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Q-switched Nd-doped double-clad fiber laser

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A Q-switched operation of a 1064 nm Nd^{3+}-doped cladding-pumped silica fiber laser using an electro-optic modulation has been presented. The laser developed worked at the repetition rate of up to 10 kHz. For a 5 m-long double-clad fiber, pulses with the energy of 0.36 mJ and the pulse duration of 84 ns have been obtained. For the same fiber of 3 m length, pulses of 154 μJ energy and 48 ns duration have been achieved.

Keywords: double-clad fiber laser, Q-switching, electro-optic modulator.

1. Introduction

Double-clad rare-earth-doped fibers are very efficient and compact sources of cw and pulse coherent radiation. The rapid development of these devices is related to the improvements in optical fiber design and in the performance of semiconductor laser diodes, especially high brightness diode bars and diode stocks.

Applications like range finding, remote sensing, laser surgical, optical parametric oscillators or laser marking require short, high-peak-power pulses. For this applications Q-switched double-clad fiber lasers, operating at high repetition rate, are preferred [1–3].

Q-switching is a widely used laser technique for producing short intense pulses of light. In this technique energy is stored in the active medium by optical pumping while a high loss is inserted into the laser cavity to prevent the onset of the laser emission. The continuous pumping process results in a population inversion increase, which is proportional to the energy stored in a laser. On removing the additional losses from the cavity, the energy stored in the active medium is released in an intense pulse of radiation. This switching from high losses to low losses can be repeated to produce a train of high power pulses with duration depending on the laser cavity length and initial gain at the moment of losses off-switching. The additional cavity losses can be switched by means of a mechanical chopper [4], electro-optic modulator [5] or acusto-optic modulator [6,7].

Several mJ Q-switched fiber lasers have been reported over the past few years. These systems have produced relatively long pulses (a few hundred of ns) and therefore they have not been suitable for many applications, especially for material processing, where shorter pulses (duration below 100 ns) characterized by good beam quality are required [7,8]. Therefore, one of the possible solutions is the use of shorter pieces of active optical fibers to produce shorter output pulses. Then, this low-energy pulses can be amplified by means of a suitable stage of amplifier.

2. Laser set-up

The diagram of the Q-switched fiber laser design utilizing a Fabry-Perot cavity is presented in Fig. 1. It consists of a high-power laser diode, two mirrors which define the optical cavity and an electro-optic Q-switch.

Two pieces of different length of the same active double-clad fiber were used as an active medium. The fiber had a high Nd^{3+} dopant concentration of about 1300 ppm in the core and the core diameter of 12 μm. It was coated with silicone rubber with diameter of 400 μm (D-letter shape). The NA of the inner clad to the core and the outer clad to the inner clad was 0.12 and 0.38, respectively. About 70% incident pump power was launched into the inner clad. One end of the fiber was cleaved perpendicularly, and the 4% Fresnel reflection provided the feedback at this end of the cavity. Due to the high gain of the Nd-doped fiber, the 4% reflection from the air-fiber interface is often sufficient to start lasing which depletes the population inversion (gain) in an active medium. For that reason, the other end-face of the fiber was polished at a suitable angle to prevent any reflected light re-entering into the fiber. In our case the fiber was cleaved and precisely polished at the angle of 15. An external high-reflecting mirror closed the laser cavity. The alternative method of suppressing the feedback is a splicing on a short piece of multimode fiber matched in dimensions with the inner layer of the double-clad fiber. This solution leads to a degeneration in laser beam quality (through the mode coupling) and therefore it was not applied.

A fiber pigtailed laser diode module HLU30FAC-808 (LIMO Laser Systems) delivering 30 W of cw power at the wavelength of 808 nm was used as a pump unit. It was equipped with special cylindrical optics which transformed the pump beam to a spot size of less than 400 μm to couple

