Single-mode pulsed tunable dye laser

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This letter describes an updated version of the grazing incidence pulsed dye laser. While this new single-mode design only differs very slightly from previous ones,[1,2] its specifications are improved significantly. The laser has a narrow time-averaged linewidth (<150 MHz), an excellent spatial mode (near TEM_{00}), a broad tuning range without mode-hop (>15 cm^{-1}), a negligible amount of background light due to amplified spontaneous emission (<0.01%), and a reasonable efficiency (3%). The improved performance comes as a result of careful attention to details which are often ignored in pulsed laser designs. Two factors above all others have contributed to the excellent performance of this laser. The first is the reduction of the cavity length to such a point that during the short time in which the population is inverted there is an opportunity for at least 10 cavity round trips. The second is the definition of an optical path by means of longitudinal pumping and focusing of the pump light so that the same portion of the gain medium is used on each cavity pass.

An exploded view of the laser is shown in Fig. 1. A complete list of components is given in Table I. As in previous versions, there are only a few optical elements. The laser consists of an end mirror, a dye cell, a diffraction grating, and a tuning mirror. Unlike previous versions, the cavity is short (~ 4–5 cm), and the pump beam is brought in nearly collinearly with the intracavity optic axis. The pump light is focused to a tight spot at the center of the cell. The laser output is derived from the zeroth-order reflection of the diffraction grating. All the elements are mounted rigidly on a precision rotation stage. (Optic elements are epoxied to mounts. All lock nuts are engaged.) The end mirror, dye cell, and diffraction grating are attached to a base plate that is bolted to the body of the stage, and the tuning mirror is attached by means of a pedestal to the rotating platform. The reflective elements have been carefully positioned with respect to the central pivot point of the stage so that the apparent surface planes intersect at the pivot.[3] As discussed in an earlier Letter, this unique choice of positioning is desirable because it results in a variation of the laser cavity size by just the correct amount so that when the angle of the tuning mirror is changed, the longitudinal mode number (i.e., the number of half-wavelengths in the cavity) remains constant.[2]

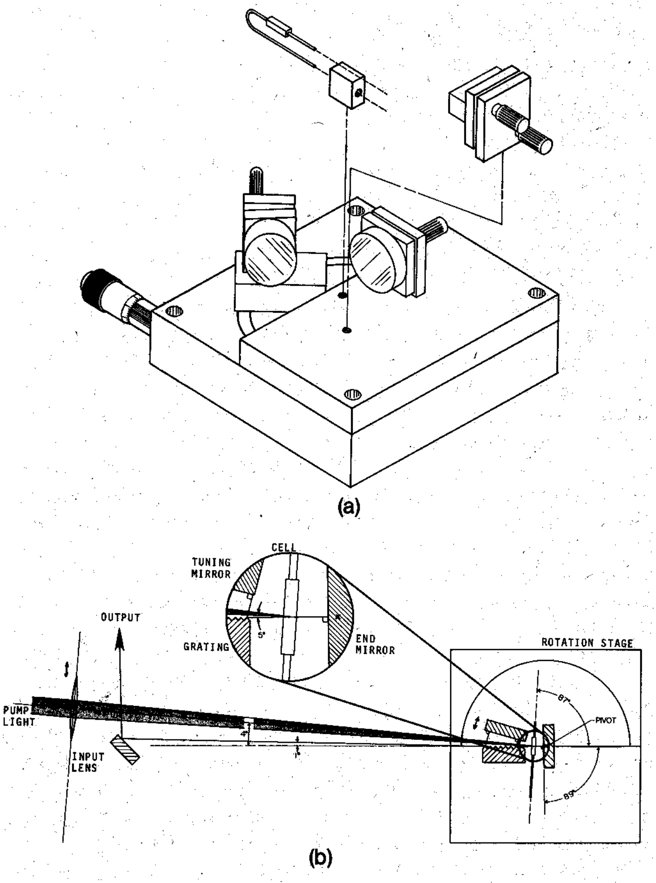

Fig. 1. (a) Exploded view of single-mode pulsed tunable dye laser; (b) top view of laser showing relative position of beams.

