A ytterbium doped silica optical fiber has been cooled by 18.4 K below ambient temperature by pumping with 20 W of 1035 nm light in vacuum. In air, cooling by 3.6 K below ambient was observed with the same 20 W pump. The temperatures were measured with a thermal imaging camera and differential luminescence thermometry. The cooling efficiency is calculated to be 1.2 ± 0.1%. The core of the fiber was codoped with Al³⁺ for an Al to Yb ratio of 6:1, to allow for a larger Yb concentration and enhanced laser cooling.

In the late 1920s, C. V. Raman discovered that when a material is exposed to light, its molecules scatter a small fraction of the incident photons inelastically. This inelastic scattering results in lower energy (Stokes) and higher energy (anti-Stokes) photons [1]. Shortly after, Pringsheim postulated that anti-Stokes fluorescence may be used to decrease the temperature of a material [2]. It was not until the end of the 20th century that optical cooling of solids was realized experimentally by Epstein and coworkers in ytterbium doped fluoride glass [3]. Since this milestone achievement, systematic investigations have resulted in the observation of laser cooling in several families of rare-earth doped crystals and glasses [4–7]. To date, the coldest temperature achieved by solid state optical refrigeration is in crystalline Yb:YLiF₄ down to 91 K [8]. For the first 24 years of laser cooling research activity, the observations of optically cooling glasses were confined to non-silicates [5]. The paradigm has shifted recently with the success of laser cooling research in several families of rare-earth doped silica fibers and glasses [4–7].

The high degree of polymerization and strong Si–O bonds make vitreous silica superior to fluoride systems, such as the ZLBAN family, with respect to mechanical and chemical durability. These attributes make silicates a more desirable material for fiber laser applications. In high-power fiber lasers, heat mitigation is required to maintain the integrity of the material and the beam profile [20,21]. Anti-Stokes fluorescence has been suggested as a viable method for heat mitigation in lasers [21–24]. Such a radiation-balanced fiber laser (RBL) experiences no increase in temperature, by effectively radiating out the waste heat generated during operation. Although silica-based radiation-balanced devices have been reported this year in pioneering work [30,31], those devices are operating at orders of magnitude below the threshold of interest for adoption by industry.

Our work here demonstrates that it is possible for silica optical fibers to reach a steady-state of net cooling when exposed to pump powers of genuine interest to fiber laser practitioners. This suggests we are rapidly approaching the realization of a technologically desirable RBL. Here, we present to the best of our knowledge, a new record in the cooling of Yb-doped silica in vacuum by more than 18 K from ambient temperature. Further, we observe record cooling in air by more than 6 K from ambient, which is two orders of magnitude greater than previously published cooling results of optical fibers in air. We achieve this by using pump powers in the range of 1 W to 185 W at 1035 nm wavelength.

The high-purity fibers (Table I) were drawn from preforms fabricated with the modified chemical vapor deposition technique. Cation (Yb, Al) doping of the core was carried out by the gas-phase doping technique [22], using Yb(thd)₃ and AlCl₃ as precursors. Relative to previously successful laser cooling compositions doped with Al and F [10], the molar concentration of Yb₃O₃ was increased by 25% for fiber A. These glasses were developed for single-mode, high-power fiber laser applications, thus a controlled core-cladding refractive index step is essential. To achieve this, codoping with fluorine was used to decrease the refractive index of the material and assure single mode operation in the drawn large-mode area double clad fiber geometry (e.g. 20/400 geometry).

Fiber lasers using these types of glasses have been used to achieve continuous wave (CW) output powers of more than 4 kW from a single fiber, while maintaining good beam quality [33,34]. Output powers like these can only be accomplished with, among other things, high-purity core materials with low background absorption. The background losses of these glasses were below 10 dB km⁻¹ measured at a wavelength of 1200 nm, which has been
The temperature difference is defined as $\Delta T = T - T_0$, where $T_0$ is taken to be the ambient temperature of 296 K. To record cooling beyond $\Delta T = 10$ K, differential luminescence thermometry (DLT) was employed. DLT exploits the temperature-dependence of the luminescence spectral form (see Fig. 2), which is dictated by the density of states. In the DLT analysis, each spectrum is normalized to its maximum (at $\lambda = 978$ nm) to eliminate influence of input power fluctuations. The difference between a spectrum at time $t$ is then taken with respect to the spectrum taken at the onset of the experiment, where the cooling is assumed to be negligible and thus the spectral density is representative of $S(\lambda, T_0 = 296$ K).

