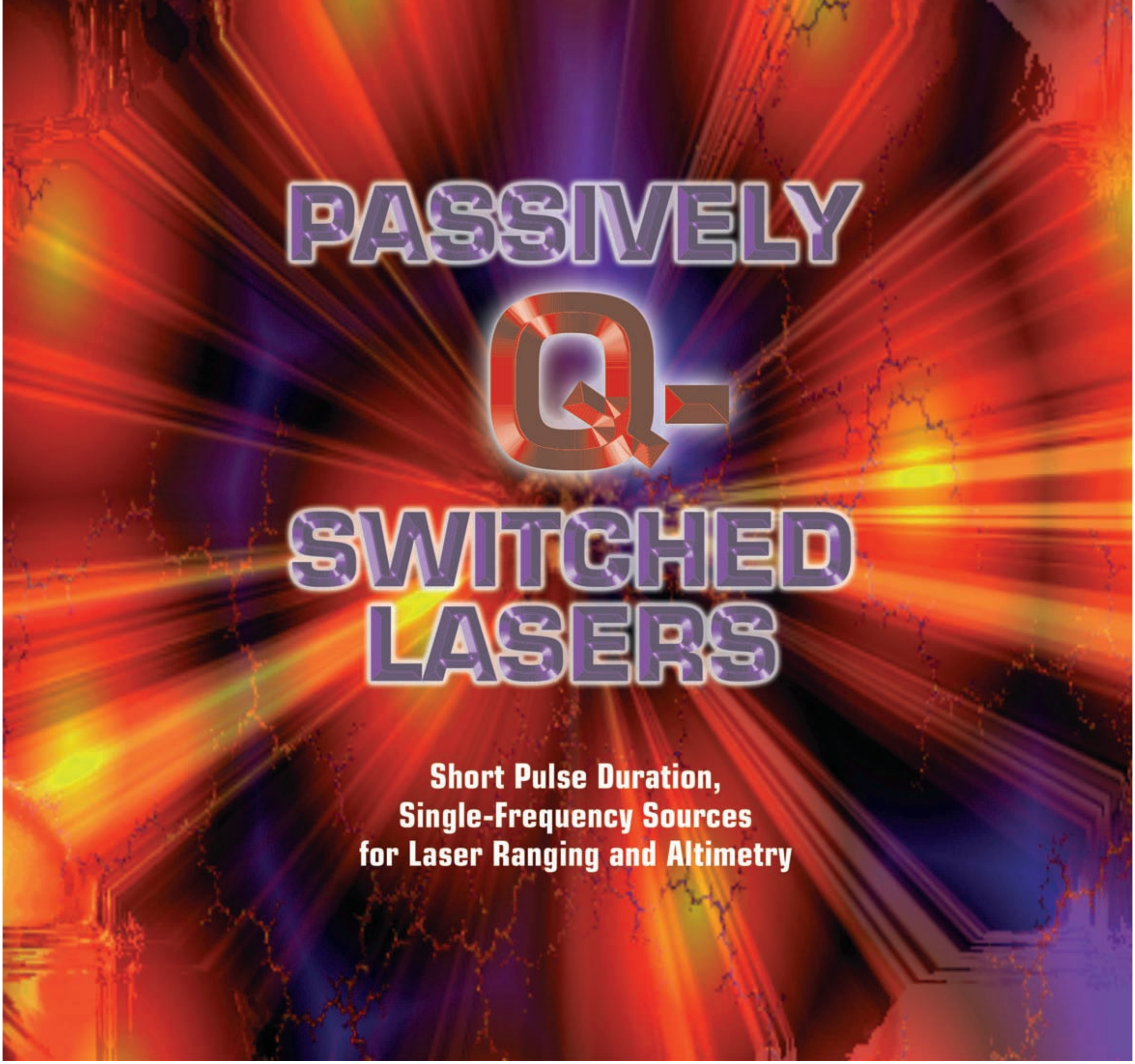

Passively Q-Switched Lasers

Short Pulse Duration, Single-Frequency Sources for Laser Ranging and Altimetry

By David Welford

The first report of short intense pulses of laser light, called giant pulses at the time, was from an actively Q-switched ruby laser [1]. Shortly thereafter, passive Q-switching using an organic dye as a saturable absorber was reported [2]-[4], and this was described using a rate equation analysis [5]. The process of Q-switching involves the introduction of loss in the laser oscillator sufficient to prevent lasing while energy is being transferred to the gain medium. When the loss is removed, an intense photon flux builds exponentially from spontaneous emission, and the coupling of these photons through a partially reflecting resonator mirror leads to the generation of a Q-switched laser pulse. Over the past 40 years, a variety of active and passive loss modulation techniques have been used to generate Q-switched laser pulses as short as several tens of picoseconds or as long as several hundred nanoseconds, with pulse energies that may range from a small fraction of a microjoule to a significant fraction of a Joule. In recent years, the advent of diode laser pumped solid-state lasers and solid-state saturable absorbers has generated renewed interest in passively Q-switched lasers.

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In passive Q-switching, the laser resonator contains a gain medium and an absorbing medium, both saturable and, therefore, nonlinear in response. As the gain medium is pumped, it both accumulates stored energy and emits photons. Over many round trips of the resonator, the photon flux sees gain, fixed loss, and saturable loss in the absorber. If the gain medium saturates before the absorber, the photon flux may build, but the laser will not emit intense pulses. On the other hand, if the photon flux builds up to a level that saturates or bleaches the absorber first, the resonator sees a dramatic reduction in intracavity loss and the laser Q-switches, thereby generating a short, intense pulse of light. This article discusses the use of the passive Q-switching process as a means to generate short-duration, single-frequency laser pulses for use in laser ranging and altimetry.

> Passively Q-switched, diode pumped, all solid-state lasers are an elegant, yet simple, means to generate single-frequency laser pulses in the nanosecond and sub-nanosecond regions.

