[REPORT DOCUMEN]TATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1994	Professional Paper

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
PERFORMANCE OF A DIODE-PUMPED LASER REPETITIVELY Q-SWITCHED WITH A MECHANICAL SHUTTER	PR: CH84 PE: 0601153N WU: DN300190
6. AUTHOR(S) R. Scheps and J. F. Myers	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Naval Command, Control and Ocean Surveillance Center (NCCOSC) RDT&E Division San Diego, CA 92152-5001	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Office of Naval Research 800 North Quincy Street Arlington, VA 22217	

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT (Maximum 200 words)

This paper describes the repetitively Q-switched operation of an end-pumped Nd:YAG laser over the range of 200 Hz to 3 kHz using an intracavity chopper. Performance is shown to be comparable to that achieved with an acousto-optic Q switch under similar conditions. The advantages and limitations of the mechanical Q switch are described. Parametric variations of output coupling and pump power lead to an extended empirical description of repetitively Q-switched laser operation. The insertion loss as a function of aperture-edge penetration into the resonator is reported, and a definition of the mechanical Q-switch opening time is provided. Q-switched pulsewidths as short as 35 ns were obtained for the Nd:YAG laser, with a peak power-enhancement factor in excess of 300.

Published in *Applied Optics*, vol. 33, no. 6, pp. 969-978.

14. SUBJECT TERMS		15. NUMBER OF PAGES
lasers Fraunhofer line	underwater communications	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

NSN 7540-01-280-5500

Standard form 298 (FRONT)

UNCLASSIFIED

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE (Include Area Code)	21c. OFFICE SYMBOL
R. Scheps	(619) 553-2630	Code 754

NSN 7540-01-280-5500

Standard form 298 (BACK)

UNCLASSIFIED

Performance of a diode-pumped laser repetitively Q-switched with a mechanical shutter

Richard Scheps and Joseph F. Myers

Repetitively Q-switched operation of an end-pumped Nd:YAG laser over the range of 200 Hz to 3 kHz using an intracavity chopper is demonstrated. Performance is shown to be comparable to that achieved with an acousto-optic Q switch under similar conditions. The advantages and limitations of the mechanical Q switch are described. Parametric variations of output coupling and pump power lead to an extended empirical description of repetitively Q-switched laser operation. The insertion loss as a function of aperture-edge penetration into the resonator is reported, and a definition of the mechanical Q-switch opening time is provided. Q-switched pulsewidths as short as 35 ns were obtained for the Nd:YAG laser, with a peak power-enhancement factor in excess of 300.

Key words: Q-switched, diode-pumped laser.

1. Introduction

Repetitively Q-switched lasers are useful for applications that require both high peak power and moderate average power. Typically these lasers are pumped with cw optical sources and use an intracavity acousto-optic (AO) Q switch to produce a train of temporally narrow output pulses. Recent progress in diode pumping has led to the development of reliable and efficient repetitively Q-switched lasers, and compact AO Q switches are now available that are particularly suited for diode-pumped laser operation. However, for evaluating specific laser-resonator designs under Q-switched operation, the AO Q switch may not be the most effective device for several reasons. The insertion loss of the Q switch is problematic for diode pumping because cw pump powers are typically lower than those of other laser pump sources. In addition, even compact Q switches require expansion of the cavity dimensions. For many resonator designs, the Q switch medium introduces astigmatism, lowering the overall optical conversion efficiency. And from a pragmatic point of view, AO Q switches and their associated electronics are expensive. This problem is compounded if one requires different Q switches for different output-wavelength ranges.

One of the earliest Q-switched lasers used a mechanical rotating aperture.[1] While this method of Q switching was abandoned for faster switching techniques, the current generation of high-quality mechanical choppers presents the opportunity to reinvestigate the use of such a device as an intracavity Q switch. The advantages of the mechanical-chopper Q switch are numerous, particularly for evaluation of end-pumped laser designs. The chopper introduces no loss in the cavity when the shutter is open and does not require different coatings for different wavelength ranges. The holdoff is essentially infinite, the costs are modest, the drive electronics are straightforward, there are no mode-polarization requirements, and the chopper adds virtually no length to the laser cavity. Of course there are also some disadvantages. For one, moving parts tend to age and eventually need replacement. The switching time is relatively slow and this leads to a certain degree of inefficiency. Phase errors due to the variation of the aperture width from slot to slot on the chopper wheel produce timing jitter in the output pulse. In addition, current chopper technology limits the maximum Q-switch pulse-repetition rate to 20 kHz. And finally, the switching time, shutter on–off times, and Q-switch repetition rate are changed simultaneously when the motor speed is adjusted. Therefore changing the repetition rate by adjusting only the motor-revolution rate can have undesired consequences. In spite of these disadvantages, however, the mechanical chopper can be a useful device for Q switching diode-pumped solid-state lasers. For longitudinally or end-pumped lasers the relatively small resonator-

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Received 11 March 1993; revision received 10 August 1993.

mode diameter mitigates the problems associated with the slow shutter speed and enhances the performance of the chopper as a Q switch. The versatility afforded by simply inserting the chopper in an operating cw laser to produce Q-switched output is compelling. Using a chopper as a Q switch, we have obtained short pulse widths and high peak power-enhancement factors.

To provide a better understanding of Q-switch performance, detailed analytical data were obtained for Q-switched laser operation as the gain, passive loss, and output coupling were varied. The mechanical Q switch was evaluated in both a diode-pumped Nd:YAG laser and a monochromatically end-pumped Yb-doped fluorapatite[2] (Yb:FAP) laser. Both lasers operate in the TEM_{00} mode. The effects of the switching time on the Q-switched laser output were investigated, and measurements of the induced intracavity passive loss as a function of the location of the chopper aperture edge relative to the resonator mode are reported. Losses that result from the use of the mechanical chopper in the cavity were measured, and their origin is described. Also, the use of pulsed pumping of the gain material with laser diodes was evaluated. Pulse width and timing of the pump pulse relative to the position of the aperture edge as it traverses the resonator mode were examined under a variety of conditions. These measurements have provided an empirical definition of the Q-switch opening time and establish the conditions required for effective Q-switched laser operation with an intracavity chopper.

