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Vertical Cavity Surface Emitting Lasers

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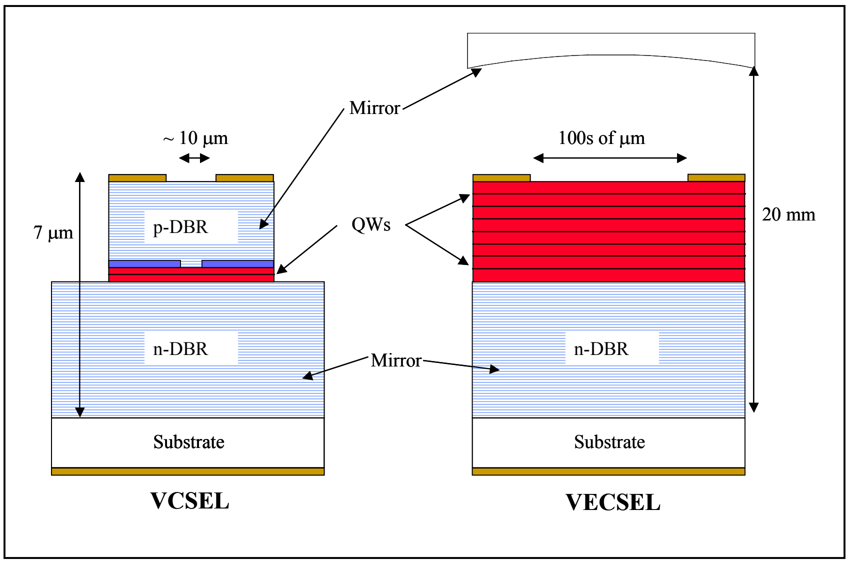
Abstract

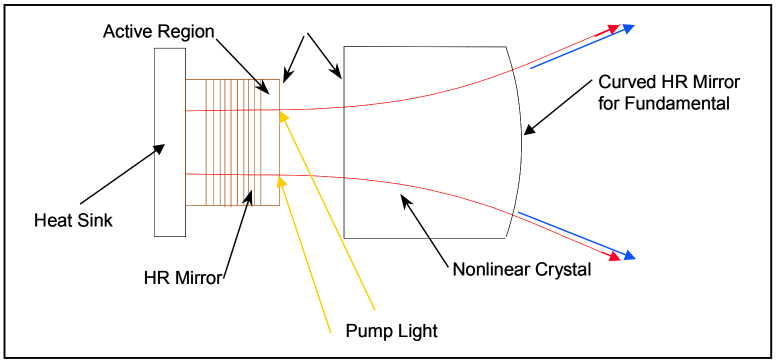
The goal of this project was to increase the power of vertical cavity surface emitting lasers and to convert their wavelength into the blue/ultraviolet and the infrared for sensing applications. We have increased the power to the multi-watt level and have generated several milliwatts of blue light using optical pumping. Electrical pump has been less successful, but we have identified the problems and begun work to overcome them using a bottom emitting design.

Vertical cavity surface emitting lasers (VCSELS) have many attractive properties including narrow line width, adjustable wavelength selected by engineering the semiconductor layer structures, high efficiency, and good beam quality. One shortcoming is their relatively low power of a few milliwatts, a limit imposed by the typically small transverse dimension of a few microns. If the size could be scaled to 100 μm or more, the power should be measured in watts rather than milliwatts. The small size normally used is chosen to maintain a lowest order transverse mode, and to ensure uniformity of the injection current across the gain aperture for good matching of the gain to the transverse mode and thus high efficiency. The challenge in increasing the mode size and power is thus to control the transverse mode, to provide the appropriate pump distribution, and to remove heat from the wafer.

Figure 1 compares a typical VCSEL on the left with a VECSEL (vertical *external* cavity surface emitting laser) on the right. The VCSEL has an aperture of a few μm, and both back and front mirrors are formed by multiplayer stacks of semiconductors with alternating refractive indices, or distributed Bragg reflectors (DBR's). Gain is provided by a few quantum well layers labeled QW's in the figure. An electric current flowing from the front mirror to the back mirror is normally used to pump the quantum wells. A current aperture formed by an insulating oxide layer confines the pump current to a small gain aperture. If the aperture of the VCSEL is expanded, the laser will operate on several transverse modes, resulting in a poor quality beam that cannot be focused tightly. If an external mirror is used in place of the DBR output coupler, the transverse mode can be limited to the lowest order Gaussian mode even for a large gain aperture. For an aperture of about 100 μm diameter this requires that the mirror be a few 10's of mm from the gain wafer. Nonlinear optical crystals can be placed in this space to double the frequency of the laser or to operate as an optical parametric oscillator to convert the laser light to tunable light of redder color.

