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Power Scaling of Resonantly Cladding-Pumped, Yb-Free, Er-Doped LMA Fiber Lasers[1]

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Abstract—The results of the recent major efforts in power scaling of resonantly cladding-pumped Yb-free Er fiber lasers are presented. Commercially available Yb-free Er-doped large mode area Er60-20/125 (LMA) DC fibers were tested in two regimes: (i), as a booster amplifier in a single-frequency (SF) MOPA configuration and, (ii), in a Bragg grating (FBG) based narrowband fiber laser configuration. We obtained ~28.5 W of output power at 1590 nm, the highest power reported so far out of Yb-free Er-doped LMA fiber with resonant cladding pumping. The achieved optical-to-optical conversion slope efficiency of ~56.6% is also believed to be the highest efficiency ever reported from Yb-free Er-doped fiber laser with resonant cladding pumping.

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INTRODUCTION

Current developments in the eye-safe ~1.5-μm Yb–Er co-doped fiber lasers (where Er ion excitation is accomplished via Yb) are promising. Output power of Er–Yb fiber lasers approaches a ~300 W level [1]. However, multi-hundred Watt power Yb–Er fiber laser systems usually carry in their output significant fraction of Yb emission (either narrowband or ASE) in the 1-μm spectral range, thus totally compromising any eye-safe application of these systems. This problem, as well as very limited power conversion efficiency of the Er–Yb laser systems (maximum of 43% before ~120 W power limit, and more like ~35% at higher powers [1]), motivated researchers to look back and re-analyze, for high power applications, the potential of the approach introduced in late 80's by Snitzer [2]—direct excitation of Er in Yb-free fibers.

Our recent successes with resonantly pumped Er:YAG bulk solid-state lasers [3, 4] point to significant advantages of using the direct resonant pumping of Er-only doped laser materials as opposed to pumping Yb–Er co-doped laser materials. In the meantime, very little is done in evaluating direct resonant pumping of Er^{3+} in Yb-free Er-doped fiber lasers as it relates to high power applications, and especially few results were reported on scalable in nature cladding-pumped operation of Yb-free Er-doped fiber lasers. Because of quite high power density required for bleaching the ground-state absorption loss in the three-level Er-doped systems, most efforts were focused on core pumping geometry using either high brightness 980-nm dye or diode lasers [5] or Raman-based fiber lasers operating in the 1480-nm spectral range [6]. In fact, the only efforts aimed at "non-telecom power level" scaling of resonantly cladding-pumped Yb-free Er fiber lasers were reported in [7, 8]. While in both these cases output power level of a little over 1 W was achieved, neither of these efforts was targeting ultimate power scaling by also addressing generation (or amplification) of the single-frequency laser radiation most suitable for further power scaling, e.g., via beam combining. Of the two mentioned efforts only one ([8]) was actually targeting the most scalable LMA fiber case. Recently we addressed the SF case and achieved significant progress in SF amplification with Yb-free Er-doped cladding-pumped LMA fiber [9] well beyond the telecom power level.

Here we present the most recent results on power scaling of resonantly cladding-pumped double-clad (DC) Yb-free Er-doped fibers. No special effort was made on fiber design: only commercially available Yb-free Er-doped large mode area (LMA) DC fibers were used. Reported here is the high power performance of Liekki Er60-20/125DC double-clad, Er-only doped LMA fiber booster amplifier pumped by fiber-coupled, highly multimode, broadband (composite bandwidth of ~20 nm FWHM), InGaAsP/InP laser diode modules centered at ~1530 nm. Booster amplifier in a single-frequency (SF) MOPA configuration demonstrated 46% slope efficiency versus absorbed pump power and maximum of ~10.4 W of CW output power at 1595 nm, which was pump-limited. This laser operated with ultra-low quantum defect of 4.2%. Also reported are the results obtained with the same Liekki Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber, pumped by fiber-coupled, spectrally-narrowed (bandwidth of ~0.5 nm FWHM), InGaAsP/InP laser diode modules centered at 1532.5 nm. In this case the fiber was tested in a simple fiber Bragg grating (FBG) based laser con-

