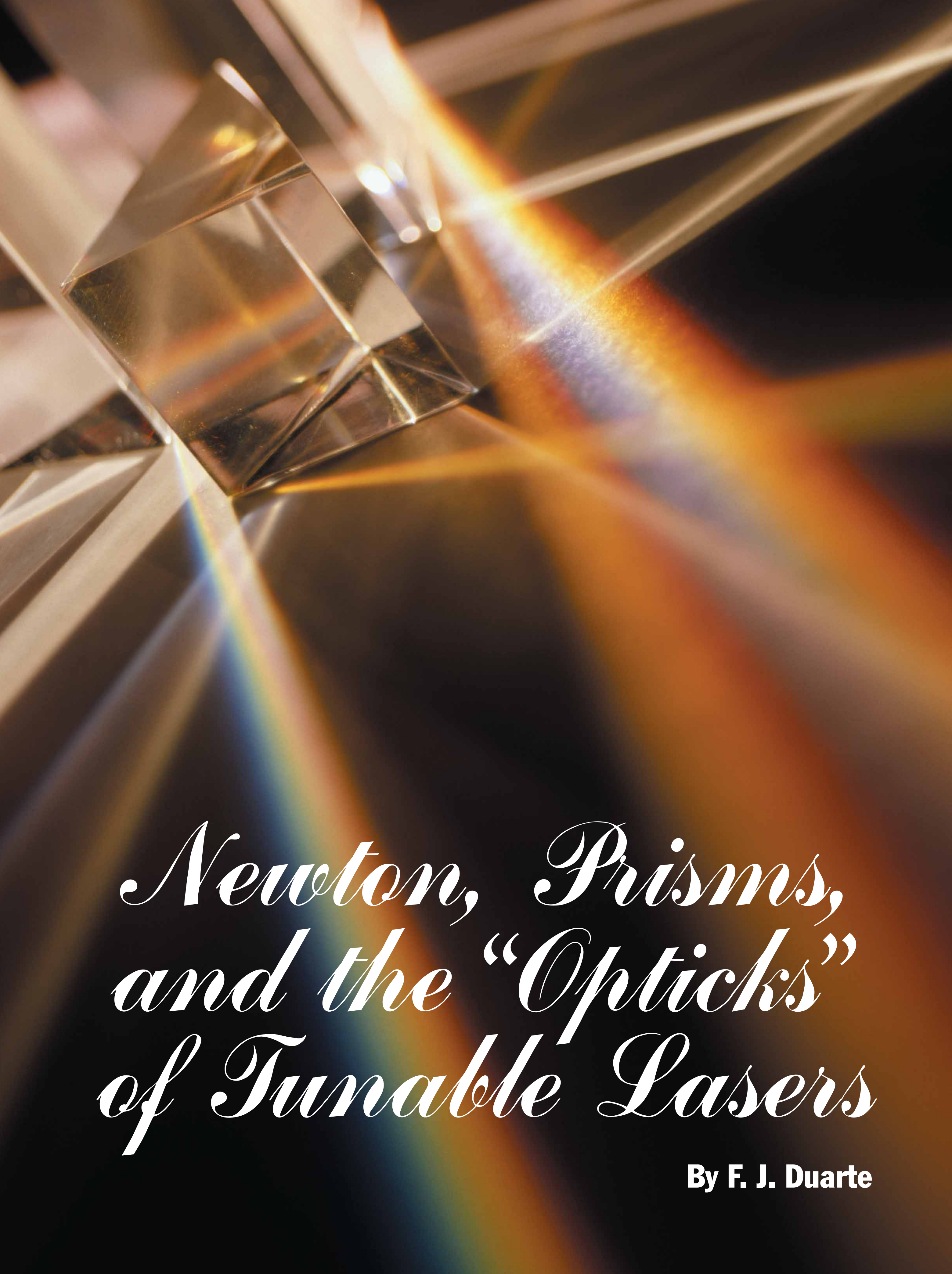

Newton, Prisms, and the "Opticks" of Tunable Lasers

By F. J. Duarte

Newton's ground-breaking work in physics, which constitutes the foundation of physics as a scientific discipline, has been exhaustively studied by scholars, physicists and students for nearly three hundred years. Scholars of optics and astronomy also identify Newton with fundamental contributions in the areas of refraction, dispersion, diffraction and telescopes. His contributions to the understanding of refraction and dispersion were central to the design of prism spectrometers; his reflection telescope introduced the basic principles of modern observational telescopes.

What is not generally recognized, however, is that Newton's original prismatic configurations also laid the foundations for some of the principles applied today in the optics of tunable lasers. This little-known fact is the focus of this article.

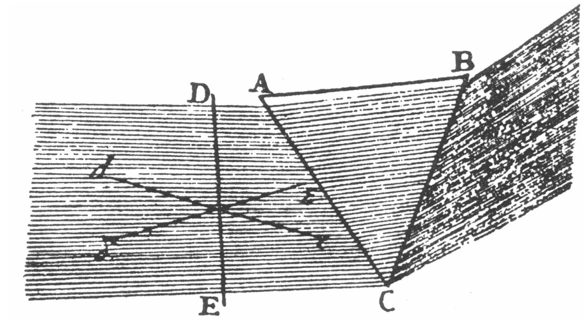

Figure 1. Single-prism beam expansion as illustrated in *Opticks* (courtesy of Dover Publications).

Newton and prisms

