Improvement of spatial and temporal coherence of a broad area laser diode using an external-cavity design with double grating feedback

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Abstract: We demonstrate a novel technique for narrow bandwidth and highly improved lateral mode operation of a high-power broad area laser diode. The system uses simultaneous feedback from the first diffracted order and the zeroth reflected order of a diffraction grating. The two feedback paths lead to simultaneously improvement of the spectral and spatial properties of the laser diode. The laser system operates in the well-known asymmetric double-lobed far field pattern with the larger lobe being extracted as the output. The bandwidth of the output beam is measured to 0.07 nm, which corresponds to an improvement of a factor of 17 compared to the bandwidth of the freely running laser. The output from the system contains 54 % of the energy reaching the grating, or 75% of the power reflected into the zeroth order. The improvements in both the spatial and temporal coherence opens the possibility of using this laser system in applications such as frequency doubling and pumping of optical parametric oscillators.

OCIS codes: (140.2020) Diode lasers; (140.5960) Semiconductor lasers; (140.3570) Lasers, single-mode; (030.1640) Coherence; (030.4070) Modes; (070.6110) Spatial filtering; (050.1950) Diffraction gratings

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1. Introduction

Due to their compactness, low cost and excellent efficiency, high-power laser diodes (LDs) are attractive laser sources for many applications. Since the invention of the semiconductor laser in 1962 [1-4], its performance has improved steadily, primarily in terms of lifetime and power level. The output power, however, is limited due to catastrophic optical damage of the laser output facet. This limitation may be overcome by increasing the width of the injection stripe, thus manufacturing broad-area lasers (BALs) or by fabricating monolithic laser diode arrays (LDAs) with several injection stripes separated by e.g. proton implantations. However, these techniques result in uncontrolled emission of several lateral modes with a double-lobe far field pattern [5, 6] and thus lasers with poor spatial and temporal coherence. The coherence properties are crucial in many applications, such as efficient coupling to optical fibers or nonlinear generation of new frequencies. For example crystals for second harmonic generation (SHG) or optical parametric oscillators (OPOs), require a pump laser with high spatial and temporal coherence. A remaining problem using diode lasers as pump sources for such applications is maintaining high power while improving their coherence.

Several techniques, such as injection locking [7-9] with an external single-mode source and various external cavities have been developed in order to control the emission from BALs and LDAs. A common way to improve the spatial and/or temporal coherence of the LD is the use of off-axis external reflectors such as conventional mirrors [10-14], diffraction gratings [16, 17], or phase conjugators [17-19] combined with spatial and/or spectral filtering. When applying feedback from an ordinary mirror, only the spatial coherence is distinctly improved. Feedback from a diffraction grating may result in an improved temporal coherence, while the spatial coherence is left unaltered. Phase conjugate feedback may, in combination with a Fabry Perot etalon lead to an output beam with high spatial and temporal coherence. Phase conjugate crystals are convenient in an external cavity due to their self-aligning nature. However, they are complex structures with a slow response time (ms to s) and a relatively low reflectivity. Furthermore, they are expensive and difficult to mass produce, since they are not easily reproduced.

In this work we demonstrate for the first time a novel configuration for improvement of the spatial and the temporal coherence, respectively of BALs. As opposed to previous realizations, this novel scheme opens the possibility for individual control of the spatial and longitudinal modes of the BAL. The key component in our external cavity is a ruled diffraction grating arranged in a configuration similar to a Littman configuration [21]. However, the present scheme allows for simultaneous feedback from the first diffraction order and the zeroth order, respectively. The longitudinal modes are discriminated by spatially filtered feedback from the first order of the grating, while the spatial modes of the BAL are controlled by asymmetrical feedback from a lateral mirror stripe in the zeroth order. The diffraction efficiency, and thus the distribution of power in the two orders, is controlled by a half-wave ($\lambda/2$) plate which is inserted before the grating. One main advantage of our novel scheme is that high performance is achieved by using passive and relatively inexpensive components. This holds promise for realizing highly efficient and high-performance laser systems at reasonable cost.

The output from the system is extracted as that part of the beam which passes through the mirror stripe in the zeroth order. When double feedback is applied we obtain a marked improvement of the spatial as well as the spectral properties of the diode laser. At 1.9 times the threshold current, $1.9I_{th}$ = 1 A, the output beam has a spectral bandwidth of $\Delta\lambda = 0.07$ nm and contains 54 % of the total power before the grating or 75 % of the power contained in the zeroth order.

