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# Relaxation oscillation studies in Nd: YAG laser—Some new results

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**Abstract.** The study of transient behaviour of a pulse pumped solid state laser system has assumed importance on account of SLM generation by self-seeding with the pre-lase signal. This paper reports on the observations of seed pulses for two different Nd: YAG laser rods, one with anti-reflection coating (AR) on end faces and the other without. The latter displays single longitudinal mode behaviour in each of the relaxation pulse train while the former displays multimode behaviour. Our observations are well explained by the 'active etalon concept' introduced earlier.

**Keywords.** Relaxation oscillations; Nd: YAG; active Fabry-perot.

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## 1. Introduction

Many studies have been carried out on the relaxation oscillation of optically pumped solid state lasers (Evtuhov and Neeland 1965; Sychev 1977). Simultaneous oscillation in many longitudinal modes in a homogeneously broadened laser, such as ruby, was explained by Tang *et al* (1963) as due to spatial hole burning effects. A fast spectral cross-relaxation and a slow spatial cross-relaxation was assumed in the analysis. An estimate of the number of oscillating modes at different pump power above threshold indicated that it is exceedingly difficult to obtain single mode operation in conventional mode masers at high pumping levels' (Tang *et al* 1963). Kimura *et al* (1971) extended the results of Tang *et al* (1963) to a four-level laser, such as Nd: YAG. In CW Nd: YAG, the number of measured oscillating modes was in good agreement with the theory of Tang *et al* extended to four-level laser. Strong multimoding even at a few percent above threshold was observed by both authors. Using a Nd: YAG rod without anti-reflection coatings on end faces as a gain medium, we have observed single longitudinal mode behaviour in each spike of train of relaxation pulses even up to ~ 100% above the threshold. However, a Nd: YAG rod with anti-reflection coatings on end faces does exhibit multimoding even at a few percent above the threshold. The importance of our observation lies in the fact that any pulse from the train of relaxation spikes can be used as a 'self-seed' pulse for generation of SLM Q-switched pulse instead of complicated electronics used in selecting the first pulse (Hanna *et al* 1972), the second pulse (Park and Byer 1981), or any pulse from the train of relaxation pulses exhibiting no modulation (Hanna and Koo 1982) as a self-seed pulse.

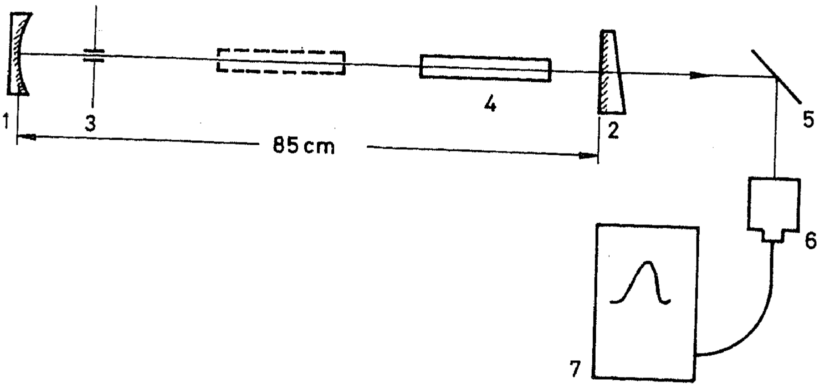

Figure 1. Schematic layout of laser set-up. 1, 2, dielectric mirrors; 3, mode-selecting aperture; 4, Nd: YAG rod; 5, beam splitter; 6, biplanar photodiode; 7, storage oscilloscope TEK 7834.

## 2. Experimental

The experimental set-up used is shown in figure 1. A hemi-concentric resonator, consisting of a 5 m radius of curvature ~ 100% reflectivity mirror and a flat output mirror of 43% relectivity, is used. Two Nd: YAG rods were used in the experiment: (a) YAG-1: 3 mm in diameter, 50 mm in length, without antireflection coating on end faces and (b) YAG-2: 3 mm in diameter, 70 mm in length with antireflection coating on end faces. The gain medium, YAG-1/YAG-2, is pumped by a single linear flashlamp in an elliptical cavity. An iris placed close to ~ 100% mirror provides the necessary transverse mode selection. Relaxation oscillation pulses were studied for different inputs above the threshold; and for each input the pulses were sampled from different parts of the train. Our observations were made with (a) YAG-1 as an active medium, (b) YAG-2 as an active medium, (c) an unpumped YAG-1 in YAG-2 system and (d) different positions of YAG-1 within the resonator. In all these cases, the rod end face was kept misaligned to the mirrors by ~ 10 minutes of arc, so that the mode selectivity could be attributed to 'active etalon' alone and not to selectivity brought about by sub-cavity formation on alignment (Bua *et al* 1972).

