Implementation of Laser-Induced Anti-Stokes Fluorescence Power Cooling of Ytterbium-Doped Silica Glass

Mostafa Peysokhan, Saeid Rostami, Esmaeil Mobini, Alexander R. Albrecht, Stefan Kuhn, Sigrun Hein, Christian Hupel, Johannes Nold, Nicoletta Haarlammert, Thomas Schreiber, Ramona Eberhardt, Angel Flores, Andreas Tünnermann, Mansoor Sheik-Bahae, and Arash Mafi*

Cite This: ACS Omega 2021, 6, 8376−8381

ABSTRACT: Laser cooling of a solid is achieved when a coherent laser illuminates the material, and the heat is extracted by annihilation of phonons resulting in anti-Stokes fluorescence. Over the past year, net solid-state laser cooling was successfully demonstrated for the first time in Yb-doped silica glass in both bulk samples and fibers. Here, we report more than 6 K of cooling below the ambient temperature, which is the lowest temperature achieved in solid-state laser cooling of silica glass to date to the best of our knowledge. We present details on the experiment performed using a 20 W laser operating at a 1035 nm wavelength and temperature measurements using both a thermal camera and the differential luminescence thermometry technique.

INTRODUCTION

The possibility of heat extraction from sodium metal vapor via anti-Stokes fluorescence (ASF) was first suggested by Pringsheim in 1929.1 Nearly 7 decades later, in 1995, Epstein et al. reported the first experimental observation of laser-induced ASF cooling of a solid in Yb-doped ZBLANP (ZrF₄−BaF₂−LaF₃−AlF₃−NaF−PbF₂).2 Several attempts have since confirmed laser cooling in various solid-state materials, primarily in rare-earth-doped (RE-doped) crystals and glasses. Laser cooling of RE-doped crystals has been the most successful so far;3−6 the record cooling of a Yb-doped YLiF₄ (Yb:YLF) crystal was reported at the University of New Mexico in 2016.7 Several RE-doped glasses have been successfully cooled over the years;8−15 Yb-doped silica glasses are the most recent additions to the list of successfully cooled RE-doped materials.16,17,24 Although laser cooling of RE-doped silica was thought to be elusive over the years, recent investigations pointed out its possibility18−20 and eventually led to its experimental observation.16,17,21−24 In all these reports, the temperature drop of the laser-cooled Yb-doped silica was less than 1 K. Here, we present, to the best of our knowledge, the largest temperature drop to 6 K below room temperature.

There are many potential applications for optical cooling through ASF. In principle, it can be used for compact, vibration-free refrigeration systems,5,8 for example, when precision cooling is demanded in low-thermal-noise detectors and reference cavities of ultrastable lasers, or even in physiological applications.24 One can even envision laser-cooled silica’s potential usage as the substrate in silicon photonics devices.25−28 Another important potential application for ASF cooling is in radiation-balanced fiber lasers (RBFLs), where ASF cooling balances the waste heat generated in the laser.29−34 Historically, RE-doped ZBLAN glasses have been more amenable to the stringent requirements needed for laser cooling. Unfortunately, ZBLAN fibers are low in mechanical durability and chemical stability and hard to cleave and splice, so they are generally less desirable than silica fibers. However, the recent advances in laser cooling of Yb-doped silica glass open a potential pathway for future applications in RBFLs. Of course, much more substantial cooling is required to make a viable impact on fiber laser designs; this paper is a step in this direction.

