Compact High-Energy Q-Switched Cladding-Pumped Fiber Laser with a Tuning Range Over 40 nm

C. C. Renaud, R. J. Selvas-Aguilar, J. Nilsson, P. W. Turner, and A. B. Grudinin

Abstract—**We describe a compact Q-switched diode pumped double-clad ytterbium-doped fiber laser. The fiber laser was bidirectionally pumped by two laser diodes (2 W of output power each) via two side-injecting pump-couplers. We used a large multimode core of 15 μm diameter to increase the laser gain volume and thus to achieve higher pulse energy. Experimentally this laser produced pulses with energy up to 170 μJ with a peak power of 2 kW (at a low repetition rate of 500 Hz) and was tunable from 1060 to 1100 nm.**

Index Terms—**Diode pumping, high energy, optical fiber lasers, Q-switched lasers, tunability, ytterbium.**

RARE-EARTH-DOPED fiber lasers offer an excellent combination of high efficiency and spatial beam quality. For high power, cladding-pumped fiber lasers are the preferred choice [1]. They can retain the small physical size of fiber lasers and utilize relatively cheap high-power diodes, for power scaling up to the point where they can replace conventional flash lamp and diode-pumped solid-state and gas lasers.

Applications such as nonlinear frequency conversion, range finding, and remote sensing require short, high energy pulses. For these applications Q-switched fiber lasers are now emerging as a leading contender due to their simplicity and compactness. The amount of energy that can be extracted from a Q-switched fiber laser is determined by the gain volume and the population inversion. Typical fiber lasers and amplifiers have doped single-mode cores which leads to small gain volumes and extractable energies. Several methods were suggested to increase the small gain volume of conventional fibers including ring doping [2], large mode area fibers with a complex refractive index profile [3], selective doping, and selective mode excitation of multimode fibers [4], [5]. The last method looks very attractive because it is simple and because the large doped area allows a high pump absorption and relatively short devices. It is also compatible with a pump launching scheme, which was employed in the laser described below.

In this letter, we describe a compact Q-switched ytterbium-doped fiber laser, tunable from 1060 to 1100 nm, with 2 kW of peak power and 170 μJ of pulse energy at an average power of 85 mW. The laser configuration is shown in Fig. 1. The laser was pumped by two 2 W, 975-nm laser diodes launched into the inner cladding of the Yb-doped fiber through a fiber-optic multimode pump injection structure. Light from the laser diodes was launched into the pump launch port of the fiber coupler via a microlens from LIMO, GmbH, with a launching efficiency of 70%. The pump fiber was a 125 μm diameter thin silica rod with silicone rubber cladding. In order to achieve high coupling efficiency into the double clad (DC) fiber the output (coupling) end of the pump fiber was tapered to approximately 20 μm and then side-spliced to the double clad fiber with a coupling of 85%. In total, 60% of diode facet power was launched into the double clad fiber with this very compact pump launch arrangement.

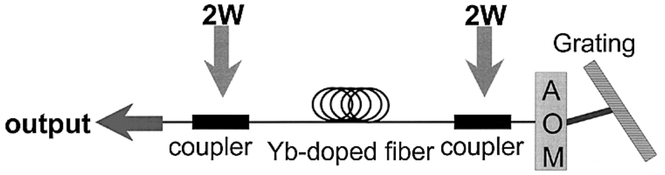

Fig. 1. Experimental setup of the ytterbium-doped fiber laser for the Q-switched regime of operation.

The Yb-doped DC fiber had a silica inner cladding of 200 μm diameter and a silicone rubber outer cladding, for a pump NA of 0.4. The Yb-doped germanosilicate core had a diameter of 15 μm and an NA of 0.25. Thus, the core supported more than 15 LP modes at 1060 nm. In order to suppress lasing on higher order modes the two sections of the DC fiber where the pump fibers were side-spliced were tapered down to 100 μm (core diameter 4.5 μm). These tapers suppressed higher order modes (except the LP_{11} mode) with a very low power penalty, as will be discussed below.

First, the laser was tested in a CW regime with feedback from perpendicularly cleaved fiber ends. The DC fiber length was 7 m for 90% of unbleached pump absorption at 976 nm. The maximum output power was 1.4 W from 2.4 W of launched power; the slope efficiency was ~78% with respect to absorbed pump power (Fig. 2).

For Q-switching, one of the ends of the DC fiber was angle cleaved to suppress feedback and an acoustooptic modulator (AOM) was inserted into the cavity. To close the cavity a high reflectivity mirror or a bulk grating at Littrow was used to reflect the first order beam back from the AOM, feedback in the other out-coupling end of the fiber came from the perpendicularly cleaved fiber facet. The output power of this new configuration was significantly lower than before,

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Manuscript received March 30, 1999.

