Laser cooling of a semiconductor load to 165 K

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Abstract: We demonstrate cooling of a 2 micron thick GaAs/InGaP double-heterostructure to 165 K from ambient using an all-solid-state optical refrigerator. Cooler is comprised of Yb^{3+}-doped YLF crystal, utilizing 3.5 Watts of absorbed power near the E4-E5 Stark manifold transition.

OCIS codes: (160.5690) Rare-earth-doped materials; (140.3320) Laser cooling.

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1. Introduction

Laser cooling of solids or optical refrigeration is based on anti-Stokes fluorescence [1]. With laser light tuned to the wavelengths just above mean emission wavelength (λ_f) of the transition, the subsequent fluorescence upconversion requires phonon absorption in order to establish quasi equilibrium. The efficient escape of the fluorescence then carries heat and entropy away from the material resulting in net cooling [2,3]. The essential conditions for achieving this cooling in solids are availability of high quantum efficiency transition and extremely high purity materials. The former requirement can be satisfied for rare-earth ions in hosts with low phonon energy such as fluoride or chloride glasses and crystals.

Net optical refrigeration was first demonstrated in a Yb-doped glass by Epstein et al. in 1995 [4]. Since then, much progress has been made in cooling a variety of glass and crystal hosts, doped with rare-earth ions of Yb, Tm and Er [2,3 and references within]. Despite tremendous theoretical [5–9] and experimental [10–13] progress, no direct net cooling has been observed in semiconductors in large due to the stringent high purity requirement.

Since the first observation of optical refrigeration, its implication for achieving an all-solid-state cryocooler, that surpasses the performance of thermoelectric (TE) coolers, was discussed. Currently, standard TE or Peltier coolers can marginally reach 170K with diminishing efficiency. Only mechanical coolers and/or using cryogens can deliver lower temperatures. In the recent work on cooling Yb-doped YLF crystal to 155K [14] the temperature barrier set by TE coolers has been surpassed thus materializing one of the essential goals of optical refrigeration. Here we report another milestone by demonstrating Yb:YLF optical refrigerator to cool a payload to 165 K. This work serves as a proof-of-principle demonstration of the feasibility of optical refrigeration to be a viable vibration-free cooling technology that is also immune to electromagnetic interference. While current results already improve over TE cooler performance, temperatures near liquid nitrogen are predicted with modest improvements in material quality [14].

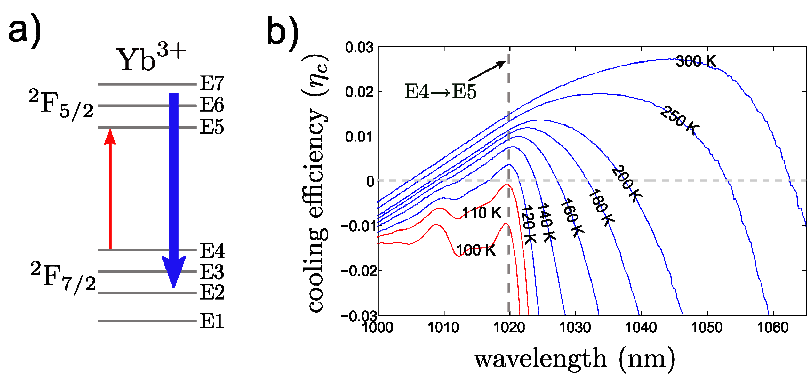

Fig. 1. (a) Stark manifold and the cooling E4-E5 transition in Yb; (b) Spectra of cooling efficiency (Eq. (1) of the Yb:YLF for different temperatures in degree Kelvin with measured values of η_{ext} = 0.995 and α_b = 4.2*10^{-4} cm^{-1} [14]. Spectra for which cooling is possible are shown in blue; cooling ceases for temperatures below minimum achievable temperature (red). Cooling efficiency is enhanced near the E4-E5 transition (1020 nm), yielding minimum achievable temperature of ~115 K.