To ascertain the SLM operation of the laser, one can either measure the spectral characteristics of the laser by a high resolution F-P interferometer or monitor the temporal pulse shape by a broad band detection system. Observation of time trace is a more sensitive indicator of mode purity than is a photograph of F-P spectrum (Koechner 1976). Often the presence of a weak secondary mode is not indicated by observing the F-P ring system, whereas it is unmistakably shown by a small degree of 'ripple' in the time trace. All measurements were made with a biplanar photodiode (Hamamatsu, response time ~ 100 ps) and a storage oscilloscope (Tektronix 7834). The overall response time of the detection system is 0·75 ns which was sufficient to observe adjacent modes beating in our case. Mode separation for the experimental arrangement used corresponds to ~ $1{\cdot}75 \times 10^8$ Hz.

## 3. Results

The relaxation oscillation spikes were recorded for each case at two sweep speeds. Slow speed (50/100/200 ns/cm) was chosen for display of an entire pulse and a fast speed

(2 ns/cm) for better temporal resolution to observe the temporal modulation, if any. Our results for the different cases studied are as follows.

(a) Figure 2 displays oscilloscope traces of typical pulses selected at the beginning, middle and end of the train for YAG-1 at 50% above threshold. For each delay, the pulses are displayed at both slow and fast sweep rates. No modulation is observed in any of the pulses. Similar results were obtained for all pulses even up to ~ 100% above the threshold. The choice of this pump energy, however, is arbitrary.

(b) With YAG-2 operated at ~ 5% above threshold, figure 3 displays a typical spike selected at random from the train. Temporal modulation is observed both at slow and fast sweep speeds. Similar observation was made on any pulse selected at random from the train. The structure and depth of modulation changes at higher inputs indicating strong multimoding. However, an interesting observation was made, when an

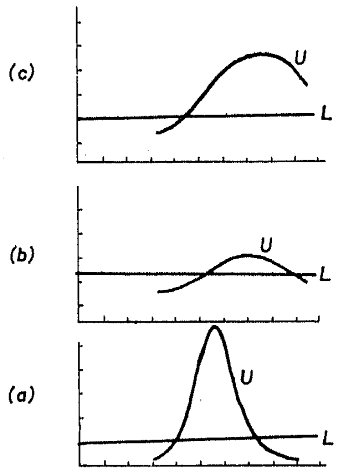

**Figure 2.** Relaxation oscillation spikes of YAG-1 at 50% above threshold. (**a**) Beginning of pulse train: sweep speeds $U = 100$ ns/cm and $L = 2$ ns/cm (**b**) Middle of pulse train: sweep speeds $U = 100$ ns/cm and $L = 2$ ns/cm (c) End of pulse train: sweep speeds $U = 50$ ns/cm and $L = 2$ ns/cm.

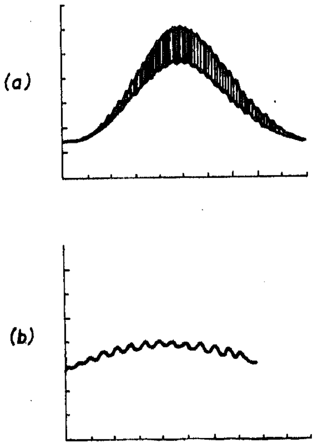

**Figure 3.** Relaxation oscillation spike of YAG-2, selected at random, at ~ 5% above threshold. Sweep speeds: (**a**) 50 ns/cm (**b**) 2 ns/cm.

