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OPTIMAL DESIGN OF PASSIVELY Q-SWITCHED MICROLASER TRANSMITTERS FOR SATELLITE LASER RANGING*

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ABSTRACT

The workhorse for third generation satellite laser ranging systems has been the modelocked Nd:YAG laser which produces pulsewidths measured in tens to hundreds of picoseconds. These systems are typically large (> 1 m long), complex, and require relatively sophisticated modulation and switching electronics, passive or active thermal control of the resonator length, and, in some cases, the use of limited lifetime dyes and carcinogenic solvents. Their complexity and reliance on inexpensive but short-lived flashlamps for pumping, with their attendant high voltage power supplies and ionozation circuits, further ensures a high level of maintenance by onsite personnel.

Recently, tiny Q-switched Nd-based microlasers, having lengths on the order of a millimeter and pumped by a single laser diode, have been demonstrated. These devices have operated at multikilohertz rates with pulsewidths as short as 115 picoseconds and single pulse output energies up to several tens of microjoules. Microlasers have been Q-switched via both active (e.g electro-optic) and passive (e. g. saturable absorber) means and generate more stable and temporally smooth profiles than many modelocked systems. Various passive diode-pumped multipass amplifier schemes have been devised for amplifying the microlaser output to millijoule levels without resorting to the use of fast switching or pulse selection devices. Thus, microlasers make ideal transmitters for the eyesafe SLR 2000 system and are a natural and inexpensive alternative to modelocked oscillators and/or regenerative amplifiers in higher power systems.

At GSFC, we have studied the manner in which both active and passive Q-switched lasers can be optimized for maximum efficiency (and coincidentally for minimum pulsewidth) and have examined the effects of thermalization among Stark sublevels and lower multiplet relaxation on pulse temporal profiles. More recently, we have begun to experimentally characterize the saturation properties of passive absorbers, such as chromium-doped YAG and Lithium Fluoride commonly used to Q-switch Nd-based lasers, as a function of pulsewidth. These theoretical and experimental efforts are combined in the present paper to derive optimum designs for an all diode-pumped SLR 2000 transmitter with the following characteristics: pulse energy $\geq$100 μJ at 532 nm, repetition rate $\geq$ 2 KHz, and pulsewidth $\leq$ 140 picoseconds.

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1. INTRODUCTION

The workhorse for third generation satellite laser ranging systems has been the modelocked Nd:YAG laser which can produce pulsewidths measured in tens to hundreds of picoseconds. These systems are typically large (> 1 m long), complex, and require relatively sophisticated modulation and high voltage switching electronics, passive or active thermal control of the resonator length, and, in some cases, the use of limited lifetime modelocking dyes and carcinogenic solvents. Their complexity and reliance on inexpensive but short-lived flashlamps for pumping, with their attendant high voltage power supplies and ionization circuits, further ensures a high level of maintenance by onsite personnel. Field lasers typically generate 100 mJ of energy per pulse at repetition rates of 5 to 10 Hz for the frequency doubled wavelength at 532 nm. This corresponds to an average green power output of only 0.5 to 1.0 Watts although single pulse peak powers are typically in the Gigawatt range.

