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A Quasi Double-Grating Grazing Incidence Pulsed Dye Laser

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Abstract. Continuous scanning of a 1 GHz pulsed laser line using only one 5-cm grating as an intracavity selective element is obtained from a pulsed dye laser pumped by a Nd:YAG (8 ns–532 nm) laser. Such a single-grating dye laser operates in the same way as a real double-grating grazing incidence laser and provides an appreciable improvement of the resolution (enhancement factor ≈ 2), compared with previous grazing incidence ones. The superiority of this laser cavity has been proved for single-longitudinal-mode operation.

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Dye lasers have become indispensable light sources for more than 20 years in a wide range of applications [1]. Particularly, tunable narrow-band grazing incidence dye lasers, first introduced by Littman and Shoshan [2, 3] are the most widely developed nowadays. In this laser-cavity type a diffraction grating is illuminated across its width by selection of an incidence angle near 90°. The cavity is completed by a high-reflectivity mirror (tuning mirror) that retroreflects a selected diffraction order back towards the grating where it is diffracted again along the laser axis. The laser beam is thus diffracted twice in one round trip of the cavity. The output laser beam is taken from the zero-order reflection off the grating or from the transmission through a low-reflectivity mirror (4%) which defines the opposite end of the cavity. The optical arrangement of this laser type is shown in Fig. 1.

According to the researchers, the achievement of a further spectral narrowing only requires the use of a wider grating. However, this desire is not always realistic because of the quality of the optical pumping system and of the intracavity dye laser beam, and because the grating efficiency near grazing angles is low. In practice, ultimate linewidths in grazing-

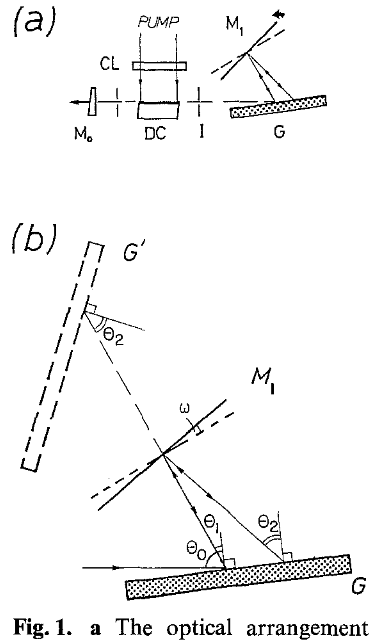

Fig. 1. **a** The optical arrangement of the dye laser cavity (3 diffractions); dc-dye cell; G: 5 cm, 2400 lines mm^{-1} grating; M_0: 4% reflecting output mirror; M_1: tuning mirror; CL: 5 cm cylindrical lens; I: 0.3 mm diaphragms. **b** Equivalence between the new single-grating cavity and a real double-grating grazing incidence laser cavity. θ_0, θ_1, θ_2 – incidence, diffracted and Littrow angles. (ω: the rotation angle of the tuning mirror from the usual Littman's working position, $\omega = (\theta_1 - \theta_2)/2$.) The dashed lines show the position of the virtual Littrow grating G′ and of the usual Littman's tuning mirror

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incidence cavities without the use of additional optical elements were limited to values $\geqq 3$ GHz ($0.1\ cm^{-1}$ FWHM at 600 nm) [2–6]. Therefore, to achieve a further spectral narrowing of grazing incidence lasers, the cavity selectivity must be usually enhanced by combining the selective properties of the grating with Fabry-Perot etalons [7–9], multi-element resonant reflectors [10] or additional gratings [11–13]. However, such laser cavities have disadvantages in wavelengths scanning and optical alignment in addition to extra-cost.

Recently, a modification to the grazing-incidence grating cavity has been proposed [14]. Although it makes use of a single grating, this such modified laser can operate as a double-grating laser, thus it is so-called "quasi double-grating laser".

Later, Dupré developed a theoretical analysis of the wavelength selection in this new laser [15]. But he mentioned in his article that his attempts to put it work were not satisfactory. That is the reason why we report in the present paper, for the first time, operation of a quasi double-grating grazing incidence pulsed dye laser in continuous scanning of a 1.0 GHz (FWHM) line using only one 5-cm grating as an intracavity selective element. While this single-grating modified cavity only differs very slightly from the previous grazing-incidence grating one, its performance is improved significantly. The main advantage of this cavity is to provide a resolution enhancement factor of ≈ 2 in spectral linewidth compared with the conventional grazing incidence cavity. Moreover, it is very easy to align and can be made very compact allowing for single-mode operation.