In his landmark volume, *Opticks*,[1] published in 1704, Newton described how a prism can be used to refract a beam of light, to disperse a beam of light and to expand a beam of light. Although most readers will be familiar with the first two contributions, the third, beam expansion by a prism, may come as something new.

In *Opticks*, Newton does not use the words "beam expansion" or "beam contraction" in relation to the prism, which subdues the significance of his disclosure. A close look at Figure 1 reveals in fact that the angle of incidence is greater than the angle of emergence, which indicates that the width of the beam in Newton's drawing *is expanded* due to refraction at the prism. Thus, around 1670, Newton did most likely observe beam expansion, although he did not include in his book a written description of the phenomenon. It should be noted at this juncture that the sketch which appears in Figure 1 was used by Newton to teach solely the concepts of refraction and dispersion. This might explain the absence, in later writings by others, of references to *Opticks* as an original source on the topic of prismatic beam expansion.

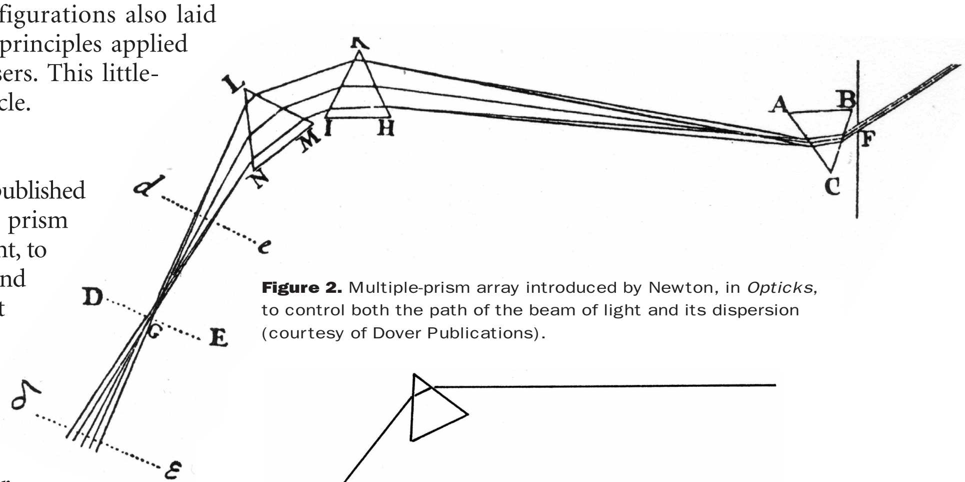

Figure 2. Multiple-prism array introduced by Newton, in *Opticks*, to control both the path of the beam of light and its dispersion (courtesy of Dover Publications).

