OPTICAL CHAOS AND HYSTERESIS IN A LASER-DIODE PUMPED Nd DOPED FIBRE LASER

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Modulated pumping of a Nd^{3+} doped silica monomode fibre laser has been investigated experimentally. For small modulation depths the laser exhibits a resonance at the relaxation oscillation frequency, providing pulses of a few microseconds duration at a repetition rate in the region of 10 kHz, dependent on the average pump level above threshold. As the pump modulation depth is increased, hysteresis is observed as a function of modulation frequency, along with optical bistability. For further increase in modulation depth, optical chaos and period doubling are observed. Gain-switching has also been demonstrated.

1. Introduction

There has been considerable recent interest in the construction of monomode fibres doped with rate earth elements to provide a fibre laser [1]. Such lasers have been mode-locked, *Q*-switched and tuned using a variety of intracavity elements [2–8]. In this paper we investigate the dynamic behaviour of a Nd doped fibre laser when subjected to modulated pumping by a diode laser. This provides a very well-controlled system for the study of laser dynamics. A wide range of phenomena has been observed including hysteresis, optical chaos, optical bistability and period doubling.

2. Experiment

The experimental arrangement is shown in fig. 1. The pump laser was a GaAlAs laser diode (Sharp LT015) operating at 820 nm. The pump beam was coupled into the fibre using two microscope objectives (20×, N.A. = 0.4 and 10×, N.A. = 0.25) through a mirror that was highly transmitting at the pump wavelength but highly reflecting at the laser wavelength of 1.09 μm. The Nd^{3+}-doped fibre had a core diameter of 3.5 μm and a numerical aperture of 0.21. A 6 metre length of fibre was used in order to absorb as much of the pump light as possible. The cavity was

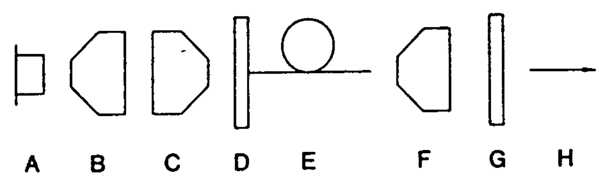

Fig. 1. Experimental arrangement for a diode pump modulated monomode fibre laser. Notation used: A – laser diode, B – collimating lens (20× M.O.), C – coupling lens (10× M.O.), D – high reflector (R = 99%), E – Nd doped fibre, F – intracavity lens (20× M.O.), G – output coupler (R = 70%), H – output beam.

completed by an intracavity microscope objective (20×, N.A. = 0.4) and a plane output coupling mirror of 70% reflectivity at the lasing wavelength. With this arrangement, the threshold absorbed pump power was found to be 1.3 mW with a slope efficiency of 20%.

The pump laser could be current modulated (sinusoidally) up to frequencies of about 100 kHz. The pump power modulation was recorded in terms of its average level P and its modulation amplitude $+\Delta P$. Both of these values were then normalized to the threshold pump power, P_{th}.

For low values of modulation depth ($\Delta P/P_{th} < 0.07$) and with the laser continuously pumped above threshold ($P - \Delta P > P_{th}$) it was found that a pulse was produced every cycle and that the peak output power went through a resonance as the modulation frequency was tuned through the relaxation oscillation

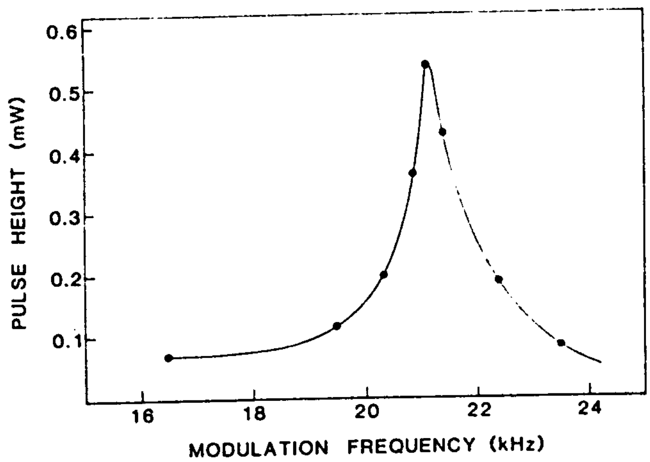

Fig. 2. Resonance behaviour for low modulation depth.

frequency. Fig. 2 shows the peak output power as a function of the modulation frequency at $P/P_{th} = 1.87$ and $\Delta P/P_{th} = 0.05$. At frequencies lower than the resonance frequency the laser output peaks in phase with the maximum pump level. There is a rapid phase shift as the modulation frequency passes through resonance and for higher frequencies the laser output and maximum pump level are in antiphase. This observation is in agreement with reported results from Nd:YAG systems [9].

