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Tunable high-power narrow-spectrum external-cavity diode laser at 675 nm as a pump source for UV generation

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High-power narrow-spectrum diode laser systems based on tapered gain media in an external cavity are demonstrated at 675 nm. Two 2 mm long amplifiers are used, one with a 500 μm long ridge-waveguide section (device A), the other with a 750 μm long ridge-waveguide section (device B). Laser system A based on device A is tunable from 663 to 684 nm with output power higher than 0.55 W in the tuning range; as high as 1.25 W output power is obtained at 675.34 nm. The emission spectral bandwidth is less than 0.05 nm throughout the tuning range, and the beam quality factor M^2 is 2.07 at an output power of 1.0 W. Laser system B based on device B is tunable from 666 to 685 nm. As high as 1.05 W output power is obtained around 675.67 nm. The emission spectral bandwidth is less than 0.07 nm throughout the tuning range, and the beam quality factor M^2 is 1.13 at an output power of 0.93 W. Laser system B is used as a pump source for the generation of 337.6 nm UV light by single-pass frequency doubling in a bismuth triborate (BIBO) crystal. An output power of 109 μW UV light, corresponding to a conversion efficiency of 0.026% W^{-1}, is attained.   © 2010 Optical Society of America

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1. Introduction

Diffraction-limited high-power narrow-spectrum red diode lasers are attractive for many applications, such as photodynamic therapy, laser display, and as a pump source to generate UV light by second harmonic generation (SHG). High-power, diffraction-limited diode lasers can be realized by the technology of lasers with a tapered gain region [1,2]. The tapered laser devices can be used in applications where narrow spectrum is not needed such as photodynamic therapy, but for other applications such as a pump source for UV light generation, the spectral quality of these devices has to be improved.

In order to improve the spectral quality of a tapered laser, different techniques are applied, such as a monolithically integrated master oscillator power amplifier by forming Bragg gratings in the semiconductor material [3,4], injection locking to an external single-mode laser [5,6], and different external-cavity feedback techniques [7–12]. Up to 1 W output power at 668 nm from a Fabry–Perot tapered diode laser was obtained with a beam quality factor of 1.7, and the spectral width was smaller than 0.2 nm [13]. Around 670 nm, tunable narrow-linewidth diffraction-limited output was also achieved from an injection-locking tapered diode laser system seeded with a single-mode external-cavity diode laser [14]; the output power

was up to 970 mW. A 670 nm micro-external-cavity tapered diode laser system was demonstrated with a reflecting volume Bragg grating as a feedback element; in continuous wave (CW) mode, more than 0.5 W output power was obtained, and in pulse mode, 5 W peak power was obtained with a beam quality factor of 10 and a spectral width below 150 pm [11]. External-cavity feedback based on a bulk diffraction grating in the Littrow configuration is a useful technique to achieve a tunable narrow-spectrum, high-power, diffraction-limited tapered diode laser system [7,10]; we have demonstrated such a tapered diode laser system around 668 nm with output power up to 1.38 W; a beam quality factor of 2.0 was obtained with an output power of 1.27 W [15].

UV light sources are interesting in many fields such as biophotonics/chemical photonics, material processing, and optical data storage. Although diode lasers based on AlGaN have been demonstrated around 340 nm in pulse mode recently [16,17], frequency doubling through a nonlinear crystal is still an efficient method to generate CW light in this wavelength range [18–22]. UV light around 340 nm has been achieved by single-pass SHG in bulk periodically poled $LiTaO_3$ [18,19] and $MgO:LiNbO_3$ [21] crystals and also achieved in a periodically poled $MgO:LiNbO_3$ ridge waveguide [22], but so far these periodically poled devices are not commercially available, and no UV light shorter than 340 nm has been demonstrated with these first-order periodically poled devices.

Here, based on two tapered amplifiers, two 675 nm external-cavity tapered diode laser systems are demonstrated. The maximum output power of both laser systems is more than 1.0 W; laser system A is tunable from 663 to 684 nm with an emission spectral bandwidth less than 0.05 nm, laser system B is tunable from 666 to 685 nm with an emission spectral bandwidth less than 0.07 nm. The beam quality factor M^2 is 2.07 with the output power of 1.0 W for laser system A, and 1.13 with an output power of 0.93 W for laser system B. Based on the laser system B and a commercially available BIBO crystal, an output power of 109 μW UV light at 337.6 nm has been obtained by single-pass frequency doubling.

