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Operation of a frequency-narrowed high-beam quality broad-area laser by a passively stabilized external cavity technique

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The average spectral bandwidth of a 2 W broad-area diode laser was narrowed to 5 GHz with wavelength tunability of up to 12 nm at a center wavelength of 790 nm with the use of a Littman-Metcalf external cavity in a displaced configuration. The use of lens and combined lens-laser transformation systems allowed precise alignment of the beam shaping optics, which led to significant improvements of the beam quality and an enhanced suppression of the free-running laser modes. We characterize the spatial beam quality of our external cavity diode laser by measuring the M^2 quality factor and relate this to our measured bandwidths. Our external cavity can be configured over a range of cavity lengths and is modular in design, enabling access to a broad frequency spectrum for a wide range of applications that require high-power, narrow bandwidth operation. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2804015]

The development of high-power semiconductor broad-area diode lasers (BALs) and diode laser arrays has opened up exciting possibilities for many applications. Due to their reliability, robustness, compactness, high powers on the order of watts, and relatively inexpensive cost, BALs immediately garner attention for being used as ideal light sources, such as for pumping solid-state lasers. However, BALs emit a highly astigmatic output with broad spectral bandwidths of ~3 nm. The high-power density in the BAL gain medium leads to spatial filamentation of the output beam along the slow axis of the emission profile, which complicates attempts to collimate the beam. This has generally limited the use of free-running BALs in spectroscopic applications. Narrowing the bandwidths of high-power BALs[1–5] and laser diode bars[6–8] in external cavities has shown to be very important for a variety of applications in spectroscopy, medicine, and atomic physics. For example, a spectrally narrowed high-power broad-area laser has been used to produce hyperpolarized xenon for enhanced nuclear magnetic resonance (NMR) imaging,[5] which can be used to greatly improve images of the lungs, brain, and other biological tissues. Improving the characteristics of high-power BALs, arrays, or bars coupled to an external cavity is important as this opens the possibility of using such laser systems in many demanding applications such as the production of laser polarized noble gas samples described above, and the development of light detection and ranging (LIDAR) instruments for atmospheric and environmental monitoring.[9] We have shown the details of our external cavity based on a displaced-configuration Littman-Metcalf design in earlier work.[10,11] In this article, we demonstrate a significant enhancement of the spatial beam quality and bandwidth narrowing to ~5 GHz while maintaining the broad tunable range up to 12 nm at an output power of 1 W of a passively stabilized external cavity broad-area laser. Because the beam quality plays an important role on the bandwidth narrowing, improvements made to the external cavity through careful design of the beam shaping optics allowed us to better control the structure of the dispersive feedback.

Figure 1 schematically represents our grazing-incidence Littman-Metcalf external cavity broad-area diode laser (ECDL). This cavity allows the position of the output beam to stay constant during frequency tuning and also provides greater dispersion that helps in narrowing broad-bandwidth lasers. The angles are related via the grating equation,

$$mn\lambda = (\sin\theta + \sin\phi), \tag{1}$$

where m is the diffraction order and n is the grating line density. Our ECDL achieves frequency selectivity by rotating the entire mirror plane about a fixed pivot point, rather than independent rotation of the mirror element itself. In our geometry, L_g is roughly equal to L_p at the grazing incidence. The grating and feedback mirror can be precisely positioned along the lengths L_p and M_p, respectively. For a well aligned grating (i.e., $d_2=0$), position errors in the placement of the feedback mirror, represented by d_3, can be compensated by an equal but opposite displacement of the laser along d_1. This displaced configuration allows optimization of the synchronous mode-hop-free tuning range, though it is limited by the spatial beam quality of the coupled BAL. Our cavity design is completely modular and, with the proper combination of laser and grating, this ECDL design can be adapted to a wide variety of wavelengths and configured with cavity lengths up to 52 cm.