Q-switched lasers for ranging altimetry, LIDAR, and other types of remote-sensing require short pulse durations (< 10 ns), TEM_{00}-mode profiles, and high spectral purity to provide high-resolution distance measurements from noncooperative targets, i.e., targets that are not highly reflective, at useful ranges. The range resolution in any time of flight measurement is directly proportional to the laser pulse duration and, in the case of smooth and reproducible pulse intensity profiles, may be smaller than one tenth of the pulse duration. On the other hand, a noisy pulse profile can easily degrade the range resolution capability of a system to a value closer to the pulse duration or a factor of ten worse than the best case. Ideally, single-frequency (i.e., single-longitudinal-mode) operation is desired to eliminate amplitude instabilities due to longitudinal mode-beating in direct-detection systems and is essential for the development of homodyne/heterodyne detection systems.

Until recently, the preferred method of obtaining single-frequency operation in a Q-switched laser was to use a single-frequency continuous wave (CW) laser as an injection seed source, or master oscillator, to force the Q-switched laser to operate on only one longitudinal resonator mode. When the laser is going to be used for range and velocity measurements of a target using a homodyne detection technique, the master oscillator is also needed as the local oscillator in the photodetection mixing process. In a range-only measurement system with a direct detection receiver, the complexity of the injection seeding process is unwarranted. This article will show that a short, passively Q-switched laser is well suited to range-only measurement systems because it can generate single-frequency pulses with durations in the sub-nanosecond to several nanosecond range, thereby enabling range resolutions less than 1 cm [6].

One example of such a high-range resolution system is the NASA airborne altimeter [7], which uses a passively Q-switched microlaser. NASA is also planning to use an amplified microlaser in the SLR2000 satellite laser ranging system [8], [9]. Both of these systems operate with pulse energies less than 1 mJ at multikilohertz rates. At the other end of the performance spectrum, a 74-mJ, passively Q-switched laser system is due for launch into a near earth orbit as the transmitter for the Geoscience Laser Altimeter System (GLAS) [10], [11]. GLAS will provide terrain mapping of vegetation, ice sheets, and other geologically and geographically significant features of Earth. The most widely publicized altimeter is the Mars Orbital Laser Altimeter (MOLA) flown by NASA and used to map most of the Martian surface (see http://pao.gsfc.nasa.gov/gsfc/spacesci/pictures/mola/ mars3d.htm for images). Because the MOLA laser was developed nearly a decade ago, it preceded the recent developments in passively Q-switched laser technology and used electro-optic Q-switching, but it could easily be replaced by the GLAS laser.

