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BY USING GLANCING-INCIDENCE GRATING

by

Lu Tongxing, Zhao Xianzhang, He Guanglong

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COMPOUND CAVITY OF PULSED DYE LASER TUNED BY USING GLANCING-INCIDENCE GRATING

Lu Tongxing, Zhao Xianzhang, and He Guanglong,
Department of Physics, Anhui Normal University

Abstract. The operating properties of a compound-cavity pulsed dye laser, which is tuned by means of glancing-incidence grating, is analyzed theoretically in this paper. We found the conditions under which the compound cavity can narrow the laser linewidth and increase laser energy. The experimental results are consistent with theory.

Key words: compound cavity, dye laser.

In many research fields using a laser as the light source, such as research on high-resolution power light spectra, it is required that the laser be continuously tuned, but also very narrow laser linewidth is required. Therefore, how the linewidth can be narrowed is always one of the important topics in laser technology. Shoshan et al. [1, 3] applied the beam expansion method of the glancing-incidence grating to realize the purpose of narrowing the linewidth. The article studies a method of applying a compound cavity in a dye laser with a glancing-incidence gravity to further narrow the laser linewidth and to increase the laser output energy. The improvement of the output properties of a compound-cavity laser was first proposed by Bjorkholm [4]. Then he placed a semireflecting mirror in front of a tuning grating of a dye laser, which was tuned with the grating, in order to prevent intense light from damaging the grating by burning. Unexpectedly, it was discovered in the experiment that this setup not only can protect a grating from being damaged by intense light, but also can better narrow laser linewidth and increase the output energy. At present, compound cavities have been extensively applied in the branch selection technique of CO_2 lasers [5, 6]. However, there are few research papers on the application and theoretical analysis of dye lasers.

Theoretical Analysis of Compound Cavity

1. Effective reflective index R_c of compound cavity

Fig. 1 is a schematic diagram of the experimental setup. In the figure, G is the grating; M_1 is a completely reflective mirror; M_2 is a tuning reflective mirror; and M_3 is a semi-transparent lens. A beam from the N_2 laser passes through the cylindrical-surface lens to focus on the dye pump. Upon exiting from the dye pool, the light is at glancing incidence to the grating at an incidence angle approaching 90°. If the appropriate grating constant is selected, after diffraction following passage through grating G, two light beams (level 1 and level 0) will be divided. If there is no M_3, level 1 light oscillates in the main resonant cavity M_1-G-M_2; level 2 is the output light from the laser. If a semi-transparent lens M_3 is placed, then some of the level 0 light, upon reflection from M_3, will produce sub-zero level and sub-one level light generated upon diffraction from grating G. Sub-level light will be lost, and only sub-zero level light returns to the resonant cavity. Thus, a supplementary cavity is formed, consisting of M_1-G-M_3, with mutual interference occurring with light from the main resonant cavity.

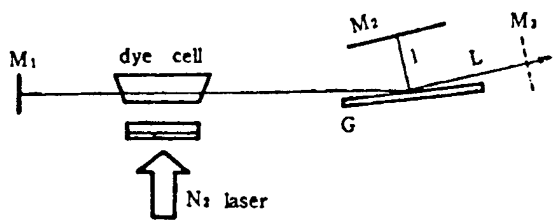


Fig. 1. Optical path diagram of compound-cavity dye laser tuned with glancing-incidence grating

Assume that the light beam exiting from the dye pool can be expressed as Aexp(i'phi$_0$); A is the oscillation amplitude of the light beam; phi$_0$ is its phase angle. Then, the level 1 light beam and the level 0 light beam generated from the grating diffraction are, respectively:

$$A\sqrt{Rg_1}\exp[i(\phi_0 + 2\pi s/\lambda)]$$

$$A\sqrt{Rg_0}\exp[i(\phi_0 + 2\pi s/\lambda)]$$

In the equations, Rg_1 and Rg_0 are, respectively, level 1 and level 0 reflective indexes of the grating. After reflection from

