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Characteristics of Diode End-Pumped Passively Q-Switched Solid-State Cr $^{3+}$:LiSAF Laser

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Abstract: We numerically investigated the characteristics of diode-end-pumped passively Q-switched solid-state Cr^{3+}:LiSAF lasers. A Cr^{4+}:YSO crystal is used as an intra-cavity saturable absorber. Our obtained results indicate the influences of resonator and pumping parameters on the characteristics of passively Q-switched solid-state Cr^{3+}:LiSAF laser. Particularly, our numerical investigations are done in respect to the Cr^{3+}:LiSAF laser medium of a very wide gain spectrum from 700 nm to 920 nm. Using a CW diode pumping at 670 nm and a Cr^{3+}:LiSAF crystal of 3 mm long and 1 at.%, a stable generation of Q-switching nanosecond Cr^{3+}:LiSAF laser pulse at 850 nm is obtainable with a pulse energy of about 2 mili-joule.

Key word: Cr:LiSAF, Cr:YSO, passively Q-switch laser

I. INTRODUCTION

The Cr:LiSAF solid-state laser, discovered by Payne *et al.* firstly in 1989, is widely tunable from 780 nm to 920 nm and has attracted attention in the past few years [1-3]. The Cr:LiSAF has a long fluorescence lifetime (67 μs) when compared to the Ti:sapphire laser (3.2 μs), which is beneficial for Q-switched operation with the peak wavelength of the free-running laser spectrum is near 850 nm [4, 5].

Many durable solid-state saturable absorbers have been reported to work effectively for the solid-state laser at various wavelengths [6-9]. Among the passively Q-switched solid-state lasers, tunable Q-switched solid-state lasers are of particular interest since the laser wavelength can be tuned to fit specific needs. The $Cr:Y_2SiO_5$ (Cr:YSO) has been shown to be an effective saturable absorber Q switch for the ruby laser, the alexandrite laser, and the $Cr:LiCaAlF_6$ (Cr:LiCAF) laser [11, 12]. Cr:YSO is demonstrated by experimentally that the Cr:YSO saturable absorber could be used to Q-switch the $Cr:LiSrAlF_6$ (Cr:LiSAF) laser effectively when the laser wavelength is at 880 nm. However, a detailed analysis on the laser performance of the Cr:YSO Q-switched Cr:LiSAF system was not provided. Therefore, we are numerically investigated the characteristics of diode-end-pumped passively Q-switched solid-state Cr^{3+}:LiSAF lasers.

II. CHARACTERISTICS OF Cr:LiSAF AND Cr:YSO

The Cr:LiSAF exhibits a broad emission spectrum, long lifetime of the upper laser level, low nonlinear refractive index, and low excited-state absorption that make it a unique source for tunable or short pulse lasers. The LiSAF host crystal is uniaxial and the Cr^{3+} emission is strongly π-polarized (*E*//*c*). The peak of the $^4T_2 \rightarrow {}^4A_2$ emission spectrum occurs at 830 nm and has a cross-section of 4.8×10^{-20} cm^2. Owing to the internal absorption caused by $^4A_2 \rightarrow ^4T_2$ transitions, the laser emission spectrum is red-shifted to be peaked near 850 nm. The some of the important material properties of Cr:LiSAF and Cr^{4+}:YSO parameters are listed in Table 1 and Table 2.

Table 1. Material properties of Cr:LiSAF [5]

Chemical formula	Cr^{3+}: $LiSrAlF_6$
Crystal system	rhombohedral, uniaxial
Main absorption peaks	440 nm and 650 nm (peaked at ~830 nm)
Emission spectrum	700 nm to 1100 nm
Peak laser wavelength	~ 850 nm
Peak emission cross-section	~ 4.8 × 10^{-20}cm^2
Fluorescence lifetime at 25°C	~ 67 µs
Refractive index	1.41

Table 2. Material properties of Cr:YSO [14]

Chemical formula	Cr^{4+}:Y_2SiO_5
Crystal system	monoclinic, biaxial
Lattice constants	a = 10.41 Å, b = 6.72 Å, c = 12.49 Å, β = 102°39’
Cr atoms/mole %	~ 9.7 × 10^{19}/cm^3
Refractive index	1.8
Main absorption peaks	390 nm, 595 nm, 695 nm, and 750 nm
Emission spectrum	1000 nm to 1500 nm (peaked at ~1250 nm)
Fluorescence lifetime at 25°C	~0.7 µs
Density	4.6 g/cm^3

