

# Multiple-prism grating tunable laser oscillators: ultra-brief introduction

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*This is a brief introduction to narrow-linewidth dispersive tunable laser oscillators. The multiple-prism grating oscillators described here yield single-longitudinal-mode emission throughout the visible spectrum in near-Gaussian temporal pulses, a few nanoseconds long, at powers in the kW regime. These dispersive architectures are applicable to all-known tunable laser gain media including semiconductors. ©*

## 1. Introduction

Tunable lasers are different to traditional lasers because they can continuously change their emission wavelength, or color, in a given spectral range. As such, these quantum devices have found numerous applications in many diverse fields. In particular, tunable lasers have played a crucial and sustained role in advancements of fundamental physics and science. Among basic fields that employ tunable lasers are

Astronomy

Atom optics

Atomic physics

Bose-Einstein condensation

Laser cooling

Molecular spectroscopy

Applied fields that employ tunable lasers include

Communications

Imaging

Medicine

Remote sensing and ranging

## 2. Brief history

Tunable lasers were discovered by Sorokin and Lankard<sup>1</sup> and Schäfer *et al.*<sup>2</sup> in 1966. This was the dye laser. At first, the radiation from these lasers was in the form of broadband emission. Broadband emission is generally comprised by several transverse modes and a multitude of longitudinal modes in each transverse mode. A significant advance towards emission control was provided with the invention of the continuous wave dye laser by Peterson *et al.*<sup>3</sup> in 1970. In the area of high-power pulsed dye lasers a most important contribution was the introduction of the telescope-grating oscillator by Hänsch<sup>4</sup> in 1972. The laser cavity introduced by Hänsch utilized most of the principles of wavelength tuning and frequency narrowing essential to practical tunable lasers. However, it was not compact and required a large two-dimensional diffraction grating.

Resonator laser architectures that yield tunable narrow-linewidth emission in compact, simplified, and improved configurations are the grazing-incidence grating cavities<sup>5-7</sup> and the multiple-prism grating oscillators.<sup>8-10</sup> These cavity architectures have been also successfully applied to wavelength tuning and frequency narrowing in gas lasers, solid-state lasers, and semiconductor lasers.

## 3. Basic ideas

In order to make a tunable laser the first element needed is a laser gain medium with a broad gain profile. Once broadband laser emission is achieved in a simple mirror-mirror cavity, lasing must be restricted to a single-transverse ( $TEM_{00}$ ) mode using a suitable intracavity aperture. Once lasing is restricted to a  $TEM_{00}$  mode then one can proceed to limit emission to a single longitudinal mode (SLM). This is done via the introduction of suitable dispersive elements, such as prisms, gratings, or a combination of these. The dispersive assemblies can provide a very narrow window for intracavity transmission in the frequency domain. A well designed multiple-prism grating assembly can restrict oscillation to a SLM. Wavelength tuning is generally achieved by rotation of either a grating or a mirror.

It can be shown that laser linewidth is directly proportional to the beam divergence and inversely proportional to the overall intracavity dispersion.<sup>4, 11-16</sup> Hence, once lasing has been restricted to a  $TEM_{00}$  emission, the main concept in linewidth narrowing consists in

reducing the beam divergence towards its diffraction limit and, at the same time, multiplying the angular dispersion provided by the diffraction grating.<sup>11, 12, 14-16</sup> The intracavity dispersion available from a suitable grating can be augmented substantially, up to 100 times or more, by multiple-prism expansion of the laser beam emitted at the gain medium in order to illuminate the whole grating.<sup>14, 15</sup> A detailed discussion of the physics of linewidth narrowing, in tunable lasers, is given by Duarte.<sup>14</sup> Briefly, the concepts outlined above can be summarized in the linewidth equation<sup>14</sup>

$$\Delta l = \Delta q (M (\partial q / \partial l)_G \pm (\partial f / \partial l)_P)^{-1} \quad (1)$$

where  $Dq$  is the beam divergence,  $(\partial q / \partial l)_G$  is the dispersion of the grating,  $(\partial f / \partial l)_P$  is the dispersion of the multiple-prism beam expander, and  $M$  is the intracavity beam expansion factor. This equation can be derived from interference principles via Dirac's notation.<sup>17</sup> Also the beam divergence  $Dq$  can be established directly from the uncertainty principle.<sup>18, 19</sup>

The generalized linewidth and dispersion theory of multiple-prism grating oscillators is given elsewhere<sup>11-17, 19, 20</sup> This theory is also applicable to prismatic pulse compression in femtosecond lasers.<sup>19, 21-23</sup>

#### 4. Solid-state multiple-prism grating dye laser oscillators

Although liquid dye lasers have been very successful, and extraordinarily pervasive, there has been an effort to find new gain media in the solid-state that would simplify the engineering of this class of lasers. The first narrow-linewidth solid-state dye laser oscillators<sup>24</sup> were reported in 1994.

