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Performance of Efficient Q-Switched Diode-Laser-Pumped Nd:YAG and Ho:YLF Lasers for Space Applications

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Solid-state lasers pumped by continuous-wave diode lasers can be Q-switched to obtain high-peak-power output pulses. In this article, the dependence of laser-pulse energy, average output power, peak power, and pulse width on pulse-repetition frequency in Q-switched Nd:YAG and Ho:YLF lasers is determined and compared. At low pulse-repetition rates, the much longer upper-state lifetime in Ho:YLF gives a distinct advantage. At higher pulse rates, the overall laser efficiency and the stimulated emission cross section are more important parameters, leading to an advantage for Nd:YAG. The results are of significance for designing lasers for use in space optical communications and remote sensing systems.

I. Introduction

Diode-laser-pumped solid-state lasers such as neodymium: yttrium aluminum garnet (Nd:YAG) and holmium: yttrium lithium flouride (Ho:YLF) are prime candidates for laser-light sources for use in deep-space optical communications and other applications. Due to the long upper-state lifetimes of the Nd^{3+} and Ho^{3+} ions doped into the YAG and YLF crystals, the energy storage capacity of such laser materials is quite high. Using a technique such as Q switching or cavity dumping, the stored energy can be extracted in the form of short laser pulses with high peak power. (This form is optimal for direct-detection optical communications use.) The pulse-repetition rate is controllable using an electro-optical or acoustical-optical device for Q switching.

A laser Q switch is effectively an intracavity shutter—when the Q switch is closed, optical pumping continues, but stimulated emission does not occur. During this time, energy is continuously stored in the upper laser level. When the Q switch is suddenly opened, the stored energy is released in the form of a "giant pulse" of laser light, depleting the upper laser level. The next laser pulse occurs only after a sufficient population of ions is again placed in the upper laser level.

Efficient diode-pumped continuous-wave (CW) Nd:YAG [1] and Ho:YLF [2] lasers were first demonstrated at JPL. In this article, the expected output power and pulse characteristics of diode-pumped, Q-switched (pulsed) Nd:YAG and Ho:YLF lasers are analyzed. In Section II below, the basic theory needed to calculate the results of interest is given. In Section III, the factors relevant to a comparison of Q-switched lasers are explicitly considered. In Section IV, the results are applied to specific laser examples.

II. Basic Theory

The most important factor determining the pulse shape and pulse energy in a Q-switched laser is the population inversion density[1] of the lasing medium just prior to the opening of the Q switch. In this section, we summarize the basic theory [3] for determining population inversion, power output, and pulse width in a CW-pumped, Q-switched laser.

In a series of periodic laser pulses, the population inversion density of the initial state (i.e., just before a laser pulse), n_i, depends on the inversion density of the final state (i.e., just after the preceding laser pulse), n_f, and on the amount of pumping that occurs during the period between the laser pulses, according to the equation

$$n_i = n_\infty - (n_\infty - n_f)e^{-1/\tau_s f} \quad (1)$$

where f is the pulse-repetition frequency and τ_s is the upper-laser-level spontaneous decay time. This equation is for continuous pumping at a uniform rate. The asymptotic density, n_∞, depends on the pumping rate and is the maximum achievable inversion density (approached when $1/f \gg \tau_s$). The value of n_∞ can be calculated from knowledge of the CW output power, P_{cw}, obtained when the cavity Q is maintained at its maximum value:

$$n_\infty = \frac{P_{cw}\tau_s}{\eta h\nu V} + n_{th} \quad (2)$$

Here, $h\nu$ is the photon energy, and V is the effective lasing volume, n_{th} is the threshold inversion density, and η is the output coupling factor. The latter two quantities are given [4], [5] by

$$n_{th} = \frac{1}{\sigma}\left[\frac{1}{l}\ln\left(\frac{1}{\xi\sqrt{r_1 r_2}}\right) + \beta\right] \quad (3)$$

$$\eta = \frac{\ln r_1}{\ln \xi^2 + \ln r_1 + \ln r_2 - 2\beta l} \quad (4)$$

for stimulated emission cross section σ, length of laser rod l, Q-switch maximum single pass transmission ξ, reflectivities of output and rear mirrors, r_1 and r_2, respectively, and laser-rod-loss coefficient β.

