# Two-Frequency Injection-Seeded Nd : YAG Laser

T. D. Raymond and A. V. Smith

***Abstract*—Dual longitudinal mode (DLM) operation of a Nd : YAG laser is achieved by simultaneously injection seeding with two seed frequencies. We show that the relative energy in the two frequency components can be adjusted by varying the relative seed power, and that they have excellent spatial, angular, and temporal overlap. The result is a deeply modulated 1.06-$\mu$m pulse with a modulation frequency that can be tuned from 185 MHz to at least 17 GHz in 185 MHz increments. In addition to the two seeded frequencies, weak sidebands are also observed in the output spectra. Their energy content is typically less than 1% of that of the seeded modes. We discuss mechanisms which might cause them.**

## I. Introduction

INJECTION seeding of solid-state pulsed lasers [1], [2] has been shown to be an efficient means of producing single-longitudinal mode (SLM) operation. Such SLM lasers are widely used in spectroscopic and nonlinear optical measurements. A natural extension of this technology is the simultaneous injection of two or more seed frequencies to generate multiple output frequencies and to tailor the temporal waveform of the output pulse. Such sources might find applications in nonlinear frequency conversion and for high-speed optically-driven electrical switches [3]. In this paper, we demonstrate that a $Q$-switched Nd : YAG laser can be reliably operated on two independently selectable longitudinal modes. We show that such dual-longitudinal mode (DLM) operation can produce pulses that are deeply modulated at the mode difference frequency, and that for our laser, the difference frequency can be tuned from 185 MHz to 17 GHz in 185 MHz increments. We also find that the modulated intensity within the laser medium generates additional weak sidebands in the spectral output of the DLM laser. We discuss mechanisms that might produce these.

## II. Apparatus

Our experimental apparatus, diagrammed in Fig. 1, consisted of two continuous-wave, tunable Nd : YAG seed oscillators (Lightwave Electronics Model 120), a beam combining optic, and a $Q$-switched Nd : YAG laser oscillator (Quanta Ray DCR2A). The beams from the temperature-tuned seed lasers were combined on a beamsplitter with 50% directed through an optical isolator to the $Q$-switched oscillator. The remaining 50% was directed to a scanning confocal etalon to monitor the frequency difference between the seed lasers. We obtained good injection-seeding performance with approximately 0.4 mW of power from each seed laser.

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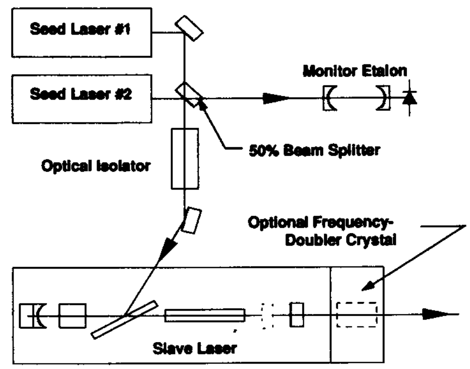


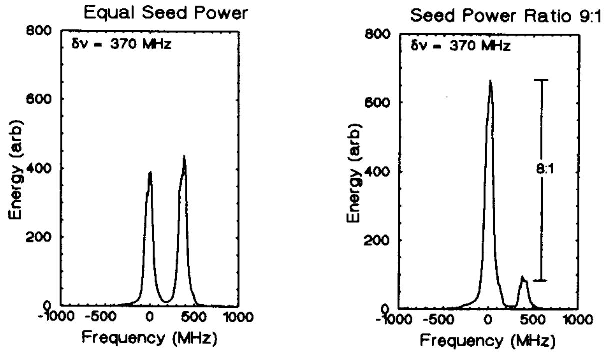

Fig. 1. The experimental apparatus consists of two low-power seed lasers whose beams are combined using a 50% beam splitter, and tuned to be resonant with different longitudinal modes of the $Q$-switched laser. The $Q$-switched laser is a flashlamp-pumped Nd : YAG laser with a graded-reflectivity output coupler and a piezo-electrically adjustable cavity length. A monitor etalon is useful for adjusting the frequency difference between the seed lasers. The $Q$-switched cavity is kept in resonance with the seed frequencies by monitoring the buildup time for $Q$-switched pulse.

