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Denis V. Gapontsev
Dahv A. Kliner
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Editors

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20W CW, 4MHz linewidth Raman fiber amplifier with SHG to 589nm

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ABSTRACT

Up to 20.7 W CW, 3.5 MHz linewidth, 1178 nm continuous-wave laser has been obtained at ESO laser labs by Raman amplification of a distributed feedback diode laser. To our knowledge it is the highest power obtained at such a narrow linewidth with Raman fiber amplifiers. The 1178nm laser has a linear polarization-extinction-ratio of 25dB. Frequency doubling with an LBO-based SHG commercial cavity has given 83% conversion efficiency and 14.5W CW at 589nm. The source is suitable to produce mesospheric laser guide stars as reference stars for adaptive optics. The presented narrow-band, high power Raman amplification technique might be used for a large number of different wavelength ranges.

Keywords: Lasers, fibers, Raman lasers, laser amplifiers, laser guide stars, Second Harmonic Generation

1. INTRODUCTION

This post-deadline paper, which has to be limited to two pages, reports on the recent breakthroughs of our research activities done in the frame of the ESO R&D programs to generate 589nm CW sources for laser guide stars. In future large telescopes instrumentation, 20-25W CW at 589nm are necessary, with linewidths ideally ≤50 MHz. Toward this goal our Laser Systems Dept is working on the development of high power, narrow band fiber Raman lasers at 1178nm, to be then frequency doubled to 589nm.

Fiber lasers are an asset and probably the best choice in remote and difficult operation sites like astronomical observatories. They are typically compact, maintenance-free, turn-key and ruggedized devices. Moreover their output beam quality is extremely good. The lasers which we are aiming at are part of Laser Guide Star Facilities; the laser beam is projected at 90 km in the Mesosphere, producing laser guide stars by excitation of mesospheric sodium atoms. Our in-house development is done in close touch with industry, with the goal to have the final laser packaged and finally engineered by industry, as a product. We are progressing with the research taking care of course of the IP protection.

2. THE LASER

A MOPA scheme is followed in our 1178nm fiber laser source, in which an 1178nm, ~10s mW DFB fiber coupled laser is used as seed for a Raman fiber amplifier. The pump wavelength is 1120nm. Both seed and pump fiber lasers are commercially available. We have found first a way to obtain narrow-band Raman amplification, with the linewidth limited so far only by the seed linewidth; then recently we have been successful in efficiently suppressing SBS in the Raman amplifier, obtaining up to 20.7 W CW at 1178 nm. The technique will work in many other wavelength ranges.

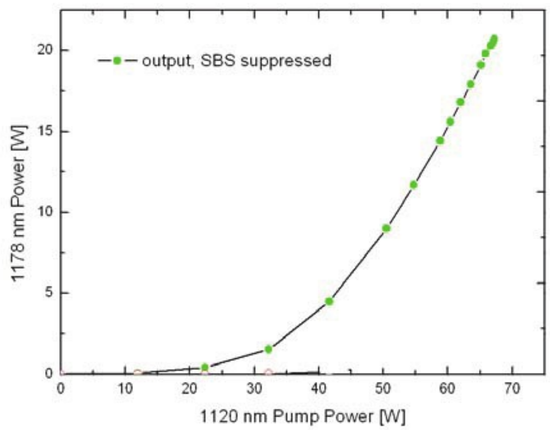
Although in our experiment still a non-polarization-maintaining fiber is used, the laser can be adjusted to emit linear polarization, with a polarization-extinction-ratio of 25dB, using waveplates in the free space beam before the SHG unit. The observed long-term stability of the output polarization is of the order of few degrees/C, at regime operation. The measured linewidth of our system is about 3.5 MHz, suitable for highly efficient resonant external cavity doubling to 589 nm for laser guide star applications.

The output of the fiber amplifier is optically isolated and then mode matched to a compact, commercially available SHG cavity. The cavity uses a 20mm LBO crystal for the SHG. Thanks to the extremely good optical quality of the input beam, we have reached a very good mode matching with the cavity. Also, the spectral phase noise properties of our high power fiber Raman amplifier are extremely good, since a SHG conversion efficiency up to 83% has been achieved.