Recently, tiny Q-switched Nd-based microlasers, having lengths on the order of a millimeter and pumped by a single laser diode, have been demonstrated. These tiny oscillators have operated at multikilohertz rates with pulsewidths as short as 115 picoseconds in active Q-switching mode using a resonant end reflector and have produced single pulse output energies up to several tens of microjoules [1]. Microlasers have also been switched via passive saturable absorbers and generate more stable and temporally smooth profiles than many modelocked systems [2,3] although they have not yet achieved the very short pulsewidths on the order of 10 picoseconds available from modelocked systems. In some cases, the gain and saturable absorber media can be doped into the same host crystsal, such as Neodymium and Chromium ions, and optical coatings deposited on both ends to form a single element, monolithic laser [3]. Furthermore, various passive diode-pumped multipass amplifier schemes have been devised for amplifying the microlaser output to millijoule levels without resorting to the use of active regenerative amplifiers which require nanosecond rate switching or pulse selection devices [4]. One can therefore design a laser ranging transmitter which operates off a single DC voltage by using a combination of CW diode pumping for both the oscillator and amplifier, passive Q-switching by saturable absorbers, and passive multipass amplifier configurations. Since the resulting transmitter would produce average powers comparable to that of current field SLR systems ($\leq$ 1 Watt) , but at much lower pulse energies and multikilohertz rates, the photon detection rate would also be similar. By allowing the low energy pulse train from the microlaser transmitter to fill the transmit/receive telescope aperture (<50 cm diameter), one can also meet current eye safety standards while maintaining average power levels comparable to current systems. Thus, microlasers make ideal transmitters for the eyesafe SLR 2000 system [5] and are a natural and very inexpensive alternative to modelocked oscillators and/or regenerative amplifiers in seeding higher power systems.

The author has previously studied the manner in which both actively [6] and passively [7] Q-switched lasers can be designed for maximum energy efficiency (and coincidentally for minimum pulsewidth in most cases of interest) and has further examined the effects of thermalization among Stark sublevels and lower multiplet relaxation on Q-switched laser energy and pulse temporal profiles [8]. More recently, Xiao and Bass [9] have demonstrated the manner in which excited state absorption, which occurs in some saturable absorbers, can be accomodated in Degnan's passive Q-switch optimization process. More recently, we have begun to experimentally characterize the saturation properties of passive absorbers, such as chromium-doped YAG and Lithium Fluoride commonly used to Q-switch Nd-based lasers, as a function of pulsewidth [10]. These theoretical and preliminary experimental efforts are combined in the present paper to derive optimum designs for an all diode-pumped SLR 2000 transmitter with the following characteristics: pulse energy $\geq$100 μJ at 532 nm, repetition rate $\geq$ 2 KHz, and pulsewidth $\leq$ 140 picoseconds.

2. OPTIMIZATION EQUATIONS FOR A CW-PUMPED, PASSIVELY Q-SWITCHED SYSTEM

Using Eqs. (21), (35), (36) and (38) in [7], one can show that, in order to optimize the output energy of a CW-pumped, passively Q-switched laser, the following three equations

$$z = \frac{\left(1-e^{-\alpha\rho}-\alpha\rho\right)^2}{\left(1-e^{-\alpha\rho}-\alpha\rho\right)\left(1-e^{-\alpha\rho}-\alpha\rho e^{-\rho}\right)-\alpha\left(1-e^{-\rho}-\rho\right)\left(1-e^{-\alpha\rho}-\alpha\rho e^{-\alpha\rho}\right)} \tag{1a}$$

$$z = z_{cw}\frac{1-\exp\left(-\tau_c/\tau_a\right)}{1-\delta\exp\left(-\tau_c/\tau_a\right)} \equiv z_{cw}F \tag{1b}$$

$$\delta = 1-\frac{f_a}{\gamma}\left(1-e^{-\rho}\right) \tag{1c}$$

must be solved simultaneously for the parameters z, δ, and ρ where

$$z = \frac{2\sigma n_i l}{L} = \frac{2\ln(G_o)}{L} \tag{2a}$$

$$\rho = \ln\left(\frac{n_i}{n_f}\right) \tag{2b}$$

and δ is the fraction of the original inversion remaining from the previous Q-switch cycle as determined from a steady state analysis.