We utilized a Coherent Semiconductor single-stripe broad-area laser of type S-780-2000C-150-C with dimensions of $150\times1\times1000\ \mu\text{m}^3$ mounted in a C-block. The ECDL was passively stabilized to minimize the transient noise effects due to ECDL sensitivity to mechanical vibrations. We used a holographic gold-coated diffraction grating with 2400 lines/mm at a grazing incidence that served as the wavelength selective output coupler in the external cavity. The grating grooves were fully illuminated for narrow-band operation. A feedback mirror was used to reflect the first order diffraction from the grating back into the BAL cavity. The 12 nm coarse tunable range of the

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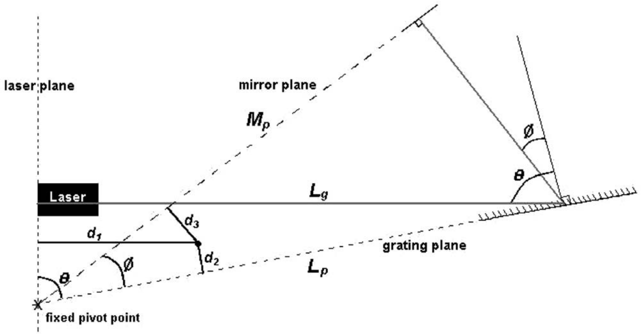

FIG. 1. Littman-Metcalf based grazing-incidence external cavity broad-area laser.

ECDL was accomplished by rotation of the feedback mirror mounting stage via a computer-controlled, high-precision actuator.

The spatial beam quality of high-power BALs is very important as it affects not only the ability to collimate the laser, but also influences important characteristics such as spectral bandwidth and the wavelength tunability. The beam quality factor M^2 compares the divergence of the output beam to that of an ideal Gaussian diffraction-limited TEM_{00} beam. BALs, due to the multiple transverse modes supported by the elongated gain medium, can typically have M^2 values ranging from tens to hundreds.[12] Ideally, M^2 should be 1,[13] corresponding to a Gaussian intensity profile. We have measured the M^2 factor of the output beam of our ECDL by using the Rayleigh range method,[14] which determines how tightly the beam can be focused under certain conditions and how well the beam propagates over long distances. The Rayleigh method has the advantage of being simpler to execute, requiring a minimum of two measurements (beam waist and Rayleigh length). This method yields similar results to the more involved International Organization for Standardization (ISO) method.[15] The experimental apparatus used to measure M^2 is shown in Fig. 2 within the dashed box. To perform the beam quality measurement, the beam was focused with an antireflection coated 35 mm focal length converging lens. The focused beam was recorded with a charge-coupled device (CCD) which consists of a 640×480 array mounted on a three-axis translation stage. The CCD was placed at the beam focal point where the image from the CCD yields a minimum beam waist D_m. When the focal point was found, its position and the beam waist were recorded. The CCD was then translated to a point $\sqrt{2}$ times larger than the minimum beam waist. The distance from that point to the focal point defines the Rayleigh length z_r. From these measurements, we calculated the embedded Gaussian beam parameter d_o, which represents the beam waist of an idealized, diffraction-limited beam. This value is then compared to the minimum beam waist of the laser to determine its beam quality factor as $M^2=(D_m/d_o)^2$, where $d_o=2(z_r\lambda_0/\pi)^{1/2}$. Here, λ_0 is the center wavelength of the output beam. During the measurements, the laser beam was strongly attenuated to prevent CCD saturation. Beam images were recorded on a one-to-one scale, and beam waists were determined using a program for digital image processing and analysis.