2. Experimental

The mechanical chopper used in this work has several features that facilitate its use as a Q switch. The chopper wheel is driven by a precision motor capable of a rotation rate as high as 100 Hz (6000 rpm). The rotation rate is controlled by a separate electronics package supplied with a digital read-out of the shutter frequency and a potentiometer for adjusting the motor revolution rate. Chopper wheels contain 2 to 60 slots or apertures, allowing a maximum repetition rate of 6 kHz. Two chopper wheels with diameters of approximately 98 mm and 109 mm were used. The ratio of the opaque area to the transparent area is 1:1. At the maximum motor speed, the linear velocity of the aperture edge near the outer edge of the 98-mm diameter wheel is 3.1×10^3 cm/sec. Thus approximately 32 ns are required for the aperture blade to traverse 1 μm. The wheel with the lowest phase error ($\pm 0.2°$) contained two slots and provided a repetition frequency of 200 Hz at the maximum motor speed. This wheel was used for much of the evaluation data reported below. The width of the aperture can be adjusted by mounting two identical wheels on the motor shaft, with the apertures of one wheel offset relative to those of the other. This allows a variable duty factor between 0 and 50%. Accurate setting of the aperture width was achieved with feeler gauges. The chopping frequency is detected by an optical trigger integrated within the motor-support structure so that the readout displays the true frequency independent of the number of slots on a given wheel. Several manufacturers provide this type of chopper, and numerous variations of the basic design are available and include such features a faster chopping frequencies and chopper-phase control.

Most of the analytical measurements were performed on a diode-pumped Nd:YAG laser. The laser gain element was fabricated in the shape of a pentaprism and was pumped along one of the nonorthogonal faces with a 1-W laser diode. The diode is a single-stripe emitter operating at 808 nm. For measurements that required variation of the pump power, the diode heat-sink temperature was adjusted at each drive current to maintain a constant diode-emission wavelength. The pentaprism laser has an important advantage for the present application in that it can be longitudinally pumped while simultaneously allowing visual diagnostics of the resonator mode at the highly reflective (HR) exterior prism face. This design was described in detail in a previous publication.[3] The laser resonator is shown in Fig. 1. The resonator mode is nearly hemispherical. We monitored both

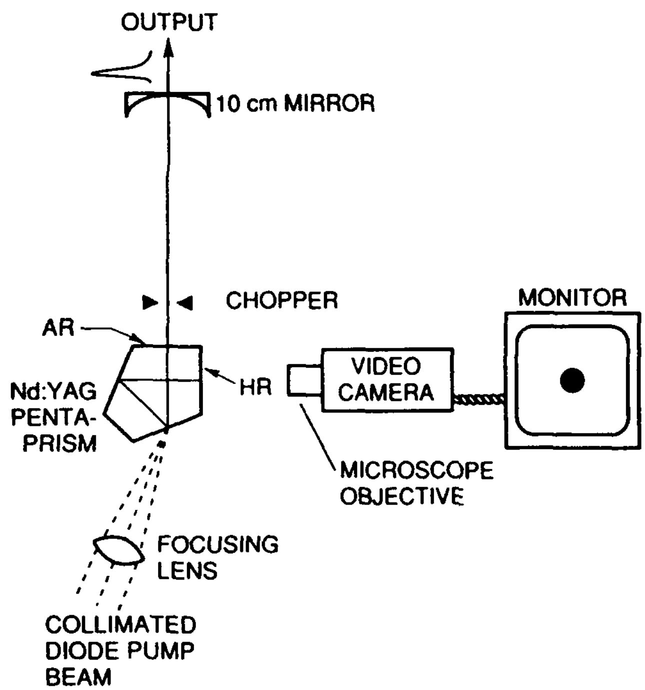

Fig. 1. Nd:YAG laser and location of components used for the evaluation of the mechanical Q switch. The pentaprism design allows diode pumping along one fold face (coated HR at 1.06 μm and highly transmissive at 808 nm) while simultaneously monitoring the resonator mode waist dimension at the exterior HR face. A video camera with a microscope-objective lens provides a high-resolution image of the waist. The location of the chopper is shown. Projection represents a top view, and the term *vertical* as used in the text refers to the direction normal to the plane of the figure.

the mode waist and shape simultaneously at the HR face, using a video camera with a spatial resolution of 10 μm. This ensured TEM_{00} operation and provided a high degree of continuity from one measurement to another. The mode waist at the HR face was 40 μm. Several 10-cm radius-of-curvature output mirrors were used in the resonator, with reflectivities ranging from 99.4% to 86.0%. The beam path in the pentaprism was 17 mm. The chopper was placed 5 mm from the interior antireflective (AR) face of the prism, where the mode radius was 124 μm.

A second laser was used to demonstrate the versatility of the mechanical-chopper Q-switch. The gain medium was Yb:FAP [$Yb{:}Ca_5(PO_4)_3F$], which has a fluorescence lifetime of 1.08 ms compared to 230 μs for Nd:YAG. The resonator mode was hemispherical and similar in size to that used for Nd:YAG, although the Yb:FAP gain element was an 8-mm-long rod. The details of the overall performance of the laser are reported separately.[4] In this paper only a brief description of Q-switched operation is presented. The gain element was end-pumped with the output of a Ti:sapphire laser emitting at 905 nm.