One optical phenomenon that is clearly illustrated and explained in *Opticks* is the use of more than one prism to control the dispersion of a beam of light. This multiple-prism configuration, incorporating nearly isosceles prisms, is illustrated in Figure 2. Here, Newton provides a written description of multiple-prism dispersion. His writings on this point demonstrate that he was intimately familiar with the subtleties of refraction and knew how to deploy prisms either in additive or compensating configurations to add or subtract dispersions. In the particular optical architecture outlined in Figure 2, one prism is used to disperse light; the dispersion is subsequently neutralized by a pair of prisms deployed to compensate the dispersion of the first. In this manner, Newton demonstrated how to control the direction of the rays as well as the dispersion of the beam. However, nowhere in his treatise does he offer a mathematical description of multiple-prism dispersion.

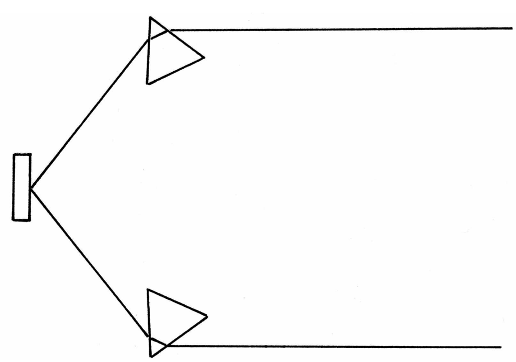

Figure 3. Double-prism arrangement in an additive configuration as applied to prism spectrometers.

Newton's seminal contribution illustrating the principles of addition and subtraction of dispersion is fundamental to modern optics. For the next couple of centuries, numerous spectrometer designs were based on the addition of dispersions from two or more prisms deployed in series. An example of such a classic optical architecture is provided in Figure 3. This class of prism spectrometer, exploiting the addition of dispersions, was common in optics and metrology laboratories until fairly recently.

Dispersion in multiple-prism arrays

From the literature of geometrical optics, it can be established that the linewidth in a dispersive optical system is given by[2-5]

$$\Delta\lambda \approx \Delta\theta \, (\nabla_\lambda \Phi)^{-1} \qquad (1)$$

where $\Delta\theta$ is the beam divergence, $\nabla_\lambda = \partial/\partial\lambda$, and $\nabla_\lambda\Phi$ is the overall dispersion. This relation can also be derived from physical arguments including the uncertainty principle.[6] It should be noted that this equation applies to the

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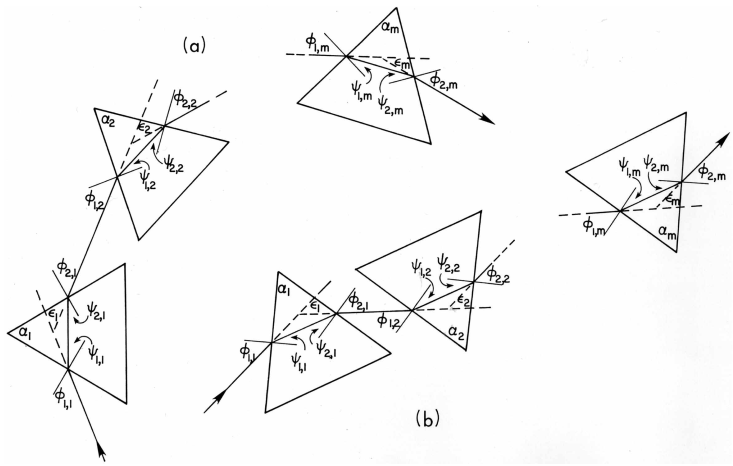

Figure 4a. Generalized additive multiple-prism array and **(b)** generalized multiple-prism array in a compensating configuration.[8]

prism configurations examined by Newton in *Opticks*.

