SME} are higher compared to J_{th} of LD_R due to the additional scattering losses into the substrate and metallic layers caused by the surface grating. However, LD_{SME} shows in comparison to LD_G a significant lower J_{th}, since the feedback from the surface mode into the laser diode (which is missing in case of LD_G) provides an additional gain for the main wavelength and consequently decreases the threshold current density.

The thickness and the refractive index of the surface waveguide play a decisive role for determination of the emission wavelength and depends on the (optical) thickness of the surface waveguide. A variation of the surface waveguide thickness or refractive index shifts the emission wavelength. This is clearly demonstrated in Fig. 4 , which shows the variation of the emission wavelength for different waveguide thickness'. The surface waveguide thickness of the LD_{SME} was stepwise reduced by low power plasma etching. A reduction of the dielectric thickness from 240 to 235 *nm* and then to 230 *nm* shifts the emission wavelength from 872.45 to 870.48 *nm* and to 868.86 *nm*.

This feature has a high potential for many applications. It allows, for example, the fabrication of laser bars with adjacent lasers coated by different waveguide thickness', which emit at slightly different wavelengths. A variation of the emission wavelength can also be achieved by changing the refractive index of the surface waveguide. The use of an electrooptically active polymer as surface waveguide would allow a refractive index change in the surface waveguide by applying an electric field to the polymer waveguide. This would provide a pure electrical tuning of the laser emission wavelength. These properties make the SME type of laser diodes best suited to be employed as a source for Wavelength Division Multiplexing (WDM).

Moreover, wavelength tuning in LD_{SME} is accompanied by a change in the emission angle and therefore SME laser diodes can also be employed as beam steering devices. For example a wavelength change from 872.45 to 868.86 *nm* has resulted in a shift of the surface emission angle α from 40.90° to 39.67°.

The crucial advantage of SME laser diodes compared to DFB/DBR laser diodes is their flexibility in fabrication. The emission characteristics can be adjusted entirely by external parameters and there is no need for complicated

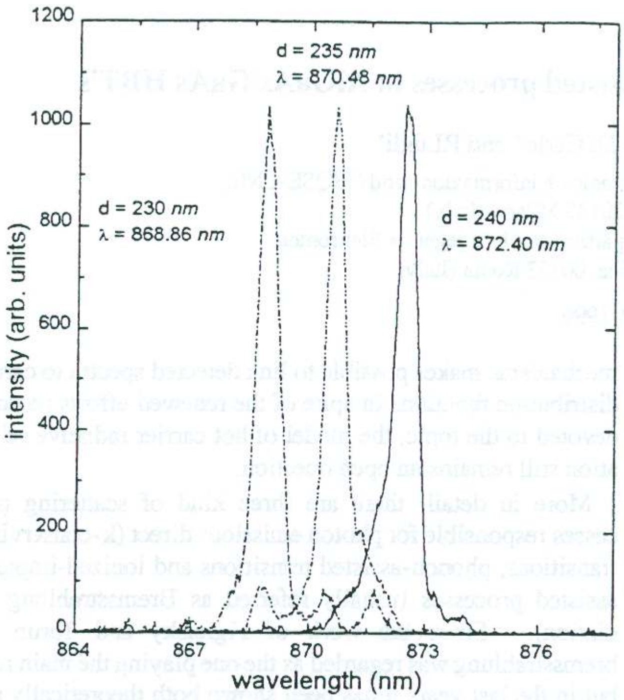

Fig. 4. The variation of the emission wavelength via change in the surface waveguide thickness. Reducing the waveguide thickness from 240 to 235 nm and then to 230 nm shifts the emission wavelength from 872.45 to 870.48 nm and then to 868.86 nm.

regrowth processes. In contrast to second order grating couplers, where wavelength tuning is achieved with complicated current adjustments in the gain regions, wavelength tuning and beam steering in SME laser diodes is possible by simply changing the refractive index of the surface waveguide. This emphasizes the high practical application potential of SME laser diodes.

Discussion and conclusion

The achieved beam divergence (1°) and the FWHM of the emission spectrum (0.58 *nm*) are higher than we would have expected by employing the first order grating coupling. This is due to the considerable grating inhomogeneities and deformations as a consequence of the used wet chemical etching process. This broadens the TE_0 mode dispersion curve and consequently several laser wavelengths satisfy the coupling condition (1) and single mode emission could not be achieved. However, this can be improved by fabricating better defined uniform gratings by dry etching techniques. This would result in a less divergent single mode surface emission with a more amplified intensity. This work is currently under progress.

In conclusion we present the first results of the SME laser diodes based on first order grating coupling. A strongly enhanced surface emission has been achieved. The feedback effect in these structures is clearly shown and the beam steering capability of this structure is demonstrated.

The main advantage of the SME laser diodes compared to DFB/DBR laser diodes and other second order grating couplers is their high flexibility in fabrication, where no regrowth process is necessary. This is of high importance for many practical applications and makes this type of laser diodes very suitable to be employed, for example, as a source for WDM applications.

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