Passively Q-switched microlaser performance in the presence of pump-induced bleaching of the saturable absorber

Martin A. Jaspan, David Welford, and Jeffrey A. Russell

Unabsorbed pump light in passively Q-switched microlasers leads to suboptimal pulse generation by bleaching the saturable absorber. This mechanism increases the effective unsaturated transmission of the absorber, which leads to a change in the system dynamics that results in increased pulse durations and decreased pulse energies. We report experimental evidence of pump-induced bleaching of the saturable absorber, an increase in the pulse duration from 360 to 880 ps, and develop a simple analytical treatment that includes this effect within the framework of existing passive Q-switching models.

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1. Introduction

Passively Q-switched (PQSW), diode-pumped solid-state lasers, in particular microlasers, provide a relatively straightforward means for the generation of subnanosecond laser pulses with high peak power.[1] The most commonly used material system for these devices is Nd:YAG with Cr:YAG as the saturable absorber. Theoretical treatment of passive Q switching[2] in a microlaser would lead one to believe that the design and implementation of a 200-ps, or shorter pulse duration, PQSW Nd:YAG–Cr:YAG microlaser can be readily achieved. However, this is not the case because of the effect of partial bleaching of the saturable absorber by unabsorbed pump radiation. Experimental observation of this effect, first reported by Welford,[3] and the means to analytically account for it are the subject of this paper.

Most, if not all, solid-state saturable absorbers have broad absorption features that often extend to the optical pumping wavelength of the associated solid-state laser. This is particularly problematic in end-pumped, diode-laser-pumped PQSW lasers in which a significant fraction of the pump radiation may reach the saturable absorber, be absorbed, and partially bleach the absorber. This problem is further compounded by the fact that diode-laser pump sources have approximately 3-nm spectral bandwidth and often poor spectral overlap with the gain-medium absorption features, thereby increasing the amount of residual pump radiation incident on the saturable absorber. In the case of a typical Nd:YAG–Cr:YAG PQSW microlaser, as much as 50% of the pump radiation may be unabsorbed in the gain medium and incident on the absorber. The beam sizes in a typical microlaser are of the order of 100-μm diameter, which leads to pump intensities that can be as high as the saturation intensity of the absorber, thereby leading to partial or even full bleaching.

Pump-induced bleaching of the saturable absorber is significant because it increases the transmission value of the absorber at the onset of Q switching, which leads to a change in the system dynamics with increased pulse durations and decreased pulse energies.[3] We present experimental data for the variation of pulse duration and energy of a PQSW microlaser as a function of unabsorbed pump radiation incident on the saturable absorber and develop an analytical treatment that includes this effect within the framework of existing passive Q-switching models. Zayhowski and Wilson[4] recently reported

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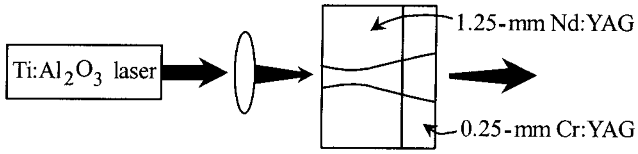

Fig. 1. Illustration of the optical pumping arrangement for a Cr:YAG passively Q-switched Nd:YAG microlaser pumped with a cw Ti:Al_2O_3 laser.

similar experimental data confirming our observations and analysis.

In contrast, others have used external sources to intentionally bleach the saturable absorber at a predetermined time as a means to control the Q-switching process with the aim of controlling the pulse rate and reducing pulse-to-pulse timing jitter.[5] External bleaching of the saturable absorber for the purpose of laser-pulse timing may also lead to the type of pulse broadening and energy reductions described in this paper.

2. Experimental Results

We investigated the operating characteristics of the cw, Ti:Al_2O_3-laser-pumped Nd:YAG–Cr:YAG microlaser shown schematically in Fig. 1. The total cavity length was 1.5 mm, of which 1.25 mm was 1.3% Nd-doped YAG. The Cr:YAG unsaturated absorption coefficient was 7.5 cm^{-1}, and the output coupler reflectivity was 85%.