Alternatively, equations (1a) through (1c) can be combined to yield a single transcendental equation for the value of ρ in the optimized case, i.e.

$$z_{CW} = \frac{\left(1-e^{-\alpha\rho}-\alpha\rho\right)^2\left[1+\frac{f_a}{\gamma}\frac{\left(1-e^{-\rho}\right)}{\exp\left(\tau_c/\tau_a\right)-1}\right]}{\left(1-e^{-\alpha\rho}-\alpha\rho\right)\left(1-e^{-\alpha\rho}-\alpha\rho e^{-\rho}\right)-\alpha\left(1-e^{-\rho}-\rho\right)\left(1-e^{-\alpha\rho}-\alpha\rho e^{-\alpha\rho}\right)} \tag{3}$$

Parameters appearing in (3) , which are assumed to be known or estimated apriori, are:

> $z_{cw} = 2\,\sigma n_{cw} l/L = 2\ln(G_o)/L$ where G_o is the roundtrip CW small signal power gain in the absence of Q-switching, L is the dissipative roundtrip optical loss (which excludes the mirror transmission and saturable absorption loss), σ is the spectroscopic stimulated emission cross-section; n_{cw} is the population inversion density produced by the CW pump, and l is the gain length.

$\alpha = \dfrac{F_{sat}^{amp}}{F_{sat}^{abs}}$ = the ratio of the saturation fluences for the amplifying and absorbing media

τ_a = upper laser multiplet relaxation time = 230 μsec for Nd:YAG

τ_c = desired Q-switch cycle time (inverse of repetition rate) = 500 μsec for SLR 2000 at 2 KHz

f_a = fractional Boltzmann population of laser Stark sublevel within the upper multiplet = .41 for Nd:YAG

γ = inversion reduction factor[6] where $f_a \leq \gamma \leq 2$and takes on the upper value (2) when all thermalization and terminal level relaxation processes are slow relative to the resonator photon decay time and the lower value (f_a) when the processes are all relatively fast [8] . We have assumed a value of $f_a + f_b = 0.6$ for these Nd:YAG calculations which implies thermalization among Stark sublevels is fast but lower multiplet relaxation is slow compared to the resonator photon decay time.

By substituting (1c) in (1b), the quantity F, which represents the amount the initial Q-switch gain is reduced from its CW value due to the pulse repetition rate, can be written in the form

$$F = \left[1 + \frac{f_a}{\gamma}\frac{\left(1-e^{-\rho}\right)}{\exp\left(\tau_c/\tau_a\right)-1}\right]^{-1} \tag{4}$$

and computed once ρ is computed from (3). One can then use equations (22), (23), and (30) in [7] to compute the optimum unsaturated absorber transmission (T_{opt}) , the optimum mirror reflectivity (R_{opt}), and the optimized laser output energy (E_{opt}). For our CW-pumped case, these equations can be written in a somewhat more transparent form, i.e.

$$T_{opt} = \exp\left[-\sigma n_{cw} lF \frac{\alpha\left(1-e^{-\rho}-\rho\right)}{\left(1-e^{-\alpha\rho}-\alpha\rho\right)}\right] \tag{5a}$$

$$R_{opt} = \exp\left[-\left(2\sigma n_{cw} lF + 2\ln(T_{opt}) - L\right)\right] \tag{5b}$$

$$E_{opt} = \frac{h\nu A\rho}{2\sigma\gamma}\ln\left(\frac{1}{R_{opt}}\right) \tag{5c}$$

and computed sequentially in the order the equations are given. In (5c), A is the effective beam area in the gain medium and hν is the laser photon energy. The time averaged output power of the energy-optimized, CW-pumped microlaser is in turn given by

$$P_{ave} = \frac{E_{opt}}{\tau_c} = \frac{h\nu A\rho}{2\sigma\gamma\tau_c}\ln\left(\frac{1}{R_{opt}}\right) \tag{6}$$

