

Letters to the Editors should be addressed to the Editor, APPLIED OPTICS, 7 Norman Road, Newton Highlands, Massachusetts 02161. If authors will state in their covering communications whether they expect their institutions to pay the publication charge, publication time should be shortened (for those who do).

Grazing-incidence dye lasers with and without intracavity lenses: a comparative study

A. G. Yodh, Y. Bai, J. E. Golub, and T. W. Mossberg

Harvard University, Physics Department, Cambridge, Massachusetts 02138.

Received 7 September 1984.

0003-6935/84/132040-03\$02.00/0.

© 1984 Optical Society of America.

Tunable pulse dye laser technology has undergone rapid development since its introduction.¹⁻¹⁵ Lisboa *et al.*¹¹ have recently reported that insertion of a lens in the cavity of a grazing-incidence pulsed dye laser¹²⁻¹⁵ results in output pulses of higher power and narrower spectral width. They did not, however, indicate the extent to which the lens should improve dye laser performance or present systematic measurements of actual observed improvement. We present here results of an analytical and experimental study of this problem.

We restrict our attention to the dye laser configuration of Fig. 1(a), in which the cavity end mirror serves as the output coupler. Output taken through the end mirror has the advantage of being relatively free of broadband spectral background at the expense of being relatively low in power¹³ when compared to laser output taken from the zeroth order of the grating.

Generally speaking, the linewidth of a dye laser is given by an expression of the form

$$\Delta\lambda = \frac{d\lambda}{d\theta} \phi_R, \quad (1)$$

where $\Delta\lambda$ is the linewidth in centimeters, θ is the angle between the grating normal and light incident from the dye cell,

$$\frac{d\theta}{d\lambda} = \frac{2}{a \cos\theta}$$

is the angular dispersion of the light returning from the grating when the grating operates in first order,¹⁶ a is the groove spacing on the grating, and ϕ_R is the effective angular spread of light returning from the grating which is amplified in the dye cell. We discuss limiting expressions for ϕ_R with and without an intracavity lens.

Consider the case in which there is no intracavity lens. When the grating is not filled with light, a single spectral component of the light incident on the grating with divergence ϕ_I [see Fig. 1(b)] returns toward the dye cell with its divergence essentially unchanged, i.e.,

$$\phi_R \approx \phi_I \quad (l \cos\theta > w_2). \quad (2a)$$

Here w_2 is the beam diameter just before the grating. In the opposite limit, in which the grating acts as the limiting aperture (i.e., if $l \cos\theta \lesssim \sqrt{w_1 w_2}$, where w_1 is the beam diameter at the dye cell), the divergence of an isochromatic beam returning toward the dye cell will increase so that

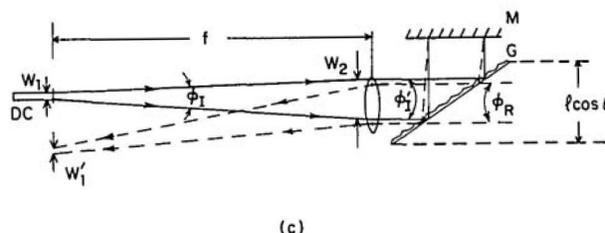
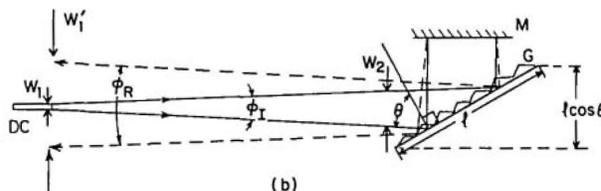
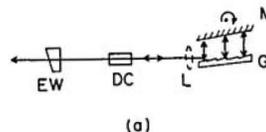


Fig. 1. (a) Schematic of the grazing-incidence dye laser studied. (b) Amplified broadband end window reflection propagating toward the grating and the path (dashed lines) of a single returning frequency component. (c) Same as (b) except that the intracavity lens is in place. Light at a frequency which does not pass through the dye cell is shown for clarity. The lens is positioned approximately one focal length from the dye cell and as close to the grating as possible.

$$\phi_R \approx \lambda/l \cos\theta \quad (l \cos\theta \lesssim \sqrt{w_1 w_2}). \quad (2b)$$

Here and throughout this analysis we assume that the grating-tuning mirror distance can be neglected.