III. THEORY

Rate equation analysis:

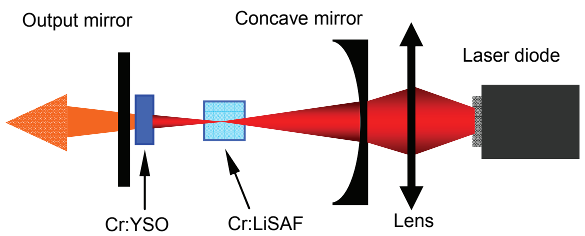

Fig. 1. Schematic diagram for a solid-state Cr:LiSAF laser end-pumped by diode laser with a Cr:YSO Q switch

We investigated theoretically the dynamics of diode end-pumped solid state Cr:LiSAF laser, as shown in Fig. 1. The laser crystal Cr:LiSAF (850 nm), it is optically pumped by diode laser pulses at 670 nm and is Cr:YSO Q-switched. The laser resonator consists of a concave mirror with high reflection coating at 850 nm and anti-reflection coating at 670 nm on both sides and an output-coupling mirror. The saturable absorber Q-switch can be placed either between the laser crystal and concave mirror or between the laser crystal and the output coupler.

In order to study the laser dynamics of the Cr:YSO Q-switched solid-state Cr:LiSAF laser, we have used the well-known rate equation system as follows [15, 16]:

$$\frac{dn}{dt} = K_g N_g n - K_a N_a n - \beta K_a (N_{a0} - N_a) n - \gamma_c n, \quad (1)$$

$$\frac{dN_g}{dt} = R_P - \gamma_g N_g - \gamma K_g N_g n, \quad (2)$$

$$\frac{dN_a}{dt} = \gamma_a (N_{a0} - N_a) - K_a N_a n, \quad (3)$$

where population reduction factor γ is 1 for a four-level laser and 2 for a three-level laser. Other parameters used in these coupled rate equations are defined as follows: n is the photon number in the laser cavity; N_g is the population inversion of the laser; N_a is the ground-state population of the saturable absorber; N_{a0} is the initial value of N_a; $\gamma_g = 1/\tau_g$ is the effective decay rate of the upper laser level, where τ_g is the laser's emission lifetime; $\gamma_a = 1/\tau_a$ is the saturable absorber's spontaneous relaxation rate, where τ_a is the saturable absorber's emission lifetime; R_p is the pumping rate; the cavity decay rate, where τ_c is the cavity lifetime; $K_g = 2\sigma_g/\tau_r A_g$ is a coupling coefficient, where σ_g is the laser emission cross section, τ_r is the cavity round-trip transit time, and A_g is the effective laser beam area on the laser gain medium; $K_a = 2\sigma_a/\tau_r A_a$, where σ_a is the saturable absorber's ground-state absorption cross section at the laser wavelength and A_a is the effective laser beam area on the saturable absorber; and $\beta = \sigma_{ESA}/\sigma_a$ is the ratio of the excited-state absorption cross section to the ground-state absorption cross section of the saturable absorber.

Loss parameter, *Loss*, is defined from Eq. (1) as [16]

$$Loss = \frac{K_a N_a + \beta K_a (N_{a0} - N_a) + \gamma_c}{K_g} \quad (4)$$

According to the threshold condition for passive Q-switching with the slowly relaxing saturable absorbers, if $A_g \cong A_a$ the absorption cross section of the saturable absorber at the laser wavelength, σ_a, must be greater than the emission cross section of the laser gain medium, σ_g, for the laser to be Q-switched effectively.

We numerically solve rate equations to investigate the passive Q-switching performance of the tunable Cr:YSO Q-switched Cr:LiSAF laser system. The parameters used in this simulation are as follows: length of laser cavity, $L = 5$ cm; thick of Cr:YSO, $l = 0.1$ cm; reflectivity of output coupler, 0.9; effective laser beam diameter, 0.75 mm; $\sigma_g = 4.8 \times 10^{-20}$ cm^2; $\sigma_a = 1.67 \times 10^{-19}$; $\gamma = 1$; $\gamma_c = 1.29 \times 10^8$ s^{-1}; $\gamma_g = 1.49 \times 10^4$ s^{-1}; $\gamma_a = 1.43 \times 10^6$ s^{-1}; $K_g = 4.03 \times 10^{-9}$ s^{-1}; $K_a = 1.52 \times 10^{-8}$ s^{-1}; $\beta = 0.33$; $R_p = 5.5 \times 10^{21}$s^{-1} and $N_{a0} = 2.3 \times 10^{16}$. The output energy and the pulse width obtained of the Q-switched laser pulse are 1.7 mJ and 11.5 ns at 45 kHz.