Table I. Dye Laser Parts List

Part	Vendor	Model	Comments
Dye cell	NSG Precision Cells Hicksville, N.Y.	T-506	2-mm path length
Diffraction grating	American Holographic Acton, Mass.	—	2400 lines/mm, 1.27 × 2.5 cm (½ × 1 in.)
Mirrors (2)	Newport Research Corp. Fountain Valley, Calif.	10D20BD.1	dielectric, λ/20, 2.5-cm diam
Rotation stage	Newport Research Corp. Fountain Valley, Calif.	470A	(4-in.) diam
Differential micrometer	Newport Research Corp. Fountain Valley, Calif.	DM-13	0.1-μm resolution, for use with rotation stage
Mounts (3)	Newport Research Corp. Fountain Valley, Calif.	MM-1	2.5-cm square
Lens	Edmund Scientific Barrington, N.J.	—	750-mm f.l., 2.5-cm diam
Translation stage	Newport Research Corp. Fountain Valley, Calif.	TSX-1A	For lens positioning

To test the prototype dye laser, the second harmonic beam from a Nd:YAG laser (Molectron MY-34) was used. Nd:YAG offered the advantage of a clean spatial mode. The pump light was focused to a tight spot at the center of the 2-mm path length dye cell using a simple 750-mm focal length lens. The dye cell was of optical quality. The focusing lens was mounted on a translation stage that was oriented transverse to the laser axis which allowed for precise positioning of the active medium with respect to the dye laser cavity. The positioning of the active medium was one of the most critical adjustments in the alignment of the laser. The pump energy was kept below 1 mJ/pulse to prevent damage to the dye cell. The axis of the pump light was nearly, but not exactly, collinear with the optic axis of the dye laser. The two axes formed an angle of ~5°.

The dye concentration was adjusted so that ~80% of the pump light was absorbed in the 2-mm dye path length. With rhodamine 6G in ethanol, this corresponds to a dye concentration of $\lesssim 1 \times 10^{-4}$ M. The dye was circulated at a flow rate of 1 cc/sec using a gear pump (Paragon model P10). Particles were removed from the dye solution using a sintered bronze in-line filter. At the peak of rhodamine 6G tuning curve, the efficiency was measured to be 3%. The laser was also operated with other dyes, including a variety of rhodamines and oxazines. The laser has not yet been tested with the coumarin dyes.[6]

One of the unanticipated benefits of the reduction of the size of the dye laser is the extreme reduction of amplified spontaneous emission background (ASE). This property is a direct consequence of the fact that the gain per pass is maintained at a relatively low level. In most conventional pulsed dye lasers the single-pass gain is maintained at a high level to obtain reasonable efficiency. High gain is needed because there is time for only a couple of cavity round trips during the time that the laser medium is active. The short grazing-incidence pulsed dye laser described here supports multiple-cavity round trips and thus functions in a manner that is more analogous to continuous wave (cw) lasers. Here a small amount of spontaneous emission is repeatedly and resonantly fed back into the active medium by the cavity. Thus the ratio of the ASE, which is due to single-pass amplification, to the dye laser light, which is due to multiple-pass amplification, is quite small. While the low level of ASE is desirable with regard to laser peformance, it does make alignment of the laser more difficult. In fact, the initial setup of the dye laser is virtually impossible without use of a He–Ne alignment laser.

