Observation of Anti-Stokes-Fluorescence Cooling in a ZBLAN Fiber with a Yb-doped Cladding

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ABSTRACT

This paper reports the first experimental observation of anti-Stokes cooling of fibers in which both the core and the cladding doped with Yb^{3+} to increase to number of Yb ions contributing to cooling and induce greater refrigeration. Two ZBLAN fibers were designed, fabricated by Le Verre Fluoré, and evaluated experimentally. Two cladding profiles were tested, both with asymmetric boundaries to induce greater mode mixing, and therefore better pump filling of the fiber and greater cooling. Temperature measurements showed that the fiber with a double-D cladding did not perform as well (it cooled to –78 mK for 240 mW of input pump power at 1025.5 nm) largely due to limited mode mixing. The octagonal cladding profile of the second fiber produced greater cooling, down to –1.3 K with 3 W. Fitting experimental results to a model showed good agreement with theory, and confirmed the high critical quenching concentration (N_c = 3.2x10^{27} Yb/m^3), low absorptive background loss (40 dB/km), and good filling ratio (~38%) achieved in this second fiber. This study establishes that with straightforward improvement in mode filling, a cladding-pumped ZBLAN fiber can readily be cooled to ~10 K below room temperature at atmospheric pressure with only ~15 W of pump power.

Keywords: anti-Stokes fluorescence cooling, fiber Bragg gratings, Yb-doped fibers, ZBLAN fibers.

1. INTRODUCTION

Of the many materials that have been successfully cooled via anti-Stokes fluorescence (ASF) [1], be it crystalline or amorphous, in a bulk, waveguide, or fiber form, oxide or non-oxide, fluorozirconates stand out as the most promising on the broadest scale thanks to a number of beneficial properties. First, trivalent rare earths can be incorporated at high concentration levels in fluorozirconates, a property that fosters greater heat extraction per unit volume and higher cooling efficiency. Second, thanks to the lower phonon energy of fluorozirconates, compared to silicate glasses in particular, many more of the electronic transitions of trivalent rare earths are purely radiative, and as a result a far wider choice of transitions is available for cooling. Finally, and unlike most if not all of the bulk crystals that have been cooled, fluorozirconates is can readily be drawn in high-quality fibers with comparatively low loss. A number of laboratories have in fact already demonstrated cooling in Yb-doped ZBLAN fibers, the record being to 65K below room temperature [2], both in a vacuum [2] and at atmospheric pressure [3,4]. Cooling has also been reported in a Tm-doped tellurite fiber [5]. In light of these significant benefits, and in spite of the recent success at cooling silica [2,6,7,8,9,10], it is important to explore this material in anticipation of practical laser-cooled applications.

To this end, in this paper we report the observation of ASF cooling in two ZBLAN fibers in which both the core and the cladding are doped with Yb^{3+}. The main goal was to provide an experimental validation of the concept proposed by Nemova and Kashyap [11] of cooling a fiber more aggressively by doping its cladding with a cooling ion and pumping the cladding. In core-pumped fibers, the amount of heat that can be extracted by ASF cooling is significantly limited by the small size of the core. In this alternative geometry, the core provides the gain used to amplify the signal or make a laser, as in a conventional fiber, but it is now the cladding that performs (most of) the cooling. This doped-cladding design provides a larger pumped area, which translates into greater extracted heat. The main challenge with this

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geometry is that to take full advantage of the large cladding and maximize heat extraction the pump mode must fill the entire cladding area. In this work we compare the performance of three fiber designs, namely a conventional large-core multimode fiber and two doped-cladding fibers, one with a cladding that has a double-D shape, and the other with an octagonal cladding, both shapes designed to induce greater mode mixing. The octagonal fiber is shown to provide significantly more uniform excitation of the doped cladding, resulting in -2 K of cooling with 15 W of pump power at 1025.5 nm. Comparison to an existing mode of cooling in multimode fibers enabled us to extract useful values of the key cooling parameters of Yb-doped ZBLAN fibers, in particular the very high critical quenching concentration (3.2×10^{27} Yb/m^3) and the relatively low residual absorptive loss due to impurities (40 dB/km).

