Blue Light Emitting Electrically Pumped VECSELs with Optical Powers in the Milliwatt Range

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We report on intracavity frequency doubling of electrically pumped vertical-extended cavity surface-emitting lasers (VECSELs), establishing a blue light source emitting near 485 nm wavelength. The VECSELs have an InGaAs/GaAs gain region and incorporate a nonlinear optical crystal for frequency doubling. Continuous-wave optical output powers of more than 1.5 mW are achieved.

1. Introduction

In the last few years, VECSELs have become an attractive laser source for various applications. Due to favorable features, such as high output power and good beam quality, optically pumped semiconductor VECSELs (OPS-VECSELs) [1] can be used, e.g., in laser printing, absorption spectroscopy or as a pump laser in the near-infrared spectral range. Furthermore, the extended cavity configuration gives the possibility to use a nonlinear optical crystal for second-harmonic generation (SHG) in the visible spectral range. This approach has recently received an increasing interest in applying such OPS-VECSELs in projection television and laser displays. Output powers up to several watts have been demonstrated over a wide spectral range from blue light (∼ 460–488 nm) [2] to green-yellow (∼ 555–580 nm) [3,4] and orange near 610 nm [5]. Much more challenging than optical pumping is the electrical pumping concept due to demanding issues such as current spreading in doped layers, ohmic heating, processing and device mounting. Electrically pumped VECSELs (EP-VECSELs) have been first reported by Hadley et al. [6]. Output powers of a few milliwatts in continuous-wave (CW) operation from InGaAs-based devices emitting near 985 nm were demonstrated at that time. In recent years, optical output powers of over 900 mW in multi-mode operation have been achieved from EP-VECSELs with active diameters of 150 μm [7]. Intracavity frequency doubling at 490 nm emission wavelength with output powers of 5–40 mW has been also demonstrated by Novalux [8], where unfortunately, rather few device details are known. To our knowledge, no other group has reported blue-emitting EP-VECSELs with output powers in the milliwatt range. In this paper, we present blue light generation by intracavity frequency doubling in substrate-removed EP-VECSELs with high round-trip gain.

2. Device Structure

The layer structures are grown by solid-source molecular beam epitaxy and are designed for emission wavelengths near 980 nm. The active region contains two stacks of three

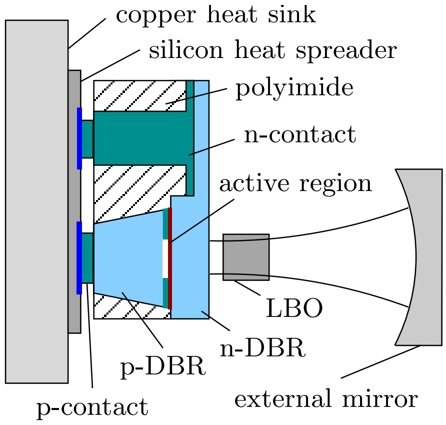


Fig. 1: Schematic VECSEL cross-section.

8 nm thick InGaAs/GaAs quantum wells (with half-wavelength distance) surrounded by two 30 nm thick GaAsP layers for strain compensation. The active diameter is defined by selective oxidation of a 30 nm thick AlAs layer above the active region, located in a node of the standing-wave pattern. Intracavity n-contacts with electroplated gold posts are applied on the epitaxial side. Polyimide is used for chip planarization, as schematically illustrated in Fig. 1. The bottom-emitting laser contains a 30 pairs p-doped distributed Bragg reflector (DBR) and a 5 pairs n-doped DBR for wavelength selection. For laser operation, an external curved mirror with a radius of curvature approximately equal to the extended cavity length provides sufficient optical feedback and controls the output transverse modes. This dielectric mirror is coated for high reflectivity in the near-infrared range and is transparent for blue light emission. A lithium triborate (LBO) nonlinear optical crystal is inserted into the extended cavity close to the laser chip for frequency doubling. The VECSEL chip has dimensions of $1.7 \times 1.7\,\text{mm}^2$ and is indium-soldered up-side down on a semi-insulating silicon heat spreader with metal traces for current supply. The heat spreader is soldered on a copper heat sink with indium as well. The applied mounting technique facilitates individual addressing of different lasers on one chip. Complete GaAs substrate removal significantly reduces the optical round-trip loss.

