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On Longitudinal Mode Spacing of Laser Cavities with Pairs of Gratings

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Abstract. It has recently been suggested that a laser cavity formed by a pair of gratings would show anomalously large longitudinal mode spacing which should favor single-longitudinal-mode emission. An experimental verification of that prediction with a TEA–CO_2 laser is presented. The repeatedly negative results obtained under various conditions are given a tentative explanation, based on the well-known analysis of a closely related problem: the grating-pair pulse compression scheme.

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A proposal for a new type of resonator appeared recently in this Journal [1]. It was claimed that such a resonator, made essentially of two identical gratings located at both ends of the laser cavity, shows interesting properties, the most obvious one being, as the title of the paper implied, a longitudinal mode spacing much larger than the mode spacing of a standard cavity (i.e. two mirrors facing each other) of the same length.

This surprising property is easily explained, according to the author, by the fact that the length of such a cavity increases with the wavelength in a way such that the dispersion relation $\varphi(\omega)$ shows an absolute minimum at a frequency corresponding, with reflecting gratings, to a Littrow angle of 45°.

Although the exact physical significance of some of the consequences of such a peculiar dispersion curve are not easy to establish (for instance, the meaning of negative or infinite group velocities), the proposal seemed sound enough to suggest some experiments. The purpose of this paper is to present the results of these experiments, which tried to check one of the most interesting practical advantages of the proposed resonator, namely the ability to ensure single-longitudinal-mode emission (SLM) under conditions where usual cavities fail to provide this mode of operation. This would represent an enormous advantage for TEA–CO_2 lasers, as the known techniques providing stable SLM operation require additional components, like interferometers or cw gain sections.

1. Experimental Set-Up

We used the resonator shown in Fig. 1, which is a particular case of the resonators discussed in [1]. Note that the NaCl window was in fact rotated by 45° along an axis *perpendicular* to the rotation axis of the gratings, resulting in a value of the output coupling suitable for our laser, a TEA–CO_2 laser. This double output allowed simultaneous measurements of the laser line and the temporal structure of the pulses. The

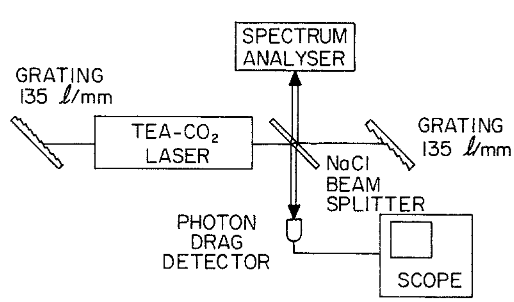

Fig. 1. Experimental set-up; NaCl beam splitter should be represented as rotated along an axis parallel to the plane of the paper

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latter was detected with a photon-drag detector and monitored on a Tektronix 7834 oscilloscope with 400-MHz bandwith. We performed measurements using two different cavity lengths: 175 cm and 230 cm. At those lengths, one has normally to use mode-selecting components in order to get single-mode operation, as the mode separation, for a standard cavity, is 86 MHz and 130 MHz respectively, much less than the emission bandwidth of laser pulses (about 1 GHz). The experiment was repeated for two lines of the CO_2 laser: 10P(8) at 10.476 μm and 10R(28) at 10.195 μm. The first corresponded to a Littrow angle of nearly 45°, with 135 l/mm gratings, thus in the region of the minimum of the dispersion curve. A simple calculation, following the analysis of [1], gives values of 46 GHz and 40 GHz for the mode spacing of 173-cm and 230-cm cavities respectively, more than an order of magnitude over the laser linewidth and nearly three orders of magnitude over the usual mode spacing for such cavity lengths. The second line was chosen because the corresponding mode spacing (650 MHz for 230-cm cavity, again according to [1]) was around the maximum frequency we knew our detection system would respond to.

2. Results and Discussions

The results of the experiments are the following. First, the spectrum analyser always showed single-line emission, without any line switching between successive pulses, as one could expect with a mode separation of the order of the separation between adjacent lines. Second, measurements with the photon drag failed to reveal any of the characteristics that could be expected for the various mode separations calculated above. Figures 2 and 3 show typical oscillograms corresponding to the various experimental conditions. Readers familiar with TEA–CO_2 lasers will easily recognize normal multimode operation, i.e. $2L/c$ periodicity superimposed on an irregular behavior. Examination (Fig. 2c) of the pulse tail doesn't reveal any difference, as one could argue that the mode-filtering effect of the resonator requires many roundtrips to build up. Finally, a close-up (Fig. 3) on a pulse obtained with the 10R(28) line and 230-cm cavity fails to show any evidence of 650-MHz beatings; such beatings are easily observed in mode-controlling set-ups [2].