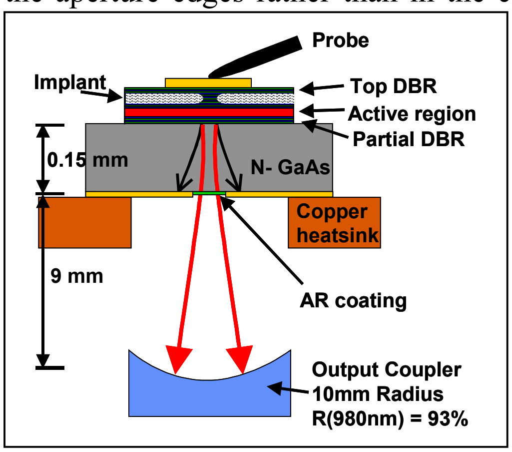


In this project we first tried electrically and optically pumping a VECSEL with an aperture of about 100 μm. The electrically pumped device performed poorly because the pump current distribution, and thus the gain distribution, was a poor match to the lowest order mode. The current was concentrated around the edge of the aperture rather than peaked at the center of the aperture as desired. Optical pumping with a beam well matched to the lasing mode worked well, giving 40% conversion from pump to laser power. In this device we placed a $KNbO_3$ crystal to double the 980 nm lasing light to give about 5 mW of 490 nm blue light. The pump light was provided by an edge emitting diode laser with its beam profile adjusted to match the VECSEL mode profile.



In attempting to scale this device to higher power we found that with larger diameter lasing modes heat removal became a limiting factor. When the wafer temperature becomes too high lasing ceases. For small lasing modes the heat flow is radial as well as longitudinal, but with increasing diameter the flow becomes predominantly longitudinal. The shortest thermal path from the heat deposition is to the front of the wafer, so we placed a sapphire window in contact with the front of the wafer. This allowed us to double the pump power to about 8 W cw with a conversion efficiency of 20%.

An electrically pumped version of this device would be more appealing for most applications, so we turned to improving the current distribution. Adding current spreading layers to the top of the structure helped but the distribution was still peaked at the aperture edges rather than in the center. Taking the light out of the bottom of the wafer was our next effort (the figure at left shows the laser structure). This permits the electrode near the gain zone to completely cover the aperture while the ring electrode is located far away on the opposite side of the substrate. This structure is also attractive because it allows us to extract heat from the top of the wafer near the source of heat. The current distribution with this device is uniform over the aperture, but absorption in the substrate layer limits the laser efficiency. Reducing this absorption is the subject of continuing development.



To summarize, the optically pumped VECSEL works well as a laser in the near IR and, with frequency doubling, in the blue. Heat dissipation limits the power to a few watts. The electrically pumped VECSEL is less developed, with the primary problem being inefficiency due to substrate absorption. The attached papers give more technical details on the optically pumped versions.

APPENDIX A

High power and good beam quality at 980 nm from a vertical external-cavity surface-emitting laser

High power and good beam quality at 980 nm from a vertical external-cavity surface-emitting laser

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We demonstrate 1.5-W continuous-wave output power from a vertical external-cavity surface-emitting laser (VECSEL) based on InGaAs quantum wells as the gain medium. The VECSEL is pumped by the output of a single-bar diode-laser array at 814 nm and produces an optical-to-optical efficiency of 19%. The high output power is made possible by the use of a sapphire window optically contacted to the intracavity semiconductor surface for heat removal. We demonstrate the good beam quality of the VECSEL output by obtaining 1-W output from a single-mode fiber for 1.5 W launched with simple lenses. Pulsed operation produces a maximum peak power of ~4.4 W and maximum average power of ~2 W. © 2002 Optical Society of America

OCIS codes: 140.3480, 140.5960.

1. INTRODUCTION

There is a need for high-power diode lasers with good beam quality, particularly for pumping fiber amplifiers in the telecom industry. The preferred geometry for obtaining good beam quality from a semiconductor laser is to extract light along the growth direction, perpendicular to the planar layers of materials. A well-known example of such a surface-emitting laser is the VCSEL (vertical-cavity surface-emitting laser), which efficiently produces single-transverse-mode output at low powers, milliwatts and less.[1] The beam quality from surface-emitting lasers is far better than that obtained from the more common edge-emitting diode laser, which extracts light perpendicular to the growth direction, parallel to the planar layers of materials. A VCSEL typically consists of a quantum-well gain region sandwiched between two distributed Bragg reflectors (DBRs) with high reflectivity. Electrically pumped VCSELs are restricted to low powers primarily because of the small apertures (~10 μm) that one can uniformly drive current through. In addition it is difficult to obtain single-transverse-mode operation from the short, flat–flat cavities typically used with VCSELs when the current aperture is >10 μm.