The cumulative single-pass generalized multiple-prism dispersion at the mth prism of a multiple-prism array, as illustrated in Figure 4, is given by[7,8]

$$\nabla_\lambda \Phi_{2,m} = \mathcal{H}_{2,m}\nabla_\lambda n_m + (k_{1,m}k_{2,m})^{-1}(\mathcal{H}_{1,m}\nabla_\lambda n_m \pm \nabla_\lambda \phi_{2,(m-1)}) \quad (2)$$

In this equation, $\mathcal{H}_{1,m} = \tan\phi_{1,m}/n_m$, $\mathcal{H}_{2,m} = \tan\phi_{2,m}/n_m$, $k_{1,m} = (\cos\psi_{1,m}/\cos\phi_{1,m})$, and $k_{2,m} = (\cos\phi_{2,m}/\cos\psi_{2,m})$. Here, $k_{1,m}$ and $k_{2,m}$ represent the physical beam expansion experienced by the incident and the exit beams, respectively. This equation can be applied to quantify the single-pass dispersion in all the configurations studied by Newton.

Equation 2 indicates that $\nabla_\lambda \Phi_{2,m}$, the cumulative dispersion at the mth prism, is a function of the geometry of the mth prism, the position of the light beam relative to this prism, the refractive index of the prism, and the cumulative dispersion up to the previous prism $\nabla_\lambda \Phi_{2,(m-1)}$.

For an array of **r** identical isosceles or equilateral prisms arranged symmetrically in an additive configuration so that the angles of incidence and emergence are the same, the cumulative dispersion reduces to[8]

$$\nabla_\lambda \Phi_{2,r} = r\,\nabla_\lambda \phi_{2,1} \quad (3)$$

Under these circumstances, the dispersions add up in a simple and straightforward manner. For configurations incorporating right-angle prisms, the dispersions must be handled mathematically in a more subtle form.

Mutiple-prism arrays in tunable lasers

Multiple-prism arrays incorporating isosceles prisms, similar to those used by Newton, were introduced into tunable lasers in additive configurations.[9,10] In this case, however, at one end of the assembly a mirror was deployed to reflect the radiation back to the prism array and the gain region. The dispersive linewidth can be estimated via Equation (1), with $\nabla_\lambda \Phi$ being entirely prismatic in character. This dispersion can be calculated using Equation (2), in general, or Equation (3) for the special case of identical isosceles prisms deployed at the same angle of incidence.

It is widely recognized that the first high-performance, narrow-linewidth tunable laser was introduced in 1972 by Hänsch.[11] This laser yielded a linewidth of 2.5 GHz (or $\Delta\lambda \approx 0.003$ nm at $\lambda \approx 600$ nm) without the use of an intracavity etalon. In his work, Hänsch clearly demonstrated that the laser linewidth from a tunable laser was narrowed significantly when the beam incident on the tuning grating was expanded using an astronomical telescope. Thus, the linewidth equation can be modified to include the beam magnification factor, M, so that[11]

$$\Delta\lambda \approx \Delta\theta\,(M\,\nabla_\lambda \Theta_G)^{-1} \quad (4)$$

This equation captures the essence of linewidth narrowing in tunable laser oscillators. In other words, a narrow $\Delta\lambda$ is achieved by reducing $\Delta\theta$ and increasing the intracavity dispersion $(M\,\nabla_\lambda \Theta_G)$. The intracavity dispersion is augmented by maximizing the size of the beam incident on the diffractive surface of the tuning grating until it is completely illuminated.