M_2 and again diffraction with D, the level 1 light beam enters into the resonant cavity as

$$A\sqrt{Rg_1}\cdot\sqrt{Rg_1}\cdot \exp i[\phi_0 + 2\pi(2s+2l)/\lambda]$$

The sub-zero level wave returned from reflection by M_3 is

$$A\sqrt{Rg_0}\cdot\sqrt{R_3}\cdot\sqrt{Rg_0}\cdot \exp i\left[\phi_0 + \frac{2\pi}{\lambda}(2S+2L)\right]$$

In the equation, R_3 is the reflective index of M_3. Thus, the overall light beam returning to the resonant cavity is

$$A\sqrt{R_c}\,e^{i\phi'} = A\exp i\left[\phi_0 + \frac{2\pi}{\lambda}(2S+2l)\right]\cdot\left(Rg_1 + Rg_0\sqrt{R_3}\,e^{i2\Delta\phi}\right) \tag{1}$$

In the equation, R_0 is called the effective reflection index of the compound cavity

$$\Delta\phi = \frac{2\pi}{\lambda}(L-l)\text{。}$$

From Eq. (1), R_c is derived as:

$$R_c = Rg_1^2 + Rg_0^2R_3 + 2Rg_1\sqrt{R_3}\,Rg_0\cos 2\Delta\phi \tag{2}$$

For sake of comparison, the authors analyzed the reflective index R_s of the simple grating cavity in the absence of M_3. According to general grating formulas, we obtain the grating level 1 reflective index Rg_1 (when lambda = $\lambda_0 + \Delta\lambda$):

$$Rg_1 = Rg_{10}\sin c^2\left(\pi N\frac{\Delta\lambda}{\lambda_0}\right) \tag{3}$$

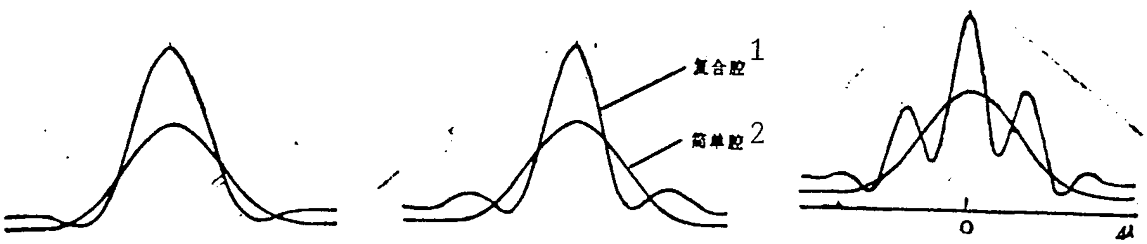
In the equation, Rg_{10} is the level 1 reflective index of the grating when lambda = lambda$_0$; N is the number of fringes at the grating with light beam illumination. Therefore, R_s can be expressed as:

$$R_s = Rg_1^2 = Rg_{10}^2\sin c^4\left(\pi N\frac{\Delta\lambda}{\lambda_0}\right) \tag{4}$$

Substitute Eq. (3) into Eq. (2) and we obtain that the effective reflective index R_0 of the compound cavity is:

$$R_c = Rg_{10}^2 \mathrm{sinc}^4\left(\pi N \frac{\Delta\lambda}{\lambda_0}\right) + Rg_0^2 R_3 + 2Rg_0 Rg_{10}\sqrt{R_3}\,\mathrm{sinc}^2\left(\pi N \frac{\Delta\lambda}{\lambda_0}\right)\cos\left[\frac{2\pi}{\lambda_0 + \Delta\lambda}\cdot 2(L-1)\right] \quad (5)$$