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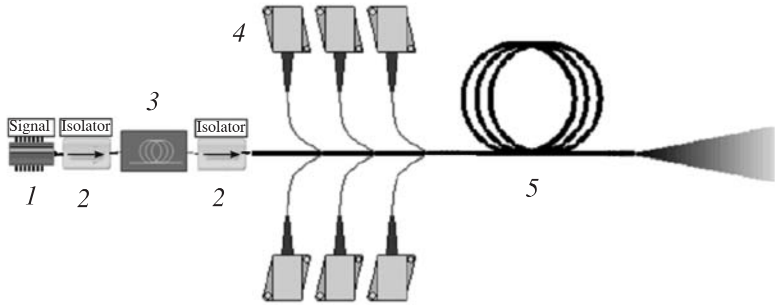

Fig. 1. Experimental setup of the SF MOPA used for testing resonantly cladding-pumped LMA fiber booster amplifier based on Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber. (*1*) Tunable semiconductor SF seeder; (*2*) low loss optical isolators; (*3*) L-band Er fiber preamplifier, (*4*) fiber coupled InGaAsP/InP laser diode pump modules; (*5*) booster amplifier under study.

figuration and exhibited maximum output power of ~28.5 W at 1590-nm with the optical-to-optical conversion slope efficiency of ~56.6%. The latter result presents the highest power ever achieved out of Yb-free Er-doped LMA fiber with resonant cladding pumping and is strictly pump-limited. The achieved slope efficiency is also the highest optical-to-optical conversion slope efficiency ever reported from Yb-free Er-doped fiber laser with resonant cladding pumping. This laser operates with the ultra-low quantum defect of 3.75%.

EXPERIMENTAL DETAILS AND RESULTS

In the first set of experiments we tested the commercially available Liekki Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber, core NA 0.07, cladding NA 0.22, in a booster amplifier, as a part of the SF, MOPA setup (Fig. 1). The latter comprised a tunable semiconductor seeder (1) (single frequency, spectral width under 1 MHz, output power ~6 dBm), Er fiber preamplifier (3) with the output power level of ~1 W, and the booster amplifier under study (5). Unlike [9], an L-band preamplifier was used in this effort. Optimized length of the booster amplifier fiber was found to be ~9.5 m. All three MOPA stages were separated by low loss optical isolators (2) in order to prevent the undesirable feedbacks. Booster amplifier was co-pumped by six fiber coupled InGaAsP/InP laser diode pump modules (4) through the SIFAM 6-port pump combiner matching the Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber profile and numerical aperture (NA). Maximum of 5–6 W of pump power coupled into the 105/125 μm multimode fiber with 0.15 NA was launched into each pump port. The pump combiner loss was found to be around 11%, and the total maximum pump power at the pump combiner output, i.e., launched into the booster amplifier cladding, was measured to be ~30 W. Nominal pump wavelength was ~1530 nm, but combined spectral output of the six modules was as wide as ~20 nm FWHM (see Fig. 2). The reason for such a wide spectral width is that: (i) the original spectral width of each individual InGaAsP/InP laser diode module is as wide as ~10 nm, (ii) all six pump diode modules were mounted on the same cooling heat sink, and were not thermally adjusted each individually, and, (iii) the available individual pump diode lasers were not pre-selected for a very specific spectral position. The temperature of the heat sink was adjusted in order to maximize the pump absorption at the highest pump power level. This surely provides the highest output power, but with the pump spectral width as wide as 20 nm FWHM we could only achieve maximum effective absorption coefficient which does not exceed ~0.67 dB/m while the expected peak absorption value for the cladding-pumped Er60-20/125DC fiber is 1.5 dB/m.

The amplifier performance was tested with the seeder SF signal, unpolarized, amplified in the fiber pre-amplifier to about 1 W of power, estimated to be sufficient in order to saturate the booster amplifier. The