1. Description and Analysis of the Cavity

The optical components of the cavity are entirely the same as those of the conventional grazing-incidence cavity. As shown in Fig. 1, this cavity only differs from the conventional grazing incidence one by the working position of the tuning mirror. This mirror is rotated an angle ω, as defined below by (1), from Littman's working position so that the beam diffracted at an angle θ_1, is reflected back to the grating at the Littrow incidence angle θ_2. Compared with the behaviour of the previous single-grating grazing incidence laser it is seen that a Littrow dispersion is added in this new design. The laser beam is thus diffracted three times in one round trip of the cavity. This modification is equivalent to use two gratings of the same type in the previously mentioned double-grating grazing incidence laser [11]. Here, the virtual Littrow grating G' is symmetrical to the grazing-incidence grating with respect to the tuning mirror, as shown in Fig. 1b.

Two possible orientations of the tuning mirror can result in an additional Littrow diffraction. However, for an improved operation in spectral linewidth, the dispersion of the grazing incidence grating and that of the virtual Littrow grating must add. This condition is met only for the grating-mirror configuration shown in Fig. 1a. From simple geometry we find that the rotation angle (ω) of the tuning mirror is given by

$$\omega = \frac{\theta_1 - \theta_2}{2}. \tag{1}$$

Now we can express the single-pass linewidth $\Delta\lambda_{3d}$ for the quasi double-grating cavity (three diffractions) by the simplified [Ref. 4, Eq. (21)], when

$\alpha = -\beta = \frac{m}{a}$:

$$\Delta\lambda_{3d} = \frac{2\sqrt{2}\lambda}{\pi l(m/a)\left(1 + \frac{1}{2}\frac{\cos\theta_1}{\cos\theta_2}\right)}, \tag{2}$$

where m is the order and a is the groove spacing on the grating, and l is the illuminated width of the grating.

It can be compared with the similar expression for conventional single-grating cavity:

$$\Delta\lambda_{2d} = \frac{2\sqrt{2}\lambda}{\pi lm/a} \quad \text{[Ref. 4, Eq. (19)]}.$$

It leads to

$$\frac{\Delta\lambda_{2d}}{\Delta\lambda_{3d}} = \left(1 + \frac{1}{2}\frac{\cos\theta_1}{\cos\theta_2}\right) = R. \tag{3}$$

It is interesting to remark that

$$\frac{\cos\theta_1}{\cos\theta_2} = \left(\frac{1 - (\alpha\lambda - \sin\theta_0)^2}{1 - \left(\frac{\beta\lambda}{2}\right)^2}\right)^{1/2} \geqq 0. \tag{4}$$

Thus, this ratio R indicates that the new single-grating design with three diffractions results in an actual resolution enhancement, in the spectral linewidth, compared with conventional grazing incidence lasers.

In our quasi double-grating cavity, with $|\sin\theta_0| \simeq 1$ (grazing incidence) $|m| = 1$; $\alpha = -\beta = m/a$ and $\lambda/2 < a < \lambda$, when these values are substituted into (3), we have

$$1 + \frac{1}{\sqrt{3}} < R < 1 + \frac{1}{\sqrt{2}}. \tag{5}$$

It is seen that to obtain resolution enhancement of ≈ 2 one can use two gratings of the same type as in previous grazing incidence cavities, but a best choice is to modify the very simple previous single-grating cavity. Such a modified laser cavity is effectively equivalent to a real double-grating grazing incidence laser.

It is noted that as a result of the resolution enhancement of ≈ 2, a given spectral linewidth can be obtained from this new laser with a smaller value of the incidence angle θ_0. This feature is very important for grazing incidence laser operation and results in a higher conversion efficiency and a reduction of the working grating width.