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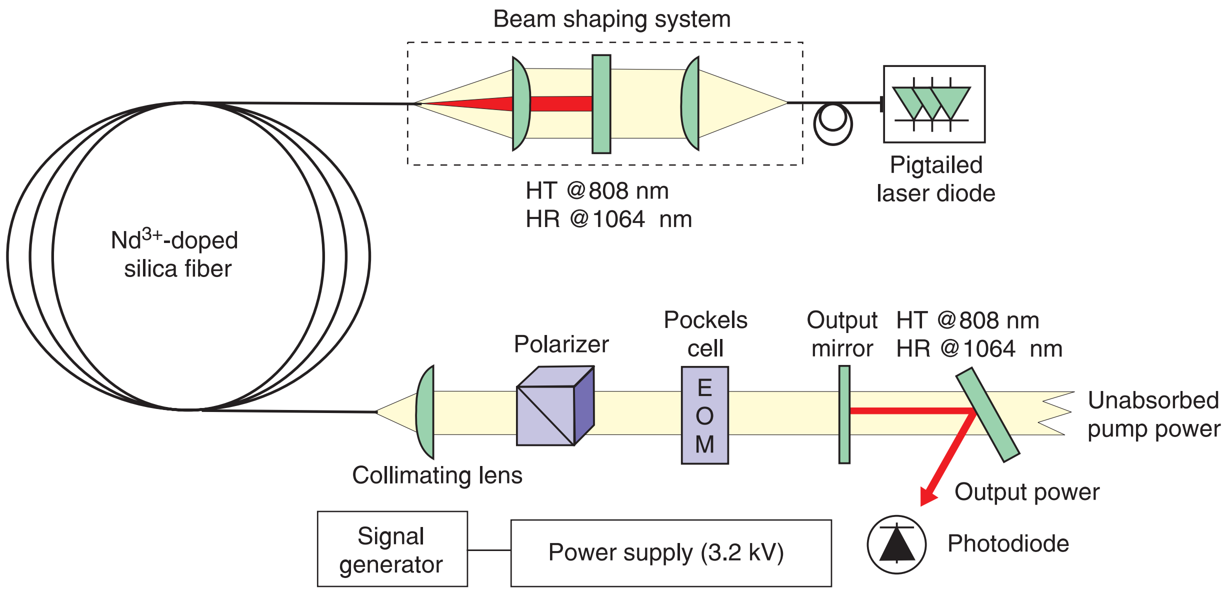


Fig. 1. Experimental Q-switched fiber laser set-up.

the pump light into the transmitting fiber. The 1.5 m-long transmitting fiber was characterized by numerical aperture NA = 0.22. The spectral width of the pump beam (FWHM) was smaller than 3 nm and a temperature drift (0.3 nm/K) made the pump match the maximum of absorption band of the active dopant. The laser diode was current-controlled by means of power supply system SDL 830 (Spectra Diode Labs) and was cooled by water cooling system. To control the working temperature of the diode, a Peltier cell was applied. Pump radiation coming out of transmitting fiber, thanks to shaping system (two aspheric lenses, AR-coated) was launched into the active optical fiber. To protect laser diode module from destruction by laser light on this end, we used a dichroic mirror, which was highly transmittive for pump wavelength and highly reflective for laser wavelength.

In order to provide the modulation of the cavity finesse, an electro-optic switch and a Glan polarizer were introduced intra-cavity just in front of the high reflection mirror. In our experiment we used a KDDP crystal (C1001S, DoroTEK) with the fall time of 20 ns. The laser worked in the off Q-switching configuration. For the fastest switching times electro-optic modulators remain the only option. Electro-optic Q-switching provides the fastest form of Q-switching with good pulse to pulse stability, high excitation ratio and relatively lower insertion losses than acusto-optic modulators. The use of this Q-switch, however, is coupled with the need for high switching voltages (typically 0–5 kV), which can produce severe electrical interference to nearby equipment and high cost.

In order to produce an efficient fiber laser, the polarization must be maintained during each round-trip time of the cavity. If the fiber significantly alters the otherwise linearly polarized light on each round-trip than the laser threshold will increase and efficiency will be reduced. Therefore the voltage of 3.2 kV was applied to the Pockels cell, which was sufficient to convert the linearly polarized light to circular polarized light and in conjunction with a Glan polarizer it was sufficient to prevent cw lasing. This voltage introduced a large electrical noise spike on the detectors for the duration of the electrical pulse. To eliminate this drawback, the proper insulation of the detector and shielded cables were done.

3. Results and discussion

The aim of the experimental research was to determine the possibility of ns-pulse generation in double-clad fiber laser systems based on an active Q-modulation technique. In the setup depicted in Fig. 1, a laser pulse generation at the wavelength of 1064 nm was obtained. The variation of peak power and pulse width was measured as a function of repetition rate and the results are shown in Figs. 2–7. These results were obtained using two fiber lengths: 5 m and 3 m.