For larger modulation depths we observed a discontinuous change in the laser peak power as a function of modulation frequency. The frequency at which this discontinuity occurred was dependent on whether the resonance was approached from above or below. A typical hysteresis curve generated in this regime is shown in fig. 3, where we have plotted peak

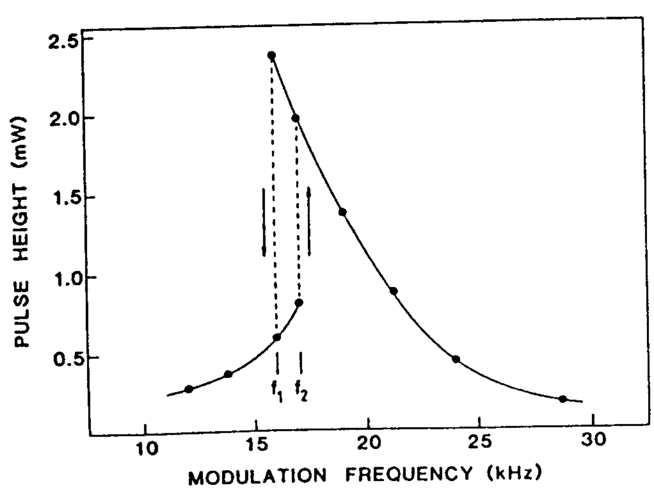

Fig. 3. Hysteresis curve showing bistable region (between f_1 and f_2).

output power as a function of modulation frequency at $P/P_{th} = 1.87$ and $\Delta P/P_{th} = 0.25$. The frequencies f_1 and f_2 represent the points of discontinuity. The frequency difference between f_1 and f_2 and the magnitude of the change in intensity varied with the average pump level and modulation depth. The example given in fig. 3 was observed during single spike operation but hysteresis was also apparent in period-doubled pulses. The conditions required for hysteresis to occur are dependent on the average pump level and modulation depth in a complex fashion. Detailed behaviour of this effect will be reported in a future publication.

An interesting feature of this regime is that when the modulation frequency is between f_1 and f_2 it is possible to induce the laser to change from a state of high intensity to low, or vice versa, by changing the average pump power, thus providing an example optical bistability.

By further increasing the depth of modulation to $\Delta P/P_{th} = 1$ and by suitably reducing the average pump level to $\Delta P/P_{th} = 1.25$, so that the laser dropped below threshold during part of the modulation cycle, it was possible to observe chaotic effects similar to those reported on other systems [10]. Fig. 4 shows a typical sequence of laser output signals as the modulation frequency was increased from low frequency towards the resonance value for relaxation oscillations. Lower traces monitor the injection current to the laser diode. Fig. 4(a) shows unstable multispike pulses which denote the onset of relaxation oscillations. At a slightly higher frequency (about 10 kHz), fig. 4(b) shows stable single spike operation, producing a giant output pulse every pump modulation cycle. By further increasing the frequency (fig. 4(c)), a region of extremely unstable operation was observed. The output intensity was no longer synchronized in any discernable way to the pump modulation. Further increase in frequency took the laser through a bifurcation point and led to stable period-doubled pulses (fig. 4(d)). A similar sequence of events occurred at higher frequencies where the region of period doubling gave way to further unstable behaviour, followed by a region of period tripling. The presence of these windows of stable period-doubled and period-tripled output suggest that the unstable behaviour observed is an example of deterministic optical chaos. Detailed study of this system will be the subject of a