The cooling efficiency, defined as the ratio of the cooling power (P_c) to the absorbed laser power, has been given as [2]

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$$\eta_c(\lambda,T)=\eta_{ext}\left[\frac{1}{1+\dfrac{\alpha_b}{\alpha(\lambda,T)}}\right]\frac{\lambda}{\lambda_f(T)}-1, \quad (1)$$

where η_{ext} is the external quantum efficiency (EQE) defined as the fraction of excited ions that lead to a fluorescence photon exiting the host material. The absorption coefficients $\alpha(\lambda,T)$ and α_b are associated with the cooling transition of the active ion (e.g. Yb^{3+}), and the background parasitic absorption. Rare-earth ions in low phonon energy hosts (such as fluorides) have provided high η_{ext} (> 99%), making them ideal candidates for laser cooling. However, what ultimately limits the minimum achievable temperature is that only a fraction of absorbed photons lead to an excitation of cooling transition. This quantity, also known as the absorption efficiency η_{abs}, is indicated by the bracketed term in Eq. (1), which depends on the ratio $\alpha_b/\alpha(\lambda,T)$. As the temperature is lowered, the cooling efficiency decreases due to primarily two factors: decreasing of the resonant absorption and red-shifting of $\lambda_f(T)$, as a consequence of Boltzmann distribution of excitations in the ground- and excited states respectively. The background absorption originates from unwanted contamination such as transition metals, and is taken to be temperature independent and broadband within the spectral region of cooling transition [15].

Enhancement of the absorption efficiency is possible either by decrease of background absorption or by enhancement of the resonant absorption. Such enhancement is available in hosts with long range order – i.e. crystals, due to homogeneous broadening associated with the Stark manifold states, hence preserving the oscillator strength of the transitions. Figure 1 shows cooling efficiency spectra (Eq. (1)) at different temperatures for an optical $^2F_{7/2}$ – $^2F_{5/2}$ transition in Yb^{3+}-doped YLF crystalline host (5% doped, excitation is polarized along the c-axis). As is evident from the figure, cooling efficiency is enhanced at 1020 nm, corresponding to E4-E5 Stark manifold transition. In a recent set of experiments, by exciting Yb:YLF sample near the E4-E5 transition (1023 nm) with 9 Watts of incident power we demonstrated cooling to 155K [14]. This sample is grown by Czochralski method resulting in high-purity (low background absorption) material [16].

2. Experiment and results

In this work, we exploit Yb:YLF optical refrigerator to cool a load comprised of a GaAs semiconductor passivated by GaInP cladding in a double heterostructure geometry with high external quantum efficiency. The payload material is chosen such that the mean luminescence wavelength of the Yb emission is above the band-edge absorption of the semiconductor even at room temperature, making the payload optically transparent to the fluorescence. This allows for direct thermal contact of the heterostructure with the crystal surface by means of a thin and nominally transparent high conductivity adhesive layer. Load thickness is 2 μm with the diameter of 0.8 mm corresponding to a weight of ~5 micrograms.

Temperature of an optical refrigerator and load is deduced by simultaneously monitoring the fluorescence spectrum of Yb:YLF and GaAs band-edge emission. Figure 2 outlines experimental setup [17,18] where a continuous wave Yb:YAG thin-disk laser, delivering 9W at 1023 nm, excites the Yb:YLF crystal in a non-resonant cavity geometry. Blackbody thermal load is minimized by housing the cryocooler assembly in a tightly fit clamshell inside of which is coated with a low thermal emissivity coating that is highly absorbing for the near IR and visible radiation [19,20].

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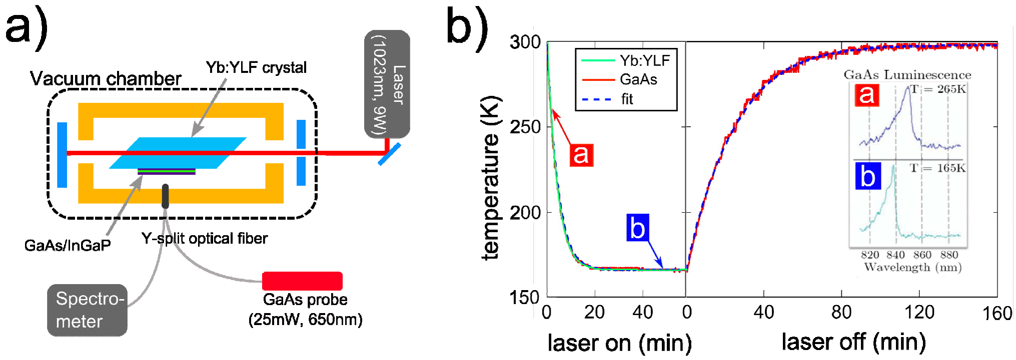