The $Q$-switched oscillator was a standard 10 pulse per second, flashlamp-pumped, Nd : YAG laser, with a graded-reflectivity output coupler and a rear mirror mounted on a piezo-electric transducer, to permit fine cavity-length adjustment. Two quarter-wave plates positioned on opposite ends of the Nd : YAG rod minimized the effects of spatial hole burning. An optional, low-finesse etalon could be inserted into the cavity to balance the gain at the two-seed frequencies. The output beam from the oscillator passed through an unpumped amplifier rod. A frequency-doubling crystal could be inserted in the output beam to generate 532 nm light.

Injection-seeding was accomplished in the usual fashion [4] by injecting the $Q$-switched cavity via the $Q$-switch polarizer and monitoring the buildup time of the $Q$-switched pulse in order to optimize the length of the Q-switched cavity. The attenuated 1.064-$\mu$m or 532-nm pulses were monitored using a fast vacuum photodiode (Hamamatsu R1328-2) and a 4.5-GHz transient recorder (Tektronics SDC5000). A scanning 7.5-GHz free spectral range (FSR) confocal etalon with a finesse of 100 monitored the spectrum of the 1.06-$\mu$m pulses, and a fixed-gap 30-GHz FSR Fabry–Perot etalon monitored the spectrum of the 532-nm light.

## III. Technique

To obtain DLM operation, both seed frequencies must be nearly resonant with separate longitudinal modes of the $Q$-switched oscillator. To achieve this, we first optimized the $Q$-switched cavity's length for one of the seed lasers (frequency $\nu_1$) by minimizing the buildup time of the $Q$-switched pulse. Keeping the cavity length fixed, we then blocked that seed laser and injected light from the other seed laser. Its frequency,




(a) (b)

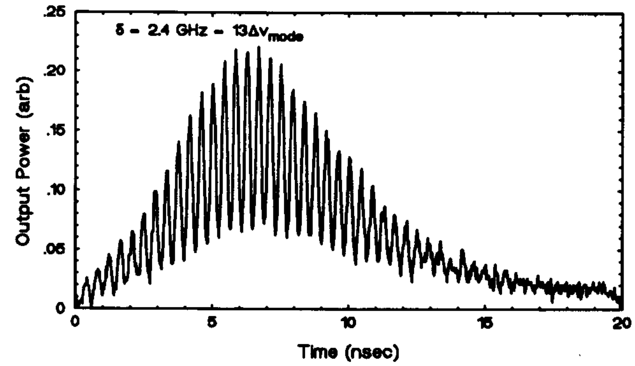
Fig. 2. The spectrum of the 1.06 $\mu$m, DLM laser output as taken with a scanning confocal etalon having a 7.5 GHz free spectral range. Each spectrum required about 100 seconds to acquire with four shots averaged per 8 MHz frequency increment. (a) Two seeds are injected with equal power to generate equal output energies in each injected mode. (b) With a seed power ratio of 9:1, the output energy ratio becomes 8:1.

$\nu_2$, initially coarsely set to produce the desired modulation frequency, was then fine-tuned to again minimize the pulse buildup time. This procedure set the frequency difference between the seed beams, $\delta\nu = \nu_1 - \nu_2$, nearly equal to an integral multiple of the FSR of the $Q$-switched cavity, so it was simultaneously resonant for both seed frequencies. We observed reliable seeding for seed frequencies tuned within ±20 MHz of exact cavity resonance. The excellent frequency stability of the seed lasers precluded the need to actively control the frequency difference between the seed lasers.

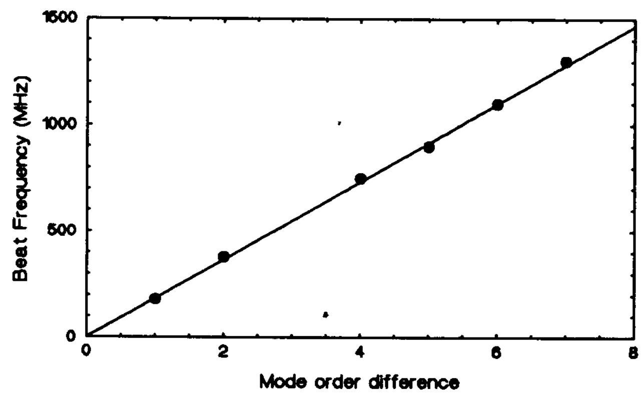
Once $\delta\nu$ was properly adjusted, the $Q$-switched cavity could be held in resonance with both seed frequencies in the usual way by minimizing the pulse buildup time [4]. To monitor the buildup time, we used a low-bandwidth detector (<100 MHz) to minimize the effects of the intensity modulation of the $Q$-switched pulse on the locking circuit. When the seeded modes differed by more than one cavity FSR, the detector did not resolve the high-frequency modulation and locking proceeded without additional effort. However, when the seeded modes were only a single FSR apart (185 MHz), the detector could resolve the intensity modulation and this created difficulty in locking because of randomness in the phase of the intensity modulation relative to the $Q$-switch firing time. This problem was corrected and highly reproducible waveforms were produced by triggering the $Q$-switch in phase with the modulation. We accomplished this by detecting the phase of the modulation of the seed light in the light rejected from the beam combiner using a fast photodiode and a gated discriminator. The discriminator's output was enabled with our normal laser-fire-command signal to trigger the $Q$-switch. We could vary the phase of the beat signal relative to the pulse envelope by adjusting either the time delay to the $Q$-switch or the discriminator threshold setting.