The short grazing-incidence dye laser also has a distinct advantage over larger pulsed dye lasers in that it naturally tends to run in a single longitudinal mode. This is a benefit of multiple passes through a homogeneously broadened laser medium. The single-mode tendency of the laser is also enhanced by introduction of a pinhole, which results from focusing of the pump radiation to a tight spot in the dye cell. Since the virtual pinhole forces the intracavity light to interact with the same portion of the active medium on each round trip, mode competition is encouraged. Once in a single-mode, a linewidth of 150 MHz is obtained routinely. The linewidth is monitored using a high-reflectivity Fizeau interferometer (i.e., Fabry-Perot interferometer with slightly wedged plates).[4] Interferometer fringes are viewed either on a white card or are recorded on each shot using a Reticon diode array. A series of spectra are shown in Fig. 2. [In checking the performance of the laser it is helpful to use two Fizeau interferometers of different free spectral ranges. One Fizeau interferometer is used with a free spectral range that is somewhat larger than the mode separation of the laser (e.g., 0.5 cm^{-1}) to assure that the laser is running in a single mode. The other interferometer is used with a free spectral range that is smaller than that of the laser (e.g., 0.03 cm^{-1}) to check that the linewidth of the laser is sufficiently narrow.]

One of the unique features of this laser is that it can be mechanically scanned while maintaining a single mode without the complication of electronic feedback. To date, the largest single-mode scan that has been obtained was 15 cm^{-1}.[7] The single most important factor that determines the extent of the scanning range is the precision of the placement of the optic elements with respect to the pivot axis of the rotation stage. In the prototype laser, the elements were mounted using only visual alignment with respect to scratches on the base plate. Errors in the alignment of the elements with respect to the pivot were compensated for by slight adjustment of the yaw angle of the tuning mirror. Yaw angle adjustments were made to maximize the scanning range. (Note that in the case of perfect positioning of the optic elements, the yaw angle would be zero degrees.) Single-mode scanning of the laser is demonstrated by a series of spectra obtained using a fixed Fizeau interferometer with a 0.5-cm^{-1} free spectral range. The width of the fringes here reflects the resolution of the interferometer—it is not a measure of laser spectral purity. Besides demonstrating the scanning ability of the laser, these spectra also illustrate what happens when the end of the scanning range is reached. At the limits of the scan the principal mode fades while an adjacent mode strengthens.

Another desirable aspect of the short-longitudinal-pumped grazing-incidence laser is its excellent spatial mode. The

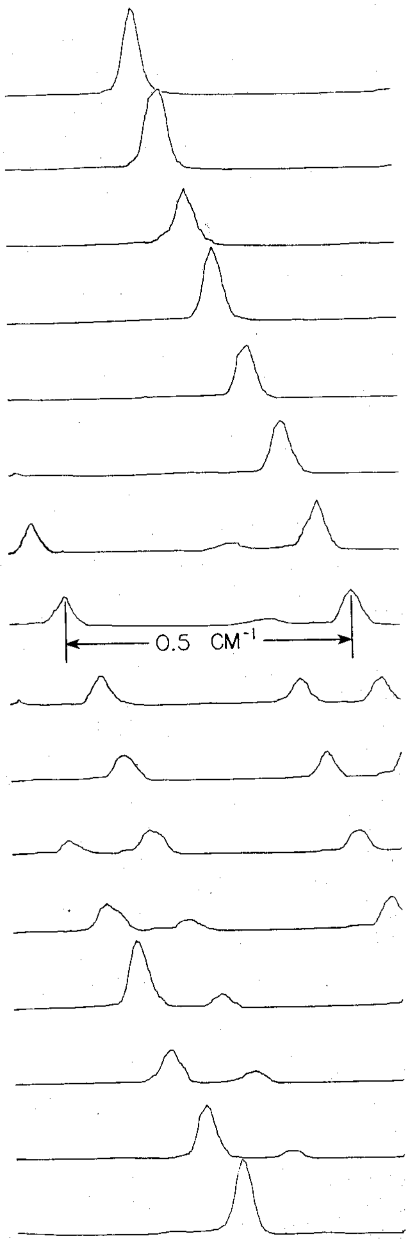

Fig. 2. Series of Fizeau interferograms showing smooth scanning of the tunable laser. The free spectral range of the interferometer is 0.5 cm^{-1} as indicated. The linewidth here is due entirely to the finite resolution of the interferometer. Note that as the end of the scan range is reached, one laser mode fades while an adjacent mode builds.

spatial mode is near TEM$_{00}$ and is repeatable from shot to shot. A photograph of a single shot from the laser is shown in Fig. 3. The excellent spatial mode is one of the benefits of the use of longitudinal pumping.