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Publisher Item Identifier S 1041-1135(99)05892-9.

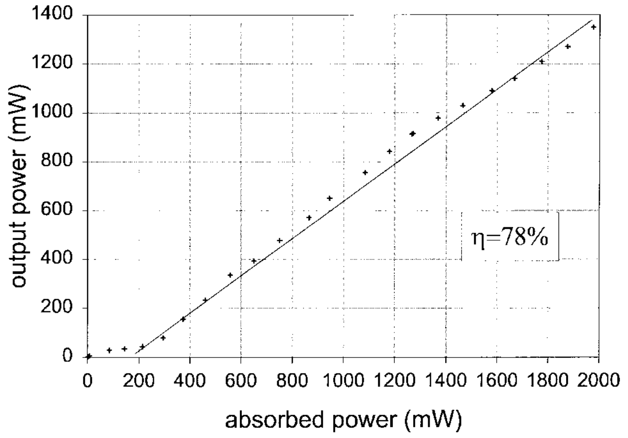

Fig. 2. Output power versus pump power in CW regime of operation.

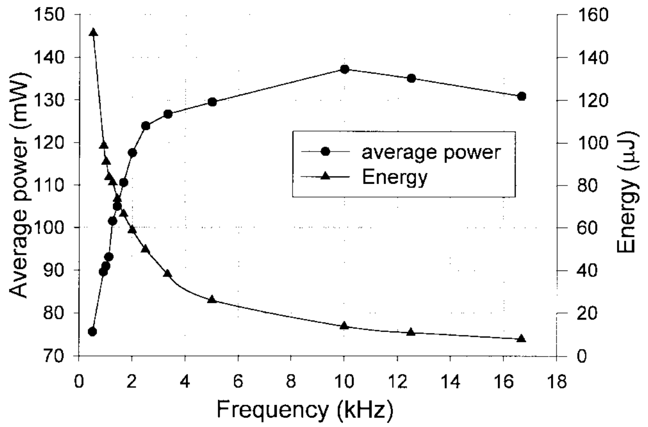

Fig. 3. Energy (triangles) and average power (dots) versus repetition rate in Q-switched regime of operation.

providing 200 mW at a high-repetition rate of 10 kHz. At this repetition rate, the pulse width was 300 ns with no significant fraction of amplified spontaneous emission (ASE) between pulses, thus the pulse energy and peak power were 20 μJ and 67 W, respectively. With a lower repetition rate the pulse energy has increased and the maximum pulse energy of 170 μJ was achieved at a 500-Hz repetition rate with the mirror closing the cavity in the AOM end. At this low repetition rate the pulse width was 80 ns but there was significant ASE between pulses (20%). For an accurate measurement we therefore used an external AOM to separate the pulses from the background ASE. At 500 Hz of repetition rate, with a mirror to close the cavity, the energy in the pulse was 170 μJ. The average laser power was 85 mW and the peak power was 2 kW. Then, after replacing the mirror by the grating, we measured the pulse energy at different repetition rates and the results are shown in Fig. 3. In this configuration an energy of 150 μJ at a repetition rate of 500 Hz was achieved.

At a 1-kHz repetition rate, the fraction of ASE was less than 10%. The pulse energy remained above 100 μJ over a tuning range from 1065 to 1095 nm (Fig. 4). This tuning range remained the same at all investigated repetition rates (0.5 to 20 kHz). The external diffraction grating resulted in a clean output spectrum with a linewidth of 0.5 nm over all the tuning range.

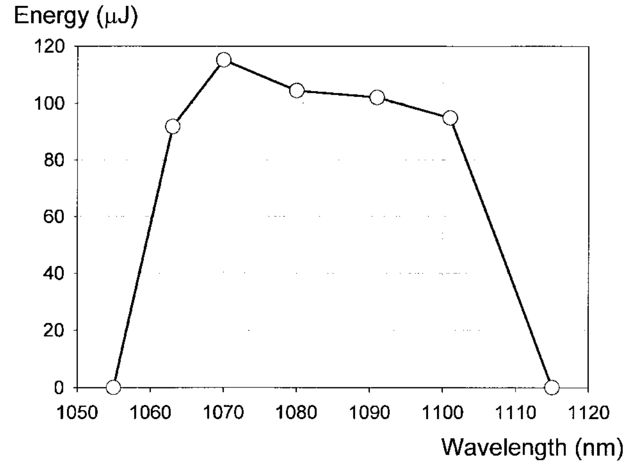

Fig. 4. Tuning range in Q-switched regime. The pulse repetition rate is 1 kHz.