2. Experiment

The experimental setup is illustrated in Figs. 1(a)-(c). Fig. 1(a) illustrates the generation of far field image planes using the collimating optics and Figs. 1(b)-(c) present a side view and a top view, respectively of the setup. The purpose of this setup is to allow simultaneous feedback from both the zeroth reflected order and the first diffracted order, respectively. The laser diode is a GaAlAs, BAL (1 μm $\times$ 200 μm) with a specified maximum output power of 3 W at drive current I = 3 A and T = 25°C. The laser is TM-polarized, i.e. linearly polarized along the y-axis. The spectral bandwidth at these settings is specified to $\Delta\lambda = 1.4$ nm (FWHM) with a center wavelength of $\lambda_0 = 806$ nm. The temperature is controlled with a Peltier element and the laser is operated at T = 36°C in this work. This temperature corresponds to a center wavelength around $\lambda_0 = 809.5$ nm at I = 1 A, which is the drive current applied here. The spectral bandwidth at T = 36°C of the multi-mode, freely running laser is measured to $\Delta\lambda = 1.2$ nm.

The BAL is mounted with its high-coherence axis (fast axis) parallel to the transverse direction (y-axis) and its low-coherence axis (slow axis) parallel to the lateral direction (x-axis). The output is collimated using three anti-reflection (AR) coated lenses, L1-L3. L1 is inserted at a focal length distance from the BAL emission facet, thereby collimating the transverse direction. At the same time L1 generates a far field plane, FF, for the lateral direction in its front focal plane. The lenses L2 and L3 collimate the beam in the lateral direction and generates an image

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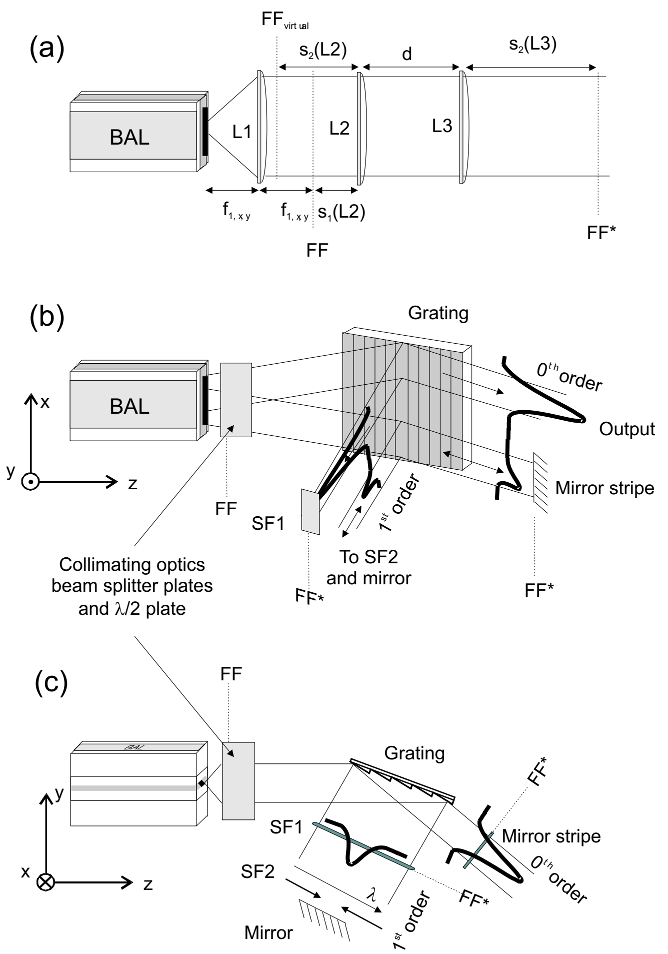

Fig. 1. Collimation and generation of image planes (a), side view (b), and top view (c) of experimental setup. BAL: Broad area laser; Li: Collimating lenses; $f_{1,x}$: Focal length of L1, $s_1(Li)$: Distance from object plane to Li; $s_2(Li)$: Distance from Li to image plane; FF: Lateral far field plane; $FF_{virtual}$: Virtual image plane of FF; FF*: Image plane of FF; SF1: Spatial filter in the lateral direction; SF2: Spatial filter in the transverse direction; x, y, z: Lateral, transverse and longitudinal directions, respectively. The shapes of the intensity profiles are outlined in black.

