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A simple technique for improved performance of intracavity Fabry-Perot frequency selectors

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Abstract

By placing an intracavity Fabry-Perot transmission etalon between quarter-wave plates it is possible to operate it at normal incidence without spurious oscillation due to reflections from the etalon. The insertion loss and reduced finesse associated with a tilted etalon are thereby avoided. This technique will allow the use of longer etalons thus allowing much greater mode selectivity.

The use of an intracavity Fabry-Perot etalon is a well established technique for frequency selection in lasers [1,2]. In principle such an etalon with high reflectivity faces can provide very good mode-selectivity when used as a transmission filter. However it is necessary to ensure that laser oscillation is confined to radiation transmitted by the filter and this is usually achieved by tilting the etalon to suppress oscillation due to reflections from it. The tilt causes the multiply-reflected beams within the etalon to walk off transversely. This degrades the laser performance in a number of ways - it introduces an insertion loss [3-7] and it distorts the transverse profile of the laser beam. Also the etalon selectivity is degraded since the finesse is reduced. Thus attempts to increase mode-selectivity by using higher reflectivity surfaces or longer etalons are largely frustrated since these measures result in an increased sensitivity to walk-off. In this letter we report a simple remedy, involving the use of quarter-wave plates on either side of the etalon. By this means one can suppress oscillation from etalon reflections even when the etalon is aligned perfectly normal to the laser beam and at the same time allow oscillation due to light transmitted through the etalon. The full mode selection capability of a transmission etalon can therefore be realised and the insertion loss can be kept to a very low value.

The principle of using a polariser and quarter wave plate to suppress feedback from reflections is well known in situations where the feedback arises from a component outside the laser, see fig. 1a. A simple extension of this idea suggests an arrangement which ensures that the reflections from an intracavity etalon are suppressed, while transmission through the etalon is unaffected. An example of such an arrangement is illustrated in Fig. 1b. The quarter-wave plates 1 and 2 are placed either side of the etalon and a polariser separates this etalon assembly from the laser medium. The $\lambda/4$ plates can either have their fast axes parallel to each other or perpendicular. In either case these are at 45° to the plane of polarisation transmitted by the polariser. To simplify the discussion we shall assume the fast axes to be perpendicular, hence light which passes through both plates will have its polarisation state restored. Light which exits from the right hand face of the polariser is horizontally polarised (in the plane of the page) and any reflections from the etalon will return as vertically polarised light, just as in fig. 1a, and hence be rejected by the polariser. Laser oscillation due to feedback between mirror 1 and the etalon reflection will therefore be suppressed. On the other hand light which continues through plate 2 will be restored to horizontal polarisation and after reflection from mirror 2 and transmission again through plates 1 and 2 it remains horizontally polarised and hence transmitted by the polariser. The laser is therefore constrained to oscillate on a feedback path which involves transmission through the etalon. This arrangement still allows the possibility of resonance effects due to reflections between the etalon and mirror 2 (although note that two round trips between them are needed to restore the polarisation state and furthermore, those frequencies which have high transmission through the etalon will be only weakly reflected by the etalon.) One could in principle eliminate this resonance completely by adding a second polariser (polariser 2, as shown in fig. 1b). However in practice the effect of this resonance can be reduced to insignificant proportions by making mirror 2 the output mirror (hence having a low reflectivity) or by a very small tilt of the etalon, which has a negligible effect on the etalon performance. We have therefore dispensed with the second polariser. Since passage through the etalon assembly produces no polarisation change one can also use a Pockels cell Q-switch, in the usual quarter-wave configuration, placed adjacent to mirror 2.

A number of variations on this basic arrangement of components is possible. For example the role of the second quarter-wave plate could be taken by the Pockels cell Q-switch itself, with the closed condition corresponding to zero voltage and the open condition to quarter-wave voltage. Another possibility is to insert the quarter-wave plates as shown in fig. 1c, enclosing the etalon and laser medium. In this way the same quarter-wave plates can serve the additional purpose of preventing spatial hole burning effects in the laser rod as described by Siegman and Evtuhov [8] . It should be added that this configuration relies on there being only minimal birefringence in the laser medium. In fact the resonator configuration we have adopted for most of our tests is essentially as shown in fig. 1b, but without polariser 2; mirror 1 was a 5m concave total reflector, mirror 2 a plane 70% reflector. An aperture adjacent to mirror 1 selected the TEM_{oo} mode and the Pockels cell Q-switch was placed adjacent to mirror 2. The $^{\lambda}/4$ plates were thin quartz plates AR coated on both faces (Electro-Optic Developments Ltd.) In addition to the

