Progress towards cryogenic temperatures in intra-cavity optical refrigeration using a VECSEL

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ABSTRACT

We report on the use of a high power InGaAs quantum well vertical external-cavity surface-emitting laser (VECSEL) emitting at a wavelength of 1020 nm for intra-cavity cooling of a 5% Yb-doped YLF crystal to 148 K from room temperature. Similar crystals have now reached temperatures below the NIST-defined cryogenic temperature of 123 K when pumped outside a laser cavity. We discuss the progress, advantages, and challenges of laser cooling inside a VECSEL cavity, including the VECSEL active region design, cavity design, and cooling sample choice for optimal cooling.

Keywords: Optical refrigeration, laser cooling of solids, VECSEL, SDL, OPSL

1. INTRODUCTION

Optical refrigeration or laser cooling of solids is based on anti-Stokes fluorescence[1], where an electronic transition is excited with low-entropy light (e.g. a narrow linewidth laser) having a photon energy below the mean fluorescence energy of the system. Subsequent thermalization of the electronic populations in the ground- and excited-state manifolds therefore requires phonon annihilation in order to establish quasi-equilibrium. The upconverted broadband fluorescence leaving the medium will carry heat (and entropy), thus resulting in net cooling of the sample. This principle was proposed in 1929 by P. Pringsheim[2] but it took more than six decades before it was first experimentally observed in 1995 by R. Epstein et al.[3] in ytterbium-doped fluoro-zirconate glass Yb:ZBLAN. More recently, cooling of a 10% doped Yb:YLF crystal from room temperature to 114 K has been reported[4], well below the NIST-defined cryogenic temperature of 123 K. For a comprehensive review of the physics and requirements of optical refrigeration, as well as a summary of experimental advances see Ref. [5].

In this paper, we focus on the optical engineering challenges of using a VECSEL for intra-cavity optical refrigeration. In section 2, we will discuss the design and performance of a high power VECSEL at 1020 nm, section 3 will discuss the experimental setup and cooling results.

2. VECSEL DESIGN AND PERFORMANCE

A VECSEL, sometimes also referred to as semiconductor disk laser (SDL), is an optically pumped semiconductor laser (OPSL), consisting of a gain region on top of a distributed Bragg reflector (DBR). It combines the wavelength flexibility of semiconductor active regions with excellent beam quality[6] and high continuous wave (CW) output powers[7].

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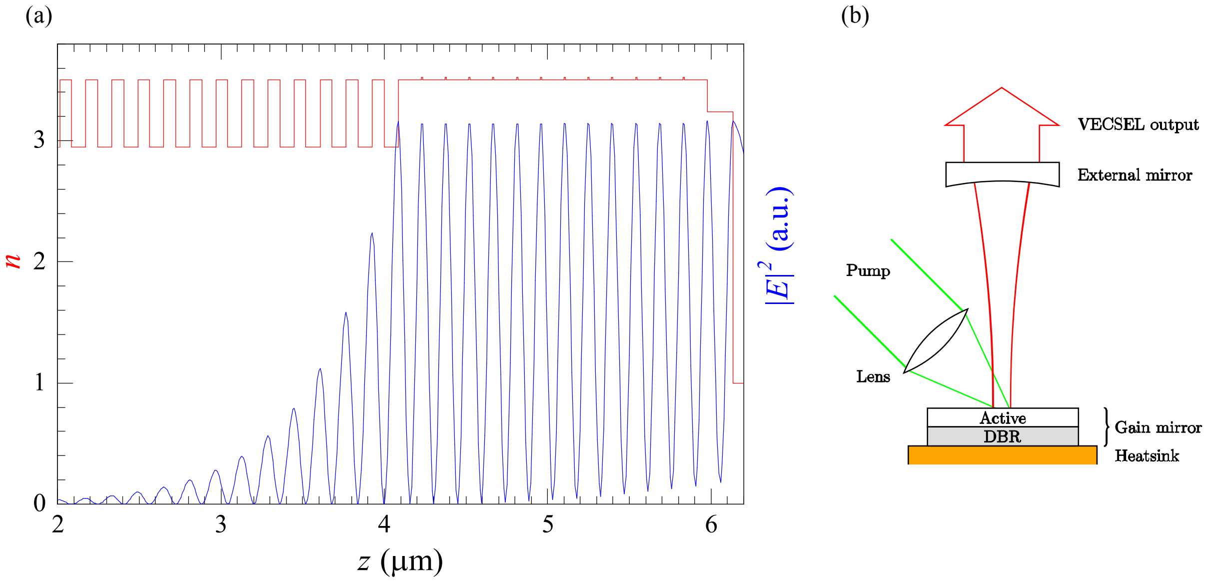