The population inversion just after the laser pulse, n_f, is given[2] by the (transcendental) equation

$$n_i - n_f = n_{th}\ln(n_i/n_f) \quad (5)$$

This equation, together with Eq. (1) above, determines the values for n_i and n_f for a given set of conditions. Once the change in the population inversion $n_i - n_f$ is known, the energy per pulse is given simply by

$$E_{pulse} = (n_i - n_f)\eta h\nu V \quad (6)$$

The average power output from the laser is then

$$P_{avg} = E_{pulse} f \quad (7)$$

The pulse shape is determined by the laser rate equations. From those equations, the peak laser power is found [3] to be

$$P_{peak} = \frac{Vh\nu \ln\left(\frac{1}{r_1}\right)}{\frac{1}{2}t_R}\left\{n_i - n_{th}\left[1 + \ln\left(\frac{n_i}{n_{th}}\right)\right]\right\} \quad (8)$$

where t_R is the round trip cavity time. Since $t_R = 2L/c$ where L is the cavity optical path length and c is the speed of light, a significant consequence of the equation for P_{peak} is that the peak output power of a Q-switched laser is inversely proportional to the cavity length.

III. Comparison of Lasers

Consider first the energy per pulse, E_{pulse}. Use of Eqs. (1), (2), and (6) gives

$$E_{pulse} = P_{cw}\tau_s\left(1 - e^{-1/\tau_s f}\right)\left(1 + \frac{\hat{n}_f}{\hat{n}_\infty}\right) \quad (9)$$

where $\hat{n}_\infty = (n_\infty - n_{th})/n_{th}$ and $\hat{n}_f = (n_{th} - n_f)/n_{th}$. The variables $\hat{n}_\infty$ and $\hat{n}_f$ are normalized versions of their "unhatted" counterparts, and have ranges $0 < \hat{n}_\infty < \infty$, and $0 < \hat{n}_f < 1$ (i.e., the final inversion density is less than the CW laser threshold).

The exact value of $\hat{n}_f$ can be determined only by solving Eqs. (1) and (5) numerically. Alternatively, we note from the

[1]The inversion density, n, is the difference between the population density of the upper laser level and that of the lower laser level.

[2]Subject to the approximation that the effect of pumping *during* the laser pulse is negligible.

form[3] of Eq. (5) that $\hat{n}_f < \hat{n}_i$. Since $\hat{n}_i < \hat{n}_\infty$ by definition, $0 < \hat{n}_f < \hat{n}_\infty$ and hence the rightmost factor in Eq. (9) ranges at most between 1 and 2.

Thus, within a factor close to unity, Eq. (9) says that the energy per pulse for a Q-switched laser depends only on the laser's CW output power level, the upper-state lifetime for the laser, and on the pulse-repetition frequency, and not on other factors such as the laser-stimulated emission cross section or the passive characteristics of the laser cavity.

For high pulse rates $f \gg 1/\tau_s$, Eq. (9) reduces to $E_{pulse} \simeq P_{cw}/f$, i.e., effectively the laser's CW power is collected over the pump time $1/f$ and emitted as a short pulse. For low pulse rates, the pulse energy saturates as the pumping time becomes long compared to the "storage time" τ_s. In this latter case, Eq. (9) reduces to $E_{pulse} \simeq P_{cw}\tau_s$.

Also of significance in comparing two lasers are the respective pulse widths. The laser pulse width limits the modulation alphabet size, limits the ability to reduce background light by narrowing the signal slot width, and (in the extreme) limits the maximum achievable Q-switched pulse frequency. The pulse shape can be determined exactly only by numerically integrating the laser-rate equations. Here we calculate only an estimate (actually a lower bound) for the laser pulse width given by

$$t_{pulse} \cong \frac{E_{pulse}}{P_{peak}} \tag{10}$$

where E_{pulse} and P_{peak} are given by Eqs. (6) and (8) above. For high pulse rates such that $f \gg 1/\tau$ and $n_i - n_{th} \ll n_{th}$, this reduces to

$$t_{pulse} \cong \frac{t_R\ \eta h\nu V f}{2\sigma l P_{cw}} \tag{11}$$

i.e., the pulse width is directly proportional to the pulse rate. For low pulse rates, $f \ll 1/\tau_s$, the pulse width approaches a constant (minimum), as both the pulse energy and the peak power saturate. This constant value is given by

$$t_{pulse}^{(min)} = \frac{t_R \eta}{2\ln(1/r_1)} \frac{\hat{n}_\infty}{\hat{n}_\infty - \ln(\hat{n}_\infty + 1)} \tag{12}$$

where $\hat{n}_\infty$ is defined above.

[3]Equation (5) can be rewritten as $(1 + \hat{n}_i) - \ln(1 + \hat{n}_i) = (1 - \hat{n}_f) - ln(1 - \hat{n}_f)$, where $\hat{n}_i = (n_i - n_{th})/n_{th}$.

