Mode stabilization of a laterally structured broad area diode laser using an external volume Bragg grating

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Abstract: An external volume Bragg grating (VBG) is used for transverse and longitudinal mode stabilization of a broad area diode laser (BAL) with an on-chip transverse Bragg resonance (TBR) grating. The internal TBR grating defines a transverse low-loss mode at a specific propagation angle inside the BAL. Selection of the TBR mode was realized via the angular geometry of an external resonator assembly consisting of the TBR BAL and a feedback element. A feedback mirror provides near diffraction limited and spectral narrow output in the TBR mode albeit requiring an intricate alignment procedure. If feedback is provided via a VBG, adjustment proves to be far less critical and higher output powers were achieved. Moreover, additional modulation in the far field distribution became discernible allowing for a better study of the TBR concept.

OCIS codes: (140.2020) Diode lasers; (140.3410) Laser resonators; (140.3425) Laser stabilization.

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#235170 - $15.00 USD Received 24 Feb 2015; revised 23 Mar 2015; accepted 23 Mar 2015; published 1 May 2015

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1. Introduction

Broad area diode lasers (BALs) are very efficient sources for laser radiation of up to several Watts output power from a single emitter [1]. These devices cover a wide range of scientific and industrial applications from atomic physics [2] to telecommunication, biophotonics [3, 4] and material processing [5]. However, due to the broad emitter and the lack of spectral mode selection mechanisms, standard BALs suffer from poor spatial beam quality in the lateral direction and longitudinal multimode operation.

Several techniques have been developed to improve the emission behavior of such edge emitting diodes. External feedback can be used to improve the beam quality [6] or optimize output power and spectral properties [7]. Furthermore, mode selective elements can be implemented on the chip itself like lateral tapered structures for beam preserving power amplification [8] and Bragg gratings for longitudinal mode selection [9]. Another way to achieve spatial mode selection is transverse Bragg resonance (TBR) [10–12]. The internal TBR grating of the BAL defines a low loss transversal mode at a specific angle of incidence matching a certain wavelength.

We have recently shown that, when feedback is provided at this angle, the TBR mode can be stabilized with just a plane mirror [13]. With that setup near diffraction limited, narrow bandwidth emission with a single lobed far-field pattern was achieved. The TBR BAL tends to operate at a wavelength close to the gain maximum. Furthermore, the TBR angle and the corresponding wavelength depend slightly on the injection current and other laser parameters. A standard way to address this issue for diode lasers in general is to set up an external cavity with diffraction gratings [14]. Another simple, compact, robust and cost effective way is to utilize a volume Bragg grating (VBG) as selective element in the external cavity for both feedback angle as well as operating wavelength [15, 16].

Here we investigate the emission characteristics of a TBR BAL while using an external VBG for wavelength locking. Furthermore, the influence of angular selective feedback is investigated and compared to results with the plane mirror resonator. The TBR BAL could be wavelength stabilized for almost all feedback angles. The experimental results give insights in the transversal mode behavior of this novel laterally structured BAL design.

2. Experimental setup

The chip, designed and manufactured by the Ferdinand Braun Institute in Berlin, is the same one as in our previous work [13]. It comprises two unpumped 1D TBR gratings bilaterally positioned alongside a 91.5 μm wide and 1 mm long electrically pumped central emitter region.

#235170 - $15.00 USD Received 24 Feb 2015; revised 23 Mar 2015; accepted 23 Mar 2015; published 1 May 2015

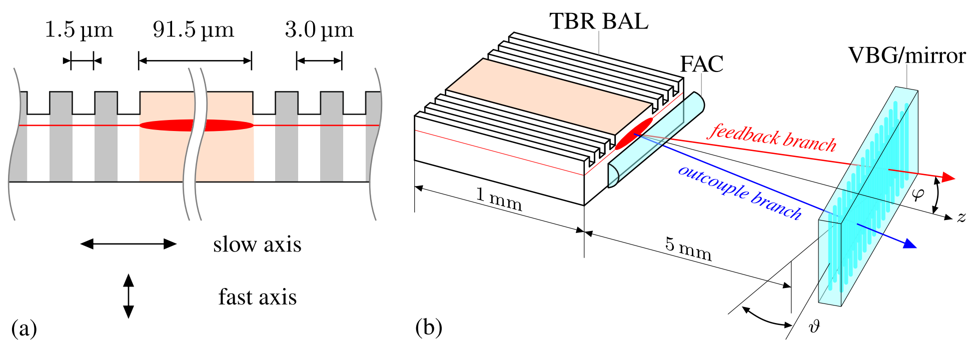

Fig. 1. (a) Sketch of the lateral BAL structure with active core and TBR grating and (b) of the external resonator setup with VBG or mirror.

