Scanning geometry for broadly tunable single-mode pulsed dye lasers

G. Z. Zhang and K. Hakuta

Department of Applied Physics and Chemistry and Institute for Laser Science, University of Electro-Communications, Chofu, Tokyo 182, Japan

Received March 3, 1992

We describe a scanning geometry for broadly tunable single-mode lasers that use a grazing-incidence grating as the dispersive element. This geometry is a generalized version of the Liu and Littman cavity [Opt. Lett. **6**, 117 (1981)] but has much more flexibility in the configuration compared with theirs. Based on the present geometry, we have obtained a broad single-mode tuning range of 190 cm^{-1} for a pulsed dye laser.

Several schemes have been proposed for pulsed dye lasers to get single-mode operation with broad tunability.[1-7] Among them, the scheme proposed by Liu and Littman[4] and realized by Littman[6] is the most innovative one, because it demonstrated the possibility of obtaining a broad single-mode scanning with only mechanical rotation of a mirror. The central idea of their scheme is to employ a short cavity with a grazing-incidence grating for obtaining single-mode operation and to track the cavity length so that when the angle of the tuning mirror is changed, the longitudinal mode number remains constant. They showed that this tracking condition can be satisfied if the surface planes of the three optic elements that make up the cavity (tuning mirror, grating, and end mirror) intersect exactly at the rotation axis for the tuning. However, it might be quite difficult to satisfy this tracking condition strictly in a practical laser apparatus. Actually, owing to the misalignment problem, the tunable range of this type of laser is limited typically to 30 cm^{-1}.[8]

In this Letter we show that the exact tracking can be realized under much more flexible conditions than those of Liu and Littman[4] by formulating the cavity length. The present conditions include Liu and Littman's tracking conditions as one special case. The flexibilities may make it possible to achieve the broad single-mode scan with a much simpler adjustment procedure. Based on the present conditions, we have obtained a broad single-mode tuning range of 190 cm^{-1} for a pulsed dye laser. A similar analysis has been carried out by McNicholl and Metcalf[9] from a different approach by using scalar diffraction theory, but the results have not been verified experimentally.

Figure 1 illustrates the schematic diagram of the laser cavity geometry. The tuning can be accomplished by rotating a reflecting mirror (the tuning mirror) around the center O. The tuning mirror is fixed on a rotation stage. The bold solid lines denote the paths of the oscillating laser radiation. It is assumed that the optic elements that make up the cavity are adjusted so that the plane determined by the laser paths is perpendicular to the rotation axis. In this Letter we restrict our discussion to the geometry on this plane.

We define the rotation angle for tuning by angle MOG as θ. Surface lines GP and MP are tilted to lines GO and MO by angles of α and β, respectively. This geometry coincides with that of Liu and Littman when both angles α and β are zero. We define a point Q on the surface line of the tuning mirror by drawing a perpendicular from the rotation center O. The length $\overline{OQ}$ is designated R_f, and the R_f value is defined to take a negative value when the length $\overline{GM}$ is shorter than the length $\overline{GM'}$. An important feature of this geometry is that the R_f value is kept constant for the rotation of the tuning mirror, since the tuning mirror is fixed on the rotation stage. In other words, the point Q draws a circle of radius $|R_f|$ about the origin O for the mirror rotation.

For this cavity geometry, we can write the equations for wavelength selection and single-mode operation. The oscillating wavelength is determined by the diffraction condition of the grating as follows:

$$\lambda = \frac{d}{m}(\sin\chi + \sin\varphi). \tag{1}$$

Here λ is the oscillating wavelength, d is the grating period, m is the diffraction order, χ is the incidence angle, and φ is the diffraction angle. For the grazing-incidence case, we have another condition of $\sin\chi \approx 1$. From Fig. 1, we can easily obtain a relation between the rotation angle and the diffraction angle,

$$\theta - \beta = \varphi - \alpha. \tag{2}$$

In order to obtain a continuous scan with the single-mode operation, the cavity length must be varied so that the longitudinal mode number is kept constant for the wavelength tuning. For the geometry of Fig. 1, the cavity length can be expressed as

$$\begin{aligned} L &= L_f + L_t, \\ &= L_f + \overline{MM'} + \overline{GM'}, \\ &= L_f + R_f + L_p \sin(\theta - \beta), \end{aligned} \tag{3}$$