It is instructive to estimate the maximum energy obtainable from such a laser. As it is known [6], [7] the maximum energy that can be extracted by a pulse from a CW-pumped Q-switched laser can be expressed as

$$E = h\nu V \Delta N \tag{1}$$

where $h\nu$ is the photon energy, V is the gain volume and ΔN is the difference in population inversion per unit volume between high and low Q-operation, i.e., $\Delta N = (n_q - n_Q)$.

The power in the CW regime is proportional to the difference of the population inversions [6]

$$P_{CW} = h \cdot \nu \cdot V \cdot \frac{(n_\infty - n_{\mathrm{th}})}{\tau_{21}} \tag{2}$$

where n_∞ is a measure of the pump rate by the given population inversion that would result in the absence of any stimulated emission, nth is the population inversion at the laser threshold and τ_{21} is the upper level lifetime of Yb^{3+}. To determine nth we used [6]

$$n_{\mathrm{th}} = \frac{\ln\left(\dfrac{1}{R_1 \cdot R_2}\right) + n_T \cdot \sigma_a^s \cdot L}{2 \cdot (\sigma_e^s + \sigma_a^s) \cdot L} \tag{3}$$

where $R_1 = 0.4$ and $R_2 = 0.035$ are the reflectivity at the grating after the AOM and the fiber output end, respectively, σ_e^s (0.2 pm^2) and σ_a^s ($\ll \sigma_e^s$) are the emission and absorption cross section at the signal wavelength, n_T is the concentration of ytterbium (the correction given by this term is negligible in our laser) and L is the fiber length. In the laser describe previously we have a ASE output power of 60 mW. This represents less than 5% of the CW lasing power. Therefore, we can assume as a first approximation that there is no ASE in the system, so since n_Q is negligible, ΔN for a Q-switched laser with a repetition rate f_r can be written in the form [6]

$$\Delta N = n_\infty \cdot \left(1 - e^{-(1/(\tau_{21} \cdot f_r))}\right). \tag{4}$$

Now combining (1)–(4), we obtain the following expression for the pulse energy:

$$E = (P_{CW} \cdot \tau_{21} + n_{th} \cdot h \cdot \nu \cdot V) \cdot \left(1 - e^{-(1/(\tau_{21} \cdot f_r))}\right). \tag{5}$$

Note that one can increase the gain volume using longer fiber length but this would result in greater fraction of ASE and consequently lower pulse energy.

The last remaining parameter for determination of gain volume is the mode field diameter of the propagating mode LP_{01} mode. Assuming a Gaussian intensity distribution for LP_{01}-mode one can use the approximated expression of the mode field diameter 2ω as a function of the core diameter $2a$ and the V-parameter of the fiber [8]

$$\omega = a \cdot \left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\right). \tag{5}$$

In our case, $V = 11$ and the LP_{01} mode field diameter $2\omega = 10$ μm.

Thus, the fiber laser with 1.4 W of CW power can produce Q-switched pulses with energy as high as 0.8 mJ at a repetition rate of 1 kHz. In a fiber with a single-mode core (4.5 μm) the level of ASE would be much higher. Therefore, the model presented would overestimate the output energy. In order to have a more accurate idea about the energy extractable from such a fiber, we performed a numerical model including ASE. This simulation gave an energy of 60 μJ for the small core fiber and an energy of 0.75 mJ for the fiber, which we used.

As mentioned above, we used two tapered sections integrated with the pump couplers to suppress higher order modes. This resulted in an output M^2 of 1.9. In the taper, the core diameter is small enough to disable propagation of most higher modes, and then if the mode conversion in the fiber is sufficiently low we should obtain a single mode output. More details can be found elsewhere [5], while here we mention that a single-mode operation power penalty was about 1 dB.

The theoretical estimate of pulse energy is considerably higher than the one obtained experimentally due to a significantly lower CW power with the AOM in the cavity. The main source of loss was the low efficiency of the AOM (only 25% of signal in the first order) which led to a decrease of the CW output power by 1.1 W (when the AOM is kept continuously in the on state). For this level of average power the pulse energy reduces to 177 μJ at 500 Hz, which is in fairly good agreement with experimental results.

In conclusion, we have demonstrated a Q-switched Yb-doped fiber laser, with 150 μJ of pulse output and 2 kW of peak power, and tunable from 1060 to 1100 nm. This compact fiber-laser was pumped by two 2-W laser diodes through integrated tapered pump-couplers with effective suppression of high order modes. Thus, although the fiber had a multimode core, the beam quality of the laser was good with $M^2 \sim 1.9$. A simple theoretical analysis shows that pulse energy near 1 mJ can be reached with better feedback from an AOM unit.

ACKNOWLEDGMENT

The authors wish to thank J. J. Lewandoski, B. K. Nayar, and F. J. Wilson from GEC-Marconi Materials Technology Ltd., for providing them with laser diodes used in the first stage of this experiment.

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