A sketch of the lateral structure is given in Fig. 1(a). Each grating consists of fifty 3 µm wide stripes parallel to the core and the substrate and is stretched along the whole length of the BAL. Within each stripe, a 1.5 µm wide superficial groove was etched into the finalized epitaxial structure. The active region consists of an AlGaAs asymmetric super large optical cavity (ASLOC, see [17]) heterostructure with two InGaAs quantum wells and spreads through both the core as well as the grating regions. The TBR BAL features an anti-reflective coating with $R \approx 6 \times 10^{-4}$ at 968 nm at the front facet for an optimal operation in an external cavity. The emission of the free running BAL is characterized by amplified spontaneous emission with a broad spectral bandwidth of ≈ 30 nm (FWHM) centered around a wavelength of 960 nm. The laser threshold injection current for the free running TBR BAL without external feedback was found to be $I_{thr} \approx 1.7$ A. The maximum emission power at $I = 3$ A amounts to 350 mW.

The mode selection process can be understood as follows: The light field can continue to propagate in the extended active region outside the core of the BAL. Partial reflection will occur due to the effective refractive index gradient between the etched and unetched sections in the TBR region. Interference between reflections from the corresponding periodic junctions will result in a variable overall grating reflectivity toward the core or, equivalently, loss into the TBR structure, depending on the internal propagation angle. When providing external feedback under an angle conform with the grating's constructive Bragg condition, a special low loss TBR mode should be excitable.

As pointed out in [18], 1D TBR structures need at least one additional angular selective element to ensure operation in the low-loss TBR mode. Our approach is an external resonator assembly as pictured in Fig. 1(b). A feedback element such as a mirror, or in our case a VBG, is positioned at a distance of 5 mm from the front facet. Our VBG was recorded into photo thermal refractive (PTR) glass by OptiGrate Corp, Florida, and offers a clear aperture of 25 mm by 5 mm. It demonstrates a reflectivity of $R \approx 0.41$ at the resonance wavelength of 968.16 nm, while the transmission outside the resonance bandwidth of 275 pm is close to unity. For comparison, all measurements were repeated with a dielectric mirror of $R \approx 0.40$ instead of the VBG and an otherwise identical assembly.

The mount for the feedback element allows for a variable tilt angle θ toward the optical axis to directly tune the assembly for the low-loss Bragg resonance. An additional aspheric cylindrical lens, the fast axis collimator (FAC) with a focal length of $f = 1.49$ mm and a high numerical aperture of 0.5, is inserted to collimate the beam along the vertical, fast diverging axis.

#235170 - $15.00 USD Received 24 Feb 2015; revised 23 Mar 2015; accepted 23 Mar 2015; published 1 May 2015

3. Experimental results

The emission spectra of the two resonators measured with an optical spectrum analyzer (ANDO AQ-6315) are given in Figs. 2(a) and 2(b). In general, the VBG assembly (see subplot (a)) emits at a central operation wavelength corresponding to the VBG resonance wavelength for all tested feedback angles. Small deviations are observable according to the bandwidth of the VBG. Moreover, longitudinal single mode operation could easily be achieved. This was verified with a wavelength meter (HighFinesse WS/6-200) with a resolution of 200 MHz well below the expected mode distance of the external resonator of $\approx 17.6\,\text{GHz}$. On the other hand, spectra of the mirror resonator emission generally exhibit multiple longitudinal modes (Fig. 2(b)). Single mode operation is only possible in proximity to the transverse Bragg resonance at $\vartheta \approx 8.5°$ and demands elaborate adjustment.

Figure 3 shows the far field evolution for the VBG resonator (Fig. 3(a)) as well as for the mirror resonator (Fig. 3(b)), respectively, as a function of the feedback angle at an injection current of 2 A. The plots give the emission power in gray scale over the far field emission angle φ along the ordinate axis for different feedback angles ϑ along the abscissa. The emission power was measured with a power detector behind a vertical slit aperture (width 0.5 mm) at a distance of 300 mm from the BAL. This combination was then moved across the slow axis using a translation stage with a step size corresponding to the slit width, resulting in an angular

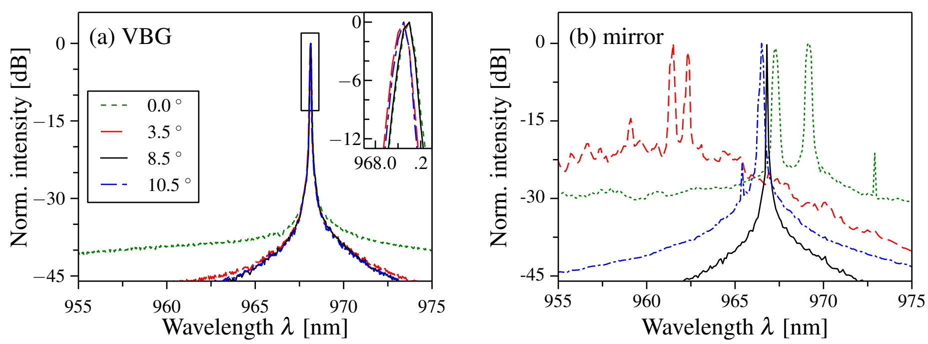

Fig. 2. Emission spectra of the total far field emission of the (a) VBG and (b) mirror resonator assembly at an injection current of 2 A for selected feedback angles.

