The unstable-resonator yag

By Robert L. Byer and Richard L. Herbst

UNSTABLE RESONATORS provide the best way to extract diffraction-limited energy from large-volume, highgain laser media. The laser medium must be of high optical quality, however, for an unstable resonator to be effective. This requirement has limited applications of unstable resonators primarily to gas lasers because the time- and power-dependent thermal distortions occurring in solidstate lasers make this type of resonator unattractive.[1]

> It offers better performance and reliability at a lower cost than conventional stable-resonator yag designs

In this article we show that, contrary to the above expectation, a properly designed Nd-yag unstable resonator provides marked improvements in performance, reliability and cost over the conventional stable resonator.

The theory and design of unstable resonators has been reviewed at an introductory level[2] and in detail[3] by Anthony E. Siegman and by R. J. Freiberg et al.[4] In this article we discuss the design criteria and performance of the Nd-yag unstable resonator laser first described by Richard L. Herbst et al.[5]

Comparison of laser sources

The performance of an unstable-resonator oscillator-amplifier is compared to that of a stable-resonator system in Fig. 1. Both lasers have been operated at Stanford University. The unstable system not only requires fewer components, but also produces more output. With a wall-plug efficiency of 0.5%, the unstable resonator is about five times more efficient than the stable one.

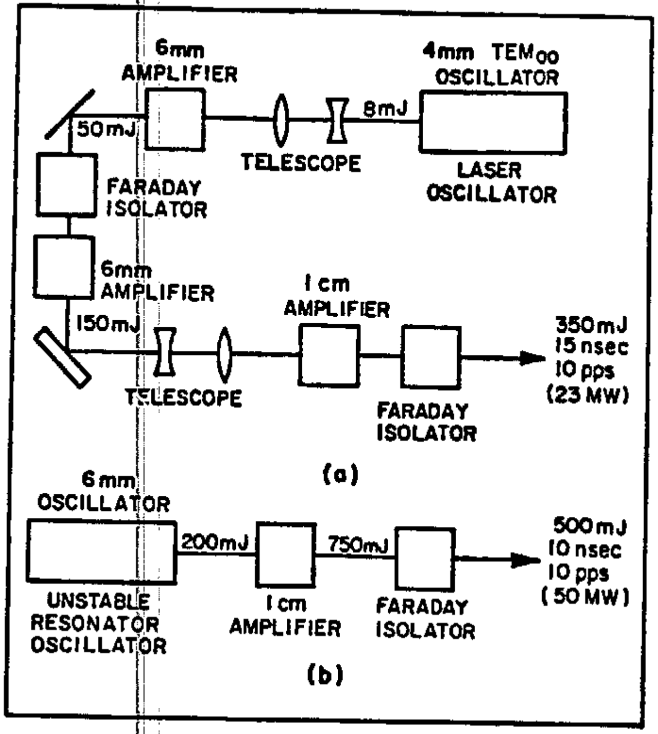

Fig 1 *Schematics of the Stanford high energy TEM$_{00}$-mode Nd-yag laser* a *and of the high energy unstable-resonator Nd-yag laser* b

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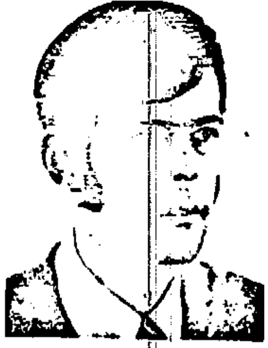
The design of an unstable-resonator cavity is a more complicated procedure than for a stable resonator because of the interdependence of cavity length, output coupling and mirror radii of curvature. Unstable-resonator theory and design have been discussed by Dr. Siegman.[2,3] The requirement to avoid focal points in the cavity, and the desire to have a collimated output beam, dictate the choice of