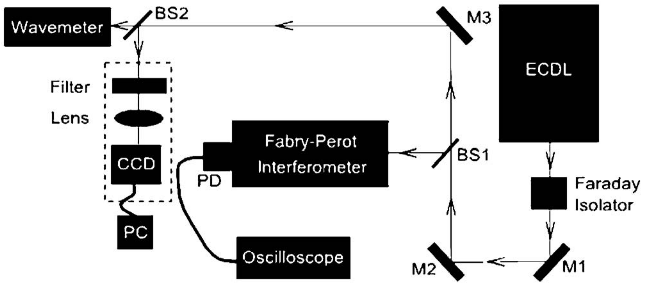

FIG. 2. A schematic diagram of the experimental apparatus. The dashed box represents the beam quality M^2 measuring setup. BS1 and BS2 represent beamsplitters; M1 and M2 are coated mirrors for near-infrared wavelength.

Because the BAL output beam is highly astigmatic and difficult to collimate, we developed a lens transformation system (LTS) with a 0.001 in. adjustment resolution in three dimensions in order to carefully shape the diverging beam along the fast and slow axes simultaneously. The LTS served as the beam shaping optic, which consists of a high quality antireflection coated aspheric lens with 2.7 mm focal length and a cylindrical lens with 5 cm focal length. Therefore, the highly diverging fast axis (35°) was collimated to a diffraction-limited divergence, and the slow axis to 0.02° divergence over 7 m distance from the raw 12° divergence. The precise alignment afforded by the LTS allows collimation of the ECDL output to a ~4.24 mm slow-axis beam width at the Rayleigh length. For the emitted beam waist of 3 mm, this is very close to the Rayleigh length limit of $\sqrt{2}(3\ \mathrm{mm})=4.24$ mm. The LTS and BAL are combined as a lens-laser transformation system in three dimensions so that they can precisely be moved together along, and normal to, the laser plane to access the different cavity lengths and to compensate for position errors in the feedback mirror. When the cavity is well aligned and the position of the LTS is near the optimum, the intrinsic free-running mode structure is significantly suppressed and a narrow bandwidth emission of ~5 GHz appears on the output spectrum. The excellent collimation of the output beam and precise control of the feedback are critical in achieving high-beam quality and narrow bandwidth operation.

To characterize the laser output from our ECDL, we used a plane-parallel scanning Fabry-Pérot interferometer with a free spectral range (FSR) of 15 GHz to measure the spectral bandwidth and a Coherent wavemeter to measure the center wavelength to a precision of 0.001 nm. Figure 3 shows the measured spectral bandwidth of our ECDL output as a function of injection current and cavity length. The injection current measurements were taken at 0.6 A (slightly above the threshold), 1.2 A, and 2.0 A (the BAL maximum current limit) at a wavelength near 790 nm. The average spectral bandwidth of our ECDL stayed approximately constant at about 5 GHz with increasing injection current. Typically, when the injection current increases, longitudinal and transverse mode competition increases as the higher current density favors multimode excitation. This tends to degrade the quality of the beam and enlarge the spectral bandwidth.[16] This demonstrates the ability of the lens transformation system within our external cavity to suppress the BALs intrinsic lasing modes and emit narrow-band output by dramatically improving the beam quality. Controlling these parameters is essential in producing an ECDL that is reliable over its entire operating current range. Figure 3 also shows the bandwidth

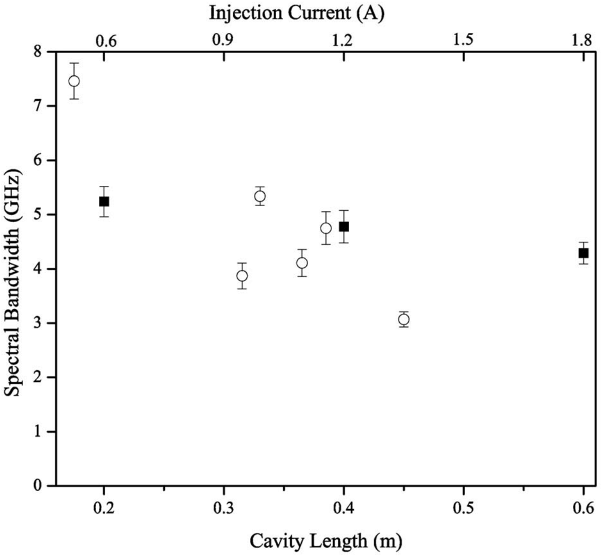

FIG. 3. The average spectral bandwidth as a function of injection current (solid squares) and cavity length (open circles) with the BAL coupled to an external cavity at a center wavelength near 790 nm.

measurements versus cavity lengths. The bandwidth measurements tends to decrease with increasing cavity length as expected. The insensitivity of the bandwidth to injection current, coupled with a decreasing bandwidth as the cavity length is increased, indicates that the external cavity has more direct control over the BAL.