In the course of upgrading the grazing-incidence laser there were a number of design constraints that became evident. For example, it was found that while it was possible to make a shorter cavity, it was not desirable. If the cavity is very short, the cavity mode separation is very large with the result that mechanical vibrations and drifts of the optic elements degrade the frequency stability of the oscillator. Another example concerns the prospect for replacing the dye cell with a dye jet, as in many cw dye lasers. Dye jets and very short dye cells were found to be less than optimal because the shorter the dye path length the higher the dye concentration that is needed. For most dyes that are commonly used, the solubility is such that a path length of <1 mm is impractical. These are but two of a number of compromises that were made duriong development of the current design.

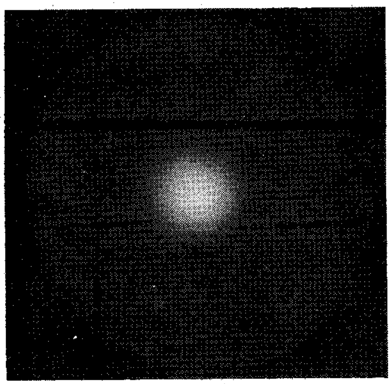

Fig. 3. Spatial mode of the tunable laser.

It is surprising to some that it is possible to obtain single-mode performance from a laser in which the only dispersive element is a grating. A grating can provide sufficient dispersion to allow for single-mode operation provided that it occupies a sizable portion of the cavity. Here the important parameters are the cavity free spectral range, $\Delta(1/\lambda) \simeq 1/2l_c$, and the ultimate resolution of the grating, $\Delta(1/\lambda) \simeq 1/2\pi l_g$. Both of these parameters are determined by physical lengths, namely, the cavity length and the grating length. Thus in the design of a single-mode cavity incorporating a diffraction grating, it is advantageous to have the grating occupy as large a portion of the cavity as possible. In the prototype laser, the grating was specified to span half of the cavity.

A final observation that is not as yet fully undestood is that the laser prototype does not operate optimally when the pump radiation is exactly collinear with the optic axis. With exact collinear pumping, single-mode operation is more difficult to obtain, and the ultimate linewidth is worsened. Worsening of the linewidth appears to occur because the laser operates simultaneously on a number of transverse modes. Whatever the case, exact longitudinal pumping is not recommended.

The alignment of the laser is straightforward although it is complicated by the lack of ASE, as mentioned previously. To align the laser it is helpful to use a microscope slide to set up lasing with the end mirror using the grazing reflection off the diffraction grating. This serves to identify the intracavity and extracavity optic axis as well as aiding in the pitch adjustment of the tuning mirror. It is also helpful to compute the tuning angle corresponding to the peak of the dye and to set the tuning mirror to this angle before attempting to get the laser to oscillate. Once the laser is oscillating, the microscope slide should be removed.

There has been interest in the temporal profile of this laser, especially from workers studying multiphoton ionization. There may be reason to expect that the temporal profile of the single-mode pulsed dye laser will be smooth because of the absence of mode beating. However, the dye is excited transiently, and the pump laser which creates the population inversion is not smooth in time. We have not yet had an opportunity to study this point carefully, but first indications are that the temporal output of the pulsed dye laser is indeed smooth.[5] This is a topic worthy of further study.