The normalized difference spectra is defined as

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

The change in temperature has been found to be linearly proportional to the integrated difference in spectral density given by

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

such that $\Delta T = \alpha S_{\text{DLT}}$ with $\alpha = 34.5 \pm 0.4$ K for fiber A. The temperature difference measured by the TIC is compared to the temperature difference by DLT in Fig. 3 for a 20 W pump power incident on the fiber held under vacuum. In Fig. 3, we see that, in the absence of convective heating contributions, both DLT (black line) and TIC

| TABLE I: Material properties of Yb doped fibers |
|------------------------------------------------|
| Fiber | A   | B   |
|-------|-----|-----|
| Codopants | Al, F | Al, F |
| $Yb_2O_3$ (mol%) | 0.15 | 0.12 |
| $Yb^{3+}$ density ($10^{25}$ atoms/m$^3$) | 6.56 | 5.26 |
| Al:Yb ratio | 6:1 | 8:3:1 |
| $N_A$core | 0.06 | 0.05 |
| $D_{\text{core}}/D_{\text{cladding}}$ (µm/µm) | 900/1000 | 900/1000 |

For fiber A, the details of the cooling experiment are akin to those used in Ref. [19] and will only be briefly summarized here. Approximately 45 mW of 1035 nm light from a CW Ti:Sapphire laser is coupled through free space to a single mode fiber with an objective lens. A custom-built fiber amplifier increases the signal power, providing an output adjustable between 1 W and 20 W.

For fiber B, an independent set of measurements were obtained using an amplifier capable of reaching 185 W output of 1033 nm light. The measurements on fiber B were made in air and data acquisition was carried out with a FLIR T540 thermal camera.
The Stefan-Boltzmann constant, $\sigma$, is the specific heat of fused silica, $c_v$, is the emissivity of the doped glass, $\rho$ is the density of fused silica, $\sigma$ is the Stefan-Boltzmann constant, $T_0$ is the ambient temperature, and $V$ is the volume of the fiber. For the given fiber geometry, evaluation of Eq. (4) gives $\tau_c = 81$ s. This agrees well with the average experimental value $\tau_c = 84\pm3$ s. Taking $\tau_c = 84\pm3$ s and determining the $\Delta T_{\text{max}}$ from the TIC or DLT data, Eq. (3) was found to model the experimental data quite well. Next determine the absorbed power, $P_{\text{abs}}$, with the Beer-Lambert law

$$P_{\text{abs}} = P_{\text{in}}T_{\text{tot}}(1-e^{-\alpha l}).$$

$P_{\text{in}}$ is the pump power measured before the focusing lens, $T_{\text{tot}}$ is the total transmission coefficient, $l$ is the length of the fiber, and $\alpha_r$ is the resonant absorption coefficient. $T_{\text{tot}}$ is the product of the transmission of the focusing lens ($T_1 = 0.998$), the transmission of the chamber window ($T_{\text{cw}}=0.92$), and the transmission into the glass fiber after accounting for Fresnel losses at the surface ($T_g = 0.96$) such that $T_{\text{tot}} = T_1T_{\text{cw}}T_g$. The resonant absorption coefficient was found to be $\alpha_r(\lambda=1035$ nm$) = 1.92 \pm 0.04$ m$^{-1}$. The magnitude of the cooling of fiber A in-vacuum was found to increase with increasing absorbed power. With the absorbed power now known for each trial, we next inspect the slope of the $\Delta T(t)$ curves at $t = 0$ to find the cooling efficiency, $\eta_c$, of fiber A at 1035 nm wavelength via

$$\eta_c = \frac{-\rho V c_v}{P_{\text{abs}}} \partial_t \Delta T\bigg|_{t=0}.$$  

The TIC data was used to calculate $\eta_c$ for each trial, as the $\Delta T(t)$ for small $t$ was below the saturation limit. We find the cooling efficiency of fiber A to be $\eta_c = 1.2\pm0.1\%$ (Fig. 4).

For fiber B, experiments were conducted under ambient pressure conditions. Cooling by 6.3 K from room
FIG. 4: Calculated cooling efficiency (fiber A) correlation with increasing absorbed power alongside the mean (solid blue line) and the standard deviation (blue dotted line).

FIG. 5: Temporal cooling behavior of fiber B illuminated with 185 W of 1033 nm light under ambient pressure conditions. The dotted horizontal line is positioned at -6.3 K to aid the eye.

higher pump powers to yield cooling to about 30 K below room temperature.

In summary, for the first time, to the best of our knowledge, optically cooling silica in-vacuum to more than 18 K from room temperature has been achieved. Compared to our previous work, increasing the Yb$^{3+}$ concentration and significantly reducing the thermal load of the passive cladding increased the cooling achieved by a factor of three. These results suggest that these fibers may serve as a platform for a desirable radiation-balanced laser.

