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Resonator Transients of all Solid-State Cr: LiSAF and Nd:YVO_4 Lasers-Generation of Single Short Laser Pulse

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Abstract: The resonator transients and, in particular, the phenomenon of relaxation oscillations of diode end-pumped solid-state Cr:LiSAF and Nd:YVO_4 lasers have been investigated at 850 nm and 1064 nm, respectively. The obtained results allow to understand clearly the resonator transients and show a generation of single laser pulses from the Cr:LiSAF and Nd:YVO_4 lasers at near-threshold pumping levels. By proper choices of solid-state laser resonator and pumping parameters, obtainable duration of single solid-state laser pulses is computationally studied to be in nanosecond range and much shorter than the diode laser pumping pulse (100 µs). As a result, a technique of single short laser pulse generation at high repetition rate of diode pumping pulses has been experimentally demonstrated. In our Nd:YVO_4 laser pumped by 100 µs diode laser pulse, single laser pulses as short as 93 ns at 1064 nm and pulse repetition rate as high as 3 kHz has been produced. The superior limit (about 3 kHz) in repetition rate of single Nd:YVO_4 laser pulse mainly resulted from the fluorescence lifetime of active ion Nd^{3+}.

Key words: resonator transients, solid-state lasers, short laser pulse

I. INTRODUCTION

Nd:YVO_4 (Yttrium Vanadate) has been growing in popularity because of its high gain, low threshold, and high absorption coefficients at pumping wavelengths, which result from the excellent fit of the neodymium dopant in the crystal lattice. These advantages make Nd:YVO_4 a better choice than Nd:YAG in many applications. In recent years, Nd^{3+}:YVO_4 crystals have been strongly used as gain media at 1064 nm for diode-pumped all solid-state lasers [1-8]. The *a*-cut Nd^{3+}:YVO_4 crystal has the stimulated emission cross sections at 1064 nm (25×10^{-19} cm^2) about 5 times higher than that of Nd^{3+}:YAG (6×10^{-19} cm^2) and, in particular, its diode pumped optical to optical efficiency may be larger than 60% [9]. These spectroscopic features improve diode-pumped solid-state laser operations at 1064 nm.

For diode-pumped solid-state lasers tunable from 720 nm to 920 nm, many researchers have paid attention to the Cr:LiSAF (Cr^{3+}:$LiSrAlF_6$) lasers in the past few years [11-21]. This laser crystal has a fluorescence lifetime (67 µs) comparable with the fluorescence lifetime of Nd^{3+} ions in YVO_4 (90 µs) [9, 10]. The peak wavelength of the Cr:LiSAF laser free-running spectrum is near 850 nm, however, its stimulated emission cross sections is low (4.8×10^{-20} cm^2) – about 10 times lower than that of Ti:Al_2O_3 (4.6×10^{-19} cm^2) [19-21].

The phenomenon of relaxation oscillations was observed and studied very early in solid-state, gas and dye lasers under pulsed excitation [22-26]. It is generally recognized to be a phenomenon due to the interaction between the excess population inversion of the active medium and the photon energy of the electromagnetic field inside the resonator. The characteristics of the relaxation oscillations depend on the rate of change of the population inversion due to pumping, spontaneous decay and stimulated emission, and the rate of buildup and decay of photons in the resonator due to stimulated emission and various loss mechanisms such as output coupling and absorption. In the past, lasers were usually pumped by flash lamps or in single-shot regime, therefore, most cases random relaxation pulses of irregular spacings and amplitudes were observed. However, in solid-state and dye lasers under stable pulsed laser pumping, there were observations of perfectly regular damped relaxation oscillations [22, 23]. Such regular damped relaxation oscillations are expected from theoretical analyses using the coupled rate equations [22-26].

