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Cavity dumping of neodymium-doped fibre lasers using an acoustooptic modulator

I. ABDULHALIM, C. N. PANNELL, K. P. JEDRZEJEWSKI, E. R. TAYLOR
Optoelectronics Research Centre – Optical Fibre Group, Southampton University, Highfield, Southampton SO9 5NH, UK

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We report high-repetition-rate pulses obtained by cavity dumping of a neodymium-doped phosphate glass fibre laser operating at 1053 nm using a specially constructed acoustooptic modulator. With 27 mW absorbed pump power at 812 nm we obtained stable trains of output pulses with repetition rate in the range 0.5 to 8 MHz having corresponding pulse widths in the range 127 to 19 ns without significant sacrifice in the average output power of 8 mW.

1. Introduction

Cavity dumping is a technique to obtain high-repetition-rate pulses from a continuously pumped laser while maintaining its full average power capability [1]. This technique offers pulsed operation with repetition rates in a range inaccessible to the conventional techniques such as mode-locking and Q-switching. With mode-locking, the pulse repetition rate is usually higher than 100 MHz, while with Q-switching it is smaller than 50 kHz. Cavity dumping has a similarity with Q-switching in that in both cases the energy is stored in the cavity then released in the form of a repetitive train of pulses. The difference is that the energy storage and accumulation between the pulses is in the excited atoms in the case of Q-switching and primarily in the radiation field for cavity dumping. Cavity dumping is also often used with mode-locking to select out a single high-peak-power ultrashort pulse. If a single ultrashort pulse is circulating inside the cavity, turning on the cavity dumping modulator can dump out that single pulse.

Fibre lasers have attracted the attention of many researchers recently because of their potential applications as coherent light sources with guided light output [2]. Their Q-switching and mode-locking were investigated extensively; however, their cavity dumping has not been reported to our knowledge. In this article we report the first cavity dumping of fibre lasers using a specially constructed acoustooptic modulator (AOM).

2. Experimental

Figure 1 shows the cavity dumping fibre laser setup. A 5 cm length of neodymium-doped phosphate fibre was inserted into a silica capillary using conventional UV-cure adhesive and the ends of the capillary were polished perpendicular to the tube axis [3]. A dichroic dielectric mirror having >99% reflection at 1.053 μm and >95% transmission at 812 nm was bonded with UV-cure adhesive to one end. A neodymium-doped phosphate compound glass fibre was

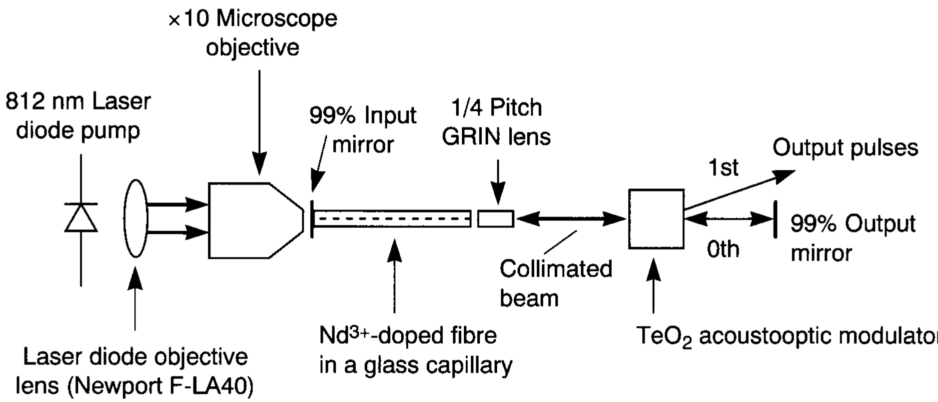

Figure 1 Schematic of the fibre laser cavity dumping setup.

used as the amplifying medium. The core material of the fibre was Schott LG750 (1% wt neodymium) which was fabricated into a single-mode fibre with a compatible phosphate cladding glass using a rod-in-tube manufacturing technique described elsewhere [3]. Fibres with LG750 as the core material have the advantage of a higher emission cross-section than that of silica-based fibres [4]. These fibres exhibit a gain of 0.95 dB mW^{-1} of pump for pumping at 812 nm, which is the highest gain coefficient reported so far for neodymium-doped fibre amplifiers [2]. In addition, the relatively high neodymium concentration in the fibre means that only a short fibre length (of the order of a few tens of millimetres) is required to absorb the pump. An intracavity quarter-pitch GRIN lens was used to collimate the fibre output through the AOM and onto the 99% reflection mirror, which replaces the output coupler. The output coupler was aligned to reflect the zeroth-order beam back into the gain medium and the output was obtained from the first-order diffracted beam. The beam waist of the collimated laser output was measured using the knife-edge technique [5] and was estimated to be 105 μm. The total cavity length is 11 cm with the AOM occupying only 28 mm of it. A 100 mW single-stripe laser diode operating at 812 nm (SDL 5411) was used as the pump source and was coupled into the fibre using conventional launch optics. Using an undoped fibre with similar waveguide characteristics, the optimum coupling efficiency was estimated to be 40% to 45%. With the ratio of the absorbed to coupled pump power being $\sim$80%, we determined that a maximum of 27 ± 2 mW of the incident 90 mW pump power could be absorbed in the doped fibre. The optimum CW output level from this laser configuration was measured to be 13 mW, with a slope efficiency of $55 \pm 3\%$ and a threshold of 4.0 ± 0.3 mW when the AOM is OFF using a 50% output coupler.

