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Intracavity laser cooling using a VECSEL

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ABSTRACT

We report on the first observation of intracavity laser cooling inside of a vertical external-cavity surface-emitting laser (VECSEL). A Yb:YLF crystal is placed under Brewster angle inside the cavity of an InGaAs quantum well VECSEL emitting around 1030 nm. With the crystal in air, we observed cooling by about 0.5 degrees. By placing the sample and cavity end mirror inside a vacuum chamber, with the window also at Brewster angle to the laser mode, cooling by 20 degrees has been realized. Furthermore, the development of a compact and efficient integrated cryocooler device is underway.

Keywords: Laser cooling of solids, laser refrigeration, cryocooler, VECSEL

1. INTRODUCTION

Laser cooling of solids is based on anti-Stokes fluorescence[1]. When an electronic transition is excited above the mean luminescence wavelength (λ_f), the subsequent upconverted fluorescence requires phonon annihilation for the quasi thermal equilibrium to be established. This radiation extracts heat from the material, resulting in bulk cooling. This mechanism was proposed by P. Pringsheim in 1929, utilizing monochromatic light sources[2]. There are two strict requirements for laser cooling to become feasible[1]: i) high external quantum efficiency and (ii) high purity, low parasitic loss materials.

It was in 1995 that R. Epstein *et al.* at Los Alamos National Laboratory have demonstrated bulk cooling in a low-loss rare-earth doped glass fiber preform of ytterbium-doped fluoro-zirconate glass Yb^{3+}:ZBLAN[3]. The work on Yb:ZBLAN materials has culminated in bulk cooling to 208 K[4]. Since then, tri-valent ions of Yb, Tm, and Er have been demonstrated to cool in a variety of glassy and crystalline hosts (see e.g. Ref. [1,5] for a comprehensive review).

Recently, researchers at the University of New Mexico have realized cryogenic operation of Yb^{3+}-doped into yttrium lithium fluoride crystal host, by achieving bulk cooling to 155 K[6]. This was accomplished through realization of a dramatic enhancement of the resonant absorption in the Yb^{3+} ions, when excited at the E4-E5 Stark level of the ${}^2F_{5/2}$-${}^2F_{7/2}$ multiplet in the YLF host. In contrast to crystals, this transition is substantially inhomogeneously broadened and hence weakened in glass hosts, due to the loss of long-range order in the matrix.

A model of the cooling efficiency for currently available high-purity Yb:YLF has predicted the possibility of cooling down to 110 K[6] at the E4-E5 transition (~ 1020 nm). These predictions were verified in experiments that measured temperatures of local (to 110 ± 5 K[7]) and bulk (to 118 ± 1 K[8]) cooling of the Yb:YLF. Cooling down to ~ 85 K was predicted upon an order-of-magnitude reduction of the parasitic absorption in the host crystal[9].

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Maximal pump absorption is necessary for high cooling powers. In bulk cooling experiments up to now, this was achieved by non-resonant cavities, used to fold the pump beam through the cooling medium up to 6-8 round-trips[1,8]. This approach however becomes increasingly difficult at lower temperatures due to precipitous drop of the resonant absorption in the cooling region. In contrast to the non-resonant case, a resonant cavity, once critically coupled (impedance-matched), can be used to obtain near unity absorbance in the weakly-absorbing sample. In a proof-of-principle experiment, a laser was coupled to an external and length-stabilized cavity with an intra-cavity Yb:ZBLAN absorber resulting in 20 times absorption enhancement, corresponding to 93% absorbance by the sample[10]. However, the longitudinal mode instability of currently available pump lasers has limited this approach to cooling by 70 degrees[11].

Placing the cooling sample inside of a laser cavity can mitigate aforementioned problems of passive cavities. This was first demonstrated by cooling Yb:ZBLAN sample inside of a Yb:KYW laser by 6 degrees[12]. For cryogenic operation however, lasing exactly on the E4-E5 transition of Yb:YLF is required. Semiconductor-based vertical-external-cavity surface-emitting semiconductor lasers (VECSELs) are an excellent choice for gain medium in this case, as they offer lasing wavelength design flexibility (and tunability), high gains needed to surpass additional intra-cavity loss and an excellent beam quality.

2. VECSEL DESIGN AND PERFORMANCE

For laser cooling experiments, we designed a VECSEL gain chip as shown in Fig. 1: The DBR consists of 25 pairs of quarter-wave optical thickness AlAs/GaAs layers. Twelve InGaAs quantum wells (QWs) in a resonant periodic gain structure are placed at adjacent antinodes of the standing wave inside the semiconductor subcavity. The barrier between the QWs, typically GaAs, has been replaced with $GaAs_{0.97}P_{0.03}$ for strain compensation. The structure is completed by a lattice-matched InGaP window layer, transparent to both the VECSEL emission and pump light provides carrier confinement.