In this paper we investigate the resonator transients of the solid-state Cr:LiSAF and *a*-cut $Nd:YVO_4$ lasers pumped by diode laser pulses and, in particular, the phenomenon of regular damped relaxation oscillations. One of the obtained results led one to a simple technique to produce high repetition rate, single and short laser pulses from diode-pumped solid-state Cr:LiSAF and $Nd:YVO_4$ lasers basing on the resonator transient. As a result, the generation of single Cr:LiSAF (75 ns, 850 nm) and $Nd:YVO_4$ laser pulses (71 ns at 1064 nm) much shorter than the pumping pulse (100 µs) at high pulse repetition rate have been demonstrated by proper choices of resonator parameters and the level of pumping. In the case of $Nd:YVO_4$ lasers, the characteristics of such a short laser pulse generation are studied experimentally and compared with theoretical considerations. Excellent qualitative agreement is obtained.

II. THEORY

Rate equation analysis

In this part we investigate theoretically the dynamics of diode end-pumped solid state laser, as shown in Fig. 1. The laser crystal may be *a*-cut $Nd:YVO_4$ (1064 nm) and Cr:LiSAF (850 nm), they are optically pumped by diode laser pulses at 670 nm and 808 nm, respectively.

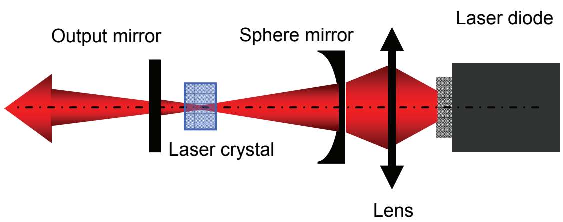


Fig. 1. Schema of the diode-pumped solid-state laser

We have used the well-known rate equation system as follows [21-23]:

$$\frac{dn}{dt} = W - Bnq - \frac{n}{\tau}$$
$$\frac{dq}{dt} = Bnq - \frac{q}{t_c} + \frac{n\alpha}{\tau}, \quad (1)$$

where n is the population inversion and nearly equal to upper state population; q is the number of photon quanta in the resonator; B is the Einstein coefficient for stimulated emission; W is the pumping rate; τ is the fluorescent lifetime; α is the coefficient (of largely arbitrary) that stimulates the initial spontaneous emission in the resonator; t_c is the photon-cavity decay time. If the cavity losses are assumed to be primarily transmissive ones, then

$$t_c = \frac{T_c}{1-R} = \frac{\eta l + (L-1)}{c(1-R)},$$

where R is the geometric mean, $R = (R_1 R_2)^{1/2}$ of the cavity mirror reflectivities. T_c is the cavity transit time,

$$T_c = \frac{\eta l + (L-1)}{c}$$

and L is the resonator spacing, l and η are the length and the refractive index of the active medium (l = 3 mm), and c is the speed of light. In equilibrium $(dn/dt) = 0$, $(dq/dt) = 0$ and we have

$$n = n_0 = \frac{1}{Bt_c},$$

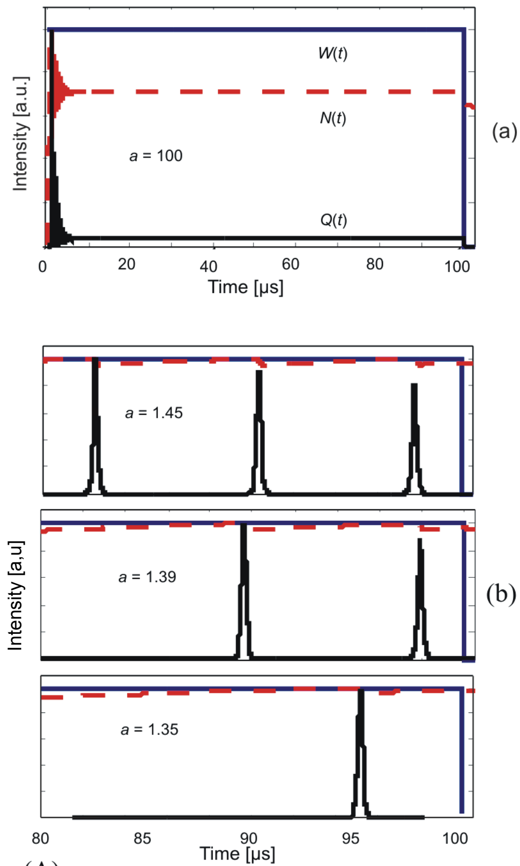
$$q = q_0 = \frac{W - n_0/\tau}{Bn_0}.$$