To measure the insertion loss of the aperture edge as a function of edge position relative to the resonator mode, the chopper was replaced with a knife edge mounted on a translation stage. The translation stage was driven piezoelectrically and was microprocessor controlled. Originally a single blade of a spectrometer slit was used as the knife edge. However, spectrometer slits are beveled on one side and can create scattering problems in a standing-wave cavity where optical flux propagates in two directions simultaneously. The slit blade was therefore replaced with a strip of blackened razor steel sharpened on both sides of one edge. When used as a Q switch, the chopper was oriented so that the aperture edges were approximately vertical as they traversed the resonator mode. The knife edge was also vertical to simulate the orientation of the aperture edge. The monitoring video camera was used to verify that the size and position of the mode waist on the HR prism face was identical for all output mirrors used for the knife-edge measurements. Thus the absolute position of the knife edge had a constant relationship to the location of the resonator mode. The knife edge initially was located well beyond the edge of the mode and then was gradually moved in to introduce loss. A second monitor camera was used to observe the knife edge as it moved through the resonator mode. From the appearance of diffracted flux on the opaque knife-edge blade one could easily locate the approximate position for which the edge first introduces losses.

3. Results

Q-switch evaluation was performed in the Nd:YAG laser under pumping conditions that approximate an optimally coupled Q-switched laser. The optimum pump power generates the highest Q-switched output efficiency and can be determined for a given output coupling from calculations recently published by Degnan.[5] Five different output couplers were used, and the Q-switched pulse width t_p, absorbed pump power P_{abs}, cw output power P_{cw}, and threshold power P_{th} were measured and are listed in Table 1. In this table, P_{th} refers to the absorbed pump power at threshold and P_{abs} is the maximum pump power used for a given output coupler. P_{abs} is approximately equal to the optimum pump power and, when Q switched, produces the measured t_p. P_{abs} also produces the listed P_{cw} when the Q switch is passive. The absorbed power is lower than the incident pump power because of small reflective losses at the pumped face of the prism and the incomplete absorption of the pump power by the gain element over the 6-mm absorption path. A representative Q-switched pulse waveform is shown in Fig. 2.

Actual mirror reflectivities at 1.06 μm were determined with a spectrophotometer and are listed in Table 1. The relatively short pulse widths obtained with the lower-reflectivity mirrors are comparable to those measured previously with an intracavity chopper to produce Q-switched pulses in both a Nd:YAG laser[6] and the lower-gain Cr:LiSAF[7] laser. The absorbed threshold power as a function of output-mirror reflectivity was used to determine the small signal gain and resonator passive loss by a Findlay–Clay analysis.[8] The linear regression fit to the data is shown in Fig. 3. The round-trip small signal gain and passive loss obtained from the curve fit are $5.7 \times 10^{-4} P\,(\mathrm{mW}^{-1})$ and 1.19×10^{-2}, respectively, where P is the pump power in mW.

Using the measured gain and loss we can calculate the Q-switched pulse width from the expression[5]

$$t_p = t_c \frac{(n_i - n_f)}{n_i - n_t\left[1 + \ln\left(\frac{n_i}{n_t}\right)\right]}, \tag{1}$$

Table 1. Q-switched Results for the Nd:YAG Laser

Mirror Reflectivity	P_{abs} (mW)	P_{th} (mW)	P_{cw} @ P_{abs} (mW)	Measured t_p (ns)	Calculated t_p (ns)	Buildup Time (μs)
0.860	822	270	212	35	14	1.9
0.898	562	205	136	40	21	2.6
0.924	333	180	72	45	49	5.2
0.959	141	110	21	100	229	10.3
0.994	24	16	2	720	362	9.1

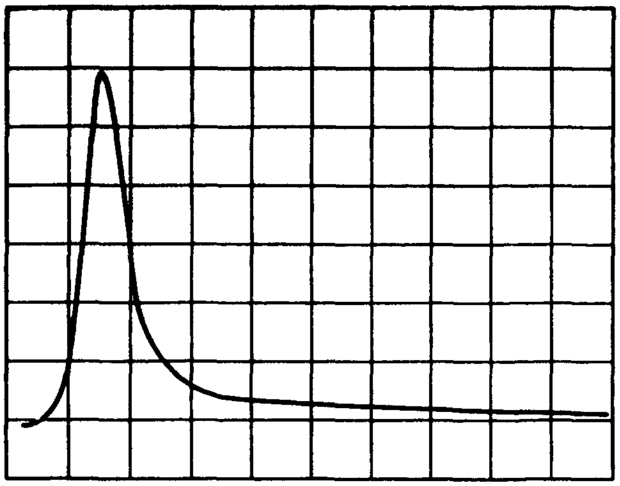

Fig. 2. *Q*-switched waveform for the 86% *R* output mirror under the pumping conditions listed in Table 1. The horizontal axis is 50 ns/division; the vertical axis is 20 mV/division; the pulse width is 35 ns.