Figure 1. (a) Index of refraction n and calculated electrical field strength E in the VECSEL gain chip along the growth direction z (only partial DBR shown for clarity), (b) Schematic diagram of high power VECSEL test setup.

Our specific gain mirror is designed for laser cooling of Yb:YLF, requiring an operation wavelength of 1020 nm at high CW powers. It consists of a 25 pair AlAs/GaAs DBR, a multi-quantum well (MQW) active region with 12 InGaAs wells aligned with antinodes of the standing wave inside a GaAsP sub-cavity for strain compensation, and is capped by a lattice-matched InGaP window layer for carrier confinement. The layer structure and simulated electrical field strength of the VECSEL structure is shown in Fig. 1(a).

The layer structure was grown by MOCVD on GaAs in reverse order, starting with the active region and followed by the DBR. This allows for the DBR to be metalized with Ti, Au, and In and subsequently soldered to an equally coated thermal grade CVD diamond plate as heat spreader. The GaAs substrate can then be removed by a selective wet etch, which stops at the InGaP window layer.

VECSEL performance was tested in a basic setup, schematically shown in Fig. 1(b): A 5% transmission concave output coupler with 25 cm radius of curvature was placed approximately 24.5 cm from the gain mirror and the cavity length and alignment was optimized to achieve highest output power. An 808 nm fiber-coupled laser diode module with 70 W of power was used at a pump laser and focused onto the VECSEL chip to a spot around 300 µm in diameter. The diamond heat spreader was mounted to a water-cooled copper heat sink, with typical cooling water temperature of 10° C during laser operation. The VECSEL output power was measured using an optical power meter and laser emission spectra were collected by coupling part of the output beam into a multi-mode optical fiber, connected to an optical spectrum analyzer.

CW output power as a function of the 808 nm pump power incident on the gain chip is shown in Fig. 2(a). The maximum output power of 18 W is achieved without signs of thermal roll-over, limited only by our currently available pump diode. Using the reflectivity of the structure to estimate absorbed pump power leads to a slope efficiency of approximately 38%. Laser emission spectra for different pump powers are shown in Fig. 2(b), they exhibit a red shift for higher powers as is expected due to the heating of the gain structure, caused by the pump.

The lasing wavelength of the VECSEL is very critical for laser cooling, so it needs to be controlled to mitigate effects caused by heating of the gain chip. For this reason, a 3 mm thick birefringent quartz filter was inserted in the external cavity under Brewster angle, and adjusted to keep the emission in a narrow band around 1020 nm. In addition, this allowed tuning of the VECSEL over a range close to 30 nm, as shown in Fig. 3(a). Such a wide tunability range is attractive for femtosecond mode-locking applications, but is also important for the laser cooling applications as means to dynamically control the intra-cavity loss, as described in detail below.