Now consider the case in which an intracavity lens is present. Assuming that the light propagating toward the grating from the dye cell is diffraction limited, the lens (located one focal length from the dye cell) reduces the divergence of the beam by the factor w_1/w_2 [see Fig. 1(c)]. If the grating is not filled, we have

$$\phi_R \approx \phi_I' \approx \frac{w_1}{w_2} \phi_I \quad (l \cos\theta > w_2). \quad (3a)$$

When the grating is the limiting aperture of the system ($l \cos\theta \lesssim w_2$), we have

$$\phi_R \approx \lambda/l \cos\theta \quad (l \cos\theta \lesssim w_2). \quad (3b)$$

We see that grating-limited linewidths of $\Delta\lambda = (a\lambda)/(2l)$ [Eq. 2(b) or 3(b) in Eq. (1)] are in principle obtainable with

or without the intracavity lens. Note, however, that this limiting linewidth is obtained at smaller angles of incidence when the intracavity lens is present. This result is important since grating efficiencies fall off dramatically as θ approaches 90° . In fact, as described below, our dye laser would not even lase at large enough angles for the grating to become the limiting aperture. When the grating is not a limiting aperture, the dye laser linewidth with the lens $\Delta\lambda'$ is given by

$$\Delta\lambda' = \left(\frac{w_1}{w_2}\right)\Delta\lambda, \quad (4)$$

where $\Delta\lambda$ is the dye laser linewidth without the lens.

The intracavity lens is useful in another way.¹¹ As shown in Fig. 1(b), without an intracavity lens, light returning to the dye cell has a large spatial extent. Spreading occurs in both vertical and horizontal directions, and hence only a fraction of the returning light is amplified. With the lens [see Fig. 1(c)] essentially all the available light within the effective acceptance angle ϕ_R is concentrated into the dye amplification region. This refocusing effect leads to higher dye laser output powers.

We have studied the effect of an intracavity lens on the output power and spectral linewidth of a home-built grazing-incidence dye laser. The laser consisted of [see Fig. 1(a)] of a 4% reflectivity wedge output coupler *EW*, a flow-through dye cell *DC*, an $l = 5$ -cm holographic grating *G* with 2400 lines/mm, and a plane front-surface tuning mirror *M*. Two intracavity lenses having focal lengths of 8 and 15 cm were successively studied. Each lens was placed approximately one focal length from the dye cell and as close as possible to the grating. Only the distance between the dye cell and lens was varied as the lenses were interchanged; i.e., other component separations were held fixed. Excimer laser pulses of ~ 5 -nsec duration, ~ 5 -mJ energy, and 308-nm wavelength were used to excite a 1.4×10^{-3} -M solution of rhodamine B dye in ethanol. The dye laser output pulses, tuned to the peak of the dye gain profile (~ 600 nm), had a duration of ~ 2 nsec. The depth of the excited region in the dye was measured to be 250–300 μm .

The results of our relative power measurements are shown in Fig. 2. We plot I_L/I_{NL} , where I_L (I_{NL}) is the dye laser intensity with (without) the intracavity lens as a function of θ . As expected I_L is $>I_{NL}$ for all θ . It is significant to note that I_{NL} itself decreased by the large factor of $\sim 10^3$ as θ increased from 87 to 89° .

Our linewidth results are in close agreement with the simple model presented earlier. Using $w_1 = 300 \mu\text{m}$ and assuming ϕ_I is diffraction limited, we expect $w_2 \approx 1.5w_1$ ($w_2 \approx 2w_1$) in the case of the 8-cm (15-cm) focal length lens. In our configuration, the grating becomes the limiting aperture at angles somewhat larger than 89° . Consequently, we expect, at least for lower values of θ , that the lenses should reduce the dye laser linewidth [see Eq. (4)] by ~ 30 and 50% in the case of the 8- and 15-cm lenses, respectively. These estimates are necessarily crude because of the complex beam profiles that actually exist in the dye laser. In practice only the 15-cm lens consistently narrowed the laser's linewidth (see Fig. 3), in which case we observed linewidth reductions of 20–40%. At $\theta = 89^\circ$, the 15-cm lens still narrows the laser linewidth despite the fact that it has essentially reached our crude estimate of the grating-limited minimum linewidth. The observed reduction at $\theta = 89^\circ$ is in agreement, however, with our expectation that the grating is not yet the limiting aperture. The dye laser would not lase, and we were hence unable to make linewidth measurements in the grating-limited high- θ regime. Two experimental drawbacks associated with the intracavity lens were the long-cavity lengths required for linewidth re-

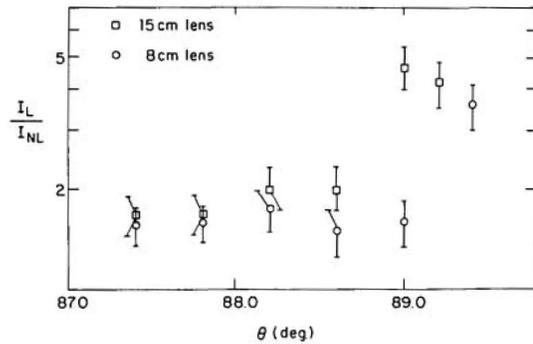


Fig. 2. Relative dye laser output power as a function of grating angle θ .

