Enhanced Q-switching in double clad fibre lasers

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Abstract:

A novel cladding pumped Nd^{3+} fibre laser operating in an enhanced Q-switched regime with stable repetition rate is described. By exploiting fibre nonlinearities in the fibre cavity, we demonstrated a peak power of 3.7 kW, enhanced by an order of magnitude over conventional Q-switched devices. Pulse durations as short as 2 ns have been achieved.

High peak power pulse fibre lasers are of interest for various applications in medicine, range finding, remote sensing, and Optical Parameter Oscillators (OPO). The two principal techniques used for the generation of short optical pulses are Q-switching and mode locking. Q-switched fibre lasers can generate high peak power and relatively long-duration pulses from widths ranging from several nanoseconds to several hundreds nanoseconds. The cavity can be switched from a high-loss to a low-loss regime by use, for example, of an acousto-optic modulator (AOM) or an electro-optic modulator. For Q-switched fibre lasers, the extractable energy depends mainly on the number of active ions in the gain medium and the lifetime of the metastable level. One approach to obtaining high peak power is to reduce the pulse width by exploiting its proportionality to the cavity length. This reduction can be achieved by using highly doped fibres[1]. However, a high active ion concentration may cause an ion clustering problem, limiting the laser performance through lifetime quenching of the clustered ions. Another approach is to use a large-mode-area fibre as the gain medium to increase the extractable energy stored in the fibre[2]. A 4 kW peak power pulse train has been obtained in Er^{3+} doped fibre laser with a mode field area of 200 μm^2. However these fibre lasers have to be pumped by single mode (SM) laser diodes whose powers are normally low, resulting in low average output powers.

On the other hand, because of the very high intensities achievable in SM fibres, nonlinearities can play an important role in generating short pulses. Recently there were reports[3-5] of exploiting distributed backscattering in the fibre as a passive Q-switching mechanism to generate short pulses (2 ns) and high peak power from a single stage Q-switched fibre laser. Unlike the conventional Q-switched fibre laser, the pulse width depends not on the cavity lifetime but rather on the dynamics of stimulated Brillouin scattering (SBS). The SBS provides strong feedback to the laser cavity in the form of a short (1 ns) SBS relaxation oscillation pulse, which is equivalent to an increase in the cavity's Q factor by a few orders of magnitude during a short period of time. However because of the nature of the nonlinear process in silica fibres, the repetition rate of this process is unstable unless special measures are taken[3,4].

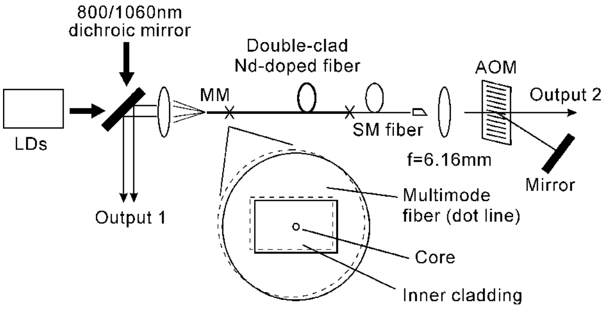

Fig. 1 Setup of an enhanced Q-switched Nd^{3+} fibre laser

We report a novel hybrid configuration which takes advantages of both fibre nonlinearity and the conventional Q-switching technique. We use the fibre nonlinearity to generate a high-peak-power and short-width pulse train, and the conventional AOM allows us to stabilize the repetition rate. The experimental configuration is shown in Fig.1. Inasmuch as the cladding pumping scheme[6] can increase the launching efficiency and scale the power level when pumping is by high power laser diodes, we chose a double clad Nd^{3+}-doped fibre as the gain medium. The pump source comprised two polarization-combined 3 W laser diodes operating at 800 nm. The Nd^{3+} fibre had a high Nd^{3+} dopant concentration of about 2 wt% in the core and a core diameter of 5.1 µm. It was coated with silicone rubber, which could be treated as the outer cladding. The NA of the inner cladding to the core and the outer cladding to the inner cladding was 0.12 and 0.39, respectively. The inner cladding had a rectangular shape with 150µm x 75µm to match the dimension of pump laser diodes. About 60% incident power was launched into the inner