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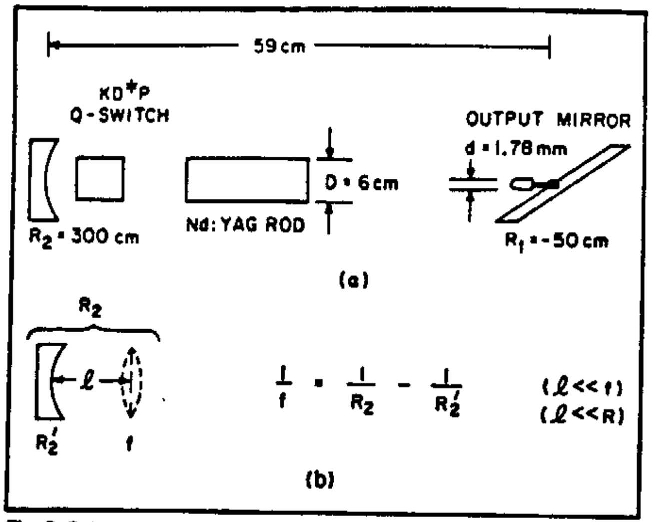

Fig 2 Schematic of the unstable-resonator cavity designed for 550 watts average pump power **a** *and Nd-yag rod thermal-focusing correction to the back-mirror radius of curvature* **b**

a positive-branch confocal unstable resonator.

Within the constraints of commercially available components, we have developed a procedure that quickly leads to a useful unstable-resonator design. Fig. 2a shows a schematic of the unstable-resonator cavity. The geometrical ouput coupling is related to the magnification M by

$$\delta_g = 1 - \frac{1}{M^2} \qquad (1)$$

The magnification is the ratio of the output-beam diameter D to the output-coupler diameter d, or $M = D/d$. For a confocal resonator, the mirror radii are given by[3]

$$R_1 = \frac{-2L}{M-1} \qquad (2a)$$

$$R_2 = \frac{2ML}{M-1} \qquad (2b)$$

where L is the cavity optical length and R_1 and R_2 are the output and back-cavity mirror curvatures. Note that the output mirror has a negative curvature and thus is convex, while the high-reflection mirror has positive curvature and is concave.

Calculations show that the actual output coupling is less than the geometric value for cavities designed with equivalent Fresnel numbers

$$N_{EQ} = \left(\frac{M-1}{2M^2}\right)\frac{D^2}{4L\lambda} \qquad (3)$$

with values of 0.5, 1.5, 2.5 . . .

Physically, the half-integer equivalent Fresnel numbers correspond to Fresnel diffraction peaks centered on the output coupler, leading to increased feedback into the resonator. Corrections to the geometric value of output coupling for operation at half-integer N_{EQ} have been given by Siegman[3] and experimentally verified by R. J. Freiberg et al.[4] We choose to minimize δ by operating at half-integer N_{EQ}.

The first step of our procedure is to fix the rod diameter D and to choose R_1 to be a readily available mirror curvature. The other parameters, cavity length, back-mirror curvature and output coupling, then can be calculated for selected half-integer values of N_{EQ}. The cavity length, for example, is determined by using Eq. 2a to eliminate M from Eq. 3 and solving for L to find

$$L = -\frac{1}{2}|R_1| + \frac{1}{4}D\left(\frac{R_1}{\lambda N_{EQ}}\right)^{0.5}$$

Once L is known Eq. 2a is used to calculate M. R_2 is given by Eq. 2b, and d is given by the definition of magnification.

The accompanying table gives an example of a calculation with $D = 6$ millimeters and $R_1 = -50$ centimeters. Let us choose the cavity design with $N_{EQ} = 1.5$ because the output coupling is appropriate for a q-switched Nd-yag laser, the cavity length is long enough to lead to q-switch pulselengths near 10 nanoseconds, and the mirror radii and physical length of the resonator are convenient. We must next introduce the thermal-focusing effects of the Nd-yag rod.