of the far field plane, FF, in the plane(s) FF* at distance(s) $s_2(L3)$ from L3. The distance $s_2(L3)$ is determined by the distances between FF, L2 and L3 through the Lens-maker's equation [22]:

$$\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{f} \tag{1}$$

where s_1 is the distance from the object, i.e. the intensity distribution in FF, to the lens with focal length f, and s_2 is the distance from the lens to the image plane of FF, i.e. FF*. L1 is an aspheric lens with focal length $f_{1,xy} = 4.5\,\text{mm}$ and a numerical aperture NA = 0.55. L2 and L3 are cylindrical lenses with focal lengths $f_{2,x} = 10\,\text{mm}$ and $f_{3,x} = 60\,\text{mm}$, respectively. With L2 placed in a distance $s_1(L2) = 4\,\text{mm}$ from FF, a virtual image of FF is generated in the plane $FF_{virtual}$ at a distance $s_2(L2) = -6.7\,\text{mm}$ from L2. The third lens, L3, is inserted in a distance d = 76 mm from L2, i.e. $s_1(L3) = d - s_2(L2) = 82.7$ mm, which yields an image plane, FF*, in a distance $s_2(L3) = 219$ mm from L3. This image occurs in both orders as depicted in Figs. 1(b)-(c).

Two beam splitter plates (AR coated on one side) are inserted to extract two 4 %-reflections that are used in beam diagnostics. A $\lambda/2$-plate is inserted to rotate the polarization by 90° such that the light incident on the grating is TE-polarized parallel to the grating grooves (x direction). This choice of polarization leads to a low diffraction efficiency and thus optimizes the amount of power in the zeroth order output beam.

A diffraction grating with 1200 lines/mm is arranged such that the incident beam enters the grating at an angle of $\theta_{in} = 72°$ with respect to the grating normal $\vec{n}$. The angular dispersion of the light is optimized by inserting the grating at a large angle, thereby illuminating the entire width of the grating. This minimizes the single-pass bandwidth $\Delta\lambda$ of the output light at wavelength λ, which may be estimated by [16]

$$\Delta\lambda = \frac{d\,w}{m\,f}\cos(\theta) \tag{2}$$

where d is the groove spacing, w is the transverse waist size at the diode, m is the diffraction order, f is the focal length of the collimating lens, and θ is the angle between the grating normal and incident beam. A measure for the transverse waist size at the diode is the ratio between the transverse width of the active layer y_0 and the confinement factor Γ [23]. Typical values of Γ for broad area lasers are in the range 10-70%. For $\frac{1}{2}y_0 = 0.5\,\mu$m and assuming [24] $\Gamma \approx 60\%$, we have $w = 0.8\,\mu$m. With $d = (1200\,\text{mm}^{-1})^{-1}$, $m = 1$, $f = 4.5$ mm, and $\theta = 72$, we obtain a rough estimate of the single pass bandwidth of $\Delta\lambda = 0.05$ nm. The high angle of incidence leads to a low diffraction efficiency of the TE-polarized light and thus a large fraction of the incident light, more than 70%, is coupled out in the zeroth order.

Two orthogonal spatial filters, SF1 and SF2, are inserted in the first order beam between the grating and and the mirror. The filters select parts of the beam to pass through in the lateral (SF1) and transverse (SF2) directions, respectively. Only a narrow wavelength band is reflected back along the direction of incidence on the mirror, the wavelength depending on the mirror orientation due to the dispersive and filtered feedback. This back-reflected beam is diffracted again by the grating and is returned to the BAL. The zeroth order of this second diffraction, is lost. However, the higher diffraction efficiency at this small angle of incidence, results in a negligible loss in the order of 1 mW. SF1 is placed in the image plane of the far-field plane, FF*. In this same distance, but in the zeroth order, a mirror stripe is inserted to provide feedback to the laser and thereby to control the spatial emission profile. The lateral filter in the first order and the mirror stripe in the zeroth order are matched to allow for the same spatial parts of the beam, the small lobe, to be reflected. When the mirror stripe in the zeroth order is illuminated, the far field changes from a broad radiation pattern to the well-known asymmetric double-lobe pattern [10]. This allows that one of the lobes is used for the feedback by the mirror stripe, while the other serves as the output beam. When the mirror and the transverse filter, SF2, in the first order are correctly aligned, the spectrum narrows significantly. When allowing for feedback from the zeroth order in addition, and when the lateral filter in the first order matches the position of the mirror filter in the zeroth order, the spectrum becomes even narrower and more intense.