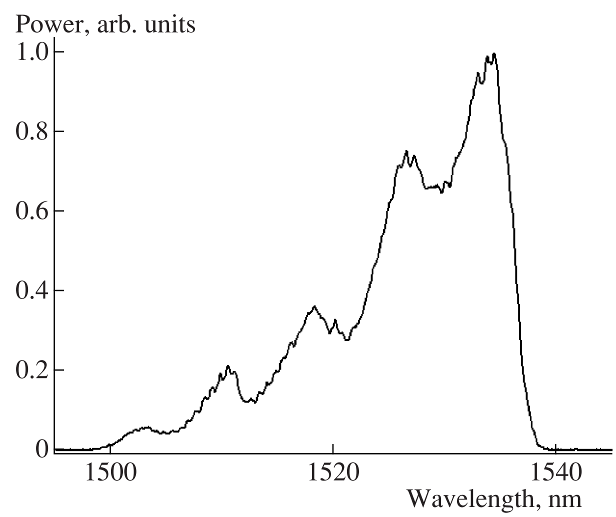

Fig. 2. Composite spectrum of the six, nominally 1530-nm, InGaAsP/InP laser diode modules at the output of the 6-port pump combiner. Spectral distribution is diode pump current dependent; the displayed spectrum was taken at the maximum power of ~30 W out of pump combiner.

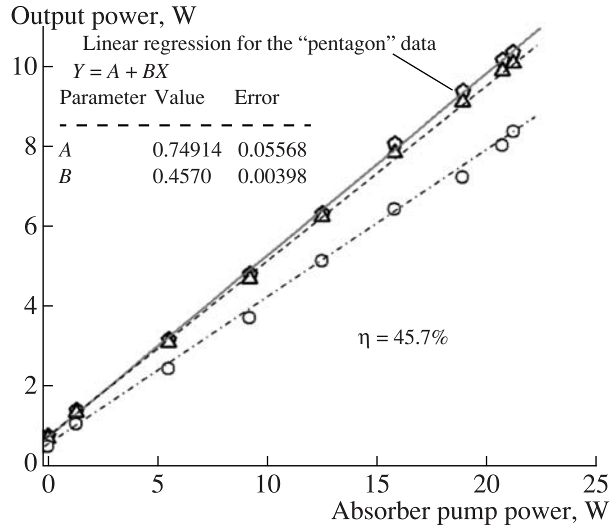

Fig. 3. Performance of the SF resonantly cladding-pumped Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber amplifier tested in the MOPA configuration shown in Fig. 1 for the three different seed laser wavelength. Pump wavelength is 1530 nm, broadband pump (~20 nm FWHM). Preamplifier signal level ~1 W. Seeder wavelength: 1595 (open pentagons), 1600 (open triangles), and 1610 nm (open circles). The solid straight line is the linear regression of the 'open pentagon' data points (1595 nm). Parameters of this regression are shown on the inset (left, top) along with the corresponding error margins.

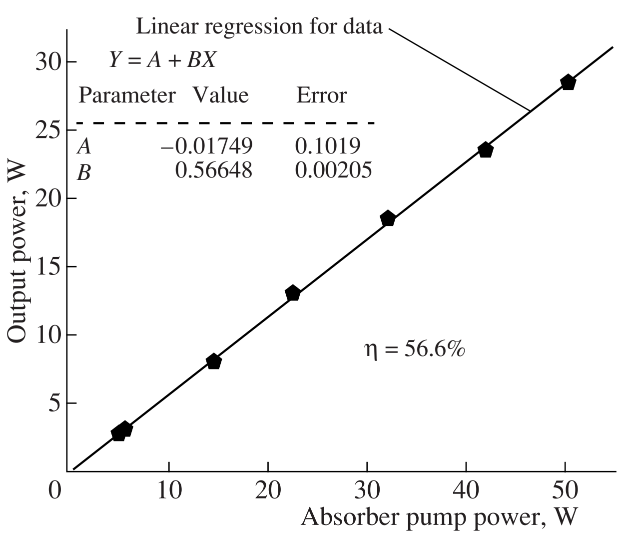

Fig. 4. Performance of the resonantly cladding-pumped Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber tested in a simple FBG based laser configuration. The straight line is the linear regression of the data points. Parameters of this linear regression are shown on the inset (left, top) along with the corresponding error margins.

seeder wavelengths were varied in the 1590–1610 nm fraction of the L-band. The performance of the SF resonantly cladding-pumped Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber amplifier is presented in Fig. 3. The SF nature of the output power after the preamplifier and the booster amplifier was monitored throughout the experiment. Output power versus absorbed pump power dependences in Fig. 3 are illustrated at seeder wavelength of 1595 (open pentagons), 1600 (open triangles), and 1610 nm (open circles). The fiber amplifier demonstrates the highest optical-to-optical conversion slope efficiency of 45.7% with the seed wavelength of 1595 nm. The maximum single-frequency output power at this wavelength was measured to be over ~10.4 W and is believed to be the highest reported SF power out of Yb-free Er-doped fiber amplifier. This amplifier was operated with the ultra-low quantum defect of only 4.2%. No output power saturation was observed with the increasing pump power. We could detect neither nonlinear effects nor ASE power, which limit the amplifier performance, so the performance is assumed to be pump power limited.

