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Optical Kerr effect in Q-switched neodymium(III): doped silica fibre laser

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ABSTRACT Operating characteristics of Q-switched Nd^{3+}:doped single mode silica fibre with a mechanical chopper as a Q-switching device are presented. Peak power as high as 16 W with pulse duration 146 ns are demonstrated. Self-mode-locking in Nd^{3+}:doped fibre is also reported. Output power of 312 W with centre pulse duration of 4 ns is observed.

ABSTRAK Sifat-sifat operasi suatu *'Q-switch'* Nd^{3+}:dopan mode tunggal gentian optik silika dengan satu mekanikal *'chopper'* sebagai satu alat *'Q-switch'* dibincangkan. Puncak kuasa setinggi 16 W dengan lebar denyutan 146 ns diukurkan dalam kajian ini. *'Self-mode-locking'* dalam Nd^{3+}:dopan gentian optik juga dilaporkan, dimana kuasa setinggi 312 W dengan lebar denyutan sebanyak 4 ns telah dicapai.

(Optical Kerr effect, fibre laser, mode-locked fibre laser)

INTRODUCTION

Rare-earth doped single mode fibre lasers and amplifiers have important applications in optical sensors and communications. This is because the interaction of the rare earth ion with the silica host induces a spectral broadening of both the absorption and emission bands. Broad emission profiles are necessary for proper tuning of a fibre laser and broad absorption bands allow pumping with different optical sources. Furthermore, the large bandwidth and large storage time of the rare earth ions make them ideal for short pulse generation by the technique of mode locking and Q-switching. A fibre has the advantage of a large volume to surface-area ratio which allows efficient disposal of heat generated during the pumping process and that does not require any cooling of the active medium. Also, the long interaction length and small core radius (1.75 μm) of the fibre allows nonlinear processes such as self-phase modulation (which is one of the mechanism for mode locking) to take place. In the continuous wave operation, the fibre lasers are capable of generating output powers on the order of tens to hundreds of milliwatts.

However, for some application, pulses with much higher peak powers are desirable and this can be achieved by Q-switching the fibre laser. This has been demonstrated by Alcock *et al.* [1] whereby an acousto-optic modulator was used to generate pulses of 200 ns duration, with peak powers of 8 W at 100 Hz from a Nd^{3+}:doped fibre. It showed that a mechanical chopper can be used instead to generate Q-switched pulses with pulsewidth of 1 ms duration and output power of 300 mW [2]. Further reducement of the pulse duration can be attained by simultaneously Q-switching and mode locking the fibre laser with a mechanical chopper together with an acousto-optic modulator [3]. Mode-locked pulses are of interest in communication due to its short duration and high peak power. Recently Mylinski *et al.* [4] reported self-mode locking in erbium doped fibre utilising acousto-optic modulator. The formation of short pulses is explained as an interplay between the mode beats, present at a low light intensity at the beginning of pulse evolution, and the self-phase modulation acting at high light levels. This high peak power can be achieved by Q-switching the fibre laser and this pulse will break into train of shorter pulses resulting in the mode locked operation.

In this paper we report the generation of self-mode locked pulses in Nd^{3+}:doped fibre laser using a mechanical chopper as a cheaper alternative to acousto-optic modulator. To our knowledge, this is the first time such a technique is used.

EXPERIMENTAL

The characteristics studies of the doped fibre in our laboratory are based on Fabry-Perot resonator with the fibre as the active waveguide medium with core diameter of 3.5 μm and cladding diameter of 125 μm which corresponds to a numerical aperture (N.A.) of 0.21. The cut-off wavelength is about 950 nm, the overall fibre length is 3.7 m and the measured absorption coefficient at 514.5 nm is 8.56 dB/m and for 1088 nm is 0.01 dB/m. An argon ion laser operating at 514.5 nm was used throughout the experiments for optical pumping of the doped fibre as shown in Fig. 1a. The pumping beam diameter is 2 mm and are directed to the fibre laser cavity through a