2. External-Cavity Tapered Diode Laser Systems

The laser structure of the red tapered amplifiers used in the experiment was grown using metal organic vapor phase epitaxy. As an active layer, a 5 nm thick compressively strained single InGaP quantum well was used, which was embedded in AlGaInP waveguide layers. On the n side, the cladding layer was made of AlInP, while the p side cladding layer was made of AlGaAs. The epitaxial structure of these tapered amplifiers was the same as that reported previously [13]. Both tapered gain devices had a total length of 2 mm. For device A, it consisted of a 0.5 mm long index-guided ridge-waveguide section and a 1.5 mm long flared section; for device B, it consisted of a 0.75 mm long index-guided ridge-waveguide sec-

tion and a 1.25 mm long flared section. The width of the ridge-waveguide section was 7.5 μm for both devices. The tapered angle was 4° for both devices, and the output apertures for device A and B were 112 and 95 μm, respectively. The rear facets of the tapered devices were antireflection-coated with a reflectivity of 5×10^{-4}, while the front facet of the devices had a reflectivity of 1%.

The external-cavity configuration is the same for both devices as depicted in Fig. 1. The detailed description on the external-cavity tapered diode laser system can be found in [15]. An aspherical lens is used to collimate the beam from the back facet. A bulk grating is mounted in the Littrow configuration, and the laser cavity is formed between the diffraction grating and the front facet of the tapered amplifier. A second aspherical lens and a cylindrical lens are used to collimate the beam from the output facet. All the lenses are antireflection-coated for the red wavelength. 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, where the spectral bandwidth and the beam quality factor M^2 are measured. The output power of the laser system is measured behind the second aspherical lens.

The lasers are TE-polarized, i.e., linearly polarized along the slow axis. The temperature of the amplifiers is controlled with a Peltier element, and they are operated at 20 °C in the experiment. The emission wavelength of the laser systems is tuned by rotating the diffraction grating.

The power-current characteristics for these two laser systems are shown in Fig. 2. For laser system A, the maximum output power is obtained at the wavelength of 675.34 nm, the threshold current is around 0.7 A, the slope efficiency is 1.03 W/A, the roll-over takes place around 1.7 A, and an output power of 1.25 W is achieved with an injected current of 2.0 A. For laser system B, the output power is measured at the wavelength of 675.67 nm, the threshold current of the laser system is around 0.6 A, the slope efficiency is 0.99 W/A, the roll-over takes place around 1.4 A, an output power of 1.05 W is obtained with the operating current of 1.8 A, and the output power decreases with higher injected current.

The output power at different wavelengths for these two laser systems is shown in Fig. 3. For laser system A, at an operating current of 2.0 A, a maximum output power of 1250 mW is obtained at the
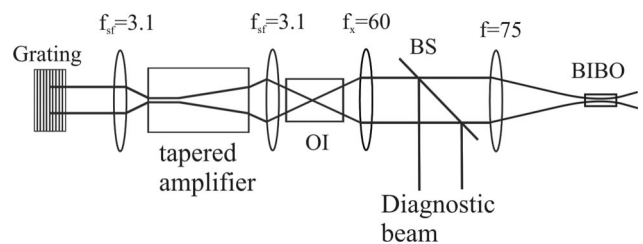

Fig. 1. Experimental setup of the external-cavity tapered diode laser system for SHG. BS, beam splitter; OI, optical isolator. Units are in millimeters.
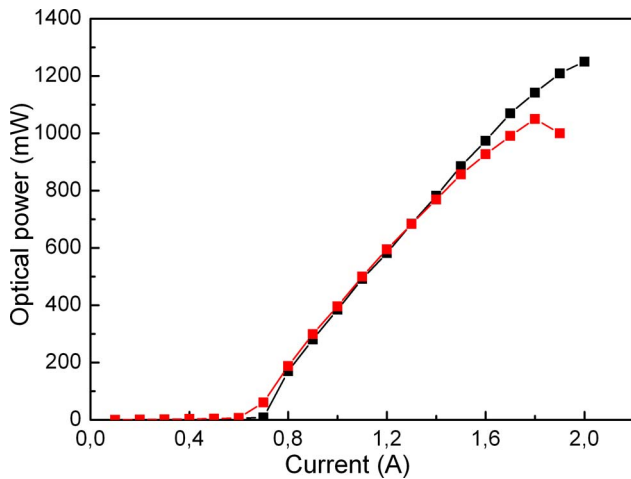
Fig. 2. (Color online) Power-current characteristics for tapered diode laser systems A (squares) and B (circles).

wavelength of 675.34 nm. The output power is higher than 550 mW in the tuning range from 663 to 684 nm. For laser system B, a maximum output power of 1055 mW is obtained at the wavelength of 675.67 nm; the laser system is tunable from 666 to 685 nm with output power higher than 460 mW.