Efforts to obtain high powers and single-transverse-mode operation from surface-emitting lasers by replacing the flat-output-coupling DBR with a curved external dielectric mirror were first carried out by Hadley *et al.*[2] They demonstrated pulsed powers of 100 mW from a 100-μm-diameter, electrically pumped InGaAs quantum-well gain region. The curvature of the external output coupler and the cavity length were chosen so that single-transverse-mode operation was obtained. Indeed, the motivation for going to the external output coupler is to maintain single-transverse-mode operation while allowing larger pumping diameters and hence higher output powers. These external-cavity VCSELs have come to be known as vertical *external*-cavity surface-emitting lasers (VECSELs) and have led to the highest powers obtained from surface-emitting lasers. Continuous-wave (cw) power greater than 0.5 W with single-transverse-mode operation was obtained by Kuznetsov *et al.*[3,4] using an optically pumped VECSEL. Peak power exceeding 1 W has been demonstrated in mode-locked operation of an optically pumped VECSEL by use of an intracavity semiconductor saturable absorber for passive mode locking.[5] The first high-power (150-mW) VECSEL based on GaAs quantum wells was recently demonstrated by Holm *et al.*[6] This group has also taken advantage of the rather broad gain bandwidth of quantum wells to demonstrate actively stabilized single-frequency operation with an 8-nm tuning range.[7] The high intracavity powers of VECSELs can be useful for intracavity frequency doubling, which was recently demonstrated by Raymond *et al.*,[8] who obtained 5 mW of 490-nm output from a compact, diode-pumped InGaAs VECSEL.

The quantum-well gain is reduced at elevated temperatures due to broadening of the electron and hole energy distribution. As a result, VECSEL performance degrades at high temperatures. Thus a key to obtaining high power from a VECSEL is to effectively remove heat from the gain region. We have accomplished this by optically contacting a sapphire window to the top (intracavity side) of the semiconductor wafer. We present improved high-power performance from a diode-pumped InGaAs VECSEL operating at a wavelength of ~980 nm, a useful wavelength for pumping Er-doped fiber amplifiers.

2. EXPERIMENT

Our VECSEL cavity consists of a semiconductor wafer containing a high-reflectivity DBR and quantum-well gain region, and a curved output coupler. The DBR and gain-region semiconductor growth takes place in a metal

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organic chemical vapor deposition machine (Emcore D125 reactor) in which a 3-in (7.5-cm) GaAs wafer (0.65 mm thick; oriented 2° from (100) toward the (110) plane) is rotated at 1000 rpm and heated to 620–750 °C. Gases such as trimethylaluminum, trimethylgallium, trimethylindium, arsine, and phosphine are flowed over the wafer at a pressure of ~60 Torr, resulting in epitaxial growth rates of 0.5–1 nm/s. *In situ* monitors (near-normal-incidence reflectance and emissivity-correcting pyrometry) are used to precisely calibrate and monitor growth conditions for these rather demanding metal organic chemical vapor deposition growths. Figure 1 shows the wafer structure for our 980-nm VECSEL. A 27-pair DBR with alternating quarter-wave layers of AlAs and GaAs provides the laser-cavity high reflector. The quantum-well gain region consists of 15 layers of 10-nm-thick $In_{0.18}Ga_{0.82}As$ quantum wells sandwiched between an $Al_{0.04}Ga_{0.96}As$ layer and a $GaAs_{0.83}P_{0.17}$ layer. The Al–GaAs layer is designed to absorb most (~90%) of the pump laser, creating carriers that relax into the quantum wells. The quantum wells alone provide very little pump light absorption because of their small thickness. The GaAsP layer is present to reduce the strain introduced by the differing lattice constants of InGaAs and AlGaAs. An $Al_{0.50}Ga_{0.50}As$ layer is grown on top of the gain region to prevent carriers from diffusing to the wafer surface and nonradiatively recombining. A top layer of $In_{0.485}Ga_{0.515}P$ is used to set the length of the microcavity defined by the DBR and the top of the wafer and to mitigate oxidation of aluminum-bearing layers.

The VECSEL cavity is shown in Fig. 2. The InGaP side of a 3 mm × 3 mm piece of wafer is optically contacted to an uncoated sapphire window (2 mm thick, 10 mm diameter) by use of methanol liquid capillarity.[9] The birefringent sapphire changes the eigenpolarization of the laser cavity from linear, without the sapphire, to elliptical. Diamond has been used for heat sinking of mid-IR lasers[10] and has a much higher thermal conductivity than sapphire (~1000 W/m K versus ~30 W/m K), but we did not have a diamond window at our disposal. The optically contacted wafer is pressed against a thin (~50 μm) indium foil in contact with a water-cooled copper block.

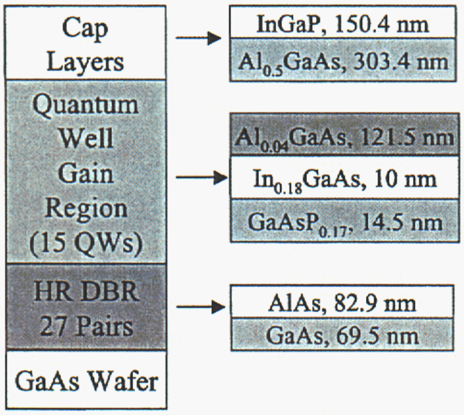

Fig. 1. Schematic of the VECSEL semiconductor layers grown by MOCVD. The $Al_{0.04}Ga_{0.96}As$ layers provide most of the absorption of the pump light while the InGaAs layers provide the gain at ~980 nm.