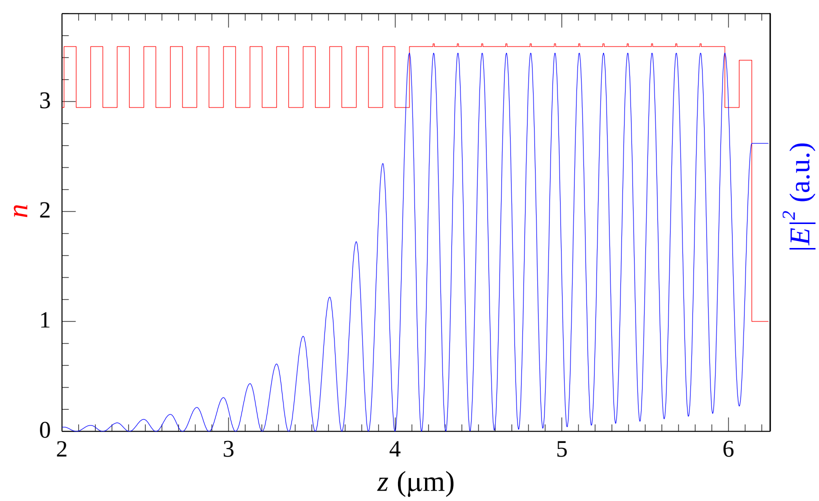

Figure 1. Index of refraction n and calculated electrical field strength E along the growth direction z of the 1020 nm VECSEL gain chip.

For thermal management necessary for high power operation, the DBR is metalized with Titanium, Gold, and Indium and soldered to a 300 µm thick thermal grade polycrystalline CVD-grown diamond heat spreader, metalized in the same way. Afterwards, the substrate is removed using a selective wet etch, utilizing the InGaP layer as an etch stop. The diamond is cooled using a water jet impingement cooler, where water from a 1 mm diameter nozzle cools the diamond plate directly behind the gain chip.

To test the VECSEL performance, a simple external cavity is set up, using a 25 cm radius of curvature output coupler of 1% transmission as external mirror, at a distance of approximately 24.5 cm from the gain chip. The resulting mode size at the VECSEL sample is matched to the roughly 300 µm diameter pump spot created by focusing the light from a fiber-coupled 808 nm pump diode. A schematic diagram of this setup is shown in Fig. 2.

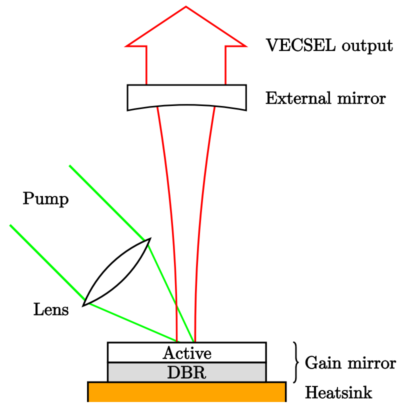

Figure 2. Schematic diagram of simple VECSEL test setup.

The VECSEL output power as function of the incident pump power curve is shown in Fig. 3(a). The achieved output power of approximately 10 W and the slope efficiency of the laser were limited by the not optimized output coupler transmission. No thermal roll-over was observed with the maximum available pump power of 70 W.

Lasing spectra for different pump powers are collected using an optical spectrum analyzer and shown in Fig. 3(b). Unfortunately, the VECSEL used in these experiments was operating at slightly longer wavelength than the 1020 nm it was designed for, and due to higher temperature as result of increased pump power, this mismatch increases with higher powers.

To estimate the maximum cavity loss the VECSEL can overcome while still reaching lasing threshold, a window was inserted into the external cavity close to Brewster angle, and the angle varied to controllably introduce increased loss. For a given pump power, the total output power vs. cavity loss is shown in Fig. 4, demonstrating that the VECSEL can support more than 10% of roundtrip loss while maintaining laser operation. This needs to be taken into consideration when choosing the laser cooling sample, or other losses in the cavity.

