Laser Cooling of Solids Using High Power Vertical External-Cavity Surface-Emitting Lasers (VECSELs)

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Abstract: Laser cooling of solids is based on phonon-assisted anti-Stokes fluorescence. Spectrally narrow-band low-energy excitation photons produce energetically blue-shifted incoherent fluorescence emission, extracting heat from the lattice in the process and resulting in cooling of the solid. Optical cryocoolers have clear advantages over mechanical cryocoolers such as compactness, the absence of vibrations and moving parts or fluids, high reliability and the ability to operate without cryogens. Here, we have laser cooled a Yb^{3+}:YLF crystal to 131±1 K from room temperature by placing it inside the external cavity of a high power InGaAs/GaAs VECSEL operating at 1020 nm.

1. Introduction to laser cooling of solids

The idea of cooling a solid-state optical material by simply shining a laser beam onto it may seem counterintuitive, but it is rapidly becoming a promising technology for future cryocoolers. Cooling of solids by fluorescence upconversion was first proposed by German physicist Peter Pringesheim [1] in 1929 and was experimentally demonstrated in 1995 [2]. In this process an atom from the cooling material absorbs a photon with energy $h\nu$ and, on average, emits another photon with slightly higher energy $h\nu_f$ ($\nu_f > \nu$) (Fig. 1(a)). The excess energy is provided by the internal lattice vibrational energy of the material. The essential requirements for the cooling material are (1) high purity or low background absorption and (2) high external quantum efficiency, which effectively describes the fraction of excited atoms that decay into a fluorescence photon exiting the system. Thus far, rare-earth ions doped into a low-phonon energy, high purity host have shown the best cooling performance.

Assuming a high external quantum efficiency material, the cooling efficiency, defined as the ratio of cooling power to the absorbed power, is given by [2]

$$\eta_c(\nu,T) = \frac{P_{cool}}{P_{abs}} = \left[\frac{1}{1+\alpha_b/\alpha_r(\nu,T)}\right]\frac{\nu_f(T)}{\nu} - 1 \qquad (1)$$

where $\alpha_r(\nu,T)$ is the active ion's resonant absorption coefficient, $\nu_f(T)$ is mean fluorescence frequency, and α_b is the background absorption which is due to unwanted contaminants and impurities. Figure 1(b) shows the cooling efficiency contour map for a 7% Yb:YLF crystal, cooled in this work. The lowest achievable temperature for this crystal is calculated to be ≈100 K at the optimal wavelength of 1020 nm.

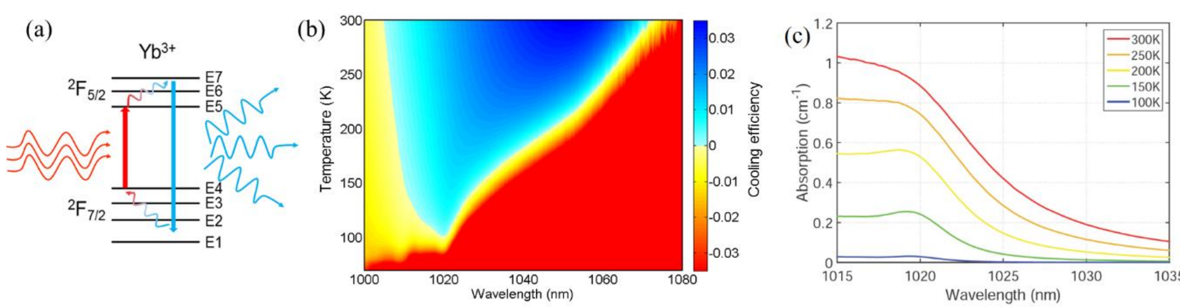

Figure 1. (a) Schematic of the Stark manifold and the cooling E4-E5 transition in Yb^{3+} ion; (b) temperature dependent spectroscopic cooling efficiency (Eq. 1) for a 7% Yb:YLF crystal with background absorption of 3×10^{-4} cm^{-1} and external quantum efficiency of 99.5 %. Red regions denote heating and blue regions cooling, with a global minimum temperature of around 100 K at the optimal wavelength of 1020 nm; (c) The resonant absorption coefficient of a 7% Yb:YLF at different temperatures as a function of wavelength. Because of the Boltzmann distribution of electrons in the ground and excited states, as the temperature drops the absorption coefficient also drops considerably.