For the external-cavity diode laser systems, the beam quality of the output beam along the fast axis is assumed to be diffraction-limited because of the waveguide structure of the tapered devices. The beam quality of the output beam along the slow axis is determined by measuring the beam quality factor M^2. A spherical lens with a 65 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 4(a) shows the measured beam widths and the fitted curves for laser system A at output powers of 385 and 1000 mW, where the estimated M^2 values are

1.28 ± 0.02 and 2.07 ± 0.02, respectively. Figure 4(b) shows the measured beam widths and the fitted curves for laser system B with the output power of 390 and 930 mW. The estimated M^2 values are 1.20 ± 0.02 and 1.13 ± 0.02 at output powers of 390 and 930 mW, respectively. For clarity, we have shifted the spatial position of the curves in the figures. In the experiments, the waists of the output beam with different output powers are located almost at the same position. This indicates that the change in astigmatism with different injection currents is negligible.

The optical spectrum characteristic of the output beam from the tapered diode laser systems is measured using a spectrum analyzer (Advantest Corporation Q8347). A typical result measured for laser system B at 675.04 nm with the output power of 930 mW is shown in Fig. 5. The figure shows that the tapered diode laser system is operated in multiple longitudinal modes. The spectral bandwidth
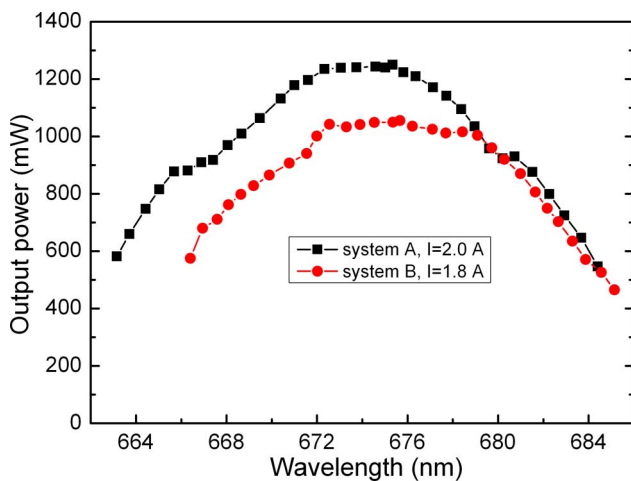