From relation (2), the single-pass linewidth that we achieved using a 5-cm, 2400 lines mm^{-1} holographic grating playing both the role of a grazing incidence grating at $\theta_0 \simeq 89°$, $\theta_1 \simeq 26°$ and of a Littrow grating at $\theta_2 \simeq 46°$ is 0.025 Å (2 GHz – FWHM) at 600 nm (instead of 0.046 Å for 2 diffractions). This corresponds to $R = 1.65$. This single-pass linewidth could be further reduced by multipass effects after a number N of cavity round trips [17]. The time-averaged as well as the final linewidth $\Delta\lambda^N$ is expected to be [17]

$$\Delta\lambda_{3d}^N = \left(\frac{\ln 2}{2N}\right)^{1/2} \Delta\lambda_{3d}. \qquad (6)$$

The pulse duration of our quasi-double-grating dye laser is measured to be ≈ 7 ns (FWHM) with a cavity length of 34 cm such that there are 3 cavity round trips. Using relation (6), we can expect to obtain a time averaged linewidth of 0.008 Å (0.7 GHz – FWHM) at 600 nm.

2. Experimental

The laser cavity is shown in Fig. 1. The pump light (2 mJ, ≈ 8 ns at 532 nm) from a Quantel Nd:YAG laser was focused in a horizontal line by a 5-cm cylindrical lens. The 1-cm dye cell containing the circulating dye mixture solution (2×10^{-3} M Rh6G and Rh640 in ethanol) was slightly tilted to avoid reflections from the walls. A wedged 4% reflecting plate is used as an output mirror. Two irises with a diameter of 0.3 mm were inserted in the cavity to reduce the background light due to amplified spontaneous emission (ASE), as reported in [14]. The grating (Jobin-Yvon, $a^{-1} = 2400$ lines mm^{-1}), is such that: $\lambda/2 < a < \lambda$, which ensures both a high spectral cavity selectivity and an elimination of the cavity losses due to other unwanted diffraction orders.

The output of the three diffractions laser has been analysed by a 17 mm solid Fabry-Perot etalon having a free spectral range of 6 GHz and a finesse of 45. Figure 2 shows a recording of the transmission through this etalon, as the laser is swept at the rate of 1.5 GHz/min. This shows that scanning of the laser cavity results in a 1.0 GHz (FWHM) laser line. With a 2 mJ pumping energy at 532 nm the oscillator output is 50 μJ, which is enough to be easily amplified.

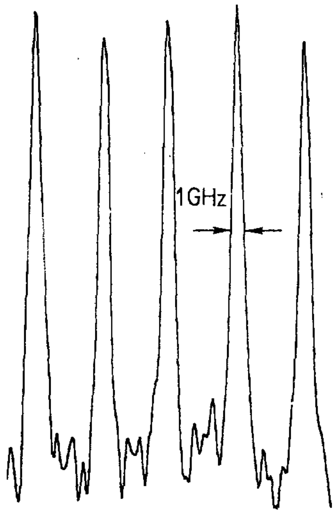

Fig. 2. Spectral analysis of the laser output measuring the transmission through a fixed Fabry-Perot etalon (17 mm, 0.2 cm^{-1} free spectral range, finesse 45) as the laser is swept continuously at a rate of 1 GHz/min. The time-averaged linewidth (limited by shot-to-shot frequency jitter) is 0.03 cm^{-1} (1 GHz – FWHM)

A high-resolution fluorescence excitation spectrum (LIF) of iodine vapor at 17° C in a 15-cm long evacuated cell has been obtained as a further test. Figure 3 shows a portion of the high-resolution spectrum of iodine vapor obtained by continuous scanning at the rate of 1 GHz/min (bottom spectrum), compared with that obtained by Fourier transform spectroscopy [18] (top spectrum). It can be noted that the contrast is better in the LIF spectrum than in the absorption spectrum in particular for the strong lines (Beer-Lambert law effect).

The spectral purity of the laser line, i.e. the amount of ASE background was examined. Since the spectral width of the ASE background is 14 nm, we found a ratio of the narrowband dye laser radiation to ASE background to be 5.10^5 as referred to the spectral width. This improvement in spectral purity is expected when inserting the diaphragms in the cavity and using the low reflectivity output mirror.