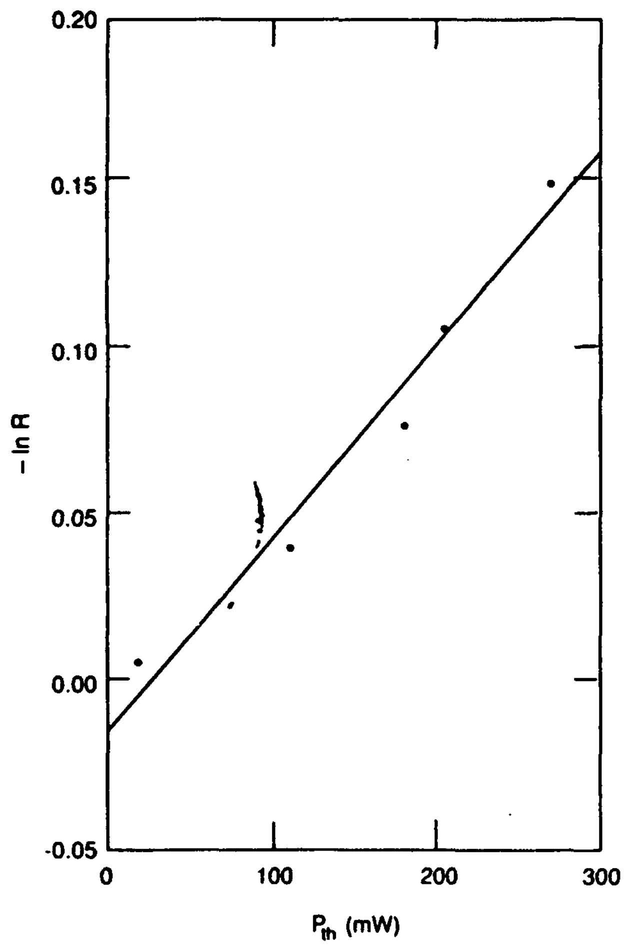

Fig. 3. Dependence of the pump threshold power on the output mirror reflectivity. Data points are shown and are listed in Table 1. The line is the linear-regression fit to the data. The fit parameters are slope = 5.7×10^{-4} mW^{-1}, intercept = 1.19×10^{-2}, and the coefficient of determination = 0.97.

where n_i and n_f are the initial and final population-inversion densities, respectively, and n_t is the threshold-inversion density. The photon-decay time t_c is given by

$$t_c = \frac{t_r}{\left[\ln\left(\frac{1}{R}\right) + L\right]}, \tag{2}$$

where R is the output mirror reflectivity, L is the round-trip passive loss (excluding output coupling), and t_r is the round-trip transit time. Both n_i and n_t can be obtained from the small signal gain at the appropriate pump power, because

$$n = \frac{g_0}{\sigma}, \tag{3}$$

where g_0 is the small signal gain coefficient and σ is the stimulated emission cross section. The final population inversion is related to n_i and n_t by the transcendental equation

$$n_i - n_f = n_t \ln\left(\frac{n_i}{n_f}\right). \tag{4}$$

The fraction of the inversion remaining after the *Q*-switched pulse, n_f/n_i, is inversely dependent on the ratio of the initial inversion to the threshold inversion. This ratio is identical to the ratio of the pump power to the threshold-pump power (referred to in this work as the pump ratio) as can be seen from Eq. (3). This conclusion can also be reached by noting that for a four-level laser, where the intracavity flux is negligible (as it is when pumping with the shutter closed), the rate equation for the population in the upper laser level n_2 is

$$\frac{dn_2}{dt} = W_p n_0 - \frac{n_2}{\tau}, \tag{5}$$

where W_p is the pump rate for population of the upper laser level, n_0 is the population of the ground state, and τ is the spontaneous-decay rate for the upper laser level. For the 200-Hz chopping rate, the pump-integration time is long relative to the spontaneous-emission lifetime of the upper laser level, so that the population of this level is in steady state. The n_2 steady-state population is given by

$$n_2 = W_p n_0 \tau, \tag{6}$$

and it is apparent that the upper laser level population is proportional to the pump power.

The transcendental function given in Eq. (4) was first treated analytically by Wagner and Lengyel.[9] The *Q*-switched pulse widths calculated with the above relations are listed in Table 1. Note that in using the cw-threshold and passive-loss values to calculate the pulse widths by Eqs. (1)–(4), it is implicitly assumed that the shutter-opening time is short relative to the pulse-buildup time. This is not always the case with the mechanical chopper. At the time that the Q-switched pulse is emitted the aperture-induced passive loss may not be completely removed. This would lead to a higher value for n_t than the steady-state value. The large discrepancies between the calculated and measured pulsewidths for the two mirrors with the highest reflectivities indicate that Eqs. (1)–(4) are inaccurate when the pump power is near threshold.

Two different measurements were performed with the knife edge. In the first, the laser was pumped at the power P_{abs} listed in Table 1. The knife edge was then gradually moved into the resonator mode at the axial position previously occupied by the chopper, i.e., 5 mm from the AR face of the prism. The laser output power was monitored as a function of the knife-edge position. This was repeated for each output coupler, and a typical plot of output power as a function of knife-edge position is shown in Fig. 4. Similar plots were obtained for each output mirror. These measurements indicate the distance traversed by the chopper edge as it scans from the threshold location (where the gain is equal to the loss) to the location where the shutter is completely open. This is seen to be approximately 160 μm in the case shown in Fig. 4. We can define a characteristic distance as that between the 10% and 90% power points. The characteristic distance was found to be similar for all mirrors and had an average value of 67 μm. While one might expect that the characteristic distance would increase as the mirror transmission decreases, note that for each output coupler the pump power is increased to compensate for the increased mirror transmission. The resonator mode is observed to remain TEM_{00} as the knife edge is introduced into the resonator, and no eclipsing of the mode is observed. This is expected for a stable resonator.

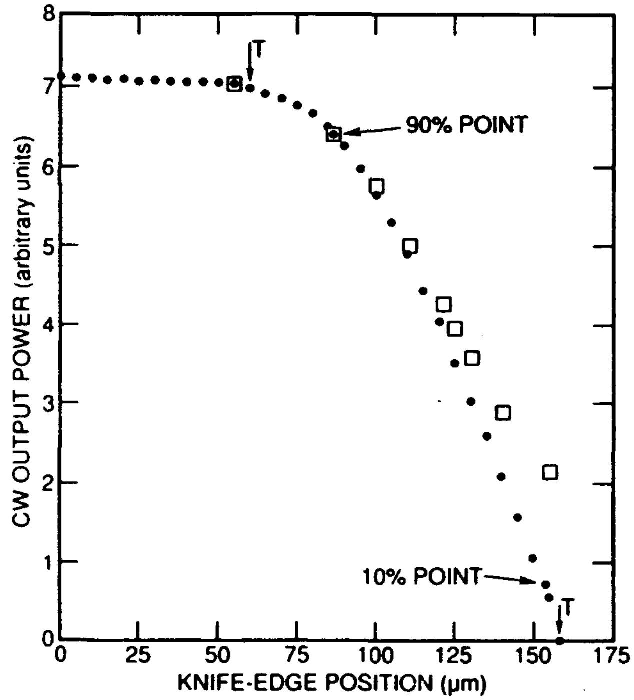

Fig. 4. Output power as a function of the knife-edge position in the Nd:YAG laser with a 0.898-R output mirror. The power units are arbitrary and the zero position corresponds to the knife edge removed from the beam. The knife-edge locations where the laser output power is 10% and 90% of the zero-position power are noted, and the termination points marking the distance traversed by the aperture as it moves from threshold to the 98% transmitted-power position are indicated with a T. The dots represent the knife-edge data. The open squares indicate calculated points representing power dependence as a function of aperture position.

