Tunable high-power narrow-linewidth semiconductor laser based on an external-cavity tapered amplifier

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Abstract: A high-power narrow-linewidth laser system based on a tapered semiconductor optical amplifier in external cavity is demonstrated. The external cavity laser system uses a new tapered amplifier with a super-large optical-cavity (SLOC) design that leads to improved performance of the external cavity diode lasers. The laser system is tunable over a 29 nm range centered at 802 nm. As high as 1.95 W output power is obtained at 803.84 nm, and an output power above 1.5 W is achieved from 793 to 812 nm at operating current of 3.0 A. The emission linewidth is below 0.004 nm and the beam quality factor M^2 is below 1.3 over the 29 nm tunable range. As an example of application, the laser system is used as a pump source for the generation of 405 nm blue light by single-pass frequency doubling in a periodically poled $KTiOPO_4$. An output power of 24 mW at 405 nm, corresponding to a conversion efficiency of 0.83%/W is attained.

OCIS codes: (140.2020) Diode lasers; (140.5960) Semiconductor lasers; (190.2620) Frequency conversion

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1. Introduction

High-power, narrow linewidth and diffraction-limited semiconductor lasers are of interest for applications such as nonlinear frequency conversion, solid-state laser pumping, and free-space optical communication. Although broad-area diode lasers can produce large amounts of optical power and are attractive due to their compactness, long lifetimes and relatively low price, these devices suffer from poor spatial and temporal coherence due to their broad emitter aperture in the slow axis, typically from several tens to a few hundred microns. Several techniques, such as injection locking[1,2] with an external single-mode master laser and various external cavities with frequency-selective elements[3,4] have been developed to improve the beam quality and temporal coherence.

High-power, diffraction-limited semiconductor lasers can be realized by the introduction of the technology of lasers with a tapered gain-region.[5] Narrow linewidth high-power emission has been obtained both from monolithically integrated master-oscillator power-amplifiers (MOPA) by forming Bragg gratings in the semiconductor material[6,7], and from the separated MOPA in which the tapered amplifier is seeded either by a single mode semiconductor laser[8] or solid-state laser.[9] Narrow linewidth high-power (around 1 W) emission was also obtained from the tapered oscillator based on a fiber Bragg grating external cavity.[10,11] Recently, a single frequency, 1.6 W tapered diode laser system using phase-conjugated feedback at 785 nm was demonstrated.[12] Based on a bulk diffraction grating external cavity, diffraction-limited, high-power (~1 W) narrow linewidth tapered oscillators were demonstrated, and the emission wavelength was tunable over a 35 nm span centered at 852 nm[13], a 20 nm range centered at 970 nm[14] and a 17 nm range centered at 783 nm.[15]

In this paper, we achieve tunable high-power, narrow linewidth emission from a tapered oscillator based on a bulk diffraction grating external cavity. The laser system is tunable over a range of 29 nm centered at 802 nm with as high as 1.95 W output power and the output power exceeds 1.5 W over a range of 19 nm. The spectral width of the output beam is below 0.004 nm with a beam quality factor M^2 below 1.3 over the tuning range of 29 nm. Using this laser system as a pumping source, 24 mW blue light at 405 nm is obtained by single-pass frequency doubling in a periodically poled $KTiOPO_4$ (PPKTP).

2. Tapered diode laser fabrication and characterization

For use in external cavities the tapered laser diode structure was designed. Especially, the vertical divergence should be small to ensure efficient coupling of the beam in and out of the tapered diode. To avoid damage by the back-coupled light the near field width has to be large enough and well confined to the waveguide.

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The 810 nm tapered diode laser we used in our external cavity experiments is based on a super-large optical-cavity (SLOC) structure as described by Knauer *et al.*[16] The structure consists of a GaAsP tensile strained single quantum well (SQW) embedded in a 3µm thick $Al_{0.45}Ga_{0.55}As$ waveguide. The Al-content of the cladding layers is 0.7. The thickness of the p-cladding layers is made as thin as possible to reduce the series resistance and the etching depth for the single mode part of the tapered structure. On the other hand the thickness must be large enough avoiding optical leakage loss higher than about 0.5 cm^{-1} to the contact layer. Higher losses would reduce the overall conversion efficiency and limit the output power and reliability.