We used a cw Ti:Al_2O_3 laser as a tunable narrow-bandwidth pump source to provide us with the means to vary the ratio of pump light absorbed by Nd:YAG versus Cr:YAG. The Ti:Al_2O_3 laser bandwidth was much narrower than the individual absorption features in the Nd:YAG. Hence, by pumping at different wavelengths (794.5, 795.7, 799.2, and 809.0 nm) in the Nd:YAG absorption spectrum, we were able obtain varying degrees of pump absorption. The unabsorbed pump light varies inversely in relation to the Nd absorption as does the pump light absorbed by the Cr:YAG, which possesses a broad featureless absorption spectrum around the 800-nm pump region.[6] We used a Burleigh Wavemeter Jr. to measure the pump-laser wavelengths and obtained the corresponding Nd:YAG absorption values from spectrophotometer measurements of a separate sample of the material.

The Ti:Al_2O_3 laser was tunable from 760 to 880 nm with 700 mW of output power in the 800-nm region and operated on several longitudinal modes with a spectral bandwidth of approximately 2 GHz. A lens focused the 1-mm-diameter, TEM_{00}-mode pump beam into the microlaser, and, by varying either the focal length of the lens or the distance to the microlaser, we were able to vary the pumped volume. The data reported here were taken with a pump beam waist diameter of approximately 25 μm positioned at the Nd:YAG input face of the microlaser. We measured the average output power, pulse duration, and pulse repetition rate of the microlaser as a function of pump wavelength.

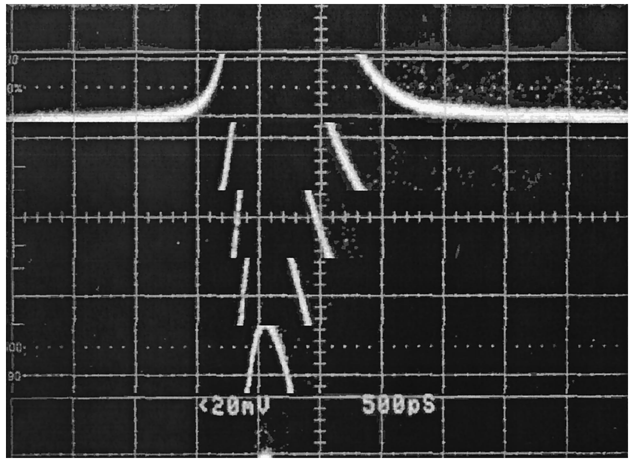

Fig. 2. Microlaser output pulse profile for 700 mW of incident pump power at 809.0 nm. The pulse duration was 640 ps.

Figure 2 shows the temporal pulse profile of a 640-ps pulse obtained for a pump wavelength of 809.0 nm. The laser pulse was detected by use of a fiber-coupled photodetector with a rise time of 18 ps and recorded with a sampling oscilloscope system having a rise time of 25 ps. Hence the recorded laser pulses did not require deconvolution of the system response. The temporal pulse profiles for each of the pump wavelengths were similar to the one shown in Fig. 2.

Figure 3 shows the measured pulse energies and durations as a function of the Nd:YAG-layer transmission. The transmission is a function of the pump wavelength with the lowest transmission, 37%, at 809.0 nm and the highest transmission, 88%, at 794.5 nm. If all the pump radiation were absorbed in the Nd:YAG layer, there would be none left to be absorbed in the Cr:YAG layer, and PQSW laser analysis[2] predicts 360-ps pulse durations, independent of pump power. However, the data clearly show that this is not the case when there is significant Nd:YAG transmission and absorption of pump radiation in the Cr:YAG layer.

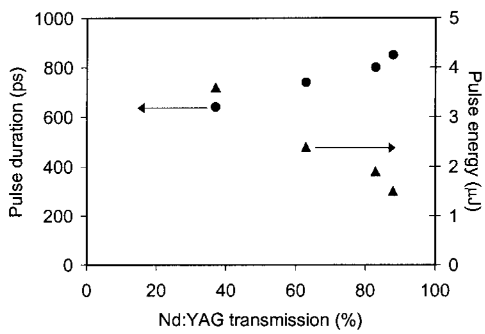

Fig. 3. Microlaser pulse duration and energy data as a function of the Nd:YAG-layer transmission. The pump power incident on the Cr:YAG layer increases with increasing Nd:YAG-layer transmission.