REVIEW OF THE RECENT RESULTS

The cooling efficiency, η_c, characterizes the potential of a material to cool via laser-induced ASF. It is defined as the net power density (per unit volume) extracted from the material (p_net) per unit total absorbed power density (p_abs). The cooling efficiency is a function of the pump laser wavelength λ_p and can be expressed as16

Received: January 7, 2021
Accepted: March 8, 2021
Published: March 18, 2021
The mean fluorescence wavelength is represented as $\lambda_f$. The external quantum efficiency, $\eta_{\text{ext}}$, and the absorption efficiency, $\eta_{\text{abs}}$, are defined as

$$\eta_{\text{ext}} = \frac{\eta_{\text{ext}} W_f}{\eta_{\text{ext}} W_f + W_{nr}} \quad \eta_{\text{abs}}(\lambda_p) = \frac{\alpha_f(\lambda_p)}{\alpha_f(\lambda_p) + \alpha_b}$$

where $W_f$ and $W_{nr}$ are the radiative and non-radiative decay rates of the excited state in the RE dopant, respectively, and $\eta_f$ is the fluorescence extraction efficiency. $\alpha_f$ is the background absorption coefficient, and $\alpha_f(\lambda_p)$ is the resonant absorption coefficient due to the RE dopants. Note that the attenuation due to scattering, including Rayleigh scattering, does not contribute to the material's heating; therefore, $\alpha_b$ represents only the background absorption and not the total parasitic attenuation.

For net solid-state optical refrigeration, the cooling efficiency must be positive; therefore, we must show that $\eta_f > 0$ is reachable over a range of $\lambda_p$. The laser pump wavelength $\lambda_p$ cannot be much longer than $\lambda_f$, otherwise, the pump absorption cross-section would become too small. This would result in a small $\alpha_f$ and hence a small $\eta_{\text{abs}}$, and a negative cooling efficiency. In practice, to observe net cooling, $\lambda_f$ can only be slightly longer than $\lambda_p$ and both $\eta_{\text{ext}}$ and $\eta_{\text{abs}}$ must be near unity. To realize the $\eta_{\text{abs}} \sim 1$ limit for $\lambda_p \gg \lambda_f$, one must increase the RE dopant density to achieve $\alpha_f(\lambda_p) \gg \alpha_b$. However, increasing the RE dopant density results in an increase in the non-radiative decay rate, $W_{nr}$, primarily because of the RE clustering and quenching, hence decreasing the external quantum efficiency, $\eta_{\text{ext}}$. This unfortunate circle of undesirable influences was recently overcome in Yb-doped silica. It was shown that by adding certain modifiers such as Al, P, F, and Ce, the quenching concentration of silica glass could be increased significantly.

The result was the successful cooling of high-Yb-concentration silica as a fiber preform by Mobini et al. up to 0.7 K and as an optical fiber by Knall et al. up to 50 mK.

To investigate the cooling efficiency as a function of the pump wavelength and obtain the optimum value of $\lambda_p$ for maximum cooling, we performed a laser-induced thermal modulation spectroscopy (LITMoS) test on our Yb-doped silica samples. In Figure 1, we show $-\eta_f \alpha_f(\lambda_f)$ as a function of $\lambda_f$ for the sample used in this paper (the same as sample A studied by Mobini et al., but some of the cladding is removed; see Table 1). This quantity is proportional to the change in the sample temperature for a fixed pump laser power. Figure 1 shows that the maximum temperature drop can be obtained at around 1035 nm. At the time when we carried out our experiments for ref 15, the only viable high-power source in our laboratory was a 1053 nm laser. In this paper, as will be explained later, we use a $\lambda_p = 1035$ nm source to achieve a higher temperature drop.

### RESULTS

**Power Cooling Experiment.** The samples that we laser-cooled in our experiments reported in ref 15 were surrounded by undoped (no Yb doping) silica glass cladding regions, which provide significant thermal load. The cooling in our experiments was achieved in spite of this large thermal load. For this work, we chose sample A studied by Mobini et al. and removed most of its undoped cladding region to reduce the thermal load and enhance the cooling effect. Moreover, we built a high-power source at the optimum cooling wavelength of 1035 nm as described below.

The characteristics of the (fiber preform) sample are listed in Table 1. The Yb$_2$O$_3$ concentration is measured by electron probe micro-analysis. The Yb density is calculated from the measured Yb$_2$O$_3$ concentration. The error for the Yb$_2$O$_3$ concentration is related to the applied method’s uncertainty in this concentration range. The OH$^-$ concentration and parasitic background absorption ($\alpha_b$) are measured by the cut-back method in the fiber form, for which the errors express the repeatability of the measurement setup.