IV. Specific Laser Examples

Now consider and compare Nd:YAG and Ho:YLF lasers characterized by a single-mode CW output power of 100 mW and a cavity length of 3.5 cm. Other laser parameters are given in Table 1. The most significant difference between the two lasers is that the lifetime of the upper laser level, τ_s, is about 50 times longer in Ho:YLF than in Nd:YAG. The parameters for the 100-mW lasers were chosen to represent the (CW) lasers reported in [1] and [2]. Scaling to higher powers is considered briefly at the end of this section.

Figure 1 shows a plot of the energy per pulse, E_{pulse}, (given by Eq. (9) with the factor $(1 + \hat{n}_f/\hat{n}_\infty)$ set equal to unity) as a function of the pulse-repetition frequency. For both lasers, the initial state inversion density saturates as the pumping time $(1/f)$ begins to be long compared to the respective upper-state lifetimes. The saturation value of the pulse energy is ($\tau_s \times 100$ mW); hence, for low pulse rates, the Ho:YLF laser pulses are about 50 times larger than those for Nd:YAG. For high pulse rates, the pulse energies become asymptotically equal. (At intermediate pulse rates, the Ho:YLF pulse energy is always larger.)

Figure 2 shows the laser average output power, P_{avg}, versus frequency. The average power goes to zero for low repetition rates, and approaches the CW laser power (100 mW) at high pulse-repetition rates. Again, values are always higher for the Ho:YLF laser.

Figure 3 shows the estimate on the laser pulse width given by Eq. (10). At low pulse-repetition rates, the Ho:YLF pulse width is about three times smaller than the Nd:YAG pulse width, due mainly to the effect of a higher $\hat{n}_\infty$ for the Ho:YLF. For higher pulse rates (above $\sim 10^3$ per second), the pulse widths are controlled by Eq. (11); here, since $h\nu$ and $1/\sigma$ are smaller for Nd:YAG than for Ho:YLF, the Nd:YAG pulse width is smaller by a factor of about 4. In the frequency range of 10^5 to 10^6 per second (upper right corner of Fig. 3), the calculated lower bound on the pulse width for both lasers exceeds the pulse interval $1/f$—the laser will not operate in a simple Q-switched pulse mode at those frequencies.

Now consider a simple scaling example—two 1-W lasers. (Laser parameters are the same as those given in Table 1, except $P_{cw} = 1$ W.) It can be seen from Eq. (9) that E_{pulse} scales linearly with P_{cw} (subject to the validity of the approximation $\hat{n}_f \ll \hat{n}_\infty$). Therefore, values of E_{pulse} (and P_{avg}) for 1-W lasers are a factor of 10 larger than those for the 100-mW lasers shown in Figs. 2 and 3. Values for t_{pulse} are smaller for the 1-W lasers than those shown in Fig. 3 for 100-mW lasers. For high pulse rates, Eq. (11) gives a reduction in pulse width by a factor of 10. At lower pulse rates, the reduction is not a linear factor–calculated values of $t_{pulse}^{(min)}$ for the 1-W lasers are 1.6 ns and 3.4 ns for Ho:YLF and Nd:YAG, respectively.

V. Conclusions

The Ho:YLF laser shows promise for use in low-data-rate optical communications systems, such as would likely be used in an Earth-to-spacecraft uplink in an all-optical communication system. At pulse repetition rates below 10 kHz, Ho:YLF offers higher performance than Nd:YAG in terms of higher energy per pulse for similar CW lasers. The upper-state lifetime, τ_s, is the dominant parameter in determining Q-switched pulse energy in this regime. Below 1 kHz, the Ho:YLF also offers shorter laser pulse widths. The large value of τ_s makes it easy to pump Ho:YLF far above threshold, resulting in short pulse widths. At higher pulse rates, τ_s becomes less important in determining the pulse energy. In the extreme, the pulse energy approaches P_{cw}/f, and hence for two lasers with equal input (pump) powers, the pulse energies depend only on the relative CW laser efficiencies. In this regime, Nd:YAG offers shorter pulses, due mainly to its higher stimulated emission cross section, σ.

Higher CW power lasers lead to proportionately higher pulsed-mode output powers, and also to shorter laser pulse widths. Hence for communications systems, the benefit of higher-power lasers comes not only from basic transmitter power considerations, but also from the ability to limit background noise by using shorter communications slot widths. An understanding of the parameters affecting pulsed laser operation is important in designing communications lasers for maximum system performance.

References

[1] D. Sipes, "Highly Efficient Neodymium: Yttrium Aluminum Garnet Laser End Pumped by a Semiconductor Laser Array," *Applied Physics Letters*, 47(2), pp. 74–77, July 15, 1985.

