Single-frequency, 500-ns laser pulses generated by a passively Q-switched Nd laser

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We demonstrate a simple, passive technique for producing 500-ns pulse lengths with a Nd laser. The measured 1.5-MHz upper limit to the pulse spectral width indicates that it is nearly transform limited.

Over the past several years, there has been a growing interest in the development of pulsed, coherent, solid-state laser radar systems for a variety of scientific, commercial, and military applications. This interest arises from recent advances in solid-state laser technology, primarily the advent of diode pumping[1] for increasing the efficiency and the operating lifetime, but also from the availability of technologies such as phase conjugation[2] that allow energy and average-power scaling beyond levels previously possible. A base-line solid-state laser radar system is generally assumed to comprise a narrow-band, frequency-stable cw or quasi-cw oscillator, which is subsequently amplified to the power level of interest for a given application. In previous reports[3,4] that documented this approach, the oscillator was typically a diode-pumped, miniature cw Nd:YAG laser producing ~10 mW output power. The oscillator beam was then amplified by a high-gain (~60–65 dB), multipass, pulsed Nd:YAG amplifier to produce a pulse energy from ~5 to 10 mJ and a pulse length from ~1 to 10 μs; this output level was sufficient to demonstrate coherent detection. Many practical applications, however, require higher energies and, therefore, greater amplification. Increasing the amplification beyond the demonstrated values ~65 dB can be challenging, primarily because of the increased requirement of optical isolation for preventing parasitic oscillations. Moreover, if efficient extraction of the energy stored in the amplifier is desired, the laser system must be designed such that the amplifier is heavily saturated. This requirement, in turn, leads to the need for some degree of temporal pulse shaping before the oscillator beam is injected into the amplifier chain; pulse shaping can avoid the severe temporal distortion that amplifier saturation imposes on a pulse with a uniform temporal pulse shape.

Here we describe the construction and performance of a narrow-band Q-switched oscillator that addresses these practical challenges. First the oscillator produces a peak power ~30 dB greater than that available from existing cw diode-pumped Nd:YAG lasers, thereby reducing the amplifier gain requirement by a corresponding 30 dB. Second, the Gaussian temporal pulse shape produced by the oscillator has been shown[5] to be subject to minimal temporal distortion in a heavily saturated amplifier. Finally the oscillator pulse has a duration of ~500 ns and is constrained to operate in a single longitudinal mode; measurements indicate that the pulse has a nearly transform-limited frequency bandwidth of ~1.5 MHz, which is sufficiently narrow for many applications.

Our oscillator comprises a lamp-pumped Cr:Nd:GSGG laser rod, a saturable absorber Q switch, a 100% reflector, an aperture for mode control, and several étalon surfaces forming the output coupler. It operates in a single-longitudinal mode and single-transverse mode. In contrast to earlier efforts[5,6] that employed active devices to produce pulse durations of ~1 μs, there are no active components in the present oscillator other than the flashlamp. We are aware of only two other attempts to generate pulse durations of ~1 μs without active components. Bespalov *et al.*[7] achieved operation in the desired pulse length regime by employing a 4-m-long resonator without a Q switch and operating the laser just above threshold. However the pulse length varied from 3 to 5 μs from shot to shot. Voss and Goldberg[8] reported the ability to control the pulse length of a Nd:YAG laser by using an approach similar to the one described here. The maximum pulse length reported was 300 ns. The

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authors' conclusion, based on the absence of any observable temporal structure, was that the laser was operating in a single-longitudinal mode. However the spectral bandwidth was not quantified. Since any of several mechanisms[9] can cause the frequency of a single-mode laser to drift during the pulse, it is important to make quantitative spectral measurements of the type reported here before a laser can be considered suitable for laser radar applications.

The design approach we selected exploits two key aspects of a saturable-absorber Q switch. First the nonlinear behavior of such a Q switch promotes operation in a single-longitudinal mode. This fact is well known and is often utilized in the design of commercial lasers. Second one can control the pulse duration over a range extending from $\sim 1\ \mu s$ to ~ 1 ns by systematically varying the unsaturated optical density of the Q switch. In the absence of any Q-switch dye, the long-pulse output consists of a series of pulselets that are representative of the relaxation oscillations typically referred to as spiking. As one increases the dye concentration from zero, the total number of spikes gradually decreases until only a single pulselet remains. In many applications of Q-switched lasers, one is primarily interested in achieving a high peak power. In such cases the dye concentration is further increased to reduce the pulse length, raise the pulse energy, and increase the peak power. The dye concentration is typically increased to the point that the pulse length is from ~ 10 to 20 ns.