Table 1. Passively *Q*-Switched Microlaser Performance Data

Parameters	Quantities			
λ_{pump} (nm)	794.5	795.7	799.2	809.0
Nd:YAG transmission (%)	88	83	63	37
Pulse energy (J)	1.5	1.9	2.4	3.6
Pulse duration (ps)	850	800	740	640
Pulse rate (kHz)	5.8	9.9	40.7	39.1

The measured pulse durations were observed to be as much as 2.4 times the ideal 360-ps value for operation at 794.5 nm with 88% of the incident pump radiation, 615 mW, incident on the Cr:YAG layer. At the same time the pulse energies were observed to decrease from 3.6 μJ, when pumped at 809.0 nm with 260 mW of pump radiation incident on the Cr:YAG layer, to 1.5 μJ, when pumped at 794.5 nm with 615 mW of pump radiation incident on the Cr:YAG layer. Table 1 provides a summary of the measured laser performance parameters.

The observed trends in pulse duration and energy are exactly those expected from the PQSW laser analysis[2] as the absorber unsaturated transmission is increased; i.e., higher-transmission absorbers require lower photon emission rates to bleach them, which translates into a lower *Q*-switching threshold, lower stored energies, and lower output energies. The lower stored energies result in smaller gains and slower pulse rise times that lead to longer pulses. In our case, all the data are from the same device with no change in the initial small-signal transmission of the saturable absorber, which requires us to introduce a new mechanism into the PQSW laser analysis that predicts the observed data. Without modification, the PQSW laser analysis predicts pulse duration and energy determined by absorber small-signal transmission and independent of changes in pump power. The mechanism responsible for the observed pulse broadening and energy reduction is partial bleaching of the saturable absorber by residual pump radiation.

We chose to vary the residual pump radiation reaching the saturable absorber by tuning the pump laser and operating at a constant 700-mW pump power, rather than vary the incident pump power directly, in an effort to minimize the influence of thermally induced lensing. The total pump absorption in Nd:YAG and Cr:YAG remains almost constant as the pump laser is tuned, which leads to little change in thermal lensing and a constant output beam size, which, in turn, prevents changes in beam size from distorting the influence of the unabsorbed pump light by changing the incident intensity at the saturable absorber. One can observe the same effect, i.e., longer, less energetic pulses for increased unabsorbed pump intensities, by intentionally changing the size of the pump beam, again at constant incident pump power.[4]

3. Theoretical Analysis of Pump-Induced Bleaching of the Saturable Absorber

Several rate-equation-based, PQSW laser models have been reported in the technical literature. We use Degnan's PQSW laser model[2] and incorporate Xiao and Bass's modification of Degnan's research to include excited-state absorption (ESA) losses in the saturable absorber.[7] Furthermore, we also include thermalization corrections for the energy levels in the gain medium.[8] We assume operation in the fast thermalization limit in which the ground-state and upper-state energy levels of the Nd:YAG are assumed to reach thermal equilibrium on a time scale much faster than the formation of the *Q*-switched laser pulses. Before describing a simple way to include pump-induced bleaching of the saturable absorber in the PQSW laser model, we describe the modification of Degnan's rate equations to include the effect of pump radiation on the saturable absorber.

The laser and saturable-absorber rate equations defined by Degnan[2] [Eqs. 1(a)–1(c)] can be rewritten as

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \left\{ 2\sigma n l - 2\sigma_s n_s l_s - 2\sigma_{esa} n_u l_s - \left[\ln\left(\frac{1}{R}\right) + L \right] \right\} \frac{\phi}{t_r}, \tag{1}$$