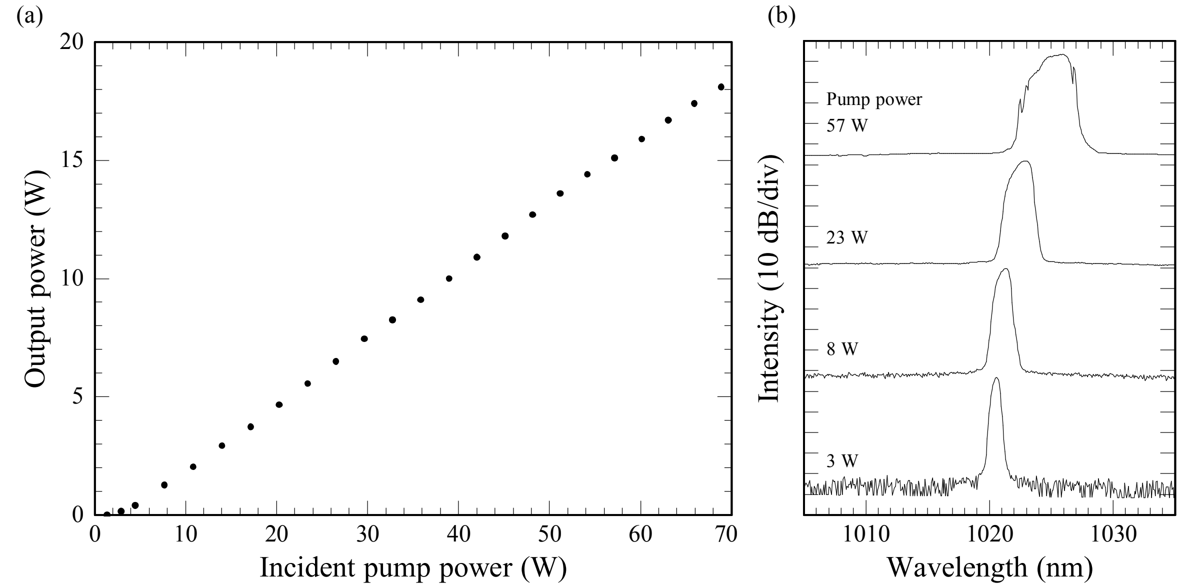

Figure 2. (a) VECSEL output power as function of 808 nm pump power incident on the gain chip, (b) VECSEL lasing spectra for selected pump powers.

Another parameter of interest for laser cooling in a VECSEL is the amount of intra-cavity loss the laser can overcome, so it will still reach lasing threshold with the cooling sample in the cavity. To simulate variable intra-cavity loss and hence to characterize the gain of the laser, a glass window was placed in the cavity initially at Brewster angle and then incrementally rotated to vary the coupled-out power from the faces of the window. The resulting output power versus roundtrip loss curve is shown in Fig. 3(b). The measurement range was limited by the 1% output coupler at low loss, and the close to normal angle of the window, making power measurements difficult. While it appears that a maximum of more than 16% of loss can be overcome, the optimal output power is achieved around 5% of loss, taking into the account outcoupling loss.