For our single-xenon-flashlamp pumped, 6.3-mm-diameter, and 50-mm-long Nd-yag rod with 0.7% Nd doping, we measured a focal length of $f = 2.1$ meters/P where P is the average lamp power measured in kilowatts. This value is in good agreement with previous measurements.[1] As shown in Fig. 2b, the distance from the back mirror to the laser rod is much less than the rod or mirror focal length. Therefore, we can compensate for rod focusing by reducing the focusing strength of the mirror. The new radius of curvature R_2 is given by

$$\frac{1}{R_2'} = \frac{1}{R_2} - \frac{1}{f}$$

Since f depends on flashlamp average power, we must choose the back-mirror curvature at an appropriate average-power operating point. As an example, for $R_2 = 300$ cm we find that the desired rod focal length is approximately, $f = 3.81$ m which occurs at an average lamp energy of 551 watts, or 55 joules per pulse at 10 pulses per second. This value of lamp energy is in the mid-operating range of the present laser oscillator and our characterization of the unstable resonator oscillator was made using a 300-cm-radius back mirror.

The unstable-resonator oscillator designed above is shown in Fig. 2. It uses a commercially available potassium-dideuterium phosphate (KD*P) electro-optic q switch, with either a calcite or coated dielectric polarizer. A single flashlamp within a gold-plated elliptical reflector pumps the Nd-yag rod. The q switch is triggered by a thyratron with a 10-ns risetime. The rod is antireflection coated but wedged to prevent self-oscillation. The output coupler was manufactured from a convex 50-cm radius-of-curvature Edmund Scientific Corp. lens by grinding to the proper 1.8-mm diameter, coating for

N_{EQ}	L	R_1	R_2	M	δ_{geom}	δ_{actual}
0.5	120 cm	−50 cm	290 cm	5.8	0.97	0.97
1.5	59 cm	−50 cm	168 cm	3.36	0.91	0.84
2.5	40 cm	−50 cm	130 cm	2.60	0.85	0.73
3.5	30 cm	−50 cm	110 cm	2.20	0.79	0.64

DESIGN CALCULATIONS for unstable resonator with $D = 6$ mm and $R_1 = -50$ cm

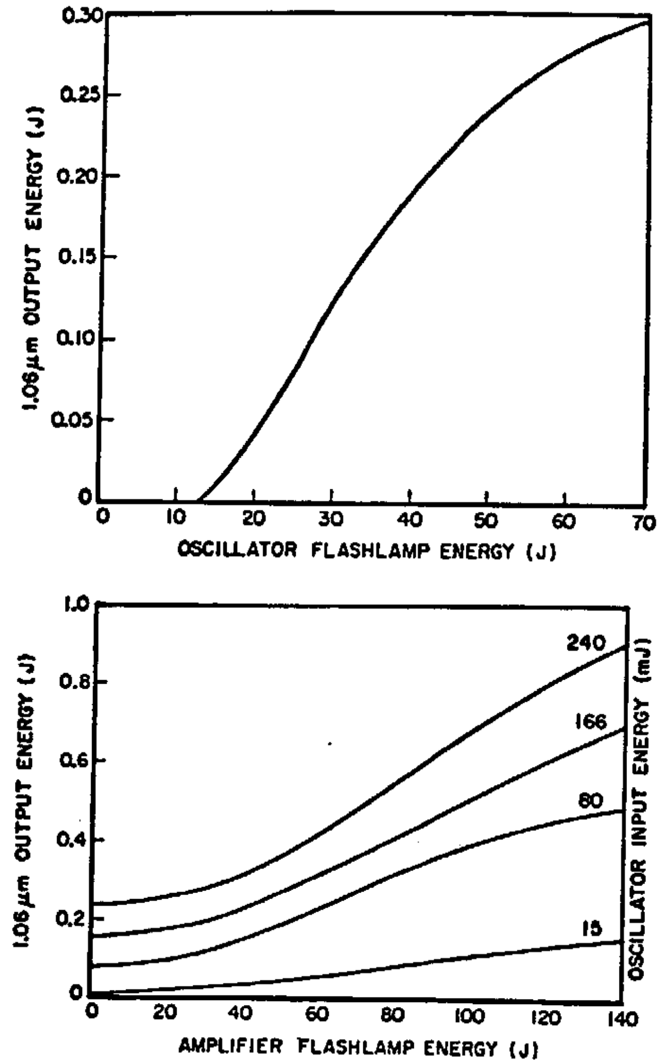

Fig 3 *Unstable-resonator oscillator q-switched output energy vs flashlamp energy* top *and amplifier output energy vs flashlamp energy for various values of oscillator input energy* bottom

high reflectivity at 1.064 micrometers and mounting on a 1-mm stainless-steel post, which was held in a hole drilled into a Brewster-angle plate.