[2] H. Hemmati, "Efficient Holmium: Yttrium Lithium Fluoride Laser Longitudinally Pumped by a Semiconductor Laser Array," *Applied Physics Letters*, 51(8), pp. 564–565, August 24, 1987.

[3] W. Koechner, *Solid-State Laser Engineering*, Chapter 8, New York: Springer-Verlag, pp. 397–408, 1976.

[4] G. D. Baldwin, "Output Power Calculations for a Continuously Pumped Q-Switched YAG:Nd^{+3} Laser," *IEEE Journal of Quantum Electronics*, vol. QE-7, no. 6, pp. 220–224, June 1971.

Table 1. Parameters for Nd:YAG and Ho:YLF lasers of Section IV

Parameters	Nd:YAG	Ho:YLF
P_{cw}, mW	100	100
τ_s, ms	0.23	12
λ, μm	1.064	2.06
V, cm^3	0.02	0.02
l, cm	1.0	1.0
L, cm	3.5	3.5
r_1	0.975	0.95
r_2	1.00	1.00
ξ	0.987	0.987
β, cm^{-1}	0.0023	0.0023
σ, cm^2	8.7×10^{-19}	1.0×10^{-19}

C-3

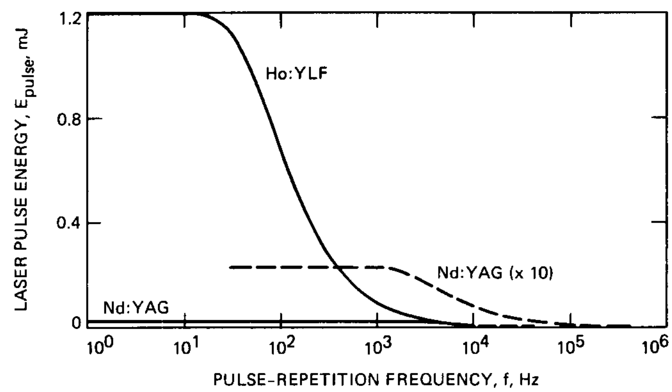

Fig. 1. Output energy per pulse, E_{pulse}, in mJ, versus pulse repetition frequency, *f*, in Hz, for Nd:YAG and Ho:YLF lasers described in Table 1. The curve marked Nd:YAG (X10) is the Nd:YAG curve multiplied by a factor of 10 for clarity.

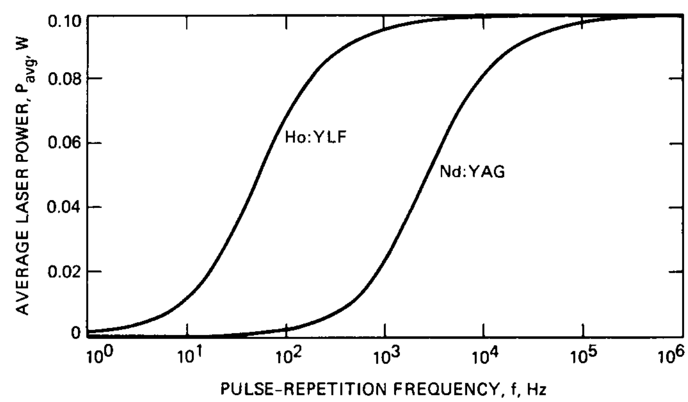

Fig. 2. Average output power, P_{avg}, versus pulse repetition frequency, *f*, for lasers of Table 1.

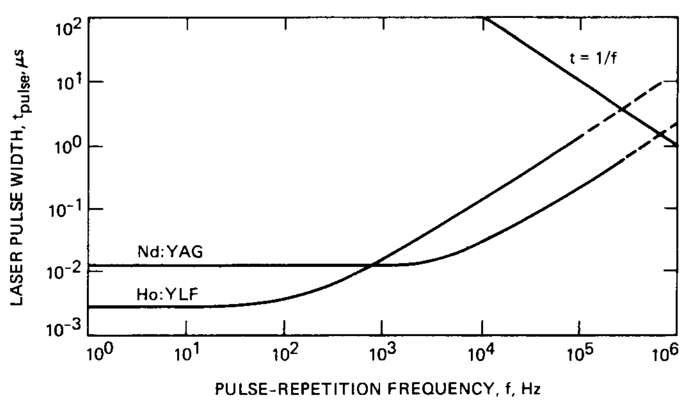

Fig. 3. Laser pulse width, t_{pulse}, versus pulse repetition frequency, *f*, for lasers of Table 1.