Under these conditions, the beam divergence of this three diffraction laser has been measured to be 2.5 mrad (FWHM), which is in good agreement with the expected value of the diffraction-limited divergence of a Gaussian beam, defined by

$$\Delta\theta = \frac{2\lambda}{\pi\omega_1}.$$

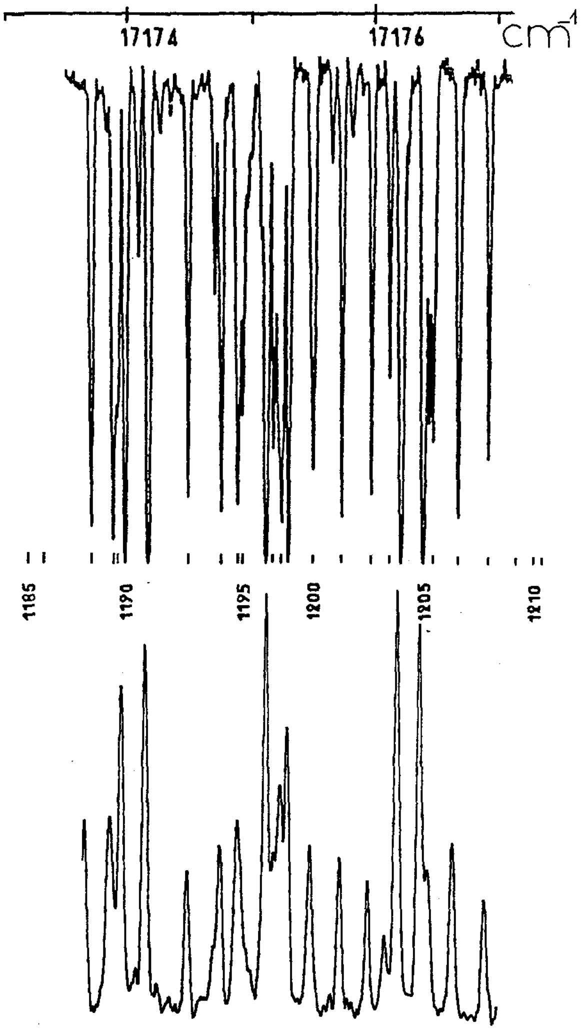

Fig. 3. Typical LIF excitation spectrum of iodine vapor recorded as the laser is continuously scanned at the rate of 1 GHz/min (bottom spectrum). The corresponding part of the absorption spectrum of the I_2 atlas [18] is shown for comparison (top spectrum)

The value of the beam divergence is stable and does not change with various adjustments in the cavity, except for alteration of the pump beam focusing and the dye concentration in the cell.

Most of the adjustments of the quasi double-grating cavity are essentially the same as those of a conventional single-grating grazing incidence laser, except for the modification of the tuning mirror. It is worth to note that, according to the basic grating equation, the rotation angle ω of the modified tuning mirror, ensures that there is no superposition between the laser operation of this quasi double-grating cavity and that of the previous single grating one, even if the laser is tuned over the entire lasing region of the dye.

All the elements of the cavity are attached to a base plate by precision adjustable mounts. For scanning the laser frequency, the rotation of the tuning mirror is controlled through a lever arm by a Micro-Contrôle translation unit driven by a dc motor through a 9 speed selectable convertor. During a scan the real position of the tuning mirror is permanently measured and monitored by an electronic captor (accuracy 0.1 μm). This allows convenient repetitive scanning of a wavelength range. For specific spectroscopic applications, other dyes were tested in the wavelength range from 570–660 nm.

We have been able to operate this quasi double-grating laser in single longitudinal mode operation by shortening the cavity length. Indeed, this length could be shortened as desirable down to 10 cm, corresponding to a free spectral range between adjacent cavity modes of 1.5 GHz. This result is not surprising because, from relation (2), the single-pass linewidth that we can achieve using a 5-cm, 2400 lines mm^{-1} in this quasi double-grating cavity is 2 GHz (0.025 Å – FWHM). This value being comparable with the cavity longitudinal mode separation allows to achieve single mode selection. In practice, a single mode laser linewidth, limited by shot-to-shot laser jitter was measured by Fabry-Perot analysis to be 385 MHz (FWHM). However, a smooth continuous wavelength scan could not be achieved in this single mode operation.

3. Conclusion

A modification of the Littman-Shoshan's type dye laser cavity which does not require any additional optical component is presented.

Such a modified single-grating laser has been operated as a real double-grating grazing incidence laser and has provided a resolution enhancement factor of 2 in spectral linewidth, compared with the conventional grazing incidence laser.

The superiority of this laser cavity has been proved in the continuous scanning of a 1 GHz (FWHM) pulsed dye laser line and also in single longitudinal mode operation (FWHM: 385 MHz) using only one 5-cm 2400 lines mm^{-1} grating as an intracavity selective element.

The present laser design is convenient for the experimentalist because it is compact, simple to align, cheap to construct and, in principle, applicable to any other laser.

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