External resonator design for high-power laser diodes that yields 400 mW of TEM$_{00}$ power

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Normal diode lasers with average output powers of 1 W or more exhibit bad beam quality and therefore cannot be applied for high-precision applications or nonlinear optics. Therefore an external output coupling mirror was used in our experiments. Diffraction-limited operation was achieved, which yielded 400 mW of power and a factor-of-12 improvement in brightness. With this resonator type 1.1 W of average output power was also obtained, with a beam propagation factor of 2.6 in the slow axis; fast axis emission is always diffraction limited. © 2002 Optical Society of America

The setup of the resonator, as illustrated in Fig. 1, is designed off axis. This means that lenses and a highly reflecting mirror are aligned at an angle of approximately $\alpha_{\text{feedback}} = \alpha_{N+2}$ in the direction of the horizontal axis with respect to the surface normal of the laser. Optionally, one can use a resonator internal aperture close to the feedback mirror to enhance further the mode selectivity of the setup. The laser light is then extracted at the angle $\alpha_{\text{extract}} = -\alpha_{\text{feedback}}$. A resonator external aperture separates the central emission lobe from its sidelobes. Both reported beam the optical axis. Emission angle $\alpha$ of the highest intensity scales approximately with order $n$ of the mode as $\alpha_n = \frac{\pi}{2D} \left(\frac{\lambda}{2D}\right)$, where $D$ is the full width of the emitting gain-guided structure.

Theory furthermore predicts that for a gain-guided array of $N$ lasers the resonator mode with $n = N$ will have the highest gain. However, for $n = N$ the mutual coupling of neighboring modes is quite large. Correspondingly, a trade-off needs to be made to get low modal operation with reasonable gain. Thus we operate the laser slightly above the $n = N$ geometry because we make the final optimization to get the highest beam quality, the highest optical power, or the highest brightness by choosing a suitable angle.

In contrast to previously proposed setups, our feedback branch of the resonator is designed as a stable resonator with a beam waist inside the chip adapted to the width of the gain guided structure.

The two key ideas of our concept are on the one hand to build two crossed cylindrical resonators for the slow and the fast axes, separately, and on the other hand to make the slow axis resonator a stable mode-selective resonator.

Fig. 1. Schematic of an external resonator for a diode laser along its slow axis. HR, high reflection.

It is well known that gain-guided diode lasers possess a set of (approximated) resonator modes, which have their highest intensity in a direction off the optical axis. Emission angle $\alpha$ of the highest intensity scales approximately with order $n$ of the mode as $\alpha_n = \frac{\pi}{2D} \left(\frac{\lambda}{2D}\right)$, where $D$ is the full width of the emitting gain-guided structure.

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The large laser cavities of standard broad-area diode lasers are not sufficiently mode selective to produce beam qualities in the slow axis of $M^2 = 20–100$; thus the brightness is $20–100$ times less than it would be for diffraction-limited beams of the same power. To overcome the limitations in brightness of today’s semiconductor lasers, several approaches have been proposed. Ridge lasers, which guarantee a transverse single mode, have been reported to yield output powers in excess of 500 mW at 980 nm. For yet higher powers, in excess of 2 W, master-oscillator power amplifiers with tapered semiconductor structures have been developed.

To cover the power range from several hundred milliwatts to >1 W and at the same time dispense with the need for costly optical insulation between master oscillator and amplifier, we look to the use of diode lasers in external resonators. Most diode lasers have in common that they appear to fail in their transverse mode selectivity for high output powers that are well above threshold. Therefore we developed an external resonator design, which we have shown can operate even at seven times threshold. With this laser we achieved diffraction-limited operation, which resulted in 12-fold improved brightness and an average output power of 0.4 W. This diode laser also provided 1-W average output power, with a beam propagation factor of 2.6 in the slow axis; fast axis emission is always diffraction limited. © 2002 Optical Society of America

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quality and power are measured outside the whole laser setup.

Owing to the strong astigmatism of semiconductor lasers, the external resonator is designed as two crossed cylindrical resonators. For the fast axis we use an aspherical fast-axis collimator (FAC) of 0.9-mm focal length with a N.A. of 0.8; thus the fast-axis aperture is imaged onto itself. Along the slow axis the resonator consists of two lenses selected to define the desired waist. The beam qualities reported here always refer to the slow axis only. The beam quality along the fast axis is assumed to be diffraction limited to within the design restriction of the FAC.

