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Demonstration of an Optical Cryocooler

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Abstract: We present the first observation of cryogenic operation in an all-solid-state refrigerator. A temperature drop of ~150 K is demonstrated in a 0.2 cm^3 rare-earth doped fluoride crystal (Yb:YLF) using fluorescence upcoversion, at a record cooling power of 110 mW. Lowest electronic transition within Yb^{3+} Stark manifold along with cavity enhanced absorption and thermal-load management were key in achieving this operation. We show that temperatures down to 100 K are achievable in this arrangement given sufficient absorbed laser power at 1020 nm.

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The process of optical refrigeration is based on anti-Stokes fluorescence. 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 [1,2]. 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.

Assuming high quantum efficiency materials, the cooling efficiency, defined as the ratio of power heat lift to the absorbed laser power is given by [1,2]

$$\eta_c(\lambda,T) \approx 1-\frac{\lambda}{\lambda_f(T)}\left(\frac{1}{1+\alpha_b/\alpha(\lambda,T)}\right), \qquad (1)$$

where wavelength and temperature dependence of resonant absorption (α) are shown explicitly. Background absorption (α_b) is mainly due to unwanted contaminants, such as transition metal impurities, which is taken to be nearly wavelength and temperature independent. Small ratio of background to resonant absorption is thus desirable to maximize cooling efficiency. The first material that was shown to satisfy this requirement was Yb^{3+} doped fluorozirconate glass Yb:ZBLAN, which in 1995 was cooled by 0.3 K at Los Alamos [3]. The efforts culminated in a long-standing record of cooling 90 degrees below room temperature with heat lift of 29 mW [4]. While fluorozirconate glasses can be synthesized with high purity,

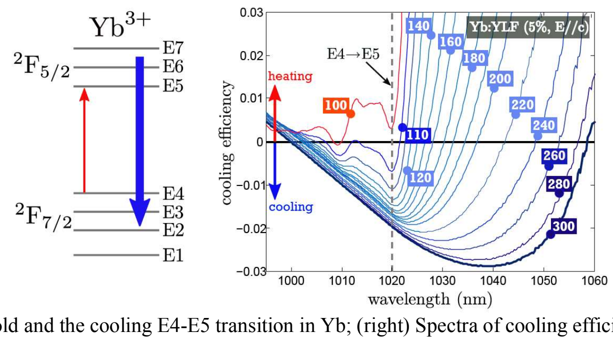

Fig 1: (left) Stark manifold and the cooling E4-E5 transition in Yb; (right) Spectra of cooling efficiency (Eq. 1) of the Yb:YLF for different temperatures in degree Kelvin (boxed values).

high dopant concentrations are not stochiometrically allowed. Furthermore, the large inhomogeneous broadening leads to diminishing resonant absorption at low temperatures. Such shortcomings can be drastically improved in certain fluoride crystals where higher doping concentrations together with crystal field splitting lead to sharp Stark manifolds with much higher absorptions at the cooling wavelengths.

Our detailed spectroscopic analysis of the cooling efficiency (Eq. 1) in a high purity 5% doped Yb:YLF crystal (Czochralski growth) predicts a minimum achievable temperature of ~105 K at 1020 nm (Fig 1, right) for α_b=4e-4 cm^{-1}, determined from an independent measurement [5]. The resonant absorption feature at 1020 nm is crucial for Yb:YLF performance as an optical refrigerator in that it maintains $\alpha_b/\alpha(\lambda,T)$ low enough for cryogenic operation to be possible . This transition corresponds to E4-E5 resonance of the Yb^{3+} Stark manifold as shown in Fig. 1(left) [6].

Experimental setup is outlined in Fig. 2 (left) and detailed elsewhere [5]. A CW thin-disk Yb:YAG laser (40 W, 1030 nm) is optically isolated from and mode-matched via lens pair (MML) to a resonant cavity that is placed inside a high vacuum chamber. A Brewster-cut Yb:YLF crystal (E//c, 5% doped) of length L_c= 1.1 cm, is positioned inside the cavity with a partially-reflective (R_{ic}) input-coupler and a highly reflective back mirror. Optical impedance matching condition $R_{ic} = \exp(-2\alpha(\lambda,T)L_c)$ corresponds to total absorption on resonance and is beneficial for small absorption coefficients, e.g. energetically below the E4-E5 transition and/or at low temperatures. For a given cooling power, lower temperatures are achieved by minimizing the thermal load which is predominantly of black-body nature. This is accomplished by placing the crystal into a tightly-fit copper clamshell structure which is coated inside with a low thermal emissivity material that is also highly absorbing at the fluorescence wavelengths. Sample is mechanically supported by seven optical fibers protruding from the clamshell walls, thus minimizing the adverse conductive heat load. Sample temperature is monitored using non-contact differential luminescence thermometry (DLT) technique [2] which deduces the temperature from corresponding variations of fluorescence spectrum.

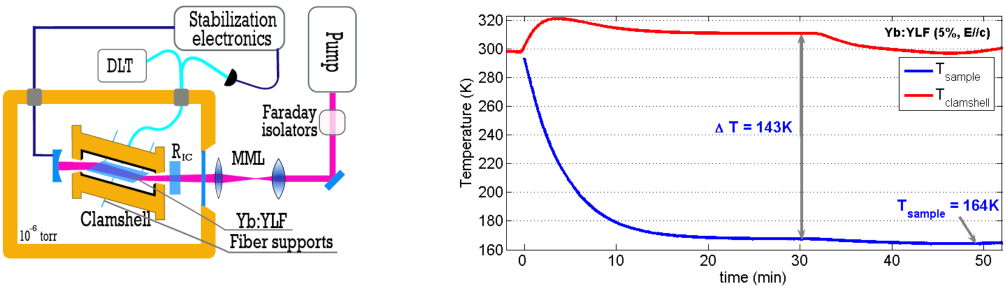

Fig 2: (left) Schematic of experimental setup; (right) Experimental demonstration of feasibility of an optical cryocooler.

Using active cavity stabilization outlined in Fig. 2 we have shown cooling by 70 K at 1030 nm [5]. In this work, we tune the laser to nearly overlap with E4-E5 resonance and maximize absorption via 4-pass non-resonant cavity geometry. Temperature dynamics of sample and clamshell are shown in Fig. 2 (right), resulting from 15.5 W laser excitation at 1022 nm turned on at t=0. Sample is seen cooling, while clamshell temperature is increasing due to heat deposition from the emitted anti-Stokes luminescence. Steady state is reached after 30 minutes, where sample has exhibited temperature drop of nearly *145 K* with respect to clamshell being at 310 K. By cooling the clamshell back to ambient, sample has reached cryogenic temperature of *164 K,* where the heating load is estimated to be 110 mW, down from nearly 300 mW of heat lift at room temperature. Both sample temperature and cooling power by far set new records in performance for solid-state laser cooling.

This result sets a major milestone in demonstrating all-solid-state cryocooler as a viable alternative to more traditional thermoelectric coolers. Temperature differential and heat lift shown in Yb:YLF cryocooler already surpass commercially available multistage TE coolers [7]. It should be emphasized that our current results are only limited by available laser power, which drops precipitously due to large detuning from the peak gain of the lasing medium. Resonant cavity absorption scheme is readily available to further maximize absorbed power in order to approach minimum achievable temperature as determined by sample-intrinsic background absorption level. With these and crystal growth improvements, absolute temperatures near 100 K are within reach.

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