Optical Cooling of a Large Core Diameter Yb:SiO$_2$ Fiber to 18 K Below Ambient Temperature: A New World Record

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Abstract Laser cooling of ytterbium doped silica glass by anti-Stokes fluorescence to 18 Kelvin below room temperature has been observed. This milestone achievement breaks the record for cooling a silica fiber by two orders of magnitude. Our new record demonstrates the viability of using silica as a material for radiation-balanced fibers and amplifiers. Numerical simulations using the parameters of the experimentally investigated fiber indicate the potential of a self-cooled laser outputting multiple watts.

Introduction

When an ultra pure rare-earth doped solid is pumped at a wavelength longer than the mean fluorescence wavelength, the anti-Stokes fluorescence (ASF) has the potential to extract heat [1]. Cooling by ASF after illumination with coherent light is prerequisite to the construction of a radiation balanced laser (RBL) [2]. In 1995, Epstein et al. reported the first experimental observation of net solid state cooling in a ytterbium doped fluoride (ZBLANP) glass [3]. Recently, laser cooling of silica has been shown to be possible from a theoretical standpoint [4]. Shortly after, laboratory experiments confirmed the viability indicating the durable host is a viable material for radiation balancing lasers and amplifiers [5, 6, 7, 8].

Experimental

Experiments were carried out on a high-purity Yb doped silica fiber pulled from a preform fabricated by the modified chemical vapor deposition technique. The glass is doped with $6.56 \times 10^{21}$ Yb$^{3+}$ ions/m$^3$ and co-doped with Al$^{3+}$ and F$^−$. Most of the passive cladding was stripped from the preform, resulting in a drawn fiber with a core diameter of 900 microns and a cladding diameter of 1000 microns. The fiber exhibits very low background absorption, with $\alpha_c (\lambda = 1200 \text{ nm}) = 10 \text{ dB/km}$, which has been found to be suitable for laser cooling in SiO$_2$ [5, 6].

Laser cooling was investigated using a 1035 nm seed from a Ti: Sapphire source that was amplified to between 1 W and 20 W using a homemade fiber amplifier. Conductive heating with the surroundings was minimized by supporting the fiber with ultra-thin rods. For some trials, convective heating was minimized by performing experiments in a vacuum cube held near 10 torr. Time-resolved temperature measurements were made perpendicularly to the optical axis of the fiber using a thermal camera and spectrometer. A calibration between the fiber temperature and the luminescence spectral form with 1035 nm excitation was carried out using a temperature controlled plate over the range 5°C to 55°C. Thus, in the event of thermal camera saturation, the fiber temperature could be accurately described by the differential luminescence thermometry technique (DLT) [9].

Results

We investigate the application of the tested fiber by carrying out laser simulations on a 25 cm length of fiber. The pump wavelength is set to 1030 nm and varied between 80 W and 100 W with a 2 W step size. The output mirror reflectivity is centered at 1590 nm and varied between 88% and 95% with a step size of 0.5%. From the simulated propagating pump and signal powers, the heat density is computed using the formalism in Ref. [10] and then converted to temperature in Kelvin via the approach in Ref. [11]. Selecting one set of values of the simulation results as an example, for $R_p = 0.95$ and $R_s (c = 0) = 100$ W the theoretical output is 6.7 W coinciding with a computed heat density of -0.1 W/cm$^3$. This corresponds to a temperature drop relative to the surroundings of $\Delta T = -0.4$ K at the end of the fiber during laser operation.

Summary

A large core diameter silica fiber has been cooled, in multiple experiments, by more than 10 K relative to ambient temperature. The cooling of silica by 18 K from room temperature brings with it a positive outlook for the future of high power radiation balancing devices.

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Outlook

We demonstrate the relationship between the experimental data and Eq. 1, the case of the 12 W pump is shown in Fig. 5. To demonstrate the relationship between the experimental data and the theoretical output is 6.7 W coinciding with a computed heat density of -0.1 W/cm$^3$. This corresponds to a temperature drop relative to the surroundings of $\Delta T = -0.4$ K at the end of the fiber during laser operation.

References