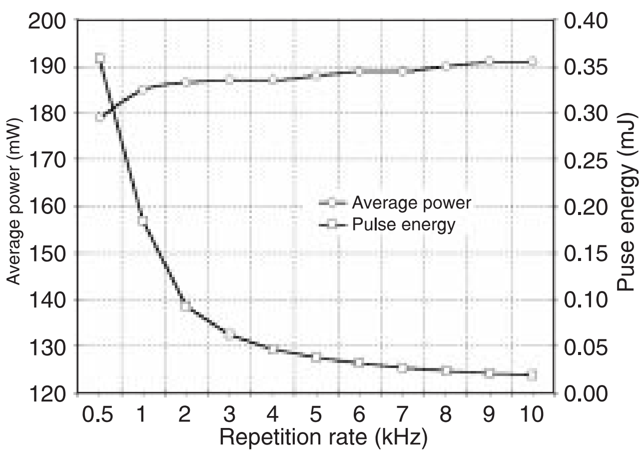


Fig. 2. Average power and pulse energy vs. repetition rate for the fiber of 5-m length.

Figures 2 and 3 present the time-energetic dependences as a function of repetition rate for the fiber of 5-m length. The pump power launched into the fiber equaled 3.5 W from which 1.8 W was absorbed by active dopant of the core. At higher repetition rate the average power is maintained around 190 mW, and the pulse energy is simply this power divided by the repetition rate. The pulse energy grows as the repetition rate decreases and exceeds 0.36 mJ at 500 Hz. It corresponds to the peak power of 4.3 kW. The average power drops for low repetition rates, as typical for Q-switched lasers. The repetition rate change also influences the pulse width. At higher repetition rates, the pulses become longer as the smaller amount of energy stored between pulses leads to a lower gain and a slower pulse build-up. For its lower values pulses of about 80 ns were generated and for 10 kHz repetition rate the pulse width equaled about 115 ns. The range of these changes also depended on pump power. For lower pumps the generated pulses were longer, for instance at pump power Pp = 1.5 W and 500 Hz the 95 ns pulses were generated while at the same pump power and repetition rate of 10 kHz the pulses extended to the value of 250 ns. For the pump power of 4.2 W and the repetition rate of 1 kHz, end-face of the fiber was damaged. In this case, the threshold of fiber damage equalled about 1.6 GW/cm^2.

Analogous measurements were done for the fiber of 3-m length (Figs. 5–6). The pump power launched into the fiber was 3.8 W while the absorbed power equalled 0.84 W. The character of characteristics measured was similar to those conducted for the fiber of 5-m length. At the repetition rate of 500 Hz a pulse train with peak power of about 3.2 kW and pulse width of 48 ns was achieved. The fall-off of peak power with increasing repetition rate is a result of the finite recovery time of the population inversion, which is directly related to the lifetime of the metastable lasing level, typically 360–400 µs for neodymium dopant in silica [9]. The lifetime of the metastable laser level is effectively reduced by the presence of ASE (Amplified Spontaneous Emission) signal which depletes

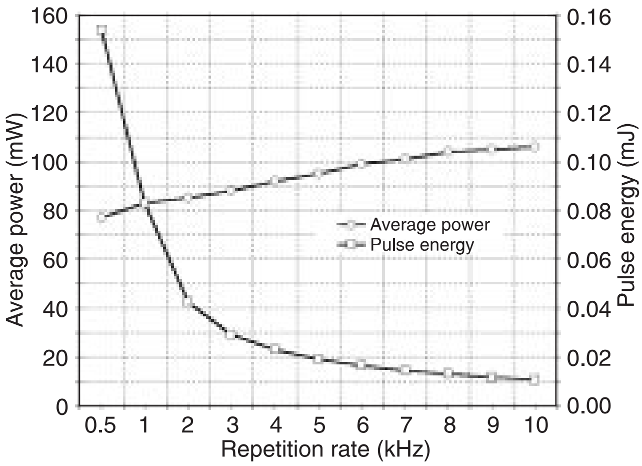


Fig. 4. Average power and pulse energy vs. repetition rate for the fiber of 3-m length.

the upper lasing level. Either damage to the facet or the onset of lasing between pulses limited the pulse energy. Damage to the out-coupling facet was observed at the pump power of 4.9 W and the repetition rate of 1 kHz. It corresponded to the power densities in the active core region of about 2 GW/cm^2.

The fiber length has the main influence on the duration and the temporal shape of the output pulses, as shown in Figs. 6 and 7. The output laser pulses are not smooth but its envelope is deformed. This deformation has a character of self-pulsation with a frequency equalled to the laser round-trip time (51.3 ns and 31.3 ns for the 5- and 3-m-long fibers, respectively). When the pump power (gain in a laser medium) is higher, the self-pulsation effect is more visible. These overmodulations are a result of the gain heterogeneity occurring in a laser cavity and the appearance of discrete elements (like a Q-switch). However, if the switching time is shorter compared to the round-trip time of the cavity then, this effect is smoothed out and the pulsed behaviour is not observed.