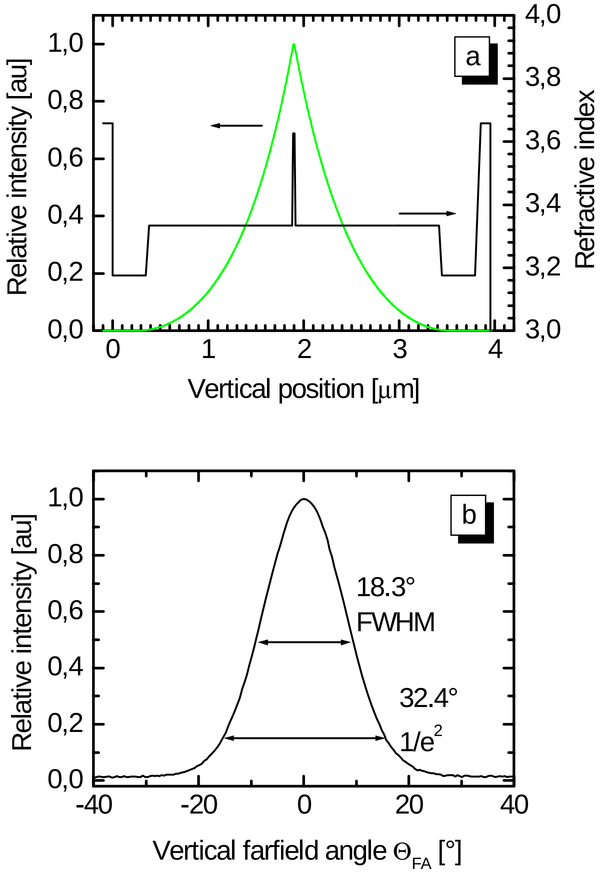

Fig. 1. Vertical beam properties of the SLOC-structure used for the 810 nm tapered amplifier; (a) calculated vertical near field and refractive index, (b) measured vertical far field.

The characteristic electro-optical data measured by length dependence of threshold and slope efficiency show excellent values of $\eta \approx 90\%$ for the internal efficiency, an $\alpha_i < 1$ cm^{-1} for the internal losses and a low transparency current density of $j_{th} = 150$ A/cm^2.[16]

The calculated near field and the refractive index is plotted in Fig. 1(a). The calculated near field width (1/e^2) is 1.8 µm. The measured vertical far field distribution is shown in Fig. 1(b). The vertical beam divergence is as low as 18.3° (FWHM) and 32.4° (1/e^2) including 96% of power, respectively. From these data it can be expected that the coupling losses caused by diffraction are below 1% if a proper aligned lens is used with a numerical aperture

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(N.A.) > 0.5. This is important for the efficient coupling of the beam in and out of the tapered laser.

The tapered devices consist of an index guided ridge-waveguide (RW) structure and a gain guided tapered section. The RW-section was fabricated by dry etching. The width of the ridge is 3 µm. The tapered current window is defined by wet chemical etching of the GaAs contact layer. A Si_3N_4 isolator is deposited for electrical isolation between the semiconductor surface and the p-contact metallization outside of the RW and the tapered regions contact areas. To ensure thermal stability and low optical load at high output power a device length of 4 mm were chosen. More technical details are given by Wenzel *et al*.[5] Within different tested designs for taper angle and ridge waveguide length devices with a 1mm ridge waveguide and a 3mm long tapered section were selected for the external cavity experiments. The taper angle was 4°.