Shortly thereafter emission characteristics were improved and single-longitudinal-mode emission, in a near Gaussian temporal pulse, was reported.<sup>25</sup> Here the optical architecture of these tunable oscillators is described.

Figure 1 illustrates a hybrid multiple-prism near-grazing-incidence (HMPGI) grating solid-state dye laser oscillator.<sup>26</sup> This oscillator has a cavity length of 73 mm and yields a laser beam with a TEM<sub>00</sub> profile and a divergence  $\sim 1.5$  times the diffraction limit. The oscillator lases in a single-longitudinal-mode at a linewidth of  $Dn \approx 375$  MHz. The tuning range is 565-610 nm. The temporal emission is in a near-Gaussian pulse 7 ns (FWHM) in duration and its conversion efficiency is 3-4%. This oscillator is excited longitudinally.

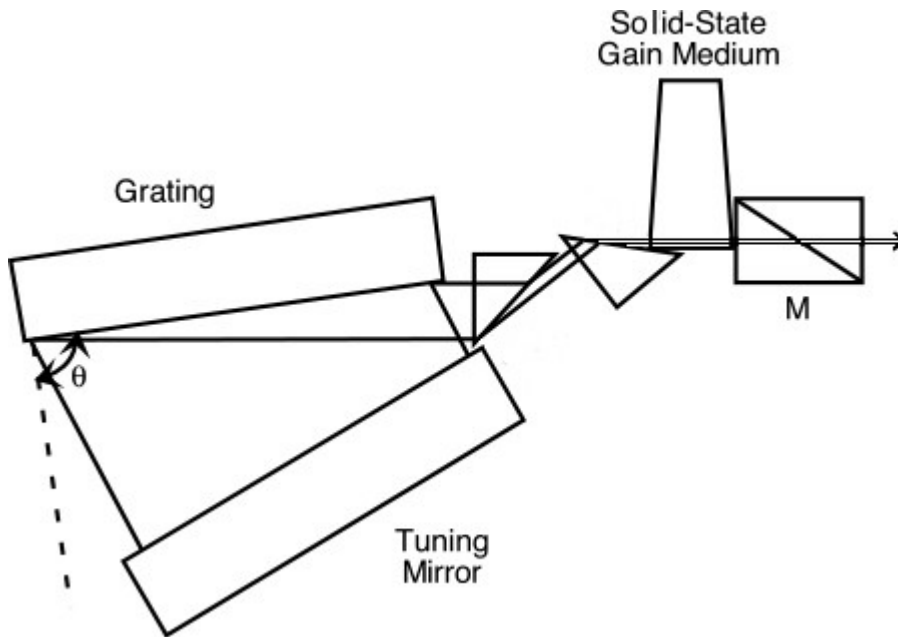


Fig. 1. Hybrid multiple-prism near-grazing-incidence grating tunable laser oscillator.<sup>26</sup>

Figure 2 depicts a multiple-prism Littrow (MPL) grating solid-state dye laser oscillator.<sup>27</sup> This is an optimized oscillator architecture with a cavity length of 75 mm. The angle of incidence at the grating, deployed in Littrow configuration, is about 77 degrees.

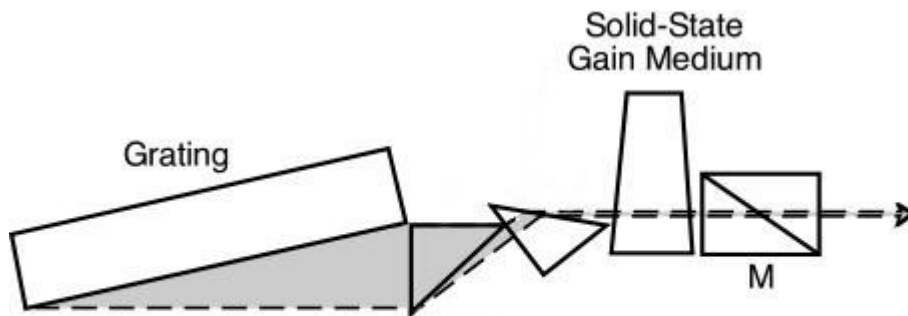


Fig. 2. Multiple-prism Littrow grating tunable laser oscillator.<sup>27</sup>

This cavity yields a laser beam with a  $TEM_{00}$  profile and a divergence 1.5 times the diffraction limit. This oscillator lases in a SLM at a linewidth of  $Dn \approx 350$  MHz. The tuning range is 550-603 nm. The temporal emission is in a near-Gaussian pulse 3 ns (FWHM) in duration and its conversion efficiency is 5%. Excitation is longitudinal to the optical axis of the cavity.