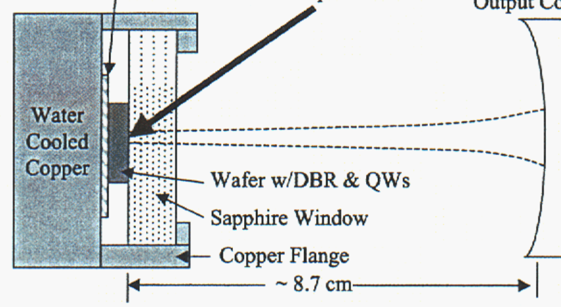

Fig. 2. Schematic of the VECSEL cavity. The semiconductor wafer is sandwiched between indium foil and an optically contacted sapphire window to remove heat from the gain region. The dashed curve is a sketch of the lasing mode.

A copper flange is used to hold the assembly and to cool the sapphire window. The water flowing through the copper block is held at a typical temperature of 10 °C by a chiller. The output coupler has a reflectivity of ~97%, radius of curvature of 10 cm, and is typically placed 8.7 cm from the wafer.

The experimental setup consists of the VECSEL cavity shown in Fig. 2, the pump laser, and diagnostics for the VECSEL output. A fiber-bundle-coupled diode-laser bar operating at ~814 nm is used as the pump source. The cooling for the diode bar is provided by the same chiller that cools the wafer. The output of the fiber bundle is collimated and apertured before being focused onto the semiconductor wafer with a 25-mm focal-length lens at an angle of incidence of ~35°. The pump spot size, as determined by the photoluminescence spot size on the wafer, is ~500 μm $1/e^2$ in diameter with a slight elongation in the horizontal direction. The VECSEL output-beam diagnostics consist of a Si photodiode for monitoring the time profile, a CCD camera for monitoring the spatial profile, and a powermeter for measuring the output power. Lasing spectra are measured with an optical spectrum analyzer.

3. RESULTS

The output power and efficiency of the VECSEL are shown in Fig. 3 for both cw (Fig. 3a) and pulsed (Fig. 3b) operation. The threshold for cw operation is seen to be ~2.8 W, which corresponds to a pump intensity of ~4 kW/cm^2. The maximum cw output power is 1.6 W with an optical efficiency (output/incident) of 19%. Note that not all of the incident pump power is coupled into the wafer due to Fresnel reflections from the air/sapphire and sapphire/wafer interfaces. The reflected power is measured to be 9% of the incident power. At an incident power of 9 W the VECSEL shuts off due to excessive heat. We were unable to obtain cw operation of the VECSEL with the window removed. Pumping with a much smaller beam diameter (~100 μm), Kuznetsov *et al.*[3,4] have demonstrated 34% optical efficiency. We have seen optical efficiencies of 40% for pump diameters of 110 μm with efficient coupling of *p*-polarized pump light into a wafer with no sapphire window.

For a given pump-power density the increase in pump diameter from 100 μm to 500 μm is expected to result in a higher temperature rise of the gain region. The reason for this is that a 100-μm spot loses heat radially and along the z axis (into the DBR and GaAs wafer) while the 500-μm spot will also lose heat along the z axis, but the radial loss will be less effective since the radial loss approaches zero as the pump spot gets very large. For a uniformly heated circular region on the surface of a semi-infinite heat-conducting medium, the temperature rise can be shown to increase linearly with the diameter of the heated region.[11] The higher efficiency observed with a 100-μm pump spot suggests that we have higher temperature rises with the 500-μm pump spot. Thus we expect that higher efficiencies and output powers may be obtained with a 500-μm pump if more efficient heat extraction is implemented.

Figure 3b shows that higher output power and efficiency can be obtained by pulsing the pump diode current at a 3000-Hz repetition rate with a width of 200 μs, yielding a duty cycle of 60%. A maximum average power of ~2 W is obtained with an efficiency of ~24%. The better performance is due to the higher peak pump power allowed with pulsed operation compared with cw operation for a given temperature rise. For a given average pump power (thermal load), pulsed operation can tolerate a higher peak pump power, and this leads to higher average output. Also shown in Figure 3b is the performance of the pulsed VECSEL with the sapphire window removed. The power and efficiency of the VECSEL are seen to be much lower than with the window. We attribute most of this difference to the reduced temperature rise of the quantum wells when the window is present. Further evidence of the reduced temperature rise, and improved laser performance with the sapphire window is shown in the time profiles of Fig. 4, which show the cutoff of lasing for a single 3-ms pump pulse at our maximum peak pump power of 14 W. The VECSEL takes much longer to stop lasing with the sapphire window than without it, presumably due to the slower rate of temperature rise. More evidence that better heat sinking should lead to higher powers comes from our observation that low-duty-cycle 200-μs, 14-W pump pulses produce 4.4-W peak power output and optical efficiency of 31%.

