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Single-mode operation of grazing-incidence pulsed dye laser

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A variation of the grazing-incidence pulsed dye laser is presented. This laser has been operated in a single longitudinal cavity mode with a single-shot linewidth of less than 300 MHz and a time-averaged linewidth of 750 MHz. The single-mode conversion efficiency of the laser is 2% using Rhodamine 6G dye.

Recently a novel pulsed-dye-laser design was introduced independently by Shoshan *et al.*[1] and by Littman and Metcalf.[2] Working models of both designs achieved narrow-band operation (linewidth $\lesssim 0.08\ \mathrm{cm}^{-1}$ at ~ 600 nm) without use of an intracavity beam expander. A schematic of the design of Littman and Metcalf (MIT laser) is shown in Fig. 1. [The design of Shoshan *et al.* (Technion laser) differs in that the partially reflecting output mirror is replaced with a fully reflecting one and the zero-order reflection from the grating is used for output coupling.] To illuminate the full width of the diffraction grating, which is necessary for narrow-band operation, a grazing angle of incidence is used. Unlike with the conventional Hänsch dye laser,[3] the grating is not used in a Littrow configuration (i.e., the diffracted beam is not collinear with the incident beam), and a plane mirror is used to complete the cavity. Tuning of the laser is accomplished by rotation of this mirror, not the grating.

The tuning curve of the laser[2] is given by

$$\lambda = (x/m)(\sin\theta_0 + \sin\phi) \approx (x/m)(1 + \sin\phi), \quad (1)$$

where x is the grating period, m is the diffraction order, θ_0 is the angle of incidence (roughly 90°), and ϕ is the angle between the normals of the grating and tuning mirror. The single-pass linewidth (full width at half maximum) has a minimum value when the separation between the dye cell and grating equals the Rayleigh length ($L_R \equiv \pi w^2/\lambda$, where w is the beam waist). In that case,

$$\frac{\Delta\lambda}{\lambda} = \frac{2\sqrt{2}\lambda}{\pi l(\sin\theta_0 + \sin\phi)} \approx \frac{2\sqrt{2}\lambda}{\pi l(1 + \sin\phi)}. \quad (2)$$

Here l is the illuminated width of the grating. This expression predicts a linewidth about 30% smaller than that expected for the Hänsch laser.

The most significant advantage of the grazing-incidence design over the Hänsch design, however, is not the reduced single-pass linewidth but the ease with which a narrow-band model can be constructed. To obtain a narrow linewidth with the Hänsch design, high-quality intracavity optical elements are needed, and alignment is quite difficult. With the grazing-incidence design, no intracavity elements are needed, and alignment is unusually simple.

The MIT laser achieved a linewidth of $0.08\ \mathrm{cm}^{-1}$ (at 600 nm) using a 5-cm-wide, 1800 lines/mm holographic grating with $\theta_0 = 89.2°$. The conversion efficiency was 3% using a doubled Nd:YAG laser pump beam (532 nm, 250 kW peak power, 7-nsec pulse duration) and $2.5 \times 10^{-3}\ M$ solution of R6G dye in ethanol. The Technion laser operated with the same linewidth using a 15-cm-wide, 316 lines/mm echelle grating with $\theta_0 = 89.5°$. The conversion efficiency was 3% using a N_2 laser pump beam (337 nm, 50 kW peak power, 12-nsec pulse duration) and a $2.5 \times 10^{-3}\ M$ solution of R6G dye in hexafluoroisopropanol. In addition, stable longitudinal cavity modes were observed in the MIT laser, and single-mode operation was achieved near threshold.

In this Letter, we describe an improved version of the grazing-incidence dye laser, which has been operated reliably in a single longitudinal cavity mode. In addition, this new design offers the advantage of improved conversion efficiency when operated multimode.