The top of Fig. 3 shows the q-switched output energy from the oscillator only; the bottom shows the output energy from the 9.5-mm diameter amplifier at various oscillator input energy values. The q-switch pulsewidth is close to 10 ns at pumping levels greater than twice threshold.

The measured peak-to-peak energy stability is ± 5%. Subnanosecond- resolution observation of the q-switched output shows that axial-mode beating is present, so that peak-to-peak power stability varies by as much as 20%. Axial-mode beating is also observed in stable-resonator Nd-yag sources and our measurements show that the temporal behavior of the stable—and unstable-resonator Nd-yag lasers is nearly identical.

Transverse-mode properties

The transverse-mode profiles of unstable resonators have received considerable attention in the literature.[3] Unlike Gaussian beam profiles generated by low-gain stable oscillators, the unstable-resonator mode is not described by a simple analytical expression. In a near-field, unstable-resonator beam the energy is distributed in an annular ring about the central beam axis. This mode profile leads to less peak intensity for a given beam diameter than for a Gaussian beam. In addition, the phase front of the unstable resonator mode is within a few degrees of a plane wave over all but the obscured central portion of the mode. A Gaussian beam, on the other hand, has a phase deviation of more than 20° across the beam profile.

Figs. 4a and 4b show the near-field and far-field beam-intensity profiles of an unstable resonator taken with a line-scan television camera. Without focusing or beam reduction the conversion to the far field takes over 30 m. With a 3-to-1 Galilean beam-reducing telescope the far field is reached in 3 m and the beam profile then evolves into a modified Airy disk as shown in Fig. 4b.[7]

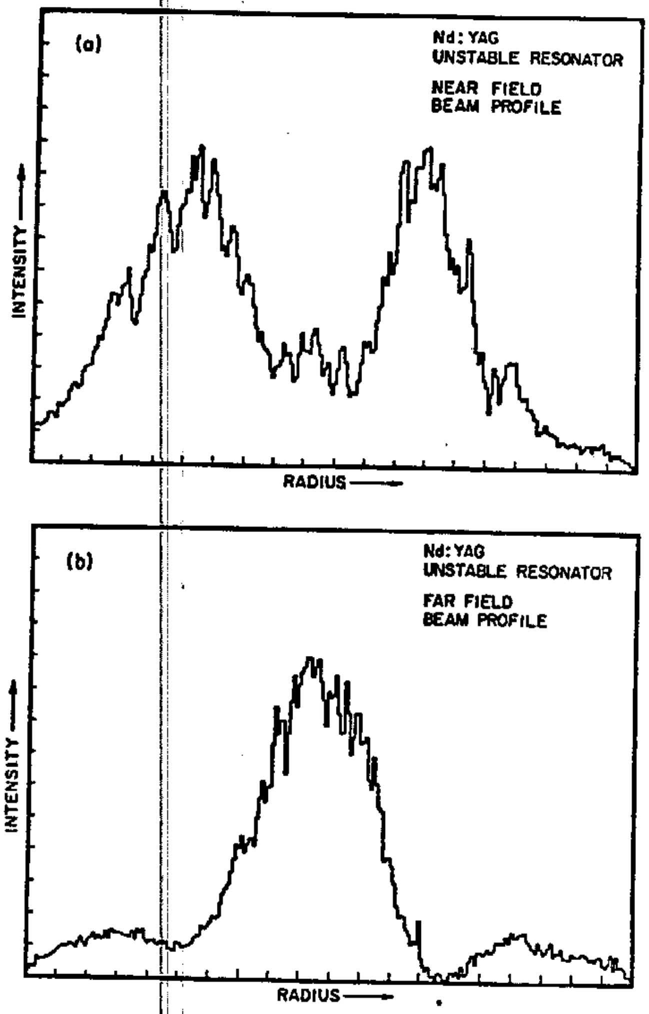

Fig 4 *Intensity profiles in near field* a *and far field* b *from unstable resonator*