To make a high-power source at the nearly optimum $\lambda_p = 1035$ nm wavelength, we have designed and built a fiber amplifier to amplify the output of our continuous-wave tunable Ti:Sapphire laser. The fiber amplifier’s gain medium is a 1.2 m piece of Yb-doped double-cladding fiber pumped using a high-power diode laser at the wavelength of 976 nm. The amplifier’s input is approximately 300 mW, and the amplified output of the fiber amplifier is on the order of ~20 W at the 1035 nm wavelength. We note that any residual diode pump power at the 976 nm wavelength can be a significant source of heating in the material because of the Yb-silica sample’s absorption peaks at 976 nm. Therefore, to observe laser cooling, a spectrally pure laser is essential. To reduce the fiber amplifier’s 976 nm pump leakage in the output as much as possible, we implement a cladding mode stripper scheme at the fiber amplifier’s end. We also use a stack of two 1000 nm wavelength long-pass dichroic mirrors to filter out the rest of the 976 nm pump leakage.

The experimental setup for the power cooling experiment is shown in Figure 2. The Ti:Sapphire laser is tuned to a wavelength of 1035 nm, which is then amplified by the fiber amplifier. The output laser light is then collimated and filtered. The collimated light is coupled to the sample through a long-

![Table 1. Properties of the Yb-Doped Silica Glass Sample](image)

| parameter            | value | error |
|----------------------|-------|-------|
| codopants            | AL, P |       |
| Yb$_2$O$_3$ [mol %]  | 0.12  | ±0.01 |
| Yb density [10$^{15}$ m$^{-3}$] | 5.3 | ±0.4 |
| OH$^-$ concentration [ppm] | 3.0 | ±0.5 |
| core diameter [mm]   | 1.7   | ±0.1  |
| cladding diameter [mm] | 2.9  | ±0.1  |
| length [mm]          | 15.1  | ±0.1  |
| $\alpha_b$ [dB km$^{-1}$] | 10   | ±2    |

![Figure 1. Value of $-\eta_f \alpha_f(\lambda_f)$, which is proportional to $\Delta T$ at a fixed input laser power (in the low-absorption regime), versus the pump laser wavelength for our sample. The solid line presents the best fit to the experimental measurements reported by Mobini et al. This figure is adapted from Figure S3 of Mobini et al.](image)
The focal length of a stack of two one-micron long-pass dichroic mirrors is 12 cm. The sample is held inside a vacuum chamber. The upper-left inset shows a sketch of the Yb-doped silica glass sample supported by a set of thin silica fibers to minimize the heat load.

The vacuum chamber pressure is maintained at 10^{-6} torr during the power cooling experiment to minimize convective heat transfer. A spectrometer captures the sample’s fluorescence through a KCl salt window mounted in the chamber. Similarly, the thermal images are recorded via a thermal camera through a KCl salt window mounted in the chamber. Similarly, the thermal images are post-processed to measure the changes in the sample’s temperature. The mean temperature evolution as a function of time follows the following exponential form (see Mobini et al. for a derivation)

\[ \Delta T(t) = \Delta T_{\text{max}} \left( e^{-\frac{t}{\tau}} - 1 \right) \]  

where we use the following definitions

\[ \Delta T_{\text{max}} = \eta \frac{P_{\text{abs}}}{4\varepsilon\sigma T_0^4 A} \]

Here, \( V \) is the sample volume, \( \varepsilon \approx 0.85 \) is the emissivity of the implemented Yb-doped silica glass fiber preform, \( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4} \) is the Stefan–Boltzmann constant, \( T_0 \) is the ambient temperature, \( A \) is the surface area of the sample, \( \rho = 2.2 \times 10^3 \text{ kg m}^{-3} \) is the silica glass mass density, \( c_v = 741 \text{ J kg}^{-1} \text{K}^{-1} \) is the specific heat of the silica glass. \( P_{\text{abs}} \) is the absorbed laser power that can be estimated from the Beer–Lambert law in a single pass

\[ P_{\text{abs}} = \rho_T(1 - e^{-\alpha_\lambda l}) \approx \rho_T\alpha_\lambda l \]