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -\gamma\sigma c\phi n, \tag{2}$$

$$\frac{\mathrm{d}n_s}{\mathrm{d}t} = -\gamma_s\sigma_s c\phi n_s + \frac{n_0 - n_s}{\tau_s} - \gamma_p\sigma_p\Phi_p n_s, \tag{3}$$

where ϕ is the laser photon density, Φ_p is the pump photon density at the saturable absorber, n is the gain-medium population inversion density, n_0 is the active-ion density in the saturable absorber, n_s is the saturable-absorber ground-state population density, n_u is the saturable-absorber excited-state (upper-level) population density, σ is the laser-stimulated emission cross section, σ_s and σ_p are the absorber ground-state absorption cross sections at the laser and pump wavelengths, respectively, σ_{esa} is the absorber ESA cross section, and τ_s is the absorber upper-state lifetime. The constants γ and γ_s account for the degeneracy and thermalized population distributions of their respective energy-level manifolds[8] and are assumed to be equal to 0.6. The gain and absorber lengths are l and l_s, respectively, and t_r is the round-trip transit time of the resonator. R and L are the resonator passive losses due to output coupling and all losses except the saturable absorber.

The third term in Eq. (1), which describes the loss of laser photons to ESA in the saturable absorber, was treated by Xiao and Bass[7] by a simple modification to Degnan's analysis that we incorporate in our data analysis. The second term in Eq. (3) describes the decay of the excited state of the absorber, and the third term in Eq. (3) describes the absorption of pump radiation by the absorber. The additional terms in Eq. (3) lead to a reduced initial absorber ground-state population, n_{si}, at the onset of Q switching, which affects the *Q*-switched pulse energy and duration by changing the solution to the rate equations for the

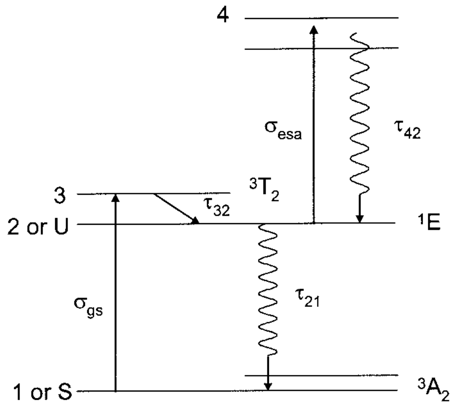

Fig. 4. Cr:YAG energy-level diagram.

initial, n_i, and final, n_f, population densities in the gain medium. The relationship among n_{si}, n_i, and n_f is given by Degnan's Eqs. (8) and (9), which we used in conjunction with Eqs. (7) and (12) to calculate the pulse energies and durations.[2] However, before proceeding, we need to determine how to incorporate the reduced value for n_{si} into the analysis.

In all cases of practical interest the laser pulses are much shorter than the saturable-absorber lifetime, which, in turn, is much shorter than the time between pulses, the pumping period τ_p. The net result is that at the time the Q-switching threshold is reached the saturable absorber is in a quasi-cw steady-state condition with the energy levels above the ground state partially populated in proportion to the incident diode-laser pump radiation that remains unabsorbed by the gain medium.

With reference to the energy-level diagram shown in Fig. 4, both laser photons and pump photons are absorbed in transitions from the ground state, $^3A_2$, and the excited state ^1E. When PQSW microlasers with quasi-cw or cw pumping are operated, the relatively long excited-state lifetime, τ_{21}, 3.2 μs[8] to 4.1 μs,[4] allows the rate equations for the saturable absorber to be integrated to express the initial ground-state population as

$$n_{si} = \frac{n_0}{1 + I/I_{sat}}, \tag{4}$$

where I is the radiation intensity incident on the absorber, I_{sat} or $h\nu/\sigma_s\tau_{21}$ is the saturation intensity, which for Cr:YAG has an average value of 35 kW cm^{-2} in the 800-nm region on the basis of the range of values for the absorption cross section and lifetime quoted in the literature. The following discussion of the saturation behavior of the absorber transmission is generic in nature and will not refer to the pump radiation intensity until specifically required, which means the incident intensity will be described by I.

