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A 3.5 W 977 nm Cladding-pumped Jacketed Air-Clad Ytterbium-Doped Fiber Laser

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Abstract: A cladding-pumped ytterbium-doped jacketed air clad fiber laser operating at 977 nm generates a record-breaking 3.5 W of output power in a nearly diffraction-limited output beam, with a slope efficiency of 42% and a threshold of 410 mW with respect to launched power.
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Introduction

High-power laser sources operating on a single transverse mode at 980 nm are important for pumping erbium-doped fiber amplifiers. This application is completely dominated by traditional laser diodes, which are limited in power up to ~1 W or less. Higher-power sources would be useful for higher-power erbium pumping as well as for many other applications such as pump sharing schemes [1] and frequency-doubling. Consequently, alternatives such as optically pumped, vertically emitting, semiconductor lasers as well as cladding-pumped ytterbium-doped fiber lasers (YDFLs) [1, 2] have been investigated for high-power 980 nm operation. So far, however, these too have been limited in output power to ~1 W. Thus, they have so far failed to decidedly improve on thc cw power available from traditional diodes, though they may bring some particular advantages. For example, fiber lasers can be Q-switched to generate high pulse energies. Nevertheless, cladding-pumped YDFLs at 980 nm can be scaled into much higher power than that.

Here, we report a cladding-pumped Yb-doped jacketed-air-clad (JAC) fiber [3] laser generating 3.5 W of output power at 977 nm in a nearly diffraction-limited beam. To the best of our knowledge this result is the highest power, by far, achieved from any 980 nm source with nearly diffraction-limited output. It demonstrates the capability of YDFLs to generate the power needed for efficient frequency conversion at this wavelength. In our fiber laser, high power and high slope efficiency are achieved by using an intrinsically efficient, high numerical aperture JAC fiber, together with high-brightness pumping.

Fiber design and set-up

There are two important issues for an efficient cladding-pumped 980 nm YDFL. First of all, the pump must be able to reach the threshold intensity of the two-level 980 nm transition, meaning that a high-brightness pump source must be used. The second, even more important issue is how to avoid lasing at quasi-four level wavelengths around 1030 – 1040 nm. This puts an upper limit on the inner-cladding to core area ratio that can be used [4], and since the core size is constrained by the requirement of single-mode operation at 980 nm, this effectively puts an upper limit of the inner-cladding, or pump waveguide, size. In practice we have found that an inner cladding diameter of ~30 μm works best. In order to launch as much pump power as possible into this relatively small inner cladding, it is important, again, to use a high-brightness pump source. Equally important is to use an inner cladding with a high numerical aperture.

Three features of our set-up allowed us meet these prerequisites: We used two high-brightness pump sources that were in addition polarization-multiplexed, and the pump beam was furthermore double-passed through the fiber. We used a JAC fiber [3], which we developed to allow for cladding-pumping with small inner claddings and high numerical apertures. We used wavelength-selective feedback to promote 980 nm over 1030 nm.

Figure 1 shows our experimental set-up. Pump light at 915 nm from two multi-emitter broad-stripe diodes sources (New Optics) were collimated and polarization-multiplexed with a halfwave-plate and a polarization beam-combiner. The polarization-combined pump beam was then passed through a dichroic mirror and a focusing lens before being launched into a JAC Yb-doped fiber (YDF). Together, the two pump sources provided up to 18 W of power incident on the fiber, of which roughly 50% could be launched into the JAC fiber. The launch efficiency was relatively poor, since the focused pump spot size was too large for an efficient fiber launch – the pumps were general-purpose sources that had not been optimized for this particular application. The JAC YDF had a 10 μm, 0.1 NA core centered in a 28 μm diameter inner cladding with a high NA of up to 0.5, surrounded by a silica:air structure outer cladding. This in turn was jacketed by a solid silica cylindrical shell and a mode-stripping, high-index polymer. See Fig. 1. The pump launch end of the fiber had a perpendicularly cleaved fat facet providing around 4% broadband reflection. The other end of the fiber was angle-cleaved. There, a lens and a dichroic mirror were used to reflect pump, and signal light at 977 nm back into the fiber, while at 1030 nm was rejected. Thus the pump and signal at 977 nm were double passed. The total single-pass pump absorption was 3 dB in a 40 cm long fiber. We estimate that in the double-passed configuration, 65% of the launched pump power was absorbed by the fiber, with the rest either being transmitted twice through the fiber or lost in the pump reflection arrangement.