In our case, we fixed the dye concentration at the value that ensures just a single stable output pulse. For a given resonator configuration and length, the duration of this pulse depends primarily on the laser medium selected. Analysis of relaxation oscillations in lasers[10] indicates that the oscillation period, or duration of a single pulselet, varies approximately inversely as the square root of the stimulated-emission cross section of the laser medium. For this reason, we selected Cr:Nd:GSGG as the laser medium rather than Nd:YAG, because the Nd cross section in GSGG is a factor of ~ 2.5 smaller than in YAG.[11] Cr:Nd:GSGG also offers a pumping efficiency that is nearly twice that of YAG.[12]

The laser design is shown schematically in Fig. 1. As mentioned above, it comprises a lamp-pumped Cr:Nd:GSGG laser rod 4.3 mm diameter × 83 mm long, a saturable-absorber Q switch, an aperture for mode control, and several étalon surfaces that form the output coupler. The positions at the laser rod, Q switch, and aperture within the resonator are shown roughly to scale in Fig. 1. The geometry of the resonator is flat–flat with a few hundredths of a diopter thermal lens developed in the laser rod. The Q-switch dye is Kodak bis(4-dimethylaminodithiobenzil) nickel dissolved in spectrophotometric grade 1,2-dichloroethane, which has been demonstrated to be photochemically stable[13] and gives a ground-state relaxation time of 3–4 ns (see Ref. 14). The dye concentration was sufficient to obtain an unbleached optical density of 0.03 at the laser wavelength in the Q-switch cell. When the dye concentration was increased by a factor of 2, the laser pulse length decreased by approximately the same factor. The laser operated in a single-longitudinal mode and single-transverse mode. The resonator length was kept relatively short at 1.25 m, although we characterized the performance with lengths as great as 4.5 m. Longer lengths produced longer pulse durations, but they suffered from excessive mode beating–locking. A computer program was used as an aid in setting the étalon spacings in such a way as to provide a narrow spectral selectivity.

By using this configuration, the laser output was nearly diffraction-limited, and produced an output energy of ~ 0.2 mJ. The pump energy to the flash lamp was 2.4 J. It operated at a pulse repetition frequency of 10 Hz, which is convenient for most laboratory experiments, and had a reasonable shot-to-shot energy stability with a rms variation of 20%. The pulse temporal evolution is shown in Fig. 2. The measured pulse duration was 500 ns (FWHM) with an rms variation of 100 ns.

We characterized the frequency content of the output pulse by using several complementary diagnostics, including a fast photodetector, a Fabry–Perot interferometer, and finally an interferometer with which we measured the coherence length. The output of the fast photodetector was connected to a Tektronix 7834 oscilloscope (overall system frequency response was ~ 400 MHz) for searching for longitudi-

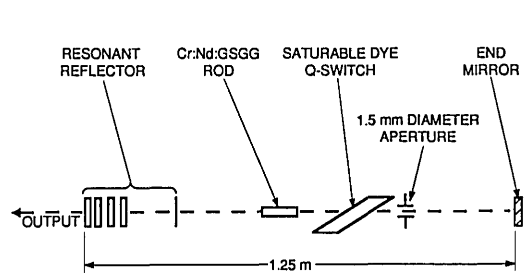

Fig. 1. Schematic of resonator producing a 500-ns Q-switched pulse. The frequency bandwidth is nearly transform limited, and the beam quality is essentially diffraction limited.

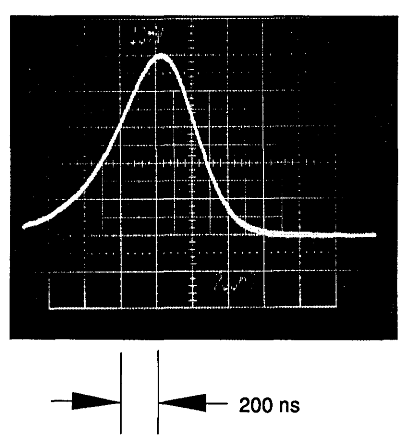

Fig. 2. Temporal pulse shape produced by the resonator in Fig. 1. The absence of any temporal structure is evidence of the absence of any longitudinal modes adjacent to the primary mode.

nal modes in the vicinity of the main mode. Given the resonator length, the longitudinal mode spacing is 120 MHz. The presence of side modes would appear as a temporal structure or beating in the oscilloscope trace of Fig. 2. Because a side mode with an energy of 1% of the main mode corresponds to a relative electric-field amplitude of 10%, it would produce a peak-to-peak ripple of 20%. Figure 2 shows clearly that such modes do not exist, at least within the bandwidth of the detector-oscilloscope combination. The Fabry–Perot interferometer was employed for determining whether spectral components existed at large frequency excursions (>300 MHz) from the main mode. Measurements were made with three different free spectral ranges, 3.7, 15, and 40 GHz. In no case was any spectral component visible, other than the main mode. The Fabry–Perot measurement could identify any side mode with a relative energy of at least $\sim 1\%$. On the basis of these results we were reasonably confident that the output was single mode.