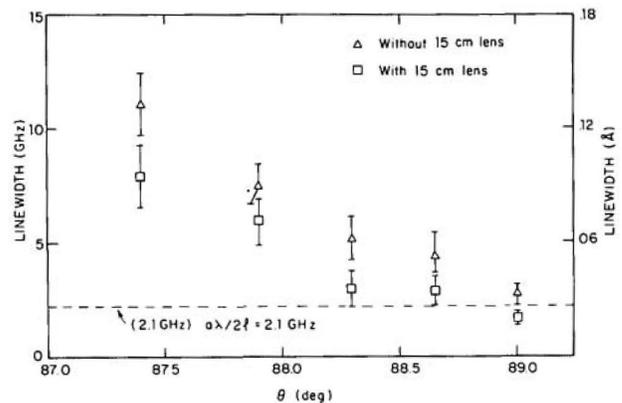


Fig. 3. Dye laser linewidth as a function of grating angle θ .

duction at excitation depths of 300 μm and the complication of an additional lens mount in the cavity. Stray reflections off the lens did not cause noticeable problems.

In summary, we note that a dye laser's linewidth is minimized by minimizing $(d\lambda/d\theta)\phi_R$. The basic Littman laser design minimizes $(d\lambda/d\theta)$ by working at large grating angles but has no provision for minimizing ϕ_R . This approach works well except that gratings tend to be very inefficient at the extremely large angles of incidence necessary to achieve grating-limited linewidths. The basic Hansch design minimizes ϕ_R by using a high-quality high-magnification telescope but works at grating angles where efficiency and $(d\lambda/d\theta)$ are relatively large. Grating-limited performance is reached only when expensive quality telescopes are employed. In the present modified Littman design, addition of the simple intracavity lens provides a small reduction in ϕ_R so that somewhat smaller more efficient grating angles can be used.

One of us, A.G.Y., gratefully acknowledges the support of Army fellowship DAAG29-83-G-0008. This work is supported financially by the Joint Service Electronics Program (contract N00014-75-C-0648).

References

1. T. W. Hänsch, "Repetitively Pulsed Tunable Dye Laser for High Resolution Spectroscopy," *Appl. Opt.* 11, 895 (1972).
2. E. D. Stokes, F. B. Dunning, R. F. Stebbings, G. D. Walter, and R. D. Rundel, "A High Efficiency Dye Laser Tunable from the UV to the IR," *Opt. Commun.* 5, 267 (1972).

3. D. C. Hanna, P. A. Karkkaian, and R. Wyatt, "A Simple Beam Expander for Frequency Narrowing of Dye Lasers," *Opt. Quantum Electron.* **7**, 115 (1975).
4. S. A. Meyers, "An Improved Line Narrowing Technique for a Dye Laser Excited by a Nitrogen Laser," *Opt. Commun.* **4**, 187 (1971).
5. L. G. Nair, "On the Dispersion of a Prism Used as a Beam Expander in a Nitrogen-Laser Pumped Dye Laser," *Opt. Commun.* **23**, 273 (1977).
6. W. H. Steel, "Prisms for Producing Slit Beams from a Laser," *Opt. Eng.* **16**, 86 (1977).
7. R. Wyatt, "Comment on 'On the Dispersion of a Prism Used as a Beam Expander in a Nitrogen-Laser Pumped Dye Laser,'" *Opt. Commun.* **26**, 9 (1978).
8. F. J. Duarte and J. A. Piper, "A Double-Prism Beam Expander for Pulsed Dye Lasers," *Opt. Commun.* **35**, 100 (1980).
9. B. Rácz, Zs. Bor, S. Szatmári, and G. Szabó, "Comparative Study of Beam Expanders Used in Nitrogen Laser Pumped Dye Lasers," *Opt. Commun.* **36**, 399 (1981).
10. T. F. Gallagher, R. Kachru, and F. Gounand, "Simple Line-width-Reducing Modification for a Hänsch Dye Laser," *Appl. Opt.* **21**, 363 (1982).
11. T. Lisboa, S. R. Teixeira, S. L. S. Gunha, R. E. Franke, and H. P. Griensen, "A Grazing Incidence Dye Laser with an Intracavity Lens," *Opt. Commun.* **44**, 393 (1983).
12. M. G. Littman and H. J. Metcalf, "Spectrally Narrow Pulsed Dye Laser Without Beam Expander," *Appl. Opt.* **17**, 2224 (1978).
13. M. G. Littman, "Single-Mode Operation of Grazing-Incidence Pulsed Dye Laser," *Opt. Lett.* **3**, 138 (1978).
14. I. Shoshan, N. W. Danon, and U. P. Oppenheim, "Narrowband Operation of a Pulsed Dye Laser Without Intracavity Beam Expansion," *J. Appl. Phys.* **48**, 4495 (1977).
15. I. Shoshan and U. P. Oppenheim, "The Use of a Diffraction Grating as a Beam Expander in a Dye Laser Cavity," *Opt. Commun.* **25**, 375 (1978).
16. M. K. Iles, "Unified Single-Pass Model of Linewidths in the Hänsch, Single- and Double-Grating Grazing-Incidence Dye Lasers," *Appl. Opt.* **20**, 985 (1981).