2. YB-DOPED ZBLAN FIBERS

2.1 Double-clad ZBLAN fiber with Yb-doped core and cladding

Three Yb-doped multimode ZBLAN fiber designs were tested. The first one (Fig. 1a) is a conventional fiber with a circular core 200 µm in diameter. The Yb concentration was 3 wt.%. The second fiber (Fig. 1b) was a custom double-clad fiber in which both the core and the cladding were doped with Yb^{3+}. For improved mode mixing, the cladding had a double-D shape. The core diameter was 10 µm, the cladding diameter 125 µm, and the flat-to-flat distance was 115 µm. The Yb concentration was 5 wt.% in the core and 1.4 wt.% in the cladding. The third fiber (Fig. 1c) is similar, except that its cladding has an octagonal cross section, for even better mode mixing. Its core has a diameter of 30 µm, and its cladding has a flat-to-flat diameter of 170 µm. The inner cladding was surrounded by a lower index outer cladding made of a low-index resin with a relatively low absorption in the 1-µm region. The core was doped with 3.5 wt.% Yb, and the inner cladding with 1.8 wt.% Yb. These concentrations were obtained from simulations of the fiber performance as a radiation-balanced amplifier, assuming a uniform distribution of the pump energy across the core and the cladding [12]. The higher Yb concentration in the core favors gain over cooling, which turns out to be a necessary compromise, at least with this fiber design, to produce as high a gain as possible while maintaining the average fiber temperature at room temperature. The second and third fibers were designed in collaboration with Le Verre Fluoré in Rennes, France, where all three fibers were fabricated.

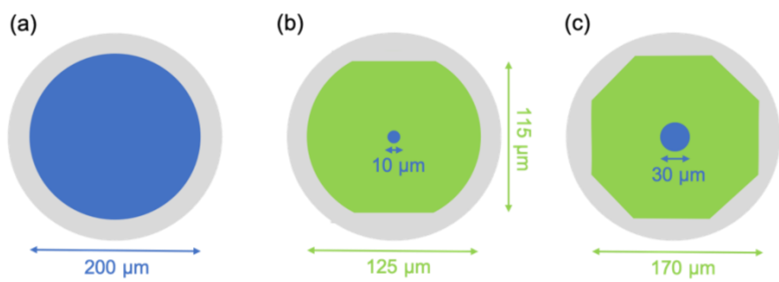

Figure 1. Cross section of the multimode Yb-doped ZBLAN fibers used in this work: (a) conventional multimode fiber, (b) double-D cladding-doped fiber, and (c) cladding-doped fiber with an octagonal inner cladding.

3. EXPERIMENTAL SETUP

Figure 2 is a schematic of the experimental set-up. The pump light from a 1025.5-nm fiber-pigtailed semiconductor laser (and on one noted occasion a 1040-nm high-power Yb-doped fiber laser) was butt coupled into the ZBLAN fiber under test. In some measurements, to excite a more uniform mode distribution across the cladding a short length of intermediary multimode fiber was placed between the pump laser fiber pigtail and the ZBLAN fiber. In this case, one end of the intermediary fiber was fusion spliced to the laser fiber, and the other end was butt-coupled to the ZBLAN fiber.

To measure the temperature change of a fiber, we used a custom slow-light FBG sensor with a sub-mK resolution [13]. As illustrated in Fig. 2, and as described in earlier publications [4,6,12], the FBG was placed in physical contact with a stripped section of the ZBLAN fiber. When the fiber cooled, the transmission spectrum of the silica FBG, which contains several narrow (slow-light) resonances, shifts toward shorter wavelength at an approximate rate of ~12 pm/K. This shift is measured by launching light from a tunable laser into the FBG and tuning its wavelength to the peak of a resonance. The frequency of the laser light entering the FBG is modulated with a phase modulator, which sweeps the laser frequency periodically across the resonance. A Pound-Drever-Hall closed loop system is ten used (see Fig. 2) to measure the shift in resonance with the required high resolution. The resolution of the sensors used in all measurements was of the order of 1 mK, and stability over a typical 30-s measurement around a few mK. In all measurements, the FBG sensor was positioned ~20-25 cm from the fiber input end for the 200-µm multimode fiber, and 30 µm for the other two fibers. All measurements were performed at atmospheric pressure.

