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# A simple beam expander for frequency narrowing of dye lasers

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Design considerations and performance of a prism beam expander are presented. Using a prism beam expander and holographic grating, a dye laser pumped by a nitrogen laser has given 15 kW of diffraction limited power in 0.1-0.2 $cm^{-1}$ linewidth. Addition of a single etalon gave a single frequency output of 10 kW in a linewidth of less than 0.01 $cm^{-1}$.

## 1. Introduction

Narrow linewidth dye lasers pumped by commercial nitrogen lasers are of interest for a wide range of spectroscopic applications. In an important paper by Hänsch [1], a successful dye laser of this type was reported together with a discussion of the basic design principles. His design, which incorporates a diffraction grating and beam-expanding telescope, has since been widely adopted and is used in a commercially available dye laser system. The role of the telescope is to expand the laser beam and fill the grating with a collimated beam since this leads to the greatest frequency narrowing. In practice, however, the telescope is not easy to align, nor is it cheap. In an earlier paper, Myers [2] had reported the use of a prism near grazing incidence as a beam expander. The linewidths obtained by Myers were much wider than those subsequently obtained by Hänsch and this may explain why beam-expanding prisms do not appear to be widely used. The simplicity of the prism is very attractive, however, and we therefore decided to compare its performance with that of a telescope. In this paper we give an account of the design and performance of a nitrogen laser pumped dye laser using a prism beam expander. We have found that in practice it is easier to use than a telescope and that it gives linewidths which are just as narrow (being determined by the size of our grating). The output was also diffraction-limited and its power was typically 15 kW. By placing a single etalon between the prism and grating, additional frequency narrowing was produced and single frequency operation was obtained with an output power of 10 kW in a linewidth of less than 0.01 $cm^{-1}$.

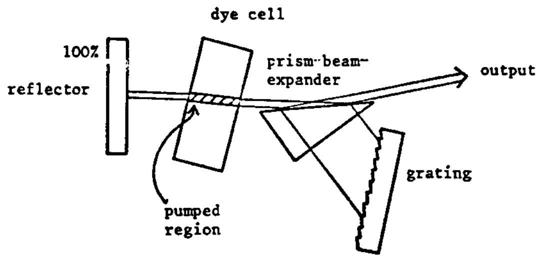


*Figure 1* Arrangement of $N_2$ laser pumped dye laser with prism beam expander and grating.

## 2. General design considerations

The dye laser arrangement is shown in Fig. 1. The nitrogen laser beam is focused to a narrow line at the pumping window of the dye cell. The cross section of the pumped region as presented to the dye laser cavity is adjusted to be roughly square by correct dye concentration and focusing of the pump beam.

The size of this pumped region is chosen so that a diffraction-limited beam of spontaneous radiation leaving the side window of the cell will return to the cell after one cavity round trip with a beam spot size somewhat larger than the pumped region. This discriminates strongly against radiation with a greater than diffraction-limited spread.

The diffraction grating when used in the Littrow arrangement as shown reflects radiation of a particular wavelength exactly along its direction of incidence. Other wavelengths are reflected at different angles, i.e. the cavity appears misaligned and the net gain is less for these wavelengths. To calculate the oscillation linewidth it is necessary to know the relationship between misalignment and cavity loss. Unfortunately this is not a simple relationship and therefore a useful working criterion is to say that radiation whose wavelength is such that its misalignment is equal to the beam divergence will be strongly suppressed relative to radiation of a wavelength corresponding to exact alignment. This leads immediately to the conclusion that the beam falling on the grating should have the smallest possible divergence consistent with the grating size. This can be achieved by a beam-expander since the beam magnification is accompanied by a corresponding decrease in beam divergence. The use of a prism is possible since beam expansion is only required in the plane of incidence of the grating.