IV. RESULTS AND DISCUSSION

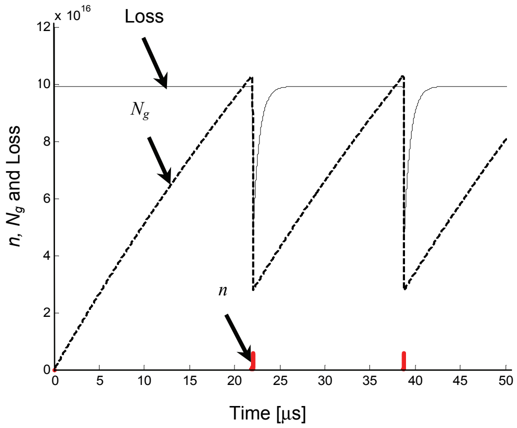

Fig. 2. N_g, *Loss*, and n as functions of time when the laser wavelength is at 850 nm

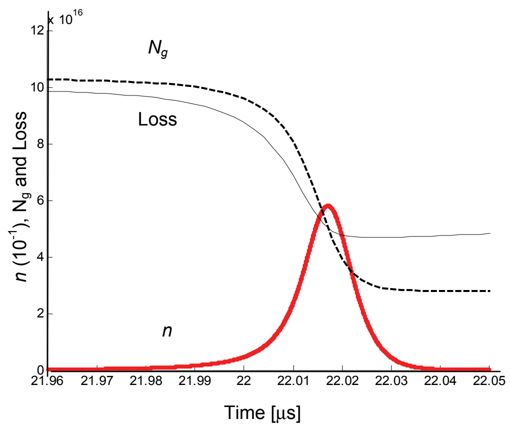

Fig. 3. Expanded picture of Fig. 3 near the occurrence of laser pulse

Figure 2 shows N_g, *Loss*, and n as functions of time at 850 nm. The results indicate that, when the photon number is low, N_a is close to N_{a0} and the loss of the laser system has an initial value of ~9.82×10^{16}. The laser action to occur when the laser is pumped and the gain will be greater than the loss; *i.e.*, $N_g > Loss$. When this condition is satisfied, the photon number will start to build up from the noise by depleting the laser population inversion, and the Cr:YSO saturable absorber will start to saturate.

Figure 3 is an expanded picture of Fig. 2 near the occurrence of laser pulse. When the photon number inside the laser cavity increases, the loss decreases accordingly as a result of the bleaching effect of the Cr:YSO saturable absorber. The photon number reaches its peak when the laser population inversion equals the cavity loss, *i.e.*, when $N_g = Loss \cong 4.52 \times 10^{16}$. Beyond this point, the laser gain is smaller than the total loss of the laser system, and the Q-switched laser pulse dies out quickly while the laser population inversion decreases gradually to minimum value of ~2.34×10^{16}. The increase of the loss after the release of the Q-switched laser pulse is due to the relaxation of the saturable-absorber population.