## IV. Results

The spectrum of the 1.06-$\mu$m light from the DLM laser is shown in Fig. 2, for a difference frequency between seed lasers of 370 MHz, or twice the FSR of the $Q$-switched cavity. The spectral width of each frequency component is consistent with the transform limit of the 8-nsec (full width at half maximum) measured pulse envelope. The total output energy for DLM operation was comparable to that for SLM operation, with the energy being partitioned between seeded modes according to the relative gain and seed power at each mode. When the seed beams had equal power, as in Fig. 2(a), the energy of the two output modes could be routinely balanced to within ±15%. In the example shown, the gain of the two-seeded modes was nearly equal because their frequency difference was small compared to the gain bandwidth of Nd:YAG. The seed-power ratio could be used to adjust the relative energy in the two output modes, as illustrated in Fig. 2(b), where a seed-power ratio of 9:1 produced an output energy ratio of about 8:1. When seeding with beams with $\delta\nu$ greater than about 10 GHz, we found it convenient to use the low-finesse intracavity etalon to balance the gain between the seeded modes. In this manner, we obtained equal-mode energy DLM operation with one seed tuned to the gain center and the other tuned 17 GHz away.




(a)




(b)

Fig. 3. The temporal waveform of the 1.06 $\mu$m, DLM laser output intensity exhibits a deep modulation at the difference frequency between the seeded modes. (a) The apparent depth of modulation is limited by the bandwidth of the detection system. (b) The measured beat frequency is an integer multiple of the $Q$-switched cavity free spectral range.

Fig. 3(a) shows the mode beating in the temporal waveform of the 1.06 $\mu$m light for $\delta\nu = 2.4$ GHz, or 13 times the $Q$-switched laser's FSR. Fig. 3(b) shows the expected linear dependence of the beat frequency with the longitudinal-mode order difference between the seeded modes for beat frequencies low enough to measure with our fast detector.

The depth of modulation in Fig. 3(a) is limited by the net bandwidth of the detection system. For smaller beat

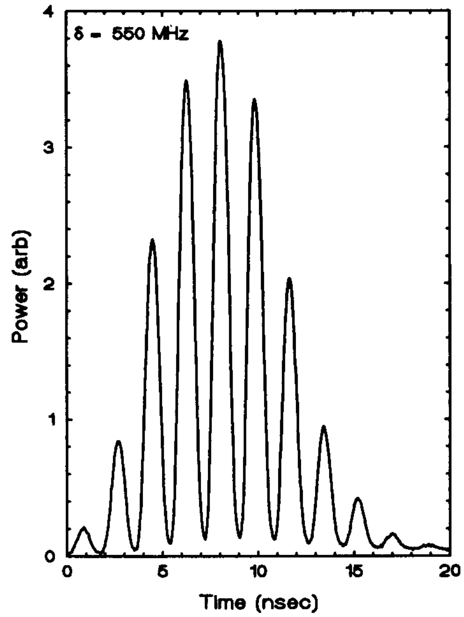


Fig. 4. The frequency-doubled output from the DLM laser.