Unlike the telescope, however, the prism cannot produce a beam waist at the grating and the diffraction loss is somewhat higher as a result. In practice, this additional loss has little effect either on threshold or output power of high gain lasers such as nitrogen laser pumped dye lasers. If the feedback from the grating were reduced too much, however, eventually a point would be reached at which amplified spontaneous emission reflected from the 100% mirror, would suppress the radiation fed back from the grating. This could in principle reduce the tuning range for any given dye but in practice no significant loss of tuning was observed.

## 3. The prism expander

A beam of light entering the prism surface at an angle of incidence $\theta_1$ undergoes a beam expansion $M$ in the plane of incidence given by

$$M = \left(\frac{n^2 - \sin^2\theta_1}{n^2 - n^2\sin^2\theta_1}\right)^{1/2}, \qquad (1)$$

where $n$ is the refractive index of the prism (see Fig. 2). It also follows that two incident rays with a small angular separation $d\theta$ in the plane of incidence will, after refraction, be separated by $d\theta/(nM)$. A large beam expansion (of the order of twenty to fifty times) implies a large reflection loss at the dielectric surface. This is not entirely wasted since one of these reflections can be used as output and the optimum output coupling is generally very high [3]. However, there is clearly some advantage in minimizing the prism losses for a given beam expansion. This means that the exit surface of the prism should be approximately normal to the beam to reduce contraction on leaving the prism. The exit beam then has an angular spread $d\theta/M$ if $d\theta$ is the spread of the entrance beam. The power reflection of the prism entrance face for polarization in the plane of incidence ($p$-polarization) is given by

$$R = \frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)}, \qquad (2)$$

and it is easily shown that for angles of incidence greater than Brewster's angle, $M/R$ increases monotonically with $n$, i.e. the larger $n$ the greater the beam expansion for a given prism loss. Data for the range of typical refractive indices and angles are given in Fig. 3. The figure shows that

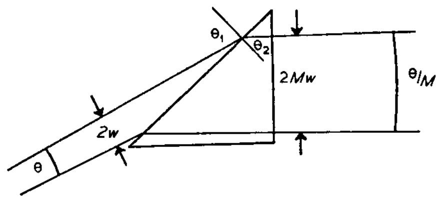


*Figure 2* **Beam expansion and divergence reduction by a prism.**

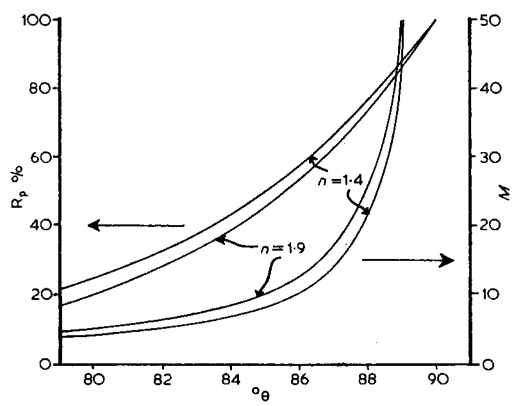


*Figure 3* **Reflectivity and beam expansion versus angle incidence for two values of refractive index (1.4, 1.9).**

the choice of prism material is not critical. The prism we have used was in fact designed for a quite different application and despite its non-optimum design it has given very satisfactory results.

Some care over the choice of prism material may be necessary as far as the temperature coefficient of refractive index is concerned. A change of temperature leads to a change in deviation by the prism and hence to a change in the wavelength selected by the grating. For a glass having $(1/n)(dn/dT) \simeq 10^{-6}\ ^{\circ}C^{-1}$, this implies a shift of typically $0.1\ cm^{-1}$ for a prism temperature change of 10°C and a grating angle of 60°. The temperature coefficient for fused quartz is more than an order of magnitude greater than this and would therefore require some temperature control. On the other hand, quartz is an ideal material for the substrate of a holographic diffraction grating on account of its small value of thermal expansion coefficient.