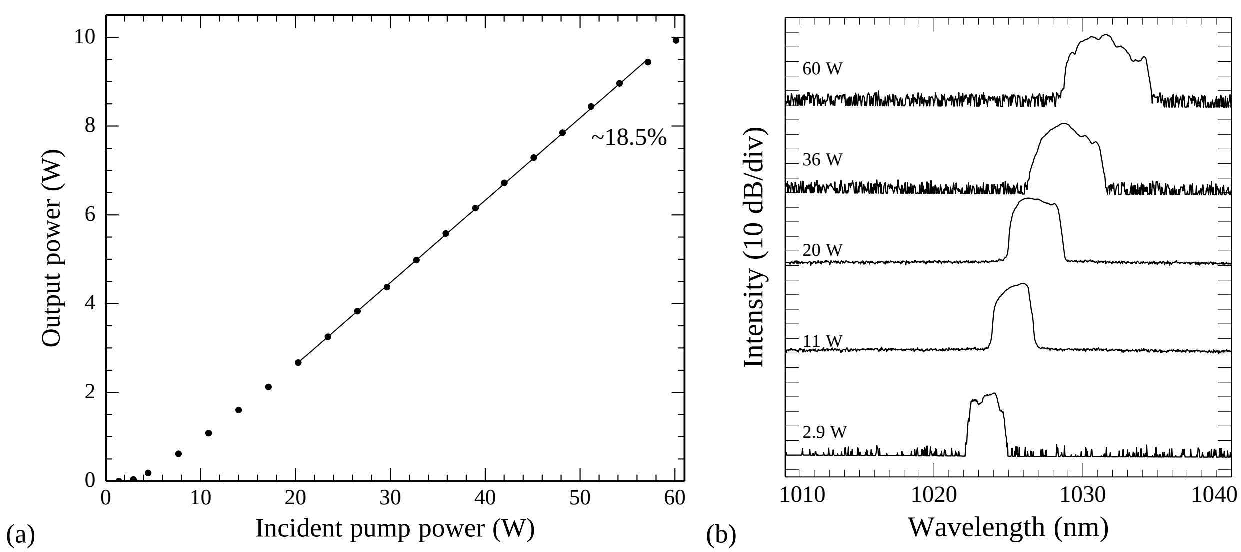

Figure 3. (a) VECSEL output power vs. incident pump power, (b) lasing spectra for different pump powers.

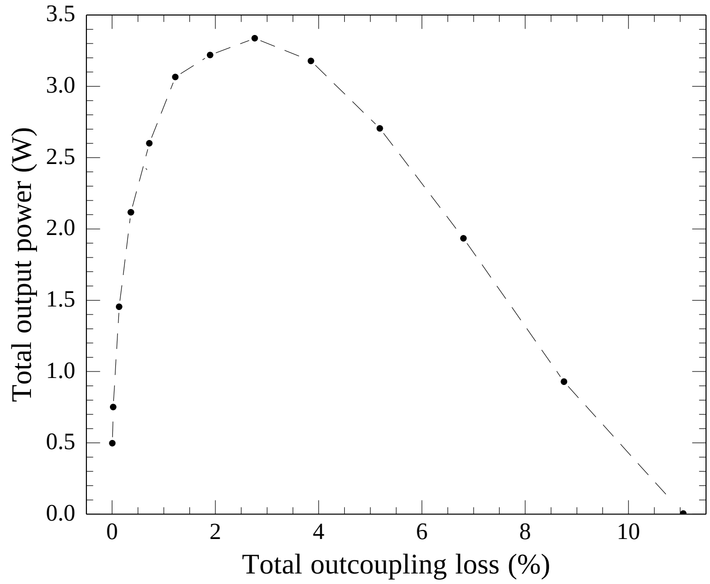

Figure 4. Total VECSEL output power from both sides of window and the external (high reflectivity) mirror, as function of total outcoupling loss.

3. LASER COOLING SETUP AND RESULTS

The cooling sample used in our experiment is a 5% Yb:YLF crystal of approximately 2.5x4x5 mm. Due to issues with the surface (polish) quality and/or flatness of the sample, intracavity use of the crystal was only possible for small laser mode sizes. Since the simple VECSEL cavity from Fig. 2 has the smallest beam diameter at the gain chip, the external cavity had to be expanded into a Z-shaped configuration as shown in Fig. 5. This design not only allows for the cooling sample to be placed at a beam waist of 200 µm, but also leaves enough space to put the YLF crystal (and one mirror) inside a small vacuum chamber, evacuated to 10^{-6} mbar using a turbopump, which effectively eliminates the convective heat load on the sample. To reduce conductive load, the sample was supported on three 300 µm diameter optical fibers.

We monitor sample temperature using differential luminescence thermometry (DLT): Fluorescence from the Yb:YLF crystal is collected through a window in the vacuum chamber using a multimode optical fiber and spectra recorded using a silicon CCD line grating spectrometer (Fig. 6(a)), and DLT is applied to monitor the sample temperature in real time (Fig. 6(b)). At an 808 nm pump power of 34 W the VECSEL intracavity power is monitored from the leakage through the curved high-reflecting mirror and estimated to be 8 W, of which approximately 6% or 460 mW is absorbed in the cooling sample. Pump power is increased in two steps to maximize cooling, with an estimated intracavity power or 10 W. After a total of 30 minutes of VECSEL operation, cooling by 20 K is demonstrated, as shown in Fig. 6(c).