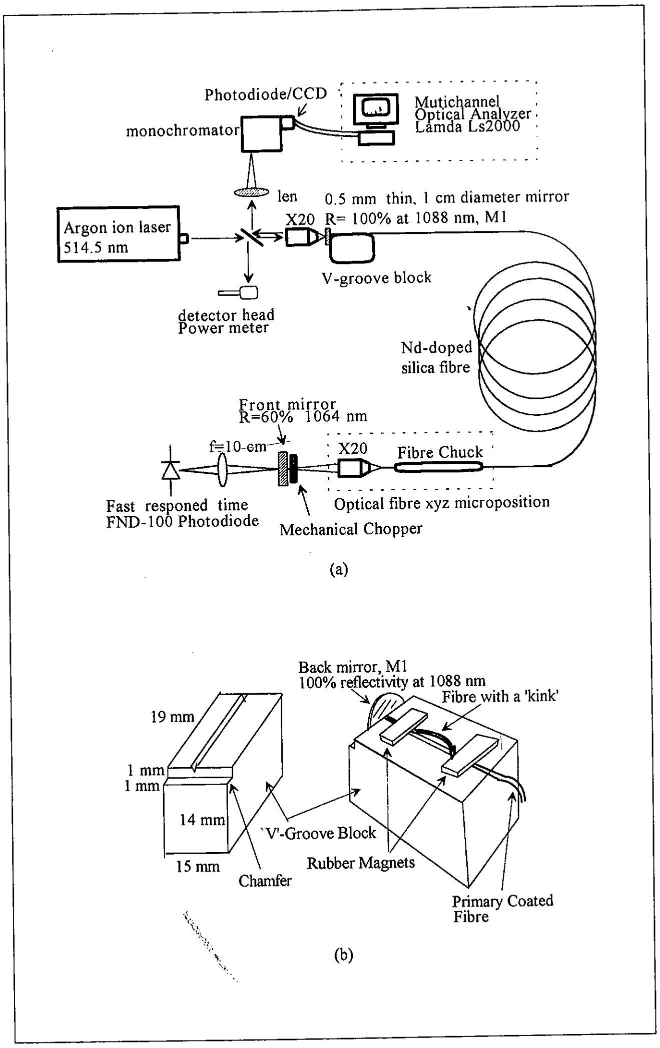

Figure 1. Experimental set-up.

80:20 beam splitter. The output power is constantly monitored using an Ophir power meter from the 20% arm of the beam splitter. The pump beam is focused into the Nd^{3+}:doped fibre with a X20 microscope objective lens with a numerical aperture of 0.20. A smaller N.A. was used for the lens as to maximise the coupling efficiency. The measured coupling efficiency for the pump beam is 27.7%. This low coupling efficiency is probably due to the mirror used in this system which is not antireflection coated at the pumping wavelength. The input end of the fibre sits on a V-groove of a stainless steel block as in Fig. 1b. The mirror with a diameter of 5 mm is glued to the chamfer of the block and the fibre is press to the mirror face with two rubber magnets. A few drops of index matching fluid are placed at the fibre end to minimise the Fresnel reflections. The output end of the doped fibre is placed in a single mode fibre chuck and mount on top of a XYZ micropositioner together with a X20 microscope objective lens. The output beam is slightly focussed onto the output coupler of 65% reflectivity at 1088 nm with the mechanical chopper placed just before the mirror. A fast photodiode, EG &G FND-100 was used together with a Tektronix 2440 (500 Msample/s) oscilloscope to detect the Q-switched and mode locked outputs of the Nd^{3+}: doped fibre laser.

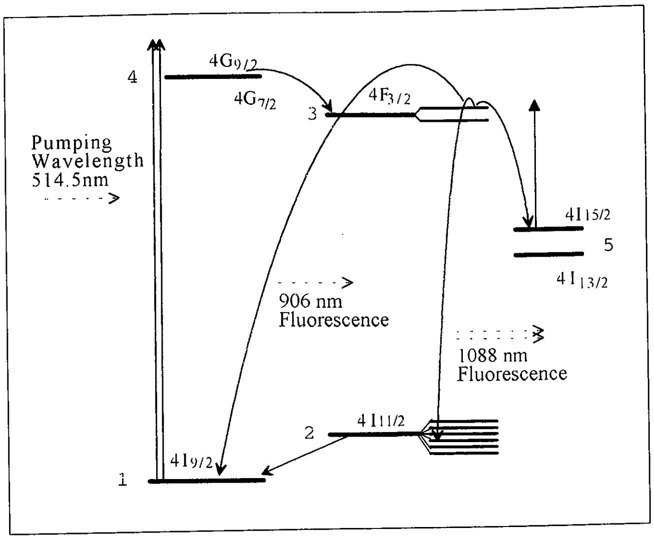

Figure 2. Level of Nd-ions concerned pumping at 514.5 nm and for emission around 1088 nm band.