Finally it should be noted that the prism must be placed as close as possible to the cell so that the beam size $w$ at the prism is nearly the same as the waist size $w_0$ in the cell. The spot size $Mw$ of the expanded beam as it leaves the prism is then essentially the same as its waist size $Mw_0$. When this expanded beam fills the grating, its divergence is very nearly the minimum possible for that grating size. If on the other hand $w$ were significantly greater than $w_0$, the expanded beam while filling the grating would have a larger than optimum divergence.

## 4. Linewidth

The angular dispersion of the grating in the Littrow arrangement is given by

$$d\theta/d\lambda = 2 \tan \theta/\lambda.$$

Here $\lambda$ is the wavelength corresponding to equal angles $\theta$ for incidence and reflection and $d\theta$ is the change in angle of reflection for a change $d\lambda$ in wavelength of the incident light. Using our assumed criterion for misalignment tolerance it follows that a grating of diameter $D$ at an angle of incidence $\theta$, will give a linewidth (full width):

$$d\lambda \simeq 2 \frac{\lambda^2}{\pi D \sin \theta}$$

when the expanded beam has a divergence (half angle) $2\lambda/(\pi D \cos \theta)$ and fills the grating [i.e. beam spot size equals $(D \cos \theta)/2$]. The prism also provides some dispersion but this is less than the grating dispersion by more than an order of magnitude typically and its effect can be ignored.

## 5. Experimental details

The output of a Molectron UV-300 Nitrogen laser was focused by means of a 50 cm spherical lens and a 15 cm cylindrical lens to give a pumped region 10 mm long and $\simeq$ 0.2 mm wide. A number of dyes have been used for operation around 600 nm and between 400 and 500 nm. The dye cell was tilted as shown in Fig. 1 to avoid oscillation between the faces of the cell. The prism, made of Schott BaLF3 ($n_D = 1.571$), had an apex angle of 65° and a base length of 20 mm. Typically the prism was oriented for an angle of incidence of 89°, giving a beam expansion of $\sim$ 40 and a reflectivity of 85% for $p$-polarization. The overall expansion was slightly less than optimum since the prism exit face was not normal to the beam.

Two different holographic gratings of 3680 and 2880 lines $mm^{-1}$ have been used and were held in a precision (0.1 arc s) mount. Both were 2.5 cm in diameter and were used in first order with angles of incidence between 50 and 60°. The efficiency was typically 70-80% for $p$-polarization. For the orthogonal polarization the efficiency was much less, and this together with the polarization selection of the prism ensured a linearly polarized output.

Alignment of the optical components was found to be very easy when the following procedure was followed. First the totally reflecting mirror was adjusted to give a strong superfluorescent output. Then the prism was put in place and its position and angle adjusted until the superfluorescent beam transmitted by the prism was sufficiently expanded. Then the grating was put in place and adjusted so that the first order reflection of the superfluorescent beam returned to the pumped region in the cell. Final alignment was achieved by optimising power and linewidth. Typical output powers were 15 kW in $0.2\ cm^{-1}$ for 200 kW input from the nitrogen laser. This output was diffraction limited, as verified by observing the output beam profile on a scanning photodiode array. The profile was close to gaussian and the measured beam divergence ~1 mrad agreed well with the dimension of the pumped region. The output linewidth of 0.2 $cm^{-1}$ could be obtained easily and with extra care this could be reduced to ~0.1 $cm^{-1}$. These linewidths were determined using plane Fabry-Perot etalons of ~0.6 $cm^{-1}$ free spectral range with the scanning photodiode array to monitor the fringes. The predicted linewidth, corresponding to a $w_0$ of 100 μm in the cell and a beam expansion of × 40, is 0.8 $cm^{-1}$. The fact that the observed linewidth is significantly less than that predicted shows that the alignment criterion is rather crude.