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[1] K. Ramanam C.V., Krishman, “A new type of secondary radiation,” Nature 121, 501–502 (1928).
[2] P. Pringsheim, “Zwei bemerkungen über den unterschied von lumineszenz-und temperaturstrahlung,” Zeitschrift für Physik 57, 739–746 (1929).
[3] R. I. Epstein, M. I. Buchwald, B. C. Edwards, T. R. Gosnell, and C. E. Mungan, “Observation of laser-induced fluorescent cooling of a solid,” Nature 377, 500–503 (1995).
[4] D. V. Seletskiy, S. D. Melgaard, S. Bigotta, A. Di Lieto, M. Tonelli, and M. Sheik-Bahae, “Laser cooling of solids to cryogenic temperatures,” Nature Photonics 4, 161–164 (2010).
[5] D. V. Seletskiy, R. Epstein, and M. Sheik-Bahae, “Laser cooling in solids: advances and prospects,” Reports on Progress in Physics 79, 096401 (2016).
[6] G. Nemova and R. Kashyap, “Laser cooling of solids,” Reports on Progress in Physics 73, 086501 (2010).
[7] C. Hoyt, M. Sheik-Bahae, R. Epstein, B. Edwards, and J. Anderson, “Observation of anti-stokes fluorescence
cooling in thulium-doped glass,” Physical Review Letters 85, 3600 (2000).

[8] S. D. Melgaard, A. R. Albrecht, M. P. Hehlen, and M. Sheik-Bahae, “Solid-state optical refrigeration to sub-100 kelvin regime,” Scientific reports 6, 1–6 (2016).

[9] E. Mobini, S. Rostami, M. Peysokhan, A. Albrecht, S. Kuhn, S. Hein, C. Hupel, J. Nold, N. Haarlammert, T. Schreiber et al., “Laser cooling of silica glass,” arXiv preprint arXiv:1910.10609 (2019).

[10] E. Mobini, S. Rostami, M. Peysokhan, A. Albrecht, S. Kuhn, S. Hein, C. Hupel, J. Nold, N. Haarlammert, T. Schreiber et al., “Laser cooling of ytterbium-doped silica glass,” Communications Physics 3, 1–6 (2020).

[11] J. Knall, M. Engholm, J. Ballato, P. D. Dragic, N. Yu, and M. J. F. Digonnet, “Experimental comparison of silica fibers for laser cooling,” Opt. Lett. 45, 4020–4023 (2020).

[12] J. M. Knall, A. Arora, P. D. Dragic, J. Ballato, M. Cavillon, T. Hawkins, S. Jiang, T. Luo, M. Bernier, and M. Digonnet, “Experimental investigations of spectroscopy and anti-Stokes fluorescence cooling in Yb-doped silicate fibers,” in Photonic Heat Engines: Science and Applications, vol. 10936 D. V. Seletskiy, R. I. Epstein, and M. Sheik-Bahae, eds., International Society for Optics and Photonics (SPIE, 2019), pp. 40–49.

[13] E. Mobini, M. Peysokhan, B. Aibaie, M. P. Hehlen, and A. Mafi, “Spectroscopic investigation of Yb-doped silica glass for solid-state optical refrigeration,” Phys. Rev. Applied 11, 014066 (2019).

[14] E. Mobini, M. Peysokhan, B. Aibaie, and A. Mafi, “Investigation of solid state laser cooling in ytterbium-doped silica fibers,” in 2018 Conference on Lasers and Electro-Optics (CLEO), (2018), pp. 1–2.

[15] E. Mobini, S. Rostami, M. Peysokhan, A. R. Albrecht, S. Kuhn, S. Hein, C. Hupel, J. Nold, N. Haarlammert, T. Schreiber, R. Eberhardt, A. Tünnemann, M. Sheik-Bahae, and A. Mafi, “Observation of anti-Stokes fluorescence cooling of ytterbium-doped silica glass (Conference Presentation),” in Photonic Heat Engines: Science and Applications II, vol. 11298 D. V. Seletskiy, R. I. Epstein, and M. Sheik-Bahae, eds., International Society for Optics and Photonics (SPIE, 2020).

[16] J. M. Knall, P.-B. Vigneron, M. Engholm, P. D. Dragic, N. Yu, J. Ballato, M. Bernier, and M. Digonnet, “Experimental observation of cooling in Yb-doped silica fibers,” in Photonic Heat Engines: Science and Applications II, vol. 11298 D. V. Seletskiy, R. I. Epstein, and M. Sheik-Bahae, eds., International Society for Optics and Photonics (SPIE, 2020), pp. 48–55.

[17] J. Knall, P.-B. Vigneron, M. Engholm, P. D. Dragic, N. Yu, J. Ballato, M. Bernier, and M. J. F. Digonnet, “Laser cooling in a silica optical fiber at atmospheric pressure,” Opt. Lett. 45, 1092–1095 (2020).