RESULTS AND DISCUSSION

Q-switched fibre laser characteristics

The pumping process of the Nd^{3+}:doped fibre is shown in Fig. 2 whereby the ions from $^4I_{9/2}$ is excited upwards to the $^4G_{9/2}$ level. It then decays to the $^4F_{3/2}$ which acts as the upper lasing level. The decay of this upper $^4F_{3/2}$ level generate optical pulses with wavelength 906 nm ($^4F_{3/2}$ to $^4I_{9/2}$) and 1088 nm ($^4F_{3/2}$ to $^4I_{11/2}$). The measured output wavelength is only 1088 nm by using a LS2000 optical multichannel, due to the limitations of the reflectivity of the mirrors used. Fig. 3 shows a typical Q-switched pulse emitted from this fibre laser with a mechanical chopper as a Q-switching device. The output power is 16.5 W with a pulse duration of 146 ns at a chopping repetition rate of 4 kHz, with an input pump power of 440 mW. The temporal shape of the pulse consisted of small

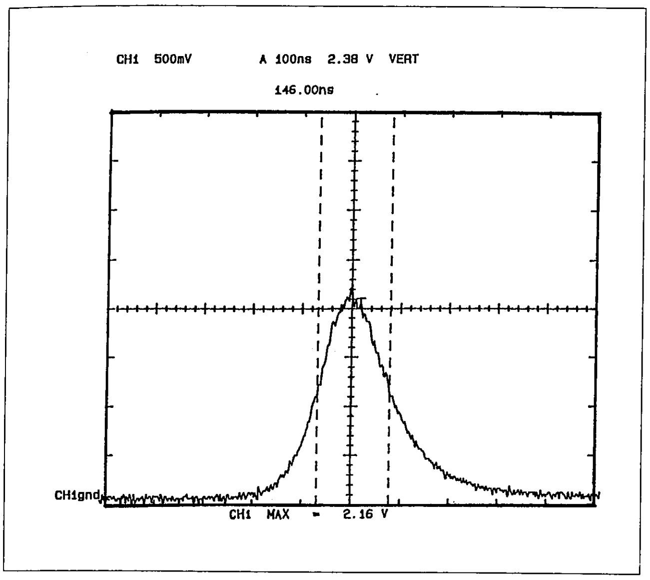

Figure 3. Q-switched pulse shape at 440 mw pump power.

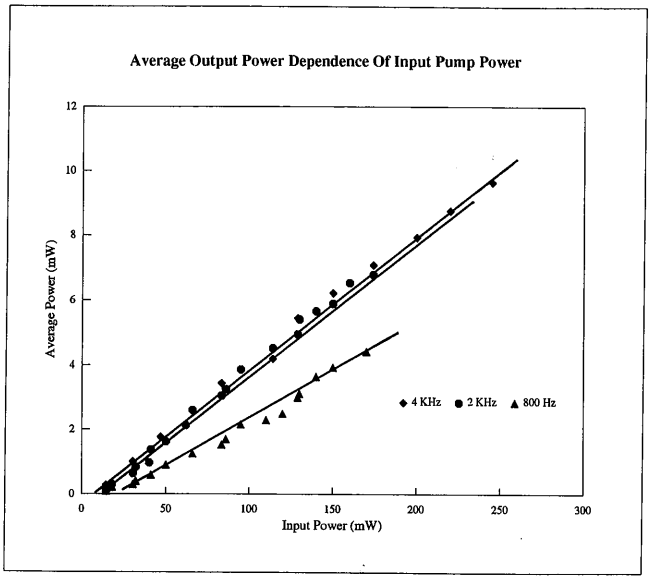

Figure 4. Average output power dependence of input pump power.

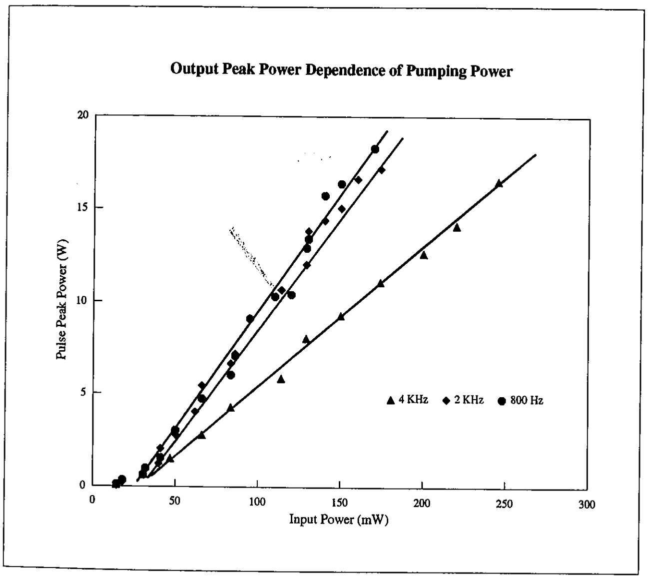

Figure 5. Output peak power dependence of pumping power.