3. RESULTS

Figure 1 shows the measured 1178 nm output as a function of the 1120 nm pump power. With the suppressed SBS amplifier we obtain up to 20.7 W at 1178nm with 67 W CW of pump power at 1120nm. This means we have obtained ~10 times increase of SBS threshold in power, with respect to a normal fiber of similar length.

To further increase the output power of the single stage amplifier, we will test in the coming months further SBS suppression schemes as a function of fiber length and pump power. The frequency conversion has produced up to 14.5W CW at 589nm, with 17.2W CW at 1178 in input. This is better than 82% conversion efficiency.



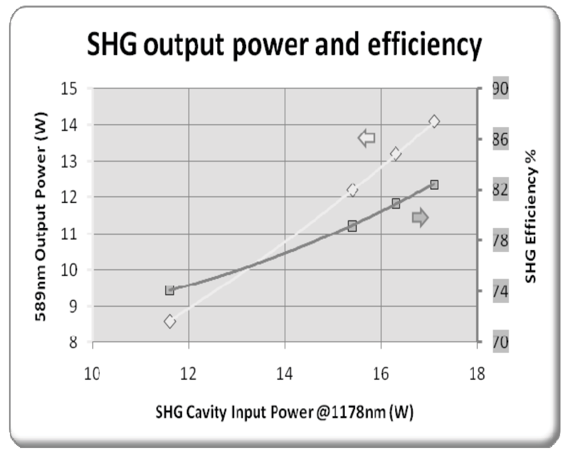
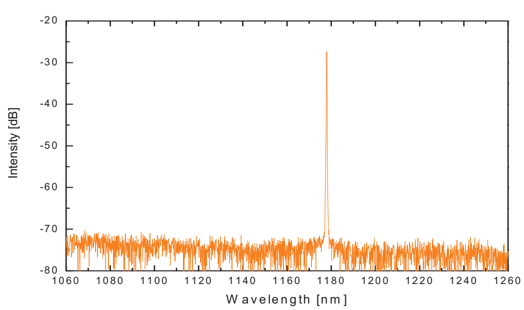


Fig. 1 Left: output power of the 1178nm fiber Raman amplifier as a function of pump power;

Right: measured SHG output power at 589nm, up to 14.1W CW in this plot, with conversion efficiency up to 82%

An Ando optical spectrum analyzer is used to check the spectral purity of the 1178nm fiber laser output. The result is shown in Figure 2. We see more than 40 dB contrast of the background noise versus the signal.



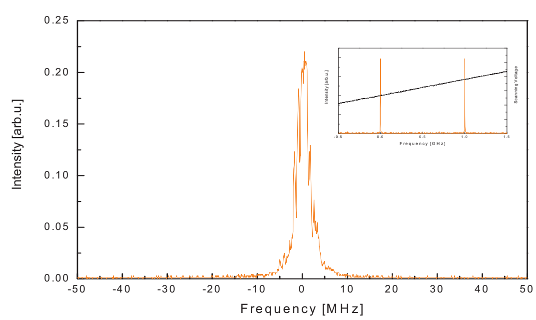


Fig. 2 Spectrum of the amplifier output. left) a broad range spectrum taken with an Ando spectral analyzer showing 40 dB contrast; right) a detailed spectrum of the 3.5MHz line taken with a Fabry-Perot interferometer (1 GHz FSR).

The spikes on the emitted spectrum are due to the well known fast frequency jitter of our DFB diode seed. The temporal separation of these spikes depends on jitter frequency, so one can see fewer spikes in the spectrum when scanning faster. The inset figure shows a full free spectral range scanning, indicating that no other frequency exists around the 1178nm line. The 1178nm signal power variation RMS as measured is <1% at full power.

Efficient Highly Ytterbium-Doped Silica Fibers with Low Photo-darkening for High Power Fiber Lasers

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Abstract: Ytterbium-doped phosphosilicate fibers with phosphate-like characteristics, lifetime and doping-levels are demonstrated, offering significantly increased peak powers from shorter fiber amplifiers. Efficient fibers with up to 4700dB/m peak absorption at 976nm, gain of 4.6dB/cm and low photo-darkening are demonstrated. The refractive index of the doped glass can also be tailored to match that of silica, which makes it especially attractive to large core fiber designs.