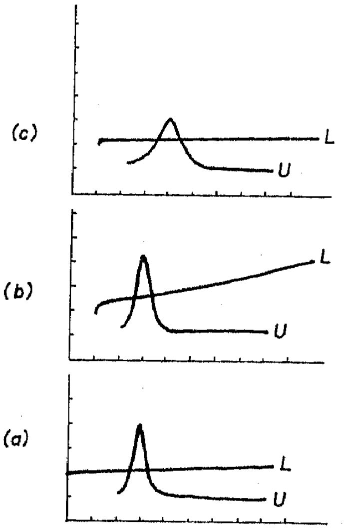

**Figure 4.** Relaxation oscillation spikes of YAG-2 at 70% above threshold with unpumped YAG-1 as passive etalon: (**a**) Beginning of the train (**b**) Middle of the train (**c**) End of the train. Sweep speed in all cases: $U = 200$ ns/cm $L = 2$ ns/cm.

unpumped YAG-1 with its axis tilted a few degrees to the axis, was inserted in the YAG-2 resonator. The output showed modulation-free behaviour in all pulses selected at random from the train even at higher inputs (up to ~ 70%) above the threshold. Figure 4 shows the output for this case were pulses are again selected from the beginning, middle and end of the train.

For the above cases, the pumped Nd: YAG rod was kept closer to the output mirror.

(c) Since in homogeneously broadened laser transition like Nd: YAG the multimode oscillations are primarily due to spatial hole burning effects, the number of oscillating modes depends on the position of the active medium within the resonator. At the centre of the resonator the mode adjacent to the oscillating mode has the highest probability to oscillate. Experiments were conducted with YAG rod at the centre of the resonator. The oscillation was constrained to SLM in all cases, similar to figure 2, indicating the strong selectivity of the 'active etalon'.

## 4. Discussion

In the free running regime the gain is locked to the loss line and oscillation in adjacent modes alone has been observed in each spike of the train of relaxation pulses (Evtuhov and Neeland 1965). Thus for ensuring SLM oscillation in each spike of the train, the 'active etalon' should provide sufficient selectivity between the oscillating mode and the adjacent ones. If mode $m$ has a frequency exactly at transmission maximum of the etalon and mode $n$ is an adjacent mode, the SLM criterion demands that the ratio of powers of mode $m$ ($P_m$) and mode $n$ ($P_n$) after $q$ round trips be at least $10^5$:1 (not observable on oscilloscope) (Nathan *et al* 1986). The ratio $P$ is given by,

$$P = \frac{P_m}{P_n} = \left[1 + \frac{8 \cdot \pi^2 \cdot \mu^2 \cdot t^2 \cdot R \cdot G_0}{L^2 \cdot (1 - R \cdot G_0)^2}\right]^q, \tag{1}$$

where $\mu$ and $t$ are the refractive index and thickness of the 'active etalon', $L$ the mirror separation of the resonator, $R$ the end face reflectivity of Nd: YAG rod and $G_0$ the small signal gain. For SLM oscillation, the above relation should be satisfied for each spike. This does not necessarily mean that in the free running regime, in our case, the output spectral width would correspond to that of single frequency oscillation. Though each spike in the train exhibits single mode, the oscillating mode could be different from one spike to the next giving rise to a larger overall oscillating bandwidth.

With a $\sim 100\%$ and a $43\%$ mirror forming the resonator, the small signal gain at threshold corresponds to $\sim 1{\cdot}52$ per pass. With this value of gain and an end face reflectivity of $\sim 8{\cdot}5\%$ for YAG-1, the SLM criterion as given in relation (1) demands a build-up time, $\tau_b^c$ (number of round trips $q*$ round trip transit time) of 0·45 $\mu$s. Since the photon build-up time is typically of the order of a few $\mu$s, modulation free spikes are observed for YAG-1. For YAG-2, on account of antireflection coating, end face reflectivity is $\sim 0{\cdot}25\%$. With identical gain as in YAG-1, SLM criteria demands build-up time of the order of 9·52 $\mu$s, which is much higher compared to the typical build-up time. Hence YAG-2 displays modulation at all inputs. However, with unpumped YAG-1 as a passive etalon inside a YAG-2 oscillator, mode selection is expected as the build-up time demanded by the SLM criteria for the passive etalon is $\sim 0{\cdot}73\,\mu$s which is smaller than the typical flux build-up time. Hence, modulation-free pulses are observed for YAG-2 with the passive etalon on account of the large build-up time available.

## 5. Conclusions

From our experiments using two Nd: YAG rods, with and without antireflection coatings, we have conclusively shown that the 'active etalon' nature of the gain medium is mainly responsible for forcing SLM oscillations in each spike of the free running relaxation oscillation.

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