0146-9592/92/140997-03$5.00/0

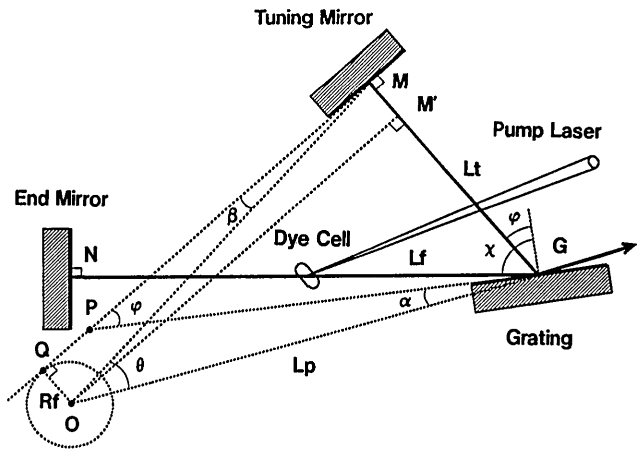

Fig. 1. Schematic geometry of the short-cavity grazing-incidence dye laser.

where L is the cavity length and L_f, L_t, and L_p denote the lengths of $\overline{NG}$, $\overline{GM}$, and $\overline{OG}$, respectively. By using Eqs. (1)–(3), we can derive an explicit expression of the cavity length for the tuning:

$$L = N\frac{\lambda}{2} + \Delta L_f - \Delta L_g, \tag{4}$$

where

$$N = 2m\frac{L_p \cos\alpha}{d}, \tag{5}$$

$$\Delta L_f = L_f + R_f - L_p \sin\chi \cos\alpha$$
$$\approx L_f + R_f - L_p \cos\alpha, \tag{6}$$

$$\Delta L_g = L_p \sin\alpha \cos\varphi. \tag{7}$$

As seen in Eq. (4), the cavity length is expressed as a sum of three terms. The first term is the main term of this expression, which permits the continuous single-mode scan. The second and third terms are the misadjustment terms, which spoil the continuous single-mode scan. If the sum of the misadjustment terms is zero, the cavity length is simply expressed as the first term in which the N value corresponds to the longitudinal mode number, and the cavity length can be varied so that the tuning keeps the mode number constant. It must be mentioned that the second term ΔL_f is determined only by the initial setup of the cavity. This fact means that the ΔL_f value can be controlled independently to the wavelength tuning by adjusting the positions of the end mirror and the tuning mirror. The third term ΔL_g varies for the wavelength tuning when the value of $\sin\alpha$ is not zero. If this term is not zero, it shows a completely different behavior for the tuning from that of the first term, since the $\cos\varphi$ term that can be obtained from Eq. (1) is not proportional to the oscillating wavelength λ.

From the above discussions, we can get the tracking conditions for obtaining the continuous single-mode scan as $\Delta L_g = 0$ and $\Delta L_f = 0$, namely,

$$\alpha = 0, \tag{8}$$

$$L_f + R_f \approx L_p. \tag{9}$$

The above two relations are the general conditions for the cavity arrangement for obtaining the continuous single-mode scan. Equation (8) imposes an essential condition to the grating adjustment; that is, the grating must be located precisely so that its surface line passes through the rotation center O. On the other hand, the mirror alignments have more flexibilities compared with that for grating. Relation (9) means that the adjustments of the end mirror and the tuning mirror are complementary, and it is not necessary to adjust precisely the two mirrors independently so that each surface line passes through the rotation center. The essential condition for the mirror geometry is that the sum of L_f and R_f must be adjusted to be equal to the length L_p by translating the mirrors along the optic axis.[10] It must also be mentioned that relation (9) naturally leads to a method to compensate for the optical path change of the cavity induced by insertion of optic elements such as a dye cell. That is, such insertion may result in an increase of the effective cavity length, and one can readily compensate for this increase to satisfy relation (9) by shortening the length L_f and/or R_f.

Here we should note that the present general conditions include the Liu and Littman conditions as one special case. That is, their conditions correspond to the case $R_f = 0$ ($\beta = 0$) of the present conditions, but the condition $R_f = 0$ is not an essential condition for obtaining a broad single-mode scan. The present conditions permit much more flexibility for the mirror arrangement.