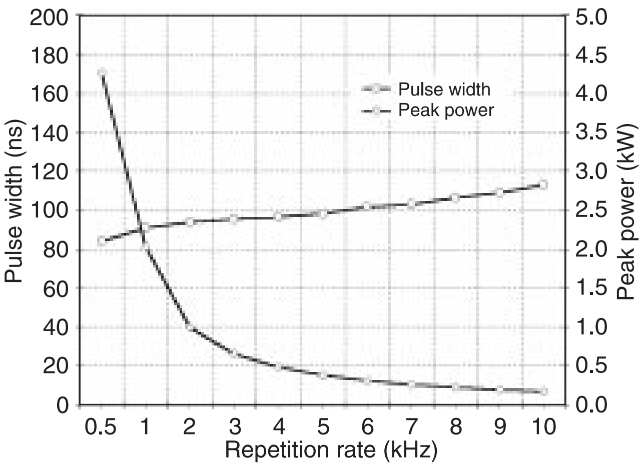


Fig. 3. Pulse width and peak power vs. repetition rate for the fiber of 5-m length.

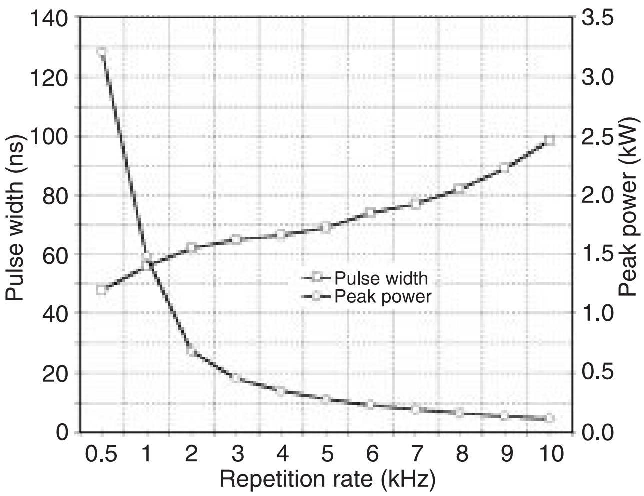
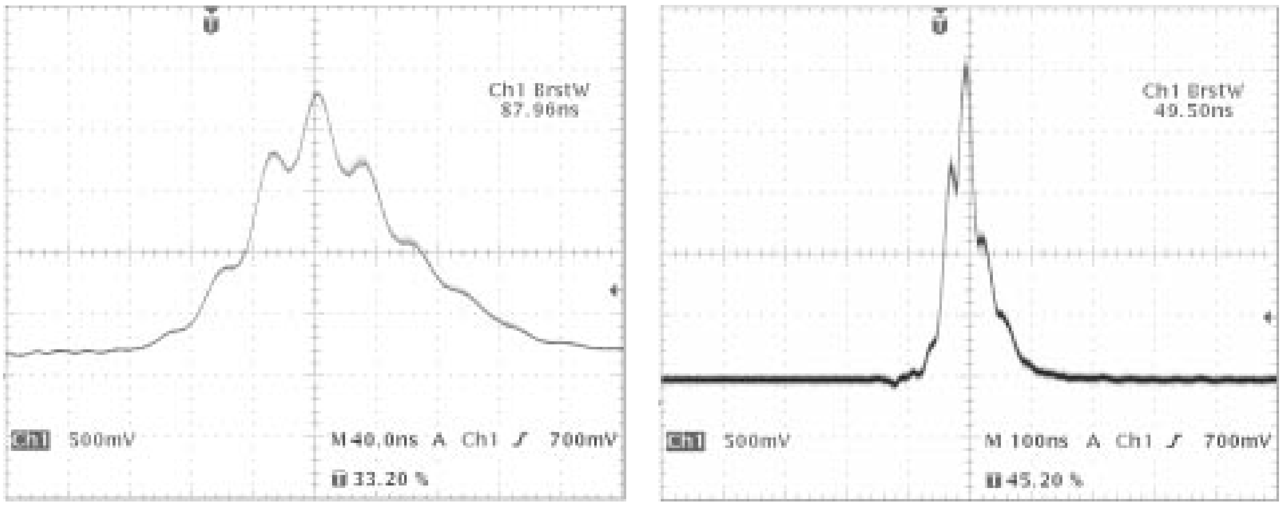


Fig. 5. Pulse width and peak power vs. repetition rate for the fiber of 3-m length.