While the results of the first knife-edge measurement can be used to calculate the insertion loss of the knife edge as a function of knife-edge position, a second set of measurements was undertaken to provide these data directly. Initially the laser was pumped with power equal to P_{th}. The knife edge was then moved into the resonator to extinguish the output. The pump power was subsequently increased by 20 mW, and the knife edge was moved further into the resonator to extinguish the output once again. This procedure was repeated with 20-mW increments in absorbed pump power until the maximum pump power listed in Table 1 was applied. Because at threshold the gain equals the loss and furthermore the gain is equal to the small signal gain, the insertion loss introduced by the knife edge can be determined at each position from the Findlay–Clay curve-fit parameters. A typical trace of the threshold pump power as a function of knife-edge position is shown in Fig. 5. This datum is particularly important as it provides the exact form of the relationship between the aperture position and the loss it introduces. The alternate axes in Fig. 5 represent conversion of the knife-edge position to time, based on a

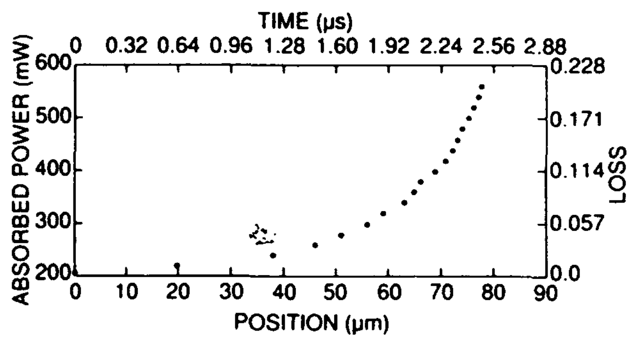

Fig. 5. Knife-edge travel required to extinguish laser output as a function of the absorbed pump power. Data are shown for the 0.898-R output mirror. The zero position corresponds to the knife-edge location required to extinguish laser output at the threshold pump power and indicates the edge of the resonator mode. Increasing position corresponds to the knife-edge penetrating deeper into the resonator mode. The alternate axes to the right and above the figure indicate the insertion loss and transit time, respectively, for the chopper operating at maximum motor speed (100 Hz). The alternate axes are configured to indicate increasing insertion loss as a function of time and represent closing of the shutter aperture.

motor speed of 100 Hz, and the conversion of the pump power to round-trip insertion loss based on the Findlay–Clay data. Figure 5 can be seen to represent the temporal dependence of the chopper-aperture insertion loss for the pentaprism laser.

For slow Q-switch repetition rates, cw pumping of the Nd:YAG laser becomes relatively inefficient. The Q-switched data listed in Table 1 were obtained with cw pumping. Because the chopping frequency was 200 Hz, the excitation-integration time represents approximately 11 radiative-decay times (50% duty factor) for the Nd ion. To achieve higher optical-conversion efficiencies, the concept of pulsing the pump diodes in synchronization with the chopper rotation was pursued. The laser performance was evaluated as a function of pump pulse width and timing of the pump pulse relative to the opening of the shutter. This was performed with the five mirrors listed in Table 1. Throughout these measurements the diode was maintained at a fixed wavelength of 808 nm by thermal control of the heat sink. The diode output was continuously monitored with an optical multichannel analyzer. The steady-state diode-output wavelength is determined solely by the pulse width, as the pulse-repetition rate and current amplitude for all pulses were identical.

Table 2 lists the data we obtained using the 0.898-R mirror. For this type of excitation, the pump pulse width determines the excited-state fraction and therefore also determines the laser threshold. For the 0.898-R mirror the threshold pulse width is 122 μs. The threshold pulse width increases for increasing transmission of the output mirror. The column labelled power ratio in Table 2 represents the ratio of average power when the cavity is Q switched to the average power when the cavity is free running. In the latter case the Q switch is removed from the cavity. The excitation pulse conditions were unchanged with the Q switch removed, and when free running, the laser output was emitted as an initial pulse approximately 600 ns wide, followed by a series of relaxation oscillations superimposed on a steady-state output. The overall free-running pulse length was shorter than the pump pulse length because of the time required to reach threshold (122 μs). The pulse amplitude listed in Table 2 represents the peak signal from a monitor photodiode and provides a relative measure of the peak power.