In his original oscillator, Hänsch used a traditional two-dimensional astronomical telescope to expand the intracavity beam incident on the diffraction grating. In this context, a simpler beam expansion method was the use of a single-prism beam expander.[12-14] The introduction of multiple-prism beam expanders represented an extension and improvement on this approach.[15-17] The main advantages of multiple-prism beam expanders over traditional telescopic devices are simplicity, compactness and the fact that the beam expansion can be reduced from two dimensions to one. Physically, multiple-prism beam expanders also introduce a dispersion component that is absent in the case of the astronomical telescope. Advantages of multiple-prism beam expanders over single-prism beam expansion are higher transmission efficiency and the flexibility to either augment or reduce the prismatic dispersion. Practical intracavity multiple-prism beam expanders[18] are depicted in Figure 5.

In general, for a pulsed multiple-prism grating oscillator, it can be shown that the dispersive linewidth is given by[19]

$$\Delta\lambda \approx \Delta\theta\,[RM\,\nabla_\lambda \Theta_G + R\nabla_\lambda \Phi_P]^{-1} \quad (5)$$

where M is the overall beam magnification and R is the number of return-cavity passes. The grating dispersion in this equation, $\nabla_\lambda \Theta_G$, can be either from a grating in Littrow or near grazing-incidence configuration. This equation includes the return-pass contribution to dispersion from the multiple-prism beam expander which is given by[20]

$$\nabla_\lambda \Phi_P = 2M\sum_{m=1}^{r}(\pm 1)\,\mathcal{H}_{1,m}\Big(\prod_{j=m}^{r} k_{1,j}\prod_{j=m}^{r} k_{2,j}\Big)^{-1}\nabla_\lambda n_m + 2\sum_{m=1}^{r}(\pm 1)\,\mathcal{H}_{2,m}\Big(\prod_{j=1}^{m} k_{1,j}\prod_{j=1}^{m} k_{2,j}\Big)\nabla_\lambda n_m \quad (6)$$

Here, $M = M_1 M_2$, where M_1 and M_2 are the total beam magnification factors given by[20]

$$M_1 = \prod_{m=1}^{r} k_{1,m} \quad (7a)$$

$$M_2 = \prod_{m=1}^{r} k_{2,m} \quad (7b)$$

For a multiple prism expander designed for orthogonal beam exit, and Brewster's angle of incidence, Equation (6) reduces to the elegant expression[8]

$$\nabla_\lambda \Phi_P = 2\sum_{m=1}^{r} (\pm 1)\,(n_m)^{m-1}\,\nabla_\lambda n_m \qquad (8)$$

Equation (6) can be used to either quantify the overall dispersion of a given multiple-prism beam expander or to design a prismatic expander yielding zero dispersion, that is $\nabla_\lambda \Phi_P = 0$, at a given wavelength.[20] Equation (6) can also be used to quantify the dispersion of multiple-prism arrays as described in *Opticks*.

At present, very compact and optimized multiple-prism grating tunable laser oscillators are found in two basic cavity architectures. These are the multiple-prism Littrow (MPL) grating laser oscillator[8,17,21] (Figure 6) and the hybrid multiple-prism near grazing-incidence (HMPGI) grating laser oscillator[8,22] (Figure 7). In early MPL grating oscillators, the individual prisms integrating the multiple-prism expander were deployed in an additive configuration, thus adding the cumulative dispersion to that of the grating and contributing to the overall dispersion of the cavity.[8,17] In subsequent architectures, the prisms were deployed in compensating configurations so as to yield zero dispersion, at a given wavelength, and thus allow the tuning characteristics of the cavity to be determined almost exclusively by the grating.[8,20,23] In this approach, the principal role of the multiple-prism array is to expand the beam incident on the grating, thus augmenting significantly the overall dispersion of the cavity as described in Equations (4) and (5). In this regard, it should be mentioned that beam magnification factors of up to 100 and beyond have been reported in the literature.[8] Using solid-state laser dye gain media, these MPL and HMPGI grating laser oscillators deliver tunable single-longitudinal-mode emission at laser linewidths in the 350 MHz $\leq \Delta\nu \leq$ 375 MHz range.[21,22] These cavity architectures have been used with a variety of laser gain media in the gas, the liquid, and the solid-state.[24] Applications to tunable semiconductor lasers have also been reported.[24-27]