Here, \( P_0 \) is the input power coupled into the fiber preform at \( z = 0 \), \( l \) is the sample length, and \( \alpha_\lambda(1035 \text{ nm}) \approx 1.93 \times 10^{-2} \text{ cm}^{-1} \). In fact, by combining eqs 4 and 5, we can see that \( \Delta T_{\text{max}} \propto \eta\alpha_\lambda \), which is the vertical axis in Figure 1 used to estimate the optimum pump laser wavelength. By fitting the exponential form in eq 3 to the experimental data (red dots) in Figure 3, we obtain \( \Delta T_{\text{max}} \approx 6.02 \pm 0.01 \text{ K} \) and \( \tau \approx 166 \pm 1 \text{ S} \)—the error bars are estimated by the fitting procedure. The dashed blue line is the theoretical fit and agrees with the experiment quite well. Using the measured value of \( \eta \approx 0.016 \) at \( \lambda_p \approx 1035 \text{ nm} \) reported by Mobini et al. for sample A, we use eqs 4 and 5 to estimate \( \Delta T_{\text{max}} \approx 9 \text{ K} \). This theoretical estimate is consistent with the measured fitted value of \( \Delta T_{\text{max}} \approx 6.02 \pm 0.01 \text{ K} \) because the heat conduction from the fiber holder contact and also the parasitic heating from fiber facet imperfections are not included in the theoretically ideal form of eq 4. Moreover, the fitted value for \( \tau \) agrees quite well with the measurement reported by Mobini et al. once the difference in geometry is taken into account (\( \tau_\text{c} \approx 175 \text{ S} \) vs \( \tau_\text{e} \approx 166 \text{ S} \)).

The goodness of the fitting in Figure 3 indicates that despite the saturation of the camera, the actual value of \( \Delta T_{\text{max}} \) cannot be much larger than 6 K.
Differential Luminescence Thermometry. In this technique, the variation in luminescence intensity distribution with temperature is used to determine the sample’s temperature. This variation is due to the temperature dependence of the Boltzmann population of the crystal field levels of the emitting state and the homogeneous line width of the individual crystal field transitions.3 Differential luminescence thermometry (DLT) has been successfully used to measure temperature variations on the order of tens of Kelvin; however, it can be quite noisy and less accurate for smaller temperature variations such as those reported here. The reason is that unlike semiconductors where substantial spectral shifts are observed as a function of the temperature,44 the 4f electrons in REs are shielded from the environment in a solid. The noise in our DLT measurement is dominated by the standard spectrometer noise, mainly due to thermal and mechanical effects.

For DLT, the temperature-dependent emission spectral density \( S(\lambda, T) \) is obtained in real time and is referenced to a spectrum at the starting temperature \( T_0 \). The normalized differential spectrum is defined as

\[
\Delta S(\lambda, T, T_0) = \frac{S(\lambda, T)}{S_{\text{max}}(T)} - \frac{S(\lambda, T_0)}{S_{\text{max}}(T_0)}
\]

Normalization to the spectral peak \( S_{\text{max}} \) is performed to eliminate the effect of input power fluctuations. The scalar DLT signal is given by

\[
S_{\text{DLT}}(T, T_0) = \int_{\lambda_1}^{\lambda_2} d\lambda \Delta S(\lambda, T, T_0)
\]

where the limits of integration bracket the sample’s spectral emission, eliminating possible contributions from the spurious laser line scattering; we choose \( \lambda_1 = 895 \text{ nm} \) and \( \lambda_2 = 955 \text{ nm} \). The temperature drop from the ambient, \( \Delta T \), is linearly proportional to \( S_{\text{DLT}} \): \( \Delta T = \gamma S_{\text{DLT}} \) where \( \gamma \) is the proportionality constant. To use DLT for temperature measurements, we first perform a calibration measurement by mounting the sample on a variable-temperature cold plate, while pumping the sample with the Ti:sapphire laser and collecting the spectrum. We find that for our sample, \( \gamma = -34 \pm 2 \text{ K} \).