On first observing the near-field mode profile of an unstable resonator, one is struck by the annular dark rings that modulate the beam intensity. Careful calculations of the mode profile show that these concentric circular fringes are the result of Fresnel diffraction of light from the edge of the output coupler and the Nd-yag rod. The intensity modulation is calculated and measured to be ± 10% of the peak intensity. The Fresnel modulation rings are evident in Fig. 4a, although they are not fully spatially resolved due to television-system limitations. Gaussian beams also are subject to Fresnel interference modulation. This is especially the case for

Gaussian-profile beams propagating through high-gain, saturated amplifiers where the Gaussian "tail" is enhanced by the gain medium, thus increasing the intensity clipping at the amplifier rod. It has been shown by A. J. Campillo et al[7] that for Gaussian beams clipping by an aperture at the ε^2 intensity level leads to a central intensity modulation of $\pm 2\varepsilon$ for $\varepsilon^2 << 1$. For example, a 1% intensity-level clip will generate a ± 20% intensity fluctuation at the beam center. While both stable and unstable resonators exhibit Fresnel diffraction effects, lower peak intensity of the unstable-resonator mode reduces the possibility of damage at a fixed energy level.

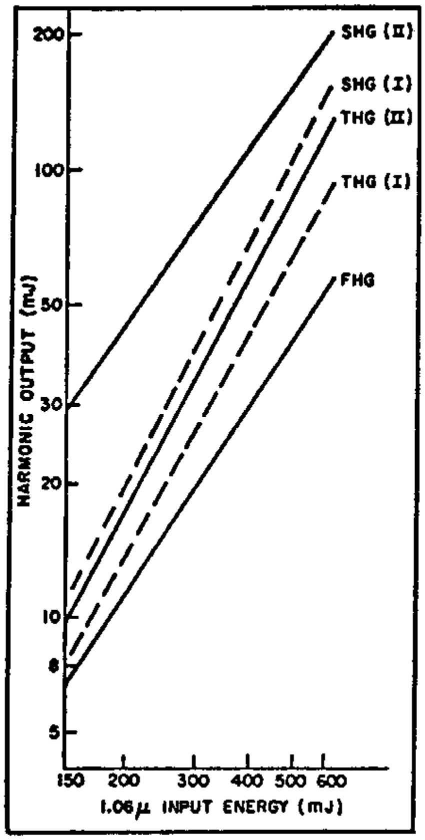

*Fig 5 Second (0.5320-μm), third (0.3547-μm) and fourth (0.2260-μm) harmonic output energies vs input 1.06-μm energy for harmonic generation in KD*P angle-phase-matched crystals (Courtesy, Quanta-Ray Inc.)*

Spectral properties

The Nd-yag unstable-resonator spectral properties are similar to those of a stable resonator. The q-switched laser oscillates at a 0.4-inverse-centimeter linewidth which is centered on the 3-cm^{-1} wide gain linewidth. With the insertion of a single tilted etalon, the linewidth is reduced to less than 0.1 cm^{-1} or approximately 5 axial modes. For further linewidth reduction the q switch must be electronically opened in a programed manner to allow for multipass linewidth narrowing by the tilted etalon. Recent developments along this line by Quanta-Ray Inc. have led to an electronic-line-narrowing option of their commerical, unstable-resonator Nd-yag laser. The results are impressive, with over 50% of the laserpulses being single axial mode. The remaining pulses have some fraction of two or more axial modes present and can be readily discriminated against when the data are analyzed. The electronic-line-narrowing approach also significantly improves amplitude stability of the output. Single-axial-mode pulses are free of axial-mode-beating modulation and thus are very close to Gaussian in time, with a peak-to-peak stability of better than 0.1% in both power and energy.