A schematic of the new laser is shown in Fig. 2. This laser differs from the previous one in that a Littrow grating is used instead of the tuning mirror. Two possible orientations of the second grating satisfy the Littrow condition (shown as bold and dashed lines in Fig. 2). The dispersion of the grazing-incidence grating and that of the Littrow grating must add for improved operation; this condition is met only for the grating configuration shown bold in Fig. 2. (In the dashed configuration the net dispersion is actually reduced because the dispersions of the gratings have opposite signs.) To determine the tuning curve of the double-grating laser we proceed as in Ref. 2. The basic equations in the double grating case are

$$m\lambda = x(\sin\theta_0 + \sin\theta_1), \quad (3a)$$

$$m'\lambda = 2x'\sin\theta_2, \quad (3b)$$

where θ_0 is the angle of incidence, θ_1 is the angle of the diffracted ray, and θ_2 is the Littrow angle (see Fig. 2). We restrict ourselves to the case in which the rays retrace their paths on reflection from the Littrow grating. From simple geometry one finds that $\theta_1 + \theta_2 = \Phi$, where Φ is the angle between the grating normals, and thus θ_2 can be eliminated from Eq. (3b). We can also eliminate θ_1 by applying Eq. (3a), which now gives an expression, quadratic in λ, that depends only on the angle of inci-

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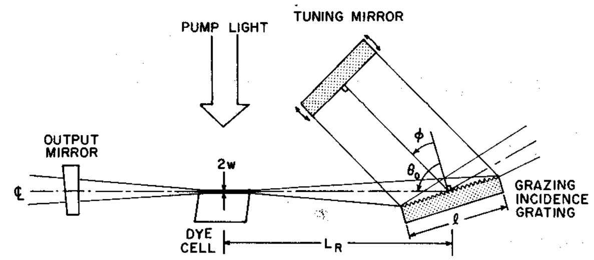

Fig. 1. Schematic of single-grating pulsed dye laser.

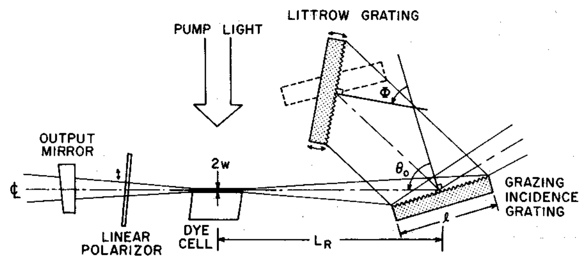

Fig. 2. Schematic of double-grating pulsed dye laser.

dence and the angle between the grating normals. The solution is

$$\lambda = \frac{(4\alpha + 2\beta \cos \Phi) \sin \theta_0 + 2 \sin \Phi[(\beta \cos \theta_0)^2 + 4\alpha(\alpha + \beta \cos \Phi)]^{1/2}}{\beta^2 + 4\alpha^2 + 4\alpha\beta \cos \Phi}, \quad (4)$$

where $\alpha = m/x$ and $\beta = m'/x'$. We have chosen the root of the quadratic equation that reduces to the previous result, Eq. (1), when $m' = 0$ (i.e., when the Littrow grating is used as a mirror). Now if we consider the case when $m = m'$, $x = x'$, and $\theta_0 \cong 90°$, Eq. (4) becomes

$$\lambda \approx \frac{x}{m}\left[\frac{4 + 2 \cos \Phi + 4 \sin \Phi\, (1 + \cos \Phi)^{1/2}}{(5 + 4 \cos \Phi)}\right]. \quad (5)$$

In Fig. 3 the tuning curves for both the original single-grating design and the double-grating design are shown for the case of 2400 lines/mm gratings used in first order. This figure shows that the double-grating configuration has the advantages of a less-steep turning curve and a broad, nearly linear region.