We use the DLT calibration result to measure the sample’s temperature evolution over time, while being exposed to the 20 W laser light at 1035 nm by collecting the emission spectral density every 10 s. The results are shown in Figure 4. The DLT data points are in blue dots, where the error bars are due to the error in \( \gamma \) as estimated from the calibration. The results are compared with the thermal camera measurements in red dots. The DLT results are quite noisy as expected; however, the trend agrees with the temperature values from the thermal camera and also hints that the sample is cooled slightly more than 6 K below the ambient temperature, consistent with the results presented in subsection (3.1), Power Cooling Experiment.

■ DISCUSSION

We have demonstrated the laser power cooling of Yb:silica glass to 6 K below room temperature. This result constitutes almost an order of magnitude improvement compared with the previous result of 0.7 K reported by Mobini et al.10 Our work points to the feasibility of an all-fiber-based cryocooler using Yb:silica after a moderate improvement in preform synthesis. For comparison, Yb:ZBLAN (2% doped) having a background absorption of \( 2 \times 10^{-4} \text{ cm}^{-1} \) was cooled to about 200 K with \( P \approx 10 \text{ W} \) at 1026 nm.11,15 Our current Yb:silica glass having a lower background absorption by an order of magnitude has the potential to outperform ZBLAN. With a moderate improvement in doping concentration (i.e., 1%), one can envision all-fiber refrigerators reaching 150 K with no moving parts. It should be noted that the emission spectrum and, consequently, the absorption spectrum of Yb-doped silica and ZBLAN are reasonably close. Future improvements are possible by increasing the pump power and implementing a multipass scheme, improving material specifications, and optimizing the sample geometry. A video clip of the cooling evolution of the sample is presented in the Supporting Information section. The video shows the temporal evolution of the sample’s temperature as captured by the thermal camera in the high-power laser cooling experiment. The thermal image of the sample gets darker as the sample cools due to the exposure to the high-power laser.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://doi.org/10.1021/acsomega.1c00116.

Cooling evolution of the sample (MOV)

■ AUTHOR INFORMATION

Corresponding Author
Arash Mafi — Department of Physics & Astronomy and Center for High Technology Materials, University of New Mexico, Albuquerque 87131, New Mexico, United States; orcid.org/0000-0002-9308-6813; Email: mafi@unm.edu

Authors
Mostafa Peysokhani — Department of Physics & Astronomy and Center for High Technology Materials, University of New Mexico, Albuquerque 87131, New Mexico, United States
Saeid Rostami — Department of Physics & Astronomy, University of New Mexico, Albuquerque 87131, New Mexico, United States
Esmaeil Mobini — Department of Physics & Astronomy and Center for High Technology Materials, University of New Mexico, Albuquerque 87131, New Mexico, United States
Alexander R. Albrecht — Department of Physics & Astronomy, University of New Mexico, Albuquerque 87131, New Mexico, United States

Figure 4. sample’s temperature change is plotted as a function of time when exposed to the high-power 1035 nm laser light. The blue dots are based on the DLT method, and the red dots represent the temperature measurements using the thermal camera.
Stefan Kuhn — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Sigrun Hein — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Christian Hupel — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Johannes Nold — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Nicoletta Haarlammert — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Thomas Schreiber — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Ramona Eberhardt — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany
Angel Flores — Air Force Research Laboratory, Directed Energy Directorate, Kirtland Air Force Base 87117, New Mexico, United States
Andreas Tünnemann — Fraunhofer Institute for Applied Optics and Precision Engineering, Jena 07745, Germany; Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität, Jena 07745, Germany
Mansoor Sheik-Bahae — Department of Physics & Astronomy, University of New Mexico, Albuquerque 87131, New Mexico, United States

