High-energy single-transverse-mode Q-switched fiber laser based on a multimode large-mode-area erbium-doped fiber

H. L. Offerhaus, N. G. Broderick, and D. J. Richardson
Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

R. Sammut
Australian Defence Force Academy, University College, Canberra, ACT 2600, Australia

J. Caplen and L. Dong
Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

Received July 6, 1998

We demonstrate that appropriately designed doped multimode fibers provide robust single-mode output when used within a fiber laser cavity. Using a novel large-mode-area fiber, we demonstrate what we believe to be record single-mode pulse energies of $0.5 \text{ mJ}$ from a Q-switched fiber laser and even higher pulse energies (as high as $0.85 \text{ mJ}$) with slightly compromised spatial-mode quality ($M^2 = 2.0$). This approach offers significant scope for extending the range of single-mode output powers and energies that are achievable from fiber-laser-amplifier systems.

Q-switched fiber lasers offer a simple and robust means for the generation of high-energy nanosecond pulses at eye-safe wavelengths near 1550 nm, which are suitable for a number of industrial, sensing, and nonlinear optics applications. $^1$-$^4$ For many of these single-transverse-mode (SM) operation is a critical requirement. Q-switched fiber lasers based on conventional single-mode erbium-doped fiber are limited to $\sim 10 \mu \text{J}$ pulse energies owing to rapid energy loss in the form of amplified spontaneous emission (ASE). This energy loss is a direct result of the high gain efficiencies of such fibers, which have been optimized as amplifiers for the communications industry. $^5$ That this is so implies that these fibers have a tightly confined optical mode, which limits their suitability for applications in which energy storage rather than gain efficiency is the major concern.

Recently we experimentally demonstrated that considerably higher pulse energies can be achieved simply by an increase in the mode field diameter (MFD) of the fiber. $^6$ As well as enhancing the energy-storage characteristics of the fiber, the increased MFD also improves the nonlinear and power-handling characteristics. With a simple low-numerical-aperture (NA) step-index fiber design (NA = 0.06) we achieved SM Q-switched pulse energies as high as $180 \mu \text{J}$ with a MFD of $\sim 20 \mu \text{m}$. $^7$ The NA was approximately as low as could reliably be achieved and the MFD as large as we could tolerate in terms of bend loss while maintaining robust single-mode guidance within the structure. New fiber designs and concepts are required for a further significant increase in the output pulse energies from such fiber-laser systems.

In this Letter we demonstrate that one can use the low-NA fiber concept, when it is extended to the case of multimode guidance with appropriate fiber design, to obtain robust single-mode operation and increased output energy. We obtained $>0.5 \text{ mJ}$ SM output pulses ($M^2 < 1.2$) from a Q-switched fiber laser and even higher pulse energies (as high as $0.85 \text{ mJ}$) with slightly degraded spatial-mode quality, $M^2 < 2.0$.

The refractive-index profile of the preform is shown in Fig. 1. The design is considerably more complex than that of the large-mode-area fibers that we previously fabricated and consists of a low-NA central core region (with a depressed index on axis owing to the fabrication technique) and an outer ring with a raised index. We used a low-NA structure to reduce the number of guided modes for a given core diameter. Erbium ions were incorporated into only the low-NA core region with a nominal erbium concentration of 400 parts in $10^6$. The outer ring of raised index was...
used for two reasons, first to give an increased spot size for the fundamental guided mode (15–25% from our calculations, depending on core radius) and second to reduce the fiber bend loss for the fundamental mode (reductions in bend loss were 40 to 10 dB, depending on core radius, and were calculated relative to the structure without the outer ring; the predicted bend loss of our fiber is 0.1 dB/m for a 30-cm bend radius). The majority of our experiments were performed with a fiber of inner core diameter of 21 µm and a corresponding fiber outer diameter of 235 µm, although an additional short section of fiber from the same preform with a core diameter of 27 µm was also tested. Superimposed on Fig. 1 are plots of the field distributions of the first- and the second-order modes for the 21-µm-core structure. (Additional weakly guided modes associated with the outer ring structure are predicted, but these modes are sensitive to bend loss that they can be ignored.) From these plots it can be seen that there is a significant difference between the fundamental and the second-order modes in their overlap with the doped inner core region. This difference results in a significant gain differential between the two modes and preferential excitation of the fundamental mode. Moreover, mode coupling between the fundamental and the higher-order modes is low owing to the large fiber outer diameters, allowing for single-mode output even in the ~10-m-long cavities reported here. SM operation of multimode fiber structures in this fashion therefore allows for considerable enhancement in energy storage or extraction and reduced nonlinear effects in active fiber systems.

The Q-switch laser configuration is shown in Fig. 2. The cavity comprises a length of large-mode-area erbium-doped fiber, an intracavity lens, an acousto-optic Bragg cell, and a mirror with high reflectivity across the full erbium band. The cavity is defined by the 4% Fresnel reflection from a cleaved fiber launch end and a highly reflective mirror that is aligned to reflect first-order diffracted light back into the cavity. The fiber was pumped with up to 2.5 W of 980-nm radiation from a Ti:sapphire laser launched into the fiber through a 980±1550-nm dichroic mirror. The radiation from a Ti:sapphire laser launched into the fiber was turned off was 37 mW. The contribution of ASE from the laser output with the Q switch turned off was 37 mW. The output laser radiation was separated from the incoming pump radiation by a dichroic beam splitter.