Figure 4 shows M^2 values for the free-running and external cavity BAL in a single-mode operation as a function of increasing injection current at 790 nm. The error bars show one standard deviation. The M^2 values do not significantly increase with increasing injection current and are averaged to 1.3 ± 0.2 for the external cavity BAL, and 23.5 ± 2.3 for the free-running BAL. This indicates that our setup significantly enhanced the beam quality of the external cavity BAL. Figures 3 and 4 show that the ECDL output beam quality does not degrade with increasing injection current and, thus, the bandwidth remain stable. This correlation is important and further demonstrates the tie between spatial beam quality and spectral beam quality that has been shown in previous work.[10,16,17]

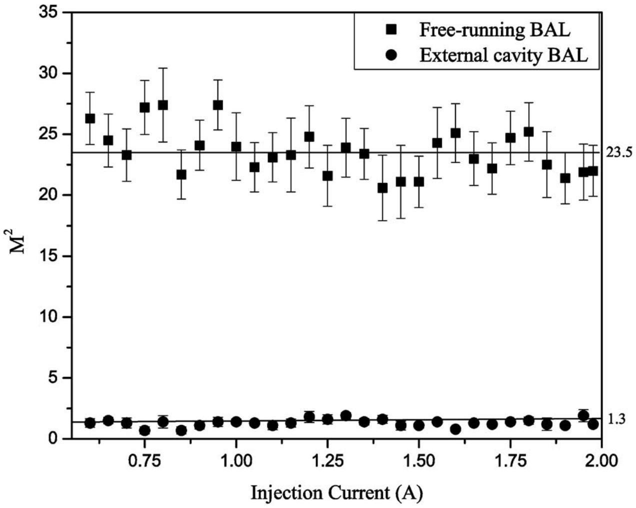

FIG. 4. Measured M^2 values as a function of injection current for a free-running BAL (solid squares) and for an externally coupled BAL (solid circles).

In conclusion, we have demonstrated that the spatial beam quality M^2 of a freely running BAL was decreased from an average value of 23.5 ± 2.3 to an average value of 1.3 ± 0.2 when optically coupled to an external cavity in a single-mode operation and did not degrade as the injection current increased. The beam quality of the dual-mode operation was typically around 8.3. Implementing a precision three-axis lens and three-axis combined lens-laser transformation systems to collimate the output from a 2 W broad-area laser significantly improved the divergence of the coupled beam. As the less divergent beam was more effectively coupled back into the BAL, the external cavity gained more control over the mode structure of the feedback, which then led to a narrowed bandwidth of ~5 GHz. Commercially available high-power ECDLs that exhibit diffraction-limited behavior utilize tapered broad-area amplifiers that combine the single spatial mode operation of low power index-guided lasers with the gain amplification characteristic of BALs. This ultimately limits the power of such devices. Tapered amplifiers are available by themselves and are comparable in expense to BALs. Although we have not tested these in our ECDL, such lasers are expected to perform well in our system without the problems imposed by multimode behavior. Demonstrating that improving beam quality and better external control of BAL output using off-the-shelf lasers, optomechanics, and cavity optics provides a good alternative to commercial designs that are often difficult to reconfigure, especially if BALs of higher output power are desired. We are continuing to improve upon the design to further improve beam quality and external cavity control for better single mode tunability. This level of control is important and has promising scientific applications.

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