An expression for the single-pass linewidth of the double-grating laser is obtained following the analysis performed in Ref. 2,

$$\frac{\Delta\lambda}{\lambda} = \left\{\frac{2\alpha + \beta \cos \Phi - \dfrac{\beta^2 \sin \Phi \sin \theta_0}{[\beta^2 \cos^2 \theta_0 + 4\alpha(\alpha + \beta \cos \Phi)]^{1/2}}}{\beta^2 + 4\alpha^2 + 4\alpha\beta \cos \Phi}\right\} \frac{4\sqrt{2}}{\pi l}. \quad (6)$$

This relationship is applicable to the case where the distance between the cell and the grazing-incidence grating is equal to the Rayleigh length. For the special case for which $m = m'$, $x = x'$, and $\theta_0 \cong 90°$, Eq. (6) simplifies to

$$\frac{\Delta\lambda}{\lambda} \approx \frac{x}{m}\left[\frac{2 + \cos \Phi - \dfrac{\sin \Phi}{2(1 + \cos \Phi)^{1/2}}}{5 + 4 \cos \Phi}\right]\frac{4\sqrt{2}}{\pi l}. \quad (7)$$

In Fig. 4 a graph of $\Delta\lambda/\lambda$ versus rotation angle for both single- and double-grating designs is shown. We see that the double-grating arrangement provides a single-pass linewidth that is almost a factor of 2 narrower than that of the single-grating design. This result also may be viewed in another way, that is, for operation with a given linewidth, the new design requires a smaller value of θ_0. (By decreasing θ_0 we can effectively decrease l, which results in an increased spectral width.) This last point is significant with regard to conversion efficiency for multimode operation, since the off-Littrow grating losses increase dramatically as θ_0 approaches 90°.

For single-mode operation of the double-grating laser, several parameters must be carefully determined. First, it is necessary to shrink the cavity length as much as possible so that the free spectral range (FSR) between adjacent cavity modes is large. In our prototype, the centerline length was about 8 cm, which corresponds to a FSR of about 2 GHz. A consequence of reducing the spacing between the output mirror and the dye cell is increased background fluorescence. We found that this fluorescence was substantially reduced by insertion of a horizontal linear polarizer between the output mirror and the dye cell (the pump laser was vertically polarized). Next, it is necessary to reduce the single-pass linewidth so that it is comparable with the cavity-mode separation. A single-pass linewidth of 2 GHz was obtained using a 5-cm-wide, 2400-lines/mm holographic grazing-incidence grating (PTR, Inc.) at $\theta_0 = 89°$ and a 5-cm-wide, 1800-lines/mm ruled Littrow grating (26° 45′ blaze, Bausch & Lomb). To achieve a 5-cm Rayleigh length, we used a high dye concentration (5×10^{-3} *M* solution of R6G dye in ethanol) and weakly focused

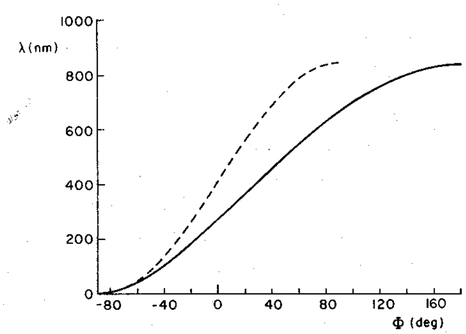

Fig. 3. Tuning curve for double-grating laser using 2400-lines/mm gratings. Dashed curve corresponds to single-grating design.

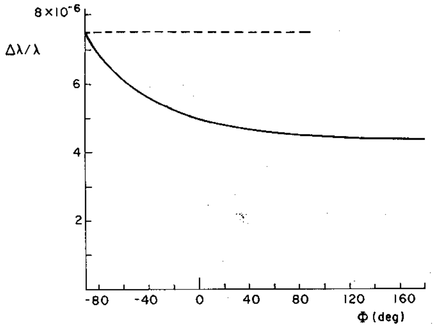

Fig. 4. Δλ/λ versus rotation angle for double-grating laser using 5-cm-wide 2400-lines/mm gratings. Dashed curve corresponds to single-grating design.