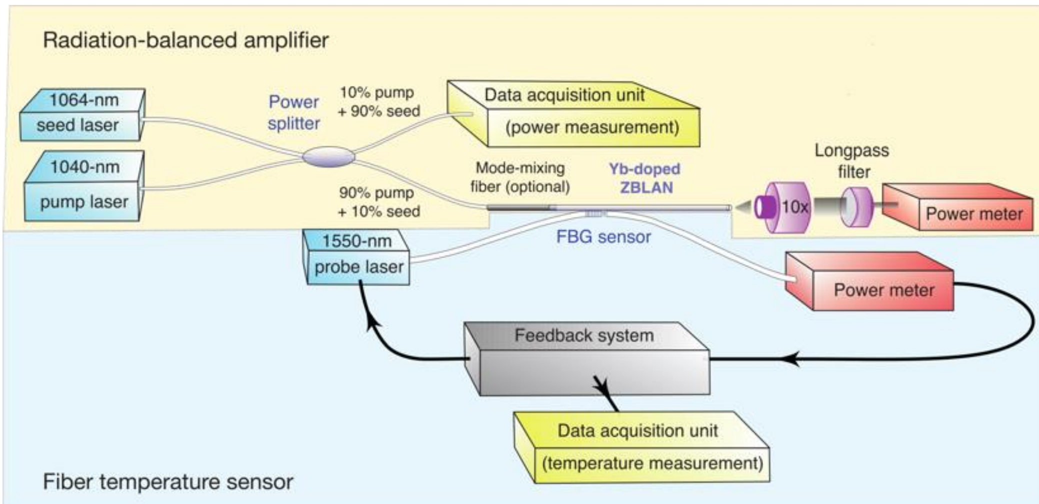

Figure 2. Experimental set-up used to measure gain and cooling in an Yb-doped ZBLAN fiber.

4. COOLING MEASUREMENT RESULTS

4.1 Multimode ZBLAN fiber

This fiber was previously cooled using ASF [3,4]; its performance is reported here as a baseline, and also to illustrate the importance of mode mixing (which was relatively poor in this fiber because of its symmetrical core) to obtain significant cooling. The maximum measured temperature change observed in this fiber under 1025.5-nm pumping was –0.65 K for 584 mW of pump power at the location of the sensor, which was the maximum power available from the pump laser. Fitting the measured dependence of the fiber temperature on pump power to a model, as described in [4] and below, gave two vital pieces of quantitative information about the fiber, namely its absorptive loss due to transition-metal ions, hydroxyls, and other impurities (25 dB/km), and the quenching lifetime of its Yb ions (78 ms) (or equivalently a critical quenching concentration $N_c = 3.8\text{x}10^{27}$ Yb/m^3). Measuring the fiber transmission at the pump wavelength and its dependence on pump power also provided the saturation power of the fiber, which was found to be 14.8 times smaller than expected. The reason for this discrepancy was simply that the pump power filled only 6.8% of the core (see Table 1 in [4]). The direct consequence was that most of the Yb ions did not contribute to cooling. As a result, although the maximum temperature drop that was observed (–0.65 K) was a record for a fiber at atmospheric pressure at the time, it was much smaller than was expected based on 100% filling of the core. This early work made it clear that although a low filling factor in an amplifier or a laser can be offset by increasing the fiber length with minimal loss of performance, in an ASF-cooled device it carries a significant penalty.

4.2 Double-D cladding-doped ZBLAN fiber

In an attempt to improve mode mixing, a second fiber was fabricated, this time with a double-D cladding doped with Yb, as described in relation to Fig. 1b. Figure 3a plots the temperature change measured in this fiber as a function of the pump power inferred at the position of the sensor. The blue crosses were obtained when the pump was launched directly from the laser's fiber pigtail (core diameter of 50 µm) into the ZBLAN fiber. As observed in other fibers [4,6], as the pump power was increased the temperature first decreased as a result of increasing population inversion and increasing anti-Stokes fluorescence escaping the fiber. Then the cooling slowed down as the population inversion approached saturation. Past this point, further increasing the pump power resulted in increasing pump power absorbed by impurities, and the fiber temperature started to increase. The largest temperature change recorded for this fiber, at the minimum in this curve, is -78 mK, for a pump power of 240 mW. The efficiency (temperature change divided by pump power) is noticeably higher (~3 times) than in the multimode fiber (see previous section).