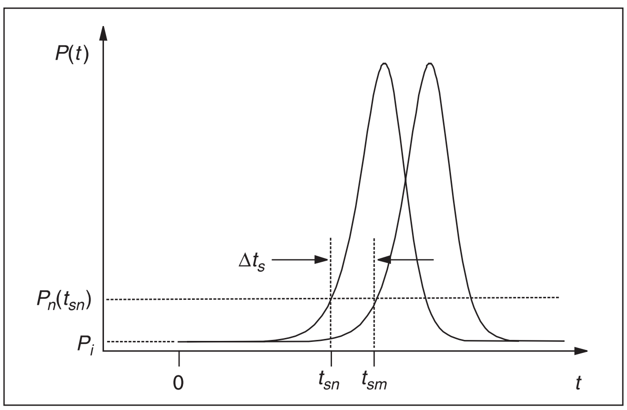
The following two sections of this article review of the operation and performance of two passively Q-switched, diode-pumped, Nd:YAG lasers designed specifically for time-of-flight ranging and altimetry and describe the mechanism by which these lasers operate on only one longitudinal mode. The high peak powers available from these sources also make them suitable for many other applications, including materials processing, micromachining, laser marking, and laser-induced breakdown spectroscopy, to name a few. The ease with which the intense Q-switched laser output can be frequency converted to harmonics of the fundamental frequency using nonlinear crystals or to the near- and mid-infrared through optical pumping of an optical parametric oscillator serve to greatly broaden utility of these devices.

Passively Q-Switched Lasers as Single-Frequency Sources

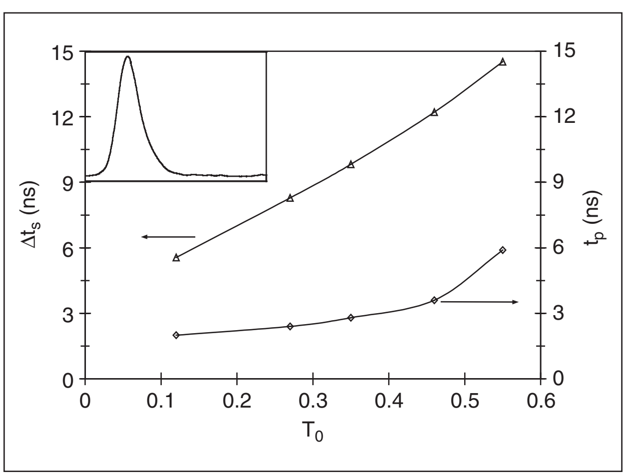
There have been many reports of passively Q-switched, all-solid-state lasers [11]-[18], with the majority of systems being diode-laser-pumped. In previous work, I reported the generation of 5-mJ, 2.4-ns, single-frequency pulses from a Nd:YAG laser using a saturable absorber based on F_2^--color centers in a LiF crystal [14]. This system used a novel diode-laser, transverse-pumping geometry [19] to obtain efficient TEM_{00}-mode operation with a simple, two-mirror linear resonator. A window-polished slab of AR-coated F_2^-:LiF material was added as the saturable absorber for Q-switched operation.

In addition to the simplicity of implementation, the major advantage of a passively Q-switched laser includes the generation of a well-defined pulse energy and duration that is insensitive to pumping conditions as long as the pump energy is above the Q-switching threshold. However, bleaching of the saturable absorber consumes stored energy, which results in lower efficiencies than for actively Q-switched systems. Pulse timing jitter is also greater than in most actively Q-switched systems, but this is not an issue for ranging applications because the transmitted laser pulse is always detected and used as a timing reference regardless of the source characteristics.

Sooy [20] showed many years ago that a relatively slowly opening, passive Q-switch provides greater longitudinal mode selection compared to faster active Q-switches because the long pulse build-up times lead to more passes of the resonator and any mode-selection elements contained therein. As a result, single-frequency operation can typically be achieved with fewer or, in some cases, no intracavity mode-selection elements. Limiting the use of mode-selection elements such as etalons is desirable because they can increase intracavity loss and are prone to optical damage. Careful selection of resonator parameters (in particular, shorter resonator lengths) makes it possible for a simple two-mirror resonator with a passive Q-switch to operate on one longitudinal mode.