$\lambda/4$ plates surrounding the etalon we also introduced a $\lambda/4$ plate on either side of the laser rod to eliminate spatial hole-burning. The etalon was made of fused silica, 1cm thick, with multilayer coatings of 65% reflectivity. The choice of etalon for these measurements was based on the fact that a similar etalon had previously been used to select a single longitudinal mode using the technique of prelase Q-switching [9,10] . It was noted then that the need to tilt the etalon caused a noticeable insertion loss and a reduction of finesse was inferred.

In testing the performance of this etalon in this new configuration we therefore had the following aims: (1) to confirm that normal incidence operation is possible without spurious oscillation due to etalon reflection. In fact at the maximum available flash lamp energies, ten times above threshold, oscillation due to etalon reflection could not be induced; (2) to measure the insertion loss of the etalon $\lambda/4$ plate assembly, including an investigation of insertion loss as a function of angular tilt; (3) to attempt a quantitative assessment of the finesse reduction due to tilt. We also compared our measured losses due to tilt with calculations based on analyses by Arnaud et al [6] and Leeb [7] . The predictions of these analyses differ somewhat and our measurements show best agreement with an expression from Arnaud. An attractive feature of Arnaud's analysis is that it also permits a calculation of finesse. For our etalon the degradation of finesse due to tilt is predicted to be small (for example, when the losses due to tilt are 20%, the finesse is also reduced by $\sim$20%). This reduction of finesse at larger angles is sufficient to cause a noticeable and measurable reduction of mode-selectivity, as evidenced by a decreased fraction of laser shots showing single mode oscillation when using the prelase Q-switch technique [9,10] . The uncertainties in these measurements are such that we can only claim qualitative rather than quantitative agreement with the calculated finesse. Nevertheless the good agreement over tilt losses does lend support to Arnaud's analysis and suggests that it can give valuable guidance in the choice of optimum etalon parameters.

The insertion loss measurements were made by first noting the pump threshold when the component to be measured was in the resonator, then replacing the component by a variable calibrated loss and adjusting this loss to give the same threshold. The calibrated loss was provided by the Fresnel reflection losses of a glass plate of known inclination. Since this technique relies on equalising thresholds it was found more convenient and reliable to keep the flash lamp input energy constant and simply observe on an oscilloscope the time delay from pump initiation to the appearance of the first relaxation oscillation. Random variations in this delay time were typically 0.5μsec, thus implying an estimated uncertainty in all of the loss measurements of 1% per single pass. It was found that the combined loss of the two $\lambda/4$ plates was too small to be measured, i.e. less than 2% per round trip, whereas the etalon had a small but measureable loss, 5% per round trip when inserted at normal incidence. With the $\lambda/4$ plates removed, and with the laser pumped to its typical operating level (32J flashlamp input) the etalon had to be tilted by 3.5 mrad to prevent oscillation from its reflections. The additional loss contributed by this tilt of the etalon was found to be 9% per round trip. The combination of $\lambda/4$ plates and normal incidence etalon therefore gave an insertion loss which was reduced by at least 7% from that of the tilted etalon alone. Much greater reductions in loss can be expected where a laser is allowed to operate in many transverse modes or is pumped harder since a larger tilt is then required to suppress spurious oscillation and the loss varies roughly as the square of the tilt angle (see [7]). The same would apply if thicker etalons were used since tilt loss varies roughly as $(\text{thickness})^2$, [7]. Figure 2 shows the results of loss measurements for a range of tilt angles and, for comparison, the calculated losses according to Arnaud et al [6] and Leeb [7]. The measured losses represent the additional losses, over and above the value found at normal incidence. The calculated values are based on a waist spot size of 0.7mm, appropriate to mirror 2 of our laser. Arnaud et al provide two different expressions for the etalon loss, one relating to the total transmission of the etalon (giving curve (d) of figure 2), the other relating to the part of the transmitted field which is in the same Gaussian beam as that incident on the etalon (curve (a) of figure 2). The latter of course corresponds to a higher loss. In fact, since Arnaud's analysis is confined to a single pass through the etalon, neither expression is strictly applicable to our experimental situation in which a measurement of double pass loss is made. Nevertheless the experimental results do show a good agreement with curve (a). Curve (b) is calculated from Leeb and curve (c) from a simplified expression given by Leeb (for small losses) viz. that the double pass in loss γ is