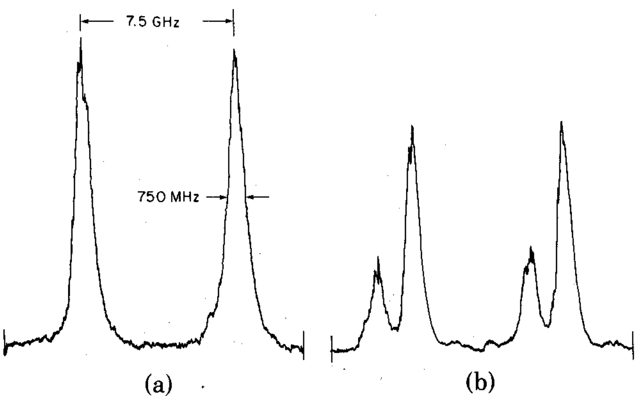

Fig. 5. Analysis of laser output using 7.5-GHz FSR scanning Fabry–Perot etalon: (a) single-mode operation—the measured linewidth is limited by shot-to-shot laser jitter. The single-shot linewidth is at most 300 MHz; (b) the laser has been misadjusted to demonstrate multimode operation. The observed mode separation agrees with the value expected for an 8-cm cavity.

the pump light. The high-quality dye cell (Molectron #DL051) was not stirred. The laser repetition rate was 10 Hz. The vertical adjustments of the 4% reflecting output mirror and gratings were not especially critical. Light from this laser was coupled out both ends of the cavity. The grating-coupled beam had higher power, whereas the output-mirror-coupled beam had a better beam shape.

The single-mode laser described above provided a single-shot linewidth of 300 MHz with 2% conversion of the 150-kW, 532-nm, 7-nsec pump light. The beam divergence was 6 mrad (full angle). A scanning Fabry–Perot interferometer was used to monitor the time-averaged linewidth, and a typical trace is given in Fig. (5a). The measured linewidth is limited by shot-to-shot laser jitter, which is believed to be caused by thermal effects in the dye solution. In Fig. (5b), the trace is similar, but the laser has been misadjusted to operate in two modes. For mechanical stability all laser elements were mounted on a common optical rail. The use of separate supports for individual components is not recommended.

Tuning of the laser is accomplished by rotation of the Littrow grating. Unless the rotation mount is carefully designed, the scan is subject to mode hops, in which one mode fades out while another fades in as the Littrow grating is rotated. It should be possible to choose the position of the stationary point in the grating mount so that the laser cavity length varies simultaneously as the grating angle is changed. In fact, one can match both the first- and second-order variations of wavelength with angle to produce a continuous single-mode scan over a large interval, throughout which only a single optical element is rotated. At present, we are constructing such a prototype. Alternatively, continuous tuning could be obtained by pressure scanning.[4]

The double-grating grazing-incidence dye laser offers the important advantage that it can be operated in a single longitudinal cavity mode. It is also the case that this new design is superior to the single-grating design when single-mode operation is not required. In addition to improved conversion efficiency and a less-steep tuning curve, which have already been discussed, the double grating arrangement provides increased dispersion, thereby making the laser even easier to align. In virtually all respects the double-grating design is preferred.

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Note added in proof: During preparation of this manuscript I learned that I. Shoshan and U. Oppenheim have also considered the double-grating arrangement [see I. Shoshan and U. Oppenheim, Opt. Commun. **25**, 375 (1978)]. In addition, I have recently learned that S. Saikan of the Max-Planck Institut für Biophysikalische Chemie, Göttingen, has obtained single-mode operation of the grazing-incidence dye laser by means of a resonant reflector. A description of this work is to appear in *Applied Physics*.

References

1. I. Shoshan, N. Danon, and U. Oppenheim, J. Appl. Phys. **48**, 4495 (1977).
2. M. Littman and H. Metcalf, Appl. Opt. **17**, 2224 (1978).
3. T. Hänsch, Appl. Opt. **11**, 895 (1972).
4. R. Wallenstein and T. Hänsch, Appl. Opt. **13**, 1625 (1974).