Table 2. Pulsed Excitation at 200 Hz with an 0.898-R Output Coupler

Pump Pulse Width (μs)	Q-Switched Pulse Width (ns)	Pulse Amplitude (V)	Average Power (mW)	Power Ratio
150	140	92	0.4	1.20
200	72	240	0.7	0.78
250	53	300	1.2	0.69
300	44	300	1.4	0.56
350	47	321	1.5	0.44
400	42	312	1.5	0.37
450	42	306	1.5	0.31
500	42	312	1.5	0.26

Pulse timing is an important factor that directly affects the Q-switched power. Optimum efficiency was achieved when the termination of the pump pulse coincided temporally with the emission of the Q-switched pulse. This timing was observed for all pulse widths, so that longer pump pulses required initiation earlier in the chopping cycle. Extending the excitation pulse beyond the time that the Q-switched pulse was produced increased the average power by producing a steady-state laser output subsequent to the Q-switched pulse that was similar to that observed for the free-running pulse-pumped laser. However, the Q-switched peak power remained fixed at a value determined by the pump pulse width up to the emission time. The delay between the initial opening of the shutter and the emission of the Q-switched pulse is referred to as the pulse buildup time, and the pulse-timing data indicate that pump power is integrated during the buildup time. Ending the excitation pulse prior to the Q-switched output pulse produced lower peak and average output powers. At high pump power, secondary low-power Q-switched pulses were observed to follow the main Q-switched pulse. Extending the pump pulse-excitation time beyond the emergence of the main Q-switched pulse did not appear to affect the amplitude or timing of these secondary pulses. Because the secondary pulses typically follow the main Q-switched pulse by only a few microseconds, the additional pumping that takes place during this time has little observable effect on the secondary output pulse.

With an opaque-to-transparent aperture ratio of 1:1, the aperture is open long enough under cw pump excitation to allow low-power steady-state laser emission following the Q-switched pulse. This output terminates when the aperture closes. While this steady-state emission is normally not a problem, if it is not recognized it can lead to erroneous conclusions about the Q-switched average power. That is, the measured average power consists of the combination of Q-switched and steady-state output. The steady-state output is simple to eliminate by using a smaller chopper aperture. The Q-switched peak output was measured as a function of aperture width and was found to be unaffected down to widths of 500 μm (approximately twice the beam diameter). At this width virtually all of the steady-state output was eliminated. Average power measurements were therefore taken with the 500-μm aperture to provide an accurate determination of the Q-switched average power.

4. Discussion

Theoretical treatment of Q switching with a slowly opening Q switch has been reported by several authors[10,11] and provides a framework for discussing the empirical data presented in the previous section. We begin this section by defining the Q-switch opening time as it relates to a mechanical copper. For an AO Q switch, the opening time refers to the time required for the acoustic wave to traverse the $1/e^2$ beam diameter. This time directly affects the Q-switched output pulse width. For the mechanical chopper, however, the relevant distance required for the aperture edge to move in order to open is that distance between the position where the loss is equal to the gain, and the extreme edge of the resonator mode. The first position occurs at the 160-μm location in Fig. 4. The practical limit for the second position is more difficult to assign. If we arbitrarily choose the 98% power-transmission point, the completely open position occurs near the 55-μm location in the figure. The two termination points for opening of the Q switch are indicated by T in the figure. The opening distance is a function of the pump power, the resonator-beam diameter at the chopper location, and the output coupling. When these parameters are varied, the shapes of the curves remain similar to that shown in Fig. 4, but the absolute values along the two axes change. For the case shown in Fig. 4, the opening distance based on the 98% transmission point is 105 μm.

The losses introduced by the chopper blade are caused by both attenuation and diffraction. The attenuation losses can be calculated using the Gaussian error function. However the measured output beam-intensity profile of the pentaprism laser is not quite Gaussian. Therefore a commercially available beam-diagnostic program was used to digitize the beam emerging from the resonator, and a computer program was used to calculate the transmission of this beam through the chopper aperture. The program does not include diffraction. The calculated transmission function was doubled to reflect the intracavity use of the aperture. The aperture insertion loss δ reduces the laser output power as[12]

$$\frac{P}{P'} = \frac{\delta + T + L}{T + L} \qquad (7)$$

where T is the mirror transmission and P' and P are the laser output powers with and without insertion loss δ, respectively. Equation (7) is valid for high pump ratios and small $\delta/(T + L)$. The calculated power dependence as a function of aperture position is shown in Fig. 4. The lateral scale for the calculated data was converted to absolute distance using the measured beam radius and normalizing the data to the 90% power point. It can be seen that as the knife edge is inserted deeper into the resonator mode, the deviation between the measured and calculated power increases. This is due in part to the increased importance of diffractive losses and to the inability of Eq. (7) to predict the output power as $\delta \rightarrow (T + L)$.

The aperture opening time for the 105-μm opening distance is 3.4 μs. To determine the impact of the opening time on the Q-switched output, the pulse buildup time must be known. The pulse buildup time is a function of the Q-switch repetition rate, the ratio of the pump power to the threshold pump power, the passive loss, and the cavity length, and may be determined from the calculations published by Chesler *et al.*[13] For the pump ratios used in this work the calculated pulse buildup times range from 1.9 μs for the 0.860-R mirror to 13.3 μs for the 0.959-R mirror, and they are listed in Table 1. For build-up times much longer than the opening time, the cavity losses will be minimized when the Q-switched pulse is emitted, and the peak output power will be at a maximum. For shorter buildup times, however, the losses are not minimized when the Q-switched pulse is emitted and lower peak power, lower efficiency, and the appearance of secondary Q-switched pulses are among the consequences of operating in this regime. In addition, buildup times shorter than the opening time prevent very short pulse-width production using the chopper.[10] Note that unlike the AO Q switch, the opening time for the mechanical chopper depends on the pump power. Lower power leads to shorter opening times because the insertion loss required for turning the laser off is lower and therefore requires less penetration of the aperture edge into the resonator mode. Secondary peaks are not observed at low pump power.

The data of Fig. 5 provide an important supplement to the knife-edge data presented in Fig. 4. From the Findlay–Clay fit parameters it can be determined that each 20 mW of incremental pump power represents 1.1×10^{-2} additional (round-trip) gain. Therefore each data point corresponds to the position of the knife edge required to introduce an incremental 1.1% round-trip loss. As the knife edge penetrates deeper into the nearly Gaussian resonator mode, the distance required for the knife edge to move to introduce a constant incremental loss decreases. The data indicate that approximately 78 μm of motion are required for the knife edge to move from the edge of the beam to the position where sufficient loss is introduced to eliminate laser operation when pumped with 562 mW. The introduced round-trip loss at full pump power is 0.20. The opening distance determined by this type of knife-edge measurement is more reliable than that represented in Fig. 4, because the scatter of the data and the oblique slope obtained for the latter measurement, when the knife edge is near the edge of the resonator mode, limits the accuracy of the determination of the 98% power-transmission point. Elimination of the laser output at threshold as performed in the measurement represented in Fig. 5 provides a more rigorous definition of the beam edge. The opening distances measured for the output mirrors listed in Table 1 using the knife-edge threshold measurements were similar and ranged from 65 to 85 μm, giving a range of opening times of 2.1–2.7 μs with the 98-mm chopper wheel.