$$\gamma \simeq \frac{2R}{(1-R)^2} \left(\frac{2t\theta}{nW_o}\right)^2 \qquad (1.)$$

where R is the reflectivity, θ the tilt angle, t the thickness, n the refractive index and W_o the waist spot size. Our results confirm that this simple expression provides a useful, rough estimate of tilt losses.

In conclusion, we have demonstrated a technique leading to improved performance of intracavity Fabry-Perot frequency selectors. Our measurements have shown that the etalon/quarter-wave plate assembly suppressed spurious laser operation with the etalon aligned normal to the laser beam and that under these conditions the insertion loss is reduced and mode selectivity improved when compared with a tilted etalon. These results suggest that considerably more mode-selectivity can now be achieved by using thicker etalons since walk-off effects are no longer a limitation. The possibility of obtaining a very high mode-selectivity is of particular relevance to the recently reported technique [10] for obtaining single longitudinal mode operation on every laser shot. The use of this etalon assembly need not be confined to high gain lasers since a very low insertion loss can be achieved in principle. In fact for a very high finesse and very low insertion loss one could use an etalon with curved surfaces chosen to match correctly to the resonator mode.

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Captions

Fig. 1 (a) The polariser transmits horizontally polarised light (in plane of page), which, after passage through the $\lambda/4$ plate, and reflection back through the $\lambda/4$ plate becomes vertically polarised,and hence is rejected by the polariser.

1(b) As in (a) light reflected off the etalon returns to the polariser with vertical polarisation and is rejected. Light transmitted by the etalon assembly, then reflected off mirror 2 and returned back through the etalon assembly has horizontal polarisation and is transmitted by the polariser.

1 (c) A configuration in which the $\lambda/4$ plates suppress etalon reflections and also suppress spatial hole burning in the laser medium.

Fig. 2 Additional single pass loss due to tilt as a function of tilt angle for the resonator configuration described in the text. Crosses represent experimentally measured values.

Full lines are theoretical predictions:

(a) Calculation following Arnaud et al [6] , for transmission into the same Gaussian beam.

(b) Calculation following Leeb [7] .

(c) Calculation using simplified expression (equation (1) in text) due to Leeb [7] .

(d) Calculation, following Arnaud et al [6] for total transmitted power.