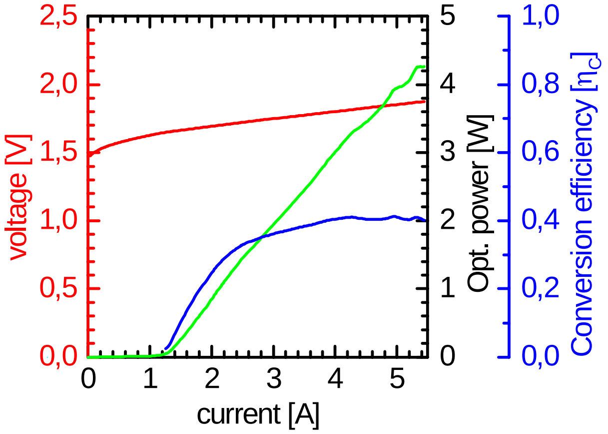

Fig. 2. Power-voltage-current characteristics of 810 nm tapered laser. The device length $L = 4$ mm, length of the ridge waveguide $L_{RW} = 1$ mm, taper angle $\varphi_{TR} = 4°$. The front facet had a reflectivity $R_f = 0.1\%$, the rear facet a $R_r = 94\%$.

For test purposes tapered lasers were fabricated by applying a high reflective coating (94%) to the ridge waveguide side and an antireflective coating (0.1%) to the tapered output side. The chips are mounted p-side down on C-mounts. The power current characteristic is shown in Fig. 2. More than 4 W output power and a wall plug efficiency of 40% was achieved.

For application in the external cavity scheme, see below, another coating was made. On the ridge waveguide side the reflectivity is reduced to below 0.1%, on the tapered output side the reflectivity was chosen to 0.5%. This value seems to be necessary in order to avoid an abrupt increase of the threshold current due to lower values of the external feedback reflectivity in comparison to 90%.

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3. External cavity experiment

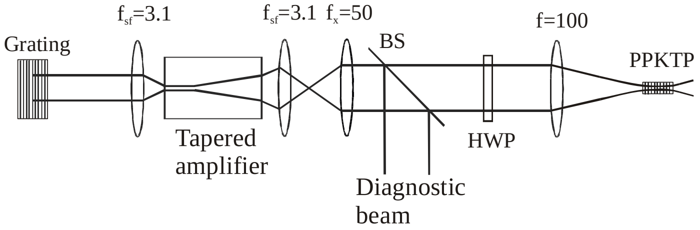

Fig. 3. Experimental set-up of the tapered diode laser system using a bulk diffraction grating external cavity. BS: beam splitter, HWP: half-wave plate, (the units are in mm).

The external cavity configuration employed is depicted in Fig. 3. An aspheric lens of 3.1- mm focal length with a N.A. of 0.68 is used to collimate the beam from the back facet in both fast and slow axes. The bulk grating is ruled with 1200 grooves/mm and has a blaze wavelength of 750 nm. The grating is mounted in the Littrow configuration[13-15] and oriented with the lines in the grating parallel to the active region of the amplifier. The laser cavity is formed between the diffraction grating and the output facet of the tapered amplifier. Another aspheric lens of 3.1-mm focal length with a N.A. of 0.68 is used to collimate the beam from the output facet in the fast axis. Together with a cylindrical lens of 50-mm focal length, these two lenses collimate the output beam in the slow axis and compensate the astigmatism simultaneously. All the lenses are antireflection coated for the near-infrared wavelengths. All optical components are mounted on a temperature-stabilized baseplate to increase the stability of the laser output. A beam splitter behind the cylindrical lens is used to reflect part of the output beam of the tapered diode laser system as the diagnostic beam; both the optical spectrum and the beam quality factor M^2 are measured in this beam.

