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Spectro-Temporal Evolution and Transient Resonator in Solid-State Cr $^{3+}$: LiSAF Laser Emissions

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Abstract: The Cr^{3+}: LiSAF crystal is widely used as a laser medium of a wide gain spectrum from 700 nm to 920 nm. Our numerical investigations demonstrate a spectro-temporal evolution in the broadband Cr^{3+}: LiSAF laser emission from Fabry-Perot resonator and particularly, from a low – Q resonator. Furthermore, the resonator transient and the phenomenon of relaxation oscillations in the solid-state Cr^{3+}: LiSAF laser have been studied. Interestingly, using a diode-pump pulse of 100 µs at 670 nm, a stable generation of single nanosecond Cr^{3+}: LiSAF laser pulse at 850 nm is obtainable by simple choices of resonator parameters such as photon-cavity time and pump level. A pulse compression factor of 1 000 is achievable. As a result, a simple technique of short laser pulse generation at a high repetition rate of diode pumping pulses has been proposed.

Key words: Cr: LiSAF crystals, the resonator transient, spectro-temporal evolution

I. INTRODUCTION

The phenomenon of relaxation oscillations was observed and studied very early in solid-state, gas and dye lasers under pulsed excitation [1-5]. 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 spacing 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 [1, 2]. Such regular damped relaxation oscillations are expected from theoretical analyses using the coupled rate equations [1-5]. However, the Cr^{3+}: LiSAF crystal used as a laser medium has a very wide gain spectrum from 700 nm to 920 nm. In the past years, the dynamic of lasers was investigated by using rate equations for a frequency only and using them still for laser medium has a very wide gain spectrum, therefore its characteristics are limited. In the dynamic investigation of solid-state Cr^{3+}: LiSAF laser, using the system of rate equations extended to all wavelengths of interest will alllow to describe the spectral and temporal characteristics of broadband solid-state laser emissions.

In this paper, we investigate the resonator transients of the solid-state Cr: LiSAF laser 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 laser basing on the resonator transient. As a result, the generation of single Cr: LiSAF

(60 ns, 850 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. Moreover, this investigative result by using the system of rate equations extended to all wavelengths be demonstrated to exist a spectro-temporal evolution in the broadband Cr^{3+}: LiSAF laser emission from Fabry-Perot resonator and particularly, from a low – Q resonator.

II. THEORY

Rate equation analysis:

We investigate theoretically the dynamics of diode end-pumped solid-state laser, as shown in Fig. 1. The laser crystal is Cr: LiSAF (850 nm) and the pump is diode laser pulses (670 nm).

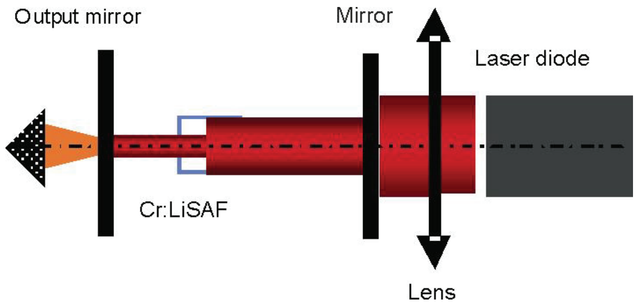

Fig. 1. Schema of the diode-pumped solid-state laser

In order to investigate the spectral and temporal characteristics of the broadband Cr^{3+}: LiSAF laser emissions, we have used a system i + 1 of rate equations extended to multi-wavelengths for i wavelength as follows:

$$\frac{dn_i}{dt} = \frac{2\sigma_{gi} N_g}{\tau_r A_g} n_i - \frac{n_i}{\tau_c}, \quad (1)$$

$$\frac{dN_g}{dt} = R_P - \frac{2\gamma}{\tau_r A_g}\left(\sum_{i=1}^{k} \sigma_{gi} n_i\right) N_g - \frac{N_g}{\tau_g}, \quad (2)$$

where n_i is the photon number in the laser cavity at wavelength λ_i; σ_{gi} is the laser emission cross section at wavelength λ_i; γ is the population reduction factor, γ is 1 for a four-level laser and 2 for a three-level laser; N_g is the population inversion of the laser; τ_g is the lifetime; R_p is the pumping rate; $\tau_c = (\eta l + L - l)/(c(1 - R_{12}))$ is the cavity lifetime; η is refractive index of laser medium; L is the length of laser cavity; l is the length of laser medium; $R_{12} = \sqrt{R_1 R_2}$ is mirror reflectivities; $\tau_r = 2(\eta l + L - l)/c$ is the cavity round-trip time; c is the velocity of light in vacuum; A_g is the effective laser beam area on the laser medium.

In equilibrium $(dn_i/dt) = 0$, $(dN_g/dt) = 0$ and we have:

$$n_i = 0;\ N_g = N_{gth} = \gamma_c/K_g.$$

The threshold pumping rate R_{Pth} is defined as $R_{Pth} = \gamma_g N_{gth} = \gamma_g \gamma_c / K_g$. The pumping rate: $R_P = R_{Pth}.r$ (r is pumping on threshold ratio).