Fiber lasers are increasingly deployed in many commercial applications. Higher peak powers from fiber lasers are, however, still limited by fiber nonlinearities. Although advanced large core designs offer a raised nonlinear threshold, an increase in rare earth doping level can lead to shorter amplifier length and additional increase in nonlinear threshold. Ease of use can deteriorate for large core fibers, it is, therefore, also highly desirable to further extend peak powers in SM fibers by increasing rare earth concentrations. It is well known that a higher rare earth concentration can lead to clustering which can render fibers inefficient and unreliable by strong non-radiative effects, reduced lifetimes and photo-darkening (PD). It is also well known that aluminosilicate fibers can lower clustering, leading to an increased doping level. Recently, an aluminosilicate fiber with 2450dB/m peak absorption at 976nm was demonstrated with a low PD loss of 17dB/m at 660nm and ~47% inversion [1]. Phosphate glass, on the other hand, is known to be capable of incorporating much higher levels of rare earth ions, ~9000dB/m at 976nm, with negligible PD [1, 2]. Unfortunately, phosphate glass can only be made with crucible techniques which tend to introduce high impurity levels, leading not only to high background loss, but also to lower damage threshold, limiting it to short length and low power applications. In addition, the low transition temperature of ~500^{o}C for phosphate glass comparing to ~1200^{o}C for silica also makes it less reliable host for lasers at high average powers where a much elevated core temperature is expected. A glass host which is capable of having high doping concentrations, low impurity levels, and is compatible to silica fibers to enable the use of technologies developed for telecommunication, is, therefore, highly desirable.

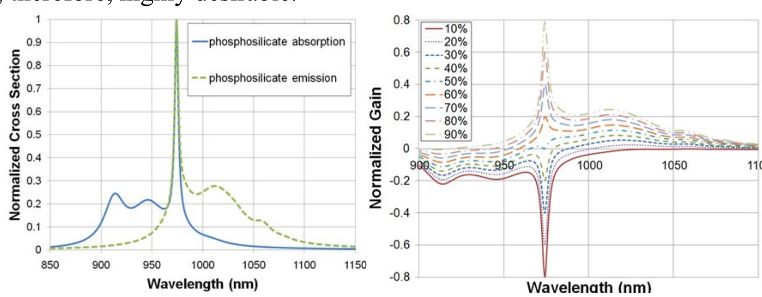

Fig. 1, from left to right, cross sections and gain spectra of phosphosilicate fibers at various inversions.

We demonstrate in this work phosphosilicate fibers fabricated with an optimized CVD process for high phosphorus and rare earth doping. Ytterbium-doped fibers are demonstrated to have phosphate-like spectral characteristics and a much longer lifetime of 1.35ms comparing to that in aluminosilicate fibers. Highly efficient and reliable ytterbium doped phosphosilicate fibers with peak absorption of 4700dB/m are demonstrated with saturated PD loss below 3.6dB/m at 1.05μm at ~50% inversion. In fibers with peak ytterbium absorption of 3200dB/m, negligible saturated PD of less than 0.08dB/m is demonstrated. Low background loss of less than 0.05dB/m is regularly obtained in all fibers. Most of these fibers are also doped with a high level of boron. This allows refractive indexes close to that of silica to be achieved even at very high rare earth doping levels, an critical requirement for most large core fiber designs.

Hundreds of fibers have been fabricated for this study. The fabrication process, has been continuously improved for maximum phosphorus incorporation and process control. Many of the fabricated fibers have been used in amplifiers and lasers, including the highly doped fibers in this paper, providing demonstrated efficient and reliable operation over long time period of a few months. Typical normalized absorption and emission cross sections are shown in Fig.1. These were obtained by curve fitting to the measured data as described in [3]. Both absorption and emission of phosphosilicate fibers are similar to that of phosphate glass, evidence that most ytterbium ions are near phosphorus sites. The absorption of phosphosilicate fibers have three peaks instead of two in aluminosilicate fibers. The emission peaks of phosphosilicate fibers are at shorter wavelengths comparing to that of aluminosilicate fibers, due to a narrower Stark split. Normalized gains at various inversion levels are plotted in Fig.1. The gain peak around 1010-1030nm has relatively higher gain and is significantly broader than that in aluminosilicate fibers, ideal for amplification of ultra short pulses with broad spectral width over a short fiber length. Measured lifetimes for a typical phosphosilicate fiber and a commercial aluminosilicate fiber are 1.35ms and 0.6ms respectively, again showing what is expected from a phosphate-like host.