The diode lasers that we employed have a design wavelength of 940 nm and an active zone of 200-μm width with a gain-guiding contact every 10 μm. When they are operated off the shelf they exhibit a laser threshold of typically slightly below 500 mA and a differential efficiency of close to 1 W/A. Our lasers, however, have an antireflective coating on the outcoupling facet.

After careful alignment of the two crossed resonators a drastic improvement in beam quality compared with that of a free-running semiconductor laser of the same kind was achieved. It turned out that, in particular, the ability to handle all five degrees of freedom of the FAC was crucial for safe operation.

In a first setup we optimized beam quality. Refer to Fig. 1; focal length f_{slow} was 60 mm and the laser resonator length was 110 mm. A stable fundamental mode radius w_0 of 70 μm inside the diode resulted that was capable of using approximately half of the inversion generated in the rectangular pump profile. Mode aperture 2 was selected for stable operation with respect to the desired beam quality. Aperture 1 was used to block light other than the fundamental and is considered part of the laser. The power behind the laser, i.e., without further apertures, was 400 mW for the diffraction-limited light for a driving current of 2.5 A, which is approximately five times the threshold value. The beam quality can be deduced from the beam caustic behind a 100-mm lens, as plotted in Fig. 2. We measured the curve with a moving-slit technique to determine the second moments of the intensity. A fit of a hyperbola onto the data yields M^2 = 0.15 ± 0.06. Figure 3 shows the intensity distribution in the waist of the caustic of Fig. 2 and a Gaussian fit to the data set.

Deviations between the measured (solid) curve and the Gaussian (dashed curve) fit are very small, in agreement with the evaluated good beam quality. The fit is practically indistinguishable from the data, except for the presence of two small tails, which carry only ~1.2% and ~1.5% of the total detected power.

In a second setup we optimized this laser concept for higher output power. With a different laser from the same wafer and an f_{slow} = 100 mm lens we obtained 1.1 W of power for a current of 5 A, i.e., seven times the threshold current. The stable waist radius was 100 μm, so the gain profile acted as an additional aperture with an approximated angular emission of a hard slit. Aperture 2 could then be dispensed with, and aperture 1 was adjusted to let the central lobe of the emission pass. The caustic and the field in the waist behind an f = 75 mm lens can be seen in Figs. 4 and 5, respectively. A hyperbolic fit of Fig. 4 yields a beam quality of M^2 = 2.57 ± 0.08.

The electro-optical efficiencies for the two setups were \( \eta_{400} = 0.4 \text{ W}/4.2 \text{ W} = 9.5\% \) and \( \eta_{1000} = 1.1 \text{ W}/6.27 \text{ W} = 17.6\% \). The decrease in efficiency compared with that of the off-the-shelf diodes is caused by the asymmetric setup in which one lobe serves for feedback and by the geometrical mismatch between gain profile and mode profile. It needs to be compared, though, with the increases in beam quality by factors of 53 and 21, respectively.

In conclusion, we have described the scheme of an external resonator for diode lasers that allows for beam-quality improvement up to the diffraction limit and thus for an increase in brightness of more than factors of 10. Although the limits of this scheme have not yet been established, it may be possible to develop diffraction-limited diode lasers with output powers in the range of a few watts if the semiconductor structures are optimized for operation inside external cavities.

![Fig. 2](image-url)  
**Fig. 2.** Beam caustic along the slow axis behind a 75-mm lens when the external resonator was optimized for beam quality. For an output power of 400 mW at a wavelength of 940 nm a propagation factor \( M^2 = 1.03 \pm 0.06 \) was obtained.

![Fig. 3](image-url)  
**Fig. 3.** Intensity distribution (solid curve) of the radiated 400 mW of power as found in the waist of the beam in Fig. 2. For comparison, a Gaussian distribution (dashed curve) was fitted to the data.
Fig. 4. Beam caustic along the slow axis behind a 75-mm lens when the external resonator was optimized for optical power. For an output of 1.1 W at a wavelength of 940 nm a propagation factor $M^2 = 2.57 \pm 0.08$ was obtained.

Fig. 5. Intensity distribution (solid curve) of the radiated 1.1 W of power as found in the waist of the beam in Fig. 4. For comparison, a Gaussian distribution (dashed curve) was fitted to the data.

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