Fig. 2. (a) Schematic of experimental setup; (b) Temperature of the crystal (Yb:YLF) and GaAs load as a function of time. High power laser is incident at t = 0 min, following by turn-off at t ~55min, when steady state was achieved, time is re-zeroed after the laser is turned off. Both Yb:YLF and GaAs temperatures are deduced by non-contact techniques. The cooling and warming dynamics are fitted with single exponential curves. Inset shows GaAs/InGaP spectra at two corresponding points (a: T = 265K, b: T = 165K).

A y-split optical fiber is fed-through the vacuum chamber in order to collect fluorescence of the Yb:YLF crystal excited by the pump laser and GaAs luminescence, excited by the weak laser diode that is coupled at one of the fiber ports on the ambient side. Second port is used to spectrally resolve both emission signals in a spectrometer in real time (Fig. 2(a)). Temperature of the Yb:YLF is determined by differential luminescence thermometry (DLT) technique [21], where raw signal is obtained by integrating spectral difference of the two luminescence signals: at known (reference) and unknown temperatures. The scalar integral value is converted to temperature by means of a separate calibration experiment performed in the optical cryostat with experimental accuracy of ± 1 degree [14]. GaAs temperature is deduced from the well-known temperature dependence of the band-gap [22]. In this method temperature accuracy is limited by the wavelength resolution of the spectrometer and is less than ± 2 degrees at low temperatures.

Cooling of Yb:YLF with GaAs load is shown in Fig. 2(b). After nearly 30 minutes of laser irradiation, a steady-state temperature of 165 K is reached by both the cryocooler and the payload. The fact that both cooler and load are at nearly the same temperature proves that no substantial thermal gradient exists between them. The cool-down and warm-up (rise) times are fitted with single exponential curves via least-squares algorithm. As is shown below, these fits provide a straightforward way of estimating the cooling and parasitic load powers in the Yb:YLF cryocooler.

It should be noted that an earlier attempt at cooling a thermal load using optical refrigeration in Yb-doped ZBLAN glass had resulted in a temperature drop of 12 degrees below ambient [23]. The achieved here temperature of 165 K is colder than the benchmark of standard thermoelectric coolers. Without the load, the bare YLF crystal has cooled to 155 K in a separate experiment [14]. As discussed below, this small discrepancy is attributed to increased parasitic absorption due to the adhesive as well as GaAs double heterostructure itself.

3. Analysis of the Temperature Dynamics

Next, we analyze the temperature evolution of the system. Under high vacuum ($<10^{-4}$ torr) conditions, the dominant thermal load on the sample is assumed to be radiative or black-body (BB), and from the 6 fiber supports that hold the sample in place within the chamber. Due to high thermal conductivity of the YLF crystal, the sample reaches a uniform temperature within a second or so. We, therefore, ignore the initial dynamics and consider temperature evolution of the whole sample at larger time scales determined by the aforementioned thermal loads as given by:

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$$C(T)\frac{dT}{dt} = -\eta_c(\lambda,T)P_{abs}(\lambda,T) + \frac{\varepsilon_s A_s \sigma}{1+\chi}(T_c^4 - T^4) + \frac{N\kappa_L(T)A_L}{d_L}(T_c - T). \quad (2)$$