One can also derive an expression for the laser pulsewidth using (32) in [7] which is given by

$$\tau = \frac{t_r}{\left[L - \ln\left(R_{opt}\right)\right]} \frac{1 - e^{-\rho} + \dfrac{\ln\left(T_{opt}\right)}{\alpha\sigma n_{cw} l F}\left(1 - e^{-\alpha\rho}\right)}{1 - \dfrac{g_t(\alpha,\rho)}{2\sigma n_{cw} l F} + \dfrac{\ln\left(T_{opt}\right)}{\alpha\sigma n_{cw} l F}\left(1 - \left[\dfrac{g_t(\alpha,\rho)}{2\sigma n_{cw} l F}\right]^{\alpha}\right) + \dfrac{L - \ln\left(R_{opt}\right)}{2\sigma n_{cw} l F}\ln\left[\dfrac{g_t(\alpha,\rho)}{2\sigma n_{cw} l F}\right]} \tag{7a}$$

where the roundtrip threshold gain, $g_t(\alpha,\rho)$,is obtained from an iterative solution of the equation [7]

$$g_t(\alpha,\rho) = \left[L - \ln\left(R_{opt}\right)\right] - 2\ln\left(T_{opt}\right)\left[\frac{g_t(\alpha,\rho)}{2\sigma n_{cw} l F}\right]^{\alpha} \tag{7b}$$

3. CW DIODE END-PUMPING OF A MICROLASER

Since our design goal is a short pulse comparable to that used in current centimeter accuracy SLR systems (<140 psec at 532 nm), the length of the microlaser must be kept fairly short, and therefore end-pumping by a single diode or fiber-coupled diode array is the only viable approach. Longer rods favor increased pump efficiencies which results in higher small signal gains, higher output energies, and higher average powers. However, the beneficial effects of higher gain on reducing laser pulsewidth are more than offset by an increase in the resonator roundtrip transit time. Thus, pulsewidth must be traded off against other important parameters such as pulse energy, peak power, or average power.

In order to begin our computation of the parameters for the optimized laser, we must compute the quantity z_{cw} appearing in Eqs. (1b) and (3) as a function of the diode pump intensity. For a CW-pumped laser, this is given by

$$z_{cw} = \frac{2\sigma n_{cw} l}{L} = \frac{2\sigma T_p \eta_p f_a \tau_a \eta_a I_p}{h\nu_p L} \tag{8}$$

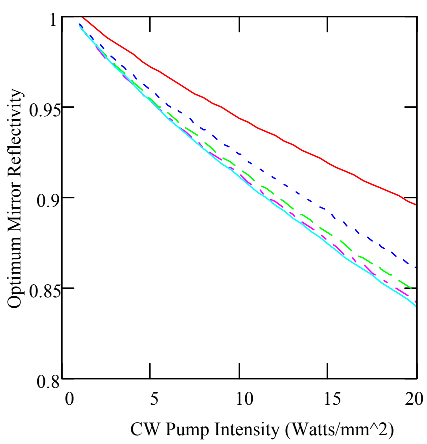
where I_p is the CW pump intensity, $h\nu_p$ is the pump photon energy (= 2.46 x 10^{-19} J at 808 nm), η_p is the efficiency with which the energy deposited in the pump bands gets deposited into the upper laser multiplet (believed to be ≅1 for the $^4F_{3/2}$ level in Nd:YAG), T_p is the transmission of the entrance face at the pump wavelength, and η_a is the fraction of the optical pump power entering the laser medium which is absorbed. The latter is given by the expression

$$\eta_a = \left[1 - \left(1 - R_p\right)e^{-\alpha_p l} - R_p e^{-2\alpha_p l}\right] \tag{9}$$

where, α_p is the pump absorption coefficient (~4.5/cm for Nd:YAG at a pump wavelength of 808 nm) and R_p is the reflectivity of the rod exit face at the pump wavelength. For one way pumping, the back face of the rod is AR-coated for the pump and laser wavelengths so that $R_p \cong 0$ whereas , for ideal two-way pumping, $R_p \cong 1$. In reality, the reflectivity of the pump wavelength must be traded off against the transmission at the laser wavelength which contributes to the dissipative loss, L, so that R_p<1.