Since the resonant absorption coefficient in the cooling sample is highly temperature dependent (Fig. 1(c)) and reduces drastically with decreasing temperature due to the Boltzmann distribution, increasing the absorption in the cooling sample is key to achieving low temperatures. Thus far, absorption enhancement has been performed utilizing resonant [3] and non-resonant cavities, with non-resonant cavities resulting in the lowest temperature [4]. In the non-resonant cavity absorption enhancement method, the cooling sample is placed between two highly reflecting mirrors and the pump laser light, coupled into the cavity through a small hole in one of the mirrors, is passed as many times as possible through the cooling sample. The crystal size and the cavity geometry limit the number of passes going through the crystal. Enhancement via resonant cavity is performed by inserting the sample inside a Fabry-Perot cavity and applying the critical-coupling condition. This method relies on the operation of a high power, highly stable laser with narrow line-width, the combination of which is a hard condition to satisfy in practice. In this work, we have focused on the enhancement of the absorbed power in the cooling sample by placing it inside the external cavity of a VECSEL. This technique has the advantages of high intra-cavity power, multi-passing property through the cooling sample and the ability to match the loss introduced by the cooling sample to the optimal loss of the laser and hence efficiently absorb the intra-cavity laser into the cooling sample.

2. Intra-cavity laser cooling setup and results

VECSELs are optically pumped semiconductor lasers (OPSLs) which consist of a multi-quantum well gain region on top of a distributed Bragg reflector (DBR) which acts as a back mirror [5]. VECSELs have successfully combined high output powers of semiconductor lasers with excellent beam quality. Our VECSEL is grown on GaAs substrate and consists of 12 GaAs/InGaAs quantum wells followed by 25 pairs of AlAs/GaA DBR layer. Figure 2(a) shows a schematic diagram of the experimental setup for intra-cavity laser cooling. To reduce convective heat load and hence to maximize temperature drop in the cooling sample, the laser cooling experiments are carried out under vacuum. The cooling sample is supported on two very thin microscope slides to minimize the contact area and hence reduce the conductive heat load. We have used a 20 cm highly reflecting mirror to complete our laser cavity and placed the cooling sample between the VECSEL gain chip and external mirror. A birefringent filter is used to tune the wavelength of the VECSEL to the optimal wavelength for the cooling (1020 nm). A 75 W fiber-coupled 808 nm diode laser is used to pump the VECSEL. We measure the temperature of the sample through a non-contact high-accuracy method called differential luminescence thermometry [4]. In a cooling experiment performed using the described setup, we were able to cool the 7% Yb:YLF crystal from room temperature to 131 K in about 6 minutes (Fig. 2(b)).

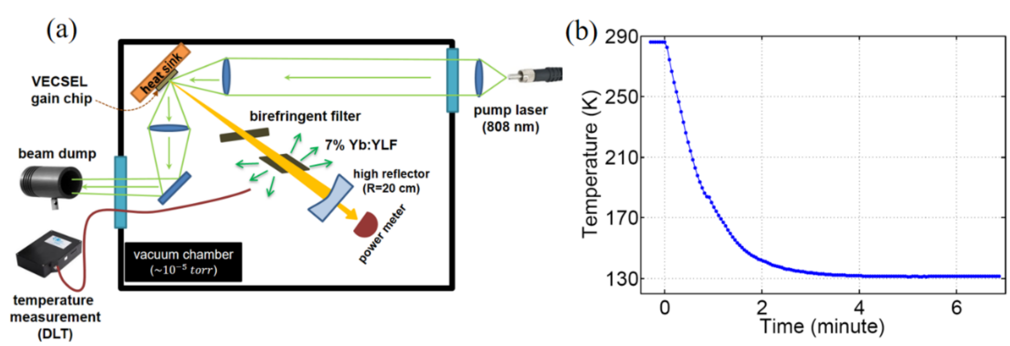

Figure 2. (a) Schematic diagram of the VECSEL intra-cavity laser cooling experiment. The experiments are done under vacuum to minimize the convective heat load. The birefringent filter is used to tune the wavelength of the VECSEL to 1020 nm, the optimal wavelength for cooling of Yb:YLF crystal; (b) temperature of a 7% Yb:YLF cooling sample as a function of time. The sample temperature reached 131 K after 6 minutes.

References

[1] P. Pringesheim, "Zwei bemerkungen ueber den unterschied von lumineszenz- und temperaturstrahlung," Z. Phys. 57, 739-764 (1929).

[2] R. Epstein and M. Sheik-Bahae, *Optical Refrigeration: Science and Applications of Laser Cooling of Solids*, 1st ed. (Wiley-VCH, 2009).

[3] D. V. Seletskiy, M. P. Hasselbeck, and M. Sheik-Bahae, "Resonant cavity-enhanced for optical refrigeration," Appl. Phys. Lett. 96, 181106 (2010).

[4] S. D. Melgaard, D. V. Seletskiy, A. Di Lieto, M. Tonelli, and M. Sheik-Bahae, "Optical refrigeration to 119 K, below National Institute of Standards and Technology cryogenic temperature," Opt. Lett. 38, 1588-1590 (2013).

[5] Oleg G. Okhotnikov, *semiconductor disk lasers: physics and technology*, 1st ed. (Wiley-VCH, 2010).