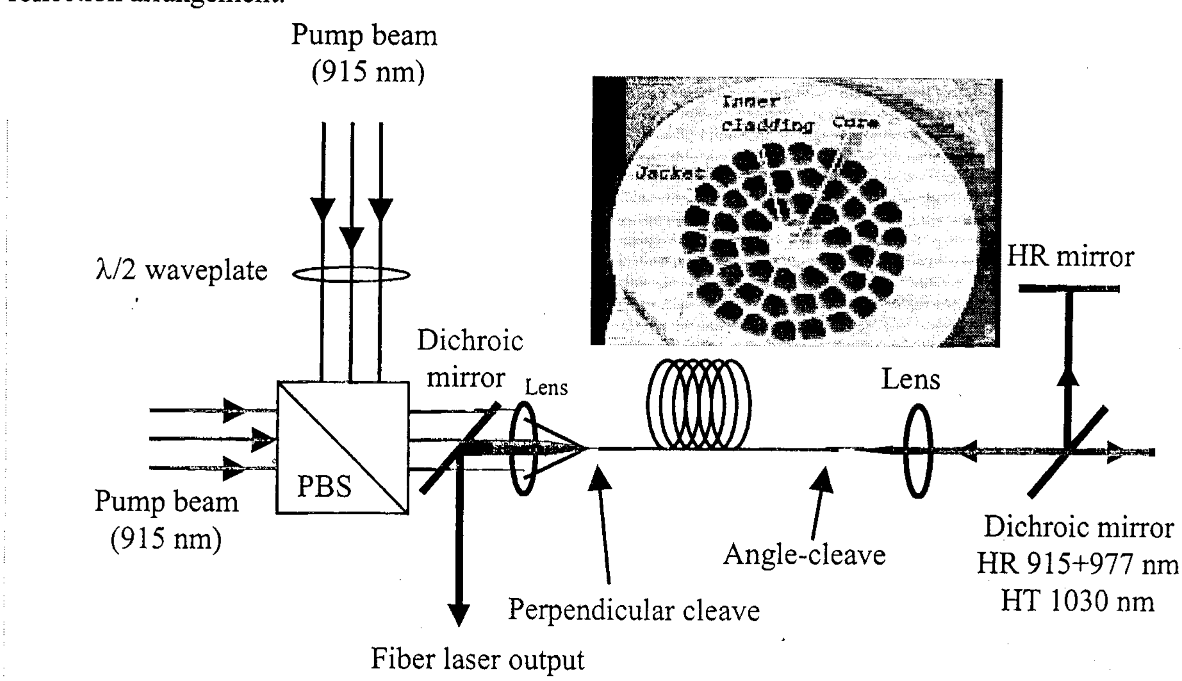

Fig. 1. Experimental set-up

Results

Figure 2 shows the power characteristics of the YDFL. At the maximum pump power we could launch 9.4 W. The YDFL produced up to 3.5 W of output power at 977 nm, with a slope efficiency of up to 65% with respect to absorbed pump power, or 42% with respect to launched pump power. The threshold was 0.26 W with respect to absorbed pump power, and 0.41 W with respect to launched power. We also measured an M^2-value of 1.2 at ~1.0 W of output power.

Because of the short fiber with a relatively low total absorption, the pump leakage was considerable. The significant fraction of unabsorbed pump power (35%) reduced the overall efficiency and the maximum power that could be attained. In addition, we found severe thermal problems at high pump powers, in many cases limiting the output power of the laser. We attribute this to the large pump launch loss and concomitant large thermal load in the pump launch end. An improved launching efficiency, possible with a smaller pump spot size (with an optimized pump source or simply with an intermediate aperture), would reduce power loss and dissipation, and, we believe, largely mitigate this limitation. We note that the curve in Fig. 2 does not show any roll-off, indicating that the fiber could deliver even more power with a higher-power, optimized, pump source.

The dichroic mirrors used in the setup provided only coarse wavelength-selectivity. However, the emission spectrum of ytterbium-doped silica fibers has a quite sharp peak in the 975 – 980 nm wavelength range, with a linewidth of a few nanometers. We obtained, in fact, a surprisingly narrow linewidth of only 0.2 nm. This may be sufficiently narrow for efficient frequency-doubling in materials such as PPKTP. Nevertheless, for improved stability, and, if necessary, a narrower linewidth, a free-space diffraction grating or a fiber Bragg grating can be used instead of the broadband dichroic mirror feedback arrangement to provide a finer wavelength selection. Figure 3 depicts the output spectrum, on a high-resolution wavelength scale as well as on a broad scale that shows the high suppression of emission at 1030 nm.

