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

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Abstract

We demonstrate that appropriately designed doped multi-mode fibers provide robust single mode output when used within a fiber laser cavity. Using a novel large mode area fiber we demonstrate record single mode (M^2 <1.2) pulse energies of > 0.5mJ from a Q-switched fiber laser and even higher pulse energies (as high as 0.85mJ) with slightly compromised spatial mode quality (M^2 <2.0). The approach offers significant scope for extending the range of single mode output powers and energies 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 around 1550nm 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 ~10μJ pulse energies due 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]. This implies a tightly confined optical mode, which limits the 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 increasing 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 180μJ with an MFD of $\sim 20\mu$m [7]. The NA was about as low as could reliably be achieved, and the MFD as large as we could tolerate in terms of bend loss, whilst maintaining robust single-mode guidance within the structure. New fiber designs and concepts are required to further significantly increase the output pulse energies from such fiber laser systems.

In this letter we demonstrate that the low NA fiber concept extended to the case of multi-mode guidance can, with appropriate fiber design, be used to obtain robust single mode operation and increased output energy. We obtain >0.5mJ SM output pulses ($M^2<1.2$) from a Q-switched fiber laser and even higher pulse energies (as high as 0.85mJ) 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 Large Mode Area (LMA) fibers that we have previously fabricated and consists of a low NA central core region (with a depressed index on axis due to the fabrication technique) and an outer ring of raised index. A low NA structure is used to reduce the number of guided modes for a given core diameter. The erbium ions were only incorporated into the low NA core region with a nominal erbium concentration of 400ppm. The outer ring of raised index was used for two reasons. Firstly, to give an increased spot size for the fundamental guided mode (15-25% from our calculations depending on core radius) and secondly to reduce the fiber bend loss for the fundamental mode (reductions in bend loss between 40 and 10 dB depending on core radius were calculated relative to the structure without the outer ring, the predicted bend loss of our fiber is < 0.1dB/m for a 30cm bend radius). The majority of our experiments were performed with a fiber of inner core diameter 21μm and corresponding fiber outer diameter 235μm, although an additional short section of fiber from the same preform with a core diameter of 27μm was also tested. Superposed on Fig.1 are plots of the field distributions of the first and second order mode for the 21μm-core structure. (Additional weakly guided modes associated with the outer ring structure are predicted but these modes are so 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 second-order mode in their overlap with the doped inner core region. This results in a significant gain differential between the two modes and preferential excitation of the fundamental mode. Moreover, mode coupling between the fundamental and higher order modes is low due to the large fiber outer diameters [8,9], allowing for single-mode output even in the ~10m long cavities reported herein. SM operation of MM fiber structures in this fashion therefore allows for considerable enhancements in energy storage/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 LMA 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 the cleaved fiber launch end and the HR mirror which is aligned to reflect first-order diffracted light back into the cavity. The fiber was pumped with up to 2.5W of 980nm radiation from a Ti:Sapphire laser launched into the fiber through a 980/1550nm dichroic mirror. The maximum launch efficiency into the fiber was ~70%. The output laser radiation was separated from the incoming pump radiation by the dichroic beam-splitter.

First we investigated the 21μm-core fiber. The laser was characterized for a number of fiber lengths under Q-switched operation to determine the maximum pulse energy and time average output power achievable from the fiber. Maximum average output powers were achieved for a cavity length of 8m. In this instance the laser threshold occurred at ~900mW of incident pump. The average slope efficiency was ~50% with respect to launched pump corresponding to an estimated quantum slope efficiency ~75% indicating that despite the unusual design the fiber is still highly efficient. Laser output powers well in excess of

500mW were achieved for Q-switching at high repetition rates(>1.5kHz) The maximum pulse energy for this fiber length was ~0.4mJ, obtained at repetition rates below 500Hz. The laser operated at 1558nm. The minimum pulse duration was 40ns giving a maximum pulse peak power of 10kW, which we believe to be a record for Q-switched fiber lasers.

Maximum pulse energies were obtained for a fiber length of 12m. Fig.3 shows the output pulse energy versus pulse repetition frequency for this length. At repetition frequencies <200Hz pulse energies in excess of 0.5mJ are obtained. The pulse energies at low repetition rates were measured in three different ways to confirm the results obtained. Firstly, we measured the average power and, from a study of the temporal laser dynamics between pulses, made a correction for the ASE emitted during the gain recovery stage. Secondly, 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 we report the average output power at 200Hz was 134mW. The average ASE power from the laser-output with the Q-switch turned off was 37mW. The contribution of ASE to the total recorded signal power during Q-switching at 200Hz was estimated at 31mW using method 1 and 28mW using method 2, resulting pulse energy estimates of 0.514 and 0.527mJ for methods 1 and 2 respectively. The direct pulse energy measurements gave a value of ~0.52mJ yielding an average value for our measurements of ~0.52mJ.