A large number of fibers with various compositions, fabrication conditions and peak ytterbium absorption ranging from 1500-5500dB/m, were tested for photo-darkening with a 675nm LED with a continuous pumping setup. A short fiber length of ~30mm was typically used. An ytterbium amplifier simulator [3] was used first to calculate 976nm pump power for a saturated inversion of ~50%. Since photo-darkening is very sensitive to inversion levels, sufficient pump power was always used to ensure inversion saturation for good repeatability. The measured absorption spectrum of the fiber with 3200dB/m peak absorption is shown in Fig.2. Loss and gain were measured in or converted to that of a fiber with ~100% overlap between optical mode and the dopant distribution in the fiber. The PD was measured in single mode fibers. The PD usually takes few hours to reach saturation. The Leftmost panel in Fig.2 gives the measured PD for three fibers, two phosphosilicate fibers with 3200dB/m and 4700dB/m peak absorption respectively, and a commercial aluminosilicate fiber with 380dB/m peak absorption. The saturated PD losses are 0.8dB/m, 36dB/m and 0.8dB/m respectively. Despite the phosphosilicate fiber with 3200dB/m peak absorption having near an order of magnitude higher ytterbium concentration, it has a PD loss level similar to that of the commercial 380dB/m aluminosilicate fiber. PD spectra were also measured in the two phosphosilicate fibers and are shown in the middle panel of Fig.2, normalized against the loss at 675nm. The long wavelength loss was not well resolved for the fiber with 3200dB/m peak absorption. The loss ratio at wavelengths of 675nm and 1.05μm is estimated to be ~10 using the data for the fiber with 4700dB/m peak absorption. Saturated PD losses at 1.05μm of 0.08dB/m and 3.6dB/m respectively were estimated for the two phosphosilicate fibers, representing the lowest PD loss at these doping levels ever reported in silica fibers. This saturated PD loss represents the highest possible loss by a 976nm pump. Since PD is a strong function of inversion and inversion in a high power double clad fiber is much lower, a much lower PD loss is expected in high power lasers and amplifiers. PD dynamics for pump on and off was also measured. The PD recovered by ~50% after pump being switched off and increased again at slightly higher rate for the second pumping cycle. Output of fresh 3cm long amplifiers made from the two phosphosilicate fibers, seeded by an ytterbium ASE source peaked at ~1030nm, was monitored for 44 and 136 hours respectively from the first pump on at ~50% inversion (see the right panel in Fig.2), showing high unit gain levels approaching that of ytterbium crystals of 2.2dB/cm and 4.6dB/cm respectively with negligible degradation over the test periods. This type of performance was also confirmed by numerous oscillator and amplifier tests using similar fibers with core diameters ranging from 5μm to 50μm.

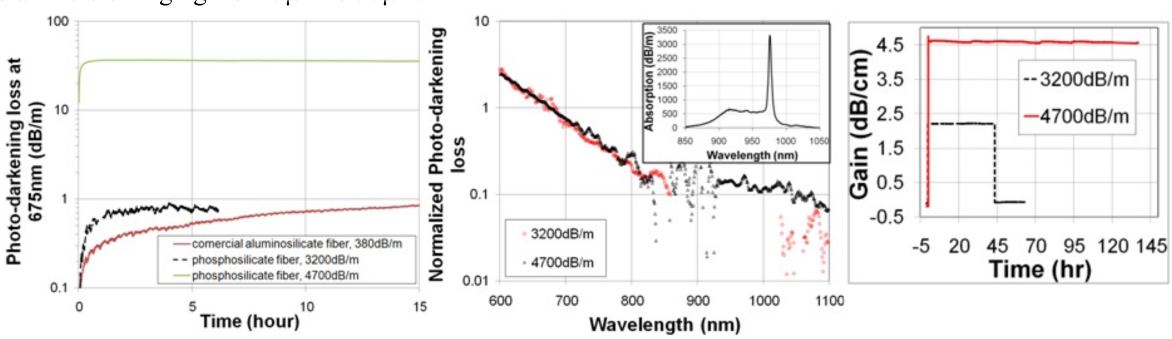

Fig. 2, from left to right, measured PD loss, PD spectra and gain versus time. Inset is absorption spectrum.