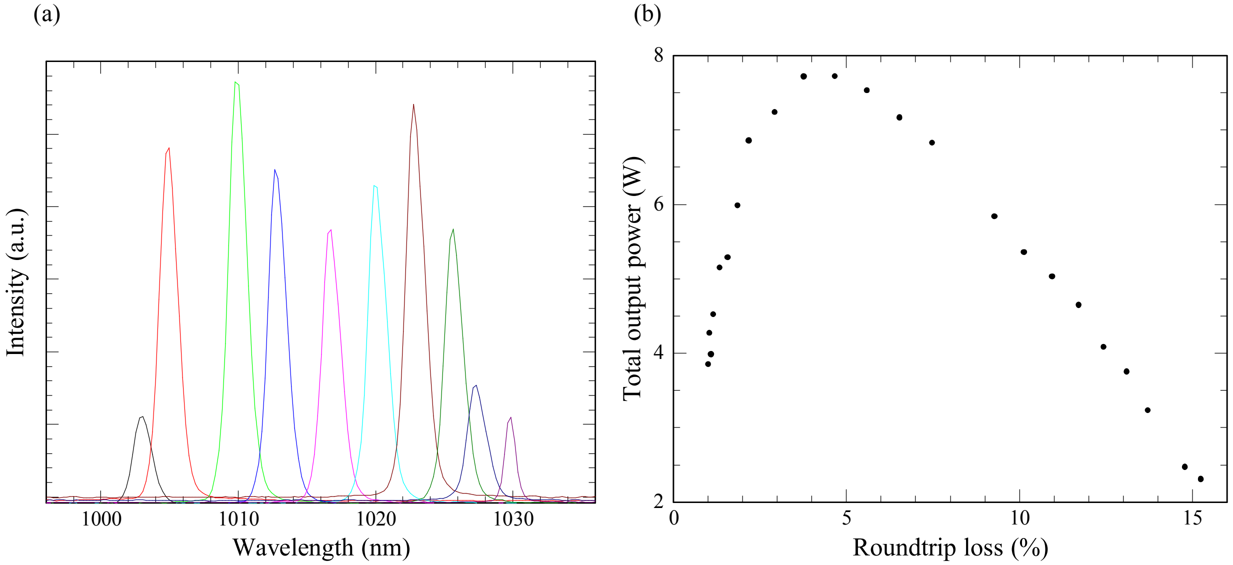

Figure 3. (a) VECSEL lasing spectra for different birefringent filter positions, (b) Total output power as function of roundtrip loss as adjusted by the angle of an intra-cavity window.

3. LASER COOLING SETUP AND RESULTS

Laser cooling experiments are carried out by placing a cooling sample inside of the VECSEL cavity. The current cooling sample is comprised of a high-purity yttrium lithium fluoride crystal, 5%-w.t. doped by the tri-valent ytterbium ions (Yb^{3+}:$YLiF_4$). To reduce convective heat load and hence to maximize temperature-drops in the sample, the laser cooling experiments are carried out under vacuum. The setup (Fig. 4) consists of the water-cooled VECSEL gain chip inside a vacuum chamber that is evacuated to below 10^{-5} torr using a turbomolecular pump. The pre-collimated 808 nm fiber-coupled pump laser is coupled into the vacuum chamber through an anti-reflection (AR) coated vacuum-port window. Residual pump light that is reflected by the gain chip is redirected outside the vacuum chamber by reflective optics to reduce heat load on the inside of the chamber. The VECSEL cavity is completed by a 20 cm radius of curvature concave high-reflecting mirror, mounted on a 3-axis piezo-controlled mirror mount and hence can be adjusted from the outside by means of a high-voltage controller, fed through a high-voltage BNC vacuum port. The intra-cavity elements include the Yb:YLF cooling sample, supported by microscope slide cover slips to reduce conductive heat load, and birefringent filter, both at Brewster angle to minimize intra-cavity losses. A multi-mode optical fiber fed through a fiber-optic vacuum port (not shown) and positioned in the vicinity of the cooling crystal is used to collect part of the fluorescence, which is used for a contact-less temperature measurement by monitoring the temperature-induced change in fluorescence spectrum and comparing it to a previously recorded calibration[8]. Finally, the gain structure copper heat sink is water-cooled from the ambient side by a water loop fed through a liquid-line vacuum port.

Optimal wavelength for the laser cooling corresponds to the E4-E5 Stark manifold resonance of the Yb:YLF crystal [4, 5] at 1020 nm. This is the target operation wavelength of the VECSEL crystal and hence the size of the cooling crystal is determined by taking into account the optimal roundtrip loss of the VECSEL [Fig. 3(b)] in combination with the absorption of the cooling sample, shown in Fig. 5 for the laser cooling crystal at various temperatures. We decided on a 2 mm thick sample, which at a wavelength of 1020 nm and a crystal temperature of 150 K corresponds to a roundtrip loss of slightly more than 6%, still very close to the optimum power extraction from the VECSEL. At room temperature, however, the intra-cavity loss in the cooling sample would exceed the lasing threshold, making the VECSEL inoperable. To mitigate this problem, for close-to-room temperature operation the wavelength is red-shifted further into the anti-Stokes absorption tail of the Yb:YLF, allowing for the laser action. As the crystal cools down, the lasing wavelength can be decreased closer to the optimal 1020 nm point by means of the birefringent filter. This procedure effectively holds the absorption loss constant, allowing for optimized power extraction and cooling at all temperatures.