The AOM, which was fabricated by Gooch & Housego Ltd [6], uses a TeO_2 crystal as the acoustooptic material, antireflection coated to give 0.1% reflectivity at 1.064 μm with 99.6% transmittance. This material was particularly selected for Q-switching purposes because of its high acoustooptic figure of merit, its high compressional wave acoustic velocity, which allows fast switching, and because of its high damage threshold. Using this AOM as a Q-switch in a similar cavity with 50% coupler we obtained 2 ns pulse duration and 1.14 kW peak power [7]. The 4.25 mm interaction length $LiNbO_3$ piezoelectric thickness mode transducer was designed to resonate at 125 MHz. The 36° rotated Y-cut $LiNbO_3$ transducer was cold-welded with indium to the TeO_2 crystal. A matching circuit minimized the RF reflected power. In order to obtain fast switching speed, a small optical beam waist must be used. A special design of top electrode was used, in order to apodize the acoustic beam and hence match its divergence to that of the optical beam, thereby maintaining diffraction efficiency. Under CW operation, using a Gaussian beam with 105 μm waist, the AOM exhibits >80% diffraction loss (in the zeroth order) and >65% diffraction efficiency in the first order with 1.5 W RF drive power. Under pulsed operation, with equivalent average RF power, the diffraction loss is >70% (zeroth order) and the diffraction efficiency is > 50% (first order) for RF pulse widths down to 10 μs and 100 ns respectively. The measured rise time of the AOM under these conditions is 34 ns.

3. Results and discussion

Cavity dumping is characterized by the existence of a minimum repetition rate below which the cavity-dumped laser output becomes unstable [8–10]. This minimum cavity dumping frequency depends mainly on the laser characteristics that determine the relaxation oscillations when the laser is operated under optimum conditions. More specifically, it was found both experimentally and theoretically [8–10] that the average power of the cavity-dumped pulses is equal to the optimum CW output power obtained from the same laser when the output coupler has the optimum coupling assuming the dumping modulator is capable of dumping all the stored energy in one pulse. In first appoximation [10] the minimum cavity dumping repetition rate is $f_c \approx f_r/2$ where f_r is the frequency of relaxation oscillations. In our fibre laser setup the relaxation oscillations under optimum CW operation had a frequency of $f_r \approx 1$ MHz for pumping levels of 10 to 27 mW, which yields $f_c \approx 500$ kHz.

Figure 2 shows typical oscilloscope traces of the cavity-dumped pulses obtained at different pumping levels and repetition rates, showing the main characteristics of the cavity dumping operation of this fibre laser. With 11 mW pump power (Fig. 2a), stable operation starts at ≈400 kHz repetition rate showing 109 ns pulse duration and 92 mW peak power. As the pump power is increased to 20 mW with the same repetition frequency, the output becomes unstable (Fig. 2b). Increasing the repetition frequency to 460 kHz, the output becomes stable again (Fig. 2c). Note that the pulse width in Fig. 2c is slightly larger (135 ns) but the peak power has increased to 120 mW simply because the pump power is higher. Further increase of the absorbed pump power (27 mW) causes the output to become unstable (Fig. 2d) since f_c, the required minimum repetition rate for stability is higher. At 500 kHz the output becomes stable (Fig. 2e) with 127 ns pulse duration and peak power of 130 mW. Increasing the repetition rate above the corresponding f_c makes the pulse train more stable, and the pulse width shorter. The peak power varies so that the average power is kept constant. At a repetition rate of 5 MHz the pulse width decreased to 23 ns and the peak power to 68 mW. To achieve higher repetition rates, the width of the RF pulse supplied to the AOM was decreased below 100 ns. For the same repetition rate, the laser output pulse width and peak power did not change significantly with the RF pulse width down to ~70 ns. This is because the diffraction efficiency of the AOM starts to decrease for RF pulse widths less than 70 ns, since the spatial width of the acoustic pulse becomes comparable or shorter than the optical beam width. For an RF pulse width of 50 ns at a repetition rate of 8 MHz, we obtained 19 ns pulses with 48 mW peak power (Fig. 2f), while the average output power decreased to only 90% of its optimum value.