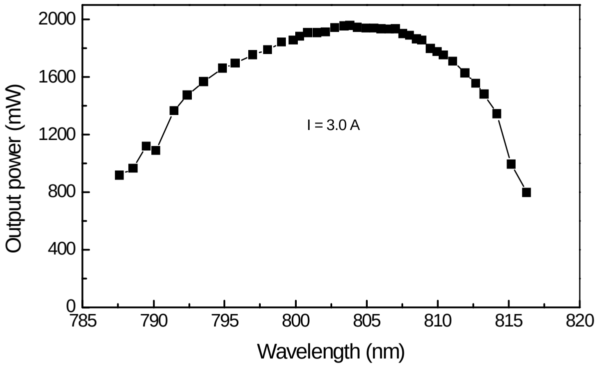

Fig. 4. Tuning curve of the tapered diode laser system at an operating current of 3.0 A.

The laser is TM-polarized, i.e. linearly polarized along the fast axis and perpendicular to the grating rulings, thus the higher *s*-polarization diffraction efficiency of the grating is utilized.[14,15] The temperature of the amplifier is controlled with a Peltier element and it is operated at 25°C in the experiment. The emission wavelength of the laser system is tuned by rotating the diffraction grating. The output power is measured behind the aspherical lens. The output power at different wavelengths is shown in Fig. 4 at an operating current of 3.0 A. The laser system is tuned over a 29 nm range centered at 802 nm. The output power is above 800 mW over the 29 nm range. As high as 1.95 W output power is obtained at 803.84 nm, and an output power above 1.5 W is achieved from 793 to 812 nm. The light-current characteristic of the laser system is measured. The threshold current is around 1.29 A. The slope efficiency is

1.11 W/A, corresponding to a differential quantum efficiency of 72.0%; both values are much higher compared with previous results.[11-15] Compared with the results shown in Fig. 2, the threshold current and slope efficiency of the external cavity laser system are almost the same as that of the tapered lasers. This means the loss caused by the external cavity is negligible and this is important to obtain high power from the external cavity laser.

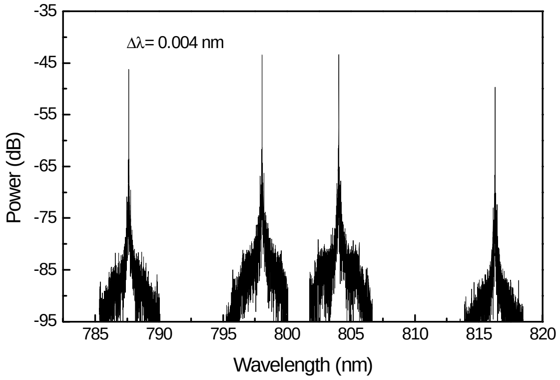

Fig. 5. The optical spectrum of the output beam from the tapered diode laser system at four different wavelengths at an operating current of 3.0 A.

The optical spectrum characteristic of the output beam from the tapered diode laser system is measured using a spectrum analyzer (Advantest Corp. Q8347) at the wavelengths of interest. The typical results measured at an operating current of 3.0 A are shown in Fig. 5. Narrow linewidth (below 0.004 nm) operation over the 29 nm span is achieved. It shows a sidemode suppression greater than 17 dB, and the amplified spontaneous emission intensity is more than 40 dB suppressed over the tunable range.

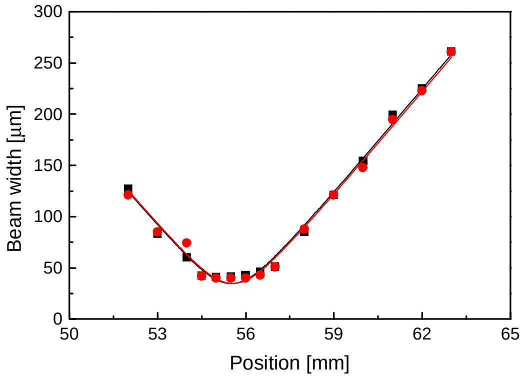

Fig. 6. Beam width measurement of the output beam from the tapered diode laser system for the slow axis at the wavelength of 798.14 nm (circles and red curve) and 804.04 nm (squares and black curve), at the operating current of 3.0 A. The curves represent hyperbola fits to the data.