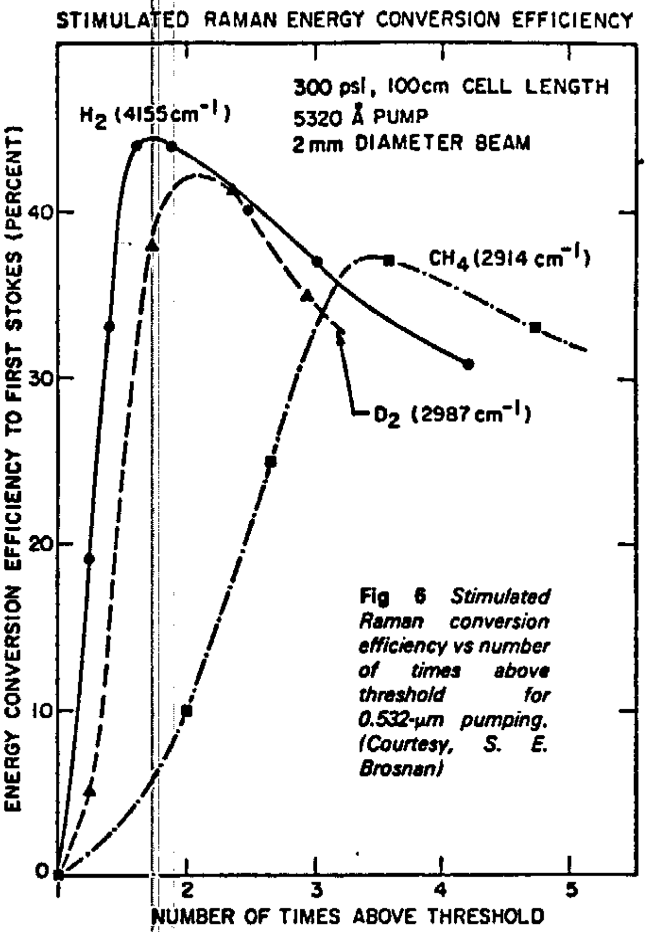

Fig 6 Stimulated Raman conversion efficiency vs number of times above threshold for 0.532-μm pumping. (Courtesy, S. E. Brosnan)

The unstable-resonator Nd-yag system is ideally suited for harmonic generation and for pumping Raman and parametric-oscillator devices. Fig. 5 shows the measured output pulse energy vs input 1.06-μm energy at the second (0.5320 μm). third (0.3547 μm) and fourth (0.2660 μm) harmonics. The low-energy range corresponds to pulse energy level available from the unstable resonator only. The high-energy limit corresponds to the pulse energy available from the amplifier.

Harmonic generation was accomplished using KD*P crystals, cut for the proper phasematching angle. The output intensity from the Nd-yag source is adequate for efficient harmonic generation without beam focusing. Output energies for second-harmonic generation with type 1 and 2 phasematching are shown in Fig. 5.

Additional fixed frequencies can be generated by stimulated Raman scattering in hydrogen, deuterium, methane and liquid nitrogen. We have found that a one-meter cell, filled to 20-atmosphere pressure, allows 40% energy conversion to the Stokes frequency by single-pass superfluorescent stimulated Raman scattering in gases. Fig. 6 shows the conversion efficiency for 0.532-μm input vs the number of times above threshold for H_2, D_2 and CH_4. Similar conversion efficiency curves apply for 1.06-μm pumping and for the third- and fourth-harmonic pumping. As an example, we have generated up to 180 millijoules of energy at 1.907 μm by stimulated Raman scattering in H_2 by direct pumping at 1.06 μm.

For a collimated beam 2 mm in diameter, the stimulated-Raman-scattering threshold energies for H_2 are 100 mJ at 1.06 μm, 36 mJ at 0.5320 μm, 23 mJ at 0.3547 μm and 18 mJ at 0.2660 μm. Stimulated-Raman-scattering thresholds in liquid N_2 are an order of magnitude lower. In all cases focusing can reduce the threshold significantly, e.g., to less than 8 mJ at 0.532 μm, but conversion efficiency also is reduced and gas breakdown may be reached. The high peak intensity available from the unstable resonator source makes stimulated Raman scattering a convenient frequency-conversion process at all of the available pump wavelengths.