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Fig. 1a

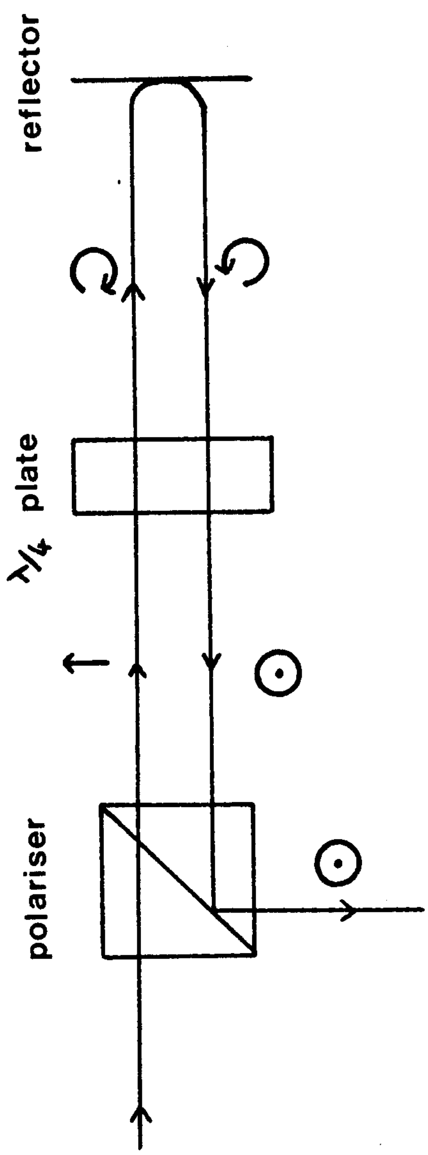
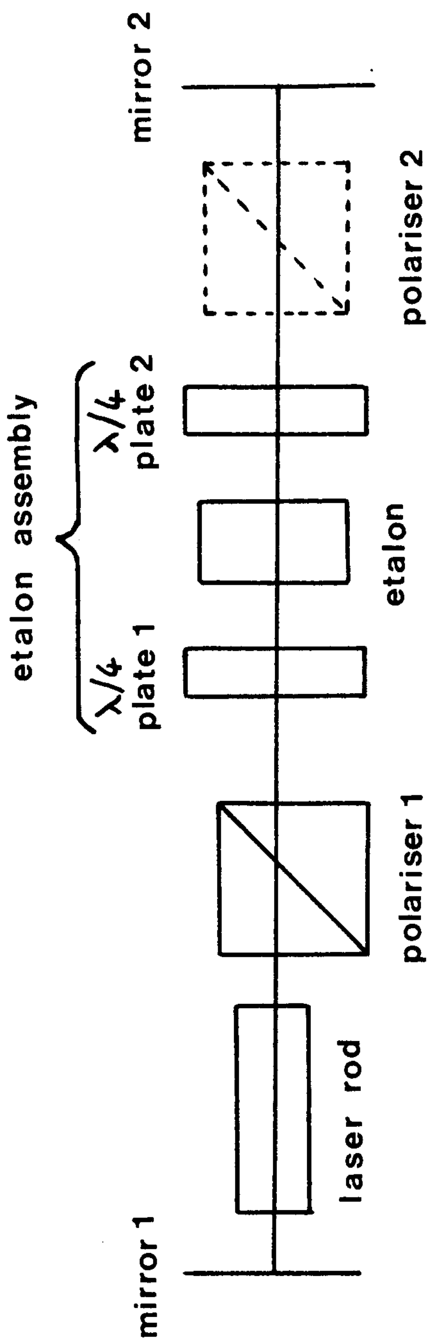


Fig 1b



mirror 1
laser rod
polariser 1
λ/4 plate 1
etalon
λ/4 plate 2
etalon assembly
polariser 2
mirror 2

Fig. 1c

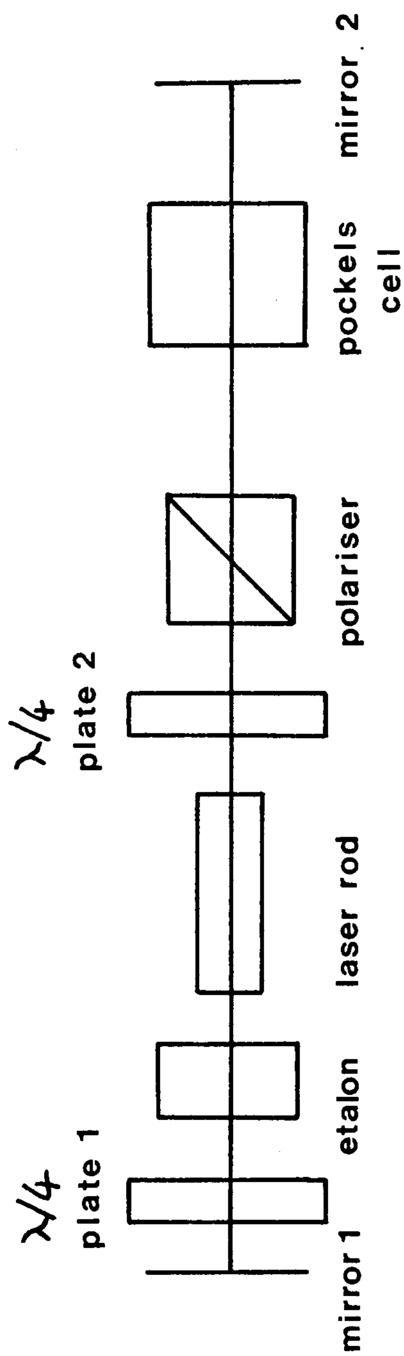

mirror 2
pockels cell
polariser
λ/4 plate 2
laser rod
etalon
λ/4 plate 1
mirror 1

Fig. 2.