(a) (b)

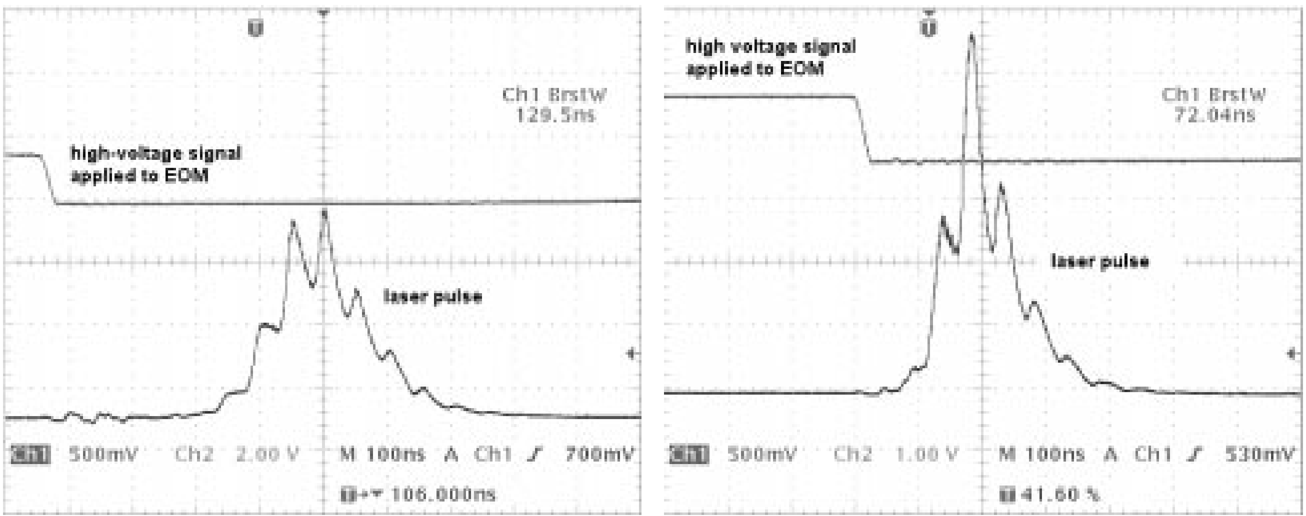
Fig. 6. Oscilloscope pictures of generated pulses for the fiber of 3-m length, (a) pulse for the pump absorbed P_{abs} = 0.56 W and the repetition rate f_r = 6 kHz, (b) pulse for P_{abs} = 0.84 W and f_r = 1 kHz.

For both pieces of fiber applied in the experiment, at higher pump power, the damage of output end-face of the fiber was observed. We estimated that the fiber damage threshold was several times lower than damage threshold of pure silica. It could result from a possible inaccuracy related to a precise fiber end-face polishing (micro-cracks) as well as low optical quality of the active fiber applied. One of the possible ways of increasing this damage threshold may be splicing a core-less end cap on the output side of the optical fiber cut at a suitable angle and dimensions suited to the inner clad. Thanks to that, the power density per unit volume is reduced, which leads to the fiber facet damage increase. The disadvantage of this solution is the degeneration of output beam quality and therefore it was not applied in our experiment.

4. Conclusions

In conclusion, the time-energy characteristics of an actively Q-switched double-clad fiber laser are presented. The laser pulse generation at the wavelength of 1064 nm was obtained. The Nd-doped fiber of 5 and 3 m length was used as an active medium. Pulses with an energy of 0.36 mJ (84 ns) and 154 µJ (48 ns) at the repetition rate of 500 Hz were achieved for 5- and 3-m-long fibers, respectively. In both cases, the extractable energy was limited due to low energy storage (as a result of ASE and lasing between pulses) and the fiber end damage.

In contrast to conventional solid state lasers, double-clad fiber lasers require long cavities to achieve efficient absorption of pump radiation from high power diode



(a) (b)

Fig. 7. Oscilloscope pictures of generated pulses for the fiber of 5 m length: (a) pulse for the pump absorbed P_{abs} = 0.77 W and the repetition rate f_r = 6 kHz, (b) pulse for P_{abs} = 1.8 W and f_r = 1 kHz.

lasers. The reason for this is the small core area, which leads to a large cladding-to-core area ratio and low pump absorption in typical double-clad fibers. The small doped core area with a tight mode confinement also leads to a high gain for relatively small amounts of energy stored in the form of excited Nd ions. The high gain leads to losses via ASE or even spurious lasing between pulses. This limits the energy that can be stored in the gain medium and thus the pulse energy of a Q-switched fiber laser. Therefore, it is necessary to increase core area, which decreases the mode confinement permitting the use of shorter fibers without compromising the absorption efficiency. Under such circumstances, to increase the extractable energy stored in the fiber, the applying of large mode area (LMA) fibers seems to be the best solution.

Acknowledgements

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