The solid curve in Fig. 3 was generated with a code [12] that models the dependence of the temperature drop induced by ASF in a fiber. For a given fiber core size and numerical aperture, and a given pump power, this model calculates the temperature at all points along the fiber, taking into account all the relevant spectroscopic parameters of the Yb ions in the fiber host, including Yb concentration, absorption and emission cross sections, radiative lifetime, and quenching rate, which is quantified by the critical quenching concentration N_c [14]. It also accounts for the heating generated by the background absorptive loss α_{ba} due to impurities. All parameter values used in the code were measured, except for α_{ba} and N_c, which were *a priori* unknown and were therefore adjusted to obtain the best fit. This fitting process is fairly straightforward, since N_c affects mostly the rate of cooling at lower pump power (below the minimum), while α_{ba} affects the temperature dependence at all pump powers. The curve fits the experimental data well, which gives confidence in the validity of the model and in the parameter values inferred from the fit. The fitted values are $N_c = 4.0\text{x}10^{27}$ Yb/m^3 and $\alpha_{ba} = 38$ dB/km. Compared to the multimode fiber, the critical quenching concentration is within ~5%, but the loss is 50% higher.

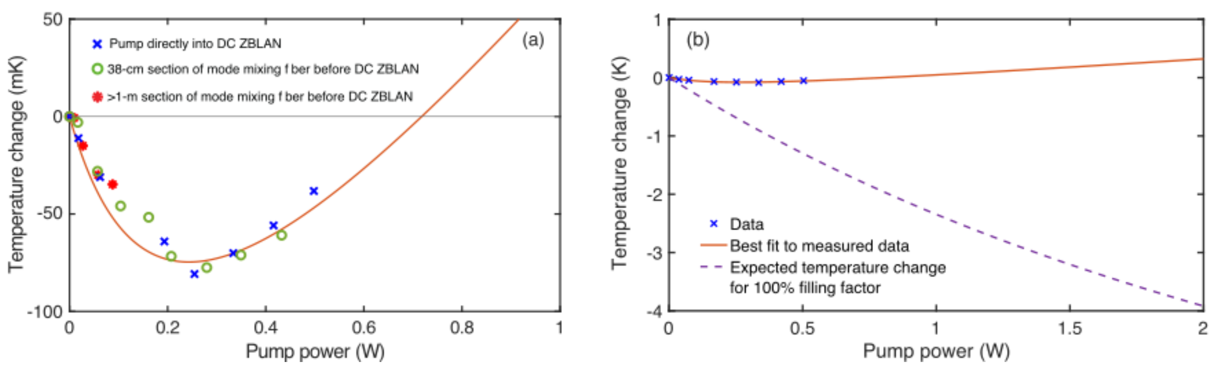

Figure 3. Experimental results and theoretical predictions for the double-D cladding-doped ZBLAN fiber. (a) Fiber temperature change as a function of the pump power at the temperature location, measured with and without a mode-mixing fiber at the input. (b) Comparison between the observed cooling and the cooling that was expected had the pump filled the entire cladding.

To perform this fit, the value of the effective area A_{eff} of the pump distribution in the cladding was also needed. This effective area was unknown and had to be measured. To this end, we measured the transmission of the fiber at the pump wavelength as a function of pump power, using the technique described in [3]. For this measurement, the ZBLAN fiber was excited in the same manner as during measurements of the cooling reported in Fig. 3. The result is shown in Fig. 4. The experimental data points (blue crosses) follow a linear trend at low power, then they grow faster as the increasing pump power depletes the Yb ground-state population and the absorption transition begins to saturate. Fitting this data to a simple model of saturated absorption gave the best fit shown as the solid red curve. The single fitting parameter used to generate this curve is A_{eff}. The fitted value is 710 µm^2, corresponding to a pump-absorption saturation power $P_{sat} = 220$ mW. This is the value of A_{eff} used to plot the theoretical cooling curve in Fig. 3. The good fits with the measured data in both that figure and Fig. 4 lend credence to the inferred value of the pump effective area.

Based on the measured pump effective area of 710 µm^2, and the cladding area of 11,390 µm^2, in this second fiber the pump filled 6.2% of the cladding, compared to 6.8% in the first fiber. The conclusion is that at least under the pump launching conditions used in this work, the double-D fiber does not provide a more uniform pump excitation throughout the cladding. The dashed curve in Fig. 4 is the saturation behavior that was expected had the pump power filled the entire cladding uniformly, in which case A_{eff} would have been equal to 11,390 μm², and the saturation power equal to 4.7 W. The dashed curve shows that saturation would have been significantly slower. A much larger Yb population would have been excited and the cooling process would have been more significant. How much more significant is illustrated by the purple dashed curve in Fig. 3b, which is the temperature change predicted by the model for full filling of the cladding. At the maximum pump power used in the experiment (500 mW), the temperature drop would have been –1.3 K, or ~17 times larger—which is, as expected, close to the ratio of pump filling ratio 710/11,390 = 6.2%.