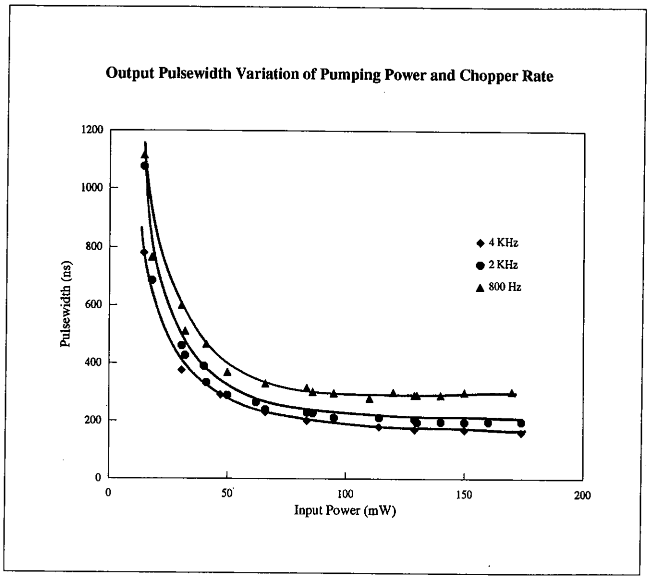

Figure 6. Output pulsewidth variation of pumping power and chopper rate.

spikes on top of the Q-switched pulse. These spikes are probably due to the onset of self-mode-locking behaviour of the doped fibre, which will be discussed later. The output power behaviour at different input power is shown in Fig. 4. The input power is the power measured from the output of the argon ion laser. The absorbed power will be much smaller that those indicated in the figure. The measured efficiencies at repetition rate of 4 kHz and 2 kHz are similar that is about 4.2% and for 800 Hz is 3.2%. It can be concluded that efficient operation are achieved when the chopper are operated at higher repetition rates. However, the peak power drops at higher repetition rate as shown in Fig. 5. At an input power of 150 mW, the output power increases from 9.2 W to 15 W when the repetition rate decreases from 2 kHz to 800 Hz. This implies that a higher peak power can be generated at a lower repetition rate. The pulse-

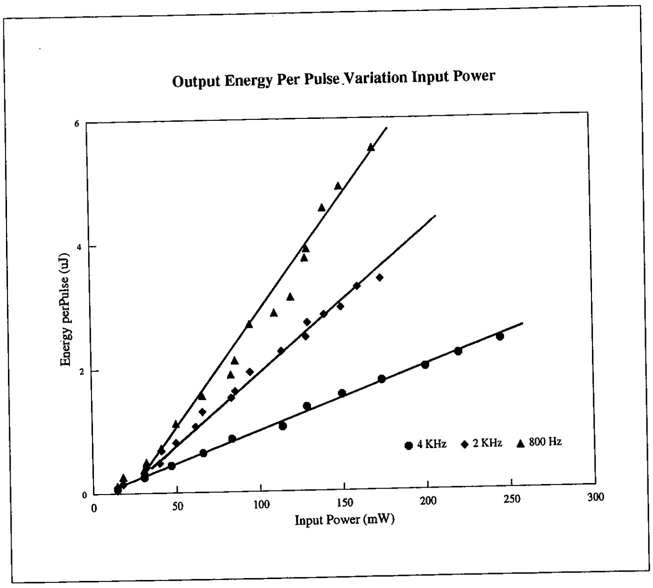

Figure 7. Output energy per pulse variation input power.

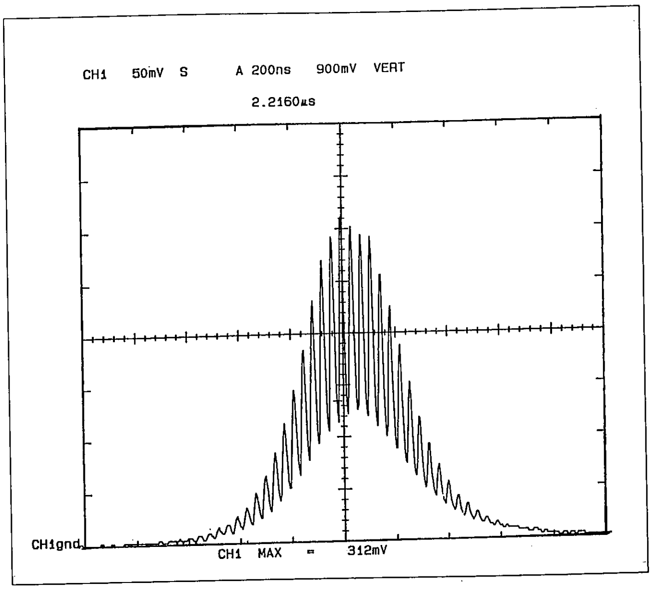

Figure 8. Self-modelocked pulses in a Q-switched pulse envelope.