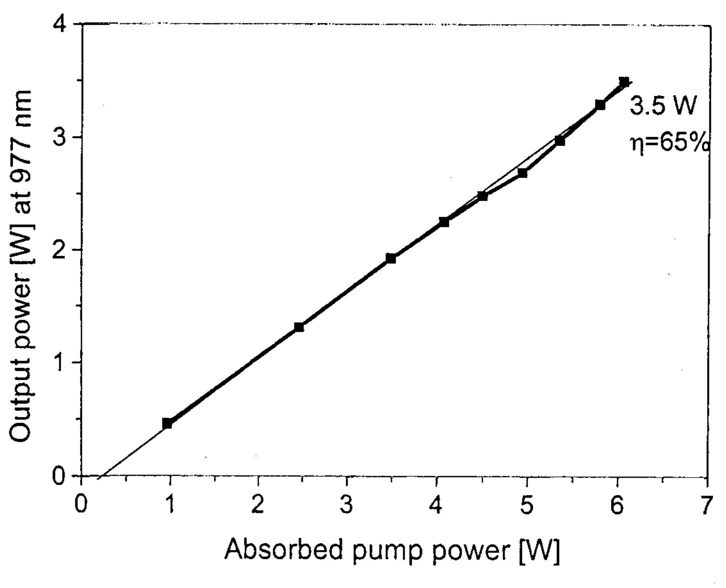

Fig. 2. Output power vs. absorbed pump power of 977 nm Yb-doped fiber laser

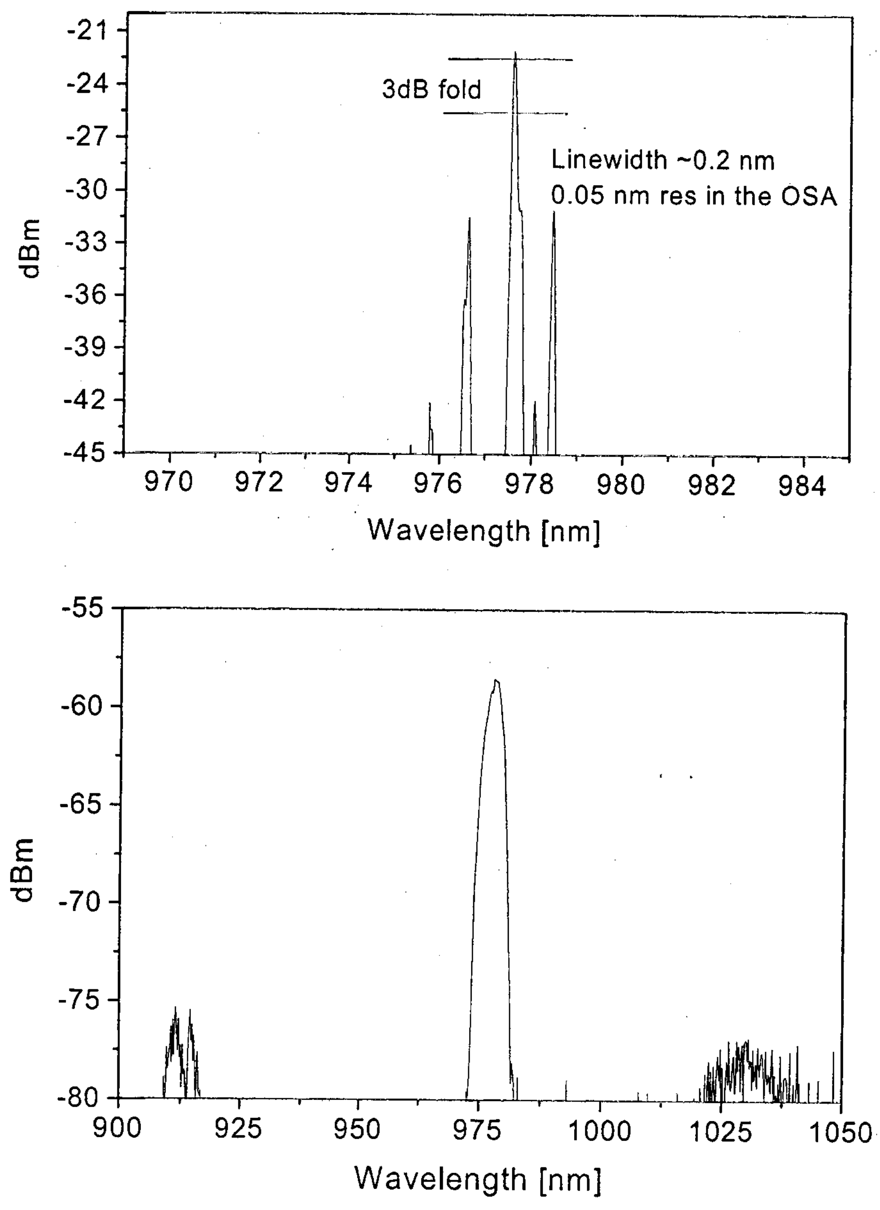

Fig. 3. High resolution and low resolution output spectra

Conclusions

In conclusion, we have described a cladding-pumped ytterbium-doped JAC fiber laser that produced a record-breaking 3.5 W of output power at 977 nm in a nearly diffraction-limited beam. We believe that this source is attractive for high-power pumping of erbium-doped fibers as well as in pump sharing schemes. Furthermore, it had a narrow linewidth as required in different wavelength conversion schemes. Though these often also require a single polarization, this is relatively straightforward to implement in a fiber laser.

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