To guarantee narrow-band operation, one needs to measure the spectral width of this mode or, equivalently, the coherence length of the output beam. The coherence length of the output pulse was determined by measuring the fringe visibility produced by the interferometer that is shown schematically in Fig. 3. The oscillator output was split by a beam splitter into two equal beams. One beam was directed through a spatial filter to serve as a reference beam. The other beam was focused into a fused-silica-fiber delay line. In order to prevent stimulated Brillouin scattering (SBS) or any other nonlinear process from occurring in the fiber, the beam was attenuated by neutral-density (N.D.) filters before entering the fiber. The amount of attenuation was determined by calculating the theoretical threshold for SBS in the fiber with 5×10^{-9} cm/W as the value for the SBS gain coefficient.[15] We then verified this experimentally by examining the temporal shape of the pulse transmitted through the fiber at powers above and below the calculated threshold. Above threshold we observed a depletion of the pump pulse that was similar to that observed by Ippen and Stolen.[15] Our observed threshold value agreed with our calculation within a factor of 2. The fiber length was 40 m for an equivalent optical length of 60 m and produced the temporal delay indicated in Fig. 4. The radiation transmitted by the fiber was recombined with the reference beam at an uncoated glass wedge beam splitter, and the time-integrated fringe visibility of the interference pattern was recorded by a Reticon line-scan camera. The fringe visibility is defined[16] by

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{1}$$

where $I_{\max}$ and $I_{\min}$ are the adjacent maximum and minimum intensities, respectively, that are observed in the interference pattern.

For two transform-limited Gaussian-shaped pulses separated in time, as indicated in Fig. 4, the calculated fringe visibility is 0.93. Any reduction of the visibility from this value may indicate that the pulse is not transform limited. Figure 5 shows the interference fringes recorded by the camera. The measured fringe visibility of 0.75 represents an upper limit to the frequency bandwidth of 1.5 MHz, or ~ 1.7 times the transform limit.

In conclusion, we have constructed and characterized a simple, narrow-band, 500-ns Cr:Nd:GSGG laser. The measured upper limit to the spectral bandwidth of the output pulses is 1.5 MHz or slightly greater than the transform limit for such a pulse. The shot-to-shot energy stability and pulse length stability are good ($\pm 20\%$), and the peak power of the 0.2 mJ pulses is ~ 400 W. This peak power is more than 3 orders of magnitude greater than the output power of the presently available miniature diode-pumped cw Nd lasers that are presently employed as oscillators for solid-state laser radar systems. This demonstrated oscillator design can be improved by converting to diode pumping. In addition, by using injection seeding techniques[17] to control the frequency bandwidth, the multiple étalons can be removed. This oscillator can be used in several applications. We mentioned above the growing importance of narrow-

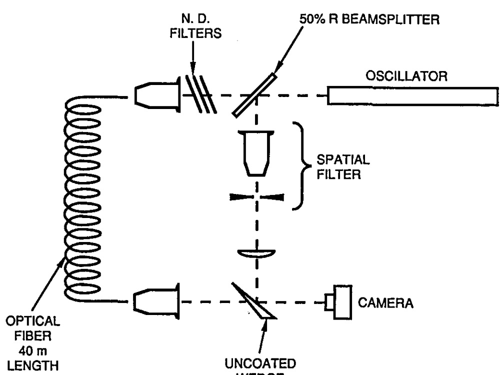

Fig. 3. Schematic of interferometer utilized to characterize the fringe visibility of the laser output pulse. An optical fiber with a physical length of 40 m provides an optical delay of 200 ns in one leg of the interferometer.

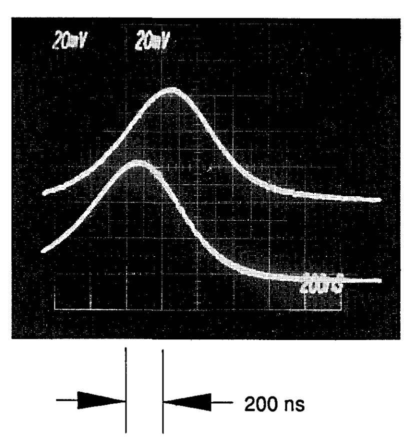

Fig. 4. Oscilloscope photo that shows the relative pulse timing of the two legs of the interferometer of Fig. 3.

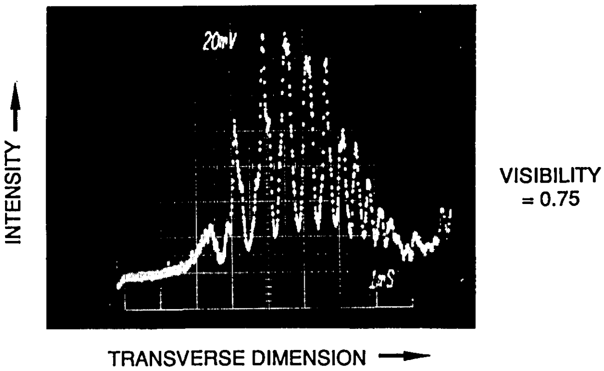

Fig. 5. Fringes formed by the interference of the two pulses shown in Fig. 4. The fringe visibility of 0.75 represents an upper limit to the frequency bandwidth of 1.5 MHz or approximately 1.7 times the transform limit.

band oscillators for solid-state laser radar sources. In addition, this laser can be used in large-base-line holography. From Fig. 5, for example, we conclude that this source can be used to form holograms of objects with characteristic dimensions of 30 m.

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