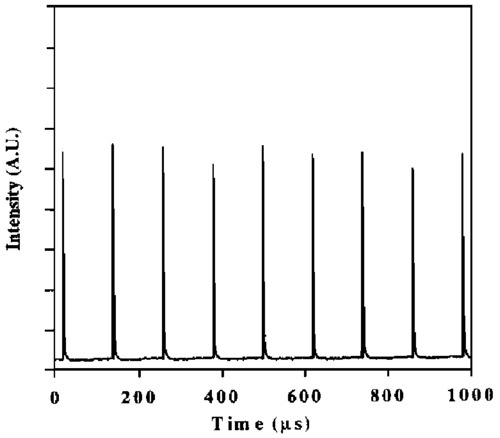

Fig. 2 A typical output pulse train at repetition rate of 14 kHz

cladding. An AOM with diffraction efficiency of ~60% at 1060 nm and RF frequency of 110 MHz, was used to modulate the cavity loss. In a conventional Q-switched fibre laser, we obtained a pulse train with peak power of ~330 W and pulse width of ~70 ns. During the experiment, we observed occasional giant pulses accompanying the Q-switching pulses. The giant pulse width of about 2 ns duration was much narrower than the normal Q-switching pulses of 70 ns, and the peak power was about an order of magnitude higher. A similar phenomenon has been observed in a self-Q-switched ytterbium fibre laser[5], where attention was paid to minimization of reflection from one of the fibre cavity ends. In our configuration we obtained a stable giant pulse train when the reflection from the front end was suppressed. Whereas in principle this result could be achieved by angle cleaving or polishing the fibre end, we found it more convenient to suppress the feedback by splicing on a short piece of multimode fibre matched in dimensions with the inner cladding of the double clad fibre. The objective is to have low reflection (~$2.85*10^{-6}$) for the signal at the input end, and at the same time not to lose any launching efficiency for the pump. Although this result can lead to a degradation in beam quality of the output mode through mode coupling, we found that beam quality was maintained when the multimode fibre was limited to about 1 mm in length. However, angle polishing will ultimately give the best performance once the termination problems associated with the low index silicone coating and rectangular structure are overcome.

With this configuration, a repetition-rate-stabilized pulse train with peak power of ~3.7 kW and pulse width of 2 ns has been obtained as shown in Fig. 2. The repetition rate was controlled by the AOM. The average power was ~500 mW. The giant pulse train only occurred at a range of repetition rate from 6.6 kHz to 16.4 kHz. We observed that the higher the pump power, the higher the repetition rate, which is similar to what has been previously reported in Ref. 5.

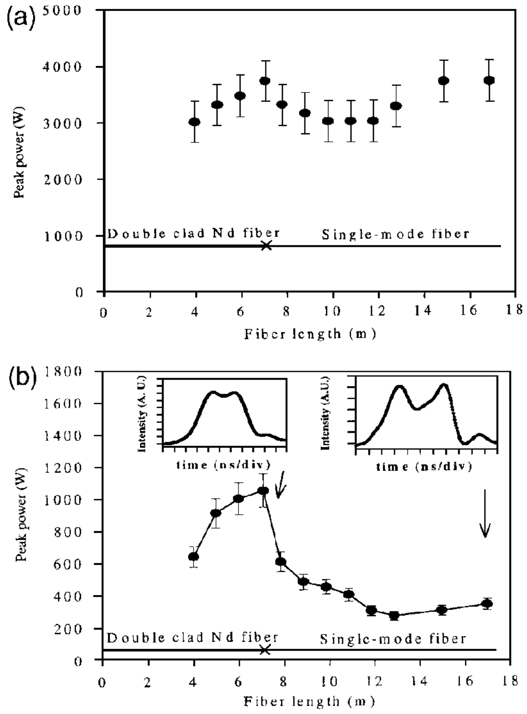

Fig. 3 (a) Peak power from output1 against fibre length (b) peak power from output2 against fibre length. (Insets) pulse shapes at the beginning and the end of the SM fibre.

In order to understand the enhancement mechanism in detail, we spliced a 10 m single mode (SM) fibre with the doped fibre and measured the laser characteristics from port1 and port2. Fig. 3a and 3b show the dependence of pulse peak power from output1 and output2 on the fibre length. The pulse peak power from output2 was lower than that from output1. Without the SM fibre, peak powers from both outputs increase gradually when the Nd^{3+} fibre length was increased. Peak powers of 3.7 kW from output1 and 1 kW from output2 have been obtained at a 7.2 m optimum fibre length. When we spliced the double clad Nd^{3+} fibre to a 10 m SM fibre, the peak powers from port1 did not change when we cut back the SM fibre and we did not find any changes in the pulse shapes. For pulses from port2, however, the peak powers decreased rapidly after the splicing of the SM fibre, and gradually stabilized at a power level of ~300 W at 10 m of

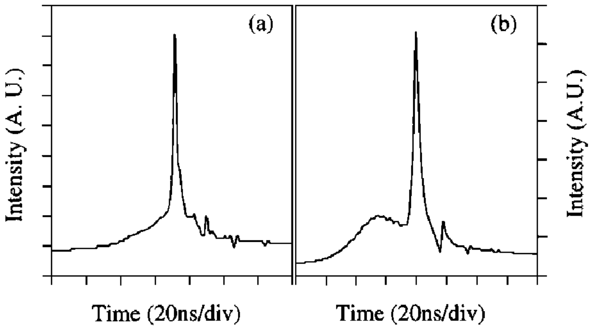

Fig. 4 (a) Pulse shape at output 1 of the enhanced Q-switched fibre laser and (b) pulse shape at output 2.

the SM fibre. The pulse shapes were depleted as shown in the insets of Fig. 3(b), and three stimulated Raman scattering Stokes components were observed in the spectrum.

