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Cladding-pumped ytterbium-doped large-core fiber laser with 610 W of output power

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ABSTRACT

We report a cladding-pumped ytterbium-doped fiber laser, generating up to 610 W of continuous-wave (cw) output power at 1.09 μm with a slope efficiency of 82% and with a good beam quality ($M^2 = 2.7$). The core diameter was 43 μm and the inner cladding diameter was 650 μm. Even at this high power, the maximum output power was still limited by the available pump power, and no undesirable roll-over was observed in output power with increasing pump power.

Keywords: *Fiber lasers, Diode-pumped lasers*

Introduction: In recent years the output powers of ytterbium (Yb^{3+}) doped fiber lasers have grown dramatically and they are now competing with conventional bulk solid-state lasers (for example, Nd:YAG lasers) in high-power application areas such as material processing, medicine, and range finding. The technique of cladding-pumping can lead to fiber lasers with high-brightness, even diffraction-limited, output, even when low-brightness diode lasers are used as pump sources. In contrast to bulk solid-state lasers, the geometry of fiber lasers benefits thermal management because the heat generated in the laser pump cycle is distributed over a long length of fiber that provides a large ratio of surface to active volume. Yb-doped fiber lasers can provide an excellent conversion efficiency of over 80% due to the low quantum defect when pumped with radiation around 915 nm or 975 nm [1]. They also offer a broad emission spectrum extending from ~1 µm to ~1.1 µm which allows for a wide tunability. These properties make cladding-pumped Yb-doped fiber lasers (YDFLs) exceptional high-power sources in the 1 – 1.1 µm wavelength range.

Although, for example, 10 kW of output power has been reported from highly multi-moded devices that combined the output power from several fiber lasers [2], the output powers achieved in high-brightness output beams from single-fiber laser configurations are still considerably lower. In early results reaching output powers at the 100 W level, the fibers had relatively small cores of ~9-µm diameter and were relatively long [3], [4]. As a consequence of the small core and the long length of fiber, stimulated Raman scattering (SRS) limited the maximum achievable output power [4]. For narrow-linewidth and especially single-frequency amplification, stimulated Brillouin scattering (SBS) is an even bigger obstacle [5]. In addition, optical damage seems likely to hamper further scaling of fiber lasers with such small cores. Thus, larger cores have been used in higher-power fiber lasers. Recently, a 485-W cw output power was reported from a 35-m long fiber with a 24.5-µm diameter core, which was doped with both Nd (neodymium) and Yb [6]. To reach this output power, double-sided end-pumping and pump wavelength-multiplexing were used. The overall slope efficiency was 72% with respect to launched pump power. Despite the large core, a nearly diffraction-limited output beam with an M^2-value of 1.5 was obtained. In more advanced configurations, a 400-W cw output power with an excellent spatial beam quality (M^2 value of 1.05) has been reported from a Yb-doped fiber laser system consisting of a laser oscillator and a booster amplifier [2]. The oscillator comprised a 24-m long multi-clad Yb-doped fiber with a 12-μm core diameter. The booster amplifier had a ~15-m length of Yb-doped fiber with an 18-μm core diameter, spliced to a passive single-mode delivery fiber with a 9-μm mode-field diameter. The overall conversion efficiency was ~50% with respect to launched pump power.

Notwithstanding these excellent achievements, there are demands for even higher output powers with the high beam quality and simplicity that single-fiber devices can offer. In this paper we report a highly efficient YDFL with 610 W of output power at 1.09 μm based on a high Yb-concentration double-clad fiber with large core and inner cladding diameters. The fiber was cladding-pumped by a diode stack emitting at 972 nm.

Experiments and Results: The double-clad Yb-doped large-core fiber used in this experiment was designed and pulled from a preform that was fabricated in-house by the modified chemical-vapor deposition (MCVD) and solution doping technique. The fiber had a 43-μm diameter Yb-doped core with a numerical aperture (NA) of 0.09, centered in the preform. Before being drawn to fiber, the preform was milled to have a D-shape so as to improve the cladding-mode overlap with the Yb-doped core. As a result, the inner cladding had a 650/600-μm diameter for the longer/shorter axis. The fiber was coated with a low-refractive-index polymer outer cladding which provided a nominal inner-cladding NA of 0.48. The small-signal absorption at the pump wavelength (972 nm) in the inner cladding was ~1.5 dB/m. This corresponds to an Yb^{3+}-concentration of ~4500 ppm by weight. A 9-m long piece of fiber was used in the laser experiments.