Fig. 3. (Color online) Tuning curves of the tapered diode laser system A (squares) at an operating current of 2.0 A and system B (circles) at an operating current of 1.8 A.
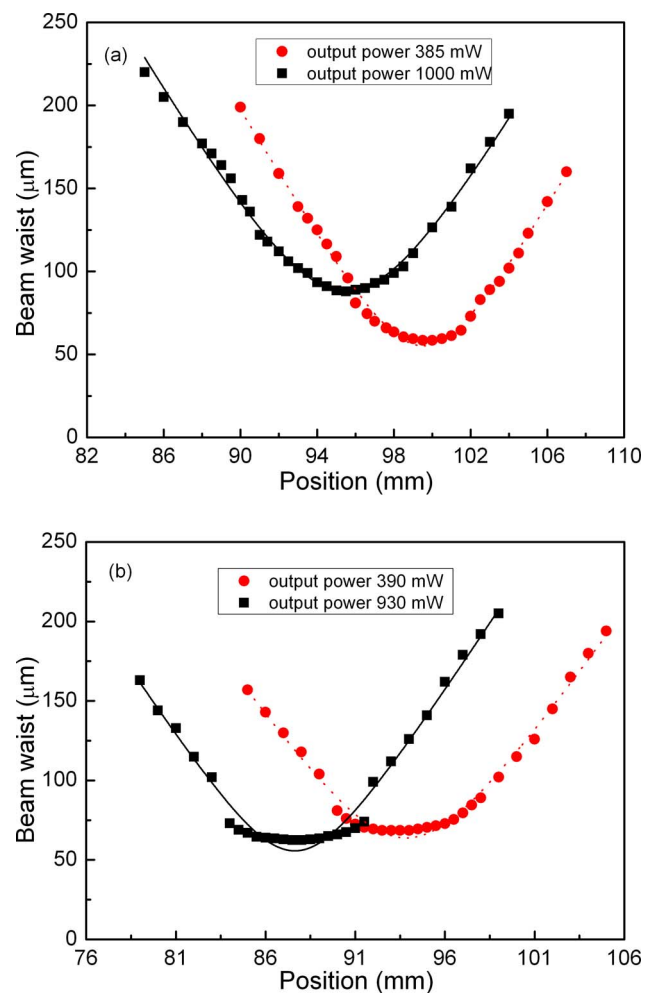
Fig. 4. (Color online) Beam width of the output beam for the slow axis from (a) tapered diode laser system A with the output power of 385 mW (circles and dotted curve) and 1000 mW (squares and solid curve), and (b) tapered diode laser system B with output power of 390 mW (circles and dotted curve) and 930 mW (squares and solid curve). The curves represent hyperbola fits to the measured data.
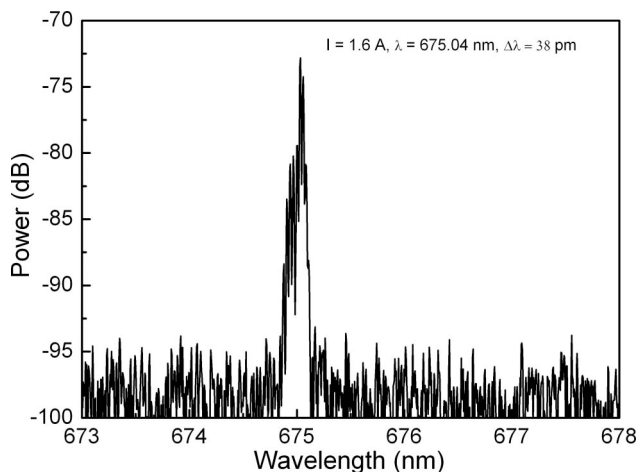
Fig. 5. Optical spectrum of the output beam from tapered diode laser system B with the output power of 930 mW.

(FWHM) is 0.038 nm (the resolution of the spectrum analyzer is 3 pm), and the amplified spontaneous emission intensity is more than 20 dB suppressed. We find the spectral bandwidths of the output beams for laser systems A and B are less than 0.05 and 0.07 nm throughout their tunable ranges, respectively.

Two tunable high-power 675 nm diode laser systems based on the tapered amplifiers are demonstrated. The main parameters of these two laser systems are summarized in Table 1; the results of the diode laser system in Ref. [15] are also listed in the table for comparison. Laser system A can produce more output power than laser system B, but the beam quality of laser system B along the slow axis is significantly better than that of laser system A, especially with high output power. The two gain media are from the same wafer, so the different behavior of the two laser systems is originated from the different sizes of the ridge-waveguide section and the tapered section. Laser system A produces higher output power since device A has a longer tapered gain section, but this laser system has worse beam quality due to insufficient filtering of the light in the shorter ridge-waveguide section.

Compared with the results in Ref. [15], much more output power around 675.5 nm is obtained from the laser systems described above, i.e., 1.25 W versus 0.83 W, and the laser system in Ref. [15] cannot reach

wavelengths longer than 676 nm. Furthermore, we compare the results from the two laser systems based on tapered amplifiers with different geometries. This is important for us to choose tapered devices for different applications. Finally, UV light around 337.5 nm will be generated using the laser system developed above as the pump source. The generated CW UV light source will be used as the excitation source for fluorescence diagnostics. Compared with other UV laser sources around 337 nm, such as a CW krypton-ion laser and a pulsed nitrogen laser, the laser system based on a tapered diode laser is far more simple, compact, and easy to operate.

3. UV Light Generation by SHG

A BIBO crystal is used for frequency doubling the 675.2 nm red light to the 337.6 nm UV light due to its relatively high effective nonlinear coefficient. The 10 mm long crystal with an aperture of 4 mm × 4 mm is cut with $\theta = 137.7°$ and $\varphi = 90°$ for type I phase matching (*eeo*) and antireflection coated on both end surfaces for 675/337.5 nm. The spectral bandwidth of both laser systems is narrow enough for frequency doubling through the BIBO crystal (the acceptable bandwidth of this crystal is around 0.2 nm). Laser system B is chosen as the pump source for the frequency doubling experiment due to its better beam quality.