The operation of the mechanical chopper in a cw pumped laser can be described as follows. When the opaque region of the blade prevents feedback, the gain medium absorbs pump light and the upper laser level population soon reaches steady state. As the chopper blade begins to open, the insertion loss decreases, eventually reaching a point where the loss equals the gain. This is the point at which the Q switch is considered to be open. The intracavity flux begins to build up exponentially while the chopper continues to open, lowering the losses further during the pulse-buildup time. Depending on the length of the buildup time, the chopper blade may not be completely out of the beam when the Q-switched pulse is emitted. Referring to Fig. 5, it can be seen that the initial insertion-loss reduction as a function of time is large, but removal of the last 2% of loss requires that the aperture travel almost half of the total opening distance. From Eq. (7) it can be seen that residual losses of only 1–2% can have a significant impact on the output power. If the Q-switched pulse is emitted prior to the complete opening of the aperture, the population inversion remaining after the emission of the initial Q-switched pulse may be high enough to allow the production of one or more additional pulses. A secondary pulse is produced as the intracavity loss continues to be reduced, caused by progressive opening of the shutter. Note that the slower the chopper-opening time relative to the buildup time, the higher the intracavity losses at the time the Q-switched pulse is emitted. The Q-switched pulse dynamics are shown schematically in Fig. 6 and are based on calculations by Midwinter.[10]

The calculated pulse-buildup times given in Table 1 are not correct if the shutter-opening time is slow compared with the pulse-buildup time. As was discussed in relation to the calculation of the pulse width, time-dependent cavity loss and threshold pump power values higher than the steady-state values should be used to calculate the buildup time if the Q-switch opening time is not short relative to the buildup time. The buildup time increases as the pump ratio and cavity losses decrease,[13] but the pump ratio increases as the cavity loss decreases, because of the decreased threshold pump power. The decrease in cavity loss owing to the gradual withdrawal of the aperture from the beam therefore results in two simultaneous, competing factors that affect the time-dependent buildup time. The buildup time is linearly dependent on the loss but inversely dependent on approximately the square of the pump ratio in the region of interest. Therefore the buildup time typically is long at the time the shutter first opens and gradually reduces to the values listed in Table 1 as the shutter continues to move out of the beam. As was mentioned previously, the Q-switch-opening times for all of the mirrors listed in Table 1 are similar.

From the data obtained for the mirrors with the highest transmission it can be seen that Q-switched pulse widths almost two orders of magnitude shorter than the Q-switch-opening time can be obtained. This is a remarkable feature associated with the use of a mechanical chopper as a Q switch. Substituting

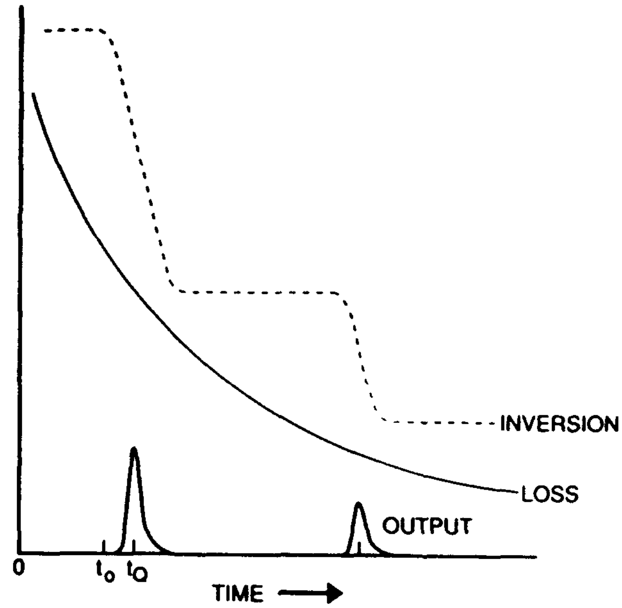

Fig. 6. Schematic representation of the temporal evolution of the Q-switched pulse, intracavity losses, and population inversion for the chopper when the Q-switch opening time is slow compared to the pulse buildup time. The first Q-switched pulse is emitted while the cavity losses are still high, leading to an intermediate population inversion. As the cavity losses continue to decrease, the gain eventually exceeds the loss once again and a second Q-switched pulse is emitted. The second Q-switched pulse width is broader and the peak power is lower than the first pulse. t_0 indicates the time where the cavity losses are reduced below threshold (initial opening position) and t_Q is the Q-switched pulse-emission time. $t_Q - t_0$ is the pulse-buildup time.

an AO Q switch for the chopper produces pulse lengths greater than 100 ns because of the large beam diameter at the Q-switch crystal. Pumping at power levels much higher than those listed in Table 1 produces somewhat shorter pulse widths but also leads to the generation of secondary output pulses. The enhancement factors for all mirrors but those with the highest reflectivities were in the 300–400 range. The enhancement is the ratio of the peak to the average output power. When the Q-switch repetition rate is lowered by reducing the rotation rate of the chopper wheel, the opening time increases, increasing the pulse width and reducing the peak power. In addition the output typically contains secondary Q-switched pulses. If desired, in some cases it is possible to remove the secondary pulse by reducing the aperture width. For the Nd:YAG laser used in this work, the smallest aperture that could be used was 200 μm. At a motor speed of 100 Hz, this width could discriminate secondary pulses occurring at times greater than 2.5 μs after the main pulse, assuming an opening distance of 78 μm, a resonator beam diameter of 200 μm, and a pulse-buildup time such that the Q-switched pulse is emitted at the time that the aperture edge reaches the edge of the mode.