Based upon the measured experiment results and observed phenomena, we can describe the mechanism by which the pulse train can be generated. At the beginning of the cycle, the pump power provides a buildup of the population inversion. Because of the special splicing, a highly inverted population can be reached. Continuous-wave lasing, however, is completely inhibited because the AOM blocks the reflection from the mirror and there is almost no reflection from either fibre end. The reflection of the output coupling facet is suppressed by the imposed angle of the fibre, and the reflection from the front end is nearly zero owing to the special splicing. So the laser threshold is very high. The measured amplified spontaneous emission was only 30 mW at each end in the open cavity, which was very low considering an absorbed pump of more than 2 W. Once the population inversion exceeds the threshold value and the AOM is switched on, then the cavity loss reduces abruptly and the photon density begins to build up very rapidly through the stimulated emission along the fibre. When the intensity is high enough to trigger the SBS process, a narrow seed pulse is generated at the peak of the photon intensity curve. The pulse width is determined by the interaction period between the transverse acoustic wave and the core, and is therefore independent of the doped ions. It is about 1 ns for a 6 µm diameter core. When this pulse travels through the Nd^{3+} doped fibre to the front port1, it experiences high dynamic gain and extracts most of the energy stored in the highly inverted Nd^{3+}-doped fibre, resulting in several kilowatts' peak power from output1. The reflected pulse due to the small reflection ($\sim 2.5*10^{-6}$) of the special splice obtains amplification on its way back to port2, takes almost all the energy left, and outputs from port2. Therefore, the peak power from output1 is higher than that from output2. Fig. 4a and 4b show the pulse shapes from output1 and output2. Considering the transient gain dynamics of an active medium, which normally has an overshoot at the leading edge and is followed by steady state gain conditions[7], we can infer from Fig. 4a and 4b that the pulse shape from output2 is the result of amplification of the reflected pulse from output1. The appearance of a small peak before the high pulse in Fig. 4(b) indicates the effect of the overshoot gain in the leading edge. Indeed, we measured the pulses from both ends simultaneously by two photodiodes, and the results showed that the giant pulse from output1 was ahead of that from output2 by half the round trip time.

Although the pulse travelling towards port1 obtains exponential amplification and reaches a high peak power at the output, the stimulated Raman scattering (SRS) process does not occur; hence the pulse is not depleted. This is so because the pulse propagates through part of the doped fibre which is not long enough to reach the Raman threshold. For the returning pulse, however, it achieves amplification from the whole doped fibre and travels through the SM fibre as well, providing a longer fibre length and thus higher Raman gain. The Raman effect then comes into play, and the pulse is depleted at 1060 nm. Once the energy has been extracted, the photon intensity dies out, and the AOM is switched off, the laser stops lasing until the next cycle. Therefore, this enhanced Q-switching can be treated as a special Q-switching technique used to generate pulses by amplifying narrow seed pulses induced by SBS. The main disadvantage of this technique is the pulse-to-pulse intensity fluctuation (about 10%) that is due to the stochastic nature of the SBS, which might be greatly suppressed by, for example, the use of an intracavity intensity limiter based on two-photon absorption.[8]

To reach higher peak power for the enhanced Q-switched fibre laser, one should optimize the system design and in particular fabricate double-clad fibres with larger inner cladding, which could permit the use of broader, higher-power pump diodes. Higher average power would result in increase of repetition rate. This scheme can actually be used in any rare-earth-doped double-clad fibres when pumped by high power laser diodes and is especially suitable for Yb^{3+} fibres where the homogeneous broadening is dominant and narrow-bandwidth spectrum can be expected. Our experiments of applying this scheme for a Yb^{3+} fibre showed that tunability could be realised if the mirror were replaced by a bulk grating.

In conclusion, we have demonstrated enhanced Q-switching in a double clad Nd^{3+} fibre laser which increased the peak power by an order of magnitude compared with the normal Q-switching regime. Narrow pulse width (~2 ns) and high peak power (3.7 kW) were obtained. The repetition rate was stable and adjustable by an AOM within a resonant range. Studies on the mechanism of the fibre laser reveal that the high peak power in the laser is obtained by exploiting the SBS process to generate a narrow pulse and amplifying the seed narrow pulse in a highly population-inverted medium. Further research is directed toward the development of a similar type of laser in a polarization-maintained double-clad fibre.

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