1. The temporal evolution of different longitudinal modes.



2. A comparison of the pulse duration τ_p and build-up time difference Δt_s for a 10-cm long, single-mode laser, passively Q-switched laser as a function of the absorber unsaturated transmission T_0. Inset shows the laser output pulse.

According to the work of Sooy, a criterion for single-mode operation in a Q-switched laser is that the dominant mode should be at least ten times greater in peak power than any other mode. Although Sooy's rule of thumb is not substantiated, it is often used to determine the differential loss required between adjacent longitudinal modes when introducing mode-selection elements. Sooy's frequency-domain approach is at odds with experimental data [14] in which no spectral filtering elements were added to the resonator. An alternative approach based on a dynamic analysis of the passive Q-switching process in the temporal domain shows that the difference in gain between adjacent longitudinal modes leads to a difference in pulse build-up times, with the highest gain mode appearing first. This mode then extracts most, if not all, of the stored energy, resulting in a single longitudinal-mode output. This view provides the physical basis for a temporal criterion for single-frequency, Q-switched operation that states: "the difference in build-up time between any two longitudinal modes of the laser resonator should be comparable to or greater than the laser pulse duration to ensure single-frequency operation." In short resonators with lengths less than 10 cm, there is usually sufficient difference in the build-up times of competing modes to ensure single-frequency operation without the use of intracavity mode-selection elements. A rate-equation analysis for the difference in build-up times of any pair of longitudinal modes was developed and applied to the experimental data [21] to demonstrate the validity of the hypothesis.

Figure 1 illustrates the evolution of two longitudinal modes and defines the difference in their build-up times. The Q-switched pulse begins to build up at the time when threshold is reached and continues until the time t_{sn} at which the saturable absorber starts to bleach. Assuming an initial population inversion N_i during this period to be constant and slightly greater than the threshold inversion N_{th}, the build-up time difference Δt_s between the n^{th} and m^{th} modes is

$$\Delta t_s = \ln\left(\frac{P_n}{P_i}\right)\frac{t_l}{2\sigma_n l_a N_{th}}\frac{(1+\varepsilon)}{\varepsilon^2}\left(\frac{\sigma_n-\sigma_m}{\sigma_m}\right). \quad (1)[21, Eq. 8]$$

The photon density at the onset of bleaching $P_n(t_{sn})$ may be obtained from the saturation intensity of the absorber, which for the F_2^-:LiF material is equal to 5×10^{18} photons/cm^2. Using the parameters of the Nd:YAG gain medium described in [19], $P_n(t_{sn})$ is 10^{19} photons/cm^3. P_i can be evaluated by considering the density of spontaneous emission coupled to the resonator mode and is found to be 10^8 photons/cm^3. Hence, $\ln(P_n / P_i)$ is approximately 27. Note, this value is only weakly dependent on P_i and $P_n(t_{sn})$.

Experimentally, weak microsecond-duration laser pulses were observed at pumping rates approximately 1.8% below the Q-switched pumping rate [14], which gives $\varepsilon = 0.018$. Note, that the Q-switched pumping rate is the rate at which a single pulse is generated. Pumping at higher rates does not necessarily result in higher pulse energies or multiple pulses until twice the pumping rate is reached; when a second pulse is generated.