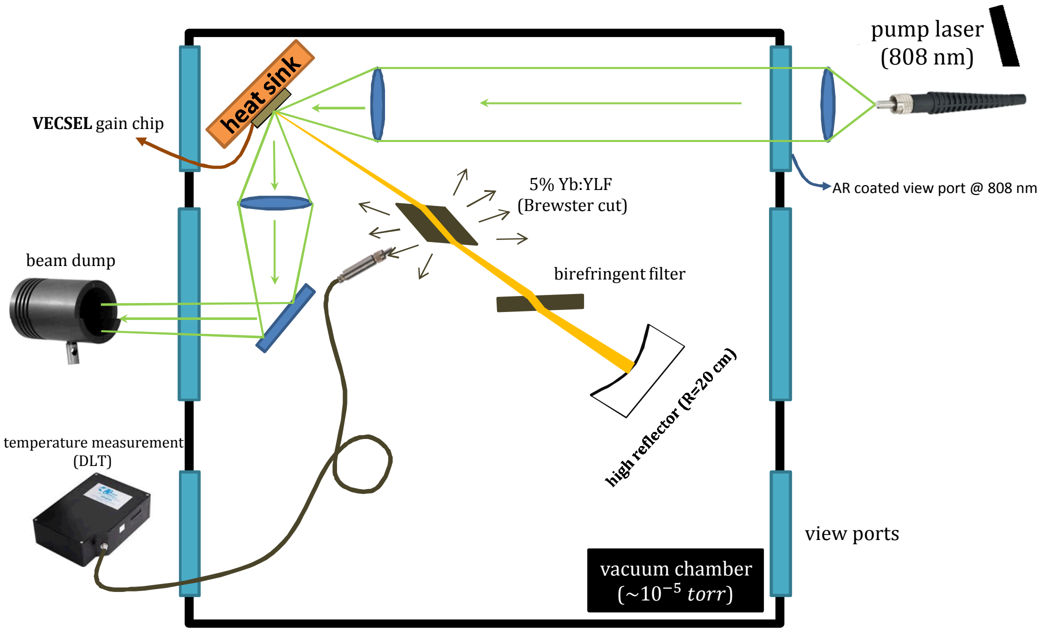

Figure 4. Schematic diagram of VECSEL intra-cavity laser cooling setup in vacuum chamber.

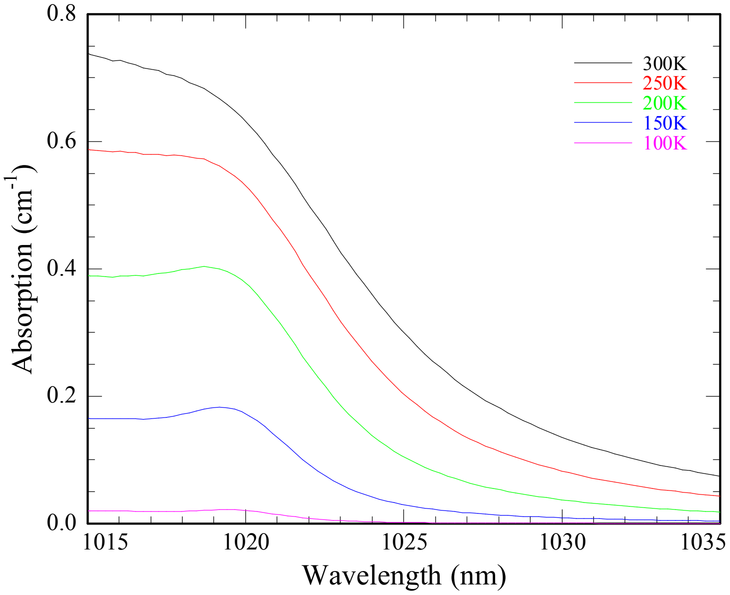

Figure 5. Absorption of 5% Yb:YLF versus wavelength for different temperatures.