3. Measurement Results

The laser chips were first characterized in the infrared regime. Room temperature light–current–voltage curves of a EP-VECSEL with 68 µm active diameter are shown in Fig. 2. The external mirror has 10 mm radius of curvature and a reflectivity of 95 %. A threshold current of 64 mA and a differential quantum efficiency of 33 % are obtained. Optical CW output powers exceeding 50 mW are generated at emission wavelengths near 974 nm. A 4 mm long critically phase-matched antireflection-coated (970 and 485 nm) LBO crystal is then inserted for frequency doubling. Here, an external mirror with 20 mm radius of curvature and a reflectivity of 99.96 % at 980 nm wavelength is used. The output characteristics is plotted in Fig. 3 (left). The blue output power is measured after filtering out the remaining infrared light. A maximum CW output power of 1.7 mW at 145 mA

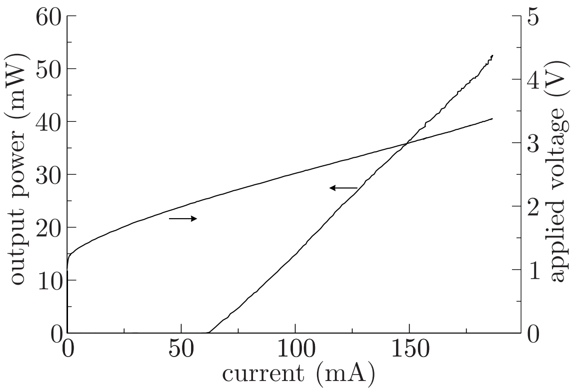
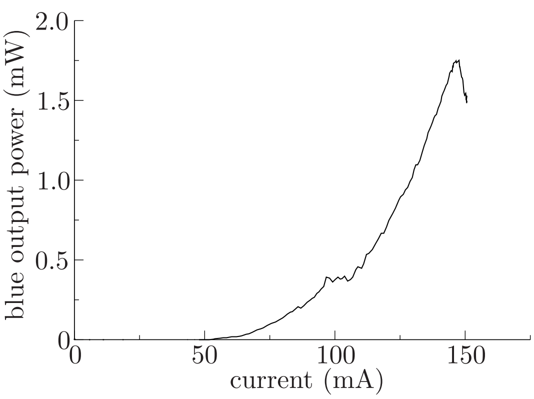


Fig. 2: CW operation characteristics of a 68 µm diameter EP-VECSEL with 10 mm cavity length emitting near 974 nm.

current is achieved, where a heat sink temperature of 10°C has been used to tune the laser wavelength towards higher SHG efficiency. Blue laser emission sets in at about 53 mA. A slight instability is observed around 100 mA and can be attributed to device heating and associated polarization switching [9], which influence the polarization-dependent critically phase-matched frequency conversion. Figure 3 (right) shows the spectrum of the laser, driven at 130 mA current. A narrow peak (0.1 nm spectral resolution) at an emission wavelength of 485 nm is observed with no side-modes.



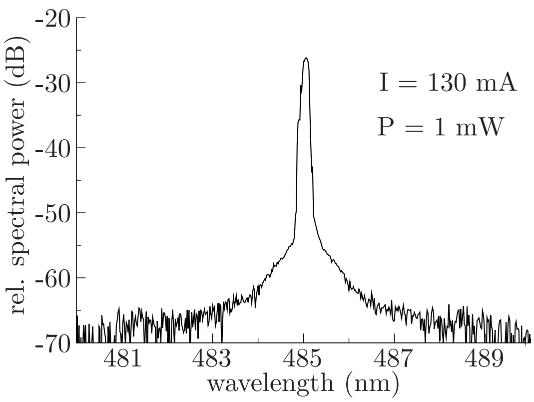


Fig. 3: Second-harmonic output characteristics of the frequency-doubled EP-VECSEL from Fig. 2 with a 20 mm long cavity (left) and the corresponding emission spectrum measured at 130 mA (right).

4. Conclusion

We have fabricated and characterized electrically pumped bottom-emitting InGaAs/GaAs VECSELs. Frequency doubling using a nonlinear optical crystal inside the extended cavity has been successfully performed. Blue light emission at 485 nm has been demonstrated with maximum CW output powers of 1.7 mW. Improvements such as noncritical phase matching and polarization control will lead to more stable and efficient SHG. Also higher performance can be expected using intracavity transparent heat sinks for more efficient cooling.

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