Here $C(T) = \rho c_v (T) V_s$ is the heat capacity of the cooling sample (YLF) in terms of its density (ρ), temperature-dependent specific heat from Debye theory ($c_v(T)$), and sample volume V_s. The first term in the right hand side of Eq. (2) is the driving term which is the total cooling power in terms of cooling efficiency (η_c, Eq. (1)) and the absorbed laser power (P_{abs}), both varying with wavelength and temperature. The second term is the black-body radiation load with σ denoting Stefan-Boltzmann constant (= 5.67 × 10^{-8} W/m^2/K^4). In our case, this radiative load is lowered by using the low thermal emissivity coating on the chamber walls by a factor of 1 + χ where $\chi = (1-\varepsilon_c)\varepsilon_s A_s/\varepsilon_c A_c$, with ε_j and A_j (j = s,c) denoting the thermal emissivity and the surface areas of the sample and chamber respectively [24]. The last term on the right accounts for the thermal conductivity through the N fiber support links each having area A_L, length d_L, and thermal conductivity κ_L. Once the Debye temperature of the Yb:YLF is fixed [25], the only free parameters describing the temperature dynamics are the warm-up time-constant $\tau_L = Cd_L/(N\kappa_L A_L)$ and factor χ. Due to non-trivial temperature dependent coefficients, we fit Eq. (2) numerically to obtain cooling (with the driving term) and warm-up (no driving term) dynamics. By fitting the temperature evolution in the warm-up regime, parasitic loads can be estimated without having to include the cooling power dynamics itself. This fit yields τ_L ~800 min and χ = 2.1, for A_s~1.5 cm^2, ε_s~0.8, ρc_v (YLF)~3 J/K/cm^3 (at 300 K) and V_s = 0.3x0.3x1~0.1 cm^3. The fact that τ_L is much longer than the time scale of the experiment suggests the black-body is the dominant load on the sample (Fig. 3(a)), consistent with the earlier findings [14] and further supported by additional experiment where removal of the two (out of the six) support fibers did not change the final temperature achieved. The χ parameter is lower than previous estimates [20], suggesting the need to improve the low-thermal emissivity coating characteristics.

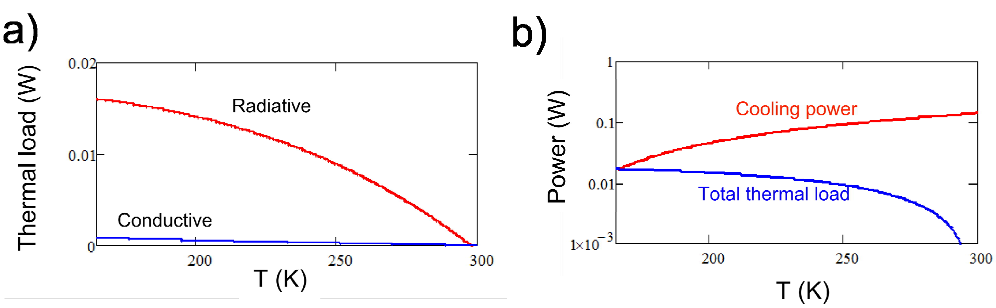

Fig. 3. (a) Comparison of temperature-dependent radiative and conductive thermal loads, as obtained from fitting the warm-up dynamics (Fig. 2b); (b) Comparison of cooling and total thermal load powers in the current Yb:YLF cryocooler, as estimated from the fits of full dynamics (Fig. 2b): at T = 300K, cooling power of 150mW is available, diminishing to a stready-state value of 20 mW at T = 165 K.

The temperature dependence of the cooling power (driving term) is also determined directly from the fits. At room temperature a cooling power of 150 mW is available for the given pumping conditions. The cooling power diminishes as temperature is decreased, reaching a balance with the parasitic load (steady-state) at T = 165 K, with the cooling power of 20 mW (Fig. 3(b)). It should be noted that the temperature dependence of the cooling power can also be estimated from the known cooling efficiency (Eq. (1)) and the absorbed power [14]. At ambient we obtain P_{cool} = 140 mW, in good agreement with the fitting results. At low temperature however we obtain agreement with the temperature dynamics only if we increase the background absorption by factor of 4 (Eq. (1)). We attribute such increase due to the parasitic absorption in the material of the load as well as the adhesive used for attachment. Finally, we note that GaAs absorption spectrally overlaps with the upconverted emission due

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to other rare-earth species in the Yb:YLF crystal which can also be responsible for the deduced increase in the background absorption.

4. Summary

We have cooled a semiconductor load by means of an optical refrigerator to a temperature of 165K, utilizing E4-E5 Stark manifold transition. This is a first demonstration of cooling a payload with an optical refrigerator, surpassing the performance of a standard thermoelectric cooler. Analysis of the temperature evolution points to the fact that radiative load needs to be decreased in order to achieve lower temperatures.

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