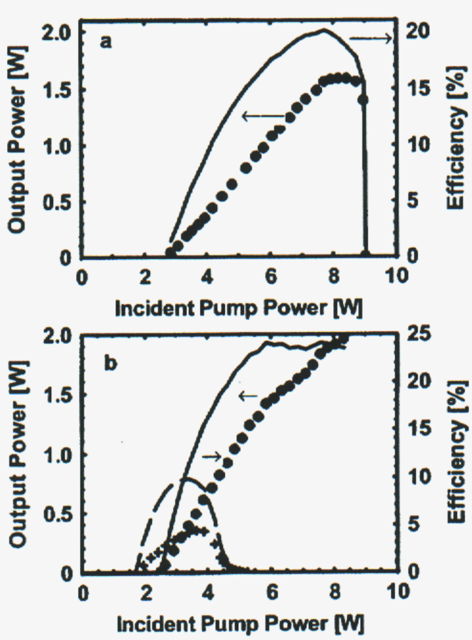

Fig. 3. Output power (points) and efficiency (curves) versus incident pump power for cw, a, and pulsed, b, operation. The dots and pluses are output power with and without the sapphire window. The solid curves and dashed curve show efficiency with and without the sapphire window.

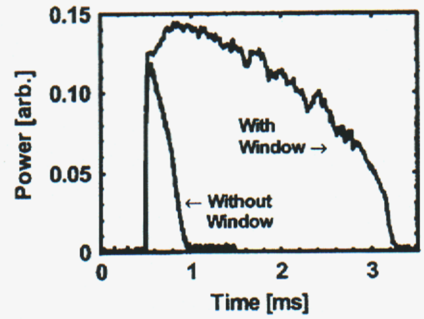

Fig. 4. Time profiles of the VECSEL output for a 3-ms, 14-W pulse of pump light.

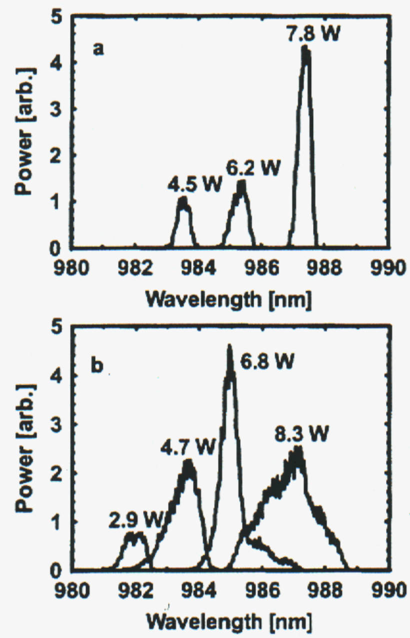

Fig. 5. Spectra of the VECSEL output at various pump powers for cw, a, and pulsed, b, operation.

VECSEL output spectra are shown in Fig. 5 for both cw (Fig. 5a) and pulsed (Fig. 5b) operation at various pump powers. Cw operation is seen to produce a linewidth of ~1 nm, while pulsed operation is slightly broader. Since the VECSEL cavity contains no wavelength-dispersive element, the lasing wavelength is free to tune as the pump power is increased. For a fixed pump power we observe a redshift as the wafer temperature is increased, much like ordinary edge-emitting diode lasers. Thus the shift to the red observed at higher pump powers is due to increased temperature in the gain region. Figure 5 shows a tuning rate of ~1 nm/W. It is interesting that the threshold pump power observed in Fig. 3b is slightly lower for windowless operation, 1.7 W versus 2.5 W. As noted by Kuznetsov *et al.*,[4] the peak gain wavelength shifts faster with temperature (~0.3 nm/°C) than does the peak of the microcavity resonance (~0.1 nm/°C). At pump powers below threshold the wavelength of maximum gain is probably to the blue of the micro-cavity resonance. As the pump power is increased, the wavelength of maximum gain shifts to the red, coming into resonance with the microcavity. Thus the lower threshold observed without the sapphire window may be due to the temperature-dependent peak-gain wavelength shifting into resonance with the microcavity resonance at a lower incident pump power because of the higher temperature rise of windowless operation.

Our VECSEL was designed to have good beam quality. The far-field spatial profiles of the output are elliptical (aspect ratio ~1.14) with reasonable fits to a Gaussian along the major and minor axes of the ellipse. We have not quantitatively measured the beam quality, but as a practical demonstration of the beam quality we measured the power passed through a 2-m, single-mode (for 1.55 μm) fiber (NRC model F-SSD). The collimated output of the VECSEL is coupled into the fiber with a 10× microscope objective. Cw operation yielded 1.05 W out of the fiber for 1.47 W incident on the microscope objective for a coupling efficiency of 71%. Pulsed operation (3000 Hz, 200 μs) gave an average output power of 1.25 W for 2.15 W incident on the microscope objective for a coupling efficiency of 58%. The higher coupling efficiency of cw operation may indicate better beam quality than obtained for pulsed operation. These results suggest the beam quality of the VECSEL output is well suited for pumping fiber amplifiers.