We numerically solve rate Equations (1) and (2) to investigate the resonator transients of the solid-state Cr: LiSAF laser pumped by diode laser pulses. The parameters used in this simulation are as follows: L = 5 cm; l = 0.3 cm; η = 1.41; τ_g = 67 μs; R_1 = 0.3; R_2 = 1; τ_P = 100 μs; effective laser beam diameter on the laser gain medium d_g = 1 mm; $c = 3 \times 10^8$ m/s; $r = R_P/R_{Pth}$; σ_{gi} is quoted in [7-9]. We used 12 coupled equations, one equation for the excited state population and 11 equations for the monochromatic intensities chosen at a constant 20 nm spectral interval.

III. RESULTS AND DISCUSSION

1. Influence of pumping and cavity parameters on relaxation oscillations of Cr: LiSAF laser

In laser medium that has a very wide gain spectrum the frequency of laser is near the peak spectral of laser medium. Therefore, the investigation of relaxation oscillations of the solid-state Cr: LiSAF laser pumped by diode laser pulses may be analysed by using the system rate equations for the frequency on 850 nm wavelength that near the peak spectral of solid-state Cr: LiSAF laser medium.

- *Influence of pumping level*

Figure 2 shows intensity of Cr: LiSAF laser as functions of time at 850 nm. The results indicate that the number of oscillation is reduced when the pumping power is decreased. At near threshold pumping levels, the Cr: LiSAF laser emissions contain a few pulses of relaxation oscillations, eventually only a single pulse remains. At pumping levels a much higher laser threshold (Fig. 2a), the Cr: LiSAF laser pulses could repeat the diode pumping shape. In the buildup, the initial pulses of considerably high intensity were always observed. Because in solid state lasers the fluorescent lifetime τ_g is usually much larger than the cavity transit time t_c, hence strong relaxation behaviors are often seen.

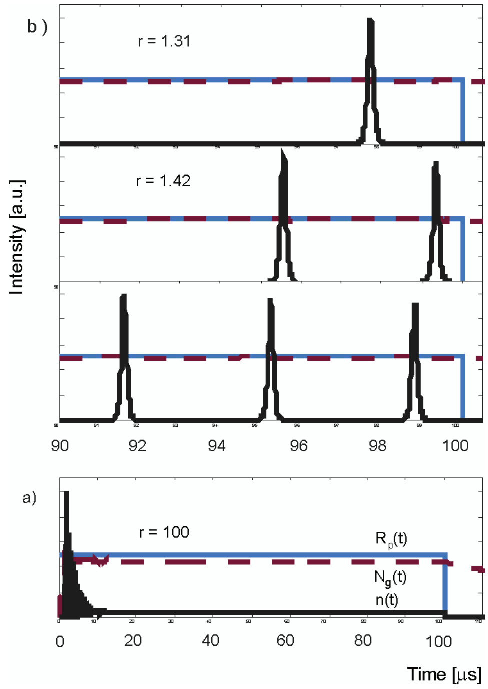

Fig. 2. The dynamics in the diode-pumped Cr: LiSAF laser emission from the 5 cm resonator at different pumping levels

- *Influence of cavity mirror reflectivity*

Figure 3 show pulse-width of Cr: LiSAF laser as functions of output coupling at 850 nm. The results indicate that the computed pulse widths of Cr: LiSAF laser depend clearly on the output coupling. When the output coupling is decreased from 0.95 to 0.4, pulse widths of Cr: LiSAF laser is shorter.

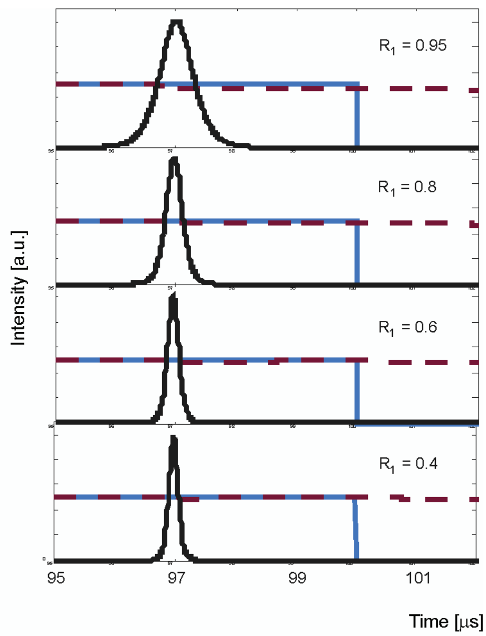

Fig. 3. Pulse widths of the Cr: LiSAF lasers emitted from the 5 cm resonators with different output mirrors at $r = 1.32$

- *Influence of cavity length*

Figure 4 show pulse widths of the Cr: LiSAF lasers emitted from the 1 cm; 5 cm and 10 cm resonators with different output mirrors. The obtained results show that large resonator length pulse-width of Cr: LiSAF laser is long. By using this method we can obtain single solid state laser pulses 60 ns with 1 cm resonator.