Tunable sources

Even though harmonic generation and stimulated Raman scattering provide a wide range of fixed frequencies extending from 0.239 to 9.18 μm, tunable radiation is essential for a number of applications. At Stanford University we have pumped a lithium-niobate parametric oscillator with 1.06 μm and tuned across the range between 1.4 and 4.0 μm.[5] The unstable-resonator system has allowed significant increase in available output energy from the $LiNbO_3$ parametric tuner. By adding a $LiNbO_3$ parametric amplifier after the parametric oscillator, we have generated up to 70 mJ of tunable radiation from 300 mJ of 1.06-μm pump radiation.

In the visible, we have used the second-harmonic output at 0.532 μm to pump dye lasers and dye amplifiers, providing tunable radiation between 0.54 and 0.69 μm. The dye-laser tuning ranges may be extended by second-harmonic generation, sum generation and difference-frequency generation to cover the spectral range between 0.26 and 5 μm.

As shown in Fig. 5, output energies of over 200 mJ per pulse at 0.532 μm and over 100 mJ per pulse at 0.3547 μm are now commercially available for dye laser pumping. In addition—unlike the nitrogen laser—the Nd-yag output is diffraction limited, thus allowing frequency extension of the dye laser by sum and difference generation with 1.06 μm and its harmonics. Using our unstable-resonator Nd-yag laser at Stanford, we have constructed a simple side-pumped dye laser with a grating and 10-power prism beam expander for linewidth control. For 5 mJ of 0.5320-μm input we obtained 1 mJ of output using rhodamine 6G dye. This corresponds to 166 kW of peak output power for the 6-ns pulse. An aperture in the dye-laser cavity assured good spatial-mode quality of the output, which had a spectral linewidth of less than 0.03 nanometer. Our simple dye oscillator already exceeds the output energy available for the best N_2-laser-pumped dye system.

In recent developments at Quanta-Ray, a dye oscillator-amplifier system has produced over 50 mJ of energy (10-megawatt peak power) at 10 pps. The mode quality is excellent, as confirmed by second-harmonic-generation results which produced over 15 mJ of tunable ultraviolet radiation. Fig. 7 shows the performance of the 0.532-μm-pumped rhodamine 6G dye laser oscillator-amplifier system at beam divergence of less than 0.5 milliradian and output linewidth of less than 0.5 cm^{-1}. The beam quality allows efficient frequency extensions to both the ultraviolet and infrared by sum and difference generation.

The research applications of unstable-resonator Nd-yag systems include tunable-laser spectroscopy, nonlinear spectroscopy, four-wave-mixing studies and coherent anti-Stokes Raman spectroscopy (Cars). Diagnostic applications include remote air-pollution monitoring, laser radar, flame and combustion measurements using Cars and Raman techniques, and stroboscopic illumination.

As an example of a spectroscopic application H. Komine and Robert L. Byer[9] used the harmonics of the Nd-yag unstable-resonator source for optical-pumping studies of the mercery dimer. The harmonic output in the ultraviolet was more than adequate to induce and allow the measurement of nonlinear upper-level absorption and state kinetics in Hg_2.

Recent four-wave-mixing studies in the vacuum ultraviolet by Gary C. Bjorklund et al[10] involved phasematched sum generation in strontium vapor, using three independently tunable dye lasers pumped by the harmonics of a single unstable-resonator Nd-yag laser. The experiment demonstrated a potentially efficient method for tunable vacuum-ultraviolet generation in metal-vapors. Infrared four-wave mixing in H_2 gas has been used to generate tunable infrared output. In one experiment S. J. Brosnan et al[11] used a tunable $LiNbO_3$ parametric oscillator source pumped by 1.06 μm as the 1.4- to 4-μm primary tuner. Coherent Raman mixing in H_2 gas pumped by 1.06 μm Stokes-shifted the output to tune over the 3.5- to 18-μm range. In a similar experiment, Peter P. Sorokin et al[12] generated 16-μm radiation by coherent Raman mixing from rotational Raman levels in H_2 gas. Again, the Nd-yag source provided the pump power to generate stimulated rotational Raman scattering. The 16-μm radiation was then generated by Stokes shifting of the input carbon-dioxide laser radiation.