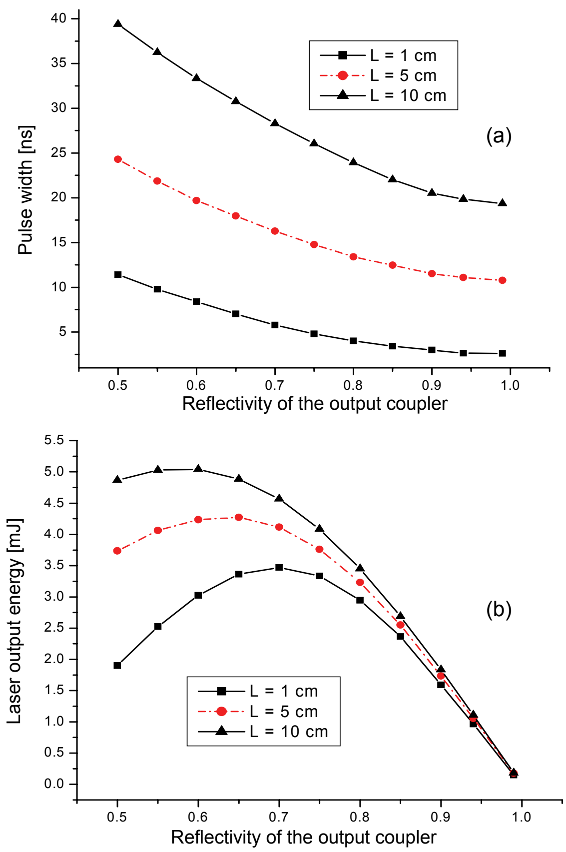

Fig. 4. Pulse width (a) and laser output energy (b) as a function of R_1 different cavity length

Figure 4 shows the laser output energy and the pulse width as functions of reflectivity of output coupler at different cavity length. It is indicated in Fig. 4 that the laser output energy is small when the reflectivity of the output coupler is high, especially when its increase from 0.55 to 0.75 the Q-switching is effective.

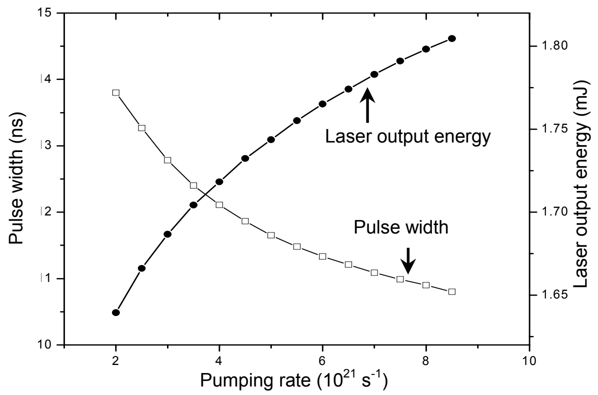

Fig. 5. Laser output energy and pulse width as functions of the pumping rate R_p

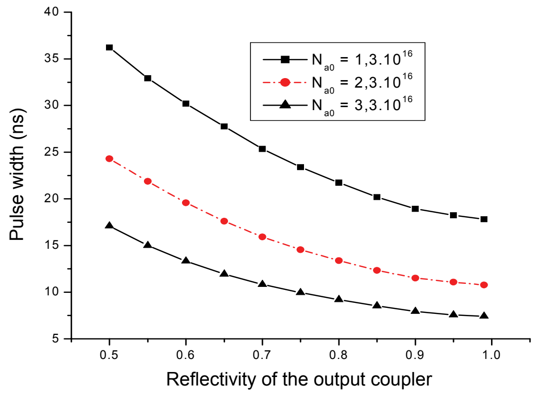

Fig. 6. Pulse width as a function of R_1 for three values of N_{a0}

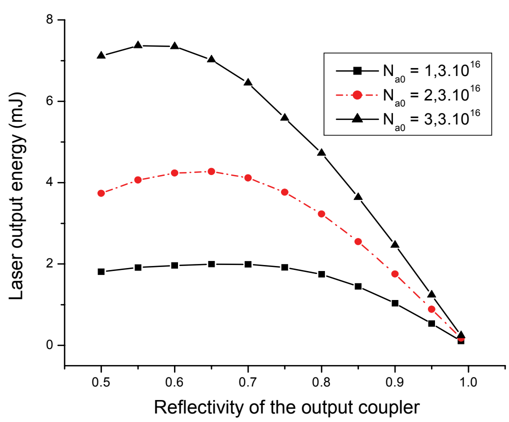

Fig. 7. Laser output energy as a function of R_1 for three values of N_{a0}

Figure 5 shows the laser output energy and the pulse width as functions of the pumping rate. It is obvious that better passive Q-switching performance can be obtained with a higher pumping rate.

Figure 6 and 7 show the pulse width and the laser output energy as functions of R_1 for several values of N_{a0}. It is indicated in Fig. 6 that the laser output energy is small when the reflectivity of the output coupler is high.

V. CONLUSION

The dynamics of a Cr:YSO passively Q-switched Cr^{3+}:LiSAF laser pumped by laser diode was investigated. The influence of pumping and resonator parameters on the laser characteristics are presented. Using diode-end-pumping and a 3 × 3 × 3 mm laser crystal, the Q-switched Cr^{3+}:LiSAF laser pulse of 11 ns, at 850 nm with pulse energy of 1.7 mJ is obtainable at 45 kHz.

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