[18] J. Knall, M. Engholm, J. Ballato, P. D. Dragic, N. Yu, and M. J. F. Digonnet, “Experimental comparison of silica fibers for laser cooling,” Opt. Lett. 45, 4020–4023 (2020).

[19] M. Peysokhan, S. Rostami, E. Mobini, A. R. Albrecht, S. Kuhn, S. Hein, C. Hupel, J. Nold, N. Haarlammert, T. Schreiber, R. Eberhardt, A. Flores, A. Tünnemann, M. Sheik-Bahae, and A. Mafi, “Implementation of laser-induced anti-Stokes fluorescence power cooling of ytterbium-doped silica glass,” ACS Omega 6, 8376–8381 (2021). PMID: 33817498.

[20] D. Richardson, J. Nilsson, and W. Clarkson, “High power fiber lasers: current status and future perspectives [invited],” J. Opt. Soc. Am. B 27, B63–B92 (2010).

[21] D. C. Brown and H. J. Hoffman, “Thermal, stress, and thermo-optic effects in high average power double-clad silica fiber lasers,” IEEE J. Quantum Electron 37, 207–217 (2001).

[22] L. Zenteno, “High-power double-clad fiber lasers,” J. Lightwave Technol 11, 1435–1446 (1993).

[23] B. Ward, C. Robin, and I. Dajani, “Origin of thermal modal instabilities in large mode area fiber amplifiers,” Opt. Express 20, 11407–11422 (2012).

[24] J. W. Dawson, M. J. Messerly, R. J. Beach, M. Y. Shverdin, E. A. Stapparta, A. K. Sridharan, P. H. Pax, J. E. Heebner, C. W. Siders, and C. Barty, “Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power,” Opt. Express 16, 13240–13266 (2008).

[25] M. Peysokhan, E. Mobini, A. Allahverdi, B. Aibaie, and A. Mafi, “Characterization of Yb-doped ZBLAN fiber as a platform for radiation-balanced lasers,” Photonics Research 8, 202–210 (2020).

[26] M. Peysokhan, E. Mobini, and A. Mafi, “Measuring the anti-Stokes cooling parameters of a Yb-doped ZBLAN fiber for radiation balancing,” in Sixth International Workshop on Specialty Optical Fibers and Their Applications (WSOF 2019), vol. 11206 (2019), pp. 112061Q–1.

[27] S. Bowman, “Lasers without internal heat generation,” IEEE Journal of Quantum Electronics 35, 115–122 (1999).

[28] S. R. Bowman, S. P. O’Connor, S. Biswal, N. J. Condon, and A. Rosenberg, “Minimizing heat generation in solid-state lasers,” IEEE J. Quantum Electron 46, 1076–1085 (2010).

[29] S. Bowman, “Low quantum defect laser performance,” Opt. Eng. 56, 011104 (2016).

[30] J. Knall, M. Engholm, T. Boilard, M. Bernier, P.-B. Vigneron, N. Yu, P. Dragic, J. Ballato, and M. Digonnet, “Radiation-balanced silica fiber laser,” Optica 8, 830–833 (2021).

[31] J. M. Knall, M. Engholm, T. Boilard, M. Bernier, and M. J. F. Digonnet, “Radiation-balanced silica fiber amplifier,” Phys. Rev. Lett. 127, 013903 (2021).

[32] S. Kuhn, S. Hein, C. Hupel, J. Nold, F. Stutzki, N. Haarlammert, T. Schreiber, R. Eberhardt, and A. Tünnemann, “High-power fiber laser materials: influence of fabrication methods and codopants on optical properties,” in Optical Components and Materia XI, vol. 10914 S. Jiang and M. J. Digonnet, eds., International Society for Optics and Photonics (SPIE, 2019), pp. 15–27.

[33] F. Beier, C. Hupel, S. Kuhn, S. Hein, J. Nold, F. Prosko, B. Sattler, A. Liem, C. Jauregui, J. Limpert, N. Haarlammert, T. Schreiber, R. Eberhardt, and A. Tünnemann, Opt. Express 25, 14892–14899 (2017).

[34] F. Beier, F. Möller, B. Sattler, J. Nold, A. Liem, C. Hupel, S. Kuhn, S. Hein, N. Haarlammert, T. Schreiber, R. Eberhardt, and A. Tünnemann, “Experimental investigations on the tmi thresholds of low-NA Yb-doped single-mode fibers,” Opt. Lett. 43, 1291–1294 (2018).

[35] B. Imangholi, M. P. Hasselbeck, D. A. Bender, C. Wang, M. Sheik-Bahae, R. I. Epstein, and S. Kurtz, “Differential luminescence thermometry in semiconductor laser cooling,” in Physics and Simulation of Optoelectronic De-
\textit{Vices XIV}, vol. 6115 (International Society for Optics and Photonics, 2006), p. 61151C.