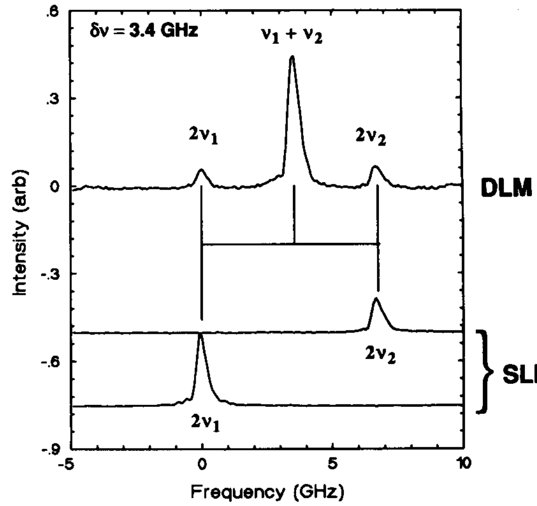


Fig. 5. The spectrum of the frequency-doubled DLM laser in the low conversion limit. The sum-frequency peak, $\nu_1 + \nu_2$, is expected to be four times greater than the doubled-frequency peaks at $2\nu_1$ and $2\nu_2$, but we observe it to be approximately six times greater.

frequencies we observed nearly 100% depth of modulation throughout the entire pulse envelope, indicating that the two lasing modes were well overlapped in angle, space, and time. Angular and spatial overlap results from operation of the laser in the same transverse mode(s) while temporal overlap follows from saturation of the homogeneously broadened gain medium. This overlap is not a function of the relative gain or the relative seed power for each mode, nor is it sensitive to the alignment of the seed beams. Furthermore, since the seed frequencies merely select which $Q$-switched laser modes oscillate, the precise beat frequency is determined by the $Q$-switched laser's mode spacing. The beat frequency and depth of modulation of the output pulses are thus, much less sensitive to alignment and frequency drifts in the seed beams than if the seed beams were directly pulse amplified.

The DLM laser light was frequency doubled by inserting a 1-cm long KDP doubling crystal in the output beam. The angle of this crystal was adjusted to be far from the phase-matching angle in order to prevent saturation of the harmonic generation process. Fig. 4 shows the highly modulated frequency-doubled power for $\delta\nu = 550$ MHz. The spectrum of the frequency-doubled light, taken with the 30 GHz FSR fixed-gap etalon, is shown in Fig. 5. These data were acquired as radial intensity profiles of the Fabry–Perot interference rings using a linear photodiode array. The position scale was converted to a linear frequency scale for these plots.

The frequency-doubling process was expected to generate light at frequencies $2\nu_1, \nu_1+\nu_2$, and $2\nu_2$ with relative intensity ratios of $I_1^2{:}4I_1I_2{:}I_2^2$ where $I_1$ and $I_2$ are the intensities of the 1.064-$\mu$m modes at frequencies $\nu_1$ and $\nu_2$. However, in the frequency-doubling process weak sidebands on the fundamental light, with detunings of $\pm\delta\nu$ from the two main frequencies, can have a significant influence on the second-harmonic intensity ratio. Thus, the frequency-doubled spectrum should be a convenient indicator of the spectral purity, and thus, the depth of modulation of the 1.06-$\mu$m light for large $\delta\nu$, where direct measurement is not practical without a streak camera. In fact, the data shown in Fig. 5 exhibits an intensity ratio of about $1:6:1$, indicating some deviation from pure two-mode operation.

It should be noted that when the second-harmonic generation process is overdriven so that back conversion from 532 nm to 1.06 $\mu$m occurs, strong sidebands are generated in the fundamental and second-harmonic light. We easily observed this. However, by limiting the conversion efficiency to low values, we avoided this effect in the data presented here.

The $1:6:1$ intensity ratio for the second harmonic light suggested the presence of additional sidebands. Indeed, close inspection of the 1.06-$\mu$m spectrum, using the confocal etalon with the second-harmonic crystal removed from the beam, revealed the presence of weak sidebands. Fig. 6(a) shows a clearly resolved sideband located $-\delta\nu$ from the lower-frequency seeded mode. It has an energy approximately 0.5% of either seeded mode. A significantly weaker feature is also present on the high frequency side. The energy in both sidebands diminishes with increasing $\delta\nu$, as shown in Fig. 6(b). These data were taken near gain center of the $Q$-switched laser. We have also conducted studies with the seed frequencies tuned $-27$ GHz from the gain maximum and obtained comparable results.