4. CONCLUSIONS

We have demonstrated cw output power exceeding 1.5 W at ~980 nm from an InGaAs-based VECSEL pumped by a single diode-laser bar at 814 nm. The high powers were made possible by the use of an intracavity sapphire window optically contacted to the gain region to improve heat removal. Optical efficiencies of ~20% have been demonstrated, which is about half that obtained with smaller pump-beam diameters. Since the smaller pump-beam diameters result in lower temperature rises, we expect higher efficiencies, and powers should be achievable with further improvements in removal of heat. Pulsed operation produces a maximum peak power of ~4.4 W and maximum average power of ~2 W.

ACKNOWLEDGMENTS

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APPENDIX B

Intracavity frequency doubling of a diode-pumped external-cavity surface-emitting semiconductor laser

Intracavity frequency doubling of a diode-pumped external-cavity surface-emitting semiconductor laser

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We present a compact, robust, solid-state blue-light (490-nm) source capable of greater than 5 mW of output in a TEM_{00} mode. This device is an optically pumped, vertical external-cavity surface-emitting laser with an intracavity frequency-doubling crystal.

OCIS codes: 140.3480, 140.3580, 140.5960, 140.7300, 160.6000, 190.2620.

Compact, efficient blue sources are important for high-density optical storage devices, projection display lasers, and chemical-sensing applications. A number of approaches using semiconductor lasers, including wide-bandgap edge-emitting lasers,[1] frequency-doubled edge-emitting near-infrared lasers,[2] and frequency-doubled lasers incorporating external build-up cavities,[3] are being pursued for such sources. Except for the wide-bandgap lasers, which are currently available at only a narrow band of near-UV–blue wavelengths, these approaches all suffer from complex optical configurations, complex electronics for wavelength stabilization, and the need for beam-conditioning optics. Intracavity frequency doubling, although it eliminates many of these undesirable requirements, has not been advantageous in edge-emitting lasers because the intracavity power is not significantly larger than that which is available externally[4] to the cavity. Vertical cavity surface-emitting lasers provide good beam quality and high efficiency in the near infrared and red,[5] and owing to their low loss and small output coupling have high intracavity power. Despite these attributes, the short cavity length severely restricts the per-pass conversion doubling efficiency and has precluded the generation of frequency-doubled powers in excess of a few nanowatts[6] by use of these devices. The recent report of high-power optically pumped vertical external-cavity surface-emitting lasers[7] (VECSEL's) with cavities long enough to permit insertion of millimeter-length doubling crystals suggests that intracavity frequency doubling could be efficient in that configuration. In this Letter we report a diode-pumped VECSEL with an intracavity frequency doubling crystal to produce blue light near 490 nm. We chose optical pumping for this prototype to facilitate mode matching of the gain region to the external-cavity mode, to eliminate ohmic heating, and to circumvent the difficulties associated with uniformly injecting large-diameter (>50-μm) active regions.

Our device is depicted in Fig. 1. It consists of a semiconductor gain region with an integrated high reflector, a frequency-doubling crystal with an integrated curved high reflector, and a single-stripe diode pump laser with associated discrete focusing optics.

The semiconductor structure, shown in Fig. 2, was grown by metal-organic vapor-phase epitaxy on a 0.65-mm-thick GaAs wafer oriented 2° from the (100) toward the (110) plane. The high reflector is a distributed Bragg reflector (DBR) consisting of 27 quarter-wave stacks of alternating AlAs and GaAs layers. The pump light is absorbed in the $Al_{0.08}Ga_{0.92}As$, creating carriers that relax into the adjacent 8-nm-thick compressively strained $In_{0.18}Ga_{0.82}As$ quantum wells and providing gain near 980 nm. The 15 quantum wells, bounded on one side by 9-nm-thick $GaAs_{0.80}P_{0.20}$ strain compensation layers and on the other by the pump-absorbing layers, are spaced so that they coincide with the antinodes of the standing electric field at the 980-nm design wavelength.[7] An InGaP cap layer mitigates carrier diffusion to the wafer surface and oxidation of the aluminum-bearing layers. We have made no attempt to antireflection coat the upper surface of the wafer, and consequently a short, low-finesse cavity is formed between the DBR and the upper wafer surface. We include a InGaP–AlGaAs top structure to permit a coarse tuning of this microcavity length by selective wet chemical etching, although no such tuning was employed here.