width variation with input power is shown in Fig. 6. From the figure, the pulsewidth is narrower when the chopper is operating at 4 kHz. For the generation of a shorter Q-switched pulse, one of the conditions is that the on time T_{on} must be equal to the build-up time $T_{build-up}$, as recently discussed by Myslinski *et al.* [5]. If the repetition rate is faster, as in the case of 4 kHz, the on time is about 0.25 ms and the off time is also 0.25 ms for a chopper with a mark to space ratio of 1:1. This implies that the ions does not have enough time to build-up the population inversion, thereby reducing the peak power as observed in this experiment. The fluorescence lifetime of the excited state is 0.33 ms for Nd^{3+} ions doped in glass host and, for a chopper opening for a period of 0.25 ms, the generated Q-switched pulse will have a pulsewidth narrower than that of a slower repetition rate [6]. The output pulse energy against the input power is shown in Fig. 7 for different repetition rates. As the repetition rate increases to a higher value, the pulse duration reduces and the energy content per pulse also reduces as shown in the figure.

Self-mode-locking

From Fig. 8 the Q-switched pulse breaks into the train of mode locked pulses. This was observed when the pump power into the fibre was increased above 100 mW and the chopping frequency was reduced to below 800 Hz. With careful adjustment of the front mirror, stable output of mode locked pulses were observed. The operating parameter for the observed mode locked pulses in Fig. 8 is taken at input pump power of 270 mW and chopping frequency of 800 Hz. The pulse duration of the mode locked pulses varies from 4 ns to 10 ns. The width of the first few mode locked pulses in the figure shown is much longer than the width of successive pulses. The measured peak power of the centre peak with pulse duration of 4 ns is about 312 W. This phenomenon in optical fibre laser was first observed by Myslinski *et al.* [4] They observed this in Er^{3+} doped fibre laser using an acousto-optic modulator operating at 1.6 kHz with input pump power of 350 mW with peak output power of 200 W.

In our experiments, we able to demonstrate and observe the same phenomenon in Nd^{3+} doped silica fibre using a simple and inexpensive mechanical chopper. The output wavelength is 1088 nm. At present, the best explaination put forward by other workers [4,5] is this observation is due to mode coupling and self-phase modulation. The initial pulses from the mode locked train is a result of coupling of oscillating modes and the high peak power generated by these initial pulses in turn induces the self phase modulation in the fibre laser. Self phase modulation comes about due to the optical Kerr effect which arises from the third order susceptibility c[3] which exists in essentially all optical materials when strong optical field strength travels into the optical medium. This will change the refractive index of the material as in the equation $n = n_0 + n_2 I$, where n_2 is the nonlinear variation of the index of refraction, and I is the laser light intensity. In nearly all instances, n_2 is always positive. As a results of this, the incident laser field, I(t), will experience a time varying phase shift or phase modulation $\exp[-j2\pi n_2 I(t)L/\lambda]$ produced by the intensity variation of the laser pulse itself. For phase modulation to take place, the peak intensity must exceed $I_0 = \lambda/(2\pi n_2 L)$, where λ is the operating wavelength [7]. For a fibre of length of $L = 4$ m and $n_2 = 3 \times 10^{-16}$ cm²/W for a silica fibre, the calculated I_0 is equal to 130 MW/cm². However, this is an over estimate because for doped fibre, the n_2 will be larger and thereby reducing the value for the peak intensity required for self phase modulation. In our experiments the diameter of the doped fibre is about 3.5 μm and the peak intensity for a Q-switched pulse with peak power of 16 W is 230 mW/cm². With intensity of this value, we expect self phase modulation to be responsible in breaking the Q-switched pulse into the mode locked train as observed (Figs. 2-8).

In conclusion, we have demonstrated the generation of mode locked pulses in a Nd^{3+} doped fibre laser using an inexpensive mechanical chopper as a Q-switching device. The generated mode locked pulses have peak power of 312 W and pulse duration of 4 ns.

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