At the present time, we are constructing another prototype that will have the added feature of electronic control of the end mirror. Using a Reticon diode array and a 0.5-cm^{-1} free-spectral-range Fizeau interferometer we intend to feed back and feed forward signals that we hope will extend the laser's continuous single-mode tuning range over the full range of the dye.

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References

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2. K. Liu and M. G. Littman, "Novel Geometry for Single-Mode Scanning of Tunable Lasers," Opt. Lett. **6**, 117 (1981).
3. Due to the fact that the index of refraction of the dye cell is $\sim$1.5, the optimal position of the end mirror is 1.5 mm closer than it would be if the index of refraction of the dye cell were 1. The 1.5 mm here corresponds to the apparent foreshortening of the cavity by the 3-mm wide (2-mm dye path plus windows) dye cell.
4. L. A. Westling, M. G. Raymer, and J. J. Snyder, "Single-Shot Spectral Measurements and Mode Correlations in a Multimode Pulse Dye Laser," J. Opt. Soc. Am. B **1**, 150 (1984).
5. L. Brewer, MIT; private communciation.
6. *Note added in proof:* Daniel Gauthier of the University of Rochester has operated the laser with coumarin 500, pumped by the UV output of an excimer laser.
7. *Note added in proof:* Frank Tomkins of the Argonne National Laboratory has obtained a single-mode scan of 25 cm^{-1}.

Meetings Calendar

1984
December

3–4	EO/IR Sensors Tech. & Applications Sem., Boston *Idea Sem., P.O. Box 3608, Dept. EOST, Torrance, Calif. 90510*
3–7	Fundamentals & Applications of Lasers course, Albuquerque *Laser Inst. of Am., 5151 Monroe St., Suite 118W, Toledo, Ohio 43623*
4–5	Optical Engineering II course, Kent *Sira, Ltd. Conf. Unit, South Hill, Chislehurst, Kent BR7 5EH, England*
4–7	Amer. Vacuum Soc. 31st Natl. Symp., Reno *Amer. Vacuum Soc., 335 E. 45th St., N.Y., N.Y. 10017*
6–7	EO/IR Sensors Tech. & Applications Sem., Atlantic City *Idea Sem., P.O. Box 3608, Dept. EOST, Torrance, Calif. 90510*
6–8	Photographic Instrumentation Techniques Sem., Rochester *RIT, P.O. Box 9887, Rochester, N.Y. 14623*
9–12	Int. Electron Devices Mtg., San Francisco *EPITAXX, Inc., 3490 U.S. Rt. 1, Princeton, N.J. 08540*
11–13	Fiber Optics Communications course, Tempe *Center for Professional Development, Coll. of Eng. & Appl. Sci., Ariz. State U., Tempe, Ariz., 85287*

1985
January

7–11	NSF Regional Conf.: Multivariate Estimation: A Synthesis of Bayesian & Frequentist Approaches, U. Florida, Gainesville *NSF, Math. Sciences, Wash., D.C. 20550*
7–11	Int. Conf. on Interactive Information & Processing Systems for Meteorology, Oceanography, & Hydrology, Los Angeles *G. Doore, 11426 Rockville Pike, Suite 300, Rockville, Md. 20852*
7–18	Optical Science & Engineering course, Tucson *P. Slater, P.O. Box 18667, Tucson, Ariz. 85287*
9–11	Fiber Optics Workshop, Lake Buena Vista *V. Amico, Coll. of Extended Studies, U. Central Fla., Orlando, Fla. 32816*
15–18	**Optical Remote Sensing of the Atmosphere, OSA Top. Mtg.,** Lake Tahoe *OSA Mtgs. Dept., 1816 Jefferson Pl., N.W., Wash., D.C. 20036*
18–20	13th All India Symp. on Optics & Opto-Electronics of the Optical Soc. of India, New Delhi *S. Prasad, Natl. Phys. Lab., Hillside Rd., New Delhi - 110012 - India: 582317, 587625*

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