Note n_0 is the threshold inversion above which $dq/dt > 0$. The threshold pumping rate W_t is defined as

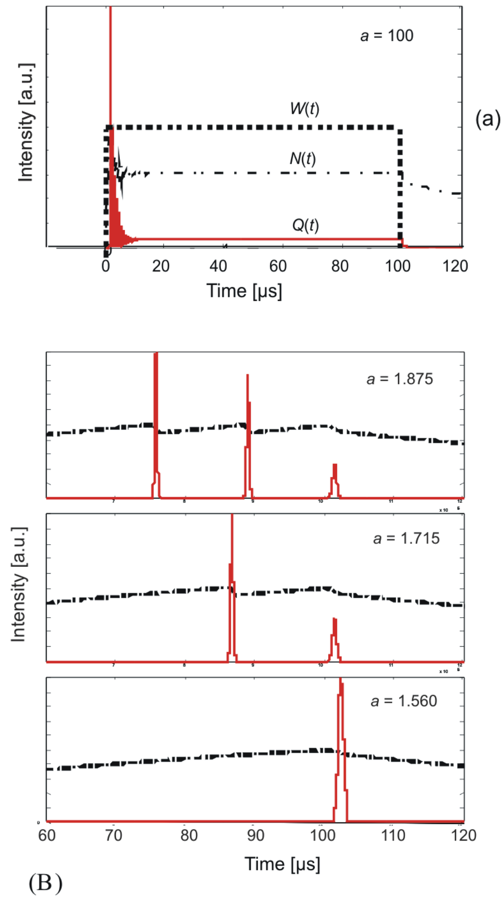
$$W_t = \frac{n_0}{\tau} = \frac{1}{Bt_c\tau}.$$

Firstly, the Cr:LiSAF and *a*-cut $Nd:YVO_4$ and lasers was theoretically investigated, we obtained numerical solutions to the coupled rate equation system (1) using Runge-Kutta method and parameters appropriate for our laser resonators. The parameters of the Cr:LiSAF and *a*-cut $Nd:YVO_4$ crystals were cited from [9, 10, 19]. We used the diode pumping pulses of 100 µs duration, this duration is comparable with the fluorescence lifetime of Cr^{3+} in LiSAF or Nd^{3+} ions in YVO_4 and, therefore, efficient pumping is obtainable.

The resonator transients of the Cr:LiSAF and $Nd:YVO_4$ lasers have similar features and the main comments on the computed results are:



(A)



(B)

Fig. 2A. Computed results of the dynamics in the diode-pumped Cr:LiSAF laser emission from the 5 cm resonator at different pumping levels. Pumping level a = 100 times above laser threshold a) Pumping levels from 1.35 to 1.45 times above laser threshold b). The dashed lines $n(t)$ and the curves $q(t)$ represent the calculated upper-state population and photon intensity, respectively. The rectangular-shaped pumping pulse $W(t)$ is of 100 µs duration

Fig. 2B. Computed results of the dynamics in the diode-pumped Nd:YVO$_4$ laser emission from the 5 cm resonator at different pumping levels. Pumping level a = 100 times above laser threshold a) Pumping levels from 1.56 to 1.87 times above laser threshold b). The dashed lines $n(t)$ and the curves $q(t)$ represent the calculated upper-state population and photon intensity, respectively. The rectangular-shaped pumping pulse $W(t)$ is of 100 µs duration

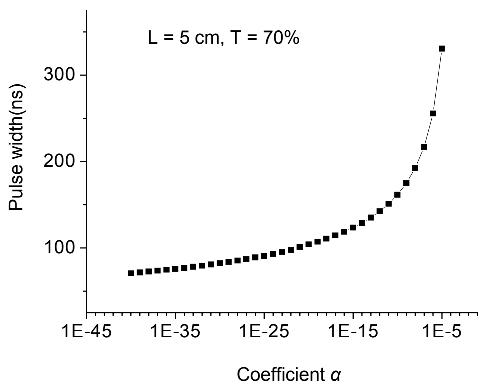


Fig. 3. Dependence of the Nd:YVO$_4$ laser pulse width on the coefficient α (representing the initial spontaneous emission in the resonator)