In general,

$$n_0 = n_s + n_u + n_3 + n_4. \tag{5}$$

The saturable-absorber population densities for the four levels are n_s, n_u, n_3, and n_4, where the subscripts s and u are used instead of 1 and 2 for consistency with the PQSW laser analysis. The relaxation rate for level n_3 is <10 ps and for n_4 falls in the 50-ps[9] to 500-ps[6] range. Hence the population n_3 is negligible. When pulse durations are equal to or less than τ_{42}, the population trapped in n_4 may play a significant role in reducing the effect of ESA. In this paper we have chosen to use the upper bound obtained by setting the population n_4 equal to zero. Hence we assume

$$n_0 = n_s + n_u. \tag{6}$$

The saturable-absorber absorption coefficient, α, at the laser wavelength, 1064 nm, is given by

$$\alpha = n_s\sigma_s + n_u\sigma_{esa}, \tag{7}$$

where σ_s is the ground-state absorption cross section (7×10^{-18} cm^2)[6] and σ_{esa} is the ESA cross section (2×10^{-18} cm^2).[6] Equations (4), (6), and (7) are used to formulate an expression for the steady-state saturable-absorber transmission, $T(I)$, under continuous optical pumping:

$$T(I) = T_0\left(\frac{I_{sat}}{I_{sat} + I}\right)T_\infty\left(\frac{I}{I_{sat} + I}\right). \tag{8}$$

T_0 is the unsaturated transmission given by

$$T_0 = \exp(-n_0\sigma_s l_s), \tag{9}$$

and T_∞ is the saturated transmission given by

$$T_\infty = \exp(-n_0\sigma_{esa} l_s) \tag{10}$$

for an absorber length of l_s. In the absence of ESA, the second term in Eq. (8) becomes unity, and the fully bleached saturable absorber has no transmission loss.

The transmission of the saturable absorber in a passively Q-switched laser increases according to Eq. (8) for unabsorbed pump radiation, I_p, incident on the absorber. Degnan's analysis for a passive Q-switched laser operation[2] may be modified to account for the effect of pump-induced bleaching of the saturable absorber simply by one's replacing T_0 with $T(I_p)$. This modification is compatible with the addition of ESA absorption losses to Degnan's theory as proposed by Xiao and Bass.[7]

In this paper the pump powers incident on the saturable absorber were estimated directly from Nd:YAG transmissions at the different pump wavelengths. Transmission values were obtained from a Nd:YAG sample by use of a spectrophotometer. The diameter of the pump beam was calculated from the Ti:Al_2O_3 laser output beam parameters, the lens focal length, and the location of the components to be 37 μm. Hence the pump intensity, I_p, ranged from 25 to 56 kW cm^{-2} or from $0.7I_{sat}$ to $1.6I_{sat}$. The corresponding range of values for the partially bleached transmission of the saturable absorber was 87.7% to

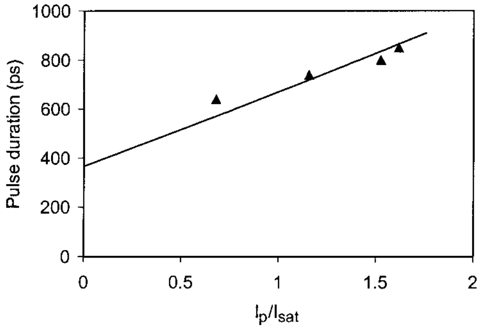

Fig. 5. Microlaser pulse duration as a function of residual pump intensity incident on the Cr:YAG layer, I_p, normalized to the saturation intensity, I_{sat}. Triangles, experimental data shown in Fig. 3; solid curve, analytical estimates of pulse duration.

90.2%. The unsaturated transmission was 83%. Note that one applies Eq. (8) by using the saturation intensity for the pump wavelength, 35 kW cm^{-2}, and the ground-state absorption and ESA cross sections for the Q-switched laser wavelength.

Figure 5 shows excellent agreement between the experimental data and the analytical pulse duration estimates by use of Degnan's analysis[2] including the effect of ESA[7] and pump-induced bleaching as described above. The intercept of the analytical curve indicates pulse durations of 360 ps in the absence of pump-induced bleaching of the saturable absorber, which at first appears to be different from that obtained by a linear fit to the experimental data. However, any discrepancies are the result of the fact that the analytical model includes the average or typical values in the literature for many of the material parameters. Pump-induced bleaching of the saturable absorber must be included to account for the observed variations in pulse duration. Other effects, such as amplified spontaneous emission, do not provide sufficient intensity to significantly bleach the saturable absorber.