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c00116

Author Contributions
M.P. and A.M. wrote the manuscript, and all authors conducted all the experiments and analyzed the data; S.K., S.H., C.H., J.N., N.H., T.S., and R.E. are responsible for the production and characterization of the silica glass preforms, and A.T. supervised their work. A.F. and E.M. helped in making the fiber amplifier. A.M. and M.S.-B. led and supervised the laser cooling aspects of the work and participated in the data analysis.

Funding
This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-16-1-0362 titled Multidisciplinary Approaches to Radiation-Balanced Lasers (MARBLE).

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
The authors would like to acknowledge R. I. Epstein, M.P. Hahlen, and S. D. Melgaard for helpful discussions.

REFERENCES
(1) Pringsheim, P. Zwei bemerkungen über den unterschied von lumineszenz- und temperaturstrahlung. Z. Phys. 1929, 57, 739—746.
(2) Epstein, R. I.; Buchwald, M. I.; Edwards, B. C.; Gosnell, T. R.; Mungan, C. E. Observation of laser-induced fluorescent cooling of a solid. Nature 1995, 377, 500—503.
(3) Seletskiy, D. V.; Melgaard, S. D.; Bigotta, S.; Di Lieto, A.; Tonelli, M.; Sheik-Bahae, M. Laser cooling of solids to cryogenic temperatures. Nat. Photonics 2010, 4, 161—164.
(4) Nemova, G.; Kashyp, R. Laser cooling of solids. Rep. Prog. Phys. 2010, 73, 086501.
(5) Seletskiy, D. V.; Epstein, R.; Sheik-Bahae, M. Laser cooling in solids: advances and prospects. Rep. Prog. Phys. 2016, 79, 096401.
(6) Xia, X.; Pant, A.; Ganas, A. S.; Jelezko, F.; Pauzauskie, P. J. Quantum point defects for solid-state laser refrigeration. Adv. Mater. 2020, 1905406.
(7) Melgaard, S. D.; Albrecht, A. R.; Hahlen, M. P.; Sheik-Bahae, M. Solid-state optical refrigeration to sub-100 Kelvin regime. Sci. Rep. 2016, 6, 20380.
(8) Gosnell, T. R. Laser cooling of a solid by 65 K starting from room temperature. Opt. Lett. 1999, 24, 1041—1043.
(9) Fernández, J.; Mendioroz, A.; Garcia, A. J.; Balda, R.; Adam, J. L. Anti-Stokes laser-induced internal cooling of Yb⁺⁺-doped glasses. Phys. Rev. B: Condens. Matter Mater. Phys. 2000, 62, 3213—3217.
(10) Hoyt, C. W.; Sheik-Bahae, M.; Epstein, R. I.; Edwards, B. C.; Anderson, J. E. Observation of anti-Stokes fluorescence cooling in thulium-doped glass. Phys. Rev. Lett. 2000, 85, 3600.
(11) Thiede, J.; Distel, J.; Greenfield, S. R.; Epstein, R. I. Cooling to 20K by optical refrigeration. Appl. Phys. Lett. 2005, 86, 154107.
(12) Fernandez, J.; Garcia-Adeva, A. J.; Balda, R. Anti-Stokes laser cooling in bulk erbium-doped materials. Phys. Rev. Lett. 2006, 97, 035001.
(13) Nguyen, D. T.; Thapa, R.; Rhonehouse, D.; Zong, J.; Miller, A.; Hardesty, G.; Kwong, N.-H.; Binder, R.; Chavez-Pirson, A. Towards all-fiber optical coolers using Tm-doped glass fibers. Laser Refrigeration of Solids VI, 2013; p 86380G.