The average Q-switched power was measured as a fraction of the cw power for the Nd:YAG laser. For this measurement a chopper wheel capable of repetition rates up to 3 kHz was used. When operated at the optimum pump power with the output mirrors with lower reflectivities, the ratio of the average Q-switched power to the cw power is typically less than 40%. For a repetition rate of 3 kHz, this represents only 60% of the ratio that is obtained with an AO Q switch.[13] The lower ratio obtained with the chopper results from the residual loss caused by partial opening of the chopper at the time that the Q-switched pulse is emitted. Higher power ratios can be achieved at lower pump power because the lower power increases the pulse-buildup time. The longer buildup time comes at the expense of the Q-switched pulse width. For the 0.898-R mirror, pumping with 562 mW resulted in a power ratio of 0.38. With a pump power of 285 mW, the ratio increased to 0.66. The pulse width at the lower pump power was 140 ns. The higher ratio is comparable to those reported for a Nd:YAG laser acousto-optically Q switched at 3 kHz.[13]

The ratio of average Q-switched power to the average free-running power in the pulsed pumping measurements is dependent on the pulse width as shown in Table 2. The free-running power increases linearly with the pump pulse width because increasing the pulse width increases the pump-duty factor. The average Q-switched power initially increases in an approximately linear manner with the pump pulse width, but as the pulse width exceeds τ the upper laser level population reaches the steady state. These two factors combine to produce the monotonic decline in power ratio with pulse width. Note that for the 150-μs pulse the Q-switched power exceeds the free-running power. This occurs as a result of the short (28-μs) free-running pulse width and the high enhancement factor for Q-switched operation. The good extraction efficiency and long pulse-buildup time near threshold allows more efficient operation in the Q-switched mode than in the free-running mode. Similar observations of increased power ratios as the pump pulse length decreases have been reported for a passively Q-switched Nd:YAG laser.[14] By maintaining short excitation pulse widths, one can operate the laser at relatively low Q-switching rates without sacrificing optical-conversion efficiency. Because diodes are simple to convert from cw to pulsed operation, the diode-pumped Q-switched laser can be made to perform efficiently over a wide range of repetition rates.

While the insertion loss introduced by the chopper is essentially zero when the shutter is open, Q switching with a chopper can introduce a certain degree of inefficiency that has the same effect as insertion loss in terms of limiting the maximum average power. The source of inefficiency is the residual population inversion that is not extracted because of the slow opening time of the aperture, as has been discussed previously. This inefficiency can be contained by controlling the Q-switch opening time relative to the pulse-buildup time. The former is controlled by the revolution rate of the motor, the diameter of the chopper wheel (or more accurately, the radial position on the wheel where the chopping occurs), the resonator beam diameter at the chopper, and the gain, loss, and output coupling.

By proper design of the laser resonator one can use the mechanically Q-switched laser over a wide range of parameters. The mechanical chopper is simply inserted into an operating cw laser cavity and turned on. As a demonstration of the versatility of the mechanical Q switch, the chopper was used with an Yb:FAP laser. The resonator used was typical for end-pumped, cw lasers.[7] The Yb:FAP rod was HR coated on the exterior face and AR coated on the interior face. A 10-cm radius-of-curvature output mirror was located approximately 9 cm away from the interior edge of the laser crystal. The chopper was placed several millimeters away from the interior edge of the crystal, where the beam diameter was approximately 200 μm. The observed pulse width and ratio of average Q-switched power to cw power were measured as a function of the pump power. At 3 kHz the ratio is 0.58 for a pump power of 50 mW. The ratio decreased to 0.34 at a pump power of 500 mW. The threshold pump power is 31 mW with an 0.899-R output coupler. The Q-switched pulse widths were 160 ns at the lower pump power, decreasing to 28 ns for the 500-mW pump.

5. Conclusions

In summary, we have characterized a mechanical chopper used as a Q switch in a diode-pumped Nd:YAG laser and a monochromatically end-pumped Yb:FAP laser. We have noted the advantages of this type of Q switch as well as its limitations. The limitations are related to the slow opening time. This produces some loss in output efficiency and average Q-switched power, pulses that are somewhat broader than optimum, and secondary Q-switched output pulses under certain conditions. We have shown that the mechanical chopper can produce both short pulse widths and high average Q-switched power relative to the cw power, but not simultaneously. High power ratios require low pump power, while short pulse widths dictate higher pump power. The most compelling advantage of using the chopper is the minimum perturbation required to convert a cw cavity to repetitively Q-switched operation. Pulsed pumping was demonstrated with laser diodes to obtain a high ratio of average Q-switched to average free-running power at relatively low repetition rates.

With appropriate design of the resonator, the mechanical chopper can operate efficiently over a wide range of parameters. The interaction between the mechanical aspects of the chopper, including the rotation rate and aperture width, and the resonator parameters, including gain, loss, beam diameter, cavity length, and pump power, have been described and must be considered for effective use of the mechanical Q switch. The key factor for good Q-switched performance is to operate with a short opening time relative to the pulse-buildup time. An empirical definition of the Q-switch opening time has been provided, and the exact temporal dependence of the aperture insertion loss was presented for a longitudinally pumped Nd:YAG laser. It was shown that Q-switched output characteristics, such as pulse width, average power, enhancement factor, and peak power, obtained with the mechanical chopper are comparable to those achieved for AO Q switches. As a result of the present evaluation we conclude that the mechanical chopper is an efficient and convenient means of demonstrating repetitively Q-switched operation for an end-pumped laser.

This work was supported in part by the U.S. Office of Naval Research.

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