A laser linewidth of  $Dn \approx 350$  MHz corresponds to  $DI \approx 0.0004$  nm at a wavelength of 590 nm. It should be noted that a typical Doppler-linewidth for single-rotational transitions, in many types of molecules, is in the 1 to 2 GHz range.

The interesting feature of this optimized MPL grating architecture is that it fully utilizes the dispersive capability of a higher density diffraction grating, at a higher angle of incidence, thus reducing the requirements on beam expansion and cavity length needed to achieve a laser linewidth similar to that obtained with HMPGI grating cavities. To date this is the narrowest laser linewidth reported for solid-state dye laser oscillators. The type of emission available from these tunable solid-state multiple-prism grating oscillators is characterized by smooth  $TEM_{00}$  beam profiles (shown in Fig. 3)

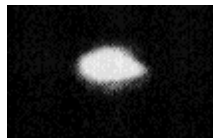


Fig. 3. Single transverse spatial mode ( $TEM_{00}$ ).<sup>25</sup>

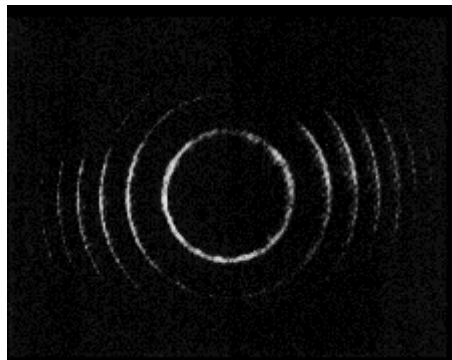


Fig. 3. Fabry-Perot interferogram depicting single-longitudinal-mode emission.<sup>25</sup>

and clean single-longitudinal-mode emission (see Fabry-Perot interferogram in Fig. 4) at very low amplified spontaneous emission (ASE) levels. This is particularly attractive when one considers that laser emission is available throughout the visible spectrum at pulses in the kW regime. A photograph of an earlier MPL grating oscillator prototype,<sup>24</sup> including a three prism beam expander, is given elsewhere.<sup>28</sup>

A more subtle issue concerning tunable laser oscillators is the class of cavity being employed. These can be divided between *open* and *closed* cavities.<sup>14</sup> Open cavities couple the output emission via reflection or diffraction losses. As such, they are vulnerable to interaction with extra-cavity optical elements. Closed cavities, on the other hand, couple the output emission via transmission of an output mirror or mirror-polarizer element.<sup>24-27</sup> Closed cavities yield better signal-to-noise ratios, than open cavities, and offer protection against unwanted external optical feedback.

HMPGI and MPL grating oscillator architectures are used with a variety of tunable laser gain media in the gas, the liquid, and the solid state. Indeed, their versatility has been amply demonstrated from compact semiconductor lasers<sup>29-31</sup> to powerful pulsed gas lasers.<sup>32,33</sup> Comprehensive theoretical and experimental reviews on this subject are given in *Tunable Lasers Handbook*.<sup>34</sup> Further applications are discussed in *Dye Laser Principles*<sup>35</sup> and *Tunable Laser Applications*.<sup>36</sup>

*Note 1:* in addition to the dispersive narrow-linewidth dye lasers described here there has also been recent progress in the development of distributed feedback solid-state dye lasers.<sup>37,38</sup> For a review on solid-state dye laser matrices the reader should refer to Costela *et al.*<sup>39</sup>

*Note 2:* recent work on external-cavity grazing-incidence grating semiconductor lasers involves the use of MEMS techniques to produce miniature resonators.<sup>40,41</sup>

*Note 3:* a detailed introduction to narrow-linewidth laser oscillators and wavelength-tuning techniques is given, at a textbook level, in *Tunable Lasers Optics*.<sup>19</sup> This material is applicable to both high-power tunable oscillators and miniature resonators. A discussion on longitudinal tuning techniques particularly applicable to miniature lasers is given in Chapter 7.

*Note 4:* new tunable solid-state laser materials described as *dye-doped polymer-nanoparticle gain media* have been recently reported in the literature.<sup>42</sup> These gain media offer reduced  $dn/dT$  coefficients which allow the attainment of laser beam divergences approaching the diffraction limit. The silica nanoparticles are arranged, in a fairly uniform distribution, in the dye-doped polymer.<sup>43</sup>

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