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intracavity frequency doubling of an optically-pumped, external-cavity surface-emitting semiconductor laser

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We have produced milliwatts of blue light from a diode-pumped, multiple-quantum-well semiconductor laser. This compact source has a pump-to-blue optical efficiency > 1%.

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Development of diode- laser- based sources of blue light is an active area of research for applications such as optical data storage and video displays. Two general approaches to the problem are being pursued: Diode lasers that emit in the blue and frequency-doubled near infrared (IR) diodes. Diode lasers emitting blue light have been slow to develop because of material issues associated with wide bandgap semiconductors[1]. Recent improvements in nitride materials should improve this situation considerably[2] but reliable diode lasers covering the near UV-blue-green part of the spectrum are still years away. Near IR diode lasers, on the other hand, are a mature, reliable technology with both edge-emitting and surface-emitting lasers available from commercial sources. With the availability of a number of nonlinear crystals that can efficiently frequency double near IR lasers to the blue, these types of sources should be useful for many years to come.

Frequency doubling of near IR diode lasers is usually accomplished by doubling edge-emitting lasers in bulk nonlinear crystals or waveguide doublers. Since efficient doubling of CW light in bulk crystals requires high powers, an external buildup cavity is often required[3]. This adds considerable complexity and cost to this approach. Waveguide doublers avoid the complications of a buildup cavity but have limited tuning ranges.

Intracavity frequency doubling with bulk nonlinear crystals is an attractive approach to efficiently doubling CW lasers and has been used for years with solid state lasers[4]. This approach is generally not used with edge-emitting diode lasers because the high output coupling of edge emitters leads

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to rather low intracavity powers. Surface-emitting diode lasers such as vertical cavity surface emitting lasers (VCSELs) usually have low output coupling which leads to high intracavity powers. Typical cavity lengths of VCSELs however, are only a few microns, making insertion of a nonlinear crystal impractical. The cavity length can be greatly extended in an external-cavity surface-emitting laser and high power has been demonstrated in optically pumped, vertical external cavity surface emitting lasers (VECSELs). The high intracavity power and long (~cm's) cavity length of VECSELs leads to an attractive system for intracavity frequency doubling.

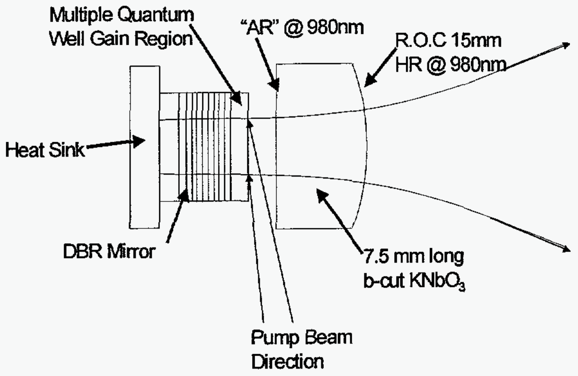

Figure 1. VECSEL Setup

We have obtained blue light from the intracavity doubled VECSEL shown in Fig. 1. The laser cavity consists of a 980nm distributed Bragg reflector (DBR) high reflector, a gain region with 8 nm wide $In_{.16}Ga_{.84}As$ quantum wells, and a b-cut potassium niobate crystal with a 980nm high reflector on the outside surface. The semiconductor wafer is grown by metal-organic vapor phase epitaxy (MOVPE) at the Sandia National Laboratories Compound Semiconductor Research Lab. The DBR is made up of 27 alternating layers of quarter-wave thick GaAs and AlAs grown on a GaAs substrate (2° off 100). On top of the DBR, the 15 periodically spaced InGaAs quantum wells are grown with $Al_{.08}Ga_{.92}As$ and GaAsP layers between the quantum wells. The GaAsP layers provide strain compensation for the compressively strained quantum wells while the AlGaAs layers absorb the pump light. The half-wave spacing between the quantum wells and their position relative to the DBR are such that the quantum wells are located at electric field antinodes of the resonated 980 nm light. A thick, non-pump-absorbing layer of $Al_{.5}Ga_{.5}As$ is grown on top of the quantum well structure to prevent pump-induced carriers from leaving the quantum-well region. A top layer of $In_{.485}Ga_{.515}P$ is used to prevent oxidation of the Al from occurring at the wafer-air interface. The wafer is mounted to a copper heat sink with zinc oxide thermal grease. The copper heat sink is held at 0°C by a thermoelectric cooler (TEC) but the wafer is at a higher temperature (~10's °C) due to heating by the pump laser.