## V. Discussion

Unfortunately, we did not make a systematic study of the second harmonic intensity ratios and sideband structure, so our discussion of their cause is necessarily somewhat speculative. Processes that could produce sidebands include gain depletion and self-phase modulation in the Nd:YAG crystal. For DLM operation, the intensity of the 1.06-$\mu$m light is deeply modulated by interference between the seeded frequencies. As the intensity varies, the population inversion is depleted in a step-like manner, with each step corresponding to a single beat between the two lasing modes. This causes the real and

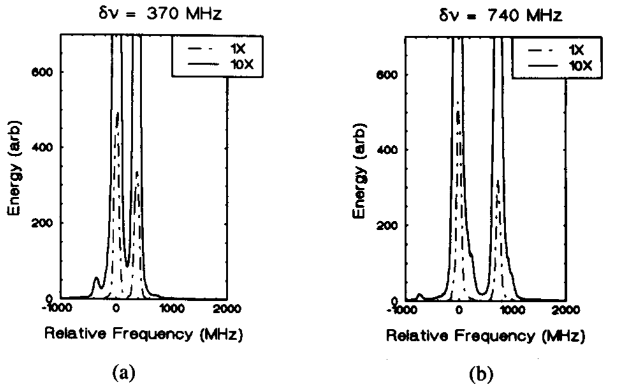



Fig. 6. Weak sidebands are produced by the DLM laser for two values of the frequency difference $\delta\nu$. The energy content in the sidebands is about 0.5% of the seeded peaks. The sidebands are located $\pm\delta\nu$ from the seed peaks. The low frequency sideband is more intense than the high-frequency sideband. These data were acquired by averaging four laser shots per 8-MHz frequency increment.

imaginary parts of the refractive index of the Nd:YAG to change in a similar step-like fashion, thereby impressing both amplitude modulation (AM) and phase modulation (PM) on each seeded mode. Due to dispersion, the nature of modulation depends on the tuning of the modes relative to gain center. In addition, the intense laser light interacts with the laser host material via the intensity-dependent index of refraction [5], $n_2$, causing a periodic change in the index of refraction in the laser medium. This creates additional PM.

For small modulations, either AM or PM leads to equal amplitude red and blue sidebands for each seeded frequency, with detunings from the respective seeded modes equal to $\pm\delta\nu$. Analysis of the relative phases of the sidebands reveals that the AM sidebands should interfere with the $n_2$-generated PM sidebands destructively on blue side and constructively on the red side. If the AM and PM amplitudes are equal to within about a factor of 2, the blue sideband will be much weaker than the red sideband as we observed. In addition, the AM sidebands should diminish with increasing $\delta\nu$, as we observe. However, the phases of these sidebands are such that the $1:4:1$ second harmonic intensity ratio should still hold. Only the PM due to gain depletion seems to have the proper sideband phases to alter this. They are $\pm\pi/2$ out of phase with the others, and thus cannot interfere to suppress a sideband. This effect should increase the $1:4:1$ ratio when the laser is tuned to one side of gain center and decrease it when tuned to the other side. This is not consistent with our observations of a $1:6:1$ ratio for several laser detunings.

We conclude with the observation that there is evidence to suggest that all three modulation processes might play roles in generating small amounts of light resonant with unseeded cavity modes. Our estimates of the magnitude of the modulations produced by the proposed mechanisms indicate that they are consistent with our observations. A more definitive discussion would require more extensive measurements, and perhaps a mathematical model of the seeded laser.

## VI. Conclusion

We have demonstrated reliable two-frequency operation of a $Q$-switched Nd:YAG laser by simultaneously injection seeding with two-seed beams. The output energy in each frequency component can be varied by adjusting the relative seed powers and/or frequency-dependent intracavity losses. The highly modulated temporal waveforms for the output pulses indicate excellent spatial, angular, and temporal overlap between the two frequency components. The frequency difference can be set to any integer multiple of the 185-MHz free spectral range of the $Q$-switched cavity.

It is likely that this multiple-seeding technique could be extended to other laser systems, including titanium-doped sapphire, and may be useful for nonlinear frequency generation. It has the advantage of providing pulses at multiple frequencies that are synchronized in time, and spatially overlapped, attributes that may be beneficial to differential absorption-laser radar systems. It should also be noted that multiple-seed beams, appropriately tuned and phased, may be used to produce periodic waveforms whose detailed characteristics can be tailored. For example, trains of square or triangular pulses should be possible.

Finally, the interaction of the highly modulated pulses with the gain medium was shown to introduce weak sidebands in the output spectrum. We described mechanisms for sideband generation, including AM and PM resulting from the quasi-stepwise manner in which the laser gain is depleted, and PM due to self-phase modulation of the highly amplitude modulated pulse in the Nd:YAG crystal.

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**T. D. Raymond**, photograph and biography not available at the time of publication.

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