- In solid-state lasers, the fluorescent lifetime τ is usually much larger than the cavity transit time T_c, hence strong relaxation behaviors is often seen. At pumping levels much higher laser threshold, the Cr:LiSAF and Nd:YVO$_4$ laser pulses could repeat the diode pumping shape (Fig. 2A (a) and Fig. 2B (a)). In the buildup, the initial pulses of considerably high intensity were always observed.
- The number of oscillation reduced when the pumping power is decreased. At near threshold pumping levels, the Cr:LiSAF and Nd:YVO$_4$ laser emissions contain a few pulses of relaxation oscillations, eventually only a single pulse remains (Fig. 2A (b) and Fig. 2B (b)). This is of interest for short laser pulse generation.
- In the regime of single pulse generation, the computed pulse widths of Cr:LiSAF and Nd:YVO$_4$ lasers depend

clearly on the resonator parameters such as resonator spacing and output coupling (Fig. 4a and Fig. 4b)

- In the regime of single pulse generation, the computed pulse widths of Cr:LiSAF and $Nd:YVO_4$ laser also depend strongly on the value of initial spontaneous emission in the resonator. The larger the coefficient α representing the intra-cavity initial spontaneous emission, the wider the pulse width of Cr:LiSAF and $Nd:YVO_4$ laser (Fig. 3). In our $Nd:YVO_4$ laser experiment, this will be discussed and compared with experimentally obtained results.

III. EXPERIMENT

The resonator of diode-pumped $Nd:YVO_4$ laser was semi-concentric and constituted of an output flat mirror and a high reflection concave mirror at 1064 nm. A three-mirror resonator configuration could be used for the high reflection concave mirror of 10 cm radius. Such three-mirror resonator has the resonator length of nearly 10 cm and the advantages offering a simple, compact and easy optical arrangement without changing the pumping optics and the laser crystal position during the experiments.

A longitudinal and end-pumping configuration was used, as shown in Fig. 1. The pump source is a diode laser (ATC-Semiconductor Devices) emitted at the wavelength of around 808 nm with a maximum CW power of 2 W. The diode laser is supplied by the LDD-10 driver (ATC-SD) designed for the diode laser operation in continuous wave and pulse modes with stabilized and controlled current. In the mode pulse, the adjustable range of diode laser duration is from 0.1 ms to 0.998 s, the adjustable range of diode laser pulse repetition rate is from 1 Hz to 10 kHz. This driver stabilizes and controls the laser diode temperature [27]. In the case of a-cut $Nd:YVO_4$, its active cooling and temperature stabilization at 22°C is provided by a built-in Peltier cooling device (LDD-10) in order to maintain its output laser wavelength exactly matched the absorption peak of *a*-cut $Nd:YVO_4$ crystal. The polarization of the diode laser emission is horizontal. The diode has a built-in cylindrical micro-lens for its fast axis collimation. This allows us to use simple pump optics to be a single lens of 35 mm focal length to collect and focus the laser diode light into the end of the laser crystal. The *a*-cut, 1% doped $Nd:YVO_4$ crystal ($3 \times 3 \times 3$ mm) that was AR coated on both sides at 808 nm and 1064 nm, is mounted on a passive copper heat sink and oriented for the maximum absorption at 808 nm. All optical components and crystals were supplied from CASIX [9].

Laser wavelength and spectra were measured with a grating spectrometer (DFS-8, 3 A^o/mm, Russia) equipped with a linear diode array (BP-2048, USA). A fast photodiode (rise time < 0.3 ns) connected with a digital oscilloscope (TD 7154B – 1.5 GHz, Tektronix, USA) was used to record the duration of laser pulses. The laser energy was measured by the Joule meter (13 PME 001, Melles Griot, USA).

IV. RESULTS AND DISCUSSION

We used the diode pumping pulses of 100 µs duration at 808 nm, this duration is shortest one available with the diode laser (ATC-2000-808-2) supplied by LDD-10 driver (ATC-SD). Furthermore, it is quite comparable with the fluorescence lifetime of Nd^{3+} ions in YVO_4 and, therefore, efficient pumping is obtainable. The highest repetition rate of diode pumping pulse is nearly 10 kHz [27].