The experimental setup is shown in Fig. 1. We used an end-coupling scheme for pumping the fiber laser. This is the simplest but often the most efficient way to pump a double-clad fiber. Furthermore, it seems most appropriate with a diode stack pump source, since alternative side-pumping techniques seem likely to fail at high pump powers, and since they generally use too thin fibers for an efficient pump launch [7]. The diode-laser stack used for pumping generated up to 1 kW of power at 972 nm in a collimated beam. When focused, the beam from this kind of source is necessarily rather large, and the pump launch optimization is critical even with a fiber as thick as ours. We used a cylindrical telescope composed of two lenses with focal lengths of 250 mm and 150 mm, respectively, to compensate for an asymmetry of the collimated beam in horizontal and vertical directions. A further spherical telescope with focal lengths of 100 mm and 50 mm followed by an 8-mm focal length lens focused the pump beam onto one end of the fiber. We could launch as much as 760 W of pump power, with an estimated launch efficiency of ~80 % relative to power incident on the fiber. Both ends of the fiber were cleaved perpendicular to the fiber axis. A laser cavity was formed between the 4% reflecting facet at the pump launch end of the fiber and a lens-coupled dichroic mirror with high reflectivity at ~1.1 μm at the other end of the fiber. The full laser output was taken through the pump launch end. A dichroic mirror separated the output beam from the input pump beam. Both ends of the fiber were held in temperature-controlled metallic V-grooves designed to prevent thermal damage to the fiber coating by any non-guided pump or signal power, or by the heat generated in the laser cycle itself. Thermal damage is primarily a problem at fiber ends, since this is where signal and pump powers, and thus heat generation, reach their maximum levels, and since any unguided beams would primarily be present at the fiber ends and absorbed there.

The laser output power characteristics are shown in Fig. 2. The maximum laser output power was 610 W at the maximum diode drive current (49.1 A). The slope efficiency with respect to the launched pump power was 82%. The power conversion and quantum conversion efficiencies were as high as 80% and 89% with respect to the launched power. A pump leakage of ~2% further accentuates the high efficiency. The standard deviation of the temporal power was <2.7%, measured with a photo-detector of 3.5-ns rise/fall time and a 400

MHz oscilloscope. The laser output spectrum measured at the maximum output is shown in Fig. 3 together with its beam profile. The laser spectrum was centered on ~1.09 μm and extended from 1.07 μm to 1.11 μm. The output power increased linearly with launched pump power. There was no evidence of any power limitation due to nonlinear scattering, nor was any SRS observed. Compared to the 24 m, 12-μm core Yb-doped fiber used in [2] and the 35 m, 24.5-μm core, Nd/Yb co-doped core used in [6], our fiber was significantly shorter (9 m) and had a bigger core (43-μm diameter). This suggests a very high threshold for undesirable nonlinear scattering for our YDFL, and thus, nonlinear scattering was completely suppressed. While the heat generation per unit length is significant in a 9 m long fiber, no degradation or thermal damage of the coating was observed.

We measured a nearly Gaussian beam profile as shown in Fig. 3(b), with a beam quality factor (M^2) of 2.7. This must be considered to be a good result, bearing in mind the relatively high V-parameter of 11.2 of the core at 1090 nm, and given that no special measures were taken to suppress operation on higher-order modes.

Fiber design is critical for high-power fiber lasers. In our case, the pump beam had an estimated M^2-value in the range 300–450. For an efficient pump launch, this necessitates the use of fibers with thick inner claddings (650-μm diameter in our case). Then, to avoid excessive fiber lengths in which background loss can degrade the output power, a large core (43-μm diameter in our case) is needed in order to reach sufficient pump absorption with an acceptable Yb-concentration (~4500 ppm in our case). If necessary, mode-selecting techniques such as a fiber taper or bend-loss filtering can be used to improve the beam quality further in the multi-mode core [6], [8].

A large core increases the damage threshold as well. In case of pure silica the damage threshold intensity is ~10 GW/cm^2, i.e., ~100 W/μm^2 [9]; however, this value should be lower when we consider a rare-earth-doped core, because the impurities and inhomogeneities caused by dopant molecules are more vulnerable to high-power beams. As a conservative estimate, we may want to keep power density at the facet below 1 W/μm^2 for reliable operation. For our fiber, the 43-μm diameter, 0.09 NA, core, the mode-field area for the fundamental mode becomes ~1100 μm^2. Thus, the power density at the maximum output power (610 W) was <0.6 W/μm^2. Further power-scaling should therefore be possible with this fiber, to the kW level, or, in view of our conservative estimate of the damage threshold, even the multi-kW level. Alternatively, at this power level, the core can be made smaller, allowing for an improved beam quality (whilst maintaining acceptable pump absorption).

Conclusion: We have demonstrated a highly efficient, high Yb concentration, double-clad Yb-doped large-core fiber laser with a cw output power of 610 W at 1.09 μm. The slope efficiency was 82% with respect to the launched pump power. The thermal load per unit length could be kept sufficiently small to avoid thermal damage when operating at power levels exceeding 600 W and using fiber lengths as short as 9 m. No evidence of roll-over in laser output power at the highest launched pump powers that we could achieve with our current pump source (~760 W launched pump power) was observed, showing that our laser could be power-scaled to even higher powers using a more powerful pump source or, for example, with additional pump sources in a wavelength-multiplexed or double-ended pumping scheme. We believe that in due course it will be possible to obtain higher output powers in a diffraction-limited output using more advanced core designs (for example, LMA fibers [10]) and / or other higher order mode suppression techniques.

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FIGURE CAPTIONS

Fig. 1. Yb-doped fibre laser arrangement used with a diode-stack pump source. HR: high reflectivity, HT: high transmission.

Fig. 2. Fibre laser output power vs. launched pump power.