As discovered from calculating Eq. (5), the maximum value of R_0 may change several times at lambda=lambda$_0$ with change of DELTA l=L-1. When Rg_{10}=0.8, Rg_0=0.15, R_3=0.7, N=34,000 (here d=1200/mm and alpha=4^0), Fig. 2 shows the curve R_0 proportional to DELTA lambda at three positions of DELTA l: 1.00002, 1.50000, and 2.70000cm. In the figure, the curve of the effective reflective index R_s of the simple grating cavity is also drawn.



a. $\Delta l = 1.00002$; b. $\Delta l = 1.50000$; c. $\Delta l = 2.70000$

Fig. 2. Curves R_c proportional to DELTA lambda for several DELTA l values, in the case alpha=4^0
KEY: 1 - compound cavity 2 - simple cavity

From the figure, the maximum positions of R_c and R_s are coincident at lambda=lambda$_0$. Of interest is the fact that, with an increase in DELTA l, R_c has a multiple-peak structure. For example, at DELTA l=1.00002cm, there is one distinct main peak for R_c. However, at DELTA l=2.70000cm, except for the central main peak, in its left and right there are symmetrically distributed two small peaks with amplitude gradually decreasing.

Besides, with increase in DELTA 1, the main peak becomes narrower and narrower. When DELTA 1 changes minutely near the position of maximum value, the R_c curve will have changed sensitively as shown in Fig. 3. In other words, the peak value position of R_c has shifted; the wave peaks are not symmetric and the height of the peak value has decreased.

a. Δl = 1.00001;   b. Δl = 1.00003

Fig 3. Effect on symmetry of curve R_c wave DELTA lambda of minute changes in DELTA lambda, in the case alpha=4°
KEY: 1 - compound cavity 2 - simple cavity

Fig. 4 is the curve showing the relationship between R_c and DELTA-1 when alpha=4.8°. By comparing Figs. 4 and 2(b), we can see that the wave peaks R_j are more numerous and that the main peak is narrower at the same DELTA 1 with larger glancing angle.

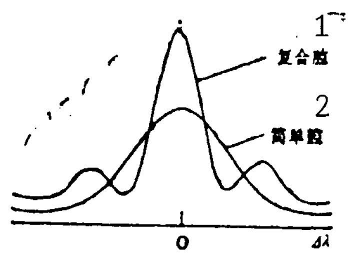


Fig. 4. Effect on curves R_c proportional to DELTA lambda for changes in glancing angle alpha: in the figure, alpha=4.8° and DELTA 1=1.5000
KEY: 1 - compound cavity 2 - simple cavity

2. Output power

The following relationship holds between laser output and cavity reflective index:

$$P = AI_0 = \frac{1}{2} I_s A(1 - a_h - R)\left(\frac{g_0}{a_0 - \frac{1}{2L'}\ln R} - 1\right) \tag{6}$$

In the equation, I_0 is the output light intensity; I_s is the saturated light intensity; A is the average laser beam cross-sectional area; a_h is the lens surface wear at the output terminal of the cavity; R is the effective reflective index; g_0 is the gain coefficient of lambda$_0$; a_0 is wear in the cavity; and L' is the length of the dye pool. Substitute Eqs. (4) and (5) in Eq. (6) and then we obtain that the output power of the simple cavity and the output of the compound cavity are as follows:

$$P_s = \frac{1}{2} I_s A(1 - a_{hs} - R_s)\left(\frac{g_0}{a_0 - \frac{1}{2L'}\ln R_s} - 1\right) \tag{7}$$

$$P_c = \frac{1}{2} I_s A(1 - a_{hc} - R_c)\left(\frac{g_0}{a_0 - \frac{1}{2L'}\ln R_c} - 1\right) \tag{8}$$