In conclusion, cavity dumping in neodymium-doped fibre lasers operating at 1053 nm was demonstrated using an acoustooptic modulator. We obtained stable trains of pulses at repetition rates in the range 0.5 to 8 MHz and pulse widths in the corresponding range 127 to 19 ns while keeping the average output power (8 mW) constant using 27 mW absorbed pump

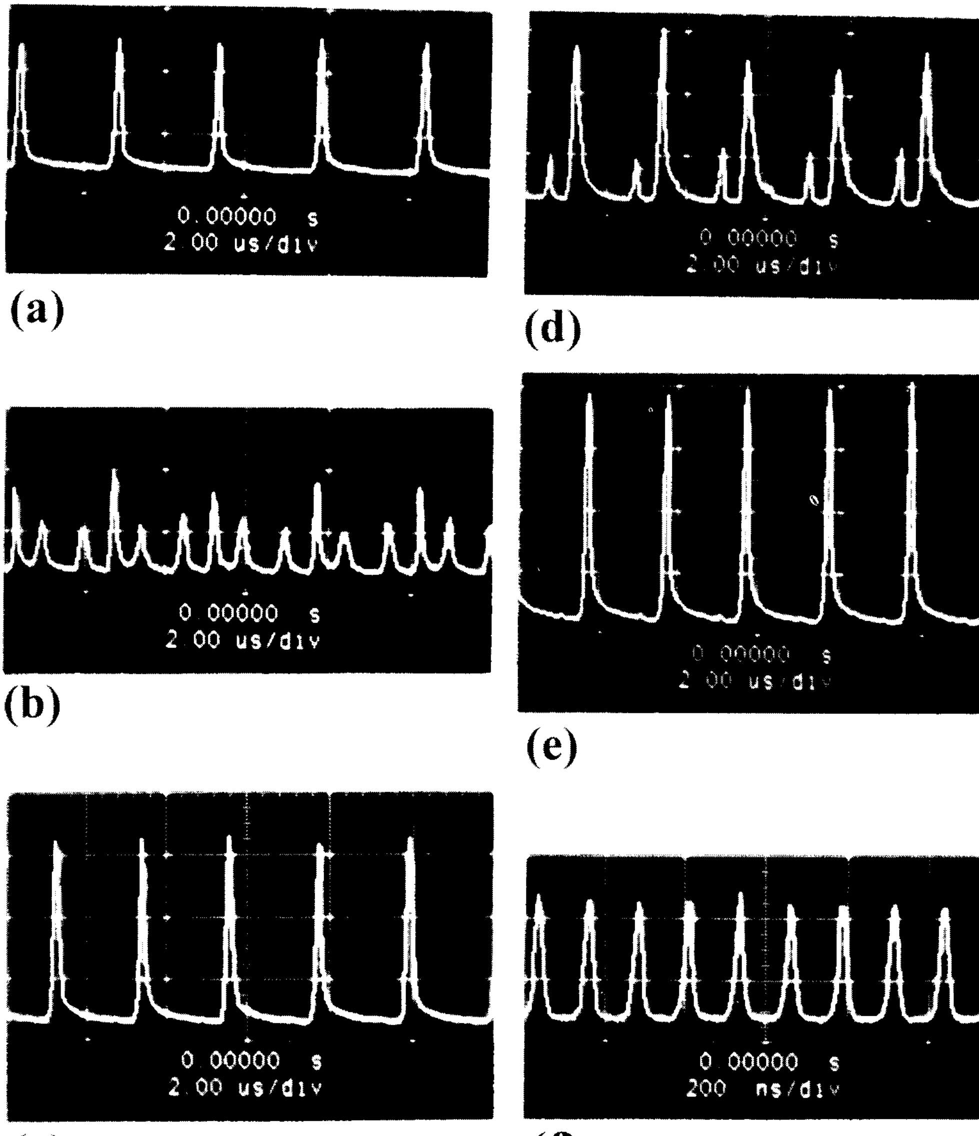

Figure 2 Photographs of oscilloscope traces showing the cavity-dumped laser output at different absorbed pump levels and different repetition rates: (a) 11 mW, 400 kHz; (b) 20 mW, 400 kHz; (c) 20 mW, 460 kHz; (d) 27 mW, 460 kHz; (e) 27 mW, 500 kHz; and (f) 27 mW, 8 MHz. The vertical sensitivity is the same for all of (a) to (e) while in (f) it is twice that for (a) to (e). The pulse durations in the stable outputs in (a), (c), (e) and (f) are 109 ns, 135 ns, 127 ns and 19 ns respectively. The corresponding peak powers are 92 mW, 120 mW, 130 mW and 48 mW.

power at 812 nm. This source of pulses at repetition rates inaccessible to the mode-locking and Q-switching techniques can be useful in optical time-domain reflectometry (OTDR) if the pulses, for example, are amplified with an optical fibre amplifier.

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