By insertion of an etalon (free spectral range 0.57 $cm^{-1}$, finesse 10) between the prism and grating, the linewidth was further reduced to less than 0.01 $cm^{-1}$ with an output power of ~10 kW. A Fabry-Perot of 10 cm spacing was used to monitor the linewidth. This could readily resolve adjacent axial modes, spaced by 0.04 $cm^{-1}$ but the single mode bandwidth was not determined since the width of the Fabry-Perot rings was instrument-limited at ~0.01 $cm^{-1}$.* Since the laser beam width is only of the order of 200 μm in the unexpanded direction it was necessary to keep the etalon normal to the expansion plane to avoid degradation of finesse by walk-off losses [1]. Alignment to within 1-2 mrad was sufficient. In the orthogonal plane the etalon could be misaligned from the beam direction by several tens of milliradians.

Despite the small amount of feedback from the grating to the pumped region (i.e. about 0.5% for ×40 beam expansion when allowance is also made for beam spreading in the unexpanded direction), it was found that wide tuning ranges (comparable to those obtained with a telescope) could be covered before superradiant emission dominated in the output.

## 6. Conclusions

We have shown that a prism beam expander can produce frequency narrowed linewidths as narrow as those obtained using a telescope beam expander and at comparable powers. Using 200 kW of $N_2$ laser pump power we have generated 10 kW of diffraction-limited output power in a 0.01 $cm^{-1}$ linewidth from dye lasers incorporating a prism beam expander and etalon. The prism is cheap and extremely simple to use. Its small size allows a short dye laser cavity, as small as 10 cm in length. The large reflection loss for large beam expansion has not led to any significant loss of either efficiency or tuning range. However for lasers of lower gain or for beam expansions greater than ×50 it would be necessary to reduce the prism reflection losses. In fact a simple two-layer dielectric coating [4] produces a considerable decrease in reflection loss. A further decrease in loss for a given overall beam expansion can be obtained by using two prisms in tandem. With two-layer dielectric coatings on both of these prisms, typical reflection losses could be reduced to a few per cent per surface. It would then be advantageous to take the output from the cavity mirror rather than from prism reflections. With these improvements in design it would be possible to work with beam expansions of ×100 and holographic gratings of 5 cm dimension, thus offering linewidths of 0.05 $cm^{-1}$ without the need for an etalon.

It should also be noticed that since the cavity length can be kept short, the same technique should be applicable to parametric oscillators having a moderately high gain [6]. For operation close to degenerate (as in applications where the signal and idler are mixed to generate longer wavelengths [7, 8], a grating offers two advantages. Since typical parametric linewidths close to degenerate are large, it would otherwise be necessary to use two or more etalons for frequency narrowing. The prism grating arrangement therefore offers an attractive alternative. Secondly, since the grating produces strong discrimination between signal and idler, it is helpful in ensuring singly-resonant oscillation.

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*The reason why axial modes could be observed at all is not clear at present. An analysis of the spectral development during the build-up phase, following the approach of Bertolotti *et al* [5], suggests that axial modes should not develop under the high gain low-Q conditions prevailing in our laser. One possibility however is that these modes could develop after the gain has saturated, a phase which lasts for several round trips in our laser because of the small cavity length.

## References


1. T. W. HÄNSCH, *Appl. Optics* **11** (1972) 895-8.
2. S. A. MYERS, *Opt. Commun.* **4** (1971) 187-9.
3. U. GANIEL and G. NEUMANN, *Opt. Commun.* **12** (1974) 5-7.
4. H. F. MAHLEIN, *Optica Acta* **20** (1973) 687-97.
5. M. BERTOLOTTI, D. SETTE and F. WANDERLINGH, *Il Nuovo Cim.* **48B** (1967) 2421-35.
6. R. L. HERBST, R. N. FLEMING and R. L. BYER, *Appl. Phys. Lett.* **25** (1974) 520-2.
7. G. C. BHAR, D. C. HANNA, B. LUTHER-DAVIES and R. C. SMITH, *Opt. Commun.* **6** (1972) 323-6.
8. D. C. HANNA, B. LUTHER-DAVIES, R. C. SMITH and R. WYATT, *Appl. Phys. Lett.* **25** (1974) 142-4.