To summarize, we have demonstrated phosphosilicate fibers with phosphate-like characteristics, doping levels and performance. These fibers will further increase peak power performance of fiber lasers and amplifiers for all fiber designs and provide more robust and reliable alternative to phosphate glass fibers for single frequency lasers.

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Power Scaling of Resonantly Cladding-Pumped Yb-free Er-doped LMA FBG Laser

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Abstract
Reported here is resonantly cladding-pumped (at 1532.5 nm) Yb-free Er-doped fiber laser delivering ~48 W of CW output at 1590 nm with the ~57% optical-to-optical conversion slope efficiency. This diode-pumped laser operates with the ultra-low quantum defect of 3.75%. Obtained efficiency is the highest efficiency reported for the cladding-pumped unidirectionally emitting Er-doped laser. Reported power is believed to be the highest power ever reported from Yb-free, Er-doped fiber laser.

Keywords: fiber laser; eye-safe; Er-doped.

Introduction

Major power scaling results in the eye-safe ~1.5 μm fiber lasers have been reported for the cladding pumped Yb-Er-co-doped fibers pumped into Yb-absorption band [1]. Due to inefficiencies associated with very large (~40%) quantum defect scalability of these devices suffers from and is limited by enormous heat deposition inconsistent with major power scaling toward DEW power levels. So far very few efforts were reported on the resonantly cladding-pumped Yb-free Er-doped fiber lasers, which can actually offer much higher efficiency as well as power scalability [2-4]. In [2, 3] output power of ~1W was achieved based on this concept (in [2] by accounting for the power emitted from the fiber bi-directionally). The [3] was the first effort actually exploiting the most scalable LMA fiber approach. The [4] was the first effort to scale significantly beyond the ~1 W power level achieved in [2, 3]. Single-frequency output power of 9.3 W was obtained in a MOPA configuration from resonantly cladding-pumped Yb-free EDFA with the optical-to-optical conversion slope efficiency of ~46% [4]. Presented here are the results of further major power scaling effort based on resonantly cladding-pumped approach. Characterization results of a resonantly cladding-pumped FBG-laser based on Yb-free Er-doped COTS LMA fiber are discussed. This is the first reported resonantly cladding-pumped FBG-based Er-doped LMA fiber laser. Obtained narrowband output of 47.6 W is believed to be the highest power reported from Yb-free, Er-doped fiber laser. This fully integrated laser also has the optical-to-optical conversion slope efficiency of 56.7%, to the best of our knowledge, the highest efficiency reported for cladding-pumped unidirectionally emitting Er-doped laser.

Experimental details and results

Shown in Fig. 1 is the fully integrated Er fiber laser based on COTS Liekki Er60-20/125 double clad (DC) fiber pumped through the FBG-mirror. The FBG, matching the 20/125 DC fiber format, was manufactured by IPG Photonics Corp. and has the ~93.5% reflectivity centered at 1589.4 nm with the 2.58 nm bandwidth (FWHM). The laser was cladding pumped by fiber-coupled (into a 105/125 μm, NA 0.15 fiber) custom made laser diode modules (centered at 1532.5 nm and spectrally narrowed to 0.5 nm). The pumping was coupled into a ~15 m long Er 60-20/125 DC LMA fiber through a standard matching (6+1)x1 SIFAM pump combiner. The output fiber end has a straight cleave used as an outcoupling mirror. The fiber was coiled in order to achieve nearly single transverse mode regime (see below).

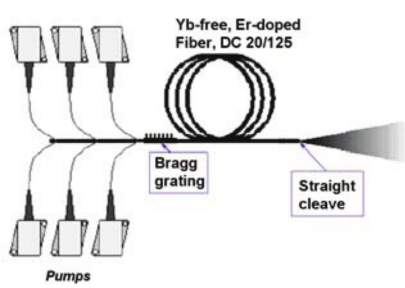

Figure. 1. Optical layout of the resonantly cladding-pumped fiber laser based on Liekki Er60-20/125 DC fiber pumped at 1532.5 nm.