3. Results and discussion

The spatial characteristics of the laser diode were improved using optical feedback from two mirror stripes, with the strongest feedback originating from the mirror stripe in the zeroth order (see Fig. 1). Fig. 2 shows the lateral far field intensity distribution from the BAL when different kinds of asymmetric feedback are applied and when the laser runs freely, respectively. The solid curve represents the intensity distribution when feedback from both zeroth and first orders is applied, in the dashed curve only feedback from the zeroth order is applied, in the dotted curve only feedback from the first order is applied, and in the dash-dotted curve, the laser runs freely. The small lobe corresponds to the part of the beam which is used for feedback by being reflected from the external mirrors, while the large lobe forms the output. The feedback from the mirror stripe in the zeroth order narrows the intensity distribution of the freely running laser and leads to the formation of the double lobed field. It is observed that the additional feedback from the first order further narrows the intensity profile and leads to a more intense output lobe. When the zeroth order feedback is blocked and the laser only operates with asymmetric feedback from the first order a small asymmetry arise in the intensity distribution as compared to the freely running profile. However, this amount of feedback is not sufficient for the laser to assume the highly asymmetric double lobe shape. For a 200 μm wide junction of a BAL at 810 nm, the diffraction limit is 0.28° [11]. The FWHM of the larger far field lobe is 1.32° in the case of double feedback, corresponding to 4.8 times the diffraction limit. This corresponds to an improvement of a factor of 6 compared to the freely running laser which is 29 times the diffraction limit. When operating the laser at drive currents above 2-3 times the threshold current, I_{th}, the freely running modes of the laser become more pronounced and the spatial filters have to be adjusted slightly for optimal operation. However, the output beam is not as close to the diffraction limit when the laser is operated at higher currents as when it is operated at lower currents. The output beam is 5.7 times the diffraction limit when operating the laser at $I = 1740$ mA ($3I_{\text{th}}$) and almost 12 times the diffraction limit at highest applied drive current $4.3I_{\text{th}}$ ($= 2500$ mA). AR coating the laser front facet, thereby reducing the quality factor of the laser cavity will lead to an improvement in performance in terms of beam quality and output power [12].

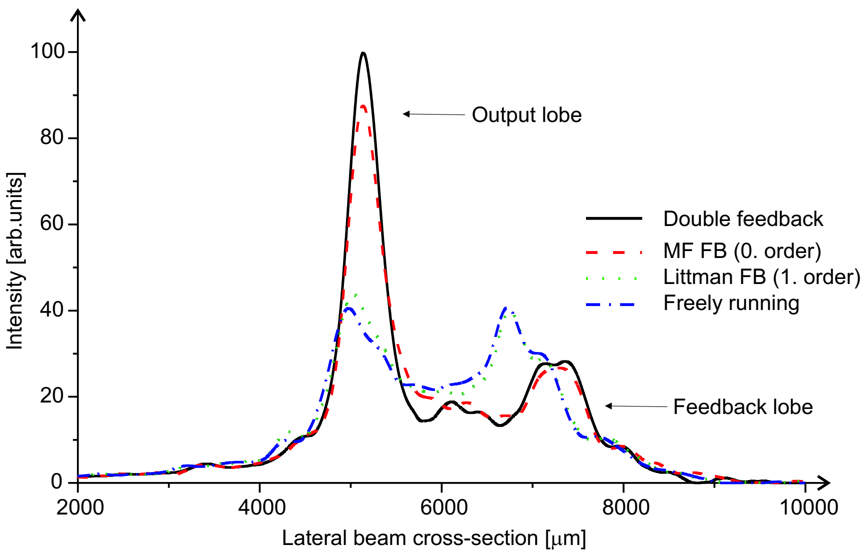

Fig. 2. Intensity profiles in the lateral far field of the double feedback (solid), the single feedback (dashed and dotted, respectively), and the freely running (dash-dotted) BAL.