Fig. 3. (a) Laser output spectrum at full power and (b) the relay-imaged output beam profile.

Fig. 1

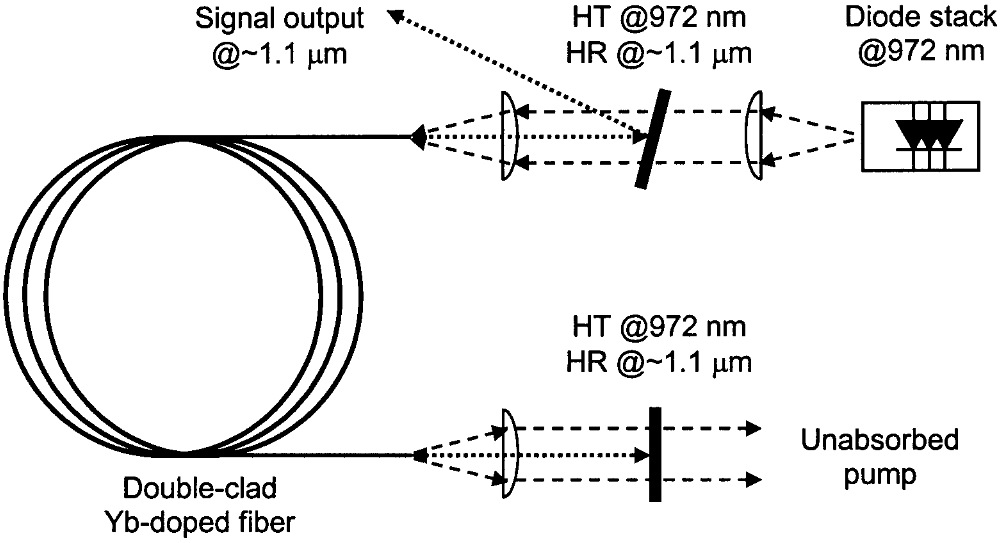

Signal output
@~1.1 μm
HT @972 nm
HR @~1.1 μm
Diode stack
@972 nm
HT @972 nm
HR @~1.1 μm
Unabsorbed
pump
Double-clad
Yb-doped fiber

Fig. 2

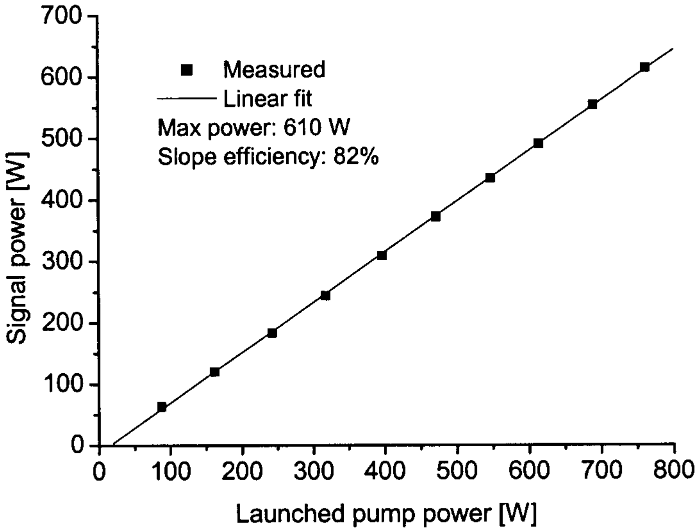
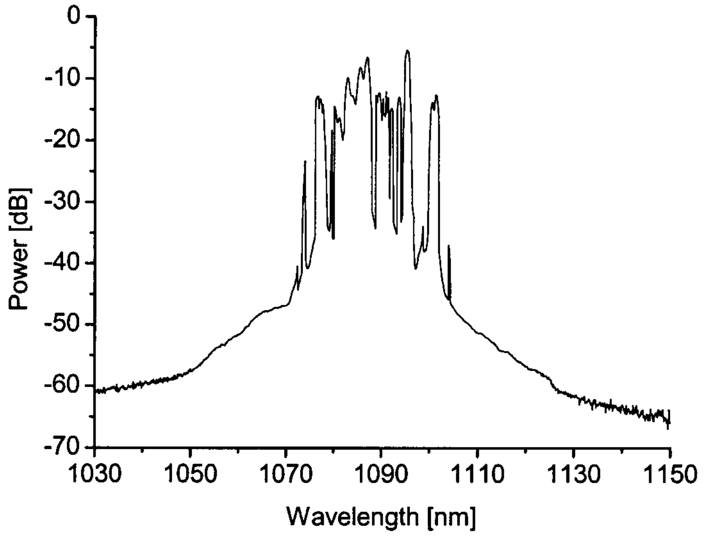

700
600
500
400
300
200
100
0
Signal power [W]
0
100
200
300
400
500
600
700
800
Launched pump power [W]
■ Measured
Linear fit
Max power: 610 W
Slope efficiency: 82%

Fig. 3(a)



0
-10
-20
-30
-40
-50
-60
-70
Power [dB]
1030
1050
1070
1090
1110
1130
1150
Wavelength [nm]

Fig. 3(b)