The potassium niobate crystal is 7.5mm long with a 3mm x 3mm aperture. The intracavity surface is antireflection coated for 980nm and the 15 mm radius of curvature output surface is high-reflectivity (~99.9%) coated for 980nm. The potassium niobate crystal is oriented with the a-axis parallel to the IR polarization which is the GaAs $01\bar{1}$ crystal direction. The second harmonic light is polarized along the potassium niobate c-axis for the Type I doubling process. The spacing between the potassium niobate crystal and the semiconductor wafer is typically 1-3mm.

The VECSEL is pumped by an SDL model 2350 laser diode operating at ~800nm. The p-polarized pump light in incident on the wafer at approximately Brewster's angle (~74°) to minimize reflection loss (R~8%). The pump beam is slightly elongated with $1/e^2$ diameters of 70μ by 90μ. We calculate the lowest order Gaussian beam of the cavity to have a diameter of ~90μ at the wafer.

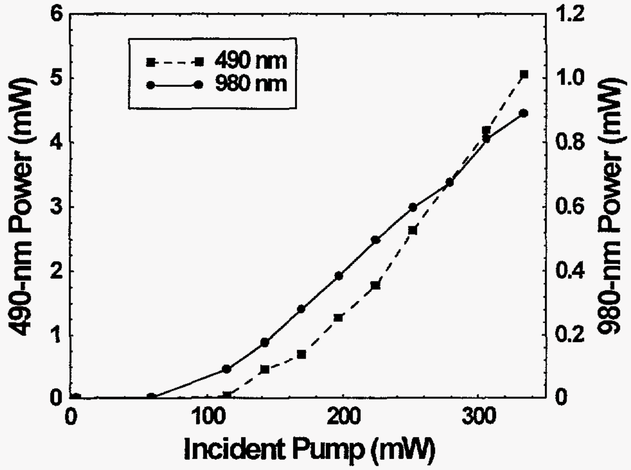

Figure 2. VECSEL Output Power.

Figure 2 shows the 980nm and 490nm output powers as a function of the incident pump power. The temperature of the potassium niobate crystal was not carefully controlled for these experiments and was ~20°. The laser operated at an IR wavelength of 980.9nm, which is near the phase matching wavelength for the potassium niobate crystal. A blue output power of 5 mW and a pump-to-blue optical efficiency of 1.5% have been observed for 333 mW of pump input. The electrical efficiency under these conditions, neglecting the TEC power, is .25%.

The blue output beam profile is shown in Figure 3 and is well approximated by a 2D Gaussian. This confirms that the system is operating on the lowest order transverse mode of the external cavity. The observed beam divergence is consistent with a beam waist diameter of ~XXXμ on the wafer.

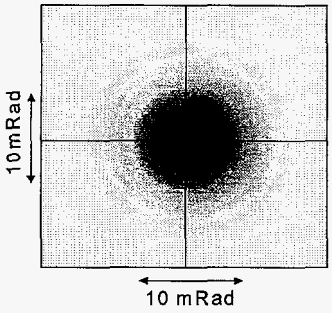

Figure 3. Blue Beam Profile.

The intracavity-doubled, diode-laser pumped VECSEL is compact (~100 cm^3 , excluding power supplies) and performance should improve as improvements are made. Better temperature control of the wafer should lead to higher laser powers and properly matching the lasing wavelength to the phase matching wavelength of the potassium niobate crystal should lead to higher doubling efficiency.

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2. S. Nakamura, et.al., J. Crystal Growth 190, 820 (1998).
3. E. S. Polzik and H. J. Kimble, Optics Lett. 16, 1400 (1991).
4. W. Koechner, *Solid-State Laser Engineering*, Third Edition, Springer-Verlag, Berlin, 1992.