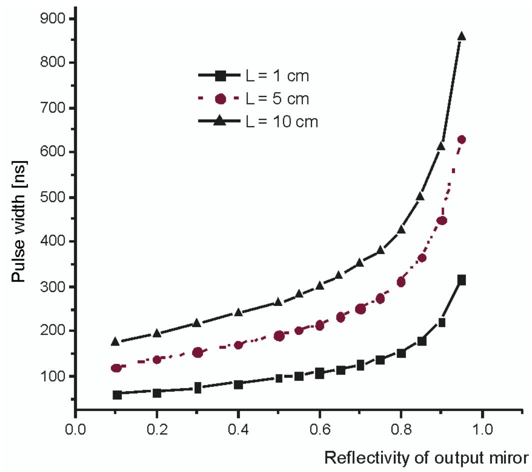

Fig. 4. Pulse widths of the Cr: LiSAF lasers emitted from the 1 cm; 5 cm and 10 cm. Resonators with different output mirrors

2. The spectro-temporal evolution in the broadband Cr^{3+}: LiSAF laser emissions

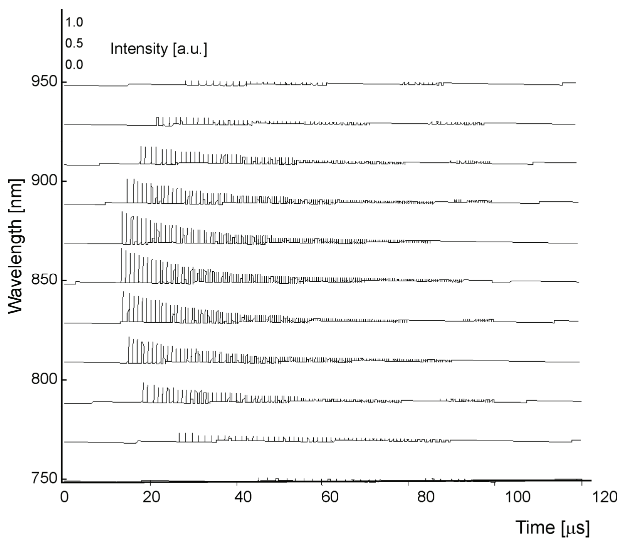

Fig. 5. The spectro-temporal evolution in the broadband Cr^{3+}: LiSAF laser emissions from the cavity $L = 5$ cm; $r = 5$; with $R_1 = 0.3$

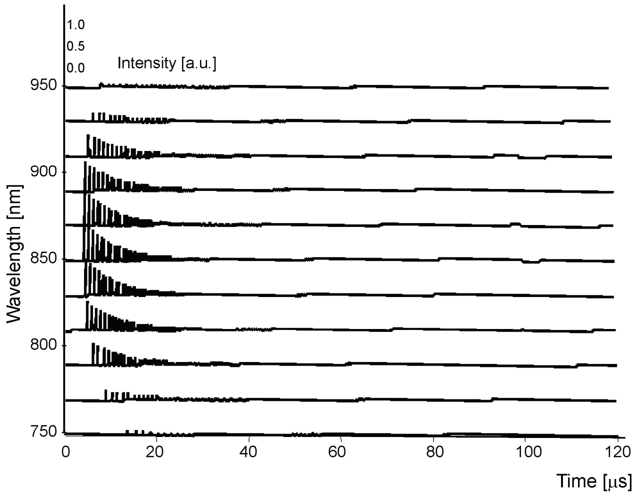

Fig. 6. The spectro-temporal evolution in the broadband Cr^{3+}: LiSAF laser emissions from the cavity L = 5 cm; r = 5; with R_1 = 0.7

Figure 5 and 6 show intensity of Cr: LiSAF laser as functions of time and wavelength are expressed with regular damped relaxation oscillations and spectro-temporal evolution. The regular damped relaxation oscillations at different wavelength is difference. At center wavelength (high gain), the appearance of relaxation oscillations is earliest and highest intensity. For a low – Q resonator relaxation oscillations is expressed clearer than high – Q resonator (Figs. 5 and 6). Therefore, we can clearly see spectro-temporal evolution of Cr: LiSAF laser by numerically solve rate equations extended to multi-wavelengths.

IV. CONCLUSION

We used the system of rate equations extended to all wavelengths to exactly describe the spectro-temporal process in the broadband Cr^{3+}: LiSAF laser emission from Fabry-Perot resonators. The obtained results show, for the first time, the spectro-temporal processes and allow us to understand clearly the spectral dynamics in the broadband Cr^{3+}: LiSAF laser emission. As a result, it is demonstrated to generate of single and short pulse laser using the resonator transient process.

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