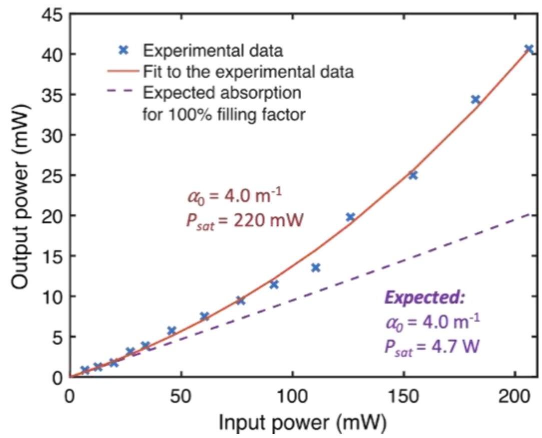

Figure 4. Measured output pump power versus input pump power for the double-D ZBLAN fiber when the pump is launched in the core and cladding, and theoretical fit.

To attempt filling the cladding more uniformly with pump power, the cooling experiment was repeated after placing a 38-cm length of undoped multimode fiber (core diameter of 125 μm) between the laser fiber pigtail and the ZBLAN fiber. The results are shown as open green circles in Fig. 3a. The cooling did not improve. Using a ~1-m length of the same multimode fiber (red filled circles) did not make a meaningful difference. These results are consistent with the pump distribution at the end of the multimode fiber measured with a CCD camera (frame (a) in Fig. 5). In this and all frames, the circular field of view represents the cladding. The color code of the modal distribution is, in order of diminishing intensity, red, yellow, green, light blue. The highest intensity clearly resides over a fairly small percentage of the cladding area, which confirms qualitatively that the pump was exciting only a small portion of the total Yb population. The uniformity in frame (a) is similar to that of the ZBLAN fiber excited directly by the laser pigtail (frame (b)). The pump distribution when the ZBLAN fiber was excited by a length of multimode fiber (frame (c)) is also comparable – it might in fact be even more confined.

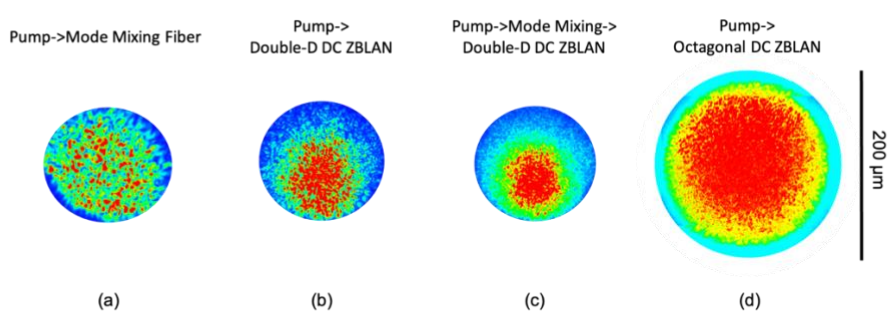

Figure 5. Mode profiles of the DC fiber with and without mode mixing fiber at the input.

4.3 Octagonal cladding-doped ZBLAN fiber

The third ZBLAN fiber, which had an octagonal cladding, was designed specifically to improve the mode filling of the cladding. As shown in Fig. 5d, under direct excitation with the laser pigtail fiber, the mode filled a noticeably larger portion of the cladding, and better performance was expected. A similar sequence of experiments was carried out on a 52-cm length of this fiber as on the other fibers. The pump-absorption cut-back measurements (Fig. 6a) showed a weaker saturation up the ~3-W power level available from the 1025.5-nm laser than with the double-D fiber, consistent with a better mode filling of the cladding. The dependence fitted to these data points (solid curve in Fig. 6a) gave a good agreement by using two fitting parameters only, namely the small-signal absorption coefficient α_0 and the saturation power P_{sat}. The fitted values are $\alpha_0 = 6.7$ m^{-1} and $P_{sat} = 3.45$ W. From the knowledge of P_{sat} and the saturation intensity, calculated to be 410 MW/m^2, and assuming that the pump has a top-hat distribution centered on the core, the inferred pump effective area is 8,410 μm^2. From the knowledge of α_0, the measured absorption cross section of Yb, and the known Yb concentrations in the core and the cladding, the pump effective area can also be inferred. This inferred value is 9,890 μm^2. The two measurements roughly agree with an effective area of 9,200 μm^2, or ~38% of the core and cladding area—approximately 6 times larger than the double-D fiber.