Additional, recently published data[4] can be accounted for only by invoking the mechanism of pump-induced bleaching of the saturable absorber and adds further verification to our analytical model. The study in question used fiber-coupled diode-laser end pumping, which results in lower incident intensities at the saturable absorber because of the larger pump beam divergence. However, the effect of pump-induced bleaching of the saturable absorber was still significant.

Other PQSW laser systems have been reported that show atypical behavior with respect to pump power. One important class of systems are those involving gain media such as Nd:YVO_4[10,11] and Nd:$GdVO_4$[12] in which the ratio of saturable-absorber to gain-media cross sections, Degnan's variable α, is close to unity when Cr:YAG is used as the saturable absorber. This is to be compared with the Nd:YAG–Cr:YAG system, where $\alpha = 32$. Systems with α close to unity show decreasing pulse durations, increasing pulse energies, and nonlinearly varying pulse rates as the pump power is increased. This behavior is a consequence of the regime of Q switching in which these systems operate[10–12] and is not to be confused with the effect of pump-induced bleaching of the saturable absorber, which will be present but probably not significant because the Nd:YVO_4 and Nd:$GdVO_4$ gain media absorb almost all the incident pump radiation.

Reducing the amount of diode-laser pump light incident on the saturable absorber will alleviate pump-induced bleaching. In a nonmonolithic structure this can easily be achieved by use of a thin-film dielectric coating, between the gain medium and the absorber, to block the pump light. However, in our monolithic device this was not an option. One can reduce the pump light incident on the saturable absorber by using a narrower-linewidth diode-laser source, by increasing the Nd concentration, or by increasing the Nd:YAG layer thickness. Alternatively, in the case of Cr:YAG, the excited-state lifetime may be reduced by the addition of another dopant, thereby increasing the saturation intensity.[4]

4. Conclusions

The mechanism of pump-induced bleaching of the saturable absorber in PQSW microlasers has been shown to significantly degrade the performance of these lasers by increasing the pulse durations and decreasing the pulse energies, in direct proportion to the pump intensity incident on the saturable absorber. A simple modification to a PQSW laser model was shown to fully account for the observed changes in pulse duration.

The only proven way to eliminate pump-induced bleaching of the saturable absorber is to prevent unabsorbed pump light from reaching the absorber by optical coatings or physical separation of the absorber from the gain medium and the pump light. However, these techniques prevent the use of diffusion-bonded or epitaxially grown monolithic structures and often result in significant increases in resonator length, which may result in pulse durations as long as those that would occur with pump-induced bleaching. In most cases, PQSW microlasers with the desired pulse durations and energies can be designed and implemented after accounting for the effect of pump-induced bleaching of the saturable absorber as described in this paper.

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Passively Q-switched microlaser performance in the presence of pump-induced bleaching of the saturable absorber: erratum

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In the original publication [Jaspan *et al*., Appl. Opt. **43,** 2555–2560 (2004)], Fig. 2 was incorrect. This inaccuracy is corrected here. © 2004 Optical Society of America

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In the top of the right column[1] of page 2556, Fig. 2 was not displayed accurately. The figure as it should have appeared is corrected here.

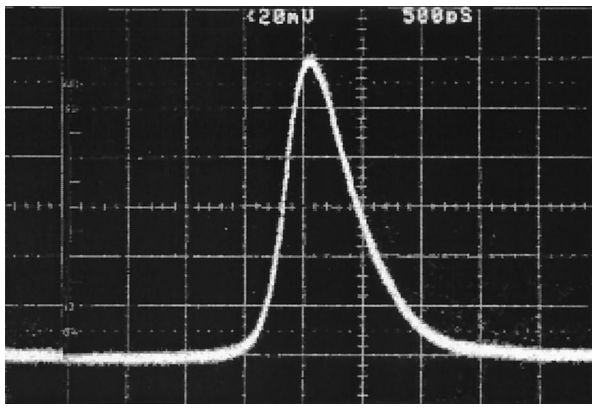

Fig. 2. Microlaser output pulse profile for 700 mW of incident pump power at 809.0 nm. The pulse duration was 640 ps.

Reference

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