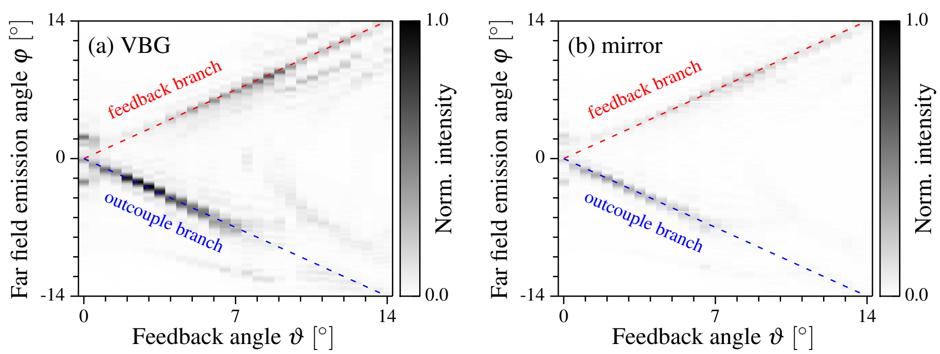

Fig. 3. Far field emission of the TBR BAL in an external resonator at an injection current of $I = 2\,\text{A}$ as a function of the tilt of the feedback element. The red (blue) dashed lines denote the feedback (outcoupling) branch. The graphs were normalized to the highest observed intensity of both resonators which occurred in the outcouple branch of the VBG setup.

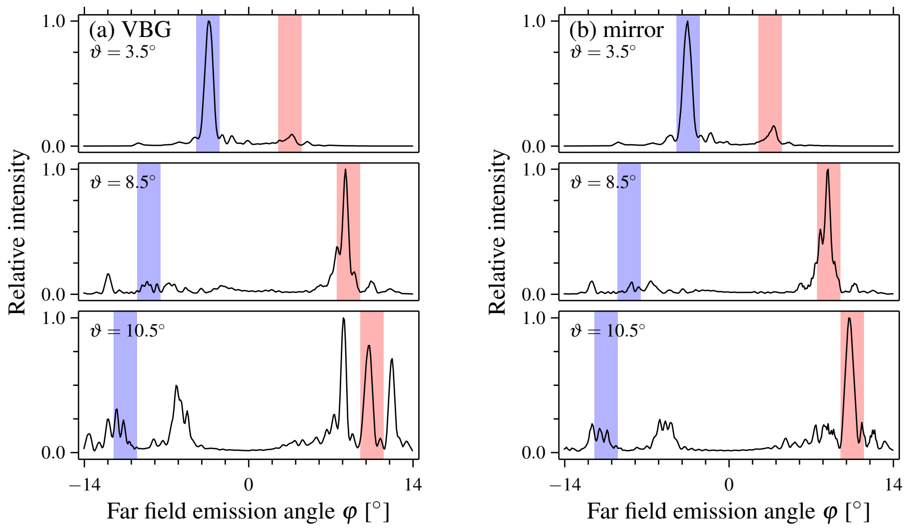

Fig. 4. Angular intensity distribution of the far field emission for (a) the VBG and (b) the mirror resonator assembly for selected feedback angles. The red/blue highlighting indicates the center of the feedback/outcouple branch. All graphs were normalized individually.

resolution of about 0.09°.

At a feedback angle of $\vartheta = 0°$, a multi-peak far field pattern is apparent symmetrically centered around the optical axis of the chip. The pattern is distributed across $\approx 5°$. This on axis emission is suppressed with feedback angles of $\vartheta \approx 0.5°$ and larger. The far field distributions then feature two main peaks, one in each branch, centered around a far field emission angle of $\varphi = \pm\vartheta$. The main peaks have a width of $\approx 0.7°$ (FWHM) which was determined from the far field distributions as can be seen exemplary in Fig. 4. This far field distribution with two peaks under off axis feedback is characteristic for BALs [6]. We will call light emitted toward the feedback element ($\varphi > 0°$) as belonging to the feedback branch, otherwise belonging to the outcoupling branch. Furthermore, the power distribution between the two branches shifts as a function of the feedback angle ϑ, as can be seen in Fig. 3. For small values of ϑ, the majority of the output power is emitted into the outcoupling branch, but shifts toward the feedback branch at $\vartheta \approx 6°$. At a feedback angle of about 8.5°, almost no power is emitted into the outcoupling branch and the feedback branch exhibits a local intensity maximum, indicating the TBR resonance.