A 3-mm-square piece of the nominally 0.65-mm-thick semiconductor wafer is mounted upon a copper

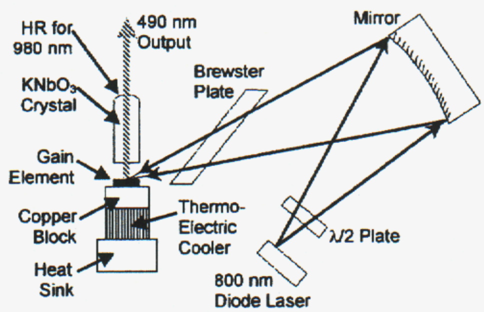

Fig. 1. The polarization of the diode pump laser is rotated with a half-wave ($\lambda/2$) plate before the beam is condensed with a 25-mm radius-of-curvature spherical mirror. The Brewster plate is used to condition the beam to project a circular profile onto the gain element. The semiconductor gain element is mounted upon a copper plate, a thermo-electric cooler, and a heat sink. The curved mirror on the $KNbO_3$ crystal and the integral mirror on the gain element complete the VECSEL cavity. HR, high reflector.

40 nm	$In_{0.49}Ga_{0.51}P$	
100 nm	$Al_{0.30}Ga_{0.70}As$	
40 nm	$In_{0.49}Ga_{0.51}P$	
100 nm	$Al_{0.30}Ga_{0.70}As$	
48 nm	$In_{0.49}Ga_{0.51}P$	
303 nm	$Al_{0.50}Ga_{0.50}As$	
30 nm	$Al_{0.08}Ga_{0.92}As$	
		Gain Region (15x)
	$Ga_{0.82}As$	
9 nm	$GaAs_{0.80}P_{0..20}$	
116 nm	$Al_{0.08}Ga_{0.92}As$	
81 nm	AlAs	**DBR (27x)**
68 nm	GaAs	
219 nm	$Al_{0.30}Ga_{0.70}As$	
68 nm	GaAs	
Substrate	GaAs (100)2°>(110)	

Fig. 2. Semiconductor gain region and the DBR grown upon a GaAs substrate. The sections labeled Gain Region and DBR are repeated 15 and 27 times, respectively.

block attached to a miniature thermoelectric cooler. The copper block was maintained at less than 10 °C for the data presented here, although the pumped region of the semiconductor is believed to have been many tens of degrees warmer. We accomplish coarse wavelength tuning by changing the temperature of the copper block. This tuning is dominated by the temperature dependence of the quantum-well gain and the thermally induced change in index of refraction of the semiconductor materials that shift the microcavity resonances. The gain region is pumped at Brewster's angle with 800-nm light from a 500-mW diode laser (SDL Model 2350-C). We orient the 50 μm by 1 μm emitting region with the long dimension out of the plane of Fig. 1 to assist in projecting a circular pump spot with an ~100-μm e^{-2} diameter onto the wafer. Projection of a circular pump profile is accomplished with a 12-mm-diameter 25-mm radius-of-curvature mirror and a 2-mm-thick fused-silica plate oriented at Brewster's angle. A half-wave plate rotates the pump polarization and minimizes reflection losses on the wafer. Although the pump laser is capable of producing 500 mW of power, the pump-collection optics deliver only 330 mW to the wafer and, of that, only 300 mW is absorbed.

The frequency-doubling crystal is b-cut $KNbO_3$, 7.5 mm long, and designed to type I noncritically phase match 980-nm frequency doubling near room temperature. The acceptance bandwidth[8] of the crystal is approximately 2.8 cm^{-1} (0.28 nm), and its large angular acceptance of approximately 64 mrad permits angular cavity alignment with little effect on conversion efficiency. The intracavity crystal surface is planar and antireflection coated ($R < 0.05\%$) for 980 nm; the other surface is polished to a 15-mm radius of curvature and is coated with a dielectric mirror that is highly reflective ($R > 99.9\%$) at 980 nm but transmissive at 490 nm. When the intracavity surface of the crystal is spaced 1–3 mm from the wafer, a stable cavity is formed with a TEM_{00} e^{-2} diameter slightly smaller than the projected pump spot. The theoretical per-pass doubling efficiency[9] for this configuration is 1.6%/W of circulating power under optimal phase-matching conditions. For the results presented in this Letter the crystal was not temperature controlled.

The input–output power characteristic of this laser is shown in Fig. 3. Laser threshold is approximately 110 mW of pump light. The intentionally low (0.029%) output coupling at 980 nm allows only ~1 mW of fundamental power to escape the cavity, yet this implies a circulating power approaching 3.4 W. As expected, the output 490-nm power increases approximately quadratically with the circulating power to a pump-limited 5 mW. The data indicate a slight hysteretic effect that is believed to be thermal in origin. The blue output power was observed to have a noise spectral power of less than 70 parts in 10^6 (ppm)/Hz$^{0.5}$ from 0 to 100 kHz; for comparison, the pump source and the 980-nm output had noise spectral powers less than the 9-ppm/Hz$^{0.5}$ noise floor of our detection system. Owing to the stable cavity and the circular pump region, the laser output is TEM_{00} throughout the pump range. The inset in Fig. 3 illustrates that the beam profile is radially symmetric and approximately Gaussian, with a near-diffraction-limited divergence of 10-mrad $1/e^2$ diameter at maximum pump power. Measurements with a similar device pumped with a Ti:sapphire laser indicate the formation of thermally induced positive lens in the semiconductor. This thermally induced lens leads to a slight power dependence in the divergence of the output beam.