Fig. 3 shows the spectral characteristics of the BAL. These properties are strongly controlled by the feedback from the first order of the grating and are further improved by feedback from the zeroth order reflected beam. The black curve shows the spectrum with double feedback, the red curve is with feedback from the first order only, the blue curve is with feedback from the zeroth

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order only, while the green curve shows the spectrum of the freely running laser. When double feedback is applied, the bandwidth was narrowed from 1.2 nm for the freely running laser to 0.07 nm (FWHM). When blocking the feedback from the zeroth order, the bandwidth increases slightly to 0.09 nm, while the intensity drops to approximately half the value of the double feedback situation. If the first order feedback is blocked and the laser only receives feedback from the zeroth order (blue curve in Fig. 3), the bandwidth (full width at zero maximum - FWZM) is measured to 1.4 nm. When aligning the system to optimal spectral properties with the first order alone, the mirror has a certain position. Due to the nonlinear interaction of the two feedback paths in the laser medium, this position should be slightly adjusted when allowing for the zeroth order feedback. By adjusting the mirror, the two feedback paths can be arranged to enhance each others influence on the emission from the BAL as evident from Figs. 2 and 3. The obtained bandwidth is comparable to the single-pass bandwidth estimated from Eq. 2. However, the estimate based on Eq. 2 indicates the possibility for further improvements of the bandwidth.

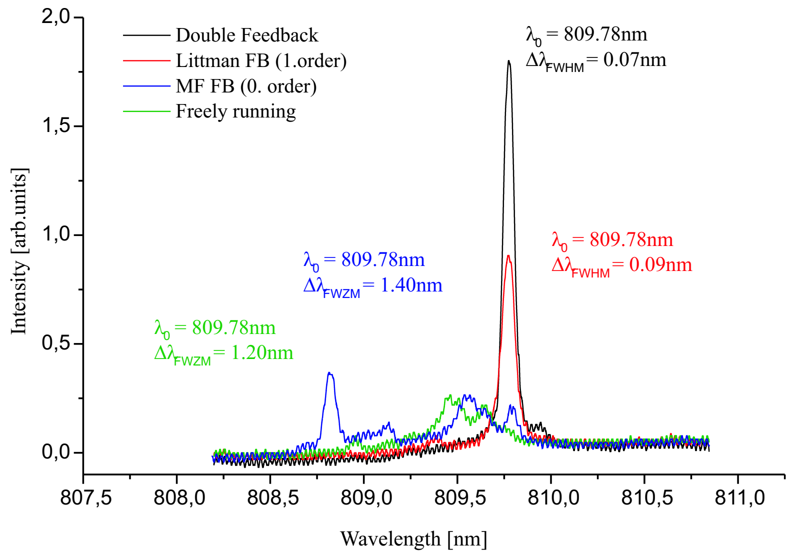

Fig. 3. Spectrum of the double and single feedback laser. Black spectrum: Double feedback applied; Red spectrum: Feedback from first order applied; Blue spectrum: Feedback from zeroth order applied; Green spectrum: Freely running laser.

The power in the beam incident on the grating is measured to be 326 mW and the power reflected into the zeroth order is 234 mW, i.e. 72% of the incident power is reflected. The output power from the system, i.e. the power measured after the mirror stripe in the zeroth order is 173 mW when the first order feedback is blocked and 175 mW with double feedback applied. Thus, 75% of the power available in the zeroth order, or 54% of the total power before the grating, is extracted in the output. The power measured after L2 is 358 mW and a loss of ca. 4 % in each BS results in a measured power of 328 mW before the $\lambda/2$ plate. Approximately 15 % of the power is lost in the first two collimating lenses, L1 and L2.

The output power may be increased by several means. Using a laser diode with AR coated front facet results in a system which may be driven far above threshold while maintaining its improved coherence. In addition we may choose a laser with higher output power and driven at a lower temperature. Furthermore, removal of the beam splitter plates will increase power. A system with these properties, i.e. with high spatial and temporal coherence while maintaining

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high power has interesting applications in e.g. SHG of new frequencies where spectral bandwidth, focus capacity and power are crucial parameters.

4. Conclusion

A novel scheme for an external cavity for broad area laser diodes has been demonstrated. The scheme uses a diffraction grating in a configuration that allows for simultaneous asymmetric optical feedback from two mirrors in the first diffracted order and in the zeroth reflected order, respectively. The advantages of this setup is that both the spatial and the temporal coherence are improved and that the two feedback paths allows for individual control of the spectral and spatial properties of the laser diode, respectively. The two feedback paths were arranged to operate in a constructive manner by means of lateral spatial filtering. The output contains 54% of the available power before the grating or 75% of the energy reflected into the zeroth order. The output beam is 4.8 times the diffraction limit and has a spectral bandwidth of 0.07 nm. In comparison, the freely running laser is 29 times the diffraction limit with a bandwidth of 1.2 nm. This scheme has promising applications e.g. as a pump source for SHG, where narrow line-width and good spatial coherence are essentials.

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