Based on the conditions obtained above, we have constructed a pulsed dye laser with a cavity length of approximately 5 cm. A holographic grating of 2400 grooves/mm was used in the first order. We used a DCM dye solution with a concentration of 6×10^{-4} M. The dye laser was pumped by a frequency-doubled YAG laser longitudinally. The grating and tuning mirror were adjusted by using mechanical translation stages. The grating was carefully adjusted so that its surface line passed through the rotation center. For the adjustments of the mirrors, we first roughly set the tuning mirror position, and after that the end mirror position was adjusted to obtain a broader single-mode tuning range. The mode spectrum was monitored by observing an interference pattern through an air-spaced étalon with a linear array detector. The free spectral range and the finesse of the étalon were 1 cm^{-1} and 20, respectively.

By carrying out the adjustment procedure carefully, we have readily obtained a broad single-mode scanning range of 190 cm^{-1}. Figures 2(a) and 2(b) display the typical interference patterns obtained for the single-mode range and for slightly out of the single-mode range, respectively. In Fig. 2(b) a weak submode is clearly seen in addition to the primary mode. The single-mode scanning range was defined as a range in which the submode oscillates with 5% intensity of the primary mode at both ends. It has also been confirmed experimentally that this scanning range is maintained by shifting the two mirrors to compensate for the optical length as

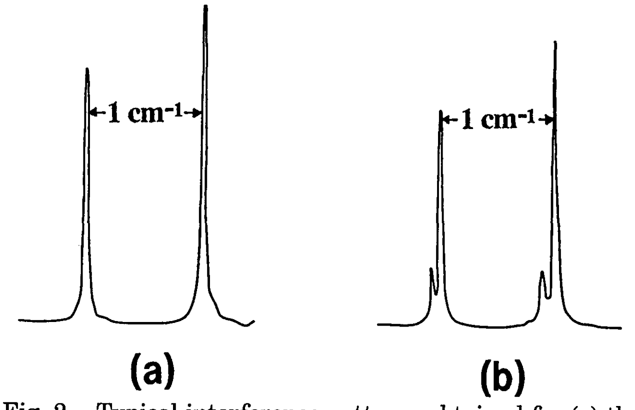

Fig. 2. Typical interference patterns obtained for (a) the single-mode range and (b) sightly out of the single-mode range. The free spectral range is 1 cm^{-1}, and the linewidth is due to the resolution of the étalon.

shown in relation (9). These results clearly demonstrate that the present flexible geometry has made it possible to obtain the broad single-mode scan with a much simpler procedure. In a practical sense, this should be a big advantage in extending the applications of the single-mode lasers to many kinds of field.

In summary, we have shown theoretically that it is possible to realize a broadly tunable single-mode laser under much more flexible conditions than those of Liu and Littman. We have demonstrated the validity of the flexible conditions experimentally and have realized a broad single-mode scan of 190 cm^{-1} for a pulsed dye laser by using only mechanical rotation of the mirror.

The authors thank T. Miyawaki and T. Naoi for their help in constructing the dye laser. G. Z. Zhang acknowledges the financial support of the Ministry of Education, Japan. This research is partly supported by a Grant-in-Aid for scientific research from the Ministry of Education and from the Matsuo Foundation.

References

1. R. Wallenstein and T. W. Hänsch, Appl. Opt. **13,** 1625 (1974).
2. M. G. Littman, Opt. Lett. **3,** 138 (1978).
3. S. Saikan, Appl. Phys. **17,** 41 (1978).
4. K. Liu and M. G. Littman, Opt. Lett. **6,** 117 (1981).
5. A. F. Bernhardt and P. Rasmussen, Appl. Phys. B **26,** 141 (1981).
6. M. G. Littman, Appl. Opt. **23,** 4465 (1984).
7. O. L. Boune and D. M. Rayner, Opt. Commun. **64,** 161 (1987).
8. M. G. Littman and J. Montgomery, Laser Focus **24**(2), 70 (1988).
9. P. McNicholl and H. J. Metcalf, Appl. Opt. **24,** 2757 (1985).
10. Practically it is possible to control the length R_f by varying the yaw angle β. However, the change by means of the translation is much better than the yaw angle adjustment, because the translation of the tuning mirror does not change the diffraction angle, and the oscillating wavelength may not be affected by the adjustment by means of the translation.