In single $Nd:YVO_4$ laser pulse operations, the pulse widths of the $Nd:YVO_4$ lasers emitted from the 5 cm, 10 cm and 1 cm resonators with different output couplers were measured and presented in Fig. 4. The pulse widths of $Nd:YVO_4$ lasers depend strongly on the resonator parameters (resonator spacing and output coupling). The smaller the photon-cavity time, the shorter the pulse widths of $Nd:YVO_4$ laser. In our experiments, the shortest resonator length used is about 1 cm corresponding to obtained pulse width of 93 ns (FWHM) which is still larger than the computated one (71 ns).

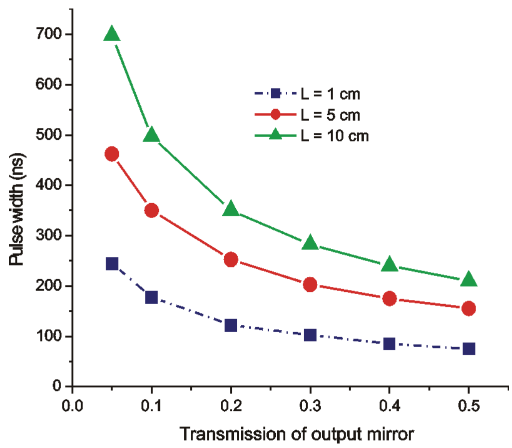


Fig. 4a. Computed pulse widths of the Cr: LiSAF laser emitted from the resonators of different output couplers (6%, 20%, 50% and 70%) at different lengths

In principle, the highest repetition rate of diode pumping pulse is 10 kHz, therefore, nanosecond $Nd:YVO_4$ laser pulses are expected to be produced at the same repetition rate of diode pumping pulse. However, the experimental re-

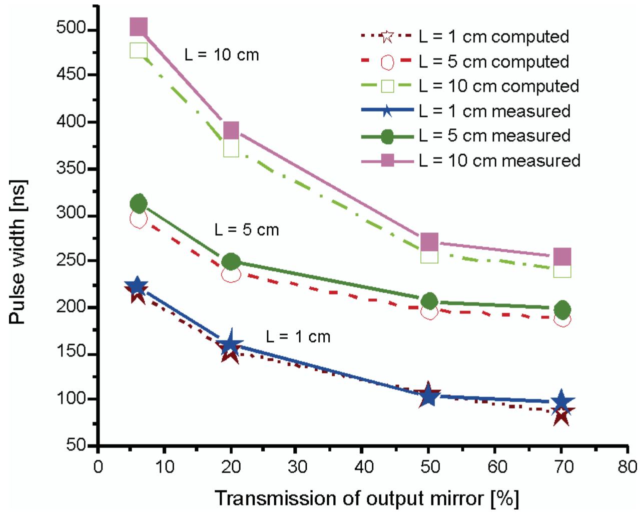


Fig. 4b. Computed and measured pulse widths of the Nd:YVO$_4$ lasers emitted from the resonators of different output couplers (6%, 20%, 50% and 70%) and different lengths

results show that the pulse width of Nd:YVO$_4$ laser increased dramatically when the repetition rate of diode pumping pulse is higher than 3 kHz (the temporal interval between two successive pumping pulses smaller than 330 μs) (Fig. 4). In order to explain this phenomenon, we use the computed results presented in Fig. 3 and remember that the fluorescence lifetime of Nd:YVO$_4$ (1%) is 90 μs that means the maximum fluorescence intensity of the laser crystal decreased 1/e in the resonator and, therefore, it takes more 300 μs (3 times larger than the fluorescence decay time of Nd^{3+}) for the intra-cavity fluorescence intensity decreased to zero. In the case, the repetition rate of diode pumping pulse is lower than 3 kHz (the temporal interval between two successive pumping pulses larger than 330 μs), the Nd:YVO$_4$ laser emission is built up with its proper spontaneous emission and, therefore, the pulse width of Nd:YVO$_4$ laser is nearly constant and independent on the repetition rate of diode pumping pulse. In the case, however, the repetition rate of diode pumping pulse is larger than 3 kHz the laser emission is built up with both its proper initial spontaneous and the remained spontaneous emission of the precedent diode pumping pulse and, therefore, the pulse width of Nd:YVO$_4$ laser emission is larger and dependent on the repetition rate of diode pumping pulse. The larger the remained spontaneous emission (corresponding to higher repetition rate of diode pumping pulse than 3 kHz), the larger the Nd:YVO$_4$ laser pulse width. This phenomenon is well predicted by the computed results (Fig. 3). Such a phenomenon is rarely observed in a laser material of short fluorescence lifetime, for example, organic laser dyes (3-10 ns).