(14) Pysokhan, M.; Mobini, E.; Mafi, A. Measuring the anti-Stokes cooling parameters of a Yb-doped ZBLAN fiber for radiation balancing. Sixth International Workshop on Specialty Optical Fibers and Their Applications (WSOF 2019), 2019; p 112061Q1-1.
(15) Pysokhan, M.; Mobini, E.; Allahverdi, A.; Aiba, B.; Mafi, A. Characterization of Yb-doped ZBLAN fiber as a platform for radiation-balanced lasers. Photonics Res. 2020, 8, 202—210.
(16) Mobini, E.; Rostami, S.; Pysokhan, M.; Albrecht, A.; Kuhn, S.; Hein, S.; Hupel, C.; Nold, J.; Haarlammert, N.; Schreiber, T.; et al. Laser cooling of ytterbium-doped silica glass. Commun. Phys. 2020, 3, 134.
(17) Knall, J.; Vigneron, P.-B.; Engholm, M.; Dragic, P. D.; Yu, N.; Ballato, J.; Bernier, M.; Digonnet, M. J. F. Laser cooling in a silica optical fiber at atmospheric pressure. Opt. Lett. 2020, 45, 1092—1095.
(18) Mobini, E.; Pysokhan, M.; Aiba, B.; Hein, M. P.; Mafi, A. Spectroscopic Investigation of Yb-Doped Silica Glass for Solid-State Optical Refrigeration. Phys. Rev. Appl. 2019, 11, 014066.
(19) Knall, J. M.; Arora, A.; Dragic, P. D.; Ballato, J.; Cavillon, M.; Hawkins, T.; Jiang, S.; Luo, T.; Bernier, M.; Digonnet, M. Experimental investigations of spectroscopy and anti-Stokes fluorescence cooling in Yb-doped silicate fibers. Photonic Heat Engines: Science and Applications, 2019; pp 40—49.
(20) Mobini, E.; Pysokhan, M.; Aiba, B.; Mafi, A. Investigation of solid state laser cooling in Ytterbium-doped silica fibers. 2018 Conference on Lasers and Electro-Optics (CLEO), 2018; pp 1—2.
(21) Mobini, E.; Rostami, S.; Pysokhan, M.; Albrecht, A. R.; Kuhn, S.; Hein, S.; Hupel, C.; Nold, J.; Haarlammert, N.; Schreiber, T.; Eberhardt, R.; Tünnemann, A.; Sheik-Bahae, M.; Mafi, A. Observation of anti-Stokes fluorescence cooling of ytterbium-doped silica glass (Conference Presentation). Photonic Heat Engines: Science and Applications II, 2020.
(22) Knall, J. M.; Vigneron, P.-B.; Engholm, M.; Dragic, P. D.; Yu, N.; Ballato, J.; Bernier, M.; Digonnet, M. Experimental observation of cooling in Yb-doped silica fibers. Photonic Heat Engines: Science and Applications II; International Society for Optics and Photonics, 2020; pp 48 — 55.
(23) Knall, J.; Engholm, M.; Ballato, J.; Dragic, P. D.; Yu, N.; Digonnet, M. J. F. Experimental comparison of silica fibers for laser cooling. Opt. Lett. 2020, 45, 4020—4023.
(24) Zhou, X.; Smith, B. E.; Roder, P. B.; Pauzauskie, P. J. Laser refrigeration of ytterbium-doped sodium—yttrium—fluoride nanowires. Adv. Mater. 2016, 28, 8658—8662.
(25) Zhu, X.; Peyghambarian, N. High-power ZBLAN glass fiber lasers: review and prospect. Adv. Optoelectron. 2010, 2010, 501956.
(26) Mobini, E.; Peysokhan, M.; Maﬁ, A. Heat mitigation of a core/cladding Yb-doped fiber amplifier using anti-Stokes fluorescence cooling. J. Opt. Soc. Am. B 2019, 36, 2167–2177.

(27) Jalali, B.; Fathpour, S. Silicon photonics. J. Lightwave Technol. 2006, 24, 4600–4615.