The single-pass frequency-doubling efficiency is observed to be ~0.04%/W, suggesting that the frequency-doubling process is not well phase matched. The fundamental and the frequency-doubled laser

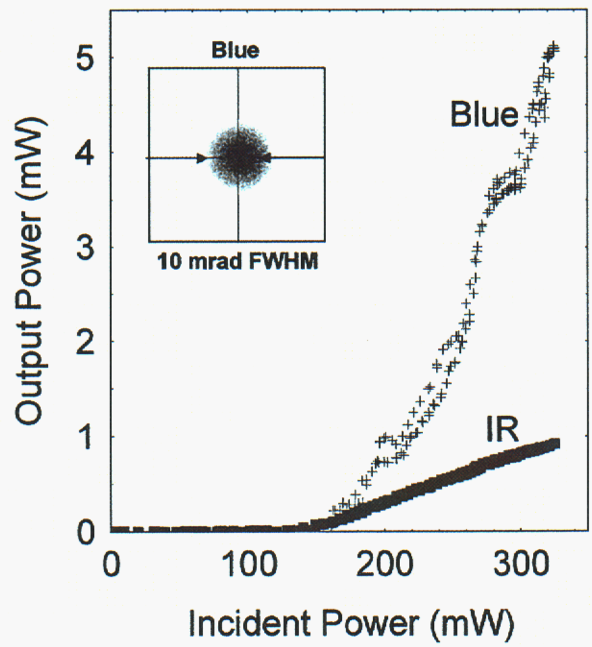

Fig. 3. Output blue power (+) exceeding 5 mW for an incident pump power of approximately 300 mW. Although the output IR power (■) is only 1 mW, the circulating power in the cavity approaches 3.4 W. The inset shows the far-field intensity pattern for the blue beam.

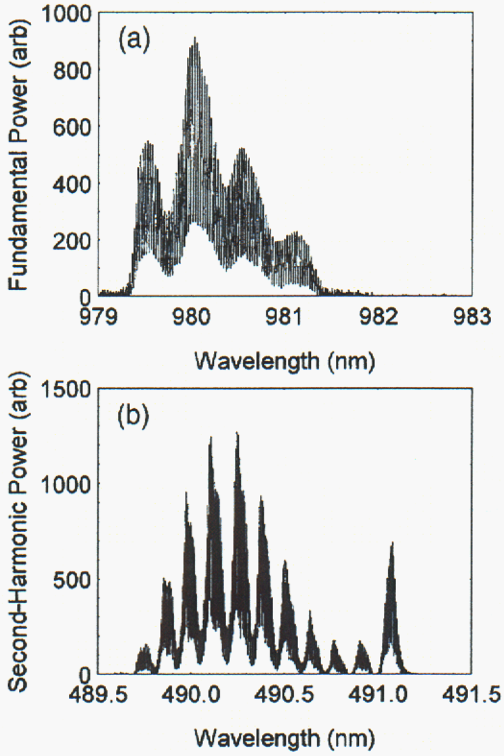

Fig. 4. Spectra of the (a) fundamental and (b) second-harmonic laser outputs, acquired simultaneously. The crystal frequency-doubling phase-matching peak is located near 982.7 nm.

spectra plotted in Fig. 4 support this conclusion. The high-frequency modulation on both spectra is attributable to the well-resolved longitudinal modes of the laser. The center wavelength of 980 nm is significantly detuned from the phase-matching wavelength of 982.7 nm, and the lasing bandwidth of more than 10 cm^{-1} FWHM (1 nm) is well in excess of the predicted[8] 2.8-cm^{-1} (0.28-nm) phase-matching acceptance bandwidth. The modulation in the envelope of the 980-nm spectrum is due to an interference effect between the antireflection-coated crystal face and the DBR. The modulation in the envelope of the 490-nm spectrum corresponds to the oscillations in the phase-matching function.[9] Because the laser gain is highly homogeneous and the nonlinear loss is maximized for phase-matched wavelengths, the laser tends not to operate near the phase-matching wavelength at which maximum conversion efficiency would be obtained. This result is strikingly illustrated in Fig. 4, in which, in spite of the relatively low power near 982.2 nm that produces it, the more-favorable phase matching results in a relatively large peak in the doubled light near 491.1 nm. Attempts to tune the laser into phase matching simply by changing the temperature of the copper heat sink were unsuccessful; however, operation at this wavelength was readily achieved with the crystal removed.

In summary, we have shown that one can intracavity frequency double a diode-pumped VECSEL to produce light near 490 nm. As much as 5 mW of TEM_{00} blue-green light was generated with an optical-to-optical conversion efficiency of 1.5%. A significant improvement in the output blue power should be attained by more aggressive spectral control of the lasing wavelength and bandwidth.

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9. Calculated using SNLO, written by A. V. Smith. SNLO may be downloaded free of charge at www.sandia.gov/imrl/XWEB1128/xxtal.htm.

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