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 side-lobes) which occurs below ~800Hz. The pulse width of the 0.52mJ pulses was 70ns, corresponding to a peak power of ~7kW. The spectral bandwidth of these pulses was ~10nm and reduced rapidly with increasing repetition rate. Bandwidths as narrow as 0.1nm could be obtained for pulse energies as high as 0.250mJ by incorporating a narrowband optical filter within the cavity.

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

We next investigated the 27μm-core fiber (outer diameter: 300μm). 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 9m. We obtain pulse energies as high as 0.83mJ at repetition rates below 100Hz (evaluated as previously for the 21μm fiber). The duration of these pulses was 80ns and their corresponding peak power ~10kW. A plot of the scanned intensity mode profile is presented inset in Fig.4, showing a reasonably Gaussian profile, although it was fairly elliptic. This observation was confirmed by M^2 measurements which gave values of 2.0 and 1.3 for the two ellipse axes. The mode quality is thus slightly degraded in this more highly multi-moded structure, presumably by mode-coupling. Although not measured, we estimate an MFD for the fundamental mode well in excess of 40μm.

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

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FIGURES

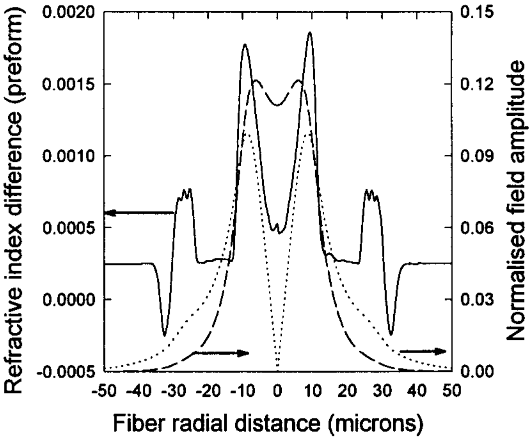

Fig. 1. Solid line: Refractive index profile of the fiber preform, scaled to match the 21mm-core fiber dimensions. Dashed, dotted line: Calculated first and second guided mode

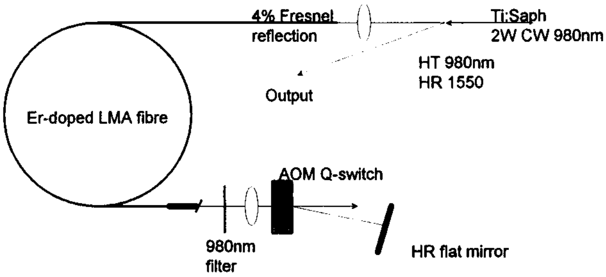

Fig. 2. Laser setup

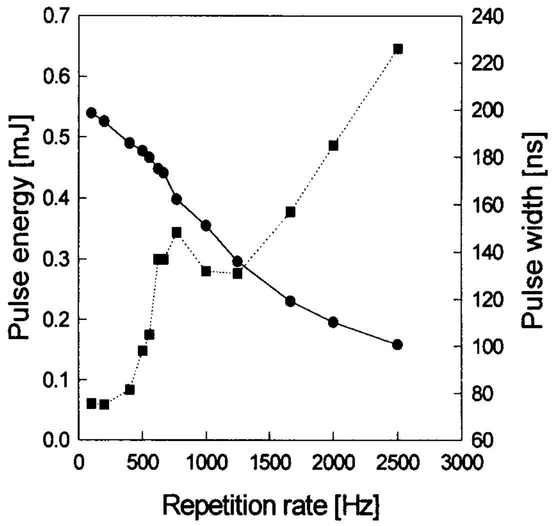

Fig. 3. Pulse energy (solid line with circles) and pulse width (dotted line with squares) as a function of repetition rate for the 21μm-core fiber

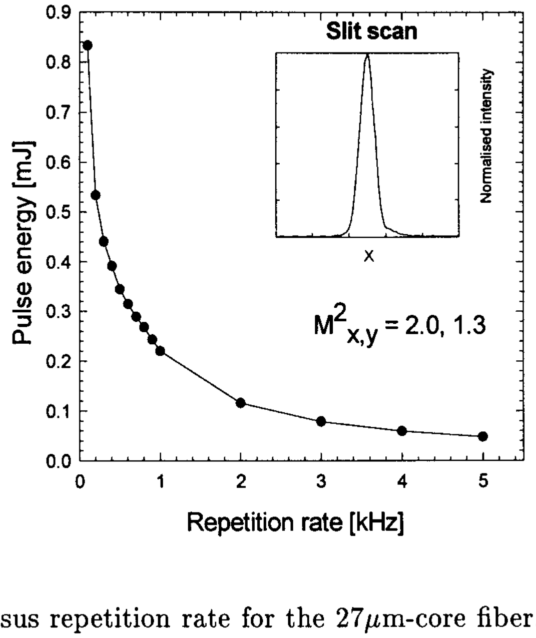

Fig. 4. Pulse energy versus repetition rate for the 27μm-core fiber. The inset shows a slit scan of the intensity profile and the M^2 values.