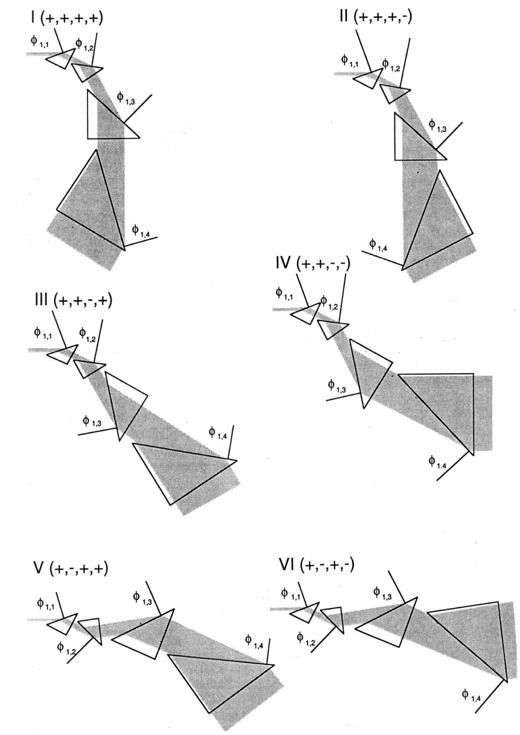

Figure 5. Various configurations for practical multiple-prism beam expanders.[18]

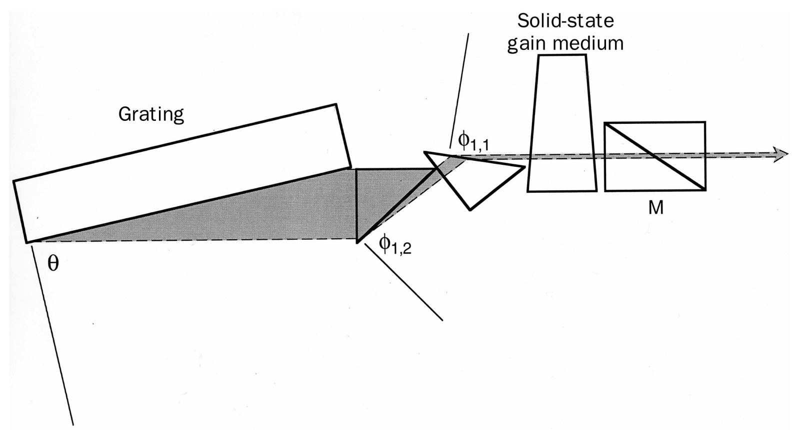

Figure 6. Solid-state MPL grating dye laser oscillator.[21] Here, the intracavity beam expansion coefficient is $M \approx 44$.

Concepts important to MPL and HMPGI grating tunable laser oscillators include the emission of a single-transverse-mode (TEM_{00}) laser beam in a very compact cavity, the use of multiple-prism arrays, the expansion of the intracavity beam incident on the grating, the control of the intracavity dispersion, and the quantification of the overall dispersion of the multiple-prism grating assembly via generalized dispersion equations. Sufficiently high intracavity dispersion leads to the achievement of return-pass dispersive linewidths close to the free-spectral range of the cavity. Under these circumstances, single-longitudinal-mode lasing is readily achieved as a result of multi-pass effects.[8,19] At this stage it is appropriate to mention that the first step in the process to achieve single-longitudinal-mode oscillation, that of obtaining TEM_{00} emission, is accomplished using the physics of diffraction[18] which is the other fundamental principle of optics discussed in *Opticks*.