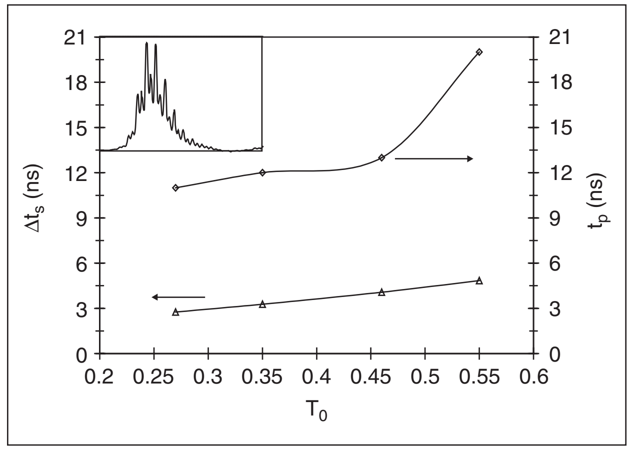
The term $\sigma_n l_a N_{th}$ in (1) is equal to the total cavity loss through the threshold condition and, therefore, includes the effect of unsaturated absorber loss T_0 and the output coupling. The resonator length L_c influences (1) through the round trip time t_l and the modal-gain difference $(\sigma_n - \sigma_m)/\sigma_m$. It can be shown that, assuming a Lorentzian gain profile, the modal gain difference is approximately equal to $(L_c^2 \Delta\nu^2)^{-1}$, where $\Delta\nu$ is the full width at half-maximum bandwidth, which for Nd:YAG is equal to 4 cm^{-1}.

Analysis of the 10- and 30-cm-long laser resonators described in [14] gives the build-up time differences for adjacent modes, e.g., $m = n + 1$, shown in Figures 2 and 3, which also include the measured pulse durations t_p. These data clearly indicate the build-up time differences are greater than the pulse durations for the short resonator and much shorter than the pulse durations for the long resonator. Hence, the long resonator should operate on several longitudinal modes because the modes all have enough time to reach threshold before the stored energy is extracted. In the case of the short resonator, the dominant longitudinal mode will have extracted almost all the stored energy by the time an adjacent mode reaches threshold, and the laser pulse is expected to be single-mode. Pulses from the short resonator (Figure 2) showed no evidence of the mode beating associated with multimode operation, while pulses from the long resonator (Figure 3) showed strong mode beating. Thus, the experimental results are indicative, as predicted, of single-mode operation for the 10-cm resonator and multimode operation for the 30-cm resonator.

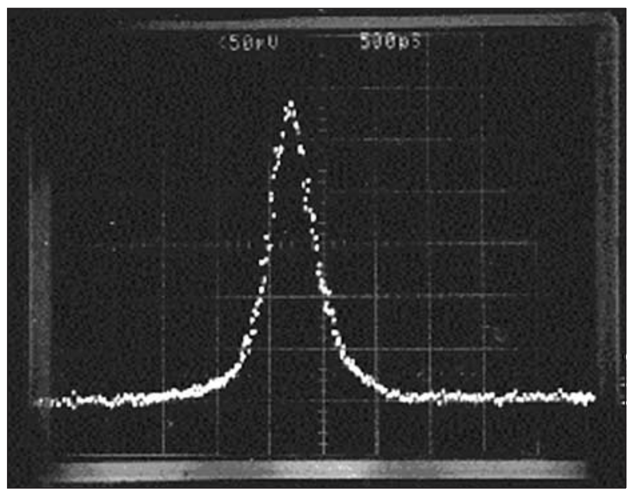
To summarize, a passively Q-switched laser may oscillate on a single longitudinal mode when the difference in build-up times between any pair of longitudinal modes is greater than the Q-switched pulse duration. This condition can be achieved without the use of additional frequency-selection elements and facilitated by the use of a short resonator and a saturable absorber with large saturation fluence. The analytical approach [21] that resulted in (1) may be applied to the design of any passively Q-switched laser to ensure single-frequency operation. The pulse duration can be estimated using expressions given by Degnan [22] or Patel and Beach [23].

Amplification of Sub-Nanosecond Passively Q-Switched Microlasers

The short resonator designs used to obtain reliable single-frequency operation in passively Q-switched systems also facilitate the generation of pulse durations in the nanosecond regime. A simplistic view would be to state that the pulses build and decay faster with a shorter resonator round trip time, hence leading to the generation of shorter pulses than for an equivalent resonator of longer length. Pulse durations as short as 2.4 ns with 5.0-mJ energies were generated with the 10-cm long resonator described above [14]. In the limit of millimeter-sized resonators, the passively Q-switched microlaser technology developed by Zayhowski [15] excels in the generation of sub-nanosecond, single-frequency pulses, but at the expense of pulse energy because



3. A comparison of the pulse duration τ_p and build-up time difference Δt_s for a 30-cm long, multimode laser, passively Q-switched laser as a function of the absorber unsaturated transmission T_0. Inset shows the laser output pulse.