Fig. 2 presents major testing results obtained with the resonantly cladding-pumped Yb-free Er-doped fiber laser shown in Fig. 1. Maximum of 101 W of launched power at 1532.5 nm (after the FBG) resulted in maximum of 84.1 W of power absorbed in the 15-m long fiber. The obtained output versus launched pump power dependence indicates clear linear behavior with no saturation effects, which is indicative of purely pump limited power scaling case. The maximum output power of 47.6 W was obtained with the optical-to-optical efficiency of 56.7%. Er-fiber laser, pumped at 1532.5 nm and emitting at ~1590 nm (see Fig. 3), operates in an ultra-low quantum defect (QD) mode. QD of ~3.75% regime is very important for further power scaling without the need for special thermal management for powers up to several hundred Watts. In this first FBG-laser experiment spectrally clean 1590 nm output was obtained with the ASE level at about 35 dB below the signal level (see Fig. 3) up to the maximum output power. Indicated in Fig. 3 are: Pump – the leaked unabsorbed pump power at 1532.5 nm; ASE – amplified spontaneous emission; Laser output – the underresolved (on the scale shown in Fig. 3) fiber laser power at ~1590 nm.

Using the optical spectrum analyzer set to a 0.05 nm resolution we found that the overall spectral width of the 1590 nm laser output never exceeds 0.25 nm FWHM. The spectral power distribution within this spectral width is not a steady-state one: there were typically 2-3 not quite fully resolved competing peaks observed in laser output around 1590 nm, but all confined to a 0.25 nm spectral width. With loose coiling laser typically emitted 2-3 lower order modes. Stable nearly diffraction limited operation was achieved, with the penalty in efficiency of ~5%, by partial coiling of the Er60-20/125 DC LMA fiber to a diameter of ~8-10 cm. Far field pattern of the output in this case is shown in Fig. 2 (inset).

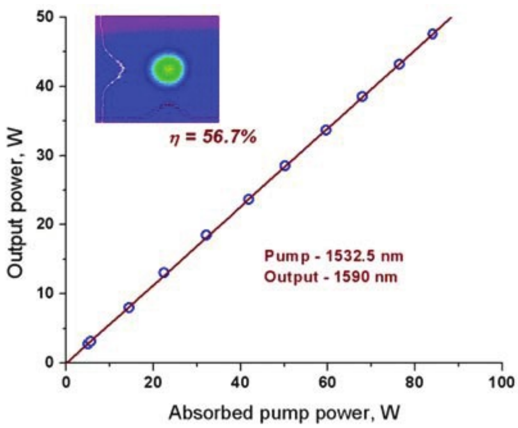

Figure 2. Output versus absorbed pump power dependence obtained for the resonantly cladding-pumped Er-doped FBG-laser shown in Fig.1.

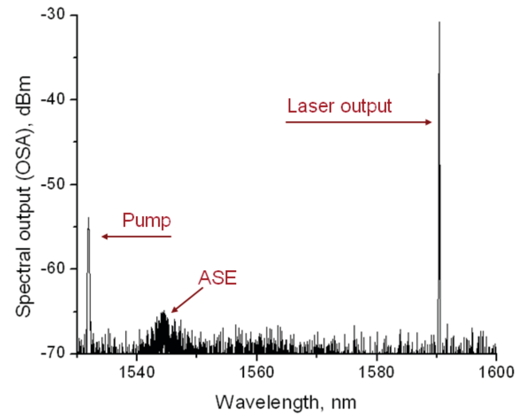

Figure 3. Spectral output of the FBG laser shown in Fig.1 (ANDO AQ6370 optical spectrum analyzer, resolution 0.05 nm).

Conclusions

Highly scalable, efficient, ultra-low quantum defect (~3.75%) operation of the fully integrated resonantly cladding-pumped Yb-free Er-doped FBG-laser based on COTS LMA fiber has been demonstrated. 47.6 W of spectrally clean narrowband 1590 nm output was obtained with the ~56.7% optical-to-optical conversion slope efficiency. This result presents, to the best of our knowledge, the highest power ever reported from Yb-free Er-doped fiber laser, as well as the highest efficiency ever reported for cladding-pumped unidirectionally emitting Yb-free Er-doped fiber laser. Our laser operated with no indication of power saturation effects, i.e., achieved power is assumed to be strictly pump limited and can be further scaled significantly. Yb-free Er-doped DC fibers for clad pumping are currently grossly underdeveloped. With specialty Er-fibers developed specifically for the application conversion efficiency can be increased to a QD-limited level - just like in Yb-doped fiber lasers.

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