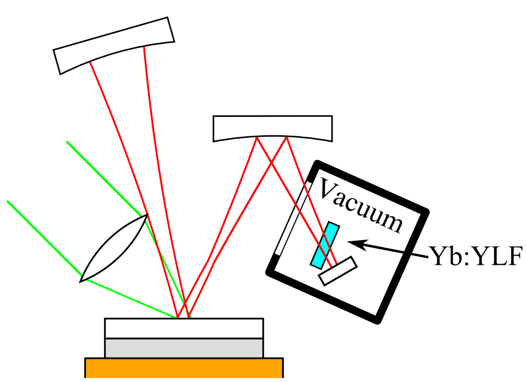

Figure 5. Schematic diagram of VECSEL cooling setup.

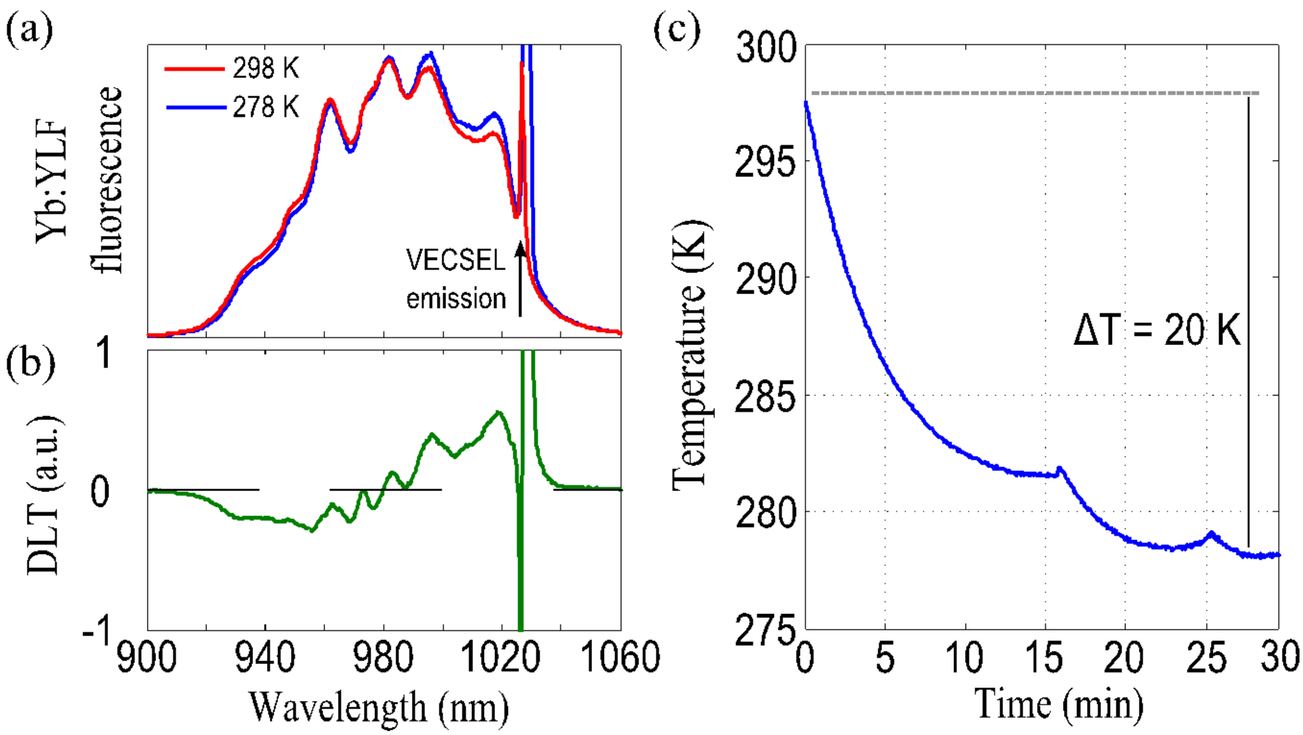

Figure 6. (a) YB:YLF luminescence as collected by CCD line spectrometer at initial and final temperature, (b) DLT signal at final temperature, (c) extracted sample temperature vs. time.

4. SUMMARY AND CONCLUSIONS

Laser cooling of solids is making rapid progress towards cryogenic temperatures. We report the design of a semiconductor based VECSEL as pump source at 1020 nm. We discuss the setup of a intracavity cooling experiment and report the observation of cooling of a Yb:YLF sample by 20 K using the VECSEL. This is a first step towards a compact, high-efficiency optical cryocooler.

5. ACKNOWLEDGMENTS

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