In the second set of experiments the same commercially available Liekki Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber was efficiency and power tested in a simple fiber Bragg grating (FBG) based laser configuration. The FBG was used in a function of WDM separating the pump and the laser wavelengths, and served as laser's highly reflective mirror. A straight cleave on the other fiber end was used as an outcoupling mirror. The FBG had a ~93.5% reflectivity centered at 1589.4 nm with the 2.58 nm bandwidth (FWHM) and maximum transmission at 1532.5 nm. Fiber laser was co-pumped by six fiber-coupled (into 105/125 μm, NA 0.15 fiber), spectrally-narrowed (bandwidth of ~0.5 nm FWHM), InGaAsP/InP laser diode modules. The modules, spectrally narrowed by volume Bragg gratings (VBG), delivered an average of ~11 W of fiber coupled power each, centered at 1532.5 nm. This wavelength was chosen to correspond to the peak of the Er60-20/125DC fiber absorption spectrum. This is done in order to maximize the absorption of the pump power, and thus reduce the optimum laser fiber length. Fiber co-pumping was realized through the SIFAM 6-port pump combiner matching the Er60-20/125DC active fiber. Maximum of ~60 W of launched pump power was measured after the combiner.

Major laser testing results obtained with the resonantly cladding-pumped Liekki Er60-20/125DC double-clad, Yb-free Er-doped LMA fiber laser are shown in Fig. 4. The straight line represents the linear regression of data points. It indicates linear laser behavior with no obvious saturation effects, which points to a purely pump limited laser power scaling nature in this case. Parameters of this regression are shown in Fig. 4 (inset-left, top) along with the corresponding error margins. Linear regression parameters are indicative of optical-to-optical conversion slope efficiency of ~56.6% achieved in this laser operating in an ultra-low quantum defect (QD) mode. This is the highest optical-to-optical conversion slope efficiency from Yb-free Er-doped fiber laser with resonant cladding pumping reported to-date. Laser regime with the QD of ~3.75% offers significant potential for further power scaling. Maximum laser output power of ~28.5 W was achieved at 1590-nm with the overall spectral width of the output narrower than 0.25 nm FWHM. This result presents the highest power ever achieved out of Yb-free Er-doped LMA fiber with resonant cladding pumping. Spectral output typically exhibits 2–3 not quite fully resolved competing peaks which are all confined to the above 0.25 nm spectral width.

CONCLUSIONS

Highly scalable, efficient, high power, ultra-low quantum defect operation of the fully integrated commercially available resonantly cladding-pumped Yb-free Er-doped fiber laser was demonstrated in two regimes: a single frequency booster amplifier and a narrowband, fiber Bragg grating based, laser. Booster amplifier in a single-frequency MOPA configuration demonstrated ~46% optical-to-optical conversion slope efficiency and a maximum of ~10.4 W CW output power at 1595 nm. This is the highest single frequency power ever obtained from Yb-free Er-doped fiber laser. The same fiber tested in a simple fiber Bragg grating (FBG) based laser configuration exhibited maximum output power of ~28.5 W at 1590-nm with the optical-to-optical conversion slope efficiency of ~56.6%. The latter result presents the highest power ever achieved out of Yb-free Er-doped LMA fiber with resonant *cladding* pumping and is strictly pump-limited. The achieved slope efficiency of ~56.6% is also the highest optical-to-optical conversion slope efficiency ever reported from Yb-free Er-doped fiber laser with resonant *cladding* pumping. Both lasers operate with an ultra-low quantum defect (around ~4%) which offers significant power scaling potential unaffected by severe heat deposition effects.

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