(28) Soref, R. Mid-infrared photonics in silicon and germanium. Nat. Photonics 2010, 4, 495–497.

(29) Bowman, S. R. Lasers without internal heat generation. IEEE J. Quantum Electron. 1999, 35, 115–122.

(30) Nemova, G.; Kashyap, R. Athermal continuous-wave fiber amplifier. Opt. Commun. 2009, 282, 2571–2575.

(31) Bowman, S. R.; O’Connor, S. P.; Biswal, S.; Condon, N. J.; Rosenberg, A. Minimizing Heat Generation in Solid-State Lasers. IEEE J. Quantum Electron. 2010, 46, 1076–1085.

(32) Nemova, G.; Kashyap, R. Radiation-balanced amplifier with two pumps and a single system of ions. J. Opt. Soc. Am. B 2011, 28, 2191–2194.

(33) Mobini, E.; Peysokhan, M.; Abaie, B.; Maﬁ, A. Thermal modeling, heat mitigation, and radiative cooling for double-clad fiber amplifiers. J. Opt. Soc. Am. B 2018, 35, 2484–2493.

(34) Yang, Z.; Meng, J.; Albrecht, A. R.; Sheik-Bahae, M. Radiation-balanced Yb:YAG disk laser. Opt. Express 2019, 27, 1392–1400.

(35) Lægsgaard, J. Dissolution of rare-earth clusters in SiO2 by Al codoping: A microscopic model. Phys. Rev. B: Condens. Matter Mater. Phys. 2002, 65, 174114.

(36) Arai, K.; Namikawa, H.; Kumata, K.; Honda, T.; Ishii, Y.; Handa, T. Aluminum or phosphorus co-doping effects on the fluorescence and structural properties of neodymium-doped silica glass. J. Appl. Phys. 1986, 59, 3430–3436.

(37) Rostami, S.; Albrecht, A. R.; Volpi, A.; Sheik-Bahae, M. Observation of optical refrigeration in a holmium-doped crystal. Photon. Res. 2019, 7, 445–451.

(38) Yoder, P.; Vukobratovich, D.; Paquin, R. A. Opto-Mechanical Systems Design, 2nd Ed., 3rd ed.; CRC Press: New York, U.S.A., 1992; Vol. 4; An optional note.

(39) Karimi, M. Theoretical Study of the Thermal Distribution in Yb-Doped Double-Clad fiber Laser by Considering Different Heat Sources. Prog. Electromagn. Res. 2018, 88, 59–76.

(40) Maﬁ, A. Temperature distribution inside a double-cladding optical fiber laser or amplifier. J. Opt. Soc. Am. B 2020, 37, 1821–1828.

(41) Powerl, R. Physics of Solid-State Laser Materials: Atomic, Molecular, and Optical Physics, 1998th Ed.; Springer: Singapore, 1998.

(42) Peysokhan, M.; Mobini, E.; Abaie, B.; Maﬁ, A. Method for measuring the resonant absorption coefficient of rare-earth-doped optical fibers. Appl. Opt. 2019, 58, 1841–1846.

(43) Patterson, W. M.; Seletskiy, D. V.; Sheik-Bahae, M.; Epstein, R. I.; Hehlen, M. P. Measurement of solid-state optical refrigeration by two-band differential luminescence thermometry. J. Opt. Soc. Am. B 2010, 27, 611–618.

(44) Imangholi, B.; Hasselbeck, M. P.; Bender, D. A.; Wang, C.; Sheik-Bahae, M.; Epstein, R. I.; Kurtz, S. Differential luminescence thermometry in semiconductor laser cooling. Physics and Simulation of Optoelectronic Devices XIV; International Society for Optics and Photonics, 2006; pp 215–220.

(45) Hehlen, M. P.; Epstein, R. I.; Inoue, H. Model of laser cooling in the Yb3+-doped fluorozirconate glass ZBLAN. Phys. Rev. B: Condens. Matter Mater. Phys. 2007, 75, 144302.