Selected far field distributions for both resonator types and three feedback angles (3.5°, TBR mode at 8.5°, 10.5°) are shown in Fig. 4. First, characteristic peaks in the far field distribution obtained with the VBG resonator have shape and position similar to corresponding peaks in the distribution from the mirror resonator. In addition they exhibit higher maximum intensities and carry more output power (see Table 1 and Fig. 3 as well). An example would be the TBR resonance peak at $\varphi \approx 8.5°$. Second, new peaks alongside the main branch peak can be seen in the far field distribution from the VBG resonator. Consider for example the triple peak shape in the feedback branch at $\vartheta = 10.5°$. They are absent in the mirror resonator emission. These side peaks bilateral to the main branch peak originate from the TBR structure and are possibly a good indicator for the influence of the grating structure.

We determined the beam quality along the slow axis for selected far field peaks following the ISO 11146 standard. For a given ϑ, we selected the main branch peak with the highest intensity via a vertical slit aperture and determined the quantity M^2. Angular feedback at $\vartheta = 3.5°$ (main

#235170 - $15.00 USD Received 24 Feb 2015; revised 23 Mar 2015; accepted 23 Mar 2015; published 1 May 2015

Table 1. Beam quality M^2 (slow axis) and total output powers measured behind a slit aperture in the far field selecting the main intensity peak of the VBG and mirror resonators as a function of the three feedback angles.

	VBG		mirror	
ϑ	M^2	output power	M^2	output power
0.0°	3.07	212 mW	2.82	170 mW
3.5°	1.35	510 mW	1.26	360 mW
8.5° (TBR mode)	1.24	270 mW	1.32	200 mW

peak in the outcoupling branch) and at the TBR angle at $\vartheta = 8.5°$ (main peak in the feedback branch) results in almost diffraction limited emission with $M^2 \approx 1.3$ (see Table 1). On axis operation yields values of $M^2 \approx 3$ for the middle peak alone and $M^2 \approx 14$ for the whole multi peak structure. The output power of the VBG resonator assembly is 25 % to 42 % higher than the output power of the mirror resonator at the same feedback angles. The corresponding brightness $L = \pi^2 \cdot P/(\lambda^2 \cdot M^2_{slow} \cdot M^2_{fast})$, taking into account the diffraction limited fast axis, increases by up to 44 % for the Bragg resonance. In comparison to the values reported in our previous work [13], which featured a dielectric mirror with a reflectivity of 15 %, the output powers turn out to be lower. This originates in the higher VBG and mirror reflectivity of 40 % in the current work.

At smaller feedback angles our TBR BAL operates in a mode exceeding the output power of the TBR mode. The maximum was found for $\vartheta \approx 3.5°$. We shall refer to this mode as a "*small modal angle*" (SMA) mode according to [18]. The origin of this SMA mode is still subject of our ongoing studies. Nevertheless the higher output power of the SMA mode compared to the output power at Bragg resonance hints toward a not yet loss-less TBR operation.

4. Summary and outlook

The emission characteristics of a TBR BAL in an angular selective external resonator setup with a VBG as feedback element were investigated. In addition to typical BAL behavior a special Bragg resonance mode with a single lobed, near diffraction limited far field and an output power of up to 270 mW at an injection current of 2 A could be realized. In contrast to our previous experiments with a mirror as feedback element, the VBG offered better wavelength discrimination and longitudinal single mode operation over a wide range of feedback angles. The VBG therefore allowed us to study the transverse mode structure independently from longitudinal effects. Moreover, we could observe new peak structures alongside the main branch peaks. Due to the superior mode discrimination in the VBG assembly a more than 40 % increase in brightness could be observed compared to a setup using a feedback mirror with a reflectivity similar to the VBG.

To our knowledge this is the first time such a TBR BAL was combined with a VBG. The good performance of the TBR BAL in conjunction with the grating resonator will allow for more detailed studies of the TBR effect itself. Moreover, side effects such as the SMA mode with a higher efficiency than the TBR mode, the rather broad angular TBR resonance and the optimal feedback reflectivities from the VBG indicate room for further improvements of the current TBR concept.

#235170 - $15.00 USD Received 24 Feb 2015; revised 23 Mar 2015; accepted 23 Mar 2015; published 1 May 2015

Acknowledgments

We thank Dr. Götz Erbert and Dr. Bernd Eppich from the Ferdinand Braun Institute, Berlin, for providing the TBR diode laser chip and for fruitful discussions.

#235170 - $15.00 USD Received 24 Feb 2015; revised 23 Mar 2015; accepted 23 Mar 2015; published 1 May 2015