How can one explain these negative results? A possible answer can be found if one refers to the closely related physical situation of the grating pairs used in pulse-compression schemes [3]. In order to get the expected (and experimentally verified) result, one has to add a correction R(λ) to the term $\varphi_0(\lambda)$ describing the phase shift between the gratings in terms of the path length. For the case of the resonator described

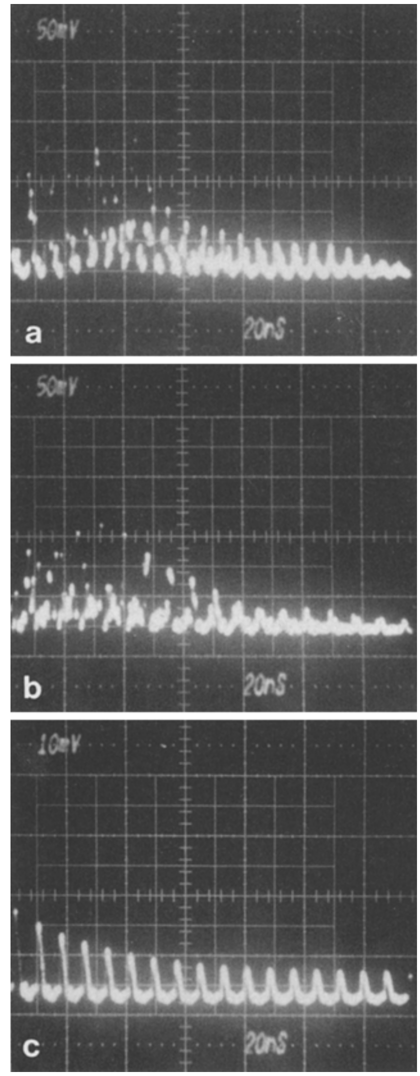

Fig. 2a–c. Typical pulse shapes, showing $2L/c$ periodicity: (a) 10P(8) line, L=175 cm, measured period: 12 ns; (b) 10P(8) line, L=230 cm, period: 15.5 ns; (c) 10R(28) line, L=230 cm, delay: 100 ns, period: 15.5 ns. Note that time scale corresponds to smaller grid

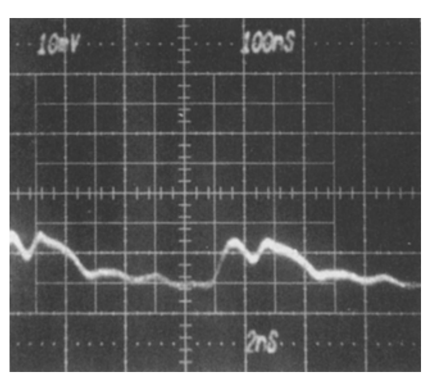

Fig. 3. Close-up obtained in the same conditions than in Fig. 2c, failing to reveal 650 MHz (1.5 ns) beating

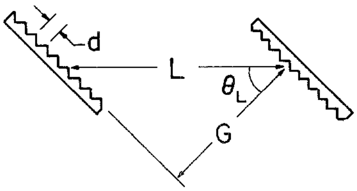

Fig. 4. Resonator geometry and corresponding notation

schematically in Fig. 4, this last term (the only one retained in [1]) is:

$$\varphi_0(\lambda) = 2L(\lambda) \cdot 2\pi/\lambda = 4\pi G/(\lambda \cos\theta_L), \tag{1}$$

where $L(\lambda)$ is the wavelength-dependent resonator length, G the perpendicular distance between the gratings and θ_L is the Littrow angle (also wavelength-dependent), while the correction term is given by [3]:

$$R(\lambda) = -2\pi G d^{-1} \tan\theta_L. \tag{2}$$

Using the phase-matching condition

$$\sin\theta_L = \lambda/2d, \tag{3}$$

where d is the grating rule separation, one obtains, after some algebra, the total phase-shift:

$$\varphi(\lambda) = 4\pi G \lambda^{-1}(1 - \lambda^2/4d^2)^{1/2}. \tag{4}$$

It is easy to show that the resulting dispersion curve possesses no minimum, and that the expression of $d\varphi/d\lambda$ (which determines, to first order, longitudinal mode spacing) is identical to that obtained for a standard cavity, i.e.

$$d\varphi/d\lambda = -4\pi\lambda^{-2}L(\lambda) \tag{5}$$

the only difference lying in the fact that L is a slowly-varying function of the wavelength. For the experiments described above, however, the cavity length was kept the same when the wavelength was changed, so that this second-order effect was not measurable.

How can one justify the introduction of this correction term? Although its necessity seems well established, its physical significance is all but clear. It is usually introduced as a heuristic term, justified *a posteriori* by considering the relation between path lengths for different parts of a plane wavefront impinging upon the grating pair. It is not obvious, however, that one can generalize the argument to the case of wavefronts of different wavelengths simultaneously reflected from different parts of the gratings. A tentative explanation may reside in the fact that when a plane wave strikes a grating, the reflected wave at non-zero orders is not a plane wave anymore, but more precisely a combination of wavefront sections corresponding to different incident wavefronts; it is only upon propagation (and diffraction) that such a structure evolves into a plane wave. The effect of this process on the total phase-shift should be wavelength-dependent. A complete quantitative analysis of the situation is clearly out of the scope of this paper, especially if one realizes that it involves a near-field diffraction problem of vectorial nature. The correction term discussed above could then be viewed as taking into account this phenomenon.

3. Conclusion

In conclusion, although the proposal made in [1] seemed well founded and very promising in terms of practical applications and theoretical investigations, it doesn't seem to pass the test of actual experiments. One possible explanation resides in a correction term not included in the above-cited analysis. This term, introduced in a heuristic manner in the studies concerning grating pairs pulse-compression schemes, could probably be accounted for, on a quantitative basis, by considering wavefront propagation near the surface of the gratings.

References

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Note added in proof: Professor A. E. Siegman has considered the same problem in [4] recently published in this journal. His conclusions, based on a different analysis, are essentially identical to ours.

4. A.E. Siegman: Appl. Phys. B **42**, 165–166 (1987).