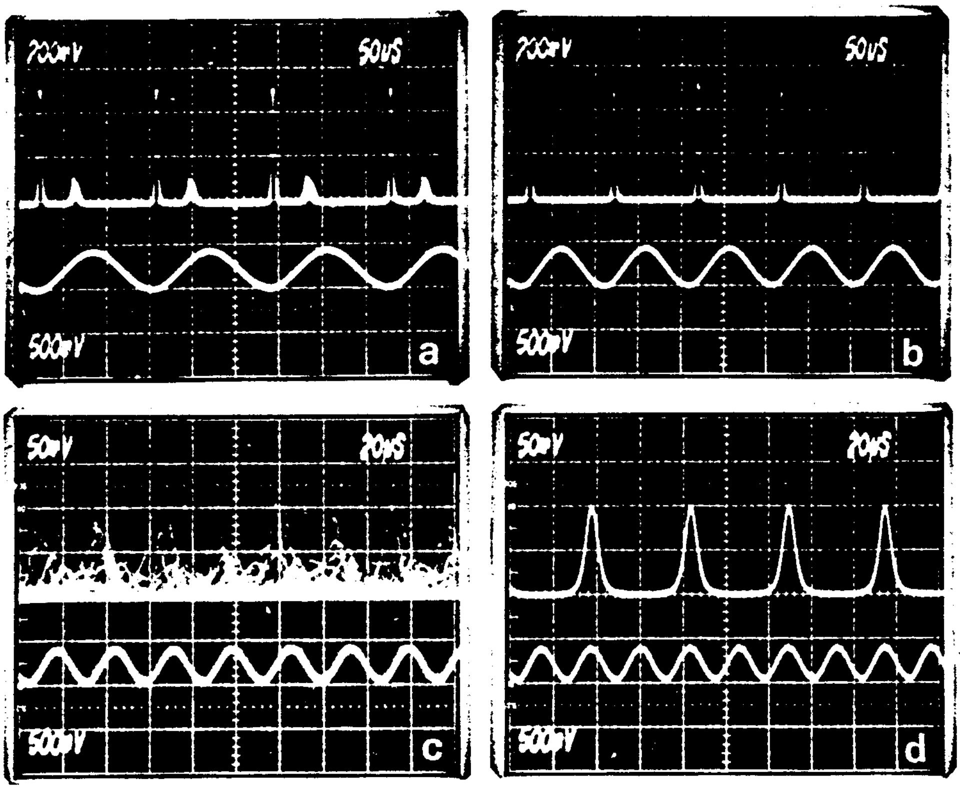

Fig. 4. Laser output showing various regions of spiking behaviour.

future publication.

The pump power was also modulated by a square pulse signal so as to produce relaxation oscillations in the fibre laser. The duty cycle of the signal was reduced until the laser output consisted of just the initial pulse of the relaxation oscillation. Fig. 5 shows such a pulse with a fwhm of about 3 μs. The lower trace (inverted) displays laser-diode injection current and shows the switching to low current before the second pulse has had time to build up (extreme right of photograph). This is an example of gain-switching in the fibre laser and provides an alternative method to Q-switching for the production of stable giant pulses.

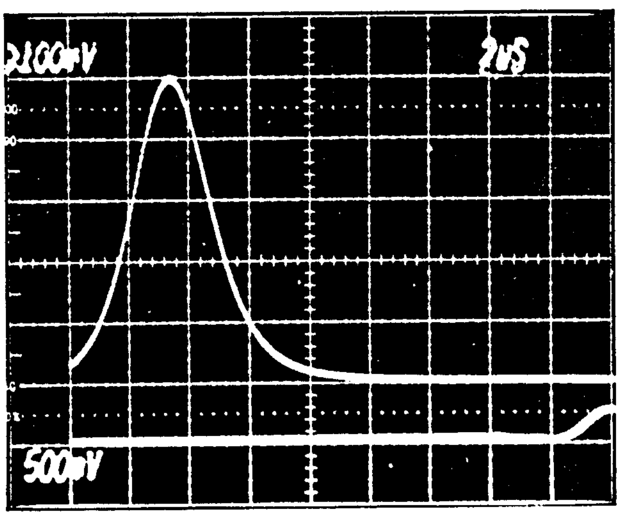

Fig. 5. Gain-switched pulse from fibre laser.

3. Conclusion

A Nd^{3+}-doped monomode fibre laser has been pump modulated with a laser diode to produce a pulsed output waveform. Variation of pump signal modulation depth and average power level has provided a range of dynamic behaviour in the laser including resonance at the relaxation oscillation frequency, hysteresis, and deterministic optical chaos. The fibre laser has provided a convenient and interesting system in which to observe dynamic nonlinear behaviour. Higher powers should be readily achievable and the laser behaviour could then move into an even more interesting regime where nonlinear optical effects, such as for example stimulated Brillouin scattering, begin to play an important role. Finally, we note that gain-switching has also been demonstrated as an alternative method to Q-switching for the production of giant output pulses, where the absence of a cavity loss modulator makes the pump modulated fibre laser a highly efficient pulsed source.

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