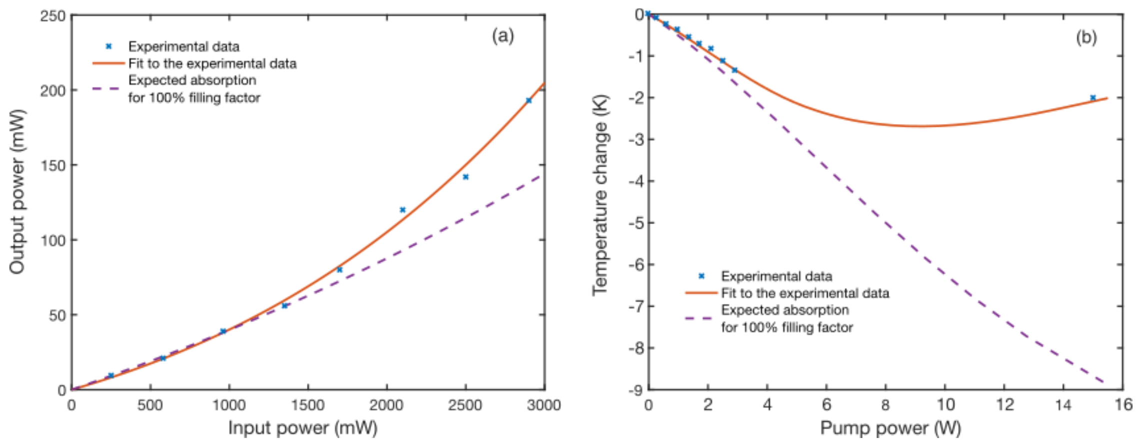

Figure 6. Experimental results for the octagonal cladding-doped ZBLAN fiber. (a) Measured output pump power versus input pump power and comparison with the model. (b) Temperature change fiber of the fiber as a function of the pump power at the location of the measurement.

Figure 6b shows the measured temperature change as a function of the pump power. Here too, as the pump power was increased from zero the fiber temperature dropped rapidly, down to –1.3 K at the maximum available pump power of 3 W available. To improve on this value, the same fiber was pumped with the more powerful 1040-nm laser (albeit with a possibly different filling of the cladding). At an input pump power of 15 W, the temperature change was -2 K (rightmost data point in Fig. 6b). The model prediction fitted to these data points (solid red curve) using the effective area obtained from the pump-absorption measurement is in excellent agreement. The values of the two fitting parameters obtained from this best fit are a critical quenching concentration $N_c = 3.2\text{x}10^{27}$ Yb/m^3 and an absorptive loss $\alpha_{ba} = 40$ dB/km. The purple dashed curve is the temperature dependence that was expected if the pump beam had excited all the Yb ions uniformly in the cladding. At 15 W of pump power, the ratio between the measured cooling (–2 K) and the expected cooling (–8.5 K) is ~23%, which is commensurate with the pump filling ratio (~38%). This analysis confirms the importance of filling the entire cladding in order to maximize heat extraction.

5. CONCLUSIONS

In conclusion, we reported the first observation of ASF cooling in a fiber with a doped cladding. Experiments were performed in two Yb-doped ZBLAN fibers in which both the core and the cladding were doped with Yb^{3+}. Temperature measurements showed that the fiber with a double-D cladding did not perform as well largely due to limited mode mixing, which resulted in only a small fraction of the ions in the cladding being excited and contributing to the refrigeration process. In the second doped-cladding fiber, the cladding had an octagonal shape to increase mode mixing and excite the cladding more uniformly, and greater cooling was observed, namely 1.3 K below room temperature with 3 W of 1025.5-nm power and 2 K below room temperature for 15 W at 1040 nm. This work demonstrates for the first time, as anticipated by modeling and basic physics [11], that cooling a fiber by pumping its doped cladding is a viable method to extract more significant amounts of heat than possible in a core-pumped fiber. It also shows that uniform excitation of the entire cladding is essential to take full benefit of the refrigeration potential of this scheme. Better results are expected in the near future by pumping at a more optimum pump wavelength (1030–1035 nm), further improving pump filling of the cladding, and reducing the fiber's absorptive loss.

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