4. NUMERICAL RESULTS FOR A MONOLITHIC Nd^{3+};Cr^{4+}:YAG CRYSTAL

We now use our theoretical expressions (3) through (7) to study the laser properties of a "monolithic" YAG crytal which is simultaneously doped with the ions producing gain (Nd^{3+}) and ions producing saturable absorption (Cr^{4+}) [3]. Since short pulses are our goal, use of a monolithic structure results in the simplest and shortest passively Q-switched laser resonator possible. In performing our numerical computations, we will assuime the following values for previously undefined parameters: T_p =1, L=.02, R_p =1, F_{sat}^{amp} = 480 mJ/cm^2 [7], F_{sat}^{abs} = 179 mJ/cm^2 [10]. We allow the length of the laser rod, l, to vary between 1 and 5 mm and assume that the optimum absorber doping for maximum laser efficiency can be accomodated within this crystal length. Figures 1 and 2 show plots of the optimum mirror reflectivity, optimum absorber transmission, and laser pulsewidth as a function of the CW diode pump intensity for different crystal lengths. The CW pump intensity was allowed to vary between 0 and 20 Watts/mm^2. The pulse energy curves are plotted against the same parameters for a total diode pump power of 1.2 Watts corresponding to the output of a Spectra Diode Labs Model SDL-2372-P3 diode laser which provides a high brightness beam in a 100 μm diameter spot via fiber optic coupling.



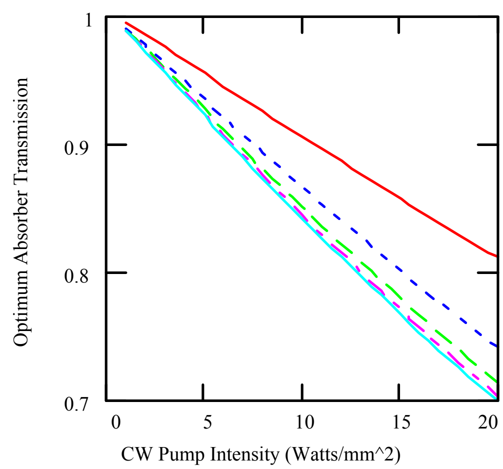
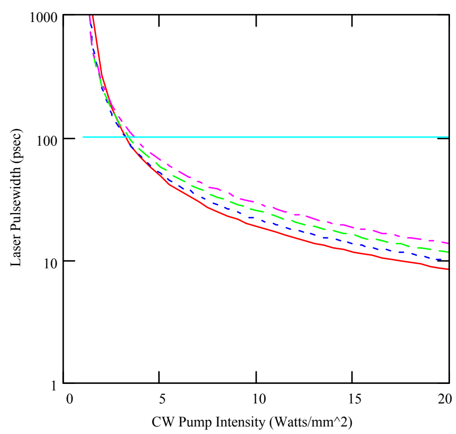


Figure 1: Optimum mirror reflectivity and absorber transmission as a function of CW pump intensity and rod length in 1mm increments. The top curve corresponds to a rod length of 1 mm and the bottom curve to a length of 5mm.

5. PASSIVE MULTIPASS AMPLIFIER

Coyle [4] has described a clever passive multipass amplifier design based on a rectangular slab shown in Figure 4. The slab is pumped on up to four sides by linear diode arrays. Typical cm long commercial arrays each produce up to 20 Watts of CW power.

One can define an amplifier "cell size", a, such that the length and width of the amplifier are equal to L = na and W = ma respectively where n and m are integers. One corner of the amplifier slab can be polished off to serve as an entrance face ,i.e. the entrance cell is cut in half along its diagonal and perpendicular to the beam.Thus, the beam size must be less than $\sqrt{2}a$ to fit within the entrance face. In addition, the beam size should be less than the width of the pumped volume in the slab. Once inside the slab, the beam will reflect internally off the sides of the amplifier at a 45^o angle until it encounters another corner. This corner can be polished off (exit cell halved) to serve as an exit face.