A 30 dB optical isolator is inserted between the aspherical lens and the cylindrical lens in the output beam to avoid feedback from the optical components and the nonlinear crystal. A biconvex lens of 75 mm focal length is used to focus the fundamental beam into the BIBO crystal. The available output power in front of the crystal is 650 mW. The size of the focus $w_s \times w_f$ is around $70 \, \mu m \times 35 \mu m$, where w_s and w_f are the beam waists (diameters at $1/e^2$) in the slow and fast axes, respectively. The elliptical beam is used to reduce the effects of walk-off in the BIBO crystal. The walk-off angle in our crystal is 72.9 mrad, corresponding to a heavy walk-off parameter B of 15.1.
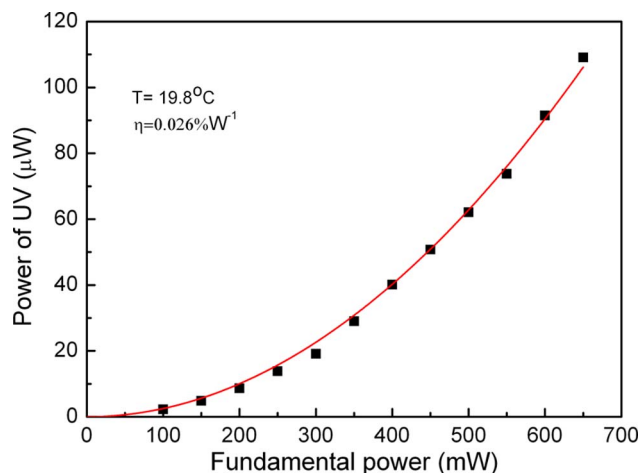
Fig. 6. (Color online) Second harmonic power as a function of fundamental power. The squares are measured data, and the curve is a quadratic fit.

Table 1. Summary of the Main Parameters for Diode Laser Systems A and B and Laser System in Ref. [15]

Parameter	Laser System		
	A	B	Ref. [15]
Max power (W)	1.25	1.05	1.38
Wavelength with max power (nm)	675.34	675.67	668.35
M^2 value	2.07 ± 0.02 (1.0 W)	1.13 ± 0.02 (0.93 W)	2.00 ± 0.01 (1.27 W)
Spectral bandwidth (nm)	<0.05	<0.07	<0.07

The elliptical beam waist was proved to be optimum in the experiments, in good agreement with the theory of frequency doubling using elliptical beams [23]. The slight change in astigmatism with output power will cause the focusing conditions to vary slightly at different power levels. In the experiments, the astigmatism was corrected at maximum pump power. Two dichroic beam splitters separate the fundamental beam from the second harmonic output beam.

The wavelength of the fundamental beam is tuned to 675.16 nm, and the temperature of the crystal is 19.8 °C. Figure 6 shows the measured second harmonic power as a function of fundamental power. The curve represents a quadratic fitting. A maximum of 109 μW UV light is obtained with a fundamental pump power of 650 mW. The conversion efficiency η is $0.026\% \, \text{W}^{-1}$, compared to a conversion efficiency of $0.019\% \, \text{W}^{-1}$ for a single-pass frequency doubling through a 15 mm long LiIO$_3$ bulk crystal [20], and the theoretically calculated value is $0.040\% \, \text{W}^{-1}$ [23].

4. Conclusion

In conclusion, two diode laser systems based on tapered semiconductor optical amplifiers in an external cavity are demonstrated. Both laser systems are tunable in a 20 nm range centered at 675 nm, and the spectral bandwidth of the output beam for both systems is less than 0.07 nm in their tunable ranges. The maximum output power is 1.25 W obtained from system A at the wavelength of 675.3 nm. To our knowledge, this is the highest output power from a tunable diode laser system around 675 nm. The beam quality factor M^2 is 2.07 with the output power of 1.0 W for laser system A, and the M^2 value is 1.13 with the output power of 0.93 W for laser system B. Laser system B is used as the pump source for the generation of UV light by single-pass frequency doubling in a BIBO crystal. An output power of 109 μW UV light at 337.6 nm, corresponding to a conversion efficiency of $0.026\% \, \text{W}^{-1}$, is attained.

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