First we investigated the 21-µm-core fiber. We characterized the laser for a number of fiber lengths under Q-switched operation to determine the maximum pulse energy and time average output power that was achievable from the fiber. Maximum average output powers were achieved for a cavity length of 8 m. In this instance the laser threshold occurred at ~900 mW of incident pump. The average slope efficiency was ~50% with respect to the launched pump power, corresponding to an estimated quantum slope efficiency of ~75%, indicating that despite the unusual design the fiber is still highly efficient. Laser output powers well in excess of 500 mW were achieved for Q switching at high repetition rates (>1.5 kHz). The maximum pulse energy for this fiber length was ~0.4 mJ, obtained at repetition rates of less than 500 Hz. The laser operated at 1558 nm. The minimum pulse duration was 40 ns, giving a maximum pulse peak power of 10 kW, which we believe to be a record for Q-switched fiber lasers.

Maximum pulse energies were obtained for a fiber length of 12 m. Figure 3 shows the output pulse energy versus pulse-repetition frequency for this length. At repetition frequencies of <200 Hz, pulse energies in excess of 0.5 mJ were obtained. We measured the pulse energies at low repetition rates in three different ways to confirm the results obtained. First, we measured the average power and, from a study of the temporal laser dynamics between pulses, made a correction for the ASE that was emitted during the gain recovery stage. Second, we used average-power measurements but made the ASE correction based on time-average spectral measurements of the laser output. Finally, we made direct pulse-energy (pulse-height) measurements on a calibrated fast detector (requiring no ASE correction). For the highest pulse energy the average output power at 200 Hz was 134 mW. The average ASE power from the laser output with the Q switch turned off was 37 mW. The contribution of ASE to the total recorded signal power during Q switching at 200 Hz was estimated by method 1 to be 31 mW and by method 2 to be 28 mW, and the resulting pulse-energy estimates were 0.514 and 0.527 mJ for methods 1 and 2, respectively. The direct pulse-energy...
measurements gave a value of $\sim 0.52 \text{ mJ}$, yielding an average value for our measurements of $\sim 0.52 \text{ mJ}$.

In Fig. 3 we also plot the variation of pulse width with pulse-repetition frequency. As expected, the pulse width decreases with reduced repetition rate and correspondingly increased energy. The hump in the curve indicates a pulse-shape change (formation of distinct sidelobes) that occurs below $\sim 800 \text{ Hz}$. The pulse width of the 0.52-mJ pulses was 70 ns, corresponding to a peak power of $\sim 7 \text{ kW}$. The spectral bandwidth of these pulses was $\sim 10 \text{ nm}$ and decreased rapidly with increasing repetition rate. Bandwidths as narrow as 0.1 nm could be obtained for pulse energies as high as 0.250 mJ by incorporation of a narrow-band optical filter within the cavity.

$M^2$ measurements yielded values of 1.1 and 1.2 for the two orthogonal, transverse spatial coordinates, confirming the high-quality SM nature of the beam. We also performed fiber MFD measurements, using a scanning knife-edge technique with which the divergence of the laser output from the cleaved fiber end (lasing between two flat cleaves) was characterized. These measurements yielded a MFD estimate of 34 $\mu \text{m}$. The mode area of the fiber was thus estimated to be $\sim 910 \mu \text{m}^2$, approximately 20–30 times that of conventional erbium-doped fibers and roughly three times bigger than we previously achieved in a strictly SM system.

We next investigated the 27-$\mu \text{m}$-core fiber (outer diameter, 300 $\mu \text{m}$). Theoretically, we estimated the fiber to guide 3–4 core modes. We optimized the cavity length for maximum pulse energy. In Fig. 4 we plot pulse energy versus repetition frequency for a fiber length of 9 m. We obtained pulse energies as high as 0.83 mJ at repetition rates below 100 Hz (evaluated as above for the 21-$\mu \text{m}$ fiber). The duration of these pulses was 80 ns, and their corresponding peak power was $\sim 10 \text{ kW}$. A plot of the scanned intensity mode profile, presented in the inset in Fig. 4, shows a reasonably Gaussian profile, although it is fairly elliptic. This observation was confirmed by $M^2$ measurements that gave values of 2.0 and 1.3 for the two ellipse axes. The mode quality is thus slightly degraded in this more highly multimode structure, presumably by mode coupling. Although it was not measured, we estimate a MFD for the fundamental mode that is well in excess of 40 $\mu \text{m}$.

In conclusion, we have demonstrated that one can use appropriately designed doped multimode fibers to construct fiber lasers that provide robust SM output, providing scope for extending the range of SM output powers and energies that are achievable from fiber-laser systems. With an optimized fiber design, the use of these concepts should permit the development of millijoule fiber-laser–amplifier systems. It should also be noted that the design that was presented is fully compatible with the cladding pumping concept, facilitating the development of higher average-power (multi-10-W) millijoule systems.

References