If $Rg_{10} = 0.80$, $Rg_0 = 0.15$, $\Delta l = 1.50000\text{ cm}$, $N = 34000, g_0|_{\lambda_0} = 0.2$, $\lambda_0 = 600\text{ nm}, a_{hs} = 0.05$, $a_{hc} = 0.1$, $L' = 3\text{ cm}$, and a_0 at 0.05, 0.10, and 0.15, respectively, then the relationship curves can be plotted between 2 Ps/IsA and 2 Pc/IsA and the wavelength, from the two equations (7) and (8). Fig. 5 shows the relationship curves. We can see that the semi-height width $\delta\lambda_s = 0.042\frac{\lambda_0}{N}\text{nm}$, of the power distribution curve for the simple cavity. The semi-height width

$\delta\lambda s = 0.066 \frac{\lambda_0}{N}$ nm, for the power distribution of the compound cavity. The ratio between the two peak widths is $\delta\lambda_c/\delta\lambda_s = 0.64$, ; $P_c/P_s=2$ is the ratio of two peak values. In other words, in conditions that the authors assumed, the compound cavity has narrower output linewidth and higher output power than that of the simple cavity.

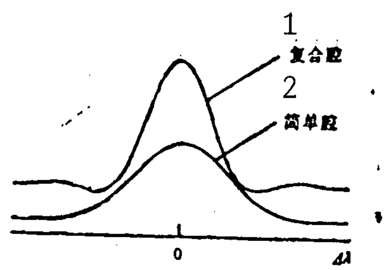


Fig. 5. Output power curves of laser for compound cavity and simple cavity
KEY: 1 - compound cavity 2 - simple cavity

Experimental Results

The dye used in the experiments was rhodamine 6G, and the alcohol concentration was at the concentration $1.5\times10_{-3}$mol/m^3. By using the N_2 laser as the pumping source, the pulse energy was 2mJ. The length of the dye pool was 3cm; and the grating constant d=1200/mm. As shown in Fig. 1, L=4cm and l=3cm; the reflective index (of the semi-transparent lens M_3) R_3=0.70. Other element parameters are shown as above.

Measurement of linewidth for the dye laser employed the Fabry-Perot interferometer. The Fabry-Perot spacing d=5mm; for the free light spectral zone, the spacing was 0.036mm

(λ_0=600nm). The mirror reflective index R=0.90; and the precision constant was approximately 60. A model RJP-700 energy meter was used to measure the pulse energy of the dye laser.

In the situation where the glancing angle alpha=4^0, measurements were conducted on changes in linewidth in the absence of the compound cavity: $\delta\lambda_s = 0.024$ nm, $\delta\lambda_c = 0.016$ nm, $\delta\lambda_c/\delta\lambda_s = 0.67$.

This value is very close to $\delta\lambda_c/\delta\lambda_s = 0.64$, as calculated theoretically.

When the grazing angle alpha=4^0, the measurements were made of the laser pulse energy before and after the absence of M_3, P_s=1.5, P_c=2.2, and P_c/P_s=1.5. These values are also very close to the theoretical value P_c/P_s=2. From the theoretical and experimental data, with the semi-reflective mirror M_3 for the compound cavity, not only does the laser linewidth become appreciably narrower, but also the output energy becomes obviously higher.

Discussion

As proven from the authors' theoretical analysis and experimental results, by placing the semi-reflecting mirror M_3, the purpose of narrowing the laser linewidth and increasing the output energy can be really attained. In the situation when the glancing angle is 4^0, the laser linewidth is narrowed to half its previous value, but the output energy is increased by 50%. However, the following points should be noted with respect to the optical path:

(1) From the discussion of the relationship between DELTA 1 and the curve R_c proportional to DELTA lambda, we know that the curve has a multiple-peak structure with increase in DELTA 1, but the central main peak is also steeper. There is a similar pattern between the output energy distribution and the curve R_c proportional to DELTA lambda. Hence, in order to obtain a narrower laser linewidth, a greater value of DELTA 1 is preferably selected within the allowable situation of laser dimensions.

(2) Since a slight change in DELTA 1 will deteriorate the symmetry of the curve R_c proportional to DELTA lambda with increase in the main peak width, increasing the output linewidth, [.... to be continued on text page 160, not supplied--Translator].

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