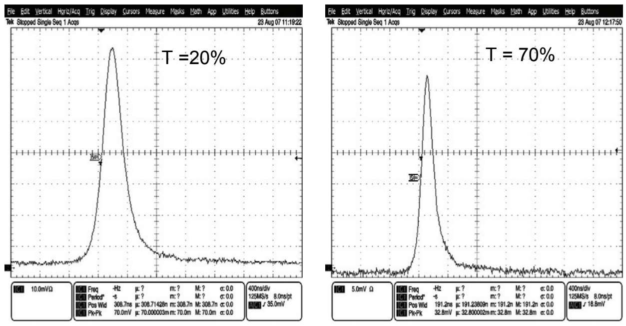


Fig. 5. The Nd:YVO$_4$ laser pulses of 191 ns and 93 ns duration emitted from the 5 cm resonator with the output couplers of 70% and 20%, respectively

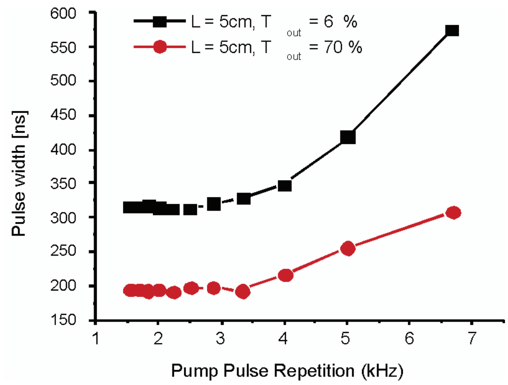


Fig. 6. Dependence of the Nd:YVO$_4$ laser pulse width on repetition rate of the diode pumping pulse

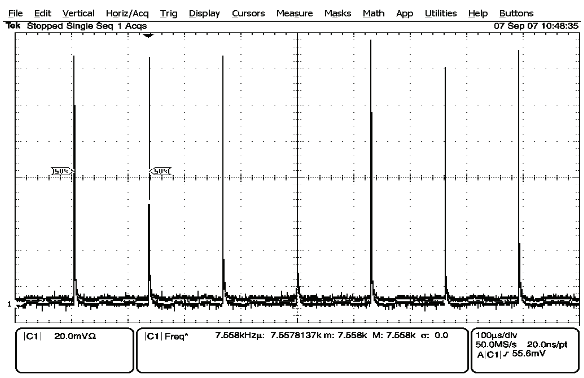


Fig. 7. Single Nd:YVO$_4$ laser pulses at 1064 nm and 7.5 kHz recorded with Tektronix digital oscilloscope (1.5 GHz)

V. CONCLUSION

We presented the results obtained in researching the phenomenon of relaxation oscillations in the all solid-state Cr:LiSAF and Nd:YVO$_4$ laser resonators pumped by diode laser pulses. The obtained results allow us to understand clearly the resonator transients and show a simple way to produce single laser pulses much shorter than the diode laser pumping pulse by proper choices of resonator and pumping parameters. In our experiment, a stable generation of single laser pulses as short as 93 ns – much shorter than the diode pumping pulse (100 µs) – at 1064 nm and a pulse repetition rate of 3 kHz has been obtained. The similar features in the resonator transients of the Cr:LiSAF laser characteristics are expected to be experimentally demonstrated.

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