The beam quality of the output beam along the slow axis is estimated by measuring the beam quality factor, M^2, for the external cavity laser system. A spherical lens with a 100-mm focal length is used to focus the diagnostic beam. Then the beam width, W (1/e^2), is measured at various recorded positions along the optical axis - on both sides of the beam waist. The value of M^2 is obtained by fitting the measured data with a hyperbola. Figure 6 shows the

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measured beam widths and the fitted curves at 798.14 nm and 804.04 nm at injected currents of 3.0 A. The estimated M^2 values are 1.10 ± 0.10 for both wavelengths. The M^2 value is below 1.3 over the 29 nm tuneable range. This is important for frequency doubling.

4. Pump source for blue light generation by frequency doubling

As an example of application, the laser system was used as a pump source for 405 nm blue light generation by single-pass frequency doubling in a PPKTP crystal. The polarization of the output from the external-cavity tapered diode laser system is rotated to parallel to the junction of the tapered amplifier by a $\lambda/2$-plate in order to use the nonlinear coefficient d_{33} of the crystal. The beam is focused into the nonlinear crystal with a double-convex lens of 100-mm focal length. Both the $\lambda/2$-plate and the double-convex lens are antireflection coated for the fundamental beam. The size of the focus is $w_f \times w_s$ = 42.5 μm x 40.8 μm, where w_f and w_s are the beam waists (diameters at $1/e^2$) in the fast and slow axes, respectively. The power available for pumping the nonlinear crystal is 1.7 W. The PPKTP crystal is 10 mm long, antireflection coated on both surfaces for 810/405 nm, with a grating period of Λ = 3.4 μm and an aperture of 1 x 2 mm^2. A dichroic beam splitter separates the fundamental beam from the second harmonic output.

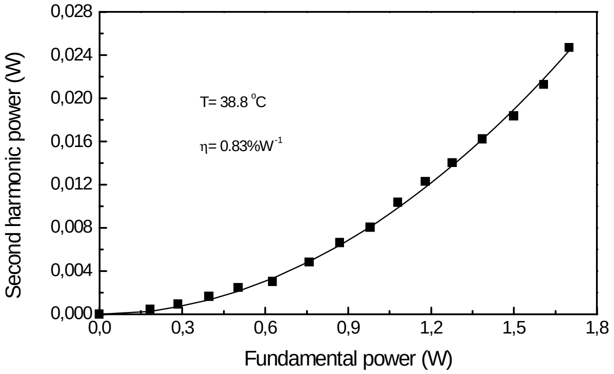

Fig. 7. Second harmonic power as a function of fundamental power. The squares are measured data; the curve is a quadratic fitting.

The wavelength of the fundamental beam is tuned to 809.42 nm, and the temperature of the crystal for quasi-phase-matching is 38.8 °C. Figure 7 shows the measured second harmonic power as a function of fundamental power. The curve represents a quadratic fitting. A maximum of 24 mW is obtained at 404.7 nm corresponding to a conversion efficiency of η = 0.83%W^{-1}. The loss of the dichroic filter is not taken into account. The theoretical maximum conversion efficiency of the crystal is 2.7%W^{-1}.[17] The discrepancy between the experimental conversion efficiency and the calculated maximum efficiency is mainly due to the discrepancy between the effective nonlinear interaction length and the physical length of the crystal.[17] The beam quality factor M^2 of the blue beam is measured to be 1.04 in both directions.

5. Conclusion

In summary, a 1.95W, narrow linewidth and diffraction-limited semiconductor laser system based on a tapered amplifier in bulk diffraction grating external cavity is demonstrated. The tapered amplifier is based on a new SLOC design. The laser system is tuned over a 29 nm range centered at 802 nm, and as high as 1.95 W output power is attained. The spectral linewidth is below 0.004 nm and the beam quality factor M^2 is less than 1.3 over the 29 nm

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tunable range. As an example of application of this tunable laser system, it is used as a pump source for the generation of blue light at 405 nm by single-pass second harmonic generation in a PPKTP crystal. An output power of 24 mW blue light is attained.

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