The temperature extracted from the luminescence of the Yb:YLF as function of time during the cooling experiment is shown in Fig. 6(a), reaching 148 K after about 3.6 minutes, starting from room temperature. Fluorescence spectra collected at different times during the experiment are compared in Fig. 6(b), showing the change in spectrum used to compute the sample temperature. Dramatic intra-manifold transition narrowing as well as overall fluorescence count decrease are clear signatures of the sample cooling. A portion of the scattered laser light, also recorded in the spectra, allows for visualizing the tuning of the VECSEL from 1030 nm to 1020 nm as the crystal temperature decreased over time.

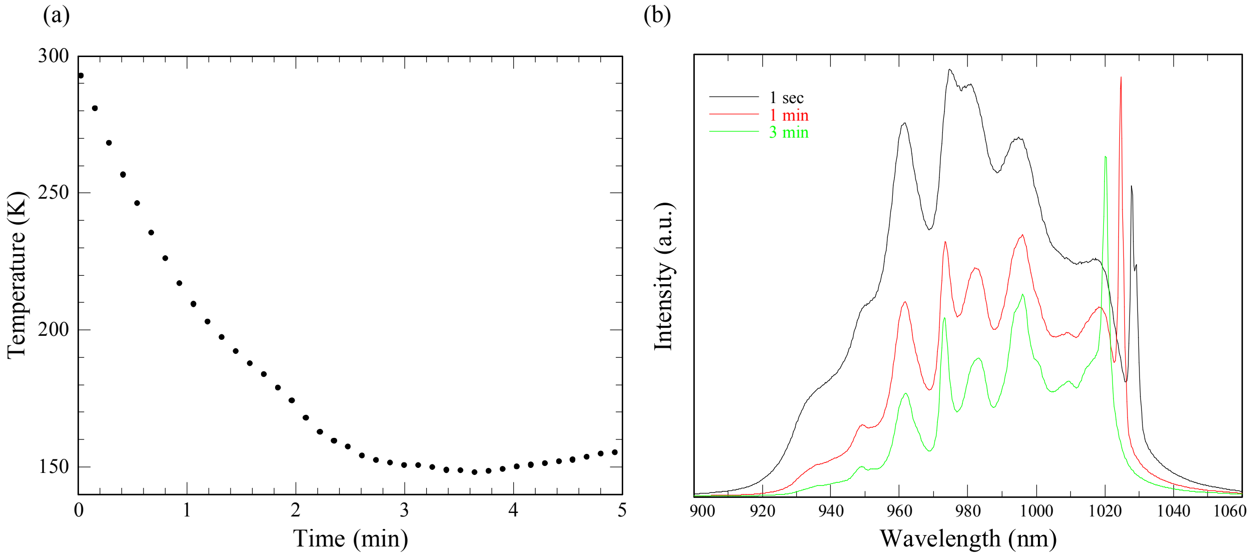

Figure 6. (a) Yb:YLF crystal temperature as function of time during cooling experiment, (b) Luminescence spectra for different times; note scattered laser light at 1020 nm to 1030 nm.

4. SUMMARY AND CONCLUSIONS

In summary, we developed a high power VECSEL around 1020 nm for laser cooling of Yb:YLF. The CW VECSEL output power of up to 18 W was only limited by the available pump power. Tunability over almost 30 nm was demonstrated, and lasing threshold was still reached with more than 16% roundtrip loss in the cavity, while maximum power could be extracted around 4-5% of intra-cavity loss. With a setup inside a vacuum chamber we were able to cool a 2 mm thick, 5% doped Yb:YLF sample from room temperature to 148 K.

5. ACKNOWLEDGMENTS

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