General planar guiding structure at 10.6 μm

Denis Vincent and Gabriel Otis

Defense Research Establishment Valcartier, P.O. Box 8800, Courcellette, P.Q., GOA 1RO.

Received 5 January 1984.

0003-6935/84/132042-03\$02.00/0.

Until now, guided-wave techniques have been used at 10.6- μm wavelength primarily for modulator purposes, power transmission,²⁻⁵ or laser construction.^{6,7} It has been noted in Ref. 1 that guided-wave structures (especially modulators) could be important in coherent laser radars. In particular, the high voltages required for electrooptical modulators at 10.6 μm could be significantly reduced by using guided-wave techniques. Relevant examples are cross-sectional reduction and sensitive structures like directional couplers, thin-film splitters,⁸ or TE-TM mode converters.⁹

In view of possible applications of guided-wave techniques to the coherent laser radars presently developed at DREV, we have studied a nine-layer slab geometry (Fig. 1) that can be reduced to the particular waveguide geometries listed in Fig. 2. We present here a set of useful equations for waveguide tuning applications or coupling length calculations. Some of these relations were derived in previous works.^{10,11} Finally, we give calculated results for a directional coupler.

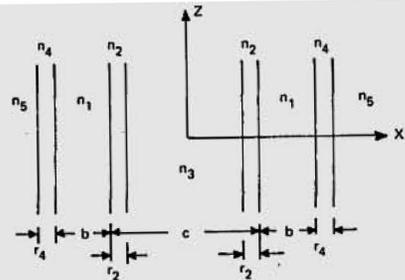


Fig. 1. Symmetrical structure with nine regions.

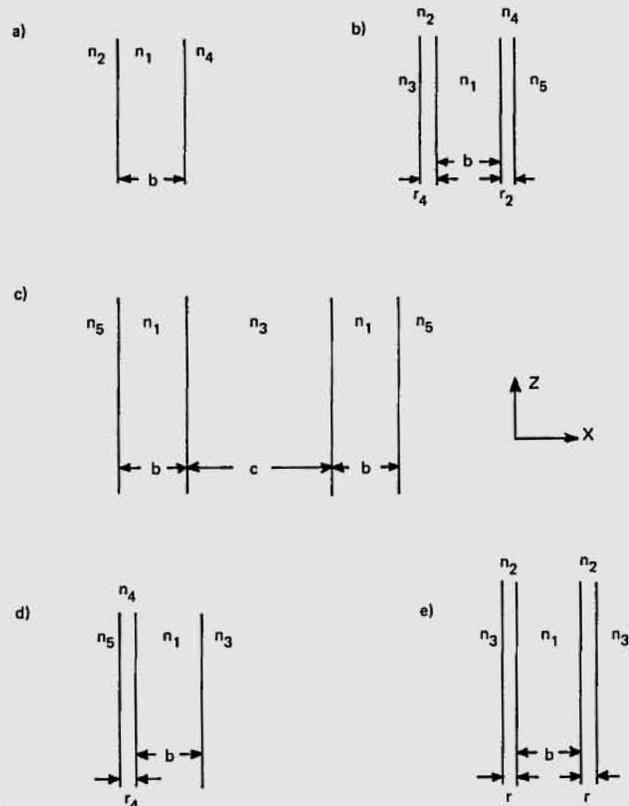


Fig. 2. Particular cases of Fig. 1: (a) isolated guide; (b) clad waveguide; (c) guide coupler; (d) tuning of a waveguide; (e) W-type waveguide.

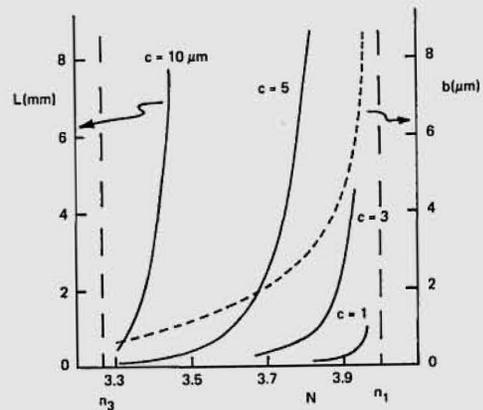


Fig. 3. $L(N)$ and $b(N)$ for $c = 1, 3, 5,$ and $10 \mu\text{m}$.