Pulse compression in femtosecond lasers also relies on intracavity prisms.[28,29] Newton's concept of addition and subtraction of dispersions, in arrays integrated by isosceles prisms,[8,29,30] is also applicable to prism sequences as deployed in femtosecond lasers.

Newton and the optics of tunable lasers

The use of prisms in tunable lasers can be summarized from a chronological perspective. First, tuning and line-narrowing was achieved using several isosceles prisms in additive configurations.[9,10] At the same time the use of a single prism as an intracavity beam expander was demonstrated.[12] This was followed by the introduction of intracavity multiple-prism beam expanders[15-17] and by the dispersion theory of generalized prismatic arrays.[7]

A survey of the early literature on tunable lasers incorporating a single prism or isosceles multiple-prism arrays does not yield citations to *Opticks*. In retrospect, however, it

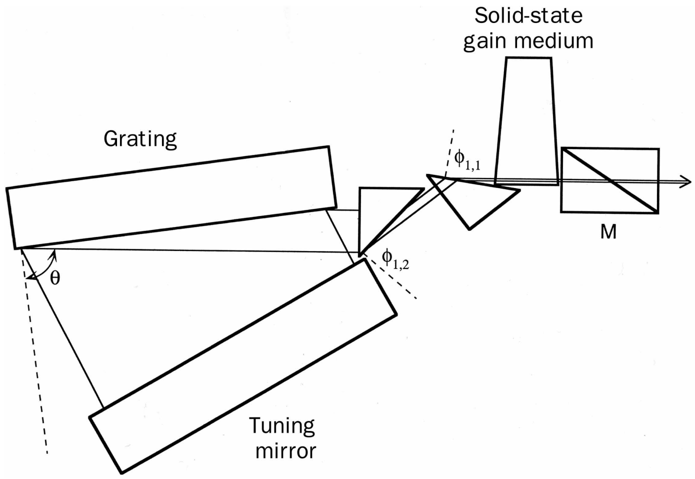

Figure 7. Solid-state HMPGI grating dye laser oscillator.[22] Here, the intracavity beam expansion coefficient is M ≈ 30.

was Newton who first hinted at the use of a single prism as a beam expander, introduced multiple-prism sequences, and applied these arrays to control dispersion, as they would later be applied in early tunable lasers. In other words, as far as these initial developments are concerned, Newton's *Opticks* constitutes at least the cultural precursor to these aspects of laser research.

Multiple-prism beam expanders in tunable lasers[15-17] were independently introduced to replace the intracavity astronomical telescopes and single-prism beam expanders. Multiple-prism beam expanders utilize right-angle prisms designed and deployed to achieve near-orthogonal beam exit. In this regard, it is appropriate to note that it was the drive to build compact and efficient narrow-linewidth tunable laser cavities that led to the development of versatile and generalized multiple-prism architectures. Once these intracavity beam expanders were shown experimentally to provide an advantageous and practical alternative to conventional telescopes, the generalized multiple-prism-grating theory of dispersion was developed.[7,19] In this instance, the link to Newton's contribution is in the application of the principle of dispersion control via the deployment of several prisms.

The fact that principles outlined nearly three hundred years ago are embodied in a device of the quantum era serves as a dramatic reminder of the profound vision displayed by Newton in his writings on physics.

Note

In addition to the original contribution from Newton, an important description of prism pairs was provided by David Brewster in "A Treatise on New Philosophical Instruments for Various Purposes in the Arts and Sciences with Experiments on Lights and Colours," (Murray and Blackwood, Edinburgh, 1813). A Brewster prism pair, in which the first prism was different from the second prism, was deployed in a compensating configuration.

The object of Brewster's research was to produce prism telescopes with corrected dispersions, or in other words, prism telescopes yielding reduced, or nearly zero, dispersion. At present, prism pairs of this class find applications as extracavity components yielding relatively low beam expansion factors. Although Brewster set forth an analytical treatment of refraction, he did not describe the phenomenon of angular dispersion quantitatively.

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