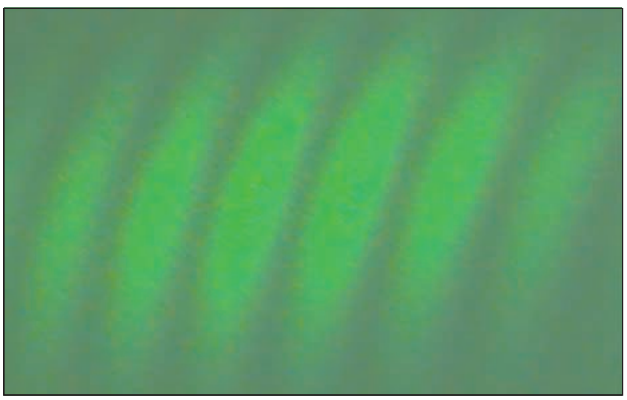
4. A 440-ps duration, passively Q-switched microlaser pulse.

the shrinking volume of the gain medium dramatically reduces the stored energy capacity.

When the pulse durations fall below 1 ns (see Figure 4), accurately measuring them requires the use of state-of-the art instrumentation. Unfortunately, the same instrumentation is not always capable of resolving longitudinal-mode beating to confirm single-frequency operation. In the case of a passively Q-switched microlaser, one way to confirm single-frequency operation is in the frequency domain using optical interferometery. One such technique is to frequency double the 1,064-nm radiation to 532 nm and observe the optical beam through a Fabry-Perot etalon with a thickness chosen to give a free spectral range two to five times that of the microlaser resonator. Figure 5, for example, shows a photograph of an image of the interference fringes obtained in this way for an etalon with a free spectral range of 30 GHz and a passively Q-switched microlaser with longitudinal mode spacing of 20 GHz. There is no evidence of multiple longitudinal mode lasing, which would fill in the dark fringes and eliminate the contrast of the interference pattern.

Zayhowski has demonstrated passively Q-switched microlasers with a range of pulse energies from 4-250 μJ and pulse durations of 218-2,200 ps [15]. The subnanosecond pulse durations from passively Q-switched microlasers are extremely useful for high-resolution ranging, and these lasers have been directly used for short-range imaging of buildings and industrial structures (go to www.cyra.com/case_studies for images), but the pulse energies are too low for direct use in most altimetry applications. The solution is to let the microlaser define the pulse width and pulse rate and to use a high-gain amplifier to increase the pulse energy [16], [18]. For a 1,064-nm, Nd:YAG/Cr:YAG, passively Q-switched microlaser, either Nd:YAG or $Nd:YVO_4$ may be used for the amplification stage. Given the relatively low oscillator pulse energies and the need to drive the amplifier into saturation for efficient extraction of energy, $Nd:YVO_4$ is the preferred gain medium because of its increased emission cross-section and lower saturation energy. The combination of microlaser oscillator and a power amplifier (MOPA) makes it possible to design a laser to meet specific performance goals such as those for SLR2000 [8].

> Longer wavelength material properties are expected to only allow the generation of longer duration pulses. ....near-term advances are anticipated in the development of higher average power systems operating at multikilohertz pulse rates.