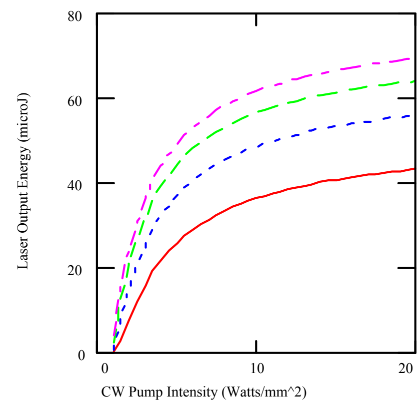


Figure 2: FWHM laser pulsewidth as a function of CW diode pump intensity and rod length in 1 mm increments. Bottom curve corresponds to a length of 1 mm and top curve to a length of 5 mm.

Figure 3: Laser pulse energy as a function of CW diode pump intensity and rod length in 1 mm increments for a total input power of 1.2 Watts. Bottom curve corresponds to a length of 1 mm and top curve to a length of 5 mm.

If m and n are chosen to have no common factors, one can show from a simple graph paper analysis that the effective multipass gain length before encountering a corner is given by

$$l_{eff} = \sqrt{2}a(mn-1) = \sqrt{2}\left(\frac{LW}{a} - 1\right) \tag{10}$$

where $\sqrt{2}a$ is the diagonal length of a single "cell" and (mn-1) is the number of cell diagonals traversed before encountering a corner (one cell is lost by halving the entrance and exit cells to create the entrance and exit faces). Furthermore, the beam undergoes a number of 45° reflections inside the amplifier given by

$$n_r = m + n + 2 \tag{11}$$

so that the net multipass power gain in the amplifier is

$$G_{net} = \exp\left(\sigma n_{cw} l_{eff}\right) R_{45^o}^{n_r} \tag{12}$$

where R_{45^o} is the reflectivity of the amplifier face at 45° incidence.

If the integers m and n are odd, the beam exits the amplifier from the corner opposite to the entrance face. If one integer is odd and the other even, the entrance and exit corners are adjacent to each other and lie on the same even numbered side.

If m and n have a common factor f, graphical analysis shows that the beam encounters a corner more quickly, and the effective gain length is reduced to

$$l_{eff} = \sqrt{2}a\left(\frac{mn}{f} - 1\right) = \sqrt{2}\left(\frac{LW}{fa} - 1\right) \tag{13}$$

and this represents a "bad" design.

If L and W are both on the order of a cm (corresponding to a standard laser diode array length) and a is on the order of a mm (a typical slab pump width [4]) , then, from (12), the effective multipass gain length, on a single pass through the amplifier, can be as large as 14 cm. Placing a mirror at the exit face, as in the SLR2000 transmitter block diagram in Figure 4, allows the multipass amplifier to be used in a double-pass configuration, resulting in an effective gain length of 28 cm. Our computations show that such a configuration, pumped by two linear diode arrays, each producing 20 watts of CW power, can produce a double-pass small signal power gain of 16 if the diode pump light is focused into a typical 1.2 mm width. Thus, a 25 μJ pulse from the oscillator can be amplified to 400 μJ, which is more than adequate for SLR2000. Significant additional gain can be achieved, if necessary, by adding arrays to the two remaining unpumped sides of the amplifier as in [4], roughly squaring the small signal gain.

6. CONCLUSIONS

A comprehensive theoretical model has been developed for the passively Q-switched microlaser which (1) can be fit well to existing experimental data, (2) is useful in estimating unknown parameters, and (3) can guide prototype hardware design. Furthermore, a simple model for a totally passive CW laser diode-pumped multipass amplifier has been developed. This compact amplifier, with a ~1cm by 1 cm by 1mm pumped volume, produces gains much higher than can be achieved in a conventional single or double pass configuration pumped by the same diode power. Our calculations predict a maximum single pass gain of 4 and a maximum double pass gain of 16 for a slab multipass amplifier pumped by two 20 watt laser diode arrays, and this can be increased substantially by adding additional arrays. The resulting oscillator/amplifier design has no high speed pulsing or switching circuits and should easily achieve the laser energy, pulsewidth, and repetition rate goals of SLR2000.

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