Wavefront conjugation for aberration correction is a recent and potentially important application of four wave mixing. In an elegant approach to the problem, D. M. Bloom et al[13] used the unstable-resonator source to demonstrate wavefront reversal and image reconstruction in CS_2 at 1.06 μm. The method offers the potential for complete correction of amplifier-induced optical inhomogenities in high-energy, high-repetition-rate laser oscillator-amplifier systems.

Cars spectroscopy puts severe constraints on the laser parameters and laser reliability. The high peak power, excellent peak-to-peak stability and good linewidth control have made the unstable-resonator Nd-yag advantageous for Cars studies. The unstable-resonator oscillator alone has more than adequate energy to carry out Cars studies in solids, liquids and gases. For laser diagnostics using Cars, the increased energy available from the unstable-resonator oscillator-amplifier system makes Cars a practical tool under severe measurement conditions, such as in flames or engine exhausts. In the same manner, the high average and peak power also significantly enhance the signal-to-noise level of spontaneous Raman scattering.[14,15]

Using a $LiNbO_3$ parametric tuner pumped with a

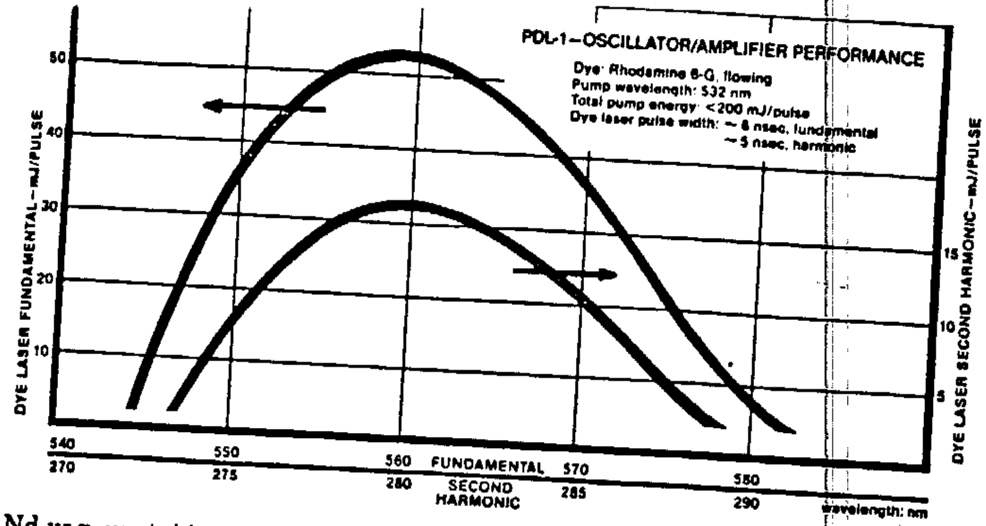

Fig 7 *Performance of a rhodamine-6G dye laser oscillator-preamplifier-amplifier system, pumped by 0.532 nm, with grating-tuned linewidth of less than 0.5 cm⁻¹ at an output-beam divergence of less than 0.5 mr. Second-harmonic generation was in angle-phase-matched KD*P. (Courtesy Quanta-Ray)*

Nd-yag unstable-resonator oscillator-amplifier, we have measured SO_2 and CH_4 remotely in the atmosphere.[15] The SO_2 measurements were made at 4 μm with a sensitivity of better than one part-per-million per kilometer. Methane measurements were made at 3.3 μm and at 1.66 μm over pathlengths up to 5 km. Infrared remote monitoring with a tunable source was possible only because of the development of the high-energy, unstable-resonator Nd-yag source.

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Reprinted from Laser Focus Magazine, July 1978, pages 48-57
Advanced Technology Publications, 1001 Watertown St., Newton, MA 02165
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