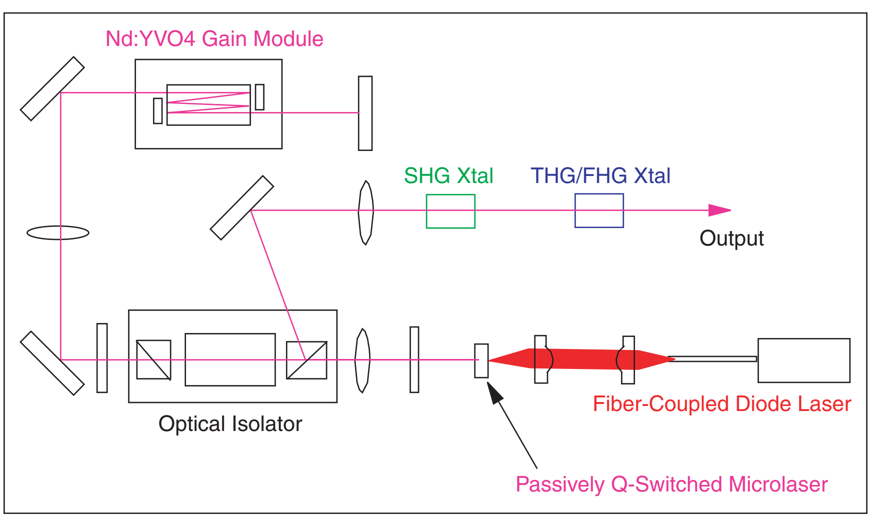


5. An interferogram of the output beam from a frequency-doubled, passively Q-switched laser pulse formed by passing through a 30-GHZ free spectral range etalon. The laser resonator mode spacing was 20 GHz.

With reference to Figure 6, a high-gain $Nd:YVO_4$ amplifier was used to generate 335-μJ pulses from a Cr:YAG passively Q-switched Nd:YAG microlaser generating 3.2-μJ pulses, in a prototype laser for the SLR200 system. The amplifier small-signal gain was approximately 40, and it was operated in a double-pass configuration with an optical isolator between the amplifier and oscillator. The oscillator pulse durations of 440 ps (see Figure 4) were compressed to 370 ps as a result of the amplification process.

The oscillator was end-pumped with a 1.2-W fiber-coupled diode laser operated in a pulsed mode at a 2-kHz rate, while under CW pumping it was capable of pulse rates on the order of 10 kHz. The amplifier used a novel mulipass slab geometery [24] to achieve high-gain and low optical aberrations. The amplified output beam quality was excellent, with M^2-values of 1.38 and 1.28 in the horizontal and vertical planes, respectively.

Approximately 14 W of average power could be extracted from the amplifier in a CW laser resonator in the TEM_{00} mode when pumped with a pair of 20-W, 1-cm diode laser bars. If we assume a corresponding amount of stored energy is available for extraction in the amplification mode, pulse energies of approximately 1 mJ could be generated with higher pulse input energies at pulse rates up to 10 kHz.



6.Schematic layout of an amplified, passively Q-switched microlaser system.

The amplified output pulses with peak powers of 1 MW were efficiently frequency-converted to the second, third, and fourth harmonics in the appropriate nonlinear crystals without resorting to beam focusing. The second harmonic was generated in a noncritically phase-matched, Type I LBO crystal, with dimensions of 3 × 3 × 15 mm, mounted in a 170 °C, temperature-stabilized oven. The third harmonic was generated in a critically phase-matched, Type II LBO crystal ($\theta = 42.7°$, $\phi = 90°$) with dimensions of 3 × 3 × 12 mm at room temperature. The fourth harmonic was generated in a critically phase-matched, Type I BBO crystal ($\theta = 47.6°$, $\phi = 0°$) with dimensions of $3 \times 3 \times 7$ mm at room temperature. The second, third, and fourth harmonic pulse energies were 200, 120, and 43 µJ, respectively, for fundamental input pulse energies of 335 µJ, which corresponds to conversion efficiencies of 60, 36, and 13%.

Summary

Passively Q-switched, diode pumped, all solid-state lasers are an elegant, yet simple, means to generate single-frequency laser pulses in the nanosecond and sub-nanosecond regions. The majority of the work on these systems has been in the 1-µm region, but recent developments at eye-safe and mid-infrared wavelengths of both diode-pumped lasers and solid-state saturable absorbers will probably lead to practical, passively Q-switched lasers at longer wavelengths. However, longer wavelength material properties are expected to only allow the generation of longer duration pulses. In the 1-µm region, near-term advances are anticipated in the development of higher average power systems operating at multikilohertz pulse rates, with pulse energies exceeding 1 mJ and corresponding improvements at second, third, fourth, and even fifth harmonic wavelengths.

I hope this brief review of the requirements for single-frequency operation of passively Q-switched lasers and the two system examples presented